PREPARING FOR A CHANGING CLIMATE

The Potential Consequences of Climate Variability and Change

Rocky Mountain/ Great Basin Regional Climate-Change Assessment

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Organizations of the participants in the five workshops
are recognized in the appropriate chapters

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EXECUTIVE SUMMARY

INTRODUCTION

In 1991, the United States Congress passed the Global Change Research Act directing the Executive Branch of government to assess the potential effects of predicted climate change and variability on the nation. This congressional action followed formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by the United Nations Environmental Program and World Meteorological Organization. Some 2,000 scientists from more than 150 nations contribute to the efforts of the IPCC.

Under coordination of the U.S. Global Change Research Program, the congressionally ordered national assessment has divided the country into 19 regions and five socio-economic sectors that cut across the regions: agriculture, coastal and marine systems, forests, human health, and water. Potential climate-change effects are being assessed in each region and sector, and those efforts collectively make up the national assessment.

This document reports the assessment of potential climate-change effects on the Rocky Mountain/Great Basin (RMGB) region which encompasses parts of nine western states. The assessment began February 16-18, 1998 with a workshop in Salt Lake City co-convened by Frederic H. Wagner of Utah State University and Jill Baron of the U.S. Geological Survey Biological Resources Division (BRD). Invitations were sent to some 300 scientists and stakeholders representing 18 socio-economic sectors in nine states. Actual assessment research began on July 1, 1998 with a grant from the U.S. Geological Survey to Utah State University. Frederic H. Wagner and Thomas J. Stohlgren of BRD were designated co-coordinators of the assessment.

The program has received guidance from a six-person Assessment Team comprised of the two co-coordinators and experts in climatology, hydrology, water resources, and agriculture. It has received advisory direction from an eight-person Steering Committee comprised of the two co-coordinators and representatives of stakeholder groups in the region: agriculture, ranching, environmental organizations, federal and state resource-management agencies, and the ski industry. The 12 members of these two bodies reside in five of the nine states in the region. More than 125 individuals have contributed assistance and input into the assessment and preparation of this report, and 13 additional professionals have provided critical reviews of parts or all of the document. The report has also been posted in the Internet for 30 days for public comment.

The assessment has followed a step-wise procedure. The first step was to identify five socio-economic sectors in the region that would be most likely to be affected by climate change. These are water resources, cultivated agriculture, livestock ranching, outdoor recreation and tourism, and natural ecosystems.

The second step was to develop a set of climate-change scenarios for the 21st century with input from a workshop of professional climatologists, analysis of 20th-century climate patterns in the region, and projections of 21st-century climate change with two, large computer models (general circulation models, or GCMs) that simulate the earth's climate system. The projections were based on the assumption of a doubled increase in atmospheric CO_2 by 2100, and programmed into the models.

The scenarios were then used as the basis of what-if exercises that analyzed the direct and socio-economic effects on the five sectors if the climate-change scenarios became reality. Since the sectors are under a variety of pressures besides climate, and are changing as a result; and since major climate-change effects are several decades in the future; it was necessary to project these sectoral trends into the future and assess climate-change effects at those future points in time. Typical questions would be "What would be the effects on Intermountain agriculture, and its contribution to the region's economy, of a 3°C (5.4°F) rise in temperatures, and a 50% increase in precipitation by 2060?" This document reports the results of these exercises.

BIOGEOGRAPHY OF THE ROCKY MOUNTAIN/GREAT BASIN REGION

The Rocky Mountain/Great Basin region includes the Rocky Mountain system from northern New Mexico through Colorado, Wyoming, Montana, the Idaho Panhandle, and the Wasatch and Uintah Mountains of Utah. It includes the Great Basin extending over the western half of Utah, most of Nevada, Idaho south of the Snake River, and parts of eastern Oregon and Washington. It is the second largest of the 19 regions being assessed, second only to Alaska.

The great size, topographic diversity produced by more than 200 mountain ranges and intervening valleys, and elevations ranging from 831 to 4,440 m (2,726-14,431 ft) all create a complex mosaic of local climates. Temperatures decline and precipitation increases with rising latitudes and elevations. Mountain ranges create rain shadows and dry conditions on their down-wind sides. General circulation models, while on the cutting edge of science, are not yet sufficiently developed to simulate climate trends at this local level of resolution.

However there are regional climatic patterns that override this localized diversity. Average temperatures decline, and growing seasons shorten from south to north in the region. In the northwestern and western portions of the region, precipitation is highest in the winter months and at its lowest levels in summer. Eastward and southward, spring and early summer months receive significant amounts. In the southeastern portions of the region, July-September becomes the peak rainfall season, and winter is the dry period. It is these regional and subregional average climates which the GCMs can approximate, and which are the scale of this assessment.

Spring melt of snowpacks that form on the mountain tops in winter feed the region's streams which provide water for agricultural irrigation; and for municipal, industrial, hydropower, and recreational uses. Some 85% of this water use comes from surface water. And the snowpacks are in essence the headwaters of the Columbia, Missouri, Colorado, Rio Grande, Platte, and Arkansas Rivers.

Cultivated agriculture, livestock ranching, and outdoor recreation and tourism contribute to the economy of the region. Some 75-80% of the area is in public ownership and covered with natural ecosystems in varying degrees of human use and consequent alteration.

Until the middle of the 20th century, much of the RMGB region's sparse human population was rural, subsisting on extractive uses of the land (agriculture, ranching, mining, timber harvest). In recent decades, the region has had the fastest-growing population in the nation. Most of that growth has concentrated in the cities, and the states are now among the most urban in the nation. The new population assigns newer, nonconsumptive values to the natural resources while at the same time creating new environmental problems of air and water quality, transportation, urban sprawl, and competition for scarce water resources.

Concerns for climate change must address both effects on traditional socio-economic sectors as well as the new culture of the region. And the effects must be evaluated in the context of stresses already operating in the region: its aridity, water shortage, and ecological and environmental changes wrought by the traditional land uses, and by activities of the burgeoning, new population.

This report, and the assessment which it describes, do not advocate policy. Their purpose is only to provide technical information and analyses that produce a factual environment within which policy alternatives can be considered by policy makers. The assessment does not make any value judgments among the alternatives, although it may point out the technical and socio-economic implications of those alternatives.

CLIMATE-CHANGE SCENARIOS

Climate-change scenarios for the RMGB region were developed with a combination of three procedures: (1) recommendations from a 3-day workshop of climatologists knowledgeable on western North American climates; (2) analysis of 20th-century climate records for the region to determine whether climate changes projected for the 21st century had started to appear in the 20th; and (3) projections of two, large computer models that are structured to simulate the earth's climate system. Both models were adapted for western North America, and programmed to project 21st-century climate change under two-fold increase in atmospheric CO_2 by the end of the century.

Climatologists Workshop on Scenarios

A workshop of climatologist, with expertise in western North American climates, was held at the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA, from September 10-12, 1998. Its purpose was to obtain recommendations on appropriate climate-change scenarios for the RMGB assessment. Brief abstracts of the participants' presentations follow.

Michael Dettinger, U.S. Geological Survey, Scripps Institute of Oceanography, La Jolla, CA: Decadal climate variations (variations with periodicities longer than 7 years) drive 30-60% of the year-to-year variation in North American precipitation and streamflow. The timing of these variations differs between the northern and southern portions of the RMGB, and their effect is more pronounced in the north. They also modulate lower-frequency variations like the El Nino-Southern Oscillation (ENSO) and annual and seasonal cycles. This variability complicates the development of models that project climate change at regional and subregional scales.

Thomas J. Stohlgren, U.S. Geological Survey, Mid-continent Ecological Science Center, Colorado State University, Fort Collins, CO: The El Nino-La Nina cycle varies on a 2-7 year periodicity. In the El Nino phase, precipitation increases in the southern portion of the RMGB, declines in the central and northern portions. The pattern is reversed in the La Nina years. These variations further complicate the problem of predicting human-induced climate changes with general circulation models (GCMs).

Roger A. Pielke, Sr., Department of Atmospheric Science, Colorado State University, Fort Collins, CO: Vegetative cover and land use have been shown to influence local, regional, and global climates. The failure to include them in GCMs raises some uncertainty about the validity of the models' simulations. A "vulnerability approach" that weighs the collective effects of a variety of stresses, including climate change, on affected socio-economic sectors may be more pragmatic.

Linda O. Mearns, National Center for Atmospheric Research, Boulder, CO: Research comparing simulations of two GCMs—the British Hadley Centre Circulation Model 2 (HadCM2) and the Canadian Coupled General Circulation Model 1 (CGCM1)—for the continental U.S. for the period 1921-1980 with actual climatic measurements for that period showed that both models underestimated the measured temperatures in the western U.S. at all seasons. The differences may in part be due to the low-elevation positioning of most weather stations in the West while the models crudely simulate the region as a single, large hill rising from the west coast and descending to the Great Plains. Both models overestimate precipitation for the test period. Both produce relatively similar errors, and neither reproduces the western U.S. climate better than the other.

Mearns also simulated climate changes for the period 2055-2065 under the assumption of doubled atmospheric CO_2. Both models projected temperature and precipitation increases, with the Canadian model projecting greater increases than the British. She also reported experiments comparing simulations for western U.S. of both previous and future climates under doubled CO_2 conditions with an Australian general circulation model, and a regional model developed at NCAR. The latter was more successful at reproducing the spatial distribution of temperature and precipitation in the western U.S.

John Fyfe, Canadian Center for Climate Modelling and Analysis, Victoria, B.C.: He outlined the structure of the first version of the Canadian Global Coupled Model (CGCM1), both with the ocean and atmosphere models uncoupled and coupled. He described experimental simulations for the period 1850-

2100 that included 1% per year increases in CO_2, both with and without sulphate aerosols. He also compared model runs with observed 1900-1990 temperature trends which showed "overall agreement" in trends and magnitude of interannual variability.

The Canadian model does not capture the detailed topography of the Rockies, but it does reflect large-scale topographic structure. The Rockies are high enough over a sufficiently large area to affect a climate-change signal, and temperatures are projected to rise more at high elevations than at low. A number of technical improvements are being made in the models.

Robert L. Wilby, National Center for Atmospheric Research, Boulder, CO: Because the outputs of the GCMs are too coarse for making precise assessment of climate-change effects at regional scales, climatologists are experimenting with a procedure termed statistical down-scaling. While there have been attempts at evaluating the approach, more analyses are needed to assess the importance of a number of identified shortcomings.

Wilby and colleagues undertook a hydrological study of the Animas River Basin in Colorado to compare scenarios from raw GCM outputs, from down-scaled GCM outputs, and from an experiment in which the difference between current weather patterns and GCM outputs were added to measured climate trends. All were coupled to a hydrologic model. While there were differences in simulated streamflow of the Animas between the scenarios, there was "qualitative consensus" between them that future low and intermediate flows would increase; and that peak flows, basin snow-covered areas, and snowpack water equivalents would all decline relative to current conditions. Wilby recommended that a range of plausible scenarios be applied in parallel.

T.H. Stohlgren, in his postworkshop, summary remarks on the presentations, commented on the great temporal and spatial variations in RMGB climates, and the consequent difficulties in separating out human-caused climate trends. He further reiterated his concerns for the ability of global-scale models to provide appropriate regional and subregional scenarios due to their limited topographic resolution; their systematic biases; and their lack of provision for biophysical feedbacks, measurement of probabilities, and consideration of other ecosystem stresses. He stated that many stakeholders are more concerned with predictions of short-term weather events than climate-change prospects 100 years in the future. He stressed the importance of strengthened climate and stream-flow monitoring and intensified research on climate patterns and regional climate scenarios.

In discussions at the workshop following formal presentations, the participants' views divided into two schools of thought. The workshop had been convened to get expert opinions on appropriate climate-change scenarios for the regional assessment. One group of participants advocated cautionary use of the GCM projections, always viewed with reservations prompted by knowledge of the biases and shortcomings discussed above. The other group considered the uncertainties of the GCMs too great to risk their use, and recommended vulnerability analysis. These two perspectives were termed "top-down" and "bottom-up" approaches. The decision was made to follow both procedures.

Historical Climate Analysis

Since atmospheric CO_2 increased by 20% during the 20^{th} century, this assessment undertook an extensive analysis of climate trends in the RMGB region during the 1900s. Its purpose was to gain some indication of whether the climate changes projected by the general circulation models for the 21^{st} century, when atmospheric CO_2 is predicted to double, began to appear during the 20^{th}. The analyses were based on weather records in the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) which are spatial averages of climate variables measured at weather stations in 0.5^{o} quadrangles across the nation.

Because of the size and complexity of the RMGB region, and the possibility that climate trends could vary across its extent, the 308 VEMAP quadrangles were subdivided into eight subregions ranging in size from 9 to 66 quadrangles. The eight, and their acronyms , are: Northern Great Basin (NGB), Central Great Basin (CGB), Southern Great Basin (SGB), Northern Rockies (NR), North-central Rockies (NCR), West-central Rockies (WCR), East-central Rockies (ECR), and Southern Rockies (SR).

Several statistical tests were used to measure the 20th-century trends in the following climate variables within each of the eight subregions:

(1) Annual average of daily minimum temperatures: Tmin.

(2) Annual average of daily maximum temperatures: Tmax.

(3) Annual average temperature (average of Tmax and Tmin for each year).

(4) Standard deviations around 30-year moving averages of Tmin, Tmax, and mean, annual temperatures.

(5) Total precipitation for each year.

(6) Standard deviations around 30-year moving averages of annual, total precipitation.

Data on several sources of 'natural" climate variation were analyzed to determine whether these vary over time scales similar to ones under analysis for the RMGB, and thus complicate attribution of any climate changes in the region to greenhouse-gas forcing. To be detectable, any human-caused climate changes must emerge out of background variation driven by nonhuman ("natural") physical forces.

There is evidence of effects on RMGB climates from three quasi-cyclic climate oscillations in the region: The Pacific Decadal Oscillation (PDO), Atlantic Oscillation (AO), and the El Nino-Southern Oscillation (ENSO). The first two had periods of approximately 24 years during the 1900s, varying between cool-moist and warm-dry periods. Their influence is more pronounced in the northern part of RMGB. The ENSO period averages 3-4 years, and also varies between cool-moist and warm-dry phases. Its influence is more pronounced in the southern portion of RMGB.

Since the phases of PDO and AO differ from the ENSO phase, the stages of the three coalesce at times and reinforce each-other's effects, fall in opposite stages at times and mute their effects, and simply fluctuate independently producing random-like variation. Moreover, each of these is a quasi-cyclic process without any evidence that there is a secular trend with each oscillation occurring at successively higher or lower levels over time periods longer than their phases. And with periodicities significantly shorter than the century-long trends under investigation here, there is no possibility that the individual oscillations correlate with those trends. As a result, the effect of these oscillations is to create a background of random-like variance in climate trend, and to require statistically that any secular, human-caused signal be of sufficient strength to emerge from this "noise." Our analyses have shown no consistent, strong effects on the 20th-century climate trends in the RMGB from these climatic influences other than imparting short-term variation uncorrelated with century-long patterns.

Some climatologists have described longer-term climate change associated with a cooling trend during the Middle Ages that culminated in a Little Ice Age in about 1650, then went into a warming trend that continued to the start of the 1900s. Any temperature rise during the 20th century could conceivably be a continuation of this natural warming trend and not necessarily human-caused.

However, several recent authors have reconstructed Northern Hemisphere temperature trends over the past 1,000 years with ice-core and tree-ring data, termed proxies, up to the middle 1900s, and instrumentally measured temperatures from 1850 to the present. These show generally declining temperatures from 1,000 to about 1850, with shorter-term ups and downs in the trend. Temperatures then rise sharply from about the 1850s to the present, and at a rate and to a level not experienced during the preceding 1,000 years. Moreover, we analyzed tree-ring proxies and measured temperatures for 1600-1950 for each of the four seasons in each of the RMGB subregions. Only 5 of the 32 showed increasing temperatures during the 1800s, while 12 showed decreases, and 15 showed no change.

Thus, any Little Ice Age effect is variable in space and time, and the available evidence does not indicate any consistent effect on RMGB temperatures. More generally, there have been a number of "natural" sources of variation in 20th-century RMGB climates. But none appears to have imposed a significant secular trend on the climate variables of the period.

Analyses of the 20th-century climate data for this assessment show increases in Tmin in 7 of the 8 subregions of RMGB, 5 statistically significant at $p<0.05$, and 2 at $p<0.20$. The five most pronounced changes ranged from 0.38°-

0.62°C (0.68°-1.12°F) over the 100-year period, and occurred in NR, NCR, WCR, NGB, and SGB. The subregion without significant change was SR.

The tests for Tmax showed significant increase only in NR ($p<0.01$) and SGB ($p=0.12$). The pronounced increases in Tmin with only slight or no increases in Tmax implies that the diurnal temperature range declined during the 1900s, a result also reported for the Rocky Mountains by Kittel et al. (2002).

Mean, annual temperatures rose significantly ($p<0.05$) during the 1900s in 3 subregions (NR, WCR, SGB), and in 2 (NGB, NCR) with $p<0.10$ in one of two tests. These are the same five subregions in which Tmin rose significantly. The increases ranged largely from 0.3°-0.6°C (0.54°-1.08°F). The subregions in which the trends conspicuously failed to reach significance were ECR and SR.

These results coincide with those of two other studies which drew on other data sources and subdivided the RMGB into other subregions. Kittel et al. (2002) found a significant rise ($p=0.005$) in Tmin during the 1900s in the northern and central Rockies, but no significant rise in their southern Rockies subregion. They also found slight increases in Tmax, but all were short of significance. Karl et al. (1996) found increases in mean, annual temperatures throughout the region.

Our analyses found declines in standard deviations around successive 30-year means of Tmin between the 1930s and 1980s in all subregions but SR. Similar declines were evident in standard deviations around successive 20-year means of Tmax in NR, NCR, NGB, and EGB. The implication is that interannual variability in temperatures declined during the period.

This assessment also found significant, 20th-century increases in annual precipitation in 5 of the 8 subregions, 3 at $p<0.05$ (CGB, SGB, NCR) and 2 at $p\leq0.1$ (NGB, NR). Increases ranged from 6-16% per 100 years. The increases occurred largely in summer, especially June. Standard deviations around successive 30-year mean, annual precipitation increased from about the 1920s or 1930s to the 1980s in those five subregions with significant 20th-century increases in precipitation. This implies that interannual variability in precipitation increased during the period.

The results are again similar to those of the above authors. Kittel et al. (2002) found significant increases in summer precipitation in their northern and central Rockies subregions during the 1900s. Karl et al. (1996) found precipitation increases in the region.

In total, the weight of the evidence points to 20th-century temperature increases in the NR, NCR, WCR, NGB, and SGB subregions. The trends are weak, if present, in the ECR and CGB, and not present in the SR. They are most pronounced in Tmin, marginally present in Tmax. As a result the diurnal temperature differences (daily differences between Tmin and Tmax) declined during the century in those areas with significant temperature increase. The declining standard deviations around successive 30-year mean, annual temperatures imply that interannual temperature variations declined. As a result, the probability of very warm years increased, and very cold years declined.

The evidence also indicates increase in annual precipitation, especially in summer, and again in the more northerly and westerly subregions of the RMGB. Increases in annual precipitation ranged from 6-16% over the 20th century. The increasing standard deviations around successive, increasing 30-year means of annual precipitation imply an increasing probability of extreme, high precipitation years; and possibly declining probability of dry years, depending on the shape of the new probability distributions.

GCM Scenarios for the RMGB Region

GCM climate-change scenarios are outputs of computer (mathematical) models structured on the basis of the known physics of the earth-ocean-atmosphere system that drives the earth's climate, and of the effects of atmospheric CO_2 on that system. Like all simulation models, the GCMs are oversimplifications, in this case of the global climate system. Their outputs should therefore be considered approximations of future climates. Thus they are not considered either predictions or forecasts of future conditions, and it is not meaningful to refer to their accuracy or predictive power. However, the scenarios assume some measure of plausibility - - i.e. are considered to approximate reality - - because the models are structured on the basis of the known physics of the earth's climate system; and in the case of the RMGB region, the GCM projections are in the same direction as the 20th-century climate trends.

Because they are global models, their outputs must be considered averages of local climates over extensive areas. They cannot be expected to project climate changes at localized areas among which climates are highly variable, especially in the RMGB with its great topographic variation.

The purpose of scenarios in this assessment is to call attention to possible effects of climate change, should they occur, on potentially affected socio-economic sectors important to society; and to stimulate stakeholders to begin thinking about potential coping strategies. Thus they are the basis of what-if, intellectual exercises.

Two state-of-the-art, atmosphere-ocean-land general circulation models have been used to project climate change by 2080-2100 under a two-fold increase in atmospheric CO_2: the British Hadley Circulation Model 2 (HadCM2) and the Canadian Coupled General Circulation Model 1 (CGCM1). These models project the following changes by 2080-2100 for the RMGB region as a whole:

Temperature:

HadCM2: +2.5°C in spring to +4.5°C in winter (+4.5°-8.1°F)

CGCM1: +5.0°C in summer to +8.0°C in winter (+9.0°-14.4°F)

Precipitation:

HadCM2: +54 to 119% in annual precipitation, greatest increase in winter

CGCM1: +59 to 184% increase in annual precipitation, greatest increase in winter

Scenario Selection

Three procedures or data sources were used to provide input into decisions on 21st-century, climate-change scenarios for the RMGB assessment: suggestions by climatologists at the 1998 workshop, analysis of RMGB climate trends during the 20th century, and output from the two GCMs. While the magnitude of changes projected by the GCMs for the 21st century greatly exceeds the measured changes that occurred during the 20th, the differences can perhaps be rationalized by the fact that atmospheric concentration of CO_2 during the 1900s rose by 22%. The projected increase in the 21st century is 100%. The GCM outputs gain in plausibility because their projections are in the same directions as the climate trends of the 1900s.

The deliberations of the climate-change workshop divided into two schools of thought: direct use of the GCM outputs as scenarios for the sectors, and a procedure termed "vulnerability analysis." The latter was never explicitly formulated into an assessment procedure, but it advocated analyzing climate-change effects in the context of the array of factors operating on a sector.

Final decisions on climate-change scenarios to pose to the sectors were based on several considerations. An array of temperature and precipitation values, ranging from no change to increases up to the values projected by the GCMs, were posed to all sectors. In addition, a precipitation-decrease scenario was posed to the Rocky Mountain-ecosystem sector. In several cases, seasonal changes most likely to affect sectors (e.g. winter temperature and skiing) were emphasized.

Each sector was examined in the context of major environmental factors other then climate affecting it, and the interaction of climate change with these was evaluated. This is considered an interactive approach combining both the top-down and bottom-up procedures. In all cases, the exercises are provisional, their precise validity contingent upon the reality of the scenarios.

WATER RESOURCES

Approximately 85% of the water used by people in the arid-to-semi-arid Rocky Mountain/Great Basin region comes from surface water largely originating as melt and run-off of montane snowpacks. The temporally and spatially variable resource is captured, stored, and distributed to urban, industrial, and agricultural areas by an extensive engineering infrastructure of dams, reservoirs, and aqueducts. Because water is scarce, fully utilized, and limiting to human activities in the region, any climate change affecting water availability could have significant social, economic, and ecological effects, either positive or negative.

This assessment analyzed twentieth-century hydrologic trends in the region to explore whether the 1900s temperature and precipitation increases detected for most of the region have affected its hydrology. The assessment effort distributed questionnaires to federal, state, and local water managers in the region to ask about major, contemporary management problems they face, and how these would be affected by climate change.

A workshop of six of the questionnaire respondents and a number of individuals familiar with water-policy issues discussed the same questions with additional emphasis on policy matters. The assessment then posed three climate-change scenarios and discussed the implications of each for water resources and management, and the socio-economic consequences. It closed with a consideration of potential coping strategies, primarily in the case of water shortages and of flooding problems.

Twentieth-century Hydrologic Trends

Data were analyzed from gaging stations, with long (e.g. 64-77 years) high-quality records, on five streams in the RMGB region: Boise River (Idaho), Humboldt River (Nevada), Yellowstone River (Montana-Wyoming), Blacksmith Fork (Utah), and San Juan River (Colorado-New Mexico-Utah). Annual flow increased during the century in the Boise, Humboldt, Blacksmith Fork (all significantly at $p \leq 0.05$), and Yellowstone ($p > 0.05$). There was no pronounced trend in the San Juan. Low-flow characteristics (annual, minimum 7-day average flows) declined during the 1900s in the Boise, Yellowstone, and Blacksmith Fork. Standard deviations around 30-year moving averages of annual flow in the four streams showing increased flow also increased.

In sum, annual streamflows increased from 12-33% during the 1900s in four streams in the northern and western portions of the RMGB. Their minimum flows declined, as would be expected of generally increasing annual flows. Combined with increasing interannual variability, the analyses imply increasing frequency of very high flows and reduced frequency of low flows. The results coincide with those portions of the region showing increased amounts and variability of precipitation, and they agree with other authors' analyses of western streamflow trends.

Analyses of the annual flows of the Colorado River and its major tributaries in Colorado show no demonstrable trend from the 1920s to the end of the century. This is the portion of the RMGB in which no precipitation increase was evident in the 1900s.

Seasonality of flow in western streams is influenced by the time in fall and early winter when rain changes to snow, by the timing of spring snowmelt and run-off, and by the seasonal distribution of precipitation. Several authors predict that as temperatures increase, fall and early winter precipitation will continue as rain later into the winter, thereby increasing fall and early-winter streamflow, delaying and reducing snowpack formation, and reducing the level of the spring run-off peak. Higher spring temperatures are projected to advance spring snowmelt and run-off.

Three tests were employed to analyze whether the predicted changes in streamflow seasonality had begun during the 1900s. In the first, monthly changes in snow-water equivalents, measured each year from 1932-1998 at a SnowTel (National Resources Conservation Service) station in Utah's Wasatch Mountains, were examined to determine whether there had been any trend in snowpack formation and melt during the century. None was evident at this station.

In a second test, unpublished data provided by Michael Dettinger on the Boise, Humboldt, and Yellowstone Rivers were analyzed to determine the annual dates of peak flow from the early 1900s through 1993. Date of peak flow advanced 10-15 days during the measurement period in all three streams. Dettinger had observed similar trends in other streams in the Northern Rockies.

In a third test, trends in the seasonality of flow during the 1900s in the five rivers studied in this assessment were compared with the seasonality of precipitation. Changes in winter and spring flow levels in four of the five streams, uncorrelated with changes in precipitation in the streams' subregions, suggested alteration by warming temperatures. In sum, limited and circumstantial evidence points to seasonal changes in streamflow in the RMGB coinciding with rising temperatures during the 1900s.

Survey of Water Managers

Analyses of 20th-century climatic and hydrologic trends, and projections of the GCMs, were used to structure a questionnaire for 19 federal, state, and local water managers in seven of the RMGB states. The recipients were asked to describe their current responsibilities, major contemporary stresses including climatic that affect their operations, and their views on how climate change would affect their management of water resources.

Population growth, with its increasing and changing demands for water, and climate variability are the major stresses with which the managers now contend. Others are water-quality issues and lack of public understanding about hydrology and water management in the West.

Increased precipitation would raise a need for greater reservoir storage and perhaps modified [dam] spillway standards. Greater snowfall would raise concerns for flooding and mud slides. Seasonality of spring run-off governs operating rules for reservoirs and affects ecology of river systems. Changes in seasonality could have the greatest impact of any of the climate changes discussed: operating rules would need to be modified, and the need for additional flood storage would need to be balanced with other uses.

Reservoir operations are now programmed to contend with droughts lasting 2-4 years. Longer droughts would require greater planning and result in economic loss. The stress would be accentuated by population growth and would accelerate the transfer of irrigation water to municipal use. Extreme heat waves increase urban water demand and evaporative loss, drive greater fluctuations in reservoir releases, and are harmful to aquatic ecosystems.

Opinions vary among managers as to whether there have been climatic changes in recent years, and if so, whether they are human-caused. But there is general consensus that their focus is on coping with contemporary climate variability. How climates might change 50 or more years in the future "is not on their radar screens."

Proceedings of Water-managers Workshop

Six respondents to the questionnaire and several individuals knowledgeable in water policy participated in a workshop at the National Center for Ecological Analysis and Synthesis, Santa Barbara, CA, on February 22-24, 1999. Discussion on operational issues centered on the same points reported on the questionnaires.

Major stresses are climate variability; population growth and changing landuse; diversifying public values (e.g. environmental, esthetic) attached to water; and lack of public understanding about water management. Climate change could pose a need for increased storage capacity at a time of public antipathy to dam construction; and for dike and levee construction around riparian zones and flood plains where much of western development has occurred.

Designed to cope with aridity and scarcity, the western hydrologic infrastructure was built by the federal government while western water laws were enacted by the states. These function on the principle of prior appropriation: water is allocated to rights holders in the chronological order in which rights were granted. Each year senior rights holders are entitled to receive their full appropriations before more junior holders receive any water. If water in a given year is scarce, junior holders may not receive any. Most western rivers are fully appropriated, aquatic ecosystems are in decline, and groundwater is being mined nonsustainably.

By law, allocated water is to be used fully for "beneficial use," a historical term generally implying agriculture and often creating difficulties for transferring rights to other users. If allocations are not fully used, rights can be lost. The latter can induce wastage.

Rapid population growth, primarily urban, new federal environmental laws (e.g. Clean Water Act, Endangered Species Act), and adjudication of historically neglected Native American water rights are increasing pressures on water law. Municipal water costs range from $200-400 per acre foot while those for agriculture are typically $10-20. Thus there are economic incentives for agriculture, which currently uses ~80% of western water, to transfer rights to the growing, alternative needs.

Reducing agricultural subsidies, broadening the beneficial-use concept, and changing the "use-it-or-lose-it" principle are all promising steps toward more efficient use. Any climate-change effects on water resources will function within this western institution of water management and allocation.

Potential Climate-change Effects and Coping Strategies

This assessment considers the potential implications of three climate-change scenarios. Scenario 1 poses a 50-100% increase in precipitation, similar in magnitude to that posed by the GCMs, and increases in annual temperatures of 2.0°-3.5°C (3.6°-6.3°F). Scenario 1 also assumes that the precipitation increase would produce an equivalent increase in water resources.

A 50-100% increase in water resources by 2100 would ease or eliminate the current shortages. It could accommodate a 2x increase in population, mostly urban which currently uses 20% of the resource; continue to accommodate agricultural use; meet the newer demands for Native American rights and in-stream environmental values; sustain evapotranspiration loss associated with higher temperatures; and if 100%, provide increased water for downstream users outside the region.

However, the altered seasonality associated with shrinking or disappearing snowpacks would require significant changes in water-management regulations and practices; and along with the increase in volume would almost certainly create a flooding problem and raise questions about dam stability and reservoir capacity. Riparian corridors and flood plains, sites of much of western urban development, would be at risk.

Scenario 2 poses the same temperature increases for the entire region as with Scenario 1, and the same precipitation increases for the northwestern three-fourths of the region. But it projects no precipitation increase for the southeastern fourth. Socio-economic effects and coping needs for the northwestern three-fourths would be the same as those for Scenario 1. But the higher temperatures and lack of precipitation increase in the southeastern fourth would increase evapotranspiration, reduce water resources, and exacerbate the current water scarcity. The socio-economic effects would be the same as those for Scenario 3.

Scenario 3 projects increased temperatures, no change or decrease in precipitation, xerification of the region, and decline in water resources. Growing demands on the resource could be met with transfer of rights from agriculture, changes that would incur social costs as farmers and farming communities would be displaced. A number of conservation measures are possible in the agriculture sector, and in the urban sector where two-thirds of water use in the Intermountain West goes to lawns and gardens.

No policy action is suggested at this point. But there is a definite need for acquiring relevant, prospective information that will both discern whether the projected changes begin to occur during the next 2 to 3 decades, and provide a data base for appropriate decisions in the future. A first need is an intensive effort at hydrological modeling of the RMGB streams to simulate the effects of projected climate on streamflow magnitudes and seasonalities; and on the abilities of dams and reservoirs to accommodate the simulated changes. A second need is an expanded monitoring effort, including more high-elevation weather and snowcourse stations, on flow and water quality in western streams, groundwater levels and quality, and status of wetlands, riparian zones, and springs.

CULTIVATED AGRICULTURE AND RANCHING

Cultivated Agriculture

Although there are areas of intensive agriculture in northern Utah, southern Idaho, and eastern Oregon, cultivated agriculture is not a major landuse form or contributor to the Rocky Mountain/Great Basin region's economy. Only 10% of the region's area is in farms, and 5% is cultivated. Hay, potatoes, wheat, and barley, in that order of importance, produce 88% of the crop income in the region. Hay, between a third and half irrigated, makes up 41% of the region's total crop value.

During the 1980s and 1990s, hay acreage remained largely unchanged, potato acreage increased, and small grain acreage declined significantly. In total, cultivated acreage in the region declined by 18% due in part to the region's rapid population growth with its expansion of urban, industrial, recreational, and infrastructure development into farmland.

During the same period, per-acre yields of the four crops increased, evidently due to genetically improved varieties, more effective machinery, and more efficient cultivation practices. Consequently total production of wheat, hay, and potatoes increased although barley production declined owing to a 44% reduction in acreage harvested.

The 20th-century increase in production was largely offset economically by falling commodity prices so that agriculture achieved little if any economic growth during the century. Moreover, rapid growth of the urban/industrial sectors reduced agriculture's already small fraction of the region's economy.

Under climate-change Scenario 1 for agriculture—no climate change—the trends of the late 1900s in the region's agriculture would be likely to continue in the 2000s. A 2x population increase by 2050 would in all probability continue to drive urban expansion into agricultural land. The population increase would double the demand for urban/industrial water at the expense of irrigated agriculture. Property values would likely increase providing incentives for farmers to sell their land. In total, in the absence of change in the present climatic pattern, agriculture would in all probability continue to decline as a fraction of the region's economy, and possibly in absolute terms.

With Scenario 2—higher temperatures without precipitation change—the net effect would be xerification. Increased evapotranspiration would accentuate the competition for water, and along with the population growth, hasten the shift of agricultural water to urban/industrial use. The warmer temperatures would probably increase growing season length, and CO_2 fertilization would increase water-use efficiency of the crops. But without additional precipitation, it is questionable whether this would offset the increased evapotranspiration. Coupled with increased transfer of agricultural water to the urban/industrial complex, it is doubtful that agriculture would experience a net benefit. The end result would be to hasten its decline.

Scenario 3: GCM projections of temperature and precipitation increases. In order to project the 21st-century crop-production trends implied by Scenario 3, a stepwise regression model was developed to analyze the correspondence between a wide range of 20th-century climate variables and yields of hay, potatoes, wheat, and barley in that century in the nine states of the region. The sampling units were 24 crop-reporting districts (CRDs) of the U.S.D.A. National Agricultural Statistics Service within nine states of the region, and which reported $\geq$ 1000 acres of one or more of the four crops. A total of 72 significant regressions between crop yields and climate variables in the 24 CRDs were calculated. Most of the variance in annual crop yields was associated with annual mean temperatures and precipitation in each of the four seasons.

The equations for these tests were then used, with the GCM climate-change scenarios as inputs, to project hypothetical yields of the four crops in the 24 CRDs for the period 2080-2100. Since the GCMs projected ranges of precipitation change, both high and low values of the ranges were used as inputs in separate tests. Simulated yields of wheat, barley, and potatoes increased in 64% of 56 crop-CRD tests. The magnitudes of change depended on whether the high or low values of the precipitation ranges, and which of the two GCMs, were used. Low precipitation values projected 14-47% increase in wheat, 6-31% in barley, and 28-56% in potatoes. High precipitation values generally projected doubled or tripled yield increases in these crops.

Simulated hay yields did not change or declined in 63% of hay CRDs. This low response may be attributable to the fact that hay is largely irrigated and probably not as sensitive to increased precipitation, and to the fact that the models do not change the current double-cutting pattern. If warmer temperatures permitted more cuttings per year, there would in all likelihood be increases in total yield.

In sum, substantial increases in per-acre yield under Scenario 3 could benefit RMGB agriculture and provide socio-economic stability for rural communities during the 21st century. But if the increased yields reduced prices, and if rapid urban/industrial population growth continued to usurp the limited acreage of agricultural land in the RMGB, it does not seem likely that the yield increases would significantly expand agriculture's small fraction of the region's total economy.

LIVESTOCK INDUSTRY

While cultivated agriculture is carried out on only 5% of the RMGB area, most of the nonurban area of the region is grazed by privately owned livestock, largely (93%) cattle. But because the area is arid to semi-arid, forage production and carrying capacities are low, and livestock sales are only about one-third of agriculture's minor contribution to the region's economy. However, ranching is part of the historic culture and character of the West, and it is looked upon as a bulwark against expanding real-estate development that threatens to change the open and wilderness character of the region.

Ranches maintain herds of cows which are bred in May and June, bear young in February and March that are sold in fall. Operations typically center on home ranches with limited (e.g. a few hundred) acres of private land. Herds are moved to extensive (thousands of acres) high-elevation national forest or U.S. Bureau of Land Management (BLM) lands for spring-to-fall grazing, and to low-elevation BLM land or home ranches for winter. The industry's dependence on natural forage produced by natural vegetation, and on irrigated hay fed in winter, and the sensitivity of these to climate variation, link the industry's welfare closely to the region's climates and changes therein.

The industry is in decline due to low economic viability, increasing pressures for other uses of the public lands, and growing competition for water used to irrigate forage crops fed in winter. Number of permits issued to ranchers to graze livestock on BLM lands, a reflection of the number of ranching operations, declined 37% between 1953 and 2000. Some observers predict disappearance of public-land ranching within 40-50 years. Recent tax and trust initiatives by private groups, and local and state governments, attempt to strengthen the industry's economy and perpetuate it.

Three climate-change scenarios portend somewhat different hypothetical futures for public-land ranching in the Intermountain West. With Scenario 1, no climate change, current trends are likely to continue unless the newer efforts at shoring up the ranchers' economies are widely successful. Continuing population growth will both increase competition for, and cost of, water; and will increase demands for other uses of the public lands. Under continuing economic stress, ranchers will be inclined to sell increasingly valuable private lands. While the end of ranching would not significantly affect the economy of the region, it would create socio-economic instability and demise of local businesses and infrastructures in small rural communities that have been supported by ranching for generations.

The climate changes of Scenario 2—increased temperatures without precipitation changes—would likely exacerbate the problems of Scenario 1 and hasten decline of the industry. Associated with longer growing seasons, and moderate precipitation levels at higher elevations, there might be some increase in range-forage production at those levels. But these would likely be offset by higher evapotranspiration at already-arid lower elevations. The result would be reduced forage productivity; and increased competition for, and prices of, declining water resources.

Scenario 3 poses the projected GCM increases in temperature and precipitation. The result would be increase in native forage production, including longer growing (and therefore grazing) seasons at high elevations, and consequent reduced need for forage supplements. Costs could be expected to decline both for hay purchased on the open market and for water used for irrigating home-ranch forage crops. Possible negative effects could be increased invasion of exotic plants into rangelands, and heightened frequency of range fires that would hasten invasion of non-native species. But the net effect could well be enhancement of the economic status of existing ranchers.

However, officials of the public-land agencies point out that the BLM and national-forest lands are now fully subdivided into grazing allotments, and could not accommodate additional ones for new ranchers. If climate change significantly increased range productivity, the agencies might allow existing permittees to stock some additional animals. But such a decision would need to be weighted against concerns for assuring healthy functioning of the land: stable watersheds, high water quality, protection of threatened and endangered species, and healthy wildlife populations. For lands that had been overgrazed for many years, improved growing conditions without increasing livestock numbers would permit the systems to recover.

The net effect of the climate changes of Scenario 3, if they should eventuate, could well be improvement in conditions for existing ranchers. But there would not be potential for significant expansion of the industry and its small contribution to the RMGB regional economy.

OUTDOOR RECREATION AND TOURISM

Economics of Outdoor Recreation and Tourism

Outdoor enthusiasts engage in a multitude of recreational activities that range from such less-physical pursuits as sight seeing, winter camping, and sailing; to more active endeavors like rock climbing, cross-country skiing, and swimming; and to motorized activities like off-road vehicle driving, snowmobiling, and jet skiing. The Intermountain West, with its spectacular scenery, challenging topography, and predominance of undeveloped public land is exceptionally attractive for such outdoor recreation, and its economic expression in tourism.

Several national studies have analyzed the potential effects of climate change on the economics of outdoor recreation. One study estimated the national expenditures in 1999 at approximately $2.5 billion for skiing and $76.3 billion for boating, camping, fishing, golfing, hunting, and wildlife viewing. The authors surmised that this outlay would increase 7-9% by 2060 with increases of 2.5^{o}C (4.5^{o}F) in temperature and 7% in precipitation; by 40-65% with 5^{o}C (9^{o}F) and 15% increases, respectively.

These are national figures and do not necessarily apply to the RMGB although they may reflect the directions of change. Moreover, they do not imply <u>additions</u> to the American economy except to the extent that visitors from outside the U.S. bring in funds and expend them on these recreational pursuits.

Outdoor tourism is here defined as one or more individuals traveling from their area(s) of residence to engage in the above outdoor activities elsewhere, and expending funds in the process. It only affects the economy of a local community, state, or RMGB region when travelers from outside these economies bring in and expend funds within them, or as it affects the outflow of its residents who spend money on outdoor recreation elsewhere. The purpose of this assessment is to evaluate the potential effects of climate change on the economic contributions of outdoor tourism to the region.

Current Value of Outdoor Tourism to RMGB Economies

The economic contributions of outdoor tourism, and potential effects of climate change, vary between local communities, the states, and the RMGB. At the local level, the contribution may go through one or more stages of a chronological succession that has taken place since World War II as the American public has become highly mobile. Up to the mid 20th century, small western communities were heavily dependent on extractive uses of local natural resources. In the latter half of the 1900s, locales that have had no attractive outdoor amenities nearby—e.g. state and national parks, quality fishing sites, ski areas—have tended not to attract significant tourist flow and remained dependent on local resource extraction. Such areas would not be sensitive to climate-change effects on outdoor tourism.

In successional Stage 2, communities with such amenities have increasingly attracted tourists, developed tourist-support services, and their economies have become heavily dependent on tourism. Gardiner and West Yellowstone, Montana, and Moab, Utah are examples. With this dependency, such communities' economies are sensitive to climate-change effects on tourism.

In many Stage 2 communities, often with up-scale ski areas, and particularly those with or near to airports that accommodate commercial airlines, affluent entrepreneurs immigrate for the quality-of-life attractions. These amenity migrants bring their businesses which they operate locally, often out of their homes. The influx stimulates development of support businesses, services, and infrastructure which together build an active and diverse economy in what becomes Stage 3 of the succession.

At this stage, direct tourism income is no longer a major contributor to the local economy, percentage-wise. One analysis shows extractive uses of the natural resources and tourism together contributing only 9% of the economy of the Greater Yellowstone Ecosystem. Other Stage 3 communities are Aspen, Colorado, Jackson, Wyoming, Bozeman, Montana, and Sun Valley, Idaho. The economies at this stage become relative insensitive to direct climate-change effects on tourism.

Trends in RMGB Outdoor Tourism

As one measure of chronological trends in RMGB outdoor tourism, total visitations to Intermountain national parks increased steadily during the 1980s and early 1990s, then leveled off in the latter part of the decade. Summer visitations, which far outnumber winter visitations, actually declined slightly while winter visitations increased steadily, more than doubling during the periods.

Nationally, skier visits increased during the 1960s, 1970s, and 1980s up to 1987, then essentially leveled off. In Colorado, skiers, including nonresidents who add to the state's economy, have continued to increase since the 1960s. But in Utah the number of out-of-state destination skiers stopped growing in 1991, although resident skiers continued to increase. Slowing growth or decreasing numbers may be a function of increasing costs. Colorado data show that the median household income of nonresident skiers rose from $55,600 in 1993-94 to $87,200 in 1997-98.

Potential Climate-change Effects

Without significant climate change (Scenario 1 for outdoor tourism) in the 21st century, continuing population growth is likely to perpetuate current rising trends in outdoor recreation and tourism, and their absolute contributions to local and regional economies. But since the other sectors of the economies are likely to increase during the period, the proportionate contribution of tourism, now small, is not likely to increase.

Increasing competition for, and cost of, water are likely to raise the expense of artificial snow-making for ski areas, ultimately raising skiing costs. If the slowing or cessation of skier interest is cost-related, the result could be further decline. Growing competition for water resources could also impact and reduce in-stream recreational uses.

Scenario 2 poses significantly higher temperatures with no change in precipitation. The increasing outdoor recreational effort and expenditures under warmer temperatures, predicted by the national assessments described above, is predicated on extended warm seasons and more time for outdoor activities. The rapidly rising winter national park visitations in the Intermountain region may reflect this tendency. The net effect again should be increased absolute, but not relative, contributions to the regional economies.

Higher temperatures with no more precipitation would increase evapotranspiration, reduce water resources, and accentuate competition for scarce water supplies. The effect would again be to diminish in-stream flows with consequent threats to water-based sports. The result could also be to raise water prices, increase the cost of making artificial snow at ski areas, and conceivably raise temperatures above levels needed for snowmaking.

All analyses based on significantly higher temperatures project reduction or disappearance of skiing. At the least, snowpack seasons would be expected to shorten by virtue of later changes from rain to snow in fall, and early melt in spring. Lower snowlines would be expected to move up slope, and lower-elevation ski areas would be at greatest risk. Two Canadian climatologists, using the Canadian model, predict zero snowpacks in the northern Rockies by 2070.

A related economic effect of a declining ski industry could be declining value of properties, often up-scale, that have developed around ski areas. In total, a significant decline in skiing, and certainly its complete demise, would mean serious economic loss to the resorts, to the economies of local communities heavily dependent on skiing, and to those not likely to move into Stage 3 of the economic succession. But because skiing is not a major part of the states' total outdoor tourism or contributor to theirs and the region's economies, the economic impacts at these levels would not be great. Increases in the remainder of outdoor tourism would still be expected to contribute positively to the region's economies at all levels under the conditions of Scenario 2.

Scenario 3 projects warmer temperatures and major precipitation increases similar in magnitude to those of the Canadian model (Table 3.9). As with Scenario 2, the warmer temperatures would be expected to extend the length of the vacation season and increase warm-season recreation and tourism. The stronger precipitation would be expected to increase water resources and enhance the prospects for water-based sports.

The effects on skiing would depend on the magnitude of temperature increase. If the Canadian model projections eventuate, skiing and associated tourism would not survive. If temperature increases were less extreme, the greater precipitation could produce more dependable mid-season snow, at least at higher elevations. But the warmer temperatures would still be likely to reduce season length, and place low-elevation resorts at risk. Increased water resources could enhance feasibility and reduce costs of snowmaking.

In total any changes in the magnitude of tourism associated with climate change, whether positive or negative, could have significant economic effects on some local communities. But they would not be expected to have major, relative effects on the state and regional economies because they would be proportional changes in what at present are low percentage contributions (perhaps 5% or less) to rapidly growing economies.

NATURAL ECOSYSTEMS I. THE ROCKY MOUNTAINS

Regional and Temporal Heterogeneity

Any effort at projecting the potential effects of climate change on Rocky Mountain ecosystems must cope with the extreme spatial heterogeneity of the subregion, the associated ecological variability, and the probability that the effects of climate change would be equally varied. The mountain chain in the U.S. extends 1,900 km (1,181 mi) from the Texas-New Mexico border to the Canadian line through three distinct climate zones, and a latitudinal gradient of insolation, temperatures, and growing-season lengths.

Elevational diversity, ranging from several hundred meters to 4,000 m (13,123 ft) imposes a third (vertical) dimension of climatic variation that produces more vegetative diversity than the 1,900 km latitudinal gradient. Superimposed on all of this is a patchwork geology and a varied landscape produced by Native American and European landuse actions that together create a diversity of environments in which climate change would be expressed.

Paleoecological evidence indicates marked, regionally varying climatic changes since the last glacial maximum, with the full range of temperature variation as much as 9-15^{o}C (16.2-27.0^{o}F). Climates during the Holocene have fluctuated over varying time scales including the Medieval Warm Epoch (11th-13th centuries A.D.), Little Ice Age (ca. 1550-1850), the Pacific Decadal Oscillation (mean period ca. 24 years), and El Nino-Southern Oscillation (mean period ca. 4-5 years). The evidence shows altitudinal shifts of tree zones, both up and down, in response to these changes.

Discerning any anthropogenically-induced, climate-change signal for the Rockies turns on the question of whether these Holocene fluctuations have been essentially cyclic, oscillating around some long-term mean trend that changed with the post-1850 increases in green house gases. Surrogate measures of North American temperature trends show abrupt, short-term (e.g. annual, decadal) oscillations around a net declining trend between ca. 1,000 and 1850 A.D. Measured temperatures since ca. 1850 to the latter 1900s show an abrupt rise to levels exceeding any in the preceding millennium.

Evidence of 20th-century climate change in the Rockies includes the Chapter 3 analyses showing rise in temperature and precipitation, Chapter 4 evidence of increased magnitudes and altered timing of streamflows, and glacial melting, all in the northern half of the mountain chain. It also includes some sign of more erect growth of stunted Krumholz trees and in-filling between tree patches, all at high elevations.

Climate-change Scenarios

Climate-change scenarios for assessing potential affects on the Rocky Mountain ecosystems were based on the Hadley model outputs because they are more conservative than those of the Canadian model. In response to the differing 20th-century climate changes between northern and western, and the eastern and southern portions of the Rocky Mountain/Great Basin region, shown by the Chapter 3 analyses, two scenarios were posed each for the combined Northern, North-central, and West-central Rockies; and for the East-central and Southern Rockies.

Scenario 1 for the north and west posed temperature increases ranging from 2.5°C (4.5°F) in spring to 4.5°C (8.1°F) in winter. Precipitation increases, primarily in fall and winter, were posed. Snowpacks were not projected to change. Scenario 2 for these subregions posed the same temperature increases, and significant precipitation increases in spring and summer. Snowpacks were projected to decline or disappear.

Scenario 1 for the east and south projected temperature increases ranging from 1.5°C (2.7°F) in spring to 3.5°C (6.3°F) in winter. Precipitation increase was posed only for winter, with decreases in the other seasons. Snowpacks were projected to decline in extent.

Scenario 2 posed the same temperature increases but with precipitation increase in summer and slight decrease in other seasons. Snowpacks were expected to decline or disappear.

Hydrologic Responses

If temperature increases were not extreme, winter-precipitation increases could compensate and snowpacks could persist. But marked temperature rise and winter precipitation changing to rain would likely reduce the magnitude and season length of snowpacks, even to the point of eliminating them. Streams would discharge more evenly through winter and spring, with peak flows earlier and lower.

The altered hydrologies would affect aquatic communities, geomorphic processes, and water-management strategies. Glacial melting would be accelerated as is now occurring in Glacier National Park. Increased evapotranspiration and less precipitation would reduce water for terrestrial vegetation, aquatic communities, and downstream human uses, in total having a xerifying effect.

If global warming were to significantly increase precipitation and intensify the hydrologic cycle, the result could be increased cloud cover and orographic precipitation with secondary effects of reduced night-time irradiation and warming, and reduced day-time insolation and cooling. A modeling case study of the Loch Vale (Colorado) headwater catchment projected greater snowpack, and less run-off and evapotranspiration with lower temperatures; but snowpacks reduced by 50% and run-off peaks advanced 4-5 weeks with 4°C (7.2°F) temperature increase.

Geomorphic Responses

Fluvial, glacial, colluvial, and aeolian erosion reshape surfaces produced by tectonic uplift, vulcanism, and sedimentary processes. These influence soil formation, plant longevity, and animal environments. Climatic factors modify these, and climate change would alter those effects. This entire subject needs to be modeled in order to get a thorough assessment of potential climate-change effects on Rocky Mountain ecosystems.

Climate-change Effects on Vegetation Zonation

The Rocky Mountain vegetation is arrayed in altitudinal zones. Three characteristics of the zonation support the inference that it is significantly controlled by climatic conditions: (1) Elevations of the zones decline with increasing latitude. (2) The effect of slope-aspect (vegetation differences between north and east slopes, and south and west slopes) on vegetation increases with latitude. (3) The nature of the zones changes with latitude as the dominant plant species change.

The general view among ecologists is that the zones would move up to higher elevations with change to warmer, dryer conditions. As a result, the areas occupied by forested zones would decline because surface area shrinks with rising elevation. With warmer temperatures and higher precipitation, the forested zones would be expected to expand both up- and down-slope. The result would be greater area occupied by forest vegetation. In all cases of altitudinal shifts, vegetative composition would be expected to change.

However, this model of zonal changes is too generalized to address the different scenarios posed above for the subregions. Scenario 1 (increased temperature and winter precipitation, reduced growing-season precipitation) for the East-central and Southern Rockies would be expected to reduce soil moisture and promote significant drying. Only species that could disperse upward would be likely to survive. Some native species would be lost.

Scenario 2 (increased temperatures and summer precipitation, reduced winter precipitation) for the east and south could increase soil moisture during the growing season, but the overall effect would still by drying along with a shift to a monsoonal precipitation pattern. High-elevation subalpine forest could be lost.

Scenario 1 (increased temperatures and winter moisture) for the northern and western mountains would produce slight drying that would favor drought-tolerant tree species such as Douglas fir. Increases in such species would alter forest composition. Scenario 2 (increased temperatures and summer precipitation) would reduce or eliminate snowpacks and favor increase of the more southerly (monsoonal) tree species such as ponderosa pine, Gambel oak, and aspen.

In one modeling study of Yellowstone National Park vegetation, forested zones were projected to move up and down with increased temperature and precipitation, but, only upslope with reduced precipitation. Whitebark and limber pine, now limited high-elevation species, would be expected to move to higher levels with reduced area, in some cases disappearing. The foothill shrub-grass zone would be expected to expand upward.

Intrazonal Changes

Climate affects plant function through such controls as soil moisture, growing-season length, and climate variability. Each species has different tolerance ranges for these variables. The species composition of a given elevational zone consists of aggregates of species whose tolerance ranges fall within the climate controls of that zone. The values of these controls may be at the limits of some species tolerance ranges, and well within the optima for others. Any climate change that altered the values of these controls would favor some species, disfavor others. The result would be changes in the species composition of a zone, even if dominant plant species and physical structure did not change.

The rate of such changes would vary with the life-history stages and life forms of the species. In forests, trees are long-lived and less sensitive to environmental conditions than their seedlings. Climate change could produce conditions that prevented survival of the seedlings of the dominant tree species, and favor seedling survival of other species and understory forms. In such cases, the trees could survive for decades or centuries maintaining the physical structure of the vegetation while its species composition was changing.

Herbaceous and shrubby vegetation, by virtue of its shorter life spans, is likely to change faster than forest types. Changes in alpine meadows could be early indicators of climate change. With increased precipitation meadows could be subject to tree invasion. Dryer conditions could stimulate expansion of xeric forms (e.g. sagebrush). Any reduction in the distribution, depth, and duration of snow cover would have strong influence on alpine tundra by altering winter soil activity, organic-matter decomposition, and nitrogen mineralization. Some observers predict disappearance of alpine tundra.

Disturbance Regimes

Environmental disturbances—wind storms, floods, landslides, avalanches, fires, insect and disease outbreaks—have occurrence frequencies that vary with location and existing climates. All of these frequencies could be altered with climate change. Research in the Rockies indicates that forest-fire numbers increase with a sequence of 2-3 years of above-average precipitation that builds a large fuel base, and then followed by 1-3 years of drought that accentuates the combustibility of the vegetation. This is a sequence produced by the El Nino-Southern Oscillation (ENSO), especially in the southern half of the Rockies. If climate change altered the frequency and/or intensity of ENSO, it could alter fire frequencies and severity.

Insect populations are affected by numerous climate variables. Drought conditions frequently make plant species more vulnerable to insect attack. Mountain pine beetle populations are constrained for periods of time and from high elevations by mortality from low temperatures. Temperature increases could increase the frequency of outbreaks which can kill entire lodgepole pine stands, and could allow the species to move upslope where it could attack and eliminate whitebark and limber pine. Nuts of these species are important food for grizzly bear.

Diversity and Conservation Issues

There are ten animal and seven plant threatened and endangered species in the Rocky Mountain system of the U.S. While their status could be affected directly by climate change, their tenuous situation is substantially the result of habitat loss associated with landuse activity. Habitat status could also be influenced by climate change. Certain landscape characteristics (e.g. patchiness, stand size, corridors) are important to the biota in facilitating migration, dispersal, gene exchange, etc. These are likely to be affected by climate change, either directly or through effects on land disturbance.

The climate relationships of the several hundred invasive, exotic species are largely unknown. Until these relationships are known, it is not possible to project potential climate-change effects which are likely to be numerous.

Natural Resources

While most of the Rocky Mountain area is public land primarily in federal ownership, it is subject to several human landuses that could be affected by climate change. Abundance of timber resources could be reduced by upward movement and reduced area of forests associated with warmer-dryer conditions; or increased by upward and downward extension associated with warmer-moister conditions. But utility of these resources would be importantly determined by the prevailing socio-economic values attached to them at the time. Warmer-dryer conditions and contraction of woody vegetation would increase the area of rangelands for livestock grazing. But unit-area productivity would decline. Warm-moist conditions would initially increase productivity of rangelands, but their area would later shrink with associated expansion of forest types. Here again utility of the changes would be affected by socio-economic factors of the time.

Needed Research

The potential effects of climate change on Rocky Mountain ecosystems are clearly complex. A thorough assessment would depend on an extensive research program that spanned the range of questions from individual organisms to ecosystems and landscapes, and including geomorphology and hydrology. Such an effort would need to address the range of time scales operating in an ecosystem from hours in the case of microbial functions to decades and centuries addressing fire-return intervals and long-lived species like Engelmann's spruce. It would need to employ the most up-to-date technologies in modeling, remote sensing, and data archiving. And it would need to address the range of landuse types from intensively managed and used lands to largely undisturbed and protected lands like national parks and wilderness areas.

NATURAL ECOSYSTEMS II. AQUATIC SYSTEMS

Current and Future Stresses

By North American standards, aquatic ecosystems are few and highly variable in the Rocky Mountain/Great Basin region because of its arid to semi-arid climate. The natural stresses on these systems are compounded by profound modification - - dams, interbasin transfers, irrigation diversions - - by Europeans who settled near water. Groundwater is being withdrawn faster than it is being recharged. Contamination with agricultural chemicals and acid deposition, and siltation from landuse practices compound the litany of human effects.

Adding to these physico-chemical stresses is the introduction of nonnative species that compete with, and prey on, the natives and alter ecosystem structure. At this point in time, 92 nonnative species have been observed in Great Basin aquatic systems, and 64 and 102 species occur in the Upper and Lower Colorado River basins, respectively.

Climate change is likely to interact with these stresses and their intensification as the region's human population burgeons. But many of the region's aquatic ecologists postulate that the anthropogenic changes to date have already modified the systems more than climate change is likely to affect them.

Spatial and Temporal Variability

The latitudinal and longitudinal extent of the RMGB region and the elevational variation from basins as low as 900 m (2,950 ft) to hundreds of mountain ranges varying in elevation up to 4,000 m (13,120 ft), produce a wide range of environments in which aquatic systems are situated. These range from highly saline lakes, ponds, and wetlands to high-elevation, oligotrophic water bodies with short growing seasons.

Much of the high-elevation terrain was cloaked in alpine glaciers during the Pleistocene. Glacial retreat and the cool moist climate of the early Holocene left an extensive network of water bodies throughout the region, much of it interconnected. Holocene drying and warming eliminated much of the network, leaving isolated water bodies in which the species evolved over time to a large number of endemics adapted to the unique conditions of each locale. The changing nature of the biota is shown in fossil remains in sediments at the bottoms of the larger, persisting water bodies.

Today, climatic conditions are highly variable on seasonal, interannual, and longer time scales. This variability is typical of arid regions, and aquatic organisms are adapted to it.

Assessment Procedures

Given the latitudinal extent of the region, its several climatic zones, and GCM forecasts of greater change in the north coupled with the Chapter 3 evidence that this occurred during the 1900s, the region was divided into northern and southern subregions. A further rationale for this separation was to divide north-south drainages into these components on the possibility of northward movement of species. The northern climate-change scenario poses increased winter precipitation; warmer fall, winter, and spring temperatures; and reduced snowpacks. The likely hydrologic implications would be (1) earlier spring peak runoffs, (2) reduced summer flows, (3) increased annual and base flows, (4) increased flooding magnitudes, and (5) warmer stream temperatures.

The southern climate-change scenario poses (1) warmer winter and late-summer temperatures, (2) reduced winter and increased summer precipitation, (3) snowpack elimination. Hydrologic consequences would be (1) reduced spring runoff, (2) reduced annual flows, (3) lower flood magnitudes, and (4) increased evapotranspiration.

The Need for Model Development

Given the complexities and variety of aquatic ecosystems in the RMGB region, any effective climate-change assessment will require models that have not yet been developed. Climate affects aquatic systems directly through water temperature and chemistry, and indirectly through effects on hydrology. Streams, rivers, ponds, lakes, springs, and wetlands constitute broad continua of conditions across which species are adapted. Western aquatic systems have distinct boundaries and are in many cases isolated. But many are linked by stream connections, overland flow, and groundwater. The isolated ones may respond to change relatively rapidly. But there may be response lags in the interconnected ones as impacts on one part of a network are transmitted across the connections to the other parts.

Large, deep bodies of water tend to change more slowly, and be more stable, than smaller, shallow ones which often are wind-driven. Species- and community-level dynamics are commonly less predictable than whole-ecosystem functions.

Models needed to project climate-change effects in western aquatic systems will need to encorporate these complexities and subtleties. They will require inclusion of both hydrologic and biotic processes. Some of the newer statistical downscaling procedures linking GCMs and hydrologic models show promise, as do multivariate approaches for analyzing complex relationships between climate trends and variability, and changing distributions and phenologies of organisms.

Potential Effects

Precipitation Effects on Hydrology and Water Chemistry

The major effect of precipitation on aquatic systems is through hydrology. Some 85% of stream flow in the RMGB originates as melting of snowpacks. Thus western hydrographs are linked to the timing, form, and amount of montane precipitation, and the timing of snowmelt. Several models project reduction or elimination of snowpacks, producing earlier spring runoff peaks and lower summer flows. Reproduction and other life-cycle stages of western stream organisms are closely adapted to current stream runoff schedules, and would undoubtedly be affected by changes in those schedules.

Increased precipitation would increase water resources if it exceeded evapotranspiration. It would also increase bank erosion and sediment transport which would affect fish spawning substrates and bottom invertebrates. It would reduce salinity of water bodies at lower elevations.

Changing hydrologies, especially with increased bank erosion, would also affect riparian vegetation. This component of stream systems plays an important role in shading which affects stream temperatures, and provides organic detritus that is an important food source for stream invertebrates.

Temperature Effects

Most aquatic species are ectothermic and have distinct thermal requirements that control their metabolic, growth, and demographic processes. As seasonal temperatures change, many species change locations either to different habitats or depths in order to seek temperatures as close as possible to their optima.

Increased temperatures would affect aquatic organisms in three ways. Operating directly, they would raise metabolic rates with subsequent effects on other life-history and physiological processes including oxygen demand. Secondly, solubility of oxygen declines with rising water temperature. The result is to reduce O_2 content at a time when the organisms need more. And third, the latter effect would be accentuated by increased metabolism by micro-organisms that break down organic matter and withdraw O_2 from the water in the process.

The net effect of warming would be to impact, both directly and indirectly, the cold-water species indigenous to western streams. As the lower-elevation stream reaches warmed to levels above the organisms' tolerance ranges, they would be forced to move upward to higher elevations with lower temperatures. The southern limits of species ranges would be forced to contract northward. The result of both the elevational and geographic contractions would be to reduce available habitat and populations. Several studies have estimated the degree of habitat shrinkage and population reduction with different levels of temperature increases.

The direct temperature pressures on the cold-water species could be exacerbated by competition from nonnative species, which typically have higher temperature tolerances, and tend to usurp the lower-elevation stream reaches. There is a distinct prospect of extinction among some cold-water endemic fish species which are already threatened or endangered.

Warmer temperatures would also be expected to affect lake systems by changing patterns of lake stratification, affecting community and trophic structure in the process. As in streams, higher temperatures would be likely to favor warm-water, nonnative species.

Need for Further Research

Climate change would be likely to interact with the ongoing, anthropogenic modifications of water resources in the RMGB: water diversions, nutrient additions, bank erosion and siltation associated with livestock grazing, road construction, etc. While the effects on some individual aquatic species can be predicted with existing knowledge, prediction of effects on community and ecosystem function await the development of models and additional species-specific information.

NATURAL ECOSYSTEMS III. THE GREAT BASIN

Biogeography of the Great Basin

The Great Basin is generally considered to be that region between the north-south Wasatch Mountains of Utah and the Sierra Nevada on the California-Nevada line. For the purposes of this assessment, it consists of the western half of Utah, most of Nevada, Idaho south of the Snake River, and parts of southeastern Oregon and Washington. Topographically, it is a washboard of over 200 north-south mountain ranges with intervening basins. Elevations range from lower basins as low as 900 m (2,950 ft) to mountain peaks as high as 4,000 m (13,120 ft).

Environments vary along this elevational span from high temperatures, low annual precipitation (e.g. 4-8 in, 10.2-20.3 cm), high soil salinity, and proximity to groundwater at the lowest elevations; to cooler temperatures, precipitation up to 50 in (127 cm) with winter snowcaps, and more diverse soil structure at the higher elevations. This climatic gradient is repeated on both sides of each north-south mountain range so that the climate of the region could be generalized as a surface undulating between hot and dry at the low elevations to cool and moist at higher ones.

The biota is similarly arrayed in elevational gradients controlled by the climatic gradients. Hence any climate change would be expected to alter the elevational gradients of the vegetation and fauna, and their composition.

Vegetation of the basins and foothills up to, on average, about 1,850 m (6,680 ft) is low-diversity shrub steppe occupying approximately 60% of the Great Basin area. In much of the shrub steppe there are few or no native annuals. But there is a pervasive flora of introduced annuals that are disturbance species. These exotics are effectively excluded by healthy stands of native perennials, but flourish with disturbance or removal of the latter. While diversity of the shrub-steppe avifauna is low, mammalian, reptilian, and insect diversity are high by North American standards. However, diversity of the entire fauna is extremely low in extensive, monotypic stands of the exotic annuals.

Vegetation above 1,850 m, on average, is woodland of various forms and densities. Immediately above the shrub steppe is the pinyon-juniper (P-J) zone occupying ca. 18% of the Great Basin area. Montane and subalpine woodlands, typically conifers, are above the P-J. With greater vegetation structural diversity, these woodland zones have higher avian diversity while retaining high mammalian, reptilian, and insect diversity. At elevations above 2,800-3,500 m (9,184-11,480 ft) the biota changes to alpine tundra, once again with low structural and biotic diversity.

These elevational levels are averages for the region, and in fact vary with latitude and slope-aspect. The zones grade to lower elevations from south to north, and on north and east slopes which receive less insolation than the warmer, dryer south and west slopes.

The Great Basin biotic zones have undergone extensive elevational shifts since the last glacial maximum. One school of thought holds that woodland largely occupied the lower terrain between the mountain ranges as well as the mountain slopes in the early Holocene. A second school maintains that the shrub steppe remained in much of the lower elevations, although woodland spread out in many areas of the lowlands. Both schools agree that the woodland zones moved up to the present elevations during Holocene drying and warming. Further shifts would be expected with climate change.

Several aspects of Great Basin ecosystem function, especially in the dominant shrub steppe, are unique to the type, and would be altered by climate change. Like vegetation in arid and semi-arid areas worldwide, annual primary production is closely correlated with annual precipitation. Average, annual production for an area is a function of mean annual precipitation. Typically in desert areas, the system as a whole is linked through successive trophic levels, and fluctuates from year to year with the vegetation, and ultimately the climate. In the shrub steppe, some components of the system are closely coupled to the vegetation. But some dominant herbivores and their predators are less tightly coupled to the vegetation. Consequently climate change would not be expected to have as pervasive effect as in more arid desert systems.

Aridland soils are generally nitrogen deficient. In the Great Basin, nitrogen is fixed each spring, when soils are moist, by algae in surface-soil crusts. It is only briefly available in spring for plant uptake, after which it is denitrified and ammonified. Surface soils in areas covered with exotic annuals tend to have higher nitrogen content despite the fact that soil crusts do not form in such growths. The condition is thought to result from mineralization of the perennials present before takeover by the annuals, and to be transitional to nitrogen deficiency caused by erosional loss and volatization associated with fire. If climate change accelerated the fire-induced conversion to exotic annuals, the long-term, net effect could be nitrogen-impoverished soils.

Recent and Current Stresses

The Great Basin ecosystem is currently under a number of stresses. Climate change would be likely to operate within these and impact the system.

Considerable evidence indicates that large, grazing herbivores were few in numbers in the Great Basin before European arrival, and the vegetation was not adapted to heavy herbivory. Livestock introduced by Europeans in the 19th century grazed out perennial herbaceous vegetation stimulating increases in sagebrush and shadscale in the shrub steppe, and pinyon-juniper in the foothills. Spread of pinyon-juniper, formerly held in check by aboriginal burning, has also been facilitated by aggressive fire control by the immigrants. In many areas, the type is now a uniform, dense growth highly vulnerable to hot and extensive stand-replacing crown fires.

A significant stress on the system is the arrival and spread of introduced annual plants, especially cheatgrass. Their growth produces a fuel understory that carries fire which eliminates the native, shrubby vegetation. Once the perennials are eliminated, the exotics produce an annual carpet that is subject to periodic fires which prevent recovery of the native perennials. By interacting with the fire-cheatgrass synergy, climate change could speed the conversion from native vegetation to the biologically depauperate annual growths.

Climate-change Effects

This assessment poses three scenarios for climate change in the Great Basin: (1) no change, continuation of current climates; (2) temperature increase, no precipitation change; (3) increase in both temperature and precipitation on the order of the general-circulation-model simulations.

Effective assessment of the potential effects of these changes would best be made with models of the Great Basin ecosystem. Several authors have emphasized the unique, environmental relationships of individual species, and the counterintuitive or unpredicted changes in natural communities following impacts on individual species. They contend that any models that effectively predicted climate-change effects on entire ecosystems would need to be structured at the species level. They would need to encorporate species interactions affecting population sizes that structured communities, and ultimately community and ecosystem structure and function.

Such models do not presently exist, nor is there ecological information on all, or most, of the species that would allow structuring models at this level of resolution. Consequently this assessment follows two approaches: (1) Review of documented responses of some species to climate change, experimentally induced and observed empirically. (2) Gross system changes are projected by analogy with the altitudinal, latitudinal, and slope-aspect correlations with climatic variables; and with Holocene changes associated with the climate changes of the period.

Species-specific Responses

A number of species changes have been documented in recent years that are hypothesized to be responses to the temperature increases of the 20th century. These include northward and up-slope range extensions of a number of avian, butterfly, and plant species. A number of phenological changes have been observed that include earlier spring arrival dates of migrating birds, earlier nesting dates, earlier emergence of hibernating mammals, and earlier growth and flowering dates for plants.

Experiments with the effects of elevated CO_2 levels on growth and water-use efficiency in Great Basin plant species have enhanced growth of species with the C_3 photosynthetic pathway, including cheatgrass. The species may become a more pernicious pest as CO_2 levels rise.

Populations of some animal species may be benefited by rising temperatures. Earlier nesting dates in some avian species appear to be associated with increased clutch size and juvenile survival. Multiple-clutch species like mourning doves are likely to have longer breeding seasons that enable production of more broods. High-elevation populations of hibernating mountain species, like ground squirrels and marmots, whose activity periods are now constrained between spring thaw and winter onset would have longer seasons for growth and maturation of young. Ungulate populations which now summer at high elevations, and occupy limited, lower winter range, are likely to be able to use all or most of mountain ranges, increase their winter forage base, and sustain higher survival rates.

An extensive literature deduces what effects altitudinal shifts in vegetation zones associated with temperature increases in Great Basin mountain ranges would have on species extinctions. Numbers of small mammal, avian, and butterfly species in different Basin mountain ranges have been shown to be correlated with surface areas of woody vegetation in the ranges. Temperature increases alone would be expected to shift the forested zone upward, and in the process it would occupy reduced areas. Some of the animal species occupying them would be expected to disappear.

With the scenario of both increased temperature and precipitation, the wooded zones would be expected to shift both upward and downward, and in the process occupy larger surface areas. The long-term effect could be an increase in the animal species occupying these zones.

Community and Ecosystem Responses

The elevational zones of the vegetation, the altitudinal variations with latitude and slope-aspect, and the temporal shifts during the Holocene are all inferred to be climatically determined, and provide a basis for postulating zonal changes associated with climate change. These variations correlate with a climatic gradient from warm-dry to cool-moist.

However a major uncertainty in projecting biotic change is the rising frequency of fire in the shrub steppe, and its increasing probability in pinyon-juniper. Fire completely alters the two types. Some 20% of the Nevada sagebrush zone has been converted to cheatgrass which has a fire-return interval of 3-5 years, effectively preventing recovery of the native species.

How much effect climate change would have on the region's biota would depend on how much native vegetation remains by the time the climate has changed sufficiently to alter the vegetation zones. Hence the actual effects will fall somewhere in the continuum between climate-induced shifts in the current vegetation and unpredictable climate alteration of a vegetation totally altered by fire. What follows is the no-fire end of the continuum with hypothetical projections of changes in the contemporary vegetation.

Scenario 2 with temperature increases and no precipitation change would be expected to increase evapotranspiration and have a drying effect. Most authors infer that lower boundaries of the elevational zones are set by minimum moisture conditions, and the upper boundaries by competition from the next higher zones. Any increase in aridity would be expected to shift the zones to higher elevations where they would occupy reduced areas. Subalpine forests in many or most cases would be expected to occupy and eliminate alpine tundra.

Scenario 3—increased temperature <u>and</u> precipitation—would produce conditions unlike any in the current climatic continua. The forested zones would be expected to move downslope and increase their areas. Pinyon-juniper would be expected to extend out into the shrub steppe, while the subalpine forest would be likely to move upward into the alpine tundra. The area of shrub-steppe would likely decline.

Such zonal changes could reasonably be expected to occur, but the species compositions of the zones could not be predicted because the vegetation would be functioning in environments in which neither it, nor its evolutionary predecessors, had evolved. Elevated CO_2 levels would benefit some species, be harmful to others. The competitive, symbiotic, and predatory interactions would likely be changed, altering resistance to invasion by introduced species. There would in all probability be marked changes in community composition.

Modeling studies project marked changes in Great Basin soil structure and function under the temperature and precipitation increases of Scenario 3. These include reduced fertility, carbon/nitrogen ratios, and microbial action. They also project physical changes in soil structure that would be less conducive to plant production, including reduced resistance to erosion.

SUMMARY OF KEY POINTS

1. On average, annual temperature during the 20th century increased 0.3-0.6°C (0.5-1.1°F) in the northern and central Rocky Mountains, but was not statistically significant in the southeastern portion of the Rockies. Lesser increases occurred in the Great Basin. Interannual variability in mean, annual temperatures narrowed. Mean, annual minimum temperatures increased more than mean, annual maxima.
2. On average, annual precipitation during the 20th century increased 6-16% throughout the Great Basin and the Northern and North-central Rockies, but was not statistically significant in the southeastern portion of the Rocky chain. Increases were most pronounced in summer. Interannual variability increased suggesting increasing probability of extreme rainfall events.
3. Two general circulation models (GCMs) project increases of 2.5-4.5°C (4.5-8.1°F) and 5.0-8.0°C (9.0-14.4°F) in seasonal temperatures in the region by 2080-2100 based on the assumption of a 2x increase in CO_2. The same models project 54-119% and 59-184% increases in mean annual precipitation. This assessment has used these projections and several less pronounced ones as a suite of scenarios to pose to the five sectors under consideration here: water resources, cultivated agriculture, ranching, outdoor recreation and tourism, and natural ecosystems.
4. On average, total annual flow of four rivers in the northern (Rocky Mountain) and western (Great Basin) portions of the region increased 12-33% during the 20th century. Interannual variability in flow increased during the period indicating rising probability of extreme events. Flow of streams in the southern portion of the region did not increase.
5. There is evidence that the dates of peak spring run-off in the region's streams have advanced, on average, during the 20th century indicating earlier melt of mountain snowpacks.
6. Some 85% of the water used by humans in the region comes from surface water, and 85% of this flows from spring melt of montane snowpacks.
7. Water resources in the Rocky Mountain/Great Basin region are totally allocated, with approximately 80% going to agriculture. Human population of the region, and its water need, is predicted to double in the next 40 years.
8. If temperatures rise without accompanying increase in precipitation, water resources will be reduced by increased evapotranspiration. Water is likely to be transferred to urban/industrial uses and away from agriculture, to the disbenefit of the latter. A number of conservation measures are possible.
9. If temperatures and precipitation rise according to GCM projections, there will be sufficient water for all needs. But it is not clear that the western U.S. engineering infrastructure of dams, reservoirs, and aqueducts would be able to control the run-off, and severe flooding problems could develop. The Wasatch Front of Utah would be at distinct risk from rising levels of the Great Salt Lake.
10. With only about 5% of the Rocky Mountain/Great Basin (RMGB) region cultivated, agriculture is a minor contributor to the region's economy. Although per-acre yields of the four major crops (hay, wheat, barley, potatoes) increased during the 20th century, declining commodity prices, reduction of cultivated acreage due to urban sprawl, and declining availability of

water reduced the region's agricultural economy.

11. If temperatures rise without accompanying increase in precipitation, increasing aridity and declining availability of irrigation water would disbenefit agriculture in the region and hasten its decline. While local areas dependent on agriculture would be hurt economically, the economy of the RMGB region would not be greatly affected because of agriculture's limited contribution.
12. If both temperature and precipitation increase according to the GCM projections, per-unit-area agricultural production would be likely to increase although this could depress commodity prices, as is projected at the national level. Hence the economic effects would be mixed. Whatever the net effect, it could affect local economies in some intensively farmed areas, but again would not significantly influence the region's economy because of the small amount of agriculture in the RMGB.
13. Livestock ranching, contributing even less to the RMGB economy than cultivated agriculture, is declining as a result of economic, political, and demographic pressures. It is predicted to disappear within 50 years.
14. Temperature increases without precipitation increases would be unfavorable for ranching and would hasten the industry's decline.
15. Increases in both temperatures and precipitation would increase forage production, lengthen grazing seasons, and ease pressures on water all to the benefit of ranching. But public lands are now fully allocated for grazing, and there is no potential for significant growth of the industry. Whether or not climate change slowed or abated industry decline, the economic effect could only be experienced at small, localized rural communities, but would be negligible at the regional level.
16. Outdoor tourism is economically important to some local communities that attract large numbers of tourists such as national-park gateway communities. But contrary to general impressions, it is not a major contributor to the states' and regional economies. As an example, it adds less than 6% to the gross state product (GSP) of Utah.
17. Outdoor tourism is increasing in the RMGB region, and climate change is projected to enhance the increase by lengthening the warm season. However that enhancement, while benefiting communities that attract large numbers of tourists, is not projected to have a large effect on the states' and region's economy because of the industry's limited contribution to their economies.
18. Skiing adds less than 1% to the Utah GSP, approximately 1% to that of Colorado.
19. Several analyses project reduction in skiing due to climate change. One climatologist's model projects disappearance of snowpacks by approximately 2070 in the northern Rockies which would eliminate skiing in the RMGB. Skiing's decline or disappearance would affect the economies of communities near to ski areas, but would have negligible effects on the economies of the RMGB states and region as a whole.
20. Ecologists generally project upward movement, and consequent reduction in area, of forest vegetation in the Rocky Mountains if temperatures increase without significant rise in precipitation. Alpine tundra could be eliminated. Such changes would take decades to occur.
21. With increased temperature and precipitation, the zones are projected to move both upslope and down.
22. Rocky Mountain ecosystems are under a variety of stresses other than climate change that include fire, livestock grazing, numerous human uses, and increasing invasion of nonnative species. Climate change will interact with these: Reduced precipitation would increase fire frequencies. Altered climatic conditions could render ecosystems more vulnerable to invasions by nonnatives.
23. Plant and animal community

compositions will change, but those changes cannot be predicted from current information.

24. Aquatic ecosystems in the Intermountain West have been subject to drastic alterations—dams, interbasin water transfers and irrigation diversions, pollution and sedimentation, and both purposeful and involuntary introduction of nonnative species—that probably have changed the systems more than will climate change.
25. Increased temperatures would reduce dissolved oxygen content of water bodies while increasing the respiration rates and oxygen demand of aquatic organisms. The result would be marked changes in the composition of aquatic communities.
26. Warmer temperatures would drive native, cold-water species to higher (cooler) elevations in mountainous regions while favoring nonnative, warm-water species that compete with the natives.
27. Vegetation of the valleys and lower elevations in the Great Basin is being converted to monotypes of nonnative annuals by fire. Fire tends to be more prevalent in years following above-average precipitation because of the increased fuel produced. Increased precipitation could increase fire frequencies and accelerate conversion of native shrub-steppe to exotic annuals. Such conversion would be expected to impoverish Great Basin soils.
28. Elevational zones of the mountain ranges in the Great Basin would be expected to move up-slope with higher temperatures, and both up- and down-slope with a combination of higher temperature and precipitation as is projected for the Rocky Mountains.
29. Up-slope movement of elevational zones, and their corresponding reduction in area, has been projected to eliminate some mammalian, avian, and butterfly species from Great Basin mountain ranges.
30. Composition of Great Basin plant and animal communities would almost certainly change unpredictably with any climate change, including invasibility of exotic plant species. Those with the C_3 photosynthetic pathway, including many exotic weed species, are benefited by elevated CO_2 levels.
31. Increased temperature and precipitation has been projected to lower fertility of Great Basin soils and alter soil structure in ways that would reduce plant production.

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Chapter 1

INTRODUCTION

THE NATION AND THE NATIONAL ASSESSMENT PROCESS

During the 1980s, scientific evidence about global climate change and its consequences led to a growing concern among scientists, policy makers, and the public. In 1988, the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO) jointly established the Intergovernmental Panel on Climate Change (IPCC). Through the IPCC process, more than 2,000 scientists representing more than 150 countries have assessed the available information on climate change and its environmental and economic effects, and have provided the scientific understanding needed to help formulate appropriate responses. A series of IPCC reports, incorporating extensive peer review and a commitment to scientific excellence, have provided the most authoritative and comprehensive information available on the science of climate change. In 2001, the IPCC published its Third Assessment Report which summarized the information as of that date on climate-change science and the vulnerability of natural and socio-economic systems.

In 1990, the United Nations (UN) General Assembly established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (FCCC). The FCCC was adopted in 1992, and over 160 signatories have now become parties to the agreement. The agreement was signed by the President of the U.S. and ratified by the U.S. Senate in 1992. The ultimate aim of the FCCC is to stabilize greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic interference with the climate system." This stabilization should be achieved within a time frame that (1) allows ecosystems to adapt naturally to climate change, (2) ensures that food production is not threatened, and (3) enables sustainable economic development to proceed.

In the United States, climate change research is overseen by the U.S. Global Change Research Program (USGCRP), which was established in 1989. Since its inception, the USGCRP has strengthened research on key scientific issues and has fostered improved understanding of earth processes. Major directions for the USGCRP include identifying and analyzing regional vulnerabilities to climate variability and climate change. The results of the research it supports have played an important role in the work of the IPCC and other national and international bodies.

In 1991, Congress passed the Global Change Research Act directing the Executive Branch of the government to assess the potential effects of the predicted changes, if they actually occur. To accomplish the assessment, the nation has been divided into 19 regions, each assigned the task of assessing the potential effects within its area. Five sectoral assessments—agriculture, coastal and marine systems, forests, human health, and water—cut across all of the regions, and look at the potential effects on these sectors nationally. The combination of all of these efforts constitutes the national assessment.

THE REGION AND THE REGIONAL ASSESSMENT PROCESS

The Rocky Mountain/Great Basin (RMGB) region (Fig. 1.1), one of the 19 regions in the national assessment, encompasses portions of

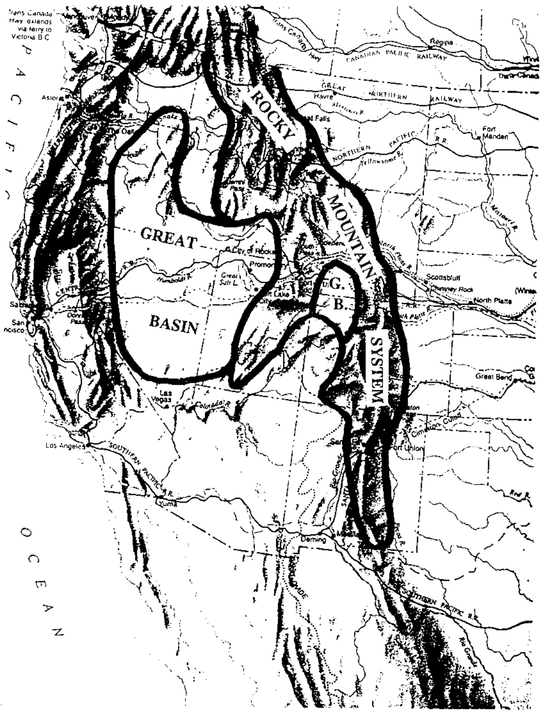

Figure 1.1. The Rocky Mountain/Great Basin region.

nine, large western states. The Rocky Mountain area consists of the mountainous zone extending from northern New Mexico northwestward to western Montana and the Bitterroot Range of the eastern Idaho panhandle. The Wasatch Mountains, north-south backbone of Utah, are commonly considered part of the Rocky Mountain system. The Great Basin portion is physiographically that region between the Wasatch and the Sierra Nevada of California, encompassing primarily the western half of Utah, and all of Nevada from about 100 km north of Las Vegas northward. But southern Idaho southward from the Snake River plains, the Columbia Plateau of eastern Oregon, and a portion of southwestern Wyoming are ecologically similar and commonly included with the Great Basin ecological type.

In essence, the RMGB regional assessment began February 16-18, 1998 with a regional workshop (Wagner and Baron 1999) held in Salt Lake City under support of a grant from the U.S. Geological Survey (USGS) to Utah State University (USU). Frederic H. Wagner of USU and Jill Baron of USGS were designated Co-Convenors. Invitations were sent to approximately 300 individuals representing the following 18 socio-economic sectors in the nine states of the region:

Academia
Mining Industry
Climatology
Native Americans
Cultivated Agriculture
Skiing Industry
Community Welfare
State Departments of Natural Resources
Public Education
U.S. Bureau of Land Management
Energy Companies
U.S.D.A. Forest Service
Environmental Advocacy Groups
U.S. National Park Service
Livestock Industry
Water Resources
The Media
Wildlife Advocacy Groups

Following a day of plenary sessions, the 124 participants spent 2 days in eight break-out sessions organized along the following sectoral lines:

Biological Resources
Skiing and Tourism
Cultivated Agriculture
Water Resources
Livestock Industry
Local Communities
Mining and energy
Environmental Advocacy
Tribal Lands
Public Education
Federal and State Land
Management Agencies

The sessions addressed four questions:

(1) What are the current climate-related stresses on the sector?

(2) What would be the effects of four climate-change scenarios on the sector?

(3) How could the sector's operations be adjusted to cope with the changes?

(4) What additional information would be needed for planning coping strategies?

Proceedings of the workshop were published in April 1999.

The present assessment began officially on July 1, 1998 with a grant from USGS to Utah State University and with USU faculty member Frederic H. Wagner designated Principal Investigator. Wagner and Thomas J. Stohlgren of the Biological Resources Division of USGS were designated Co-Coordinators of the assessment.

In order to provide expert advice, and sectoral and geographic representation for this extensive and complex region, a six-person Assessment Team and an eight-person Steering Committee were appointed as follows:

Assessment Team:

Frederic H. Wagner, Co-Chair
Ecology Center
Utah State University

Thomas J. Stohlgren, Co-Chair
U.S. Geological Survey
Midcontinent Ecological Science Center
Colorado State University

Upmanu Lall, Associate Director
Utah Water Research Laboratory
Utah State University

Linda Mearns, Climatologist
National Center for Atmospheric Research

Susan Selby, Manager
Resources Planning Division
Las Vegas Valley Water District

Booth Wallentine, Executive Vice President
Utah Farm Bureau Federation

Steering Committee:

Frederic H. Wagner, Co-Chair
Thomas J. Stohlgren, Co-Chair
Barbara Curti
Nevada Farm Bureau
Martha Hahn, Idaho State Director
U.S. Bureau of Land Management
Sherman Janke
Montana Chapter, The Sierra Club
Hardy Redd, Private Rancher
La Sal, Utah
Gray Reynolds, Manager
Snowbasin Ski Area, and
Sinclair Oil Company
Dale Toweill
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The basic plan of this assessment has been to identify five socio-economic and natural-resources sectors in the region most likely to be affected if significant climate change occurs, to pose a set of what-if, climate-change scenarios to these sectors, and to explore the effects if one or more of the scenarios became reality. The operational strategy has been to (1) develop a set of plausible climate-change scenarios jointly from analyses of 20th-century historical records and output of general circulation models (GCMs); (2) compile and analyze available statistics on each sector; (3) draw on the region's extensive professional expertise, both by consulting knowledgeable individuals in the region, and by convening workshops of experts on each of the sectors, to deliberate on the potential effects of the climate-changes posed in the scenarios; and (4) synthesize assessments for each. More than 125 individuals have contributed to these efforts, and an additional 13 have peer-reviewed portions of this report.

GOALS OF THIS REPORT

The purpose of this report is to portray results of the assessment in considerable depth to place on record the basis for the procedures used and the conclusions drawn so that both professionals in the areas covered, policy makers, and interested readers outside the technical areas discussed, can assess the evidence and logic on which these conclusions are based. The report will have limited distribution, but will be available on request to people in the region. A shorter, separate report summarizing the findings and conclusions, and written in less detail and less technical language, will be widely distributed to a mailing list of interested people in the region.

This report, and the assessment which it describes, do not advocate policy. Their purpose is purely to provide technical information and analyses that produce a factual environment in which policy alternatives can be considered by policy makers. The assessment does not make any value judgments among the alternatives, although it may point out the technical and socio-economic implications of those alternatives.

Chapter 2

THE REGION: PAST, PRESENT, AND FUTURE

DESCRIPTION OF THE REGION

Extending over 14º latitude (the full latitudinal extent of the western states) and 15º longitude (ca. one-fourth the longitudinal extent of the lower 48), the RMGB region is second in area only to Alaska among the 19 assessment regions. Associated with this areal extent is extreme topographic, climatic, ecological, and socio-economic variation.

The region's climate varies along a northwest-southeast gradient, with additional variants at the margins along the gradient. At its northwestern extreme, the climate is a Mediterranean one with precipitation largely coming from eastward-moving frontal moisture occurring between fall and spring. Southeastward, the precipitation shifts increasingly toward a late-summer (July-September), monsoonal pattern and away from winter moisture. Since, except for the higher elevations, the region is semiarid, a major concern for climate change is on the potential effects of climate change on the region's precipitation patterns, and ultimately water resources.

The topographic diversity adds further complexity to the region, and to possible climate-change effects. The region is bounded on the east and west by major Cordilleran chains rising to between 4,000-4,400 m (13,120-14,431 ft) at their highest points. The intervening Great Basin is in the rainshadow of the Sierra Nevada of California and the Cascade Mountains of Oregon and Washington, and is dotted with lesser mountain ranges forming the Basin and Range Province of geology texts, each producing its own localized rainshadow. Nevada alone contains 120 mountain ranges.

In the western U.S. there is a strong correlation between elevation and annual precipitation. As a result, the mountain ranges in the RMGB region capture a major fraction of the total precipitation falling over the region. Given lower temperatures at higher elevations, montane precipitation accumulates as snow between fall and spring, supporting the ski industry, an economic asset to Colorado and Utah, but contributing in most of the other states as well. The melt and run-off provide agricultural, municipal, industrial, hydropower, and recreational water for the fast-growing populations of the lower elevations. The importance of the montane snow accumulations is not confined to the RMGB region, however. Lying within the region are head-waters of the Colorado, Columbia, Missouri, Rio Grande, Platte, and Arkansas Rivers with the values of these snowpacks extending to the distant down-stream users of these streams.

Where water, soil, topography, and climate permit, a limited amount of cultivated agriculture is possible including potatoes in southern Idaho, small grain in a number of areas, and forage crops for the ubiquitous livestock industry and dairying near the cities. But over most of the region where cultivated agriculture is not possible, livestock grazing is practiced as is mining of hard-rock minerals. Timber harvest is locally important in the northern Rockies.

Since most of this region is not productive by standards elsewhere in the U.S., the region was not heavily populated, homesteaded, or otherwise settled by Europeans and transferred into private ownership during its early history. Consequently, three-fourths or more remains in Public Domain. Some 85% of Nevada and two-thirds of Utah and Idaho are in public ownership. There are 15 national parks, monuments, and other natural-area units of the National Park System in the region. In the Intermountain Region of the USDA Forest Service, encompassing all of Utah and Nevada, and major parts of Idaho and Wyoming, there are 16 national forests. Extensive as these holdings are, the Bureau of Land Management administers substantially more public land than either the Park Service or the Forest Service.

Similarly, the state departments of natural resources have a wide array of resource-management responsibilities in the western states for such common-property resources as wildlife and air, and especially water with its great demand and unique laws characteristic of the region. They also have substantial acreages of state lands under their jurisdictions including their own state-park systems and the School Trust Lands that occupy anywhere from 6-11% of the townships within the areas occupied by federal lands.

Since all of these agencies have responsibility for managing the lands under their jurisdictions, they will be responsible for administering any land-use changes induced by climate change and mitigating any negative effects. Their actions will affect private ranchers who graze their livestock both on their own land and on public land, and as well the miners and recreationists who use the public lands. Thus the public agencies become stakeholders as surely as the entrepreneurs of the private sectors, and are therefore represented on the region's steering committee.

REGIONAL HISTORICAL PERSPECTIVE

In large part because of the scarcity of water and arable land, and a climate unfavorable for agriculture, the Rocky Mountain/Great Basin (RMGB) region was not originally settled by large numbers of Euro-American immigrants. Because most of the land was not considered productive by midwestern and eastern standards, very little of the region was homesteaded, and that primarily where there was water (including the riparian zones). Consequently, as stated above, most of the land remained in public domain, and today 75-80% of the region is in public land.

Until the middle of the 20th century, much of the sparse human population assumed a rural lifestyle, deriving income from extractive uses of the land: agriculture where there was irrigation water, livestock ranching, mining, timber harvest. A limited agriculture was made possible by an extensive, federally funded and constructed engineering infrastructure designed to capture and distribute scarce surface water, and an extensive body of state water laws and administrative agencies designed to allocate this public resource. The federal, land-management agencies, guided by national legislation, administered their lands primarily to facilitate extractive uses by the local populace, and were in essence part of the local culture.

In recent decades, the RMGB region has become the fastest-growing part of the nation (Fig. 2.1). Between 1995-2000, 8 of the 10 fastest-growing states in the U.S. were in the RMGB region. The increase has been driven demographically by a high birth rate, and by influx of people from central and eastern parts of the nation and California who have been attracted by the region's high quality of life. The growth is largely concentrating in cities, with Denver, Salt Lake City, Boise, Albuquerque, Reno, and Las Vegas developed into major metropolitan areas. Once predominantly rural states are now among the most urban in the country in terms of the proportions of their populations living in cities.

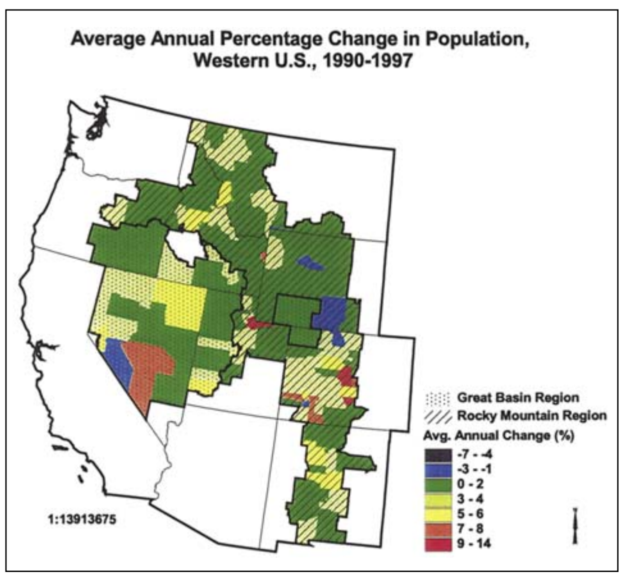

Figure 2.1. Average annual percentage change in population in the Rocky Mountain/Great Basin region, 1990-1997.

The changing social and demographic make-up of the region has brought a changing societal-value profile – the traditional, extractive uses of the public lands are being challenged in favor of nonconsumptive (e.g. recreational, esthetic) and environmental values – while at the same time creating problems of air and water quality, transportation, and uncontrolled land development due to urban sprawl and construction of recreational facilities. Pressured by the new values and more-recent national legislation, the land-management agencies are diversifying their management policies away from the historical ones, to the consternation of the traditional users who believe that landuse decisions affecting them are now being made by urban newcomers and eastern politicians in the national capitol.

The growth is also increasing demands on scarce water resources which are allocated under jurisdiction of state laws based on the Doctrine of Prior Appropriation: water is allocated according to historical issuance of rights, with junior applicants receiving water only after senior holders' needs have been satisfied. In dry, water-short periods, junior holders may not receive any allocations. Senior rights historically have been allocated largely to agriculture which operates on narrow profit margins. Within these traditions, water rights for the burgeoning populations and new businesses automatically assume junior status for water resources that are already fully allocated. These pressures are forcing consideration of ways to exchange rights, and even modification of the state laws.

The changes are altering the economic character of the region in other ways. The traditional, resource-based economies are now eclipsed by an economy supported by tourism, retirement and investment income, in some areas a developing hi-tech sector, and in Nevada entertainment and gaming. The new affluence is further fueling suburban sprawl and remote residential development that intrude on the historic natural and wilderness character of the region.

Concerns for climate variability and change must address both the effects on the traditional segment of the Intermountain culture and that segment that is "The New West."

CURRENT STRESSES AND LIKELY FUTURES WITHOUT CLIMATE CHANGE

The major stresses impinging upon the RMGB region are associated with its arid to semi-arid climate; and with arrival of the Euro-American culture which affects the region's natural resources and environments through its quest for a high standard of living for a burgeoning population. Globally, precipitation is more variable in a relative sense in arid areas than in the other climatic types. Thus the native biota copes not only with the low, mean levels of moisture, but with great variability around those means. Similarly, human land uses also cope with extreme variation.

An extensive network of dams and diversion systems has been constructed on virtually all western streams to allocate and distribute temporally and spatially variable water resources. Historically most of the water has been allocated to agriculture, and the resources now are oversubscribed. The rapidly rising urban populations, which far exceed rural inhabitants, are increasing demand for urban-industrial and recreational uses as is the adjudication of long-unresolved Native American water rights.

The dams and diversions have profoundly altered stream ecosystems leading to extinction, or threatened and endangered status, of numerous, indigenous fish species and subspecies. At the same time, more than 100 species of nonnative fish introduced into western streams are occupying the newly created aquatic environments, and the changes have altered water quality.

Terrestrial ecosystems have been, and are being, modified by a variety of human actions. Postsettlement timber cutting and subsequent fire suppression have altered community structure and fire frequencies in montane coniferous forests. Extensive areas have accumulated massive fuel stores that portend uncontrollable, stand-replacing fires in the not-too-distant future. Ubiquitous livestock grazing has altered vegetation composition in the region, especially riparian zones, in the early decades following settlement, although more-recent grazing management has effected some improvement.

Non-native plant species, inadvertently introduced, are invading and in some cases altering and dominating both montane and lower-elevation plant communities. In the latter case, their spread is facilitated by wild fires which are increasing in frequency, and burn more readily in vegetation converted to the non-natives.

Cities and towns, smaller human settlements, agriculture, and their supporting infrastructures have developed in the lower elevations where there is water. Hence aquatic habitats have been altered. These changes, and the above land uses have occupied or altered many wildlife habitats, and the region now has a substantial number of threatened and endangered plant and animal species.

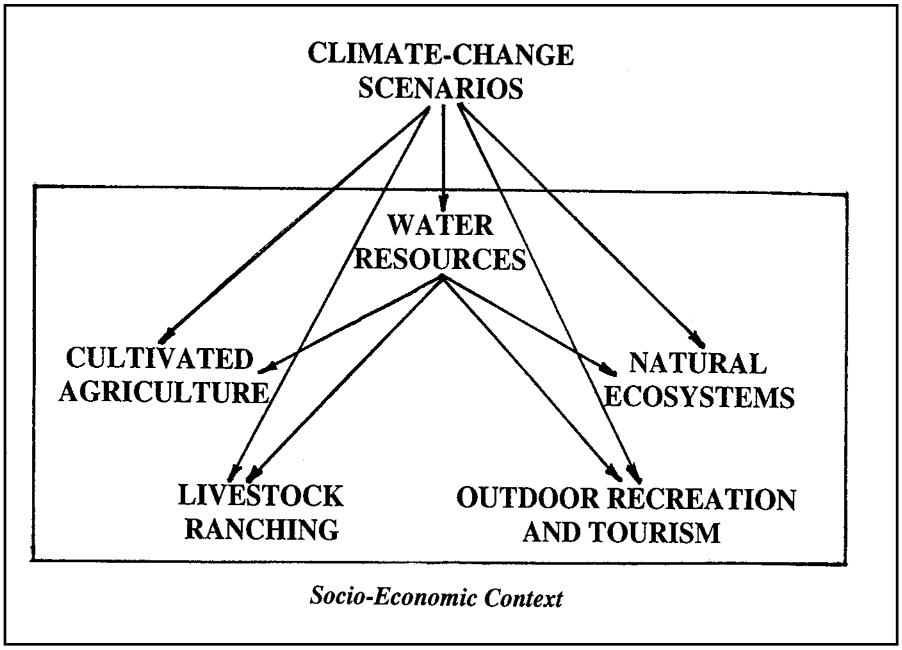

Figure 2.2 . Structure of the Rocky Mountain/Great Basin climate-change assessment. The approach is stepwise: adopt a set of climate-change scenarios; evaluate their potential effects on water resources, a key resource in the arid-to-semiarid region; evaluate the potential effects on other socio-economic and ecological sectors directly and/or through effects on water resources.

The growth has also produced air-quality problems in a number of cities of the region, including Salt Lake City, Denver, and Albuquerque.

TOPICS FOR THIS ASSESSMENT

This assessment was designed as a stepwise process (Fig. 2.2) as follows:

(1) The first step has been to develop a set of plausible, climate-change scenarios for the 21st century which could then be posed to potentially affected sectors.

(2) Second, water was designated as a key resource for this arid to semi-arid region. Potential effects of climate-change scenarios on the region's water resources were assessed and compared with 20th-century trends in the resource disclosed by analyses of the historical record.

(3) Third, the potential effects of the climate-change scenarios, either directly on affected sectors or indirectly through effects on the water resources important to them, were then assessed for:

(a) Cultivated agriculture, both irrigated and nonirrigated.

(b) Livestock ranching.

(c) Outdoor recreation and tourism.

(d) Natural ecosystems including Rocky Mountain and Great Basin terrestrial,

Chapter 3

CLIMATE-CHANGE SCENARIOS

INTRODUCTION—Frederic H. Wagner

Three procedures were used to develop a set of plausible scenarios of anthropogenic climate change by the year 2100 that could be posed to the sectors selected for assessment (Fig. 2.2). First, a workshop of climatologists with expertise in western North American climates was convened from September 10-12, 1998 at the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA to discuss and propose a set of scenarios for the Rocky Mountain/Great Basin (RMGB) region.

Secondly, the 20th-century climate record was analyzed to determine what trends might have occurred during the period. Since CO_2 and other greenhouse gases increased during the century, it was reasonable to examine whether the changes projected for the 21st century had begun to appear during the 20th, at least qualitatively though not quantitatively.

Third, on the assumption of a two-fold increase in atmospheric CO_2 by 2100, climate-change scenarios for the 21st century were projected with two, state-of-the-art computer models that simulate the complex interactions between earth, atmosphere, and ocean to produce the earth's climate system.

Each of the last two procedures has its strengths and weaknesses, and each can function to some degree as a check on the other. The historical analysis has the advantage of using empirical measurements of actual climate change taken over an extensive network of measuring stations. These make it possible to subdivide a large region like the RMGB into subreqions to assess the uniformity of climate and climate change over the region. And the historical measurements can to some degree serve as a check on the GCM simulations when the two are compared over the same time period.

The major weakness of historical analysis is that the trends of the past cannot automatically be assumed to predict the future, particularly if future conditions change as with increasing greenhouse gases, and hence it is not a reliable predictor of future climate change. Moreover, climates change naturally over numerous time scales, and observed changes cannot automatically be assumed to be anthropogenic.

The major strengths of the general circulation models (GCMs) are that they are structured on the basis of known atmospheric, oceanographic, and geophysical processes; and are parameterized with measurements of those processes. They are thus mathematical structures of the interaction of causal mechanisms driving the climate system. They are the only basis for projecting future climate change given inputs of future conditions that affect climates, including amounts of greenhouse gases.

The major weakness of GCM projections is that the models are of necessity oversimplifications of the real world both because of deficiencies in our knowledge, and current inability to develop models of the size and complexity needed to simulate all of the variables driving climate systems at spatial scales ranging from global to localized sites. They may lack provision for certain climate-forcing variables such as land-cover characteristics, and certain feedbacks. Thus they are approximations of climate systems and their projections must be considered approximations with inadequately known accuracy levels.

The size of the RMGB region further complicates the use of both historical climate analysis and the GCMs to develop scenarios of climate change. The region contains three distinct climates (Lins et al. 1990). Some precipitation occurs in all months throughout the region, but there are discrete patterns of seasonality. At the northwestern-most extreme of the region in the southeastern corner of Washington and the Idaho panhandle, precipitation is concentrated in the winter months and at its lowest ebb in summer (Fig. 3.1). This pattern prevails through much of Nevada, and western and northern Utah. But the southeastern Washington histogram (Fig. 3.1) shows a slight upturn in May-June which becomes more pronounced to the southeast and east. Through most of Nevada, parts of northern Utah, and even portions of eastern Oregon, winter precipitation remains substantial, but spring levels are comparable to those of the winter months (Fig. 3.1).

In western Wyoming and Montana, May and June emerge as the singularly dominant months (Fig. 3.1). This is the westward extension of the Northern Great Plains climate zone (Lins et al. 1990) which also includes those portions of the RMGB region in the eastern three-quarters of the Snake River plains in Idaho, northeastern Utah, and the northern one-fifth of Colorado.

In the southeasterly portion of the RMGB region, precipitation shifts to the late-summer dominance of the monsoon pattern (Fig. 3.1). This seasonality prevails over New Mexico, much of Colorado, and portions of southern and eastern Utah.

An important point in assessing the effects of climate change is that the significance of any precipitation changes induced by greenhouse gases would depend on the seasonality of the change. As one Nevada rancher commented at the February 1998 Salt Lake City climate-change workshop (Saterthwaite 1999), a 15% increase in the low, summer rainfall of this area would have no significant effect on cattle-forage production during the typical spring growth period. This would be particularly the case if temperature increases elevated levels of evapotranspiration. But a comparable percentage increase in winter moisture would be a clear benefit.

Moreover, climate-change effects on precipitation would probably vary between different parts of the region. The predominant winter precipitation over much of the region depends on the location of the winter storm

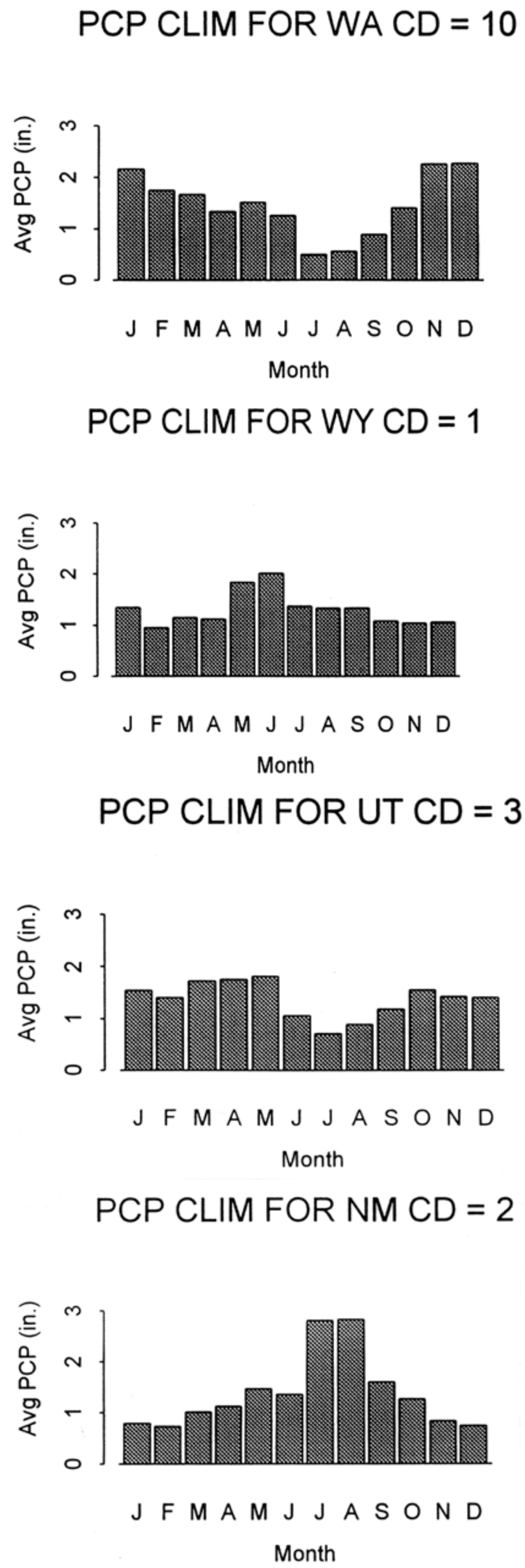

Figure 3.1. Major precipitation patterns in selected climate districts (CD) of four states within the Rocky Mountain/Great Basin region: Washington (WA), Wyoming (WY), Utah (UT), New Mexico (NM).

tracks. Any latitudinal shift in their paths —Filippo Giorgi of the International Center for Theoretical Physics (Pers. Comm.) has postulated that they may shift northward—would likely increase winter precipitation in some areas, reduce it in others. Summer precipitation at the northern fringe of the monsoon zone is evident in the seasonal patterns of southern Utah and Nevada. If the monsoonal rains advanced northward into the predominantly winter-rainfall portions of the Great Basin, as has been suggested, and increased significantly, they could substantially alter the ecology of this portion of the region.

These subregional climatic variations pose problems for using the GCMs to develop change scenarios. The models have not yet been developed to the point where they can simulate climate behavior at this spatial scale. Without that level of resolution the models cannot address the question of whether the subregional climates will respond differently to greenhouse-gas-induced changes in the global climate.

The topographic variability of the RMGB region adds further spatial complexity to its climate. In the western U.S., temperature is inversely, and precipitation is positively, correlated with elevation (MacMahon and Wagner 1985). The region's major cities are situated along an elevational span from Las Vegas at 615.9 m (2,020 ft) to Santa Fe at 2,134.2 m (7,000 ft). The total elevational span in the region is approximately 7X from the Las Vegas elevation to the top of Mount Elbert in Colorado at 4,400 m (14,433 ft). The higher elevations capture more precipitation per unit area than the lower elevations, largely as snow, and they produce numerous rain shadows on their downwind sides. Thus, the hundreds of separate mountain ranges, basins, and plateaus produce a complex mosaic of local climates. The spatial resolution of state-of-the-art GCMs precludes incorporating this level of topographic detail and simulating climates of localized areas.

Historical climate analysis is also confounded by the topographic complexity. Most weather stations in the West are in the valleys and lower elevations. Yet Farnes (1995) has shown that within localized areas, the seasonality of precipitation varies with elevation (Fig. 3.2). In six out of seven low-elevation climate stations in western Montana, the peak precipitation month is June, consistent with the Northern Great Plains climate zone. But at nearby high elevations (e.g. 1,841-2,774 m, 6,038-9,099 ft), the peak month shifts to January. Thus any inferences about climate change during the 1900s are based on low-elevation data, and this raises questions of whether low and high elevations have experienced similar, interannual precipitation trends, even if different in magnitude. The corollary questions are whether the precipitation trends shown by the predominance of low-elevation stations are similar to the trends at high elevations and therefore reasonably reflect the regional trends.

As we will show in Chapter 4, there are strong interannual correlations between annual precipitation measured at the lower elevations, and subsequent streamflows which are fed by montane snowpacks. The fact that surface area

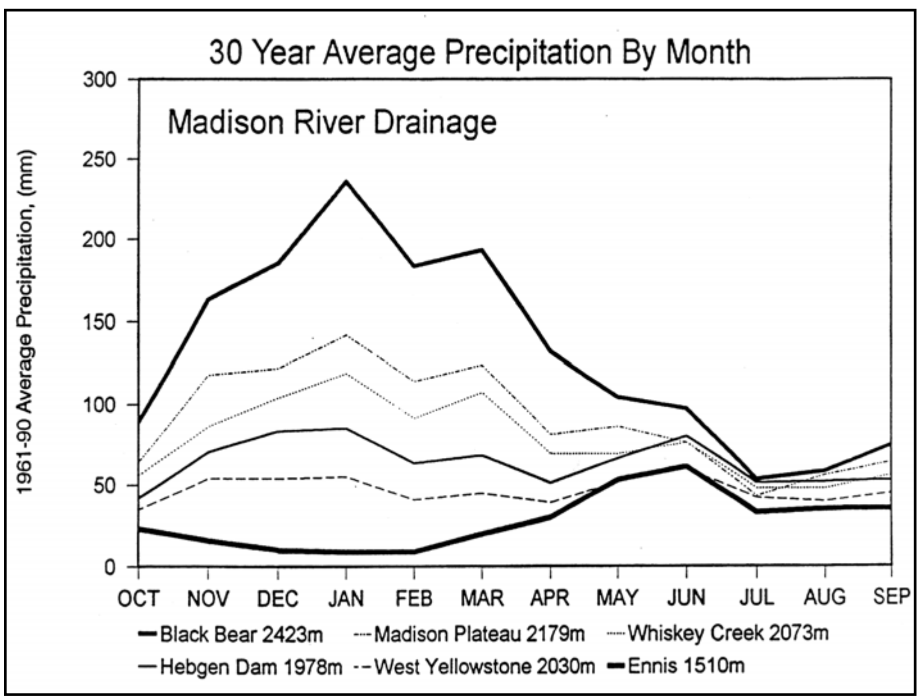

Figure 3.2. 30-year average annual precipitation by months for Madison River drainage in western Montana (Farnes, 1993).

is an inverse function of elevation, and lower elevations are therefore more representative of the region, provides further rationale for the assumption that the trends portrayed by the low-elevation stations represent, even if somewhat imperfectly, the trends for the areas under consideration.

Several sources of temporal variation, operating at different time scales, add further complexity to the region's climate. To be detectable in the historical analysis, any secular trend induced by global warming over the past 100-140 years must emerge out of this complex of short- and medium-term variations in the region's climates.

It is because of these sources of complexity in RMGB climates that the three procedures for adopting 21st-century, climate-change scenarios —with their strengths, weaknesses, and mutual checks—were followed. These three efforts are described in the sections of this chapter that follow. The scenarios that were adopted are set forth in subsequent chapters, and are varying applications of these three sources of information.

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CLIMATOLOGISTS' WORKSHOP ON SCENARIOS—Abstracted and Annotated by Thomas J. Stohlgren

This section (1) summarizes the proceedings of a climatologists' workshop held at the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA from September 10-12, 1998; (2) provides additional background information from the scientific literature; and (3) interprets and evaluates the results, including a discussion of the scientific literature. The purpose of this meeting was to seek information on appropriate climate-change scenarios for the RMGB assessment from climatologists with expert knowledge of western North American climates. Those present were:

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La Jolla, CA

Michael D. Dettinger
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Canadian Center for Climate Modelling
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The sections that follow are abstracts of the presentations by the workshop participants, with interpretative comments added.

Abstracted and Annotated Comments of Workshop Presentations

Decadal Hydrologic and Climate Variations—Michael D. Dettinger

Decadal climate variations. Longer-term and broader-scale variations in climate have important implications for climate scenarios in the region. Climate variations with time scales longer than 7 years (as an arbitrary division between interannual and decadal-interdecadal climate variations) drive roughly 30-60% of the year-to-year variance in precipitation and streamflow in North America (Fig. 3.3); for the most part, these slow variations are not simple trends but rather are true decadal to interdecadal fluctuations between wet and

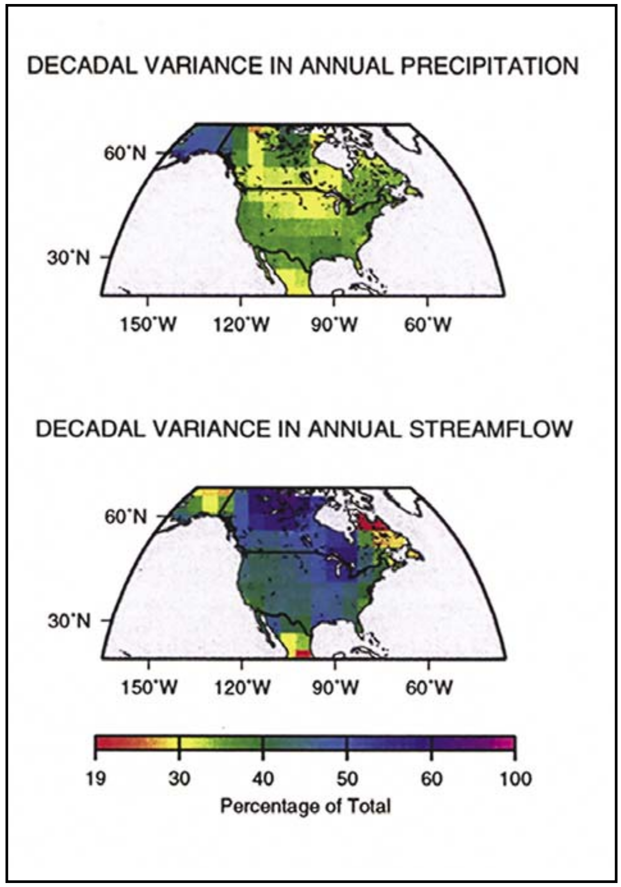

Figure 3.3. Decadal variance in annual precipitation (top) and streamflow (bottom) (courtesy of M. Dettinger). Annual variations with time scales longer than 7 years (here arbitrarily termed decadal) drive approximately 30-60% of the year-to-year variance in precipitation and stream flow in North America.

dry epochs. Notably, streamflow variations have been relatively more decadal in character than has precipitation, presumably as a result of the tendency for river basins, soil-moisture reservoirs, and land-surface processes to retain memories of droughts and wet epochs longer than the immediate precipitation conditions. Ground-water (Dettinger and Schaefer 1995), lakes (Lall and Mann 1995), and probably soil moisture are even more dominated by decadal variations than are precipitation or streamflow. Many of the causes of decadal variation in climate in the Rocky Mountains and Great Basin originate from outside the region (Schneider et al. 1999). Thus, the extended droughts and wet epochs, that have been major drains on economies in the U.S., may be difficult to predict.

Spatial scales of decadal climate variability. Cayan et al. (1998) found that decadal precipitation variations in western

North America have historically had about six sub-regions. Each is about half as large as the Rocky Mountain/Great Basin region. The Rocky Mountain/Great Basin region includes parts of at least two sub-regions, with southwestern areas experiencing important precipitation contrasts relative to the northwestern areas (Dettinger et al. 1995, 1998). Within the Rocky Mountain and Great Basin region, decadal variations are more crucial parts of climate variations of the northern half of the region, while inter-annual variations, like El Niño effects, may dominate the southern half (Bitz and Battisti 1999). Such historical contrasts could result in rather different sensitivities of human and natural systems in the two sub-regions to longer-term climate disruptions.

It is not yet known whether these longer-term historical climate variations in North America provide a prototype for the regional patterns and contrasts that would be associated with human-induced climate changes. The patterns that decadal variations have formed historically, however, are remarkably similar to patterns found at all faster time scales (e.g., Dettinger and Cayan 1995) and may correspond to natural patterns of climate that will be co-opted by human-induced changes (Held 1993).

Influences on shorter-term climate processes? Incorporation of realistic decadal variations into climate-change scenarios could be as simple as adding historical examples of decade-scale climate anomalies into whatever scenarios are examined.

However, because the decadal variations of climate in North America are themselves important contributors to overall climatic and hydrologic variability, and because they are among the more extreme tests of many natural and human resource systems, this approach would probably under-represent their role in determining climate-change susceptibility. This potential for under-representation arises because decadal variations find much of their expression as modulations of shorter-term climate processes.

Some of this intermingling of time scales is indicated by several brief examples:

(1) On interannual time scales, relations between the status of the tropical Pacific's El Niño-Southern Oscillation (ENSO) process and North American precipitation and temperatures explain important aspects of the year-to-year fluctuation of North American weather. Recent studies show that the strength and reliability of those relations are modulated by the decadal state of the North Pacific climate (Gershunov and Barnett 1998; McCabe and Dettinger 1998). Figure 5 in McCabe and Dettinger (1998) shows the strength of teleconnections between the Southern Oscillation Index of ENSO activity and seasonal precipitation totals in the western United States, including the Rocky Mountain/Great Basin region. Also shown is a 30-year moving average of the Pacific Decadal Oscillation (PDO) index—a measure of decadal North Pacific climate developed by Mantua et al. (1997). The strong negative correlation of ENSO teleconnections and PDO indicates that decadal climate variations affect not only decadal precipitation patterns (as discussed previously) but also interannual variations and connections.

(2) The Northern Hemisphere annual cycle has also varied on decadal time scales. Keeling et al. (1996), Myneni et al. (1997), and Dettinger and Ghil (1998) have shown, by analyses of atmospheric CO_2 and satellite imagery, that the annual cycle of photosynthesis has come progressively earlier in the year (and has increased in amplitude) in recent decades; these changes include both a trend and decadally fluctuating components. This change in the seasons has been related to hemispheric temperature variations, and Mann and Park (1996) have found evidence for at least some hastening of the annual temperature cycle over much of the Northern Hemisphere land surfaces, including the Rocky Mountain/Great Basin region (where they found a hastening by a few days this century). Mann and Park also modeled seasonality changes in simulations of a doubled-CO_2 climate, but in the opposite direction. Even small changes in annual cycles can be important because the annual cycle is typically much larger than any of the more irregular fluctuations of climate. Rajagopalan and Lall (1995) have shown that the annual cycle of precipitation in the western United States also has varied on decadal time scales. The connection between decadal climate processes and these fluctuations of seasonal cycles remains unexplained but provides yet another example of how decadal variations are expressed in higher-frequency variability of the climate system.

(3) Finally, on seasonal to synoptic time scales (1-5 days), the frequency of occurrence of atmospheric-circulation patterns over the North Pacific and North America is modulated by decadal climate variations. Cayan et al. (1998) report significant changes in the frequencies of occurrence of several monthly circulation patterns in relation to decadal patterns of western winter precipitation. On near-daily time scales, 3-day mean circulation patterns associated with warm-wet and warm-dry weather in California were counted for each winter from 1948-1992 (Dettinger and Cayan 1995). Clear decadal fluctuations in the fraction of time spent in the warm patterns, along with significant trends (Dettinger and Cayan 1995), were found. Thus, decadal climate variations may influence the variability of western weather on all time scales from days to decades.

Summary of climate cycles and their variation.—Thomas J. Stohlgren. Because historical climate records within the Rocky Mountain and Great Basin region are typically no more than about 100 years long, the characterization of decadal climate variability has been problematic. However, there is growing evidence that naturally occurring climate variations span time scales from minutes to millennia, and both human and natural systems are sensitive in different ways at the different scales (Cayan et al. 1998, Dettinger et al. 1998; Bitz and Battisti 1999). Thus, climate-change scenarios need to be constructed with realistic short- and long-term climate variations included, and interpretations and projections of at least some responses need to take the longer natural variations into account.

El Niño and La Niña Variability —Thomas J. Stohlgren

El Niño events are caused by a shift in the trade winds that blow from east to west around the equator, warming water currents in the eastern Pacific Ocean (http://www.ucar.edu/communications/quarterly). Rainfall follows the warm water, leading to heavy storms on the west coast of South America and droughts in Australia, Indonesia, and the South Pacific. In the opposite phase, La Niña, the Pacific waters gain heat leading to scarce rainfall on South America's west coast and above-average precipitation in Australia. El Niño periods generally affect atmospheric circulation, known as the Southern Oscillation (SO), which is measured by the difference in air pressure between the island of Tahiti and Darwin, Australia. In the past century, El Niño and La Niña periods have occurred in equal numbers, with "normal" periods in between (Fig. 3.4). However, in the last 20 years, there have been seven El Niño and only three La Niñas, with one particularly long El Niño lasting from 1990 to 1995 (Fig. 3.4).

Temperature and precipitation change naturally from season to season and on longer time scales. Throughout the U.S. and elsewhere, El Niño is a naturally occurring, longer-cycle mode of climate variability. In the northern portions of the Rocky Mountains and Great Basin region, average temperatures generally increase 2-3 degrees F during El Niño years (http://www.ucar.edu/communications/quarterly). Lesser changes in the southern parts of the region and even decreases in temperature in the southern Rocky Mountains (New Mexico, Fig. 3.5) have been measured. Precipitation generally decreases in the northern and central parts of the region, and increases in the southern-most parts of the regions (Fig. 3.5). Mountainous watershed

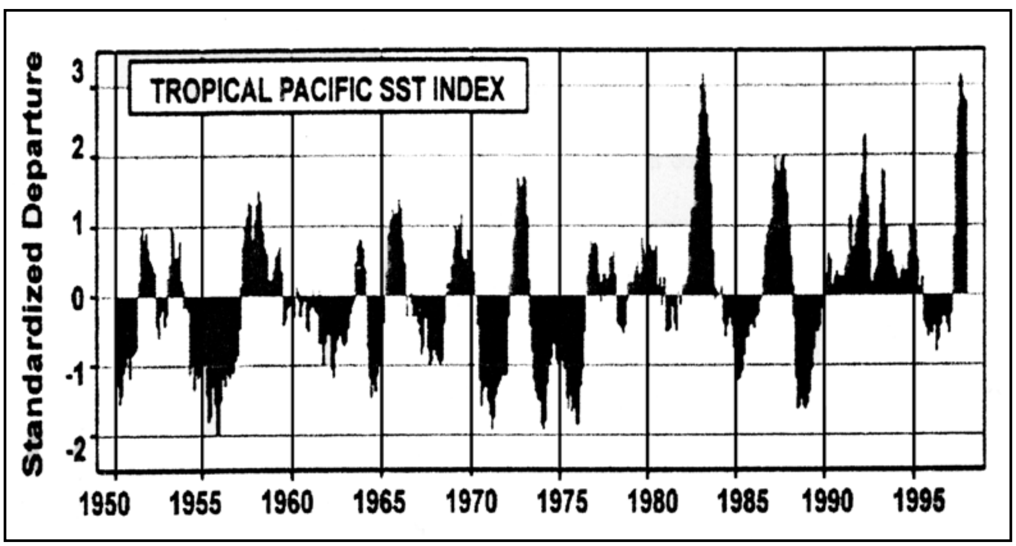

Figure 3.4. Tropical Pacific SST Index (see web site in text). Phases above zero are El Niño events, those below zero are La Niña.

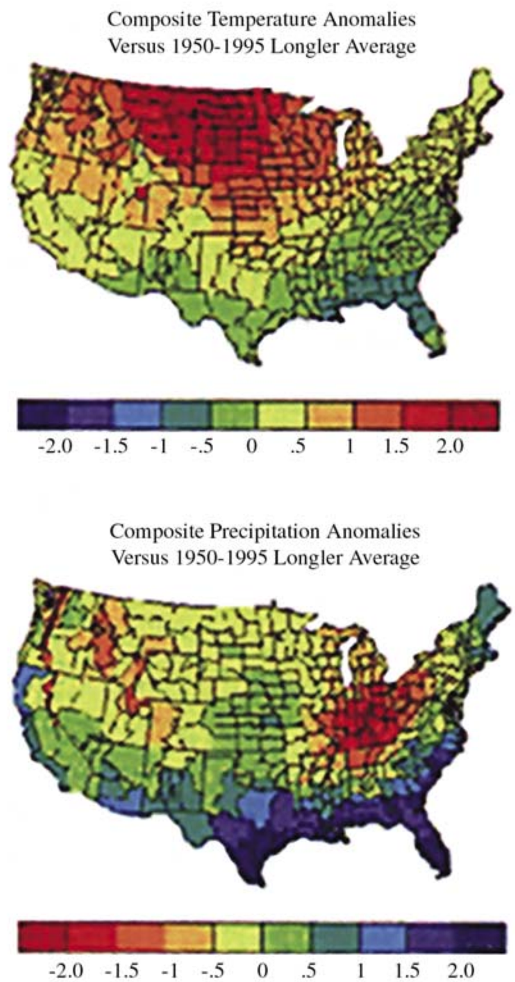

Figure 3.5. Composite temperature anomalies (top) and precipitation anomalies (bottom) during El Niño years compared with the Longler 1950-1995 averages (see Web site in text).

units in the region seem to be less affected (i.e., 0 to –0.5 in less precipitation) than arid watershed units in the Great Basin (where –0.5 in is a much higher proportion of total precipitation).

The strength of the above generalizations should be viewed with caution. Few of the statistical relationships that are used to create the composite maps of temperature anomalies (Fig. 3.5) are strongly significant (Redmond and Kotch 1991). Precipitation anomalies were strongest in the extreme northern and southern parts of the region.

Summary of El Niño and La Niña variability. Long-term natural variability makes it difficult to isolate changes in climate resulting from human activities. The several El Niño events in the past 20 years may affect statistical analysis of temperature and precipitation trends caused by human activities. Several recent, atypically hot or dry years in some sub-regional areas caused by El Niño events (Livezey and Smith 1999) can easily affect the assessment of trends by increasing the "leverage" of those data points in regression analysis. The proximate causes of El Niño and La Niña events have been linked to large-scale perturbations of atmospheric circulation patterns (Cayan and Peterson 1989, Cayan and Webb 1992, Cayan et al. 1993, Diaz and Pulwarty 1994, Diaz and Anderson 1995), volcanic activity (Gutzler 1993), and greenhouse gas emissions (K. Trenberth, NCAR Climate and Global Dynamics Division, http://www.ucar.edu/communications/quarterly). We need a better understanding of spatial and temporal variation of El Niño and La Niña events and their ecological consequences at sub-regional scales to address specific stakeholder needs. This should be a major focus of research in the coming years.

Assessing Vulnerabilities— Roger Pielke, Sr.

In any nonlinear system, the time period of predictability is dependent on the degree of nonlinearity and the level of accuracy by which the feedbacks within the system can be represented. In the context of the climate system, the temporal limits on climate prediction are determined by: (1) our understanding and ability to represent quantitatively the interactions between each important aspect of the Earth's climate system; and (2) the degree of nonlinearity of these interactions. In the context of regional and global climate prediction, these limits have not been determined. Moreover, interaction across scales must be considered because global- and regional-scale climate effects cannot be considered independently (AGCI 1997).

Atmosphere-land-cover two-way interactions occur as summarized in Pielke et al. (1998a). These interactions can be on the diurnal scale (biophysical), on the seasonal scale (biogeochemical), and on the multi-year time scale (biogeographical; e.g., Fig. 3.6).

On the seasonal time scale, prescribed leaf-area index (LAI) significantly affects the meteorological-model simulation of temperature

(Fig. 3.7a) and precipitation (Fig. 3.7b). Correspondingly, the prescription of temperature, and particularly precipitation, dramatically affects a biogeochemical model simulation of LAI (Fig. 3.8) and root density.

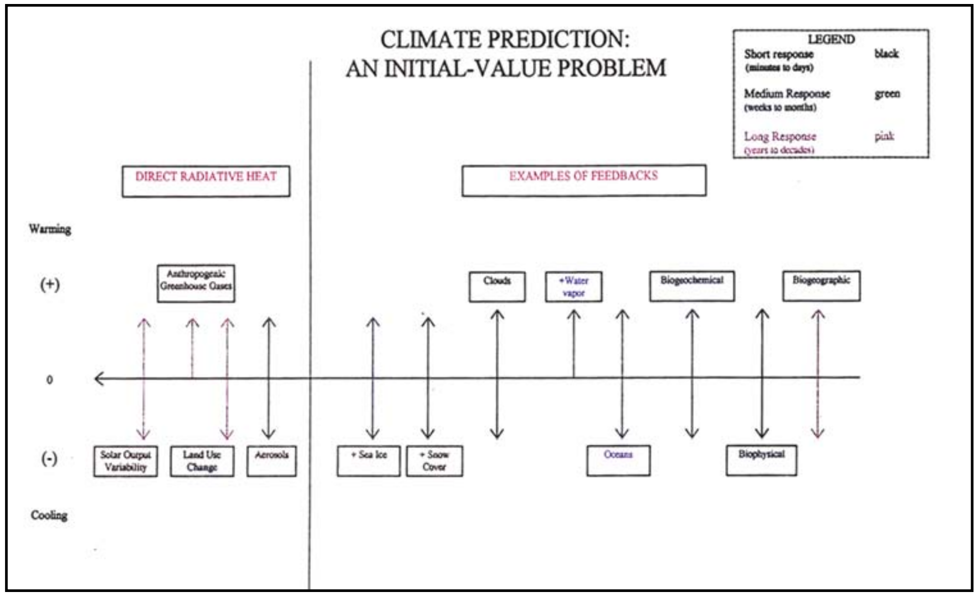

Figure 3.6. Schematic illustration of direct effects and feedback influences with respect to climate prediction. The length of the arrows has no meaning here, although the possible sign each effect could have is shown (from Pielke 1998a).

Since both the meteorological and ecological models are strongly influenced by what are dependent variables in the other models, this feedback must be considered in any climate simulation. The conclusion, therefore, is that vegetation dynamics interact with climate and weather through a coupled nonlinear interaction.

General circulation models not only have not included these land-atmosphere feedbacks, they have not yet considered the direct effect on global climate of human-induced landscape changes. Chase et al. (1996, 2000), for example, have shown that regional landscape changes in the tropics, in particular, alter climate thousands of miles away in the mid- and high-latitude polar jet flow. Longwave tropospheric wind flow was substantially altered when current, as contrasted with potential, leaf area index (LAI) was specified as a lower boundary condition in the NCAR CCM2 GCM.

The conclusion from these, and other related studies (Claussen 1994, 1998; Claussen et al. 1998; Foley 1994; Texier et al. 1997; Liu and Avissar 1999a, b; Eltahir 1998; Zheng and Eltahir 1998; Xue 1996, 1997; Laval et al. 1996; Polcher 1995; Polcher and Laval 1994; Lewis 1998; Desborough 1997; Xue et al. 1996; Copeland et al. 1996; Pielke et al. 1997; Emori 1998; Baron et al. 1998; Neilson and Drapek 1998; Stohlgren et al. 1998), is that land use plays a significant role on local, regional, and global climates. Its neglect in current GCM scenarios necessarily limits the value of GCM simulations to sensitivity studies in which important direct and feedback effects on climate are ignored.

In the absence of accurate predictions of future climates, a "vulnerability approach" to climate change, land-use change, and other stresses may be more pragmatic (Fig 3.9). Here, the major forces of change are considered simultaneously, with particular attention to the most sensitive resources and processes to subtle changes and stresses.

Summary of the vulnerability assessment approach—Thomas J. Stohlgren. Accurate forecasts of future regional climate due to a doubling of CO_2 are not possible now because of limited global climate predictability from nonlinear effects and the neglect of important direct and feedback effects on climate. By ignoring land-use change as a major driver of climate, current GCM scenarios have limited value. For these reasons, a vulnerability assessment approach to climate (with the inclusion of other environmental stresses) should be adopted (Fig. 3.9). This procedure avoids the riskier approach of assuming we can forecast the future regional climate and its interaction with other environmental factors.

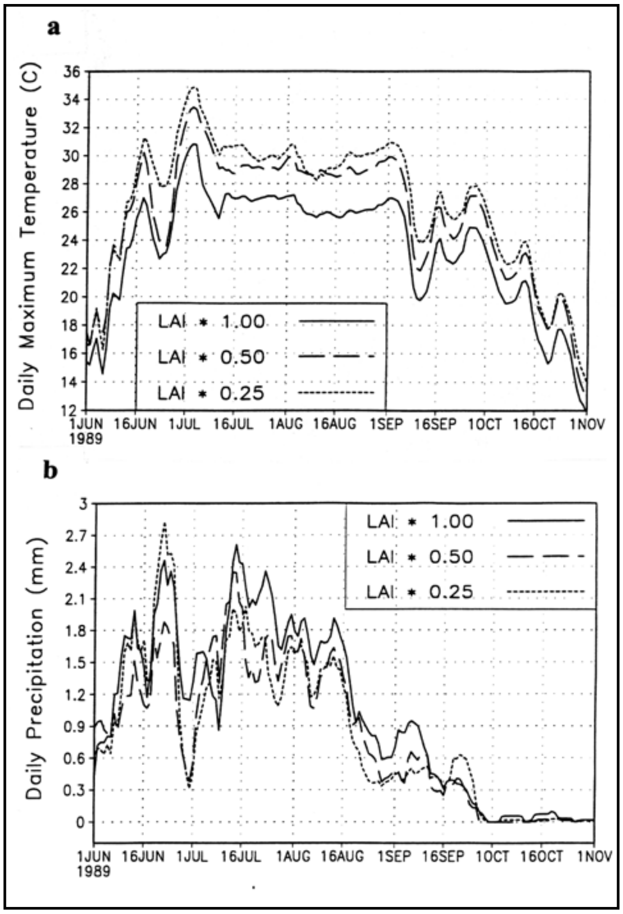

Figure 3.7a. The effect of changing leaf area index (LAI) on daily maximum temperature (°C) over Colorado (USA). Figure 3.7b. The effect of changing leaf area index (LAI) on daily precipitation (mm) over Colorado (from Pielke 1998b).

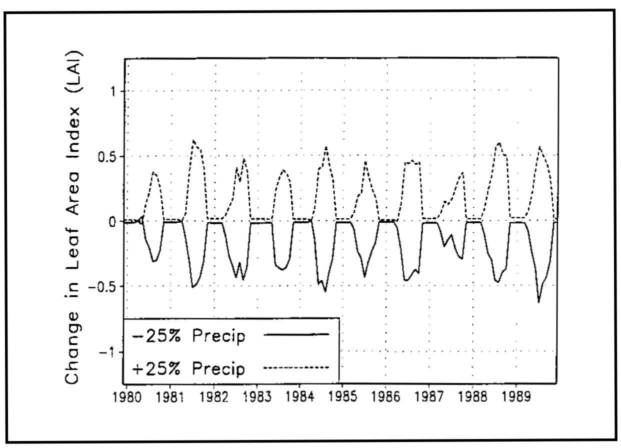

Figure 3.8. The effect of changing precipitation on LAI for short grassland over eastern Colorado. Solid curves indicate the changes of LAI when precipitation decreased 25% and dashed curves indicate the LAI changes when precipitation increased 25% (from Pielke 1998b).

Global and Regional Climate Models and Possible Scenarios—Linda O. Mearns

Model comparisons. Doherty and Mearns (1999) compared two atmospheric/ocean GCMs being used in the National Assessment. The control runs of the two models were tested against observations of temperature and precipitation over the continental United States, including on the Rocky Mountain and Great Basin region. One of the key issues for this region is the spatial resolution of the two models, since this will determine how well the models can simulate the climate in a region of very complex topography. The Canadian model (CGCMI; Boer et al. 2000b) has a spatial resolution of 2.5° by 3.75°, and the British model (HadCM2; Johns et al. 1997) has a resolution of 2.5° by 2.5°. Neither of them can resolve the complex western topography very well because of inadequate spatial resolution. The topography of the western U.S. represented in both models is coarsely represented as one large hill, rising from the west coast, and then descending to the Great Plains (Fig. 3.10).

The model temperature and precipitation results were compared to observations of Legates and Wilmott (1990a, b), which were originally developed on a 0.5° grid. To perform the comparisons, the Legates and Wilmott data were aggregated up to 2° by 2°, and the general circulation model results were interpolated onto that grid. The time period of the control runs evaluated were 1921 to 1980 since this is the period of data used in developing the Legates and Wilmott data sets.

Both the Canadian and British models exhibit mainly negative temperature biases over the western United States, of up to 6° C (10.8°F) in all seasons, although largest biases are found in spring. In winter, the Northwest extending up into Canada exhibits positive biases of up to 6° C in both models. In mountainous terrain, observational temperature data sets are often biased toward being somewhat too warm, since most observational stations are found in valleys. It is likely that the Legates and Wilmott data set has a positive bias of up to 1° C (C.J. Wilmott, pers. comm.). The bias in the observations, however, can account for only a small part of the model biases.

Precipitation biases in the models in the western U.S. tend to be positive in most seasons,

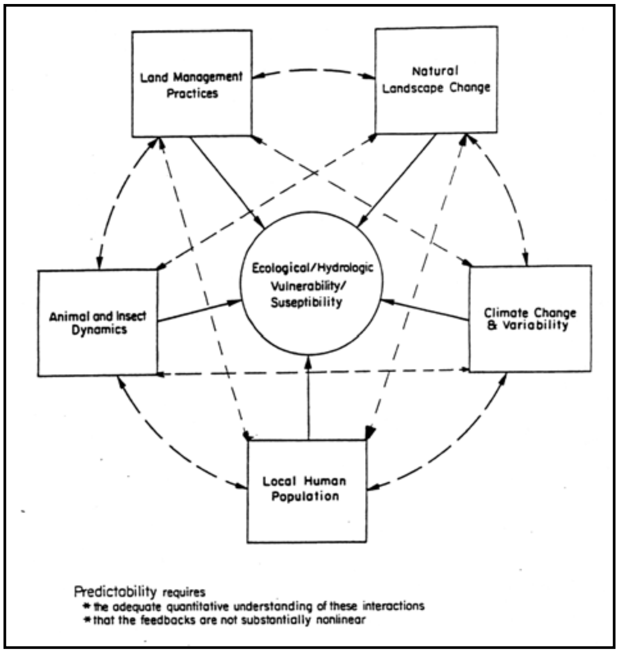

Figure 3.9. Use of ecological-hydrologic vulnerability/ susceptibility in environmental assessment (from Pielke 1998b).

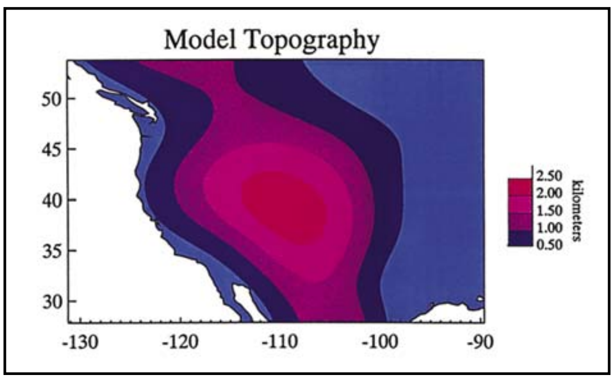

Fig. 3.10. Western North American topography used in the T32 Canadian Coupled Climate Model (units=km) (provided by John Fyfe).

with errors being largest in the Northwest in winter, when the models overestimate precipitation by more than 100%. Precipitation is best reproduced in summer in the British model. There are, of course, uncertainties in the observed data set for precipitation, so the corrected data set was used in this comparison.

From the comparisons, there is no clear indication that one model reproduces the climate of the western U.S. better than the other. The models produce relatively similar errors, and the size of the errors for both precipitation and temperature in these two models is within a range typical for GCMs.

L.O. Mearns (unpub. data) described the climate changes calculated by the two models for the time period 2055 to 2065 (doubled CO_2). The Canadian model simulated increases in temperature of between 4° to 6° C (7.2°-10.8°F) in winter and 2° to 3° C (3.6°-5.4°F) in summer. The British model simulated less extreme increases of 2° to 4° C in winter and 2° to 3° C in summer. Precipitation increased in the Canadian model in winter, spring, and fall, but both increased and decreased in summer depending on the month. The British model simulated increases in winter, spring, and summer, and decreases in fall. Thus, the Canadian model simulated larger temperature increases and larger increases in precipitation (up to 3 mm/day in winter) compared to the British model.

Regional climate modeling of the western U.S. Doherty and Mearns (1999) described results from a regional climate-modeling experiment over the western two thirds of the U.S. which produced climate-change scenarios at a spatial grid of 0.5°, or 50 km (Giorgi et al., 1998). The regional model (RegCM2; Giorgi et al. 1993a, b) was nested in the CSIRO General Circulation Model (with a horizontal grid of about 400 km), and 5 years of control and doubled CO_2 experiments were produced. The authors showed contrasts in the control-run temperature and precipitation fields from the CSIRO GCM and the regional model. The regional model was much more successful at reproducing the details of the spatial distribution of temperature and precipitation in the western U.S. in all seasons. They also showed contrasts in the spatial distribution of changes in precipitation under doubled CO_2 conditions calculated by the two models. These runs have been used to examine the effects of the spatial resolution of climate-change scenarios on the calculation of climate-change effects on crop yields in the Great Plains (Mearns et al. 1999). The CSIRO and RegCM2 runs for the western U.S. are available and in a form that could be easily used by impacts assessors for the Rocky Mountain/Great Basin region (see information sources below).

The Canadian Global Coupled Model—John Fyfe

Model description and verification. The first version of the Canadian Global Coupled Model, CGCM1 and its control climate are described by Flato et al. (2000). The atmospheric component of the model is essentially GCMII described by McFarlane et al. (1992). It is a spectral model with triangular truncation at wave number 32 (yielding a surface grid increment of roughly 3.7° by 3.7°) and 10 vertical levels. The ocean component is based on the GFDL MOM1.1 code and has a grid interval of roughly 1.8° by 1.8° and 29 vertical levels. The model used heat- and water-flux adjustments obtained from uncoupled ocean and atmosphere model runs, followed by an "adaptation" procedure in which the flux adjustment fields are modified by an integration of the coupled model. A multi-century control simulation with the coupled model has been performed using the present-day CO_2 concentration to evaluate the stability of the coupled model's climate, and to compare the modeled climate and its variability to that observed.

An ensemble of four transient climate-change simulations has been performed and is described in Boer et al. (2000a). Three of these simulations use an effective greenhouse-gas forcing change corresponding to that observed from 1850 to the present, and a forcing change corresponding to an increase in CO_2 at a rate of 1% per year (compounded) thereafter until year 2100. The direct forcing effect of sulfate aerosols is also included by increasing the surface albedo based on loadings from the sulfur cycle model of Langtner and Rodhe (1991). The fourth simulation considers the effect of greenhouse-gas forcing only. The change in climate predicted by a model clearly depends directly on this specification of greenhouse-gas (and aerosol) forcing, and of course these are not well known. The prescription described above is similar to the IPCC "business as usual" scenario.

The ability of a climate model to reproduce the present-day mean climate and its historical variation at global scales adds confidence to projections of future climate change at global scales. A comparison of modeled and observed (Jones 1994) global, annual-average, surface air-temperature anomalies from 1900 to 1990 shows an overall agreement in temperature trends, and the magnitude of stochastic inter-annual variability. In both the model and observations, the increase in global mean temperature over this century is roughly 0.6° C (1.08°F). Between years 1980 and 2050 the prescribed CO_2 concentration doubles, and over this time the greenhouse gas-only run exhibits an increase in temperature of 2.7° C (4.9°F). The increase over the same period in the greenhouse gas plus aerosol run is 1.9° C (3.4°F); the difference of 0.8° C (1.4°F) is the cooling effect of the aerosols.

Rocky Mountain and Great Basin region projections. The topography of the Canadian Climate Model over western North America does not capture the detailed topography of the Rockies (Fig. 3.10), but it does reflect large-scale topographic structure (Fig. 3.11). The model Rockies reach high enough over a large enough area to support appreciable winter and springtime snowcover, the essential ingredient for an elevation-enhanced, climate-change signal as described by Fyfe and Flato (1999).

Summers are projected to become warmer and drier and the winters warmer and wetter (see the difference fields on the right are relative to 1915; Fig. 3.11). These results are spatially-averaged over the Rocky Mountain and Great Basin region. By 2050, for example, the annually-averaged temperature and precipitation are shown to increase by 3.3° C (5.9°F) and 0.2 mm/day, respectively. After 2050, the screen temperature and precipitation continue to increase even when the levels of CO_2 are fixed at their 2050 levels, as recent Canadian model stabilization runs show (G.M. Flato, pers. comm.).

Spatially-averaged changes in 20-year return values for daily minimum and maximum temperature and precipitation increase in the future (following the analysis of Kharin and Zwiers, 2000; Fig. 3.12). Daily minimum temperatures increase more quickly than maximum temperatures. The 1975-1995, 2040-2060 and 2080-2100 periods roughly correspond to periods of present day, two-times, and three-times increase in CO_2, respectively. An increase in extremes of daily precipitation is also simulated for these scenarios for the Rocky Mountain and Great Basin region.

One feature which distinguishes the Rocky Mountain and Great Basin region from the other regions of the National Assessment is, of course, the high elevations. Fyfe and Flato (1999) show

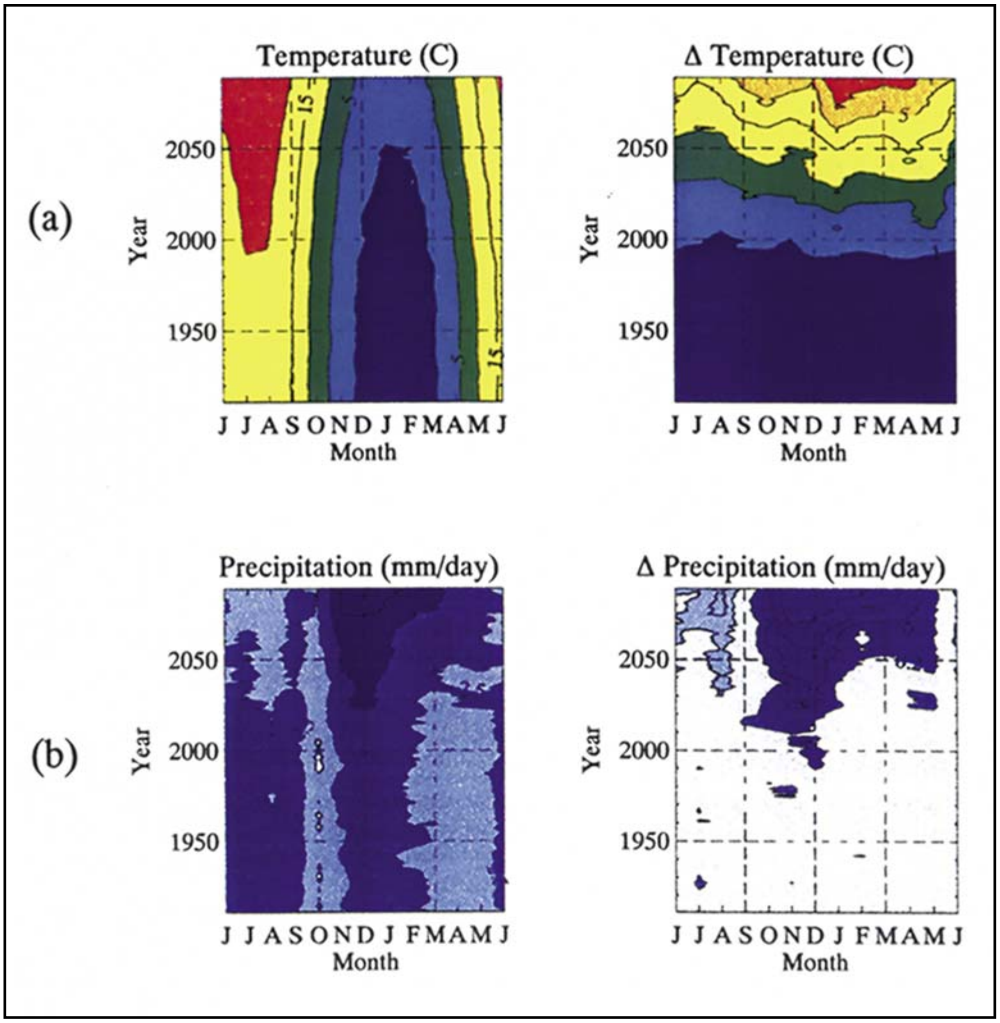

Figure 3.11. Simulated monthly-mean: (a) screen temperature (left) and screen temperature change (right); (b) precipitation (left) and precipitation change (right). The changes are relative to 1915. The precipitation contour interval is 0.5 mm/day. The precipitation change contour interval is 0.2 mm/day [positive (negative) values heavily (lightly) shaded].

that there is a marked elevation dependency of the simulated screen temperature increase over the Rocky Mountains in the winter season, with more pronounced changes at higher elevations (Fig. 3.13).

The elevation signal is linked to a rise in the snowline in the winter and spring seasons, which amplifies the surface warming via the snow-albedo feedback. Fyfe and Flato (1999) also show that although the warming signal is enhanced at higher elevations, the elevation effect has no potential for early climate-change detection at this model resolution.

Global climate models are continuously being improved. Horizontal and vertical resolution are being increased as computing power advances, with many modeling groups taking advantage of the ability to split intensive calculations between multiple, parallel processors on a single computer ("multi-tasking"). Improvements in parameterizations of physical processes are being made. Some examples are the more sophisticated land-surface schemes such as CLASS (Verseghy et al. 1993), improved representation of sub-grid-scale mixing in the oceans; improved treatments of clouds, convection, radiation; indirect effect of aerosols in the atmosphere (e.g. Zahng and McFarlane 1995); and the inclusion of sea-ice dynamics (e.g. Flato and Hibler 1992). In addition, the "technology" of coupling various model components is receiving considerable attention with new methods of "spinning up" the ocean model to equilibrium, reducing the "shock" the model components experience upon coupling, and minimizing or eliminating the requirement for flux adjustment.

Global and Regional Model Summary—Thomas J. Stohlgren

Problems at regional scales. Current global-scale climate models have successfully replicated some global-scale temperature changes, but they have several limitations for regional climate modeling including: (1) poor topographic and spatial resolution (Fig. 3.10); (2) systematic biases (Doherty and Mearns 1999); and (3) lack of biophysical feedbacks and land-

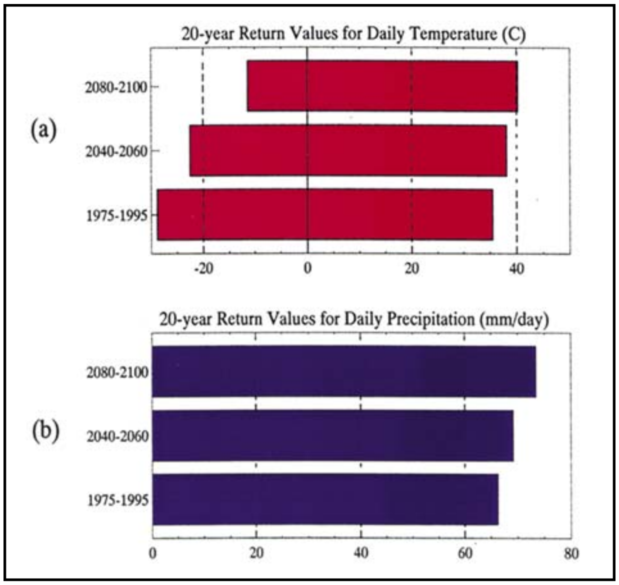

Fig 3.12. The bars project temperature and precipitation ranges for current levels of atmospheric CO_2 (1975-1995), doubled CO_2 (2040-2060), and tripled CO_2 (2080-2100) with the Canadian Climate Model for the Rocky Mountain/Great Basin region.

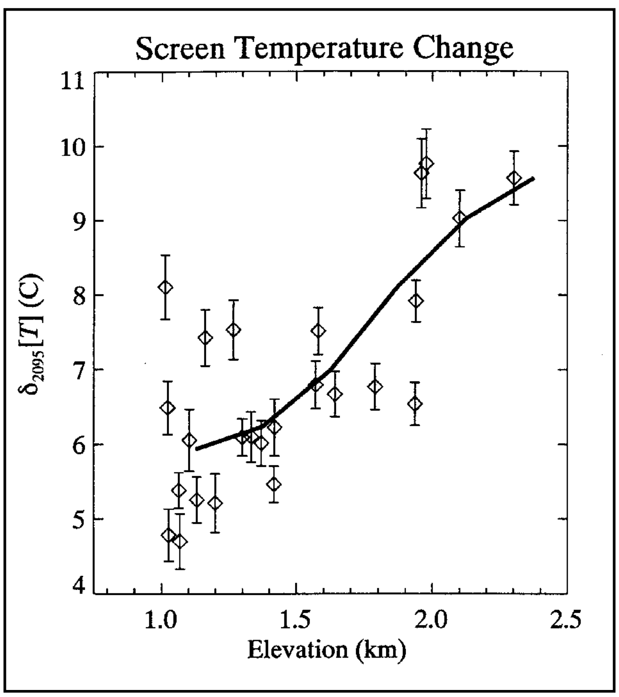

Fig 3.13. Relationship between projected temperature change in °C by 2095 and elevation in the Rocky Mountains. The height of the vertical bars measures the interdecadal variability. The temperatures are simulated with the Canadian Climate Model.

use change effects which are known to affect local, regional, and global climate (Pielke et al. 1998b, Stohlgren et al. 1998). The results of such models are "spatially averaged" and have equally severe limitations for generating realistic scenarios for sub-regions and for topographically complex areas within sub-regions (Pielke et al. 1998a, b). Current GCMs sometimes produce large biases in some regions (up to 6° C) when reproducing past patterns of temperature (Doherty and Mearns 1999). Presently there is no way to assess the spatial accuracy or probability of specific model scenarios from GCMs relative to all possible future outcomes. Confidence limits around two projected climates (from two models) can be large. Given these limitations, present GCMs may or may not produce meaningful climate scenarios at regional and sub-regional scales in the complex terrain of the Rocky Mountains and Great Basin. Regional models hold more promise, but they are receiving far less research support than global modeling efforts. Future GCMs and regional climate models that incorporate high-resolution topography, biophysical feedbacks, land-use change, and other ecosystem stresses may be more useful.

Confidence limits when models disagree. A major problem with relying on model-generated scenarios is that all scenarios about the future have unknown, and presently unknowable, probabilities. Many equally probable outcomes are ignored. Also, models rarely agree at local- or sub-regional scales (VEMAP web site). What happens when the models disagree? This creates another major, commonly overlooked problem with the scenario approach. When two models differ in outputs for a specific region, the two outputs are typically presented as a "range" rather than two sample data from an unknown population. For example VEMAP data for Wyoming show differences between the Hadley and Canadian GCMs. Reporting a "range" of modeled temperature change from 2.5° C (Hadley) to 5.0° C (CGCM) gives no indication of the confidence limits of the data. Presenting summary data from two models might create a false sense of precision to the public. The actual range of possible outcomes is usually greater, unstated, or unknowable, so management options only for scenarios might be misleading or dangerous. However, there is growing convergence among climate-model results on subcontinental and seasonal time scales (Giorgi and Mearns 1991)

Statistical Downscaling—Robert L. Wilby

Rationale for statistical downscaling. The fundamental rationale for statistical downscaling is that the raw outputs of climate-change experiments from GCMs are inadequate for assessing the effects of climate change on land-surface impacts at regional scales. This is because the spatial resolution of GCMs is too coarse to resolve important sub-grid scale processes (most notably those pertaining to the hydrological cycle), and because GCM output is unreliable at individual and sub-grid box scales. By establishing empirical relationships between meso-scale atmospheric circulation predictors and sub-grid scale surface predictands, statistical downscaling has been proposed as a means of bridging this spatial difference.

Although many papers have summarized the theory and practice of downscaling (e.g. Giorgi and Mearns 1991; Wilby and Wigley 1997), relatively few have explicitly considered the limitations of such techniques. For example, sensitivity analyses have demonstrated the susceptibility of downscaled scenarios to season definitions, the choice of data-standardization technique, length of calibration period, function form, and predictor variable(s) (Winkler et al. 1997). It has also been shown that different circulation schemes (Buishand and Brandsma 1997) and downscaling methodologies (Wilby et al. 1998) yield markedly different regional climate-change scenarios, even when common sets of GCM predictors are used. Finally, there is doubt as to the stationarity of some predictor-predictand relationships (Wilby 1997). The inclusion of low-frequency, surface-climate variability in downscaling continues to be problematic (Katz and Parlange 1996), and the neglect of important feedbacks to the climate system may have serious implications.

Case study: Animas River basin, Colorado. The relative merits of downscaled and raw GCM output need to be rigorously compared. Accordingly, Wilby et al. (1999) compared three sets of daily rainfall-runoff scenarios (Table 3.1). The climate scenarios were constructed using: (1) raw GCM output (scenario H2); (2) a conventional "delta" change experiment in which the difference between current and the scenario GCM output is added to observed time-series of the same variable (X); and (3) statistically downscaled GCM output (D2).

The downscaling models were trained using reanalysis of gridded data obtained from the National Center for Environmental Prediction (Kalnay et al. 1996) for the period 1986-1995. The predictor variables were mean sea-level pressure, 500 hPa geopotential heights, 2 meter (near surface) temperatures, and 0.995 sigma-level (near surface) relative humidities. The predictands were observed daily precipitation, maximum temperature, and minimum temperature, obtained from National Weather Service and Snow Telemetry stations in the Animas River, a sub-basin of the San Juan River, Colorado. Scenarios were developed by forcing the downscaling models with equivalent predictors from the U.K. Meteorological Office's coupled ocean-atmosphere GCM (Johns et

Table 3.1

Rainfall-runoff Scenarios for the Animas River Basin Specified for Observed (1979-95), Current GCM (1980-96), and Doubled CO_2 GCM (2080-96) Climate Data

Scenario	Years	Predictors	Technique	Domain
S1	1979-95	Station	Observed data	Animas (3)[1]
S2	1979-95	Station	Observed data	San Juan (37)
N	1979-95	NCEP	Downscaled[2]	Animas (3)
H1[3]	1980-96	GCM	Raw output	Grid-box
D1	1980-96	GCM	Downscaled	Animas (3)
X	1979-95	Station/GCM	Delta change	Animas (3)
H2	2080-96	GCM	Raw output	Grid-box
D2	2080-96	GCM	Downscaled	Animas (3)

[1]Figures in brackets refer to number of NWS and SNOTEL stations used to generate area-average daily precipitation, maximum and minimum temperatures along with corresponding domain descriptions.

[2]Downscaling models were calibrated using data for the period 1986-95 but forced using predictions for 1979-95.

[3]Had CM2 and actual years are not directly equivalent due to differences in the observed climate and GCM forcing (see Wilby et al. 1998).

al. 1997; Mitchell and Johns 1997). The three climate-change scenarios (i.e., H2, X, and D2) were then used to drive the U.S. Geological Survey's (USGS) Precipitation-Runoff Modeling System (Leavesley et al. 1983; Leavesley and Stannard 1995), a distributed hydrological model. Changes in the modeled daily flow regime and snowpack behavior between current (1980-1996) and future (2080-2096) climate scenarios were then compared.

Table 3.2

Animas River Basin Area – Averages of Daily Precipitation, Maximum Temperature, and Minimum Temperature Calculated After Redistribution (from Wilby et al. 1999)

Scenario	Precipitation (mm)	Maximum Temp. (C)	Minimum Temp. (C)
S1	2.5	9.7	-5.3
N	2.9	9.1	-5.1
X	3.2	12.8	-1.1
D1	2.6	9.3	-5.1
D2	3.2	12.8	-1.4
H1	2.2	10.5	-2.7
H2	2.5	13.7	-1.4

The modeled monthly, mean streamflows of the Animas River varied greatly for the various scenarios (Fig. 3.14). Relative to N, scenarios X, H1, and H2 yield higher winter flows, earlier peak flows (May instead of June) and lower summer/autumn flows. The flow regime of scenario D1 most closely resembles that of N, whereas D2 claims June as the month of maximum runoff, with higher flows in January to March and lower flows from April onwards.

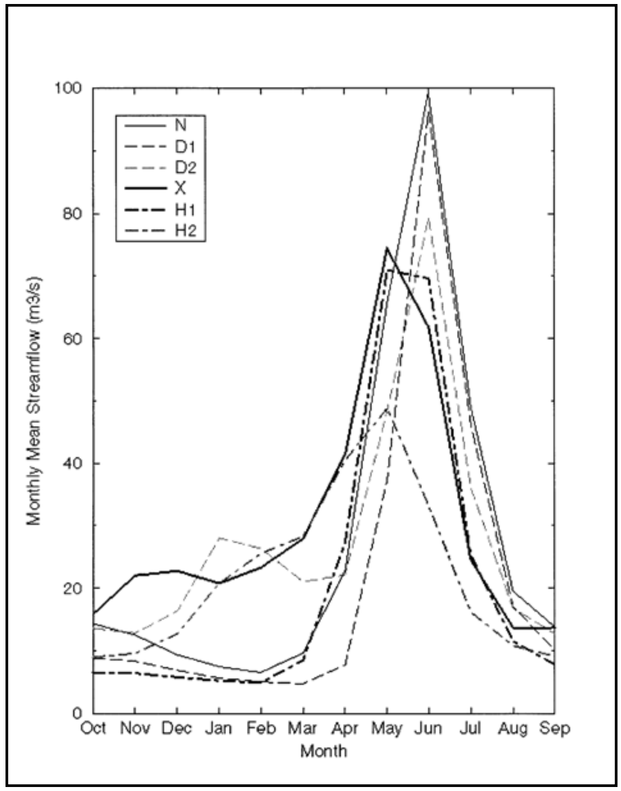

Fig. 3.14. Modeled monthly mean runoff of the Animas River simulated with scenarios N, D1, D2, X, H1, and H2 (from Wilby et al. 1999).

The reasons for the differences in the monthly flow regimes are to be found in the monthly and seasonal differences in mean precipitation, maximum temperature, and minimum temperature among the scenarios (Tables 3.2 and 3.3). For the scenarios (D2, X, H2), warmer fall and winter maximum and minimum temperature values increase the amount of precipitation occurring as rain (rather than snow) during these months, and increase snowmelt rates at lower elevations. These changes result in increased streamflow for these periods. Differences in the magnitudes of the monthly flows reflect the differences in seasonal precipitation type and amount, as well as the variations in the distribution of maximum temperature and minimum temperature. The difference in the timing of peak runoff

Table 3.3

Changes in Daily Precipitation, Maximum Temperature, and Minimum Temperature Between 1980-96 and 2080-96: A Comparison Of Raw GCM Output from HADCM2 and Downscaled Scenarios (from Wilby et al. 1999)

	Precipitation		Max Temp.		Min. Temp.	
Season	GCM	Downscaled	GCM	Downscaled	GCM	Downscaled
Dec.-Feb.	+0.7	+1.2	+3.6	+3.4	+5.4	+3.8
Mar.-May	+0.3	0	+2.0	+2.8	+3.2	+3.1
June-Aug.	-0.1	+1.3	+3.8	+3.7	+4.2	+4.1
Sep.-Nov.	+0.3	+0.1	+3.1	+3.8	+3.9	+3.6
Annual	+0.3	+0.6	+3.1	+3.5	+4.1	+3.6

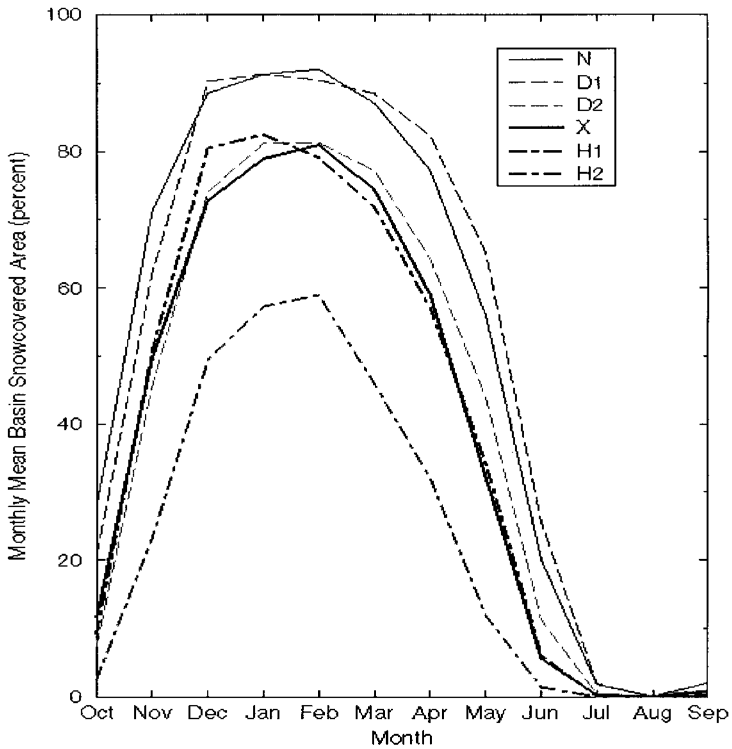

Figure 3.15. Modeled monthly snow cover areas simulated with scenarios N, D1, D2, X, H1, and H2 (Wilby et al. 1999).

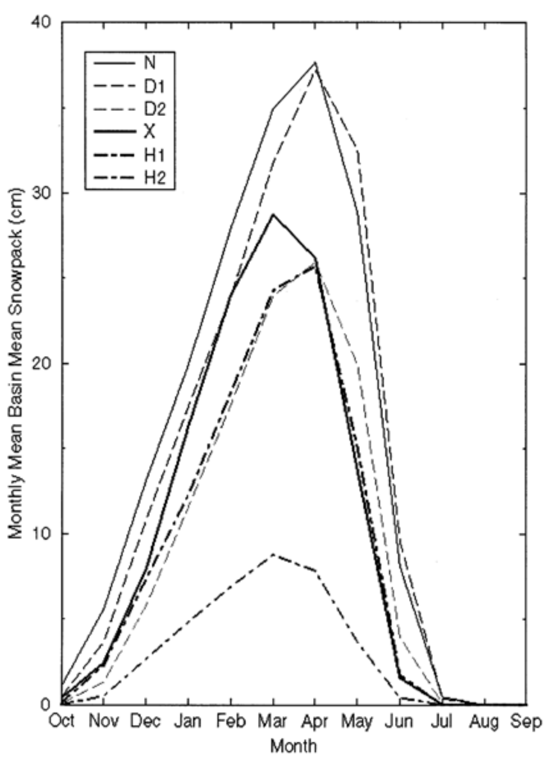

Figure 3.16. Modeled monthly snowpack water equivalents simulated with scenarios N, D1, D2, X, H1, and H2 (from Wilby et al. 1999).

between X and D2 is a function of the lower spring maximum and minimum temperatures and higher June precipitation value for D2 which delays the onset of snowmelt and enhances streamflow later in the snowmelt season.

Changes in the seasonal flow regimes are also a consequence of changes in snowpack behavior. If scenario N is taken as the datum, it is evident that scenario D1 yields snow-cover durations that are broadly consistent with current conditions (Fig. 3.15). In comparison, scenarios D2, X, and H2 all exhibit significant reductions in the duration of basin snow-covered area and snowpack water equivalent (Fig. 3.16) relative to the current climate.

The future snow-covered areas are almost identical for D2 and X, and are similar for the snowpack water equivalent, suggesting that for these indicators the delta-change scenario approximates results obtained from the more computationally demanding downscaling. In comparison, scenario H2 is by far the most extreme in terms of reduction in snowpack, presumably a consequence of the lower precipitation (relative to both D2 and X) and the higher winter maximum and minimum temperatures. Subtle changes in the timing of the snowpack accumulation/ablation are produced in these scenarios (Fig. 3.16).

In scenarios N, D1, H1, and D2 peak accumulation occurs in April-May as opposed to March-April in the case of X and H2. The later date of peak accumulation and melt for scenario D2, as compared to the other future scenarios X and H2, is consistent with projected later streamflow peaks (Fig. 3.15).

Implications for scenario choice. It is evident that the choice of technique for scenario generation has major implications for the projected climate-change impact (in this case, water balances). The legitimacy of applying the delta-change technique in preference to the downscaling depends on the quality of the baseline data to which it is applied. The Animas River basin data set provides a good example of a situation in which earlier station variables are, in fact, of less than optimal quality. In this case an underestimation of precipitation in the 1980-1985 period of the S1 data set was carried through to the X scenario. The result was a suppression of the streamflows for the first 6 years of the X scenario, thus producing a more conservative scenario of the effects of climate change for the 16-year average. Even so, scenario X still produced more total runoff than scenarios D2 and H2.

Applying delta changes also presupposes that the variable changes produced by the GCM are plausible at the (sub-grid) scale and elevation of the impact analysis, and that climate changes are only expressed through changes in daily means. However, there may be marked differences in the seasonal changes produced by the GCM and downscaling (Table 3.1). The main advantage of the delta-change approach over the statistical downscaling is the relative ease with which such scenarios may be generated. In defense of the statistical downscaling is the fact that the technique can produce changes in both the mean and variance of the sub-grid variables, as well as ensembles of plausible climate scenarios.

Which regional climate-change scenario should be used for impact analysis? If it is feasible, the approach of multiple working hypotheses should be adopted (i.e., a range of plausible scenarios should be applied in parallel). Where appropriate, paleoclimatic data might also be used to extend instrumental records, or to examine system sensitivity to extreme events. Since no technique of scenario construction is perfect, climate-impact assessments are best undertaken using an envelope of methodologies including raw GCM output, downscaling, delta-change scenarios, regional climate modeling, and paleoclimatic analogues. In the case of the Animas River basin, there is at least a qualitative consensus that the future magnitude of low and intermediate flows may increase, whereas peak flows, basin snow-covered areas, and snowpack water equivalents may all decline relative to current conditions. Research is underway to determine the generality of these weather-resource impacts for other river basins in the U.S.

Summary of downscaling—Thomas J. Stohlgren. Downscaling is the development of techniques that link low-resolution GCM outputs to higher-resolution field data. It is well recognized that raw outputs of climate-change experiments from GCMs are inadequate for assessing the effects of climate change on land-surface impacts at regional scales. Nevertheless, downscaling techniques provide important insights to linking data across spatial scales and may become more important tools as GCMs are improved.

Discussion—Thomas J. Stohlgren

The climate is changing for many reasons, and it is changing faster in some sub-regions of the Rocky Mountain and Great Basin region than in others. There likely have been abrupt climate changes (Schuster et al. 2000), including periods of cooler and wetter conditions, droughts and floods. Increased warming, even in winter, may not translate to reduced snow accumulation, as demonstrated recently for the Alps (Burroughs 2000). There may be increased precipitation in some portions of the Great Basin (Table 1, IPPC 1998), and earlier snow-melt and peak streamflow in the northern portions of the region, but spatial variation is great, and this complicates regional generalities and predictions. It is difficult to isolate the effects of atmospheric pollutants (CO_2, methane, etc.) from background, natural rates of climate change at local and regional scales, primarily due to land-use change and other factors (Pielke et al. 1998a, b, Stohlgren et al. 1998, Chase et al. 1999).

Spatial and temporal variation in temperature and precipitation trends are large, and regional assessments based on “average trends” and regional scenarios are of uncertain value in a region where sub-regional variation has been so substantial historically (also see Pielke et al. 1998a, b). Given that sub-regions respond differently to observed annual, decadal, and ENSO variation (Figs. 3.4-3.5), it may be difficult to assume that reliable short-term (<20 year) or long-term climate predictions are possible for the different sub-regions with present modeling capabilities.

Current global-scale climate models may be inappropriate for developing regional and sub-regional scenarios due to: (1) poor topographic and spatial resolution (Fig. 3.10); (2) systematic biases (Doherty and Mearns 1999); (3) lack of biophysical feedbacks and land-use change effects which are known to affect, although to unknown degrees, local, regional, and global climate (Pielke et al. 1998a, b, Stohlgren et al. 1998, Chase et al. 1999); (4) inability to assess the spatial accuracy and actual probabilities of modeled outputs; and (5) limited ability to assess multiple ecosystem stresses (i.e., deforestation, exotic species, air pollution, etc.) (Stohlgren 2000). Downscaling GCM outputs may provide important insights to linking data across spatial scales once GCMs are greatly improved (Wilby et al. 1999).

Stakeholders, particularly water managers in the Rocky Mountain and Great Basin Region, express more concern for accurate short-term predictions (on the order of days to months) at local scales, and for extreme events. They are less interested in climate-change scenarios 100 years in the future, at regional and global scales, especially given the lack of certainty in the models. Stakeholders might best be served by focusing additional efforts on short-term, local responses that are important to them. However, GCM and down-scaling models must also be improved to understand and mitigate long-term subtle change in climate and land use. Caution must be used in assuming the continuance of long-term historical trends for the very near future, realizing that stochastic shifts in climate (inter-annual, decadal, and ENSO events) will continue to obstruct most long-term trends (Dettinger et al. 1995, 1998, 1999, Cayan et al. 1989).

Improved climate monitoring is essential. There are very few weather-monitoring stations above 2,500 m (8,200 ft) elevation where much of the precipitation and snowmelt occurs. There is increasing pressure to reduce long-term stream monitoring in many areas. A better network of monitoring sites is needed to better monitor short-term trends in the topographically complex sub-regions in the Rocky Mountain and Great Basin region.

Additional synthesis of existing data is also needed that includes sub-regional trend analysis of extreme precipitation events, frost-free periods, record-setting temperatures, extreme droughts, summer base-flow periods, and minimum flow dates. We also need additional research on snow and rain patterns by elevation, the effects of land use, and water redistribution on local and regional climate.

We urgently need to better understand climate and to develop an ensemble of plausible, regional climatic scenarios. For example, GCMs require enhanced computing power for increased spatial resolution, incorporation of biophysical feedbacks and land-use changes into the models, and increased research on downscaling techniques that cross spatial scales from local (point) measurements to sub-regional, regional, national, and global scales. Additional research is also needed on ENSO and decadal climate variations at sub-regional scales and the merging of high- and low-frequency events. Regional assessments based largely on existing data and current models are probably incomplete in unknown ways.

Information Sources

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HISTORICAL CLIMATE ANALYSIS—Connely K. Baldwin

Introduction

The purpose of this section is to analyze the 20th-century climate records of the RMGB region to determine whether its climates have undergone trends in the recent past that are qualitatively in the same directions as those projected by the GCMs for the 21st century. The recent rise in atmospheric CO_2 began in the middle 1800s at the beginning of the Industrial Revolution. The

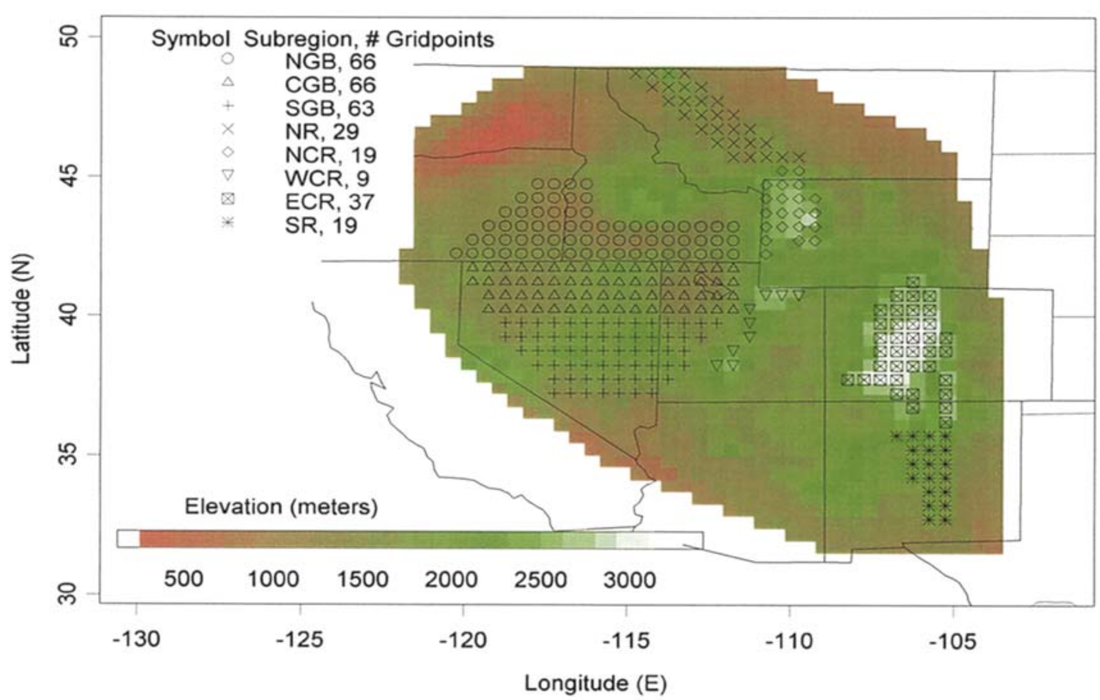

Figure 3.17. VEMAP 0.5° quadrangles grouped to form eight Rocky Mountain/Great Basin subregions. These subregions, and their acronyms, are: Northern Great Basin (NGB), Central Great Basin (CGB), Southern Great Basin (SGB), Northern Rockies (NR), North-central Rockies (NCR), West-central Rockies (WCR), East-central Rockies (ECR), and Southern Rockies (SR).

CO_2 concentration has risen at an increasing rate since that time, increasing by approximately 7% between 1850 and 1900, by 20% during the 20th century, and is predicted to increase by approximately 100% during the 21st (Backlund et al. 1997). Thus any greenhouse-gas-induced change in the 21st-century climate will likely far exceed any changes of similar cause in the 20th century.

But if 20th-century changes have been qualitatively similar to the GCM projections, although of lesser magnitude, and can be shown not to have coincided with "natural" (i.e. not anthropogenic) influences on climatic variation, they add plausibility to the 21st-century model projections. They would also provide a basis for using both the historical trends and GCM projections in formulating scenarios to pose to the sectors.

Most weather records in interior western U.S. date back to approximately the turn of the 20th century. Hence, with one exception, the analyses that follow address trends of the 1900s.

Data Sources and Methodology

VEMAP, Subregionalization, and Other Data Sets

The Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) data were used to analyze the historical patterns of daily minimum temperatures (Tmin), daily maximum temperatures (Tmax), and precipitation (ppt) for the region. The VEMAP data are spatial averages of climate variables for weather stations in 0.5° quadrangles, with corrections for altitude to account for sampling biases produced by weather stations at different elevations.

Because of the size and complexity of the RMGB region, and the possibility that climate trends could vary across its extent, the 308 VEMAP quadrangles that fall within the RMGB region were subdivided into eight subregions ranging in size from 9 to 66 quadrangles (Fig. 3.17). These subregions (Fig. 3.18) and their acronyms, are: Northern Great Basin (NGB), Central Great Basin (CGB), Southern Great Basin (SGB), Northern Rockies (NR), North-central Rockies (NCR), West-central Rockies (WCR), East-central Rockies (ECR), and Southern Rockies (SR). Analyzing trends in the individual quadrangles would emphasize local variability which the GCMs cannot at present simulate, and might be so variable as to obscure regional or subregional trends. Averaging over the entire region would obscure any variations in trends within the region. Thus subregions of moderate size based on known, existing climate patterns with latitudinal variations therein, and physiographic subdivisions were chosen. The subregions disclose differences in 20th-century climate trends within the RMGB, and provide replications among subregions that strengthen any inferences of trend.

In addition, RMGB climate trends reported by other authors based on statistical procedures different from those used in this study, different data sets, slightly different sequences of years, and different geographic subdivisions were compared with the results of this study. All of these together provide a body of evidence pointing to the 20th-century climate trends inferred for the RMGB region.

Analytic Procedures

This analysis focused on determining whether there were statistically significant, secular trends in annual means of daily,

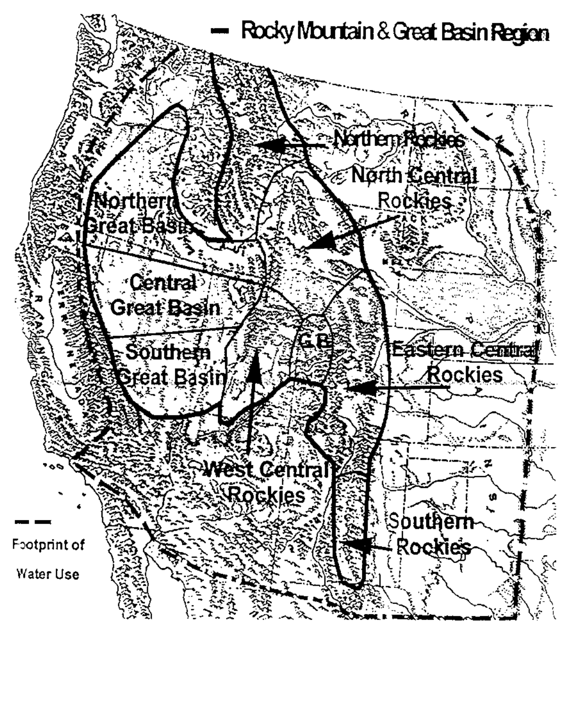

Figure 3.18. Eight Rocky Mountain/Great Basin subregions used to subdivide the regional, historical climate analysis.

minimum temperatures (Tmin) and daily maximum temperatures (Tmax), in mean annual temperature, and in total, annual precipitation (ppt) in the eight subregions during the 1900s. It also determined whether the variances in these parameters changed over time, and it explored which monthly trends were largely responsible for driving the annual trends.

The basic analytic units were the monthly values for each year of the series: mean, monthly Tmin and Tmax, and total monthly ppt. The Seasonal Kendall test was used since it is nonparametric, and does not require the data to conform to any particular distribution (Gilbert 1987). An additional value of the test is its ability to assess seasonality by weighing the trend in each month separately in order to determine its role in producing the annual trend. It also allows calculation of the homogeneity of trends among the months.

The Seasonal Kendall test uses time series for each of the monthly values through the 1900s. The slope was calculated for each monthly time series, as was the probability that it is significantly different from zero, using the Mann-Kendall test. The test aggregates the monthly values to produce slope and probability values for the years. The Sen slope and p-value were also calculated for each month to determine which months were contributing to the annual trends.

In order to represent the mean, annual Tmin, Tmax, and ppt as time series, the annual values were smoothed with 30-year moving averages. The trends in these were tested with ordinary least squares tests. The standard deviations around the 30-year moving averages of Tmin, Tmax, and ppt were calculated to ascertain whether the variances of these parameters, and hence the variability of temperatures and precipitation, had changed over time. To analyze the trends in mean, annual temperatures, the time series of raw, annual means were smoothed with the Lowess smooth (Cleveland and Devline 1988), and slopes and p-values were calculated both with ordinary least squares and Sen-slope tests.

In order to develop some understanding of the sources and magnitudes of natural climatic variation affecting the parameters under study, and out of which any greenhouse-gas-induced trends must emerge in order to be detectable, we analyzed the data for evidence of El Nin o Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Arctic Oscillation (AO). The NIN O3 sea-surface, temperature-anomaly index was used as a measure of ENSO, as were the Mantua et al. (1997 and updates available on the Internet) PDO index and the Thompson and Wallace (1998) AO index values.

Four, 3-month seasonal averages were calculated for each oscillation index for each year (e.g. winter (DJF) av. NIÑO3, spring (MAM) av. NIÑO3, summer (JJA) av. NIÑO3, etc. for 1900, 1901, etc.). Each seasonal average was then regressed on each month's climate variable (Tmin, Tmax, ppt) in each subregion in those cases in which the monthly variable showed a significant positive trend over time. In the tests that were significant ($p \leq 0.05$), the climate-variable and oscillation-index variables were plotted together. Both variables were smoothed using a locally weighted, linear regression (Cleveland and Devlin 1988). The weights were applied over a period of 30 years so that those points closest to the estimation points carried more weight.

Temperature proxies based on tree-ring analyses for the period 1600 to the middle 1900s were also examined to determine whether trends, measurable over century scales, might coincide with the 20th-century trends under analysis here. These data were taken from the National Oceanographic and Atmospheric Administration (NOAA) web site.

Results

"Natural" Climatic Variability

Several nonanthropogenic sources of temporal variation add to the region's spatial complexity to complicate inferences about greenhouse-gas effects on its climate. It is necessary to clarify these in order to perceive whether any human-induced trends emerge out of the complex. Whether any of these force climatic trends over time scales comparable with those inferred for the anthropogenic influences, and thereby complicate attribution to the latter, must also be determined.

One source of variation is simply random fluctuation, here defined as a lack of autocorrelation between successive measurements. Globally, arid regions have the highest stochastic, relative variation in precipitation of any of the major climatic types (Wagner 1980). For example, Wagner (1980) showed that in a research area in southwestern Utah with mean, annual precipitation of 15 cm (5.9 in), most of the annual values fell over a 13 cm (5 in) range, and the coefficient of variation was 30%. The latter compared with C.V.s of 28% and 12% for grassland and deciduous forest areas, respectively.

A second source of temporal variation is the El Niño-Southern Oscillation (ENSO). As Mote et al. (1999) describe, the latitudinal positioning of the winter storm tracks in western North America varies with the depths of the low-pressure cell off the coast of the Aleutian Islands, and associated phases of ENSO. Very low pressures in the Aleutian cell coincide with the warm-water (El Niño) phase of ENSO and a split in the mid-latitude, winter storm tracks. One track moves northward to bring storms to Alaska, while a southern track carries storms to southern California and southwestern U.S. The Pacific Northwest experiences warmer and dryer-than-normal winters, with reduced montane snowpack and streamflow. During the cold-water La Niña phase, the mid-latitude storm tracks remain intact and carry winter storms and precipitation across the northern part of western U.S. The ENSO periodicity varies between 2 and 7 years, and averages 3-4 (Fig. 3.4).

There is evidence that an ENSO effect extends southward through the RMGB region. But because of the region's latitudinal extent, the northern effects are those of the Pacific Northwest while the southern effects are those of the Southwest, and are therefore inverse. Baldwin (1998) has shown that winter precipitation and montane snowpack are inversely correlated with the ENSO index NIÑO3 in the northern third of Utah, but positively correlated in the southern two-thirds. Precipitation and snowpack in the north tend to be below normal in the El Niño years, above average in the south. The reverse tends to be the case in the La Niña phase. ENSO variability may be altered by increases in greenhouse gases (Karl et al. 1996, Miller 1997, Timmermann et al. 1999) and a debate about the existence of such a change is underway (Karl et al. 1996, Rajagopalan et al. 1997).

However, there is almost no evidence of an ENSO effect on the individual monthly time series generated by the Seasonal Kendall test for the eight RMGB subregions. Only September minimum temperatures in a single subregion, SGB, were weakly correlated (R^2=0.10) with the winter (DJF) NIÑO3 index. Thus it would appear that weak monthly effects can only be expressed in seasonal or annual climatic variables if the ENSO influence aggregates over blocks of months. Moreover, the effect is spatially variable, not only in terms of the north-south oscillation, but according to Cayan and Webb (1992) affecting patches [emphasis added] over Idaho, Montana, and Wyoming. As an indication of the ENSO effect on precipitation generally over the West, Miller (1997) comments "… that only 25 percent of the interannual variation in streamflow can be explained by ENSO in those patches where the impact is most significant [emphasis again added]."

Mote et al. (1999)detected an influence of the Pacific Decadal Oscillation (PDO) in the Pacific-Northwest climate. The PDO is defined as the leading mode of variability in sea-surface temperatures north of 20^o North latitude. The authors detected four alternating phases, averaging about 24 years each during the 20th century, in temperature and precipitation time series of the region: two of low temperature and high precipitation, and two of high temperature and low precipitation.

The 3-4-year ENSO periodicity undergoes several oscillations with each PDO phase, and Mote et al. comment that in years when La Niña patterns in the Pacific-Northwest (high precipitation) coincide with the cool-wet phase of the PDO, the two accentuate each-others' effects. But it is reasonable to surmise that the reverse may also take place: When the El Niño dry phase coincides with the PDO cool-wet phase, there must be some muting of both influences. However, Dettinger (see comments in preceding section of this report) observes that the PDO effect is most marked in the northern part of western U.S. and fades toward the south. The reverse is true of ENSO. Its effect was not sufficient to prevent expression of the PDO effect in the data analyzed by Mote et al. (1999) for the Pacific-Northwest. And in this analysis of the monthly time series for the RMGB subregions, a PDO correlation could only be detected with

March Tmin in the northern Rockies and October Tmax in the southern Rockies.

Thompson and Wallace (1998) described the Arctic Oscillation (AO) as the dominant mode of sea-level-pressure (SLP) variability in the Northern Hemisphere north of 20° North. It is expressed as the difference in SLP between 45° North and the North Pole. It affects the positioning of both the polar and subtropical jet streams. Its periodicity coincides roughly with that of the PDO. In the present analysis, a statistically significant correlation was detected between the AO and four of the subregional, monthly time series; and with annual mean temperatures and precipitation.

These diverse sources of natural variation were analyzed to determine what variability they have induced into the 20th-century RMGB climate pattern that might complicate inferences about CO_2-induced trends. If they have either introduced so much noise into the system that a CO_2 signal is masked, or if they have changed over time in ways that covary with a CO_2 signal, inferences about the latter become difficult if not impossible.

ENSO, PDO, and AO, as their names imply, are quasi-cyclic changes that oscillate over a much shorter phase than a century. Thus no rising or declining portion of these periodicities could covary with a century-long trend. As far as is known, they and any stochastic variation do not exhibit any century-long linear trends although there is some indication that the ENSO phase has been shortening and the amplitude increasing in recent oscillations (Karl et al. 1996).

As discussed above, some correlations were found between these indices and some monthly climate-variable time series through the 1900s. But when the indices were tested against annual precipitation and mean annual temperatures for the subregions, a number of relationships were significant but weak: one $R^2=0.16$, all others were <0.1. Thus, the effects of these influences, functioning at different frequencies, alternately nullify, amplify, or have no effect on each other's signals to the climate variables. In areas where one index is stronger than the others, its influence may be measurable, as Mote et al. (1999) discerned the effects of PDO on the Pacific-Northwest temperature and precipitation; and as discussed above, an ENSO effect on winter snowpacks in Utah. But whether imparting these oscillatory variations into the climate-variable time series, or whether the sources of natural variation cancel each other to the extent of imparting an essentially random signal, 20th-century climate trends emerge as Mote et al. (1999) showed for the Pacific Northwest, and will be shown below for the RMGB region.

Finally, as Folland et al. (1990) discuss, the earth's climate has varied in the past over longer time scales, ranging from 100,000 years to centuries. Particularly on the latter scale, any natural change coinciding with the instrumentally measured changes of the past 100-150 years, and changing at rates comparable with those induced by anthropogenic forcing, would complicate any inferences about human causation. Folland et al. (1990) show evidence of the Little Ice Age as a global cooling trend from about 1,200-1,400 A.D. to about 1,650, then a warming trend to about the beginning of the 20th century.

However the Little Ice Age evidence is equivocal. We analyzed the temperature time series, based on tree-ring proxies, for the period 1600-1950 for each of the four seasons in each of the eight RMGB subregions. The data were derived from the National Oceanographic and Atmospheric Association (NOAA) web site, and analyzed with ordinary least squares tests. Within the 32 tests (8 subregions x 4 seasons), 12 showed statistically significant declining temperatures over the 350-year period, 5 showed increases, and 15 showed no significant change. No consistent trends were evident for the 1800s.

A number of authors are showing similar patterns. Mann et al. (1999) and Crowley and Lowery (2000) have reconstructed the same patterns for the last 1000 years in the northern hemisphere: A steady temperature decline to about 1900, then marked increase during the 1900s (Fig. 3.19). There is some suggestion of short-term oscillation within the series, with temperature increase from about 1675 to 1750, but then decline to about 1900. Harvey (2000: Plate 5) showed a virtually identical pattern for northern-hemisphere temperature over the period 1400 to the present. Raymond Broadley of the University of Massachusetts has similarly reported a 100-year-long cooling trend until the

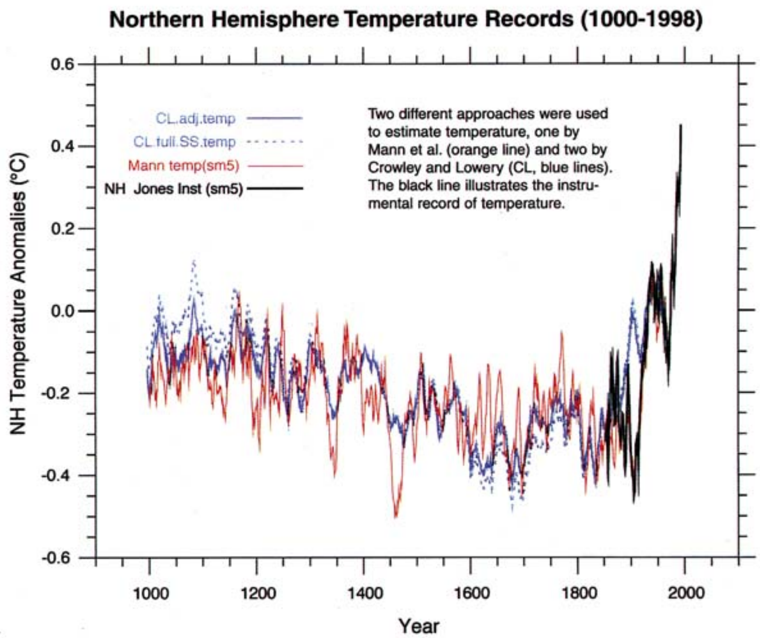

Figure 3.19. Reconstructed temperature trends for the period 1000-2000 based on various temperature proxies and instrumental records since the 1800s. This is Figure 6 in Anon. (2000).

Table 3.4

Twentieth Century Trends in Mean, Annual Minimum And Maximum Temperatures Based on the Seasonal Kendall Test (See text)

Subregion	Trend (per century)[1]	Test p-value[1]	Homogenous assuming sig.?[2]
Minimum Temperature (degrees Celsius)			
NGB	**0.38**	**0.02**	Yes
CGB	**0.21**	**0.16**	Yes
SGB	**0.38**	**0.02**	Yes
NR	**0.62**	**<0.01**	Yes
NCR	**0.40**	**<0.01**	Yes
WCR	**0.54**	**<0.01**	Yes
ECR	0.19	**0.16**	Yes
SR	0.01	0.94	Yes
Maximum Temperature (degrees Celsius)			
NGB	-0.06	0.80	No
CGB	-0.01	0.96	No
SGB	**0.33**	**0.12**	Yes
NR	**0.67**	**<0.01**	Yes
NCR	0.18	0.42	No
WCR	0.20	0.26	Yes
ECR	0.05	0.76	No
SR	0.13	0.44	No

[1]Bold-faced values are results of tests significant at $p \leq 0.20$.
[2]Trends consistent among months.

beginning of the 20th century (http://www.umass.edu/newsoffice/press/99/0303climate.html).

In sum, most of the sources of short-term natural climatic variation operate randomly, or oscillate over varying time scales which at times reinforce each other, at times offset each other. The result is the considerable, short-term variation inherent in all climatic time series, but in all cases at lower frequencies than century-long trends. There is at present no evidence that they have undergone any secular trends during the 1900s that would produce the climatic changes to be discussed below.

Moreover, the earth's climate has undergone, and is undoubtedly continuing to undergo, long-term changes measurable on scales of centuries and millennia. But there is no evidence that any temperature changes during the past 1000 years, induced by such natural forcings, have occurred at the rates, or to the extent, of those that have occurred in the 1900s (Fig. 3.19), and probably longer (Backlund et al. 1997).

Twentieth Century Temperature Trends

Subregional analyses. The results of the Seasonal Kendall tests for 20th-century trends in mean, annual Tmin and Tmax are summarized in Table 3.4. Five of the eight sub-regions experienced Tmin increases, significant at $p<0.05$, that rose at an average rate of 0.38°-0.62°C (0.68°-1.12°F) per hundred years. In two other subregions, increases of 0.19° and 0.21°C (0.34° and 0.38°F) per hundred years were significant at $p<0.20$. In the eighth subregion, the Southern Rockies, Tmin values did not increase during the 20th century, on average. Thus the increases occurred throughout the RMGB region except in the Southern Rockies, and were generally more pronounced in the northerly portion of the region.

In only two of the subregions did the Seasonal Kendall test show a significant increase in mean, annual Tmax during the 1900s (Table 3.4), although six of the eight had positive slopes. Perhaps significantly, the larger increase occurred in the Northern Rockies which also had the largest increase in Tmin.

With alternative statistical methodologies (ordinary least squares and Sen-slope estimates), the 20th-century trends in mean, annual temperatures in the eight subregions were tested and the results are summarized in Fig. 3.20. Mean annual temperatures increased significantly ($p \leq 0.05$ in both tests) in three of the subregions: SGB, NR, and WCR, with slope coefficients the same in both tests. In the NGB and NCR, the Sen test was significant at $p<0.10$, but the ordinary least squares was not. Tests for CGB, ECR, and SR were not significant.

These patterns are quite similar to those of the Seasonal Kendall tests, and the results of both sets are summarized in Table 3.5. Both show mean, annual temperatures increasing at rates ranging from 0.29° to 0.65°C (0.52° to 1.17°F) per 100 years in the northern and western subregions of the Rockies and the Southern Great Basin. Significance is borderline for the Northern Great Basin with a slope of 0.16°C (0.29°F). And temperatures did not change significantly in the Central Great Basin and southeasterly two Rocky Mountain subregions. The change was most pronounced in the Northern Rockies; next strongest in the Southern Great Basin, and North-central and West-central Rockies; weakest in the Northern Great Basin; and not statistically demonstrable in the Central Great Basin, East-central and Southern Rockies.

Table 3.5

Comparison of Slope Coefficients (Degrees C Increase per 100 Years) From Three Tests of 20th-century, Subregional Temperatures

	Mean, Annual Temperature[1]				Mean of
	Slope Coefficients[2]			Stat.	Tmin and
Subregion	OLS	Sen	Mean	Signif.[3]	Tmax Slopes[4]
NGB	0.10	0.30	0.20	No/Yes	0.16
CGB	0.10	0.10	0.10	No	0.10
SGB	0.40	0.40	0.40	Yes	0.36
NR	0.60	0.60	0.60	Yes	0.65
NCR	0.30	0.40	0.35	Yes	0.29
WCR	0.40	0.40	0.40	Yes	0.37
ECR	0.10	0.20	0.15	No	0.12
SR	0.10	0.10	0.10	No	0.07

[1]From Fig. 3.20
[2]Changes in degrees C per 100 years
[3]Signif.=$p \leq 0.20$; Yes=signif. for both OLS and Sen; No/Yes=signif. for OLS, not for Sen; No=both tests not signif.
[4]From Table 3.4

Table 3.6

Months in Which Seasonal Kendall Tests Showed Significant 20th-century Trends in Tmin and Tmax in the Eight RMGB Subregions

Subregion	Months	Trend: °C/100 yrs.
Minimum Temperature		
NGB	Mar	0.9
CGB	- -	- -
SGB	Sept, Oct	1, 0.9
NR	Mar, May, Jun, Aug	2, 0.8, 1, 0.8
NCR	Mar	1.9
WCR	Sept, Oct	0.8, 1
ECR	- -	- -
SR	- -	- -
Maximum Temperature		
NGB	Nov	-1.6
CGB	Nov	-1.6
SGB	Sept, Nov	1.3, -1.3
NR	Mar, May	1.9, 1.5
NCR	Feb, Mar, Nov	1.6, 1.4, -1.9
WCR	Nov	-1.4
ECR	Nov	-1.7
SR	Oct	1.3

The significance tests used on the monthly temperature time series, calculated by the Seasonal Kendall tests, were used to determine the months in which 20th-century temperature increases were largely responsible for producing the annual trends, whether Tmin, Tmax, or mean annual. These are shown in Table 3.6. In only five subregions—those with the most pronounced increases in Tmin in Table 3.4—did any months stand out as primarily responsible. There is also no consistency among these: March was a dominant month in three, September-October

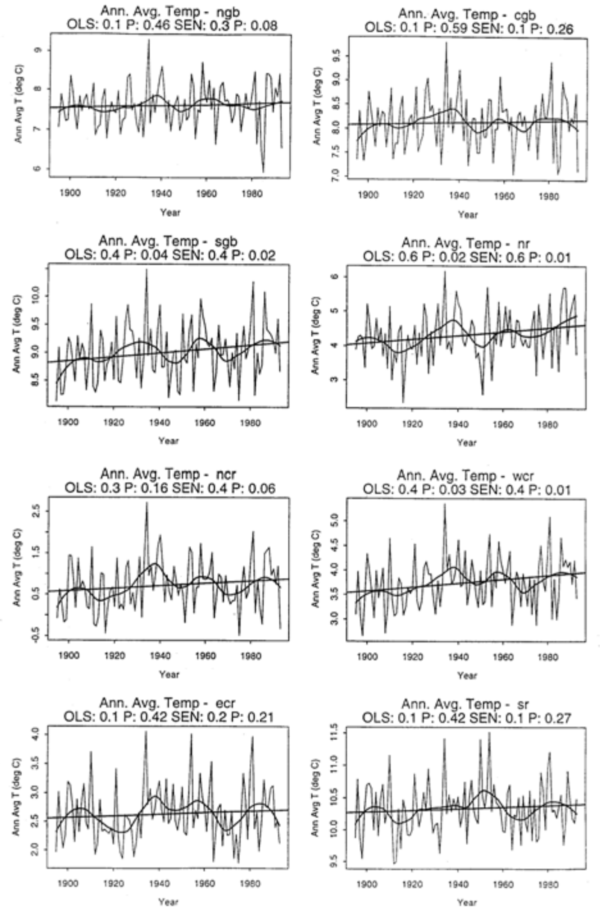

Figure 3.20. Time series of mean, annual temperatures in the eight subregions, and statistical tests of the trends. The sinuous lines are the Lowess smooths of the annual values, and the straight lines are the slopes produced by the ordinary least squares (OLS) regressions of the annual values. The four values at the top of each graph are, respectively, (1) the degrees C of change per hundred years and (2) the probability that the slope is not different from zero, both from the OLS tests; (3) the degrees C of change per hundred years and (4) the probability that the slope is not different from zero, both from the Sen-slope tests. The lower-case letters identify the subregions.

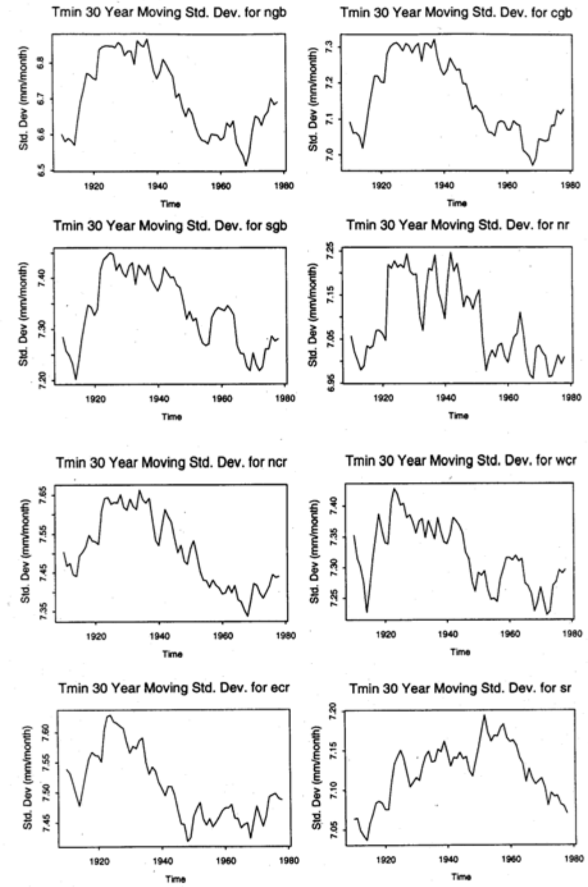

Figure 3.21. Time series of standard deviations around 30-year moving averages of mean, annual minimum temperatures (Tmin) for the eight subregions in the RMGB.

in two. No monthly trends were significant in the Central Great Basin and East-central Rockies, both subregions with positive Tmin trends, but weakly so with p=0.16. Given the homogeneity of the tests shown in Table 3.4; the prevalence of increases in mean, annual temperature among the subregions (Table 3.5); and the lack of consistency in trends of dominant months, it must follow that several or most of the months experienced rising Tmin over the 1900s.

However, the pattern is different with Tmax (Table 3.6). In six of the eight subregions, November trends in Tmax were significant, and in all cases negative: i.e. November Tmax values declined during the 1900s in those subregions. This undoubtedly explains the lack of a significant mean-annual Tmax increase in those subregions (Table 3.4). It also must explain the two subregions which did have significant, positive mean-annual Tmax increases (Table 3.4). The Northern Rockies had no negative November trend; and while the Southern Great Basin did, it had an offsetting, positive September trend of the same magnitude. More generally, the prevalence of November temperature declines probably accounts for the lesser Tmax increases (Table 3.4) and somewhat reduces the rates of mean-annual temperature increases during the 20th century (Fig. 3.20).

In order to determine whether or not interannual variability in temperatures changed during the 1900s, 30-year moving averages for mean, annual Tmin and Tmax were calculated along with standard deviations around each of the 30-year averages. The time series on these

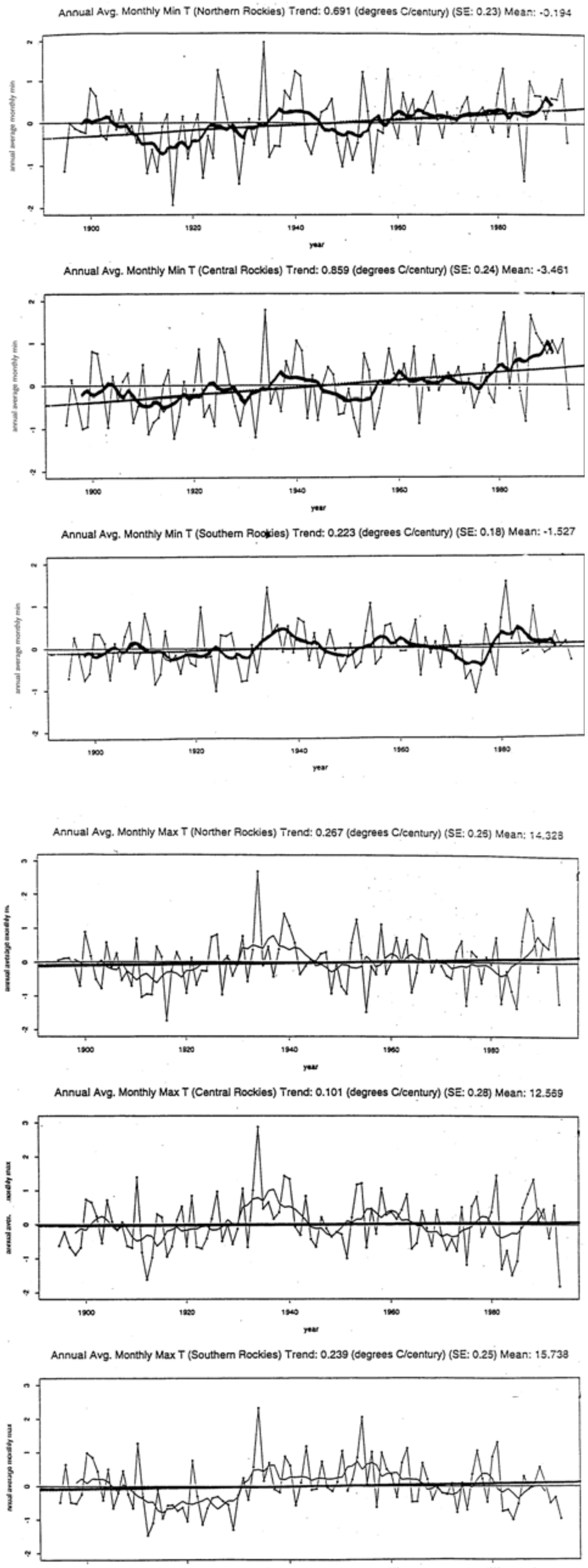

Figure 3.22. Twentieth-century trends in annual, average monthly minimum and maximum temperatures in the Northern, Central, and Southern Rocky Mountains (from T.G.F. Kittel, unpub.).

for Tmin in each of the subregions are shown in Fig. 3.21. Following high values in the 1920s and 1930s, these tended to decline during the latter part of the century. The one exception was the Southern Rockies, one of the subregions that showed no significant temperature increase during the century.

The same calculations produced similar curves for Tmax standard-deviation time series for the Northern and Central Great Basin subregions, and for the Northern and North-central Rockies. Curves for the other subregions were suggestive of the same patterns to varying degrees, but generally reached their peak values in the 1950s and had less pronounced declines in the latter part of the century.

Thus, interannual variability in temperatures has declined over most of the RMGB region since the 1920s or 1930s.

Evidence from other sources. Kittel et al. (2002) analyzed 1900-1990 U.S. Historical Climatology Network (HCN) station data for the Rocky Mountains using slightly different subregional divisions than the ones used in this assessment: Northern, Central, and Southern Rockies. Their time series for Tmin and Tmax, not shown in their publication and provided us by T.G.F. Kittel, are shown in Fig. 3.22.

The Kittel et al. results are quite similar to those shown above. Least-squares fits to the Tmin series show increases of 0.7° (1.26°F) and 0.9°C (1.62°F) in the Northern and Central Rockies that are significant at $p<0.005$. Their test of Tmin for the Southern Rockies showed an increase of 0.2°C (0.36°F) per 100 years, but was short of statistical significance. The three slopes for Tmax are positive, but short of significance. Greatest increases occurred in the Northern and Central Rockies.

Karl et al. (1996) analyzed 20th-century climate trends for the United States using National Climatic Data Center (NCDC) records. The authors mapped their results, and show mean temperature trends per 100 years in 25 subregions of the RMGB. Their results show uniform temperature increase throughout the RMGB region with the exception of a single point in southern Colorado near the borderline between the East-central and Southern Rockies subregions. The increases range largely between 1° and 2°C (1.8° and 3.6°F).

These authors' results vary in magnitude from the values obtained for this assessment. Where the 100-year increase in Tmin in Table 3.5 averaged 0.60°C (1.08°F) and 0.35°C (0.63°F) in the NR and NCR respectively, the increases were 0.7°C (1.26°F) and 0.9°C (1.62°F) in the Kittel et al. study of their Northern and Central Rockies subregions. Where the 100-year increases in Tmax in Table 3.4 were 0.67°C (1.21°F) and 0.18°C (0.32°F)—the latter not significant—for the NR and NCR respectively; the increases were 0.3°C (0.54°F) and 0.1°C (.18°F) in the Kittel et al. study of their Northern and Central Rockies subregions. The differences probably result from differing data sources—we have used the VEMAP data where Kittel et al. used the HCN station data—and in the fact that the subregions were not exactly congruent between the two studies.

Similarly the 100-year increases in mean, annual temperatures in those subregions with significant increases (Fig 3.20) range from 0.3°C (0.54°F) to 0.6°C (1.08°F) while the Karl et al. (1996) range for the Intermountain West as a whole is roughly three times as high. Here again, Karl et al. drew from a different data source (NCDC) and worked with different subregions.

However, all of the values are qualitatively similar in direction. The fact that three different data sources, analyzed for three different subdivisions of geographic areas within the Intermountain West, point to temperature increases over most of the RMGB strengthen the inference that such increases did in fact occur during the 20th century.

Twentieth Century Precipitation Trends

Subregional analyses. We analyzed the VEMAP precipitation records with the Seasonal Kendall test and calculated ordinary least squares (OLS) regressions and Sen slopes for the time series of annual precipitation expressed as mean ppt per month. The latter are shown in Fig. 3.23. All showed positive trends over the 1900s, but only those for Northern, Central, and Southern Great Basin and Northern and North-central Rockies subregions were significant at $p<0.20$. In these five subregions, nine of the ten tests were significant at $p \leq 0.1$, the OLS test for the Northern Rockies being the single exception. None of the six tests for the West-central, East-central, and Southern Rockies were significant at $p<0.20$. The percentage increases in precipitation over the century, as projected by the OLS slopes for the five subregions with significant tests, are:

NGB—10%

CGB—16%

SGB—16%

NR—6%

NCR—13%

As with the temperature analyses, trends in interannual variability in precipitation were analyzed by calculating 30-year moving averages of the precipitation time series shown in Fig. 3.23, and standard deviations around these means. The latter are plotted as time series in Fig. 3.24.

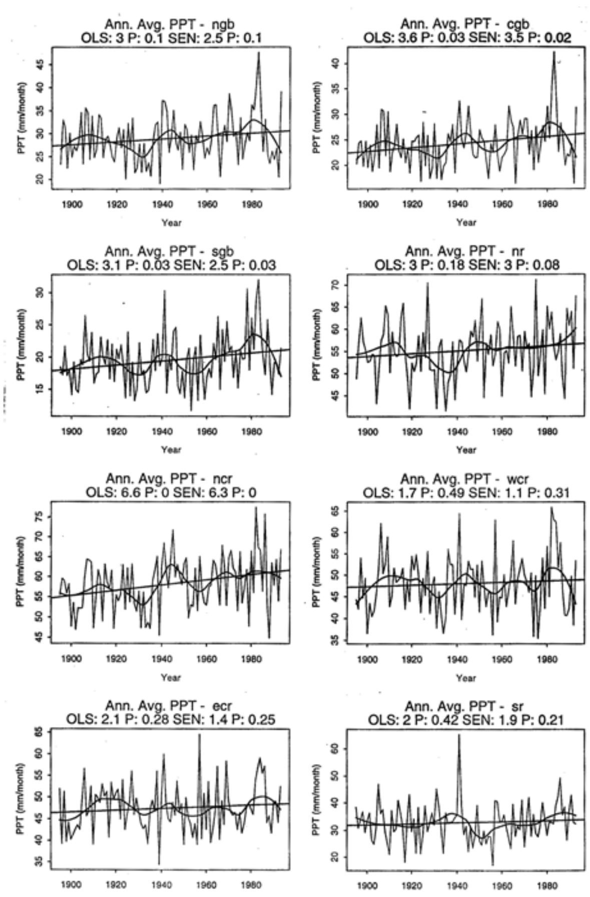

Figure 3.23. Time series of annual precipitation, expressed as average millimeters per month, in the eight RMGB subregions (lower case initials above graphs). The wavy lines are Lowess smooth of the data, and the straight lines are ordinary least squares fits. The values above each graph are, from left to right respectively, (1) OLS: least squares slope expressed as mean mm/month increase over 100 years, (2) P: the probability that the slope is not different from zero, (3) P: Sen slope expressed as mean mm/month increase over 100 years, and (4) Sen-slope probability that the relationship is not different from zero.

Trends for the five subregions in Fig. 3.23 that showed statistically significant precipitation increases showed progressive, standard-deviation increases beginning in the 1920s or 1930s. No such trends were evident for the East-central and Southern Rockies, both subregions with no significant precipitation increase. The standard-deviation trend for the West-central Rockies, also a subregion with no significant precipitation increase, is ambiguous. Obviously the interannual variability of precipitation has increased over time in those subregions in which precipitation has increased.

The results of the Seasonal Kendall tests were used to determine the months and seasons in which 20th-century precipitation trends were largely responsible for producing the annual trends in Fig. 3.23. The months in which there was a statistically significant ($p \leq 0.05$) increase in precipitation during the 1900s are shown in Table 3.7. One or more summer months are significant is six of the eight subregions, with June standing out as an influential month in five of the six.

It should be noted that there were significant, 20th-century monthly increases in precipitation in all eight subregions (Table 3.7). But annual precipitation increased significantly in only five subregions (Fig 3.23). In those subregions in which annual precipitation did not increase significantly, either the monthly increase was not sufficient to raise the annual precipitation to significance, or there were other months in which the precipitation decreased and offset the ones with increase.

The 20th-century trends in seasonal (winter, NDJF; Spring, MAMJ; summer JJAS; and autumn, ASON) precipitation were also analyzed. Only the summer trends showed consistent increase in most of the subregions, probably to be expected in light of the positive trends in the summer months (Table 3.7). These summer trends are shown in Fig. 3.25. They are generally positive with the exception of the WCR and SR subregions, two of the three in which there was no significant trend in annual precipitation (Fig. 3.23).

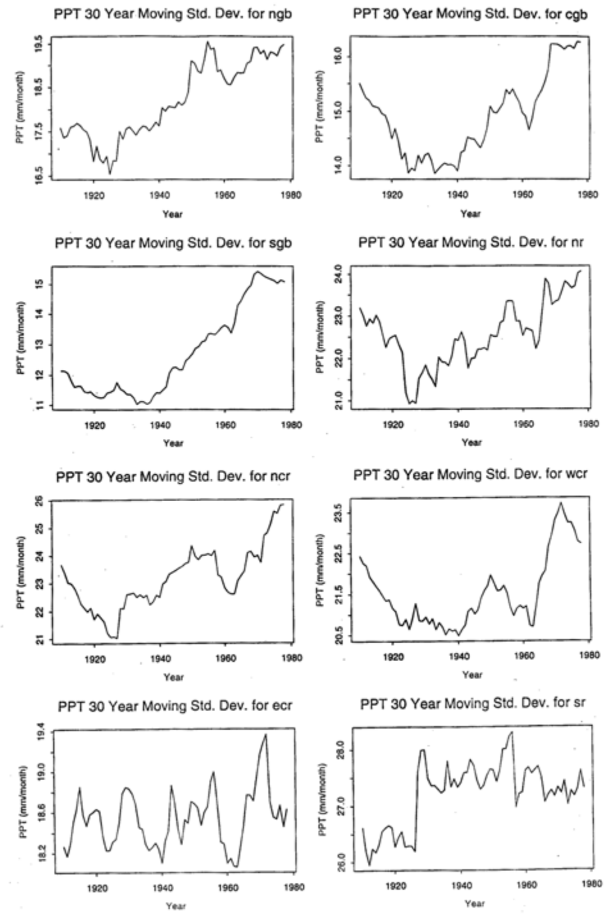

Figure 3.24. Time series of standard deviations around 30-year moving averages of annual precipitation for the eight subregions (lower-case initials above graphs) expressed as average mm/month per year.

Table 3.7

Months in Which Seasonal Kendall Tests Showed Significant 20th-century Precipitation Increases and Rates of Increase in the Eight RMGB Subregions

Subregion	Months	Trend (mm/100 yrs.)*
NGB	June	10
CGB	June, July	12, 3
SGB	June	7
NR	April	9
NCR	April, June, August	12, 14, 12
WCR	June	11
ECR	November	8
SR	August	18

*Significant at $p \leq 0.05$ using one-sided alternative hypothesis.

Evidence from other sources. As with the HCN temperature records (Fig. 3.22), Kittel et al. (2002) analyzed the HCN data to detect trends in <u>summer</u> precipitation, again subdividing the Rocky Mountain chain into Northern, Central, and Southern subdivisions. His results (Fig. 3.26) are similar to those summarized in Table 3.7 if the latter, monthly values are tripled to make them comparable with Kittel's seasonal rates. He also calculated the percentage increase per century, which showed the following:

Northern Rockies: 29.5% increase/century in summer precipitation

Central Rockies: 32.8% increase/century in summer precipitation

Southern Rockies: 5.4% increase/century in summer precipitation

The first two trends are significant at $p \leq 0.05$. The southern value is short of significance.

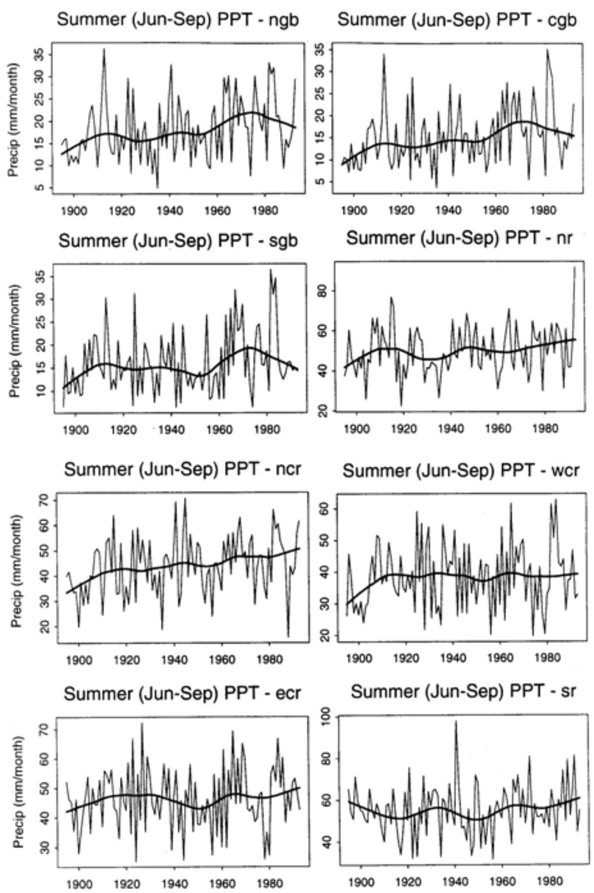

Figure 3.25. Time series of summer precipitation (June, July, August, September), smoothed with the Lowess smooth, for the eight RMGB subregions (lower case initials above graphs).

As they did with temperature trends, Karl et al. (1996) analyzed and mapped 20[th]-century precipitation trends for the U.S. Their results for <u>annual</u> precipitation in western U.S. show uniform precipitation increases throughout the Great Basin, ranging from 5-10% during the 1900s. Precipitation also appears to have increased in the Northern Rockies subregion, though to a lesser degree than in the Great Basin, and in the West-central Rockies.

However the authors' data show precipitation <u>decline</u> in the North-central Rockies. This coincides with one additional data set. Phillip Farnes, consultant on snow and mountain hydrology in Bozeman, MT, provided an unpublished data set of 5-year moving averages of temperature and precipitation measurements made during the 1900s at the Mammoth, WY headquarters of Yellowstone National Park. His trend for annual precipitation shows decline during the century. That decline is largely induced by decline in October-March precipitation. The April-June precipitation

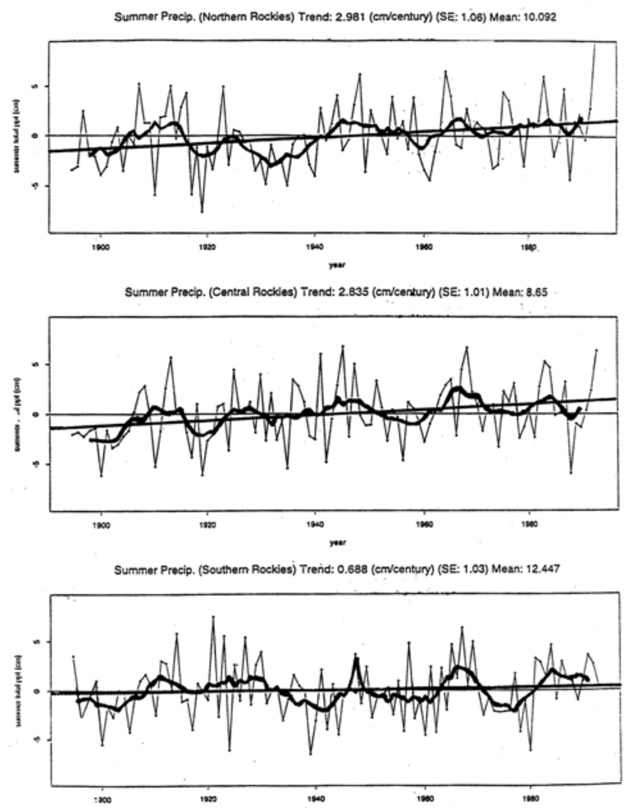

Figure 3.26. Twentieth-century trends in yearly, summer precipitation in the Northern, Central, and Southern Rocky Mountains. These figures were provided by T.G.F. Kittel in 1998, and are similar to ones reported in Kittel et al. (2002).

trend is essentially flat, but the July-September trend is highly significantly (p=0.01) positive. Thus summer precipitation increased at this one station, as it has over much of the region (Table 3.7, Figs. 3.23 and 3.26), but winter precipitation declined as also appears to have been the case in our seasonal analyses. In the case of the Yellowstone locale, the winter decline was sufficient to offset the summer increase and produce a net decline in the total, annual precipitation trend. A similar pattern may have prevailed in the other stations of the North-central Rockies subregion.

Measurement stations apparently are few in the East-central and Southern Rockies subregions. As a result, the Karl et al. findings are inconclusive in that part of the RMGB.

Discussion

The topographic variability of the RMGB region produces sharp climatic differences between localized areas. Analyzing climatic patterns of individual, local areas is beyond the scope of this assessment. It has been necessary to explore broader spatial patterns by averaging the climate variables of blocks of 0.5° VEMAP quadrangles, themselves averages of climate data from varying numbers of weather stations within each quadrangle. This study subdivided the RMGB region into eight such blocks, varying from 9 to 66 quadrangles. The trends discussed here are the averages for the subregions and do not represent the trends at individual locations or weather stations.

Despite this considerable spatial averaging, the time series for each subregion displays a large amount of short-term temporal variation. That variation is induced by several, identified quasi-cyclic influences that fluctuate on varying frequencies shorter than the century-long trends examined here, probably others not recognized or known, and stochastic variation which is probably a collective term for yet-unknown or unmeasured forces affecting climates. There undoubtedly are longer-term influences on the regional climate that operate on a time scale approaching or exceeding the century-long changes under consideration, but none is known to function at the rate of change shown by 20th-century trends under analysis here.

Several data sets point convincingly to temperature increases during the 1900s in the region. The changes are most pronounced in the northern and western subregions, and fade to statistical nonsignificance in the southeastern subregions. The trends are still positive, if slight, in the southeast but not statistically demonstrable, given the variability of the signal. On a mean, annual temperature basis, the significant increases range from 0.16° to 0.65°C (0.29° to 1.17°F) per hundred years among the VEMAP subregions analyzed here, 0.7° to 0.9°C (1.26° to 1.62°F) in Kittel's Northern and Central Rockies VEMAP subregions (Fig. 3.22), and largely 1° to 2°C (1.8° to 3.6°F) over the region in the Karl et al. analysis of the National Climate Data Center (NCDC) data sets. The increases of 0.65 to 1 or 2°C in the northern portion of the region correspond to the 0.8°C (1.48°F) 100-year increase reported by Mote et al. (1999) for the adjacent Pacific-Northwest region.

The increases have been more pronounced in the night-time minimum temperatures than in the day-time maxima, narrowing the diurnal variation during the 20th-century. The differences in Tmin and Tmax trends appear to be due, at least in part, to November Tmax declines which must dampen to some degree the increases in mean, annual Tmax.

The interannual variability of temperatures has declined as the temperatures have risen during the 1900s. Thus both the means and probability distributions have shifted to higher levels, while the latter have narrowed. The net result must be reduced probabilities of extremely low temperatures and below-average years, and increased probability of extremely warm years.

The same data sets point to increases in precipitation during the 1900s, again in the northern and western portions of the region. Though positive, the trends were not statistically significant in the West-central, East-central, and Southern Rockies subregions. Among the subregions with significant trends, the 20th-century increase in annual precipitation ranged from 6-16% per 100 years. Although trends tended to be consistent among the months, the increases were most pronounced in summer, especially the month of June. Given the summer increase, it is worth noting that it has occurred in those portions of the region with a primarily winter precipitation pattern and limited summer rain. There have been no statistically significant increases in the southeastern subregions dominated by the monsoonal, primarily summer rainfall patterns.

The Kittel et al. (2002) analysis of HCN summer precipitation data shows 100-year increases of 29.5% and 32.8% in their Northern and Central Rockies subregions, but no significant increase in the Southern Rockies. The Karl et al. (1996) analysis of NCDC precipitation data shows annual precipitation increases mostly of 5-10% per 100 years for the Northern and Western Rockies, and Great Basin subregions, but decline in the North-central Rockies, and no clear signal in the East-central and Southern Rockies.

Analyses of variability suggests increasing interannual variability which, with increasing levels of precipitation, implies more extreme precipitation years; and probably fewer drought years, depending on the shift in the probability distribution.

Thus there appear to have been clear trends in the 20th-century climate over most of the RMGB region. It cannot be stated with certainty that these are the result of greenhouse-gas (GHG) forcing. At present the relationships are only similar in directions. But the trends are qualitatively in the directions projected by the general-circulation models (GCMs) as are the more pronounced rise in Tmin than Tmax, and the increasing strength of the trends toward the north. Kittel et al. (2992) point out the latter, extending the trend into Canada. Thus the historical data analyzed here add plausibility at least to the directions of the GCM projections.

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GCM SCENARIOS FOR THE RMGB REGION—Linda O. Mearns

The Use of Scenarios

Climate-change scenarios may be considered plausible representations of the future climate that are consistent with our understanding of the effects of increased greenhouse gases and other pollutants on the earth-ocean-atmosphere system. Scenarios are neither predictions nor forecasts of future conditions. Rather, they describe alternative, plausible futures that conform to sets of circumstances or constraints in which they occur.

The true purpose of scenarios is to illuminate uncertainty by determining the possible ramifications of an issue along one or more plausible but indeterminate paths. As such, they are part of a learning process, in the present case by exploring the possible ramifications of climate change on resource systems important to society. While it is desirable that scenarios have some level of plausibility, it is not meaningful to refer to their "accuracy" or predictive power.

Exploring the implications of potential future climates is a valuable exercise for stakeholders in the potentially affected socio-economic sectors. Stakeholders are typically more concerned with current variability than with long-term climate change. But the purpose of the national, and this regional, assessment is not primarily to help them cope with current climate variability. The primary purpose is to bring them awareness of potential, long-term climate change and to stimulate their thinking on potential effects and needed coping strategies. Given our understanding of the physics of greenhouse gases, the reality of their increased concentration over time, and our knowledge, even if imperfect, of the potential effects on climate systems, we would be negligent as public servants if we did not call attention to the potentialities, and institute widespread exploration of the implications.

The model projections given below should be considered scenarios that stimulate general thought experiments about possible impacts of climate change in the Rocky Mountain/Great Basin (RMGB) region. They are not constructed for use as detailed, mathematical input for quantitative impact models. Doherty and Mearns (1999) compare model runs of current climate with observed seasonal precipitation and temperature for the continental U.S., and analyze future climate changes projected by these models. The analysis is available at http://www.div.ucar.edu/esig/doherty/.

Caveats re GCM-based Regional Scenarios

As the name implies, the general circulation models (GCMs) at this stage of their development are structured to simulate climates at global scales. The present level of development is not yet at sufficient resolution to simulate changes at every localized area, and very satisfactorily at subregional levels. At the same time climate variability is greatest at the local level—particularly a problem in the RMGB region with its complex topography—next at subregional scales, and least at regional scales.

Thus current model outputs must be considered simulations of the averages of local climates over large spatial scales. They cannot be expected to project climate changes at localized areas. And empirically, the fact that weather-station measurements vary between locations

Table 3.8

Mean Seasonal Changes in Temperature and Precipitation for the Basin and Range Region of the U.S. for the HadCM2 and CGCM1 Transient Runs for the Period 2080-2100

	Temperature Changes			
	HadCM2		CGCM1	
Season	Degrees C	Degrees F	Degrees C	Degrees F
Winter	+4.5	+8.1	+8.0	+14.4
Spring	+2.5	+4.5	+6.0 S, 7.0N	+10.8 S, 12.6 N
Summer	+4.0	+7.2	+5.0	+9.0
Fall	+3.5	+6.3	+6.0	+10.8
	Precipitation Changes			
	mm/day	in/mo	mm/day	in/mo
Winter	+2.0 to 3.0	+2.4 to 3.5	+2.0 to 4.0[1]	+2.4 to 4.7[1]
Spring	0.0 to +0.5	0.0 to +0.6	+1.0	+1.2
Summer	0.0 to +0.5	0.0 to +0.6	-0.75 to +0.5	-0.9 to +0.6
Fall	+0.5 to 1.5	+0.6 to 1.8	+0.5 to +3.0	+0.6 to 3.5

[1]Higher in west.

(Stohlgren et al. 1998) does not invalidate averaging them to depict mean climate patterns for extensive areas which the models simulate. Most regions show mixed localized trends in temperature and precipitation. Moreover, while there is some climatic variation between localized areas, the historical climate analysis in the preceding section indicated a considerable amount of uniformity in 20th-century climate change across most of the subreqions, and to a lesser extent over the region as a whole.

Finally, as stated above, the GCMs are approximations of real-world climate systems structured on the basis of the major physical forces shaping climate behavior. They cannot, and do not, contain provision for every factor influencing climate. Hence, the lack of provision for land-use effects ("biophysical feedbacks") is no basis for rejecting the models, as suggested by Pielke above. It has not been demonstrated that land-use practices significantly alter climate patterns over the RMGB region as a whole. Only about 10% of the region is in farms, and only a fraction of that is in cultivated crops. The effects of some land-use changes may even complement the influence of greenhouse gases. The model outputs thus remain as reasonable hypotheses for "what-if" intellectual exercises on potential effects if the projections become reality.

Seasonal Projections for the RMGB Region

Table 3.8 summarizes the seasonal projections for the period 2080-2100 by the two state-of-the-art Atmosphere-Ocean General Circulation Models (AOGCMs) selected for use in the U.S. Assessment - - the British Hadley Circulation Model 2 (HadCM2) and the Canadian Coupled General Circulation Model 1 (CGCM1) - - adapted for western North America. Both models project temperature increases in all four seasons, with the greatest changes occurring in winter (4.5°-8.0° C, 8.1°-14.4°F). The Canadian model projects larger temperature changes than the HadCM2 for all seasons, and these should be considered relatively extreme scenarios while the Hadley values should be considered moderate ones. Thus the temperature changes, while numerically different, are of the same direction and both show the greatest increase in winter.

The precipitation changes, while again generally in the same directions, are slightly more complex. Both show some increase in all seasons except that the Canadian is somewhat equivocal on summer change. Both show greatest increase in winter, with the Canadian again projecting more change than the Hadley.

SCENARIO CHOICES FOR RMGB ASSESSMENT—Frederic H. Wagner

Units of Measurement

Three procedures were followed to obtain information on climate-change scenarios that could be posed to the RMGB sectors: (1) obtaining recommendations of professional climatologists at the September 1998 workshop; (2) analyzing the 20th-century climate trends in the region; and (3) generating output from the Hadley and Canadian GCMs that project RMGB climate patterns at the end of the 21st century on the assumption of a two-fold increase in atmospheric CO_2. The latter two will be discussed first, followed by consideration of the presentations at the climatologists' meeting.

But before doing so, the units of measurement reported in previous sections need to be standardized. Different investigators have expressed their results over different units of time, and these need to be standardized to facilitate comparison.

Mean, <u>annual</u> RMGB temperature increase, 20th century:

(1) This assessment (Table 3.5): 0.20°-0.65°C (0.36°-1.17°F) per 100 years in subregions with statistically significant increases.

(2) Kittel for the Rockies (Fig. 3.22), mean of Tmin and Tmax for two subregions with significant increases: 0.5°C (0.9°F) per 100 years.

(3) Karl et al. (1996) for the RMGB region: 1.0°-2.0°C (1.8°-3.6°F) per 100 years.

GMC-projected mean, <u>annual</u> RMGB temperature increase, 21st century:

These were calculated by averaging the projected increases for the four seasons (Table 3.8):

(1) Hadley GCM: 3.6°C (6.5°F)

(2) CGCM1: 6.3°-6.5°C (11.3°-11.7°F)

Total, <u>annual</u>, RMGB precipitation increase, 20th century:

(1) This assessment (Fig. 3.23): The monthly OLS and SEN values in Fig. 3.23 were multiplied by 12 to obtain totals for the years. These range from 30.0-79.2 mm (1.18-3.11 in) increase in annual precipitation over the 100 years for those subregions with statistically significant increases.

    These can be expressed as percentage increase by calculating these values as fractions of the 1900 Y-intercepts in Fig. 3.23, and are 6-17% per 100 years.

(2) Kittel's values (Fig. 3.26) are only for summer precipitation, and therefore cannot be converted to annual numbers.

(3) The Karl et al. (1996) increases are expressed only as percentages and range from 5-20% over 100 years.

GCM-projected, <u>annual</u> RMGB precipitation increase, 21st century:

Per annum GCM projections were calculated by multiplying each mm/day value (Table 3.8) by 90 and then adding the four seasonal numbers to give annual values at:

(1) HadCM2: 225-495 mm/year (8.9-19.5 in/year) by 2100

(2) CGCM1: 247.5-765 mm/year (9.7-30.1 in/year) by 2100

These numbers were then transformed into percentage increase over the year-2000 values as follows. The GCM projections are for the region as a whole. In order to obtain a mean value for year-2000 precipitation for the entire region, the subregional 1900 Y-intercepts in Fig. 3.23 were added to the 100-year increases shown in the figure, and then multiplied by 12 to obtain mean, <u>annual</u> precipitation values for each subregion in the year 2000. These are, of course, regression estimates, and the intercepts must depart to some degree from the actual, measured 1900 and 2000 values. They should be considered averages of the varying, year-to-year actual numbers of those points in time.

An area-weighted average of the subregional 2000 precipitation numbers was then calculated by multiplying each subregional precipitation by its number of VEMAP 0.5° quadrangles: (These varied from 9-66, Fig. 3.17). The sum of these subregional products was then divided by the total number of quadrangles (308) to obtain an area-averaged, estimated year-2000 precipitation for the RMGB region at 416.6 mm or 16.4 in. The percentage increases by which the above GCM 2100 projections exceed this year-2000 value are:

HadCM2: 54% - 119%

CGCM1: 59% - 184%

In sum, trends in 20th-century mean, <u>annual</u> temperatures are positive in all eight RMGB subregions; but are statistically significant only in two of the three Great Basin subregions and three of the five Rocky Mountain subregions. Those that consistently show no significant increases are the East-central and Southern Rockies. The 21st-century increase in values for the significant subregions in this study and those of other authors range from 0.2°-2.0°C (0.36°-3.6°F). The projected GCM increases for the end of the 21st century range from 3.6°C (6.5°F) (HadCM2) to 6.3°-6.5°C (11.3°-11.7°F) (CGCM1).

The 20th-century trends in annual precipitation are positive for all eight RMGB subreqions, but significant only in the three Great Basin, and the Northern and North-central Rockies subregions. Among the latter five, the increases range from 30.0-79.2 mm (1.18-3.11 in) per year. Expressed as percentages, these vary from 6-17%. The Karl et al. (1996) calculations place the 20th-century increases at 5-20%. The projected GCM 21st-century increases range from 225-495 mm (8.9-19.5 in) per year (HadCM2) and 247.5-765 mm (9.7-30.1 in) per year (CGCM1). Expressed as percentage increases above averaged 2000 precipitation, these values are 54-119% and 59-184%, respectively.

Scenario Selection

It is now appropriate to explore the consistency of these results, and in turn their plausibility for a set of scenarios to pose to the sectors. Specifically, the following questions need to be addressed:

(1) Given the topographic, climatic, and ecological variability of the RMGB region, and its geographic extent, have there been coherent regional or subregional 20th-century climate trends that override that variability? The alternative would be a cacophony of independent, localized variations that do not coalesce into any regional or subregional trends. The latter would vary at random from each other. Answer to this question also provides an answer to the corollary question of whether it is reasonable to consider regionwide GCM projections for the end of the 21st century, given the complexity of the region.

(2) To what extent are 20th-century trends shown by the historical analysis similar to the 21st-century trends projected by the GCMs, qualitatively if not quantitatively?

The answer to the first question is clearly in the affirmative. Trends in mean, annual temperatures and annual precipitation were positive throughout the region, although not significant in the southeastern two or three subregions. The East-central and Southern Rockies encompass 56 (15%) of the region's 308 VEMAP quadrangles; or if the nine quadrangles of the West-central Rockies are added, 20%. Thus the trends tend to be consistent over at least 80-85% of the region.

It is not clear whether the northwest-southeast difference reflects a latitudinal gradient in degree of response, or whether the Colorado-Utah latitude is a dividing line between two climatic regions responding differently to whatever forced the 20th-century trends. These same differences will be evident in the region's hydrology, as will be discussed in the next chapter.

The 20th-century trends in the region have also coincided with more extensive, national trends as reported by Karl et al. (1996). These authors concluded that precipitation nationally since 1970 has averaged 5% above 1900-1970 levels with $p=0.10$ that the change arose from a "quasi-stationary" climate with no long-term trend. Since 1970, more of the nation has tended to be excessively wet, with $p=0.25$ that this was due to chance. Mean, annual temperatures increased across the U.S. during the 1900s with $p=0.05$ that the change was due to random variations. The percentage of the country with above-normal, mean daily minimum temperatures rose during the 20th century ($p=0.05$-0.10), while the percentage of the country with below-normal daily maxima declined ($p=0.01$-0.02).

Thus there was a considerable degree of uniformity in the 20th-century climatic trends in the RMGB region, and these tended to coincide with the national trends. This provides some rationale for projecting a single set of 21st-century climate changes for the region.

In answer to question 2 above, the 20th-century, RMGB temperature and precipitation increases are qualitatively in the same direction as the GCM simulations for the 21st century (Table 3.8). Moreover, two related trends —greater increase in Tmin than Tmax, and latitudinal increase in extent of change (assuming this is what the southeast-northwest differences reflect)—coincide with the output of the GCMs.

However, the GCM-projected increases for the 21st century greatly exceed the changes of the 1900s, and some consideration is needed to explore whether these differences can be reconciled or rationalized, at least to some degree. First, the rise in atmospheric CO_2 concentration in the 21st century is projected to far exceed the rise of the 1900s. The latter began the 20st century at approximately 295 ppm and increased by 65 to approximately 360, a 22% increase (Backland et al. 1997). Assuming continued emissions at current, increasing rates, the concentration by year 2100 is projected to reach ca. 720, a 100% increase above the 2000 concentration. The 21st-century increase is thus projected to be six times the 20th-century increase. Hence it is reasonable to expect significantly greater climatic change in the 21st century than in the 20th.

The mean, annual temperature increases in the RMGB in the 1900s ranged between 0.2° and 2.0°C (0.36°-3.6°F). The Hadley projected increase for the 21st century is 3.5°C (6.5°F). Thus the midpoint of the 1900s range constitutes an increase of nearly a third of the projected Hadley increase, and the upper value (2.0°) is more than half. The Canadian model projects a much larger increase which subjectively seems extreme. But there is no real basis for that judgment. The latest IPCC report has concluded that the projections to date are probably conservative because the models have made too much provision for sulphate aerosols. Newer projected temperature increases are nearly double previous ones.

The annual RMGB precipitation increases during the 1900s ranged from 5-20%. The Hadley and Canadian projected precipitation increases for the 21st century are 54-119% and 59-184%, respectively. The middle of the 1900s range is roughly a fifth of the lower values for both models, and 10-15% of the mid-range of the models.

Thus the GCM projections seem attainable, at least the lower portions of their ranges. This, too, is a subjective judgment, but assumes plausibility because the 20th-century increases are qualitatively in the same directions as the 21st-century projections. For these reasons, the GCM projections appear to be plausible in direction, if not fully in magnitude. As a result they have weighed significantly in the decisions on scenarios.

The climatologists' workshop raised additional considerations on the formulation of scenarios. The conferees' deliberations divided into two points of view. One was confidence in the GCM projections, and advocated their use for the region's scenarios. But the second viewpoint expressed considerable uncertainty about the GCMs, and proposed a procedure termed "vulnerability analysis." As a result the workshop concluded with a decision to adopt a dual scenario process termed "top down" and "bottom up." The top-down procedure was clearly direct application of the GCM projections. But the bottom-up algorithm was never defined, although presumably in some way applying vulnerability analysis which itself has not been explicitly described as an assessment procedure.

As stated in the proceedings section above, vulnerability analysis is based on the premise that each sector to be considered functions within a complex of factors of which climate change is only one, and not necessarily the most influential. Climate change may affect a sector directly, or may function as a second-, third-, or higher-order influence impinging on the first-order factors affecting the sector. The plight of a sector is a function of the entire complex. These complexities need to be understood to the extent possible in order to develop a full understanding of the potential effects of climate change.

The concept is of course valid. Climate change does not operate in a vacuum. In fact, the perspective is implicit in the standardized questions being asked of stakeholders nationally during the course of the assessment (cf. Wagner and Baron 1999 for its use in the RMGB):

(1) What are the major climate-related stresses affecting your operations?

(2) How might X climate change exacerbate or ease those stresses?

Thus the regional assessments are doing what those who criticize climate-change assessment and advocate vulnerability analysis (cf. Sarewitz and Pielke 2000) are faulting them for not doing: focusing on those socio-economic and natural-resource sectors most likely to be affected (vulnerable) by climate change. In the chapters that follow, potential climate-change effects on the sectors have been considered in the context of factors with which they interact.

However, vulnerability analysis is actually a conceptual approach: viewing each sector in a systems context. It does not provide guidance on which climate scenarios to pose to each sector and its system, or how. Moreover, the word vulnerability, with its negative connotation, has not seemed entirely appropriate since some sectors could be benefited by some climate changes.

The final decisions on climate-change scenarios posed to the sectors in the following chapters were based on several considerations. An array of temperature and precipitation values, ranging from no change to increases up to those projected by the GCMs, were posed to all sectors except the Rocky Mountain ecosystem. With that one exception, only the increase range was adopted because that has been both the historical and GCM-projected direction. In the case of the Rockies, an additional precipitation-decrease scenario was posed to increase the range of considerations for this immense ecosystem that almost extends, latitudinally, from the Mexican to the Canadian border. In a number of cases, specified patterns appearing in the historical analyses (e.g. more marked increases in summer precipitation than the winter increases projected by the GCMs) were used.

It is also clear that different sectors are sensitive to different climate variables. Rather than pose a single set of climate-change variables to all of the sectors, the influential variables affecting each sector were identified, and changes in these were posed. This procedure is especially applicable to the water, agriculture, and outdoor recreation sectors.

While there was no attempt to systematically elaborate all of the other environmental and land-use factors affecting each sector within its system, and develop predictive models thereof—the implicit ideal of vulnerability analysis, and more demanding of time and resources than those available to this assessment—each sector was examined in the context of major factors impinging upon it, and the interaction of climate variables within these. This approach is considered interactive between a purely top-down and bottom-up approach, and more focused than either of the two by themselves..

Finally, in all cases the exercises are provisional, what-if queries posed to the sectors. As a result the answers are hypothetical, their precise validity contingent upon the reality of the scenarios.

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Chapter 4

WATER RESOURCES

Connely K. Baldwin, Frederic H. Wagner, and Upmanu Lall

INTRODUCTION

The close adjustment of the human population in the Intermountain West to the availability of water resources makes the western populace especially susceptible to any climate-change alteration in those resources. The region's aridity was the prime factor deterring major population build-up in the first 50-100 years following European settlement. It also explains why half the area of the 11 western states, and 70-80% of the RMGB region remains in federal ownership. Recognizing that the 160 acres of land permitted for homestead entries east of the Rockies were not sufficient to allow a landowner to make a living in the arid West, Congress passed legislation in the early 1900s allowing 320-, then 640-acre, entries. But these efforts failed to encourage significant land divestiture (Donahue 1999). When in 1930 President Hoover offered the public domain to the western states, all declined because water was in short supply, and highly variable seasonally, annually, and spatially.

During the 20th century, an extensive engineering infrastructure was developed to smooth out the temporal and spatial variability. Dams on most western streams, and a network of storage and distribution systems impound water originating in the mountain ranges and distribute it to distant areas that have little or no surface water. Over much of the West, water used in a given locale originates tens or hundreds of miles away. Some 85% of the water used in the Las Vegas metropolitan area, with a population exceeding 1 million, is transported by massive underground pipes 10 miles from Lake Mead, an impoundment of the Colorado River. The river, in turn, originates in the Rocky Mountains two states to the east. Denver, situated at the foot of the Rockies' east slope, receives half of its water via subterranean aqueducts tunneled through the mountains from stream impoundments on the mountains' west slope.

The Intermountain West's population and culture grew slowly in the first half of the 20th century, and water was allocated by a complex of statutory and administrative institutions oriented to a limited agriculture and a largely rural populace. But the population has burgeoned since World War II, mostly developing in the cities. Thus a traditional engineering and administrative water-allocation system is now being forced to support the fastest growing population in the U.S. with very different values and demands, and on limited water.

At present, depending on the area, 56-99% of water used by the RMGB region's population comes from surface water (Table 4.1). Among the states in the region, Nevada with few streams has the lowest dependency on surface water (56%, Table 4.1), although as commented above, the Colorado River supplies 85% of Las Vegas' usage. In western Colorado, Wyoming, and Montana, surface water supplies over 90% of all human use (Table 4.1). In terms of total water use in the region, 85% is taken from surface sources.

Three-fourths of western streamflow is fed by melt and run-off of montane snowpacks. Thus the water resources supporting the RMGB population are closely tied to the amount, form, and timing of precipitation; the magnitude, melt, and run-off schedule of the montane snowpacks; and the effects of these variables on the size and timing of flow in the region's streams. Miller (1997) comments that streamflow in the arid West is more sensitive to variations in precipitation than in any other part of the U.S.

In the sections that follow, the potential effects of climate-change scenarios, operating through these hydrologic variables on the region's water resources, will be explored. The responses of the region's water managers, when presented with a series of what-if, climate-change scenarios, will be reviewed. And the chapter will close with a number of implications that affect coping strategies.

TWENTIETH-CENTURY HYDROLOGIC TRENDS

Streamflow Volume

Since the historical climate analysis of the last chapter indicated precipitation increase during the 20th century in six of the VEMAP subregions (Table 3.5), several data sets on the flow of streams in the region were analyzed to determine whether, and if so how, they have been affected by the precipitation increase. The purpose of the first analysis was to develop a regionwide overview of streamflow behavior. Although it was desirable to select one stream in each of the subregions, the choices were limited to streams that met two criteria:

(1) A long (most of the 20th century) period of record maintained in the Hydro-Climatic Data Network (HCDN) Streamflow Data Set 1874-1988 (Slack et al. 1992, 1993).

(2) Quality of the record. Only five of the eight subregions had gaging stations that met these criteria, and one station in drainage basins in each of the five was selected (Fig. 4.1, Table 4.2).

(3) Absence of major human impacts (e.g. diversions and dams) upstream from the gaging stations.

For each stream, successive 30-year moving averages of annual streamflows, measured in mean, annual cubic feet per second (cfs), were calculated, plotted as time series (Fig. 4.2), and regressed over time. The regressions were tested with the seasonal Kendall test.

In three of the five streams - - Boise River, Humboldt River, and Blacksmith Fork - - the flow increased significantly ($p<0.05$) during the 1900s (Fig. 4.2). The trend in the Yellowstone was similar to the three, but the regression was short of significance at 0.05. The rate of increase in the three with significant trends ranged from 12%/100 years in the Boise to 33%/100 years in the Blacksmith Fork (Table 4.2). The latter has the smallest watershed

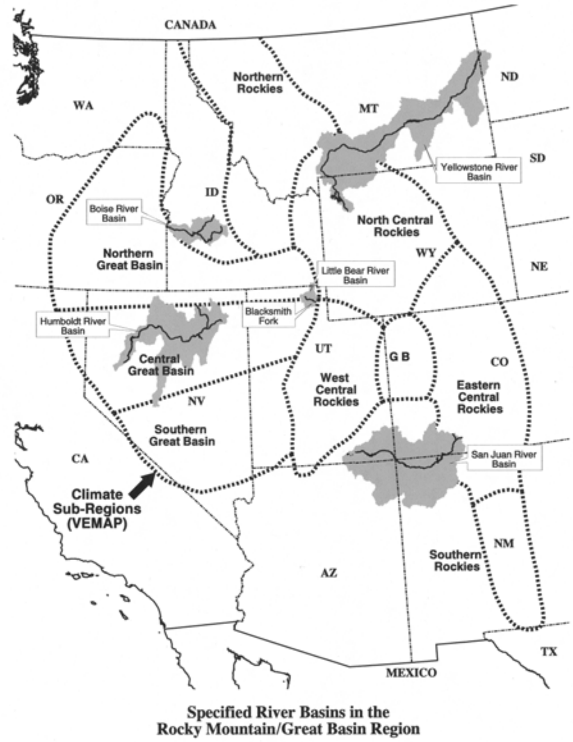


Figure 4.1. Rivers and drainage basins selected for reconstructing 20th-century streamflow patterns in the RMGB region.

Table 4.1

Sources of 1995 Fresh Water Withdrawals in the Rocky Mountain/Great Basin Region

State	Area of Region	Withdrawals (Mgal/day)	% Ground Water	% Surface Water
CO	gb	207	1	99
	rm	8,104	7	93
ID	gb	7,177	18	82
	rm	5,381	23	77
MT	rm	5,264	3	97
NM	rm	1,457	31	69
NV	gb	1,716	44	56
OR	gb	1,845	14	86
UT	gb	1,152	34	66
	rm	2,721	13	87
WY	gb	73	6	94
	rm	6,196	1	99
Total and means		41,313	16	94

Data Source: U.S. Geological Survey (http://water.usgs.gov)

Table 4.2

20th Century Flow Patterns of Rocky Mountain/Great Basin Streams

River and Gaging Station	RMGB Subregion	Basin Area (mi^2)	Period of Record	Increase in cfs[1]	% Increase
Boise, Twin Springs, ID	NGB	830	1912-88	149/100yrs.[2]	12/100 yrs.
Humboldt, Palisade, NV	CGB	5,010	1914-88	69/100 yrs[2]	16/100 yrs.
Yellowstone, Corwin Springs, MT	NCR	2,623	1911-88	--	--
Blacksmith Fork, Hyrum, UT	WC	263	1919-88	43/100 yrs.[2]	33/100 yrs.
San Juan, Bluff, UT[3]	ECR	23,000	1929-93	No signif. trend	--

[1]Mean, annual increase in cubic feet per second.
[2]Trend is homogeneous over the seasons.
[3]Naturalized flows obtained from the U.S. Bureau of Reclamation (Pers. Comm.).

situated entirely in the Wasatch Mountains with no irrigation withdrawals above the gaging station. The other two have larger basins with some irrigation withdrawals above the gaging points.

The increased flow in the Boise and Humboldt, and possibly the Yellowstone, occurred in three subregions (Northern Great Basin, NGB, Central Great Basin, CGB, and North-central Rockies (NCR), with increased precipitation during the 1900s (Table 3.5). The increase in the Blacksmith Fork, arising in the West-central Rockies (WCR), occurred in a subregion in which no significant increase in precipitation was found (Table 3.5). Moreover, the major increases occurred largely in the second half of the 20th century. The absence of any discernable trend in streamflow of the San Juan also occurred in a subregion (East-central Rockies, ECR) in which no statistically significant 20th-century increase in precipitation was detected.

The low-flow characteristics of the five rivers were examined by calculating annual, minimum 7-day average flows. These are plotted in Fig. 4.3, with Lowess smooths of the time series, for the four rivers that showed increased flows during the 1900s (Fig. 4.2). In general, the patterns are similar for three of the four (Boise, Yellowstone, and Blacksmith Fork): decreasing low flows in the early part of the century, some increase in mid-century, then decline thereafter with a net decline for the century as a whole. Such declines would be expected to occur in streams with generally rising flows (Fig. 4.2). The rather different behavior of the Humboldt may be the result of the more arid environment and generally lower elevations of its watershed.

Interannual variability of flows in the five streams was also analyzed by calculating standard deviations around the 30-year moving

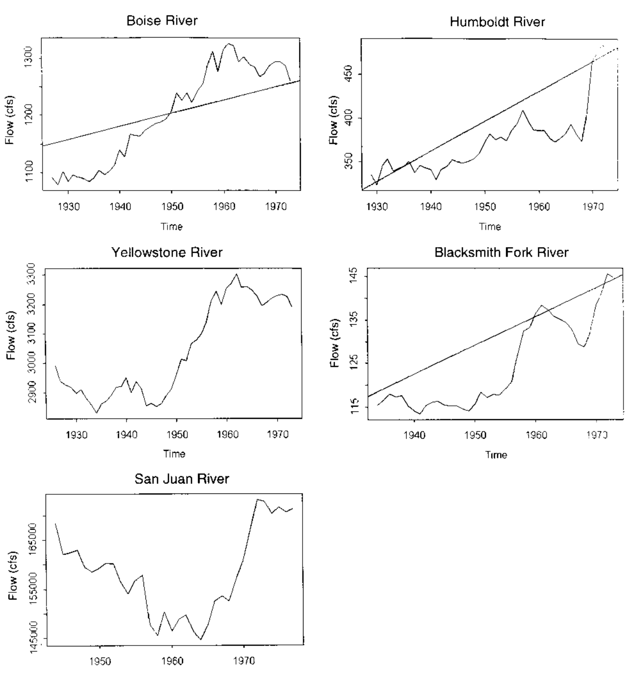


Figure 4.2. Time series of 30-year moving averages of the annual flows in five streams of the RMGB region. Linear slopes are fitted to those time series with a statistically significant (p<0.05) linear increase over time.

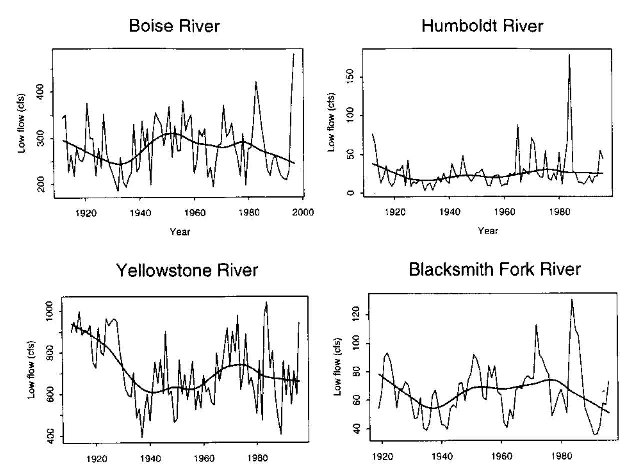


Figure 4.3. Mean, annual minimum 7-day flows, with Lowess smooth of the data, for four streams in the Rocky Mountain/Great Basin region.

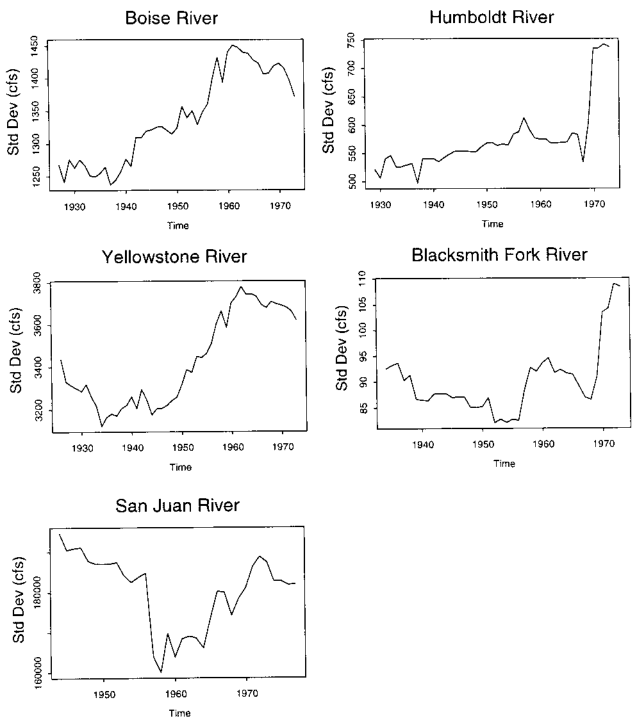


Figure 4.4. Time series of standard deviations around 30-year moving averages of annual streamflows shown in Fig. 4.2.

averages of flow (Fig. 4.2). The trends over time (Fig. 4.4) coincide with increases in flow indicating that interannual variability has increased as annual streamflow has increased. Thus the frequency of extremely high flows has increased, while the frequency of low flows has declined (Fig. 4.3). The increasing variance in streamflow also coincides with the increasing variance in annual precipitation in these subregions discussed in the last chapter.

These patterns agree with those shown by other data sets. Analyzing hydrologic trends in the entire U.S., Lettenmaier et al. (1994) found strong increases in the flow of streams in the RMGB region, particularly in winter and spring, during the latter half of the 20th century. They also noted that precipitation had increased in the region over the same period.

Dettinger and Schaefer (1995) analyzed ground-water data for eastern Nevada from the U.S. Geological Survey and the state of Nevada. They concluded:

> Ground-water levels in widely scattered wells in nearly pristine aquifers of the central Great Basin have risen significantly since the 1960s. The levels reflect filling of the basin-fill aquifers during recent wetter-than-normal conditions following drier-than-normal and near-normal conditions between the 1920s and 1950s …. the recent water-level rise has reflected mostly variations in summertime precipitation.

In the five wells analyzed by these authors, the water table rose from 1.5-5.0 m.

In a second analysis, the focus was more closely on the Colorado River and its tributaries. These originate in the East-central and West-central Rockies subregions where no 20th-century precipitation increase was detected (Table 3.5), and there was no evidence of increased flow in the San Juan River (Table 4.2), one of the Colorado tributaries. The Colorado's flow trend for the 20th century, compiled by Susan Selby from U.S. Bureau of Reclamation measurements made at Lee's Ferry, Arizona, is shown in Fig. 4.5. A regression fit to the entire series portrays a downward trend from ~18 million acre feet at the beginning of the century to 15 million in 1996, a decline of nearly 17%. The trend is corrected for human withdrawals and is therefore presumably induced by factors other than human use.

However, drawing a firm conclusion about the trend in the full dataset may be misleading because the dataset is a combination of estimated and observed values. Bureau of Reclamation flow values prior to the mid-1920s are reconstructed from tree-ring proxies. Beginning in the mid-20s the values came from actual gage measurements at Lee's Ferry, Arizona. While the slope of the entire series - - which combines two datasets - - is negative, regression on the observed values only (1920s to date) results in no significant slope.

In order to examine the origins of the river's behavior at Lee's Ferry, the dividing point separating the river's upper and lower basins (Fig. 4.6), and further explore the circumstances surrounding the absence of trend in the San Juan, 20th- century flow of five major tributaries of the Colorado were examined: the Green River arising in the southwest quadrant of Wyoming, the Yampa of north-western Colorado, the Colorado and Gunnison in the central part of Colorado, and once again the San Juan in the south. Data were provided by Tom Ryan (1996) of the Upper Colorado Basin Office of the Bureau

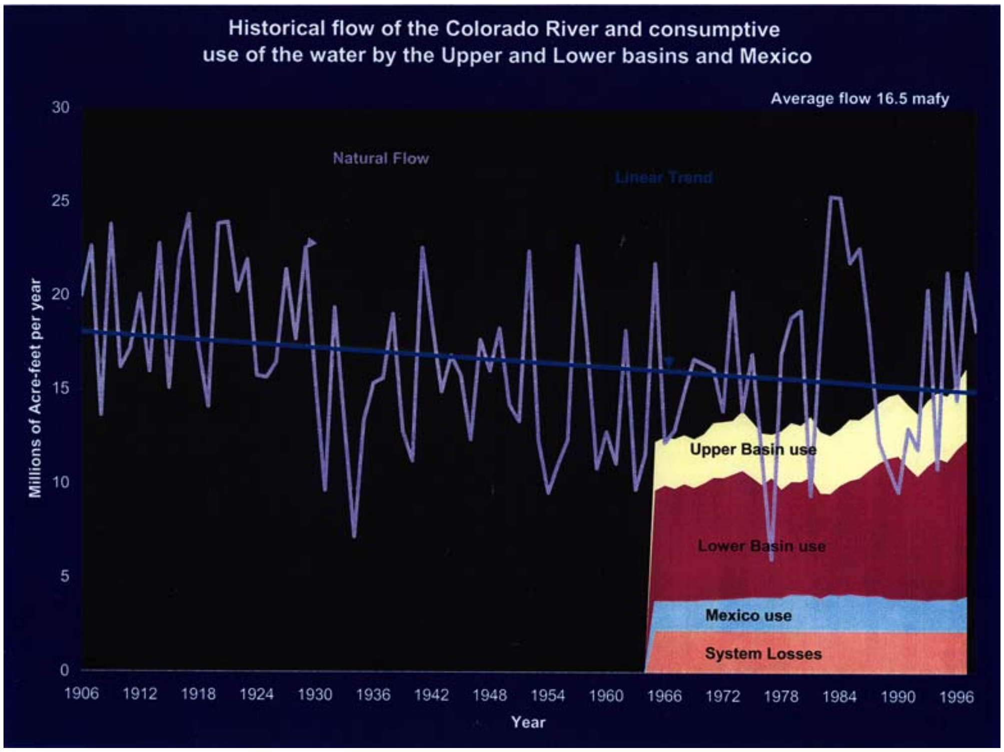


Figure 4.5. Historical flow of the Colorado River and consumptive use of the water by the Upper and Lower basins and Mexico. Data from U.S. Bureau of Reclamation.

of Reclamation in Salt Lake City. The flow data were "reconstructed" or "virgin" flows corrected for human withdrawals. They were calculated or measured for the years 1905-1990 at the following stations, respectively, of the above rivers: Green River, UT; Maybell, CO; Cisco, CO; near Grand Junction, CO; Bluff, UT.

The streamflows for the five tributaries have been gaged on the first of each month, and total, annual flows cannot be calculated. However, mean, monthly flows were calculated for each water year (October-September), and the means were regressed over time. All were negative for the period 1905-1990, with p values respectively at 0.07, 0.03, 0.14, 0.18, and 0.008. Thus these tributaries have had the same negative 20th-century flow patterns as the main Colorado which they feed (Fig. 4.5). When the 1926-1990 flows were regressed, as with the Colorado at Lee's Ferry, none of the slopes was significantly different from zero, again like the main Colorado. However the Green had a positive slope although with p=0.35, and the San Juan had a negative slope

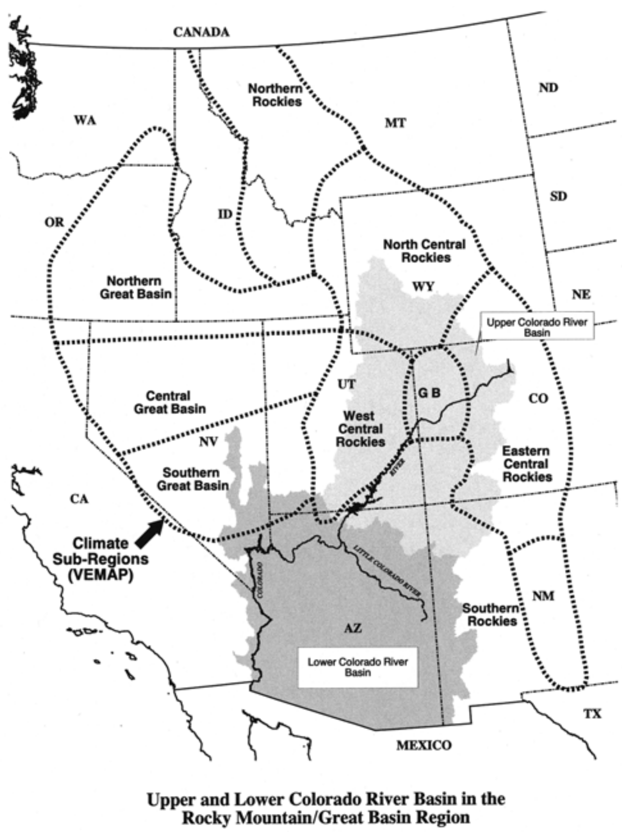


Figure 4.6. Upper and Lower Colorado River Basins in the RMGB region.

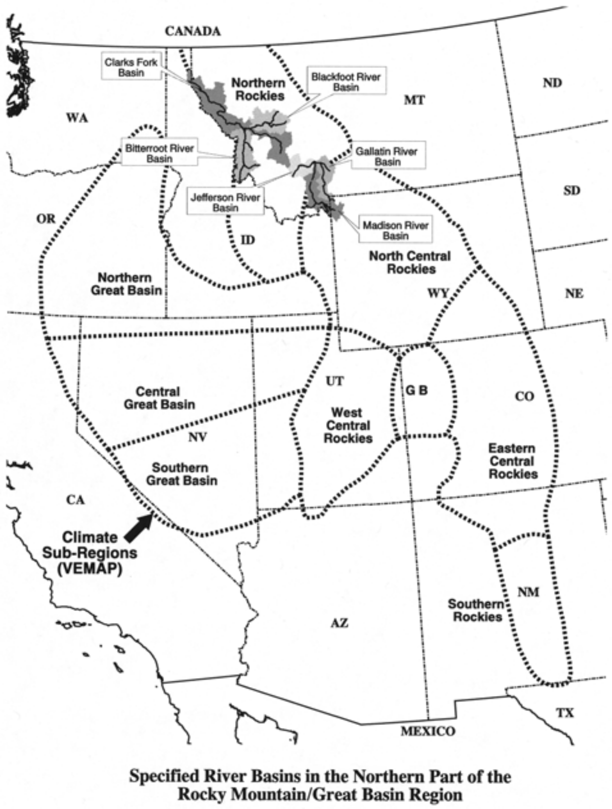


Figure 4.7. Five rivers, and their basins, in the northern portion of the RMGB region, that were analyzed for 20th-century trends in annual streamflow.

though with a high p value indicating absence of trend.

The conservative interpretation here is that the Colorado, and its headwaters in the West-central and East-central Rockies subregions, have experienced no net change in flow since 1926 although of course there has been great interannual variation (Fig. 4.5). However the moderately positive slope for the Green could suggest the approximate latitude above which RMGB streamflows increased during the 1900s (Fig. 4.2).

In a third effort, more data were obtained on streamflow at the northern extreme of the region. Hydrology reports of the U.S. Geological Survey were examined for six streams in western Montana (Fig. 4.7): Bitterroot River (Farnes and Shafer 1972a), Gallatin River (Farnes and Shafter 1972b), Jefferson River (Farnes and Shafer 1975), Madison River (Anon. 1976), Blackfoot River (Anon. 1990a), and the Clark Fork River (Anon. 1990b).

The data sets were not sufficient to discern whether or not there were trends similar to those shown in Fig. 4.2. None extended through the last 3 decades of the 20th century when much of the increase in streamflow appears to have occurred. Four of the series ended in the 1970s, two in the 1980s. There were short-term trends (i.e. 10-40 years) within the time series, but none was sufficiently long to allow inference on whether or not there was a net, century-long trend.

In sum, the evidence examined here indicates an increase of 12-33% in total annual flow of streams during the 1900s from northern Utah northward and westward in the RMGB region. There is no such evidence for the Colorado River or its tributaries in Colorado and southern Utah.

Streamflow Seasonality

Seasonality of flow in western streams is influenced by the time in late fall and early winter when rain changes to snow, by the timing of spring snowmelt and run-off, and by the seasonal distribution of precipitation. The influence of these factors on RMGB streams was examined in three separate analyses.

First, VEMAP precipitation data for one small area in the region were compared with Snowcourse and SnoTel measurements from the Natural Resources Conservation Service (NRCS) to verify the elevation correction and to identify any trends in snowpacks in two areas. April snow-water equivalents (SWE) were calculated with data from six gaging stations in the Wasatch and Uintah mountains of the West-

Table 4.3

Snow Gaging Stations in the West-central Rockies Subregion

Station	Elevation (m above MSL)	Station No.
Daniels-Strawberry	2,438	11J23
Gooseberry R.S.	2,560	11K03
Mammoth-Cottonwood	2,682	11L02
Webster Flat	2,804	12M03
Hewinta G.S.	2,896	10J04
Mosby Mountain	2,896	09J05

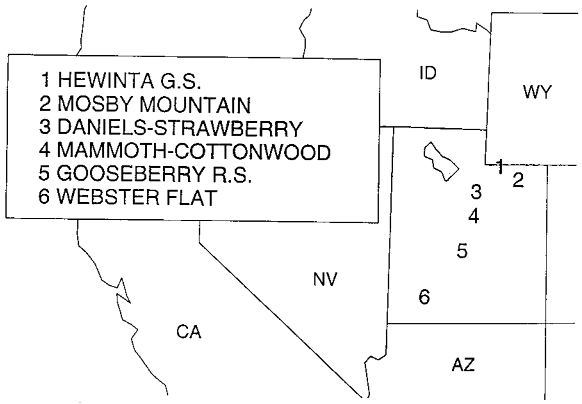


Figure 4.8. Location of Utah snow gaging stations listed in Table 4.3.

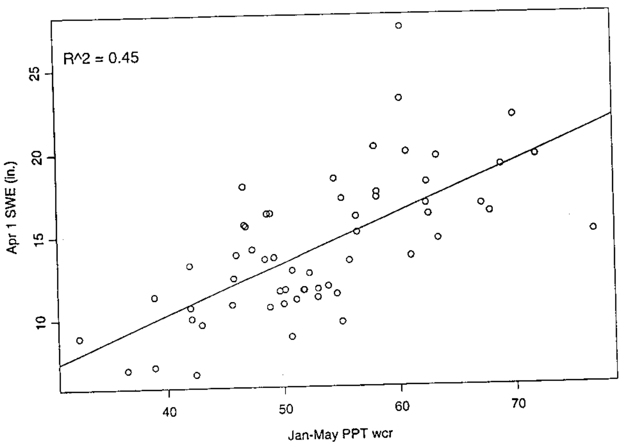


Figure 4.9. Correlation between annual snow-water equivalents of April 1 snowpacks measured at West-central Rockies (WCR) subregion gaging stations shown in Fig. 4.8, and annual precipitation in the WCR measured from VEMAP data.

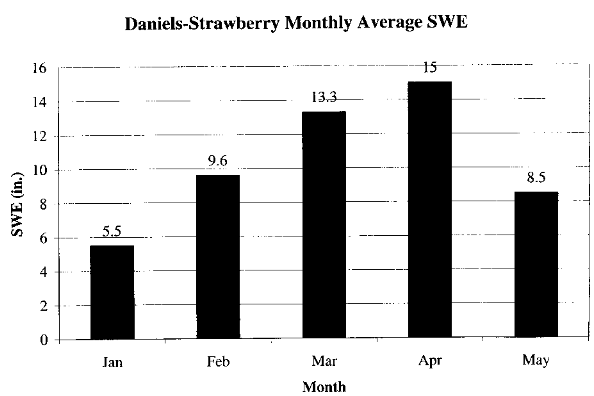


Figure 4.10. Average, monthly snow-water equivalents (SWE) at the Daniels-Strawberry snow gaging station (see Fig. 4.8).

central Rockies (WCR) subregion (Table 4.3, Fig. 4.8) for the period 1932-1998. These SWE values were regressed on January-May precipitation in the subregion producing an R^2 of 0.45 (Fig. 4.9). Thus, the VEMAP precipitation data averaged for the subregion accord well with the averaged snowcourse data for the two mountain ranges in the subregion.

The snowpack seasonality at the Daniels-Strawberry station was examined empirically. The average seasonal cycle of SWE (Fig. 4.10) indicates a normal peak in April followed by melting and reduced snowpack in May. An advance in seasonal snowpack cycle would be manifested through earlier melting which would have no clear relationship to the amount of accumulation. An increase or decrease in amount could occur, resulting in very different outcomes. The Chapter 3 precipitation analyses indicated increasing precipitation in recent decades in six of the eight subregions, but not in the WCR.

Therefore, potential changes in seasonality were investigated by calculating the change in accumulation from month-to-month and the 30-year average SWE for each month. These two approaches were used to identify changes in seasonality that would be expressed by: (1) change in the amount of accumulation (or melt) between months and (2) change in timing of the long-term mean accumulation. The first method uses the difference between the amount of accumulation in successive months and reduces the impact of interannual variability. The second method uses the 30-year average of monthly SWE and detects systematic changes in the timing of accumulation. These complementary methods allow changes in seasonality of snowpack to be identified.

The change in snowpack amounts between successive months (Fig. 4.11) does not show a clear trend in the seasonality of accumulation or melt. There is significant variability and the Lowess smooth highlights low-frequency variability, but no secular trend is evident. The signal varies from month to month. The change in SWE from January to February (Fig. 4.10) has recently been larger than the historical average, but was also higher in the 1950s. The recent changes in February to March are similar in nature to the early period of record, while the 1960s show much less accumulation and

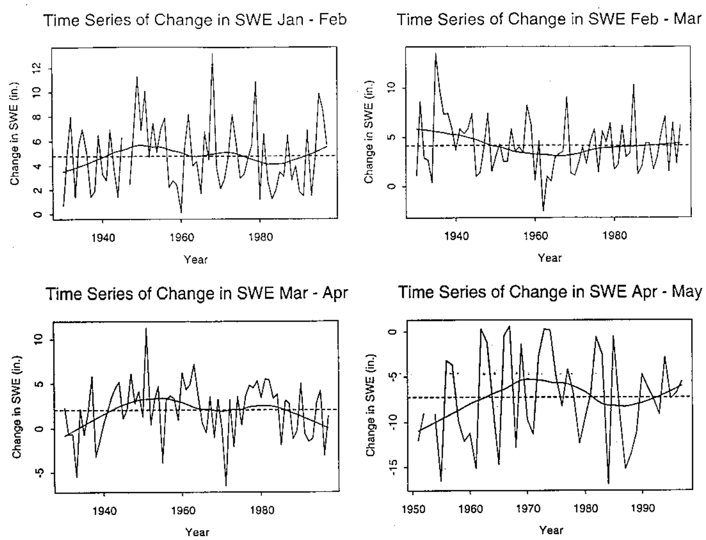


Figure 4.11. Monthly changes in SWE at Daniels-Strawberry and 30-year Lowess smooth. Difference is defined as SWE in the first month minus the SWE of the following month. The dotted line shows the mean change over the period of record (derived from Fig. 4.10). The y-axis for the April-May graph is all negative, indicating snowmelt.

even melting in some years, much less than the historical average change.

The changes from March to April are nearly opposite those observed for February to March. The 1960s had consistently more accumulation than the historical average. This period appears to represent a decadal-scale shift in seasonality consistent with that observed for precipitation and streamflow, with decreases in snowpack observed in the February to March period that may contribute to runoff. However, additional snowpack accumulates later in the year, and may make the signal more ambiguous. May SWE measurements were begun in 1952, and the April-to-May period is the only one in which historical, average change in SWE is negative (snowmelt). More snowmelt was observed in the 1950s and the recent period, consistent with the larger accumulations observed in previous months during these same time periods. Thus, while variation in seasonality of snowpack occurs over long time scales, no secular trends are evident over the period of record available at the Daniels-Strawberry station.

The 30-year moving average of SWE, measured each month was used to examine whether there have been changes in the timing of accumulation and melting (Fig. 4.12). The changes observed over the period of record are not great. There is a tendency for more snowpack to occur earlier in the year, although May SWE has changed very little. There appears to be a decrease in April SWE over the period of record. The extended period of above-average SWE ends in 1966, with only the 30-year period around 1971 being above normal since. Thus, no significant and obvious change in the seasonality of snowpack is evident from either analysis.

As a second investigation of streamflow seasonality, unpublished data provided by Michael Dettinger on the seasonality of flow in the Boise, Humboldt, and Yellowstone Rivers from the early 1900s through 1993 were analyzed. Singular Spectrum Analysis (Vautard and Ghil 1989, Vautard et al. 1992) was used to reconstruct the annual cycles and determine the date of peak flow for each year.

The results are summarized in Fig. 4.13. The dates of peak, spring run-off have advanced since about 1970 in the Boise and Yellowstone Rivers, since about 1950 in the Humboldt. In all cases, the advances have been about 10-15 days. These results coincide with those of Dettinger (2000) who measured advances in run-off peaks in streams of the northern Rockies which he attributed to "… spring temperatures which have warmed significantly since 1945 … in this region …"

As a third investigation of run-off timing, the seasonality of flow in the five rivers shown in Fig. 4.1 was compared

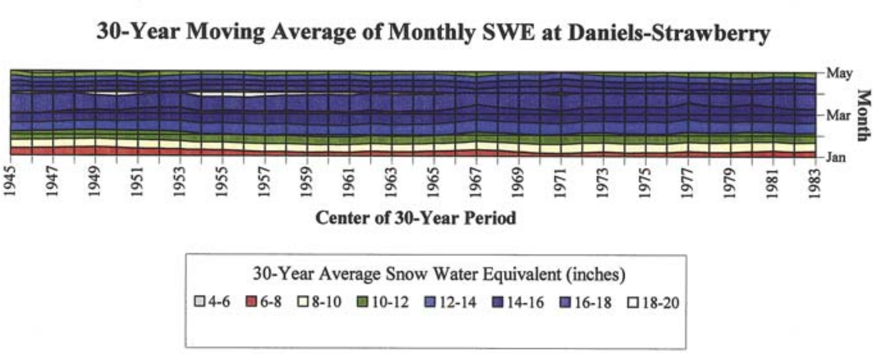


Figure 4.12. 30-year moving average of monthly SWE at Daniels-Strawberry snow gaging station. The year shown on the x-axis is the center of the 30-year period. The legend shows the SWE in inches.

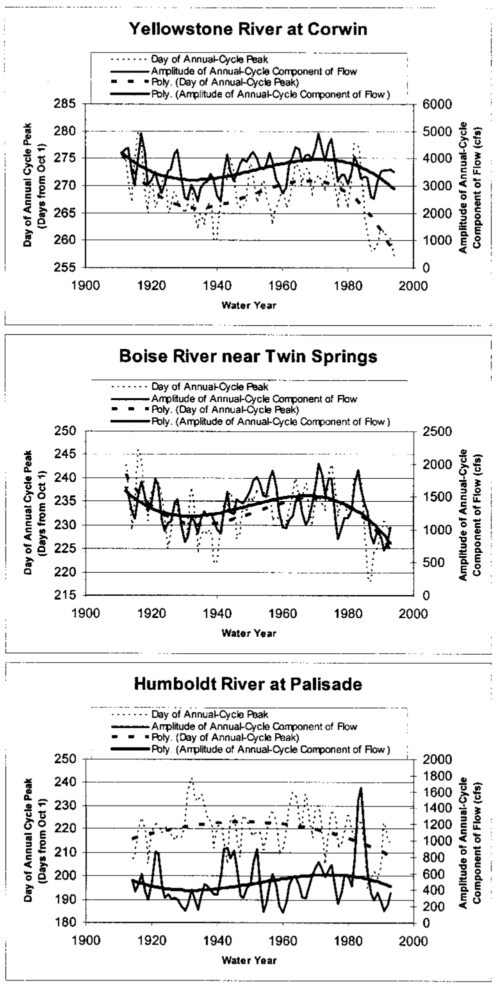


Figure 4.13. Days since October 1 of annual-cycle peak (light dashed) and magnitude of component of flow in cubic feet per second (heavier dashed). The corresponding cubic fits for days of annual-cycle peak (light solid) and magnitude of annual-cycle component of flow (heavier solid) are also shown. Unpublished results from Michael Dettinger (personal communication).

with the seasonality of precipitation in the same subregions, in each case for the four seasons: winter (December-February), spring (March-May), summer (June-August), and fall (September-November). The seasonal precipitation trends were compiled in Chapter 3. The streamflow time series were plotted for each season, and the trends smoothed with the Lowess smooth. These are shown in Fig. 4.14.

These seasonal streamflow time series were compared with the interpretation of seasonal precipitation time series not presented, but partially summarized in Table 3.7, for the subregions in which the streams occur. The comparisons are visual, as follows:

(1) Boise River, Northern Great Basin precipitation.

Spring: No trend in precip, rising trend in river flow.

Summer: Rising trend in precip, no trend in flow.

Fall: No trend in either.

Winter: No trend, or even decrease, in precip; rising trend in streamflow since ca. 1935.

(2) Humboldt River, Central Great Basin precipitation.

Spring: No trend in precip, rising streamflow.

Summer: Rising trend in precip, rising flow since ca. 1935.

Fall: No trend in precip or streamflow..

Winter: Trends do not match. Slight decline in precip since ca. 1915, increase in streamflow since ca. 1935.

(3) Yellowstone River, North-central Rockies precipitation.

Spring: Rising trend in precip, slight increase in streamflow since ca. 1940.

Summer: Precip increase through 1900s, slight increase in streamflow.

Fall: No increase in precip, sinuous trend in streamflow.

Winter: Essentially no secular trend in precip or flow.

(4) Blacksmith Fork, West-central Rockies precipitation.

Spring: No trend in precip, increase in flow since ca. 1935.

Summer: Increase in precip through 1900s, increase in flow since ca.1935.

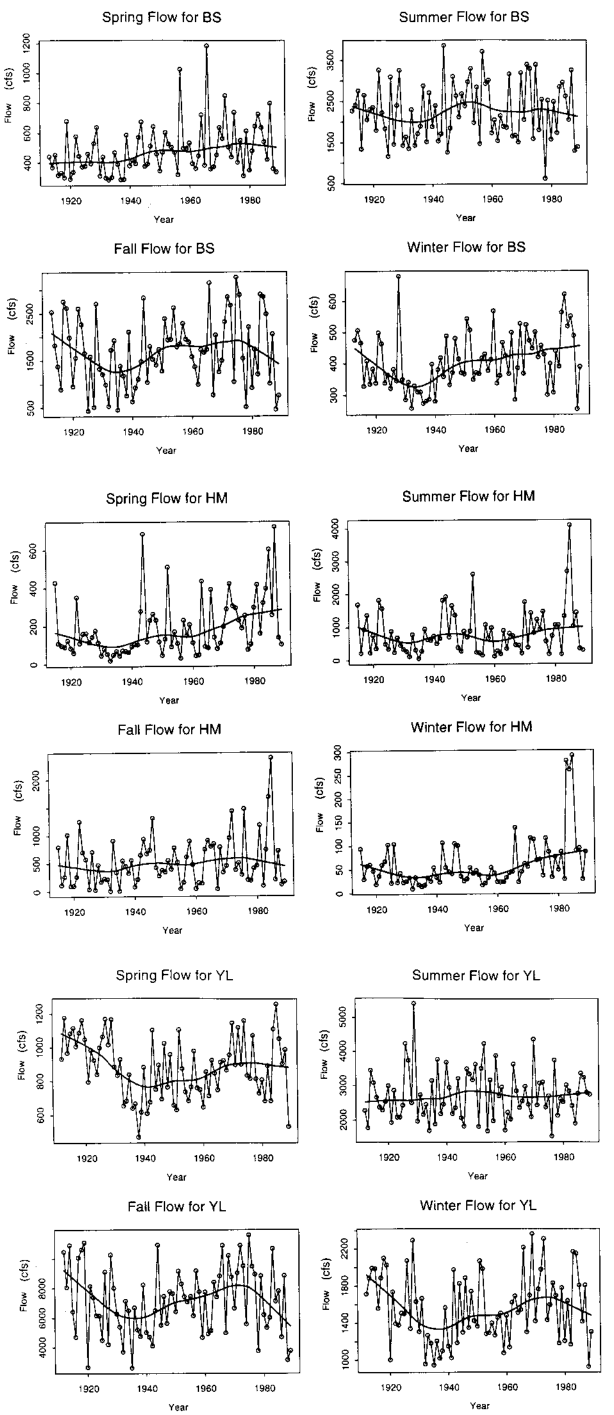
Fall: No trend in precip, slight increase in flow since 1935.

Winter: No trend in precip, increase in flow since ca. 1935.

(5) San Juan River, East-central Rockies precipitation.

Spring: No trend in precip through 1900s, increase in streamflow since ca. 1960.

Summer: No trend in precip through 1900s, no trend or decrease in streamflow.



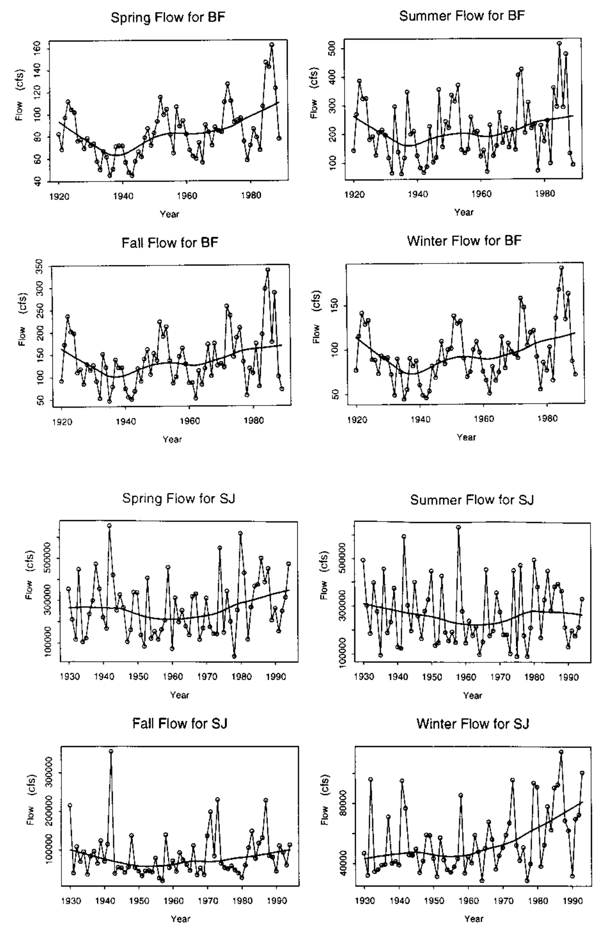


Fig. 4.14. Time series of seasonal flows in the Boise (BS), Humboldt (HM), Yellowstone (YL), Blacksmith Fork (BF), and San Juan (SJ) Rivers in cubic feet per second, and smoothed with the Lowess smooth.

Fall: Slight or no increase in precip, no change or decline in flow.

Winter: Slight or no increase in precip, strong increase in flow.

These results are summarized in Table 4.4 to facilitate overview. As commented above, and discussed by Mote et al. (1999), western U.S. streamflow is influenced by precipitation timing and form, and snowpack melt and run-off. The patterns in Table 4.4 may reflect these effects, although they are correlational and cause-and-effect inferences remain speculative.

In all five subregions, winter precipitation either did not undergo any net change during the 1900s (NCR, WCR, ECR) or it declined (NGB, CGB). Yet winter streamflow increased in four of the five streams. One expectation of global warming is that montane precipitation will continue as rain later in the fall and into winter before changing to snow. The result would be run-off of early winter precipitation that would otherwise fall as snow and begin build-up of snowpacks. The increases in winter flow shown in Table 4.4 could result from rain and subsequent run-off which in earlier years

Table 4.4

Twentieth Century Trends in Seasonal Precipitation In Five RMGB Subregions and Flow of Five Streams In the Subregions

		Trend in Subregions and Streams[1]				
		NGB	CGB	NCR	WCR	ECR
Season	Variable	Boise	Humboldt	Yellowst.	B.S. Fork	San Juan
Winter	Ppt.	-	-	0	0	0
	Flow	+	+	0	+	+
Spring	Ppt.	0	0	+	0	0
	Flow	+	+	+	+	+
Summer	Ppt.	+	+	+	+	0
	Flow	0	+	+	+	0
Fall	Ppt.	0	0	0	0	+
	Flow	0	0	0	+	0

[1]+ = Net increase during 1900s.
0 = No net trend during 1900s.
- = Net decrease during 1900s.

accumulated as snow, and without any net increase in precipitation.

Somewhat the same appears to be the case in the spring pattern. Although there was no increase in spring precipitation in four of the five subregions, all streams showed an increase in spring flow during the 1900s. At this season, the effect of increasing temperatures would be to advance the run-off. Dettinger (2000) commented that "Peak timing … in the northern Rockies … responds most to spring temperatures which have warmed significantly since 1945 to drive earlier snowmelts in this region …" The most recent dates of peak run-off in the Boise and Yellowstone have been ca. May 14 and June 15 respectively, April 30 in the Humboldt (Fig. 4.13). As commented above, these are advances of 10-15 days over peak run-off dates earlier in the century. Thus, in three of the rivers, peak run-off has in recent years occurred earlier in the spring months.

In subregions of four of the five rivers, precipitation increased in summer, particularly in the month of June (Table 3.7). Summer streamflow increased in three of the four rivers. While reduced summer flow is predicted to be a consequence of earlier snowmelt (Mote et al. 1999), in these RMGB streams, increased summer precipitation may have offset any reduction that might have occurred from early snowmelt.

Lack of change in fall streamflow in four of the five rivers is consistent with the absence of any trend in fall precipitation in four of the five subregions during the 1900s. But it does not accord with the predictions of reduced fall streamflow in response to earlier snowmelt. As with summer flow, autumnal flow is predicted to decline (Strzepek 1999, Mote et al. 1999).

Discussion of 20th-century Hydrologic Trends

While there are some localized exceptions, the evidence presently at hand indicates an increase in water resources in the western and northern portions of the RMGB region in the latter half of the 20th century. This increase coincides with increased precipitation, primarily in summer, during the same period. However, streams in the southeastern portion of the region appear not to have followed the same trend. Analyses of the Colorado and its tributaries indicate either decline over the past 100 years or no net change in flow since the 1920s. These streams have headwaters in the West-central and East-central Rockies subregions in which no net change in annual precipitation over the 1900s was detected. These subregional differences may reflect Cayan's (1996) generalization that the northwestern and southeastern portions of western U.S. are in different climate zones in terms of the snow-water equivalents of their montane snowpacks.

The rising standard deviations of mean, annual flow in those portions of the region with increasing stream flows (Fig. 4.4) indicate rising variability between years during the 1900s as apparently occurred in interannual variability in precipitation (Fig. 3.24). With net increases over the years, the implications are for an increasing fraction of years with extreme flows and flooding. This could be exacerbated if rising temperatures produce more rain-on-snow events in spring. The declining frequency of low-flow years indicates that, while the variance has increased, the entire probability distribution has shifted to higher values and away from significant probabilities of lower-flow values. Consequently there has been a declining probability of years with deficient water resources and droughts.

These changes in streamflow have occurred during a period of rising atmospheric concentrations of greenhouse gases. The relationship is, of course, correlative and it is not clear whether it represents cause-and-effect. But as discussed in Chapter 3, the GCMs project increases in precipitation in the region, although primarily in fall and winter.

The rate of increase in those RMGB streams for which the evidence indicated rising flows ranged from 12-33%/100 years during the 1900s (Table 4.2). A significant temperature rise in the next century could negate this increase through higher evapotranspiration. Nash and Gleick (1993) predicted that temperature increases in the Colorado River basin, and associated evapotranspiration, would significantly reduce run-off. A 4^{o} C (7.2^{o}F) temperature rise would require a 15-20% precipitation increase just to maintain streamflow in that basin at current levels. However, the GCMs project a much larger precipitation increase during the 21st century (Table 3.8). If this becomes reality, the result would be significantly increased streamflows despite higher evapotranspiration.

A growing literature is both predicting (Nash and Gleick 1991, 1993, Riley et al. 1996, Melack et al. 1997, Strzepek 1999, McCabe and Wollock 1999, Mote et al. 1999, Baron et al. 2000, Fyfe and Flato 1999) and documenting empirically (Dettinger and Cayan 1995, Cayan 1996, Dettinger 2000) the effects of temperature increases on western, montane snowpacks. While no measurement evidence of changes in the snowpacks themselves has been presented here, there is convincing evidence of chronological advances in spring run-off peaks and increases in winter streamflow not accompanied by increases in winter precipitation in the northern and western portions of the RMGB region. As Dettinger and Cayan (1995) comment "… winter temperature trends appear to be involved in a decades-long change in the fraction of runoff occurring in late spring and summer runoff found in the Sierra Nevada and many other snowmelt-driven streams over the western United States …. Its dependence on temperature makes snow a key diagnostic in climate change scenarios."

Thus a reasonable scenario for western streamflows by 2100, if the GCM projections become reality, is change from the contemporary pattern in the seasonal <u>proportionality</u> of flows: increased winter flow, reduced and earlier spring peaks, and reduced summer and autumnal proportions similar to the projections of Mote et al. (1999) for the Columbia River. But if the precipitation increases projected by the GCMs (Table 3.8) become reality, the <u>absolute</u> flows in each season could substantially exceed the contemporary levels. The projected increases would produce annual precipitation totals by 2100 on the order of 50-100% above contemporary levels, and conceivably comparable increases in total, annual streamflows.

These results and hypothetical projections provided the basis for a set of scenarios which were posed in questionnaires to 19 water managers in the region, and subsequently in a water-resources workshop. The results of the questionnaire and proceedings of the workshop are summarized in the sections that follow, and reproduced verbatim in appendices at the end of this chapter.

SURVEY OF WATER MANAGERS

Introduction

Schilling and Stakhiv (1998) have recently lamented that water managers have not been as involved in the climate-change issue as they should be. In order to gain some understanding of these professionals' familiarity with the issue, the extent to which they ponder its relevance to their operations, and how they might be forced to adjust, a questionnaire was sent to 19 individuals in urban, state, and federal water-management programs within the region in February 1999. In particular, information was sought on the stresses within which they operate under current climatic patterns, and how changes in the amount and variability of the resource would affect those stresses. The individuals to whom questionnaires were sent are:

Mike Turnipseed, State Engineer
Nevada Division of Water Planning
Carson City, NV

Naomi Duerr, Jeanne Ruefer, Randy Pahl
Nevada Division of Water Planning
Carson City, NV

Bruce Williams
U.S. Bureau of Reclamation
Boulder City, NV

Rick Wells
U.S. Bureau of Reclamation
Boise, ID

Lisa Wuttke and coworkers
U.S. Bureau of Reclamation
Boise, ID

Grant Salter
Weber Basin Water Conservancy Dist.
Layton, UT

Eric Millis
Utah Division of Water Resources
Salt Lake City, UT

Lyle Summers
Utah Division of Water Resources
Salt Lake City, UT

Dave Ovard and Tage Flint
Salt Lake County Water Conservancy Dist.
Salt Lake City, UT

John Lawson
U.S. Bureau of Reclamation
Mills, WY

Jade Henderson
State Engineer's Office
Cokeville, WY

Terry Gonsalez
U.S. Natural Resources Conservation Service
Cheyenne, WY

Evan Green
Wyoming Division of Water Planning
Cheyenne, WY

Mark Waage
Denver Water Department
Denver, CO

Steve Hansen
U.S. Bureau of Reclamation
Santa Fe, NM

Twelve individuals returned questionnaires, and the following is a summary of their responses. The questionnaire itself is reproduced verbatim in Appendix 4.1 at the end of this chapter.

Survey Results

Twelve of the 19 water managers contacted responded to the survey. This is, of course, a small sample of the many water managers in the Intermountain West, and their responses may or may not be representative of the views of the larger population. However, the respondents were reasonably representative of the groups sampled: six in federal bureaus and six in state or local agencies.

Population growth and climate variability were the operational stresses most frequently listed by the survey respondents. One individual stated that climate variability is "the whole story." Other stresses are water-quality issues, public perception of reservoir operations, and a general lack of understanding of hydrology by the public.

The survey respondents described impacts of climate variability at the time scales listed in the survey. Two successive questions asked about the importance and impact of (1) natural variability and (2) specific climate change at specific time-scales. The changes were based on either historical analyses or general-circulation model (GCM) predictions. The results of these two questions highlight the sensitivities of the system:

One-day extreme rainfall events have resulted in (1) high sediment loads in run-off forcing water-treatment-plant closures and (2) degradation of aquatic habitat. If the intensity of extreme 1-day rainfall events increased, (1) more flood-control space would be required in reservoirs which would reduce the probability of filling reservoirs and meeting demands; and (2) spillway standards might need to be modified. Additionally, if more of the annual rainfall came in the form of fewer, higher-intensity events, less water would be available due to reservoir spills and reduced infiltration.

Seasonal extreme high or low snowfall usually has minimal impact on areas with adequate storage, but does affect reservoir operations. Areas with low storage (Nevada, New Mexico) would be impacted most by changes in the magnitude of high or low snowfall. Greater snowfall would result in concerns for flooding and mud slides, while lower snowfall would reduce water supply for areas with low storage.

Extreme droughts observed in the past have lasted 2-4 years. This time scale is a typical planning horizon for managers, and the impact of such a drought is significant but not economically devastating. The impact of longer droughts, on the order of 25 years, would require greater planning, and even then might not avoid economic devastation. The impact would be exacerbated by population growth. However, irrigation water would likely be converted to municipal use at an accelerated rate to offset some of the consequences.

Extreme heat waves currently increase water demand and strain the delivery systems in urban areas. An increase in the length of heat waves would compound those problems, increase evaporative losses from reservoirs, and might require greater fluctuations in the reservoir releases to meet the extra demand. The greater fluctuations would be harmful to aquatic habitat in the stream channels.

Seasonality of spring run-off governs the operating rules for reservoirs and has impacts on the ecology of the river systems as well. Observed variations such as early snowmelt and early runoff due to rain-on-snow events have caused concern, but generally not a great deal of damage. Systematic changes in the timing of runoff could have the most significant impact of any change discussed here: (1) the operating rules for reservoirs would need to be modified and (2) the need for additional flood storage capacity would need to be balanced with other uses. There is now some evidence that spring runoff is occurring earlier in the year, as discussed in this chapter. However, there is much uncertainty regarding conditions that would be associated with such a change: (1) Would summer flows be lower? (2) Would the growing season be longer? (3) Would irrigators desire more storage? More information on these issues is needed.

Seven-day low flow is a commonly used parameter in water-quality regulations since temperature and oxygen demand increase during extended periods of low flow. Some agencies must make up for flow deficiencies through expensive purchases of water rights. More frequent low-flow events would increase such costs and result in habitat losses in river systems with little storage.

Opinions of the survey respondents were elicited to gauge how receptive they would be to attributing changes or perceived changes in climate variability to increases in atmospheric CO_2 concentrations. Their opinions are also valuable in identifying how responsive they would be to climate-change assessments. Only two of the survey respondents indicated that they have observed a significant change in climate which they would attribute to human influence. One other respondent noted an increase in climate variability, but would not venture attribution. Others deferred judgment to the experts, but noted that they currently deal with a large amount of variability and that projected climate change in the next 10 to 25 years is not likely to affect their operations.

Conclusions

The inadequate involvement of water managers in climate-change assessments noted by Schilling and Stakhiv (1998) may be due to the fact that climate-change scenarios are typically presented in terms of percent change in mean annual precipitation or temperature. Water managers who routinely deal with variability that is an order of magnitude greater than any such change see little reason for concern over such seemingly insignificant changes. Efforts should be made to present climate-change scenarios at decades-long time scales like those discussed here.

The results of the survey indicate that (1) understanding and predictability of climate variations at the seasonal-to-interannual time scale are of great importance to managers under current conditions and (2) climate-change scenarios need to be stated in terms of how existing regional climate variability may be altered. The latter may not be possible with present modelling capabilities. Statistical analyses of selected attributes of GCM output in conjunction with historical data may be useful. Increased understanding and predictability of seasonal-to-interannual climate variations would (1) improve current management of water resources, (2) increase water managers' capability and willingness to use climate information in their routine operations, and (3) provide the background necessary to sensibly discuss climate-change scenarios.

PROCEEDINGS OF WATER-MANAGERS WORKSHOP

Introduction

Following return of the water-managers' questionnaires, a workshop of water specialists was convened to discuss results of the questionnaires and their policy implications. Invitees included six questionnaire respondents, and a number of individuals knowledgeable on broader water policy, economics, and legal issues. The meeting was convened at the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA on February 22-24, 1999. Those present were:

Briane Adams
Water Resources Division
U.S. Geological Survey
Norcross, GA

Connely Baldwin
Utah Water Research Laboratory
Utah State University
Logan, UT

Donald Glaser
Engineering Planning Consultants
Loveland, CO

Jade Henderson
Wyoming State Engineer's Office
Cokeville, WY

Todd Hinkley
U.S. Geological Survey
Denver, CO

Brian Hurd
Stratus Consulting Incorporated
Boulder, CO

Upmanu Lall
Utah Water Research Laboratory
Utah State University, Logan, UT

Larry J. MacDonnell
Lawrence J. MacDonnell, P.C.
Boulder, CO

John Redlinger
U.S. Bureau of Reclamation
Boulder City, NV

Jeanne Ruefer
Nevada Division of Water Planning
Carson City, NV

Grant Salter
Weber Basin Water Conservancy District
Layton, UT

Susan Selby
Las Vegas Valley Water District
Las Vegas, NV

Thomas J. Stohlgren
U.S. Geological Survey
Colorado State University
Fort Collins, CO

Mark Waage
Denver Water Department
Denver, CO

Frederic H. Wagner
Ecology Center
Utah State University
Logan, UT

Rick Wells
U.S. Bureau of Reclamation
Boise, ID

Robert Wilkinson, Coordinator
California Regional Climate-change Assessment
University of California
Santa Barbara, CA

Abstracts of the workshop presentations, and a longer treatise on western water law, are presented in Appendix 4.2 at the end of this chapter. A brief resumé of the key points made in the presentations follows.

Summary of Key Points Made in the Workshop—Upmanu Lall, Susan Selby, Tom Stohlgren, and Fred Wagner

Operational Issues

Water managers in the West function within a complex of stresses on their operations:

(1) Extreme climate variability. Stream flows may vary by a factor of 10 between wet and dry years. Understanding and predicting short-term (seasonal-to-interannual) fluctuations are of greater concern than long-term trends. Extreme events are more important than long-term averages. Consequently, considerations of climate-change effects several decades in the future "are not on the radar screen." Water management is a process of managing with uncertainty.

(2) Increasing demand associated with population growth, a burgeoning economy, and changing land use. In some areas this involves rapid subdivision growth. For Upper Colorado basin managers, the concern is with more rapid growth and faster rising demand in the Lower Basin. Demand is also increasing for environmental and esthetic values.

(3) Widespread lack of public understanding about hydrology, flooding, reservoir operations, and in the case of landowners, environmental concerns and proper land use. Resulting complaints and pressures complicate the managers' operations. It is always stressful to shut off water from junior rights holders in dry years.

The participants considered several aspects of climate change. If spring run-off were advanced due to early snowmelt, it would reduce streamflows during a longer growing season. If precipitation changed from snow to rain, the effects on water management cannot be predicted at this time. If precipitation increased substantially, there would be a need for more storage, but current public antipathy to dams would make that an unlikely solution. There would be a critical need for flood-plain management. Most early homesteading and population growth in the West was near water and along streams. Increased precipitation would increase demand to dike and build levees around riparian zones. There is an urgent need to meter and monitor water use more effectively, something that is not done in a number of western areas.

Policy Issues

Aridity and scarcity are the foundation of western water law. All management responsibilities are carried out in the context of operating with scarcity. Western water laws were enacted by the states, and their administrative agencies were formed, between the 1870s and early 1900s. The basic principle underlying all of them is the principle of prior appropriation: Water is dispensed each year in the order in which the rights were allocated historically. Those whose rights were first granted historically have first priority on water allocation, and have the right to the full extent of their allocation before water is released to those with more junior rights. If water in a given year is totally allocated to senior-rights holders, junior holders will not receive any of the resource.

Most western rivers are fully appropriated and allocated. Aquatic ecosystems are in decline and far removed from the "natural state." Groundwater is currently being mined, and its use is nonsustainable.

According to western water law, allocated water is to be used fully for "beneficial use." This is a historical term dating back to a period when western culture was largely rural, and the term has tended to imply agricultural use. If water rights are not fully used, they can be lost ("use it or lose it"). Because of the "beneficial use" tradition, excess capacity often cannot be used for nonagricultural purposes. Thus the use-it-or-lose-it principle tends to promote water wastage.

A number of 20th-century events are intensifying pressures on western water resources and pressing for changes in water law. The West is undergoing rapid population growth and demographic changes, and is predicted to be the most populous and urbanized region in the U.S. by 2025 (Table 4.5). These changes are likely to increase the demand to shift water away from agriculture.

During the 1960s and 1970s, new national environmental laws (e.g. NEPA, Clean Water Act, Endangered Species Act) were superimposed upon existing state water laws and administrative structures. Establishment of Indian reservations and national reservations such as national parks and forests has been judged to imply sufficient water resources for their operations, and they are consequently senior in the chronological rights hierarchy. Native American rights are belatedly being quantified and adjudicated. Environmental values tend to be at the bottom of the hierarchy, although most western states have minimum in-stream-flow rules.

Table 4.5

Population Projections for Rocky Mountain/Great Basin States (Terleckyj 1999)

State	1997	2025	2050	% Annual Increase
Colorado	3,892,640	6,211,00	8,253,000	1.43
Idaho	1,210,230	1,775,000	2,282,000	1.20
Montana	878,810	1,127,000	1,343,000	0.80
Nevada	1,676,810	2,924,000	3,998,000	1.65
New Mexico	1,729,750	2,620,000	3,425,000	1.30
Oregon	3,243,490	4,506,000	5,623,000	1.04
Utah	2,059,150	3,481,000	4,787,000	1.60
Wyoming	479,740	419,000	754,000	0.86
Totals	15,170,620	23,062,680	30,467,000	1.24
U.S.	267,636,060	341,255,000	409,425,000	0.81

Source: NPA Data Services, Inc.

Most legal changes affecting water law have come at the federal level. Pressures on state laws have prompted the states to pay greater attention to proper use; unused rights; and increased efficiency, improved technology, and administrative procedures. Institutional changes are likely to be a combination of two models: Top-down governmental regulations to set standards and criteria, and local decision making at the watershed level.

Pricing structures are also likely to be involved in changing allocations. Municipal water costs in the West range from $200-400 per acre-foot (AF), while agricultural costs range from $10-20/AF. Impacts of climate change on water uses are likely to be mitigated by market exchanges between low- and high-valued uses. Reducing agricultural subsidies is likely to promote conservation: "The best way to conserve water is to raise the price."

Other needed changes are to broaden the concept of "beneficial use" and the "use-it-or-lose-it" philosophy. In general, water managers already deal with climate variability. Climate change may need to be dealt with in a policy framework. Managers ask rhetorically whether it will present a large enough problem soon enough to warrant their consideration, especially in view of the other rapid changes underway and current pressures on their operations.

POTENTIAL CLIMATE-CHANGE EFFECTS AND COPING STRATEGIES

The Contemporary Scene

Any climate-change effects on the RMGB region's water resources and the people who use them will occur in the contemporary social and economic context of water use, and changes in that context in the decades ahead. Hence any consideration of potential effects must begin with a review of the contemporary scene and trends underway that are independent of any climate change.

As a general truism, RMGB streams are fully appropriated and allocated. There are some localized exceptions. In the less populous Upper Colorado River Basin in Wyoming, eastern Utah, and western Colorado (Fig. 4.6), the river's appropriations may not be fully used. But use in the more populous Lower Basin (i.e. Arizona and southern California) exceeds appropriation. So in total, the river is fully utilized.

Demands for the region's water now exceed the supply. In below-average water years, junior-rights-holders' needs are not met, and many suffer economic losses. Moreover, the demands are increasing. The fast-growing urban populations of the eight western states in which the RMGB is largely situated are predicted to double by the year 2050 (Table 4.5). If per capita water use remains the same, an uncertain assumption, urban/industrial demand will double by the middle of the 21st century. Only a third of Native American reservation rights have been quantified and adjudicated so far. And there are growing demands to address environmental and recreational in-stream values.

Obviously the available resource cannot accommodate all of these demands, and some changes in the status quo are already occurring. With agriculture absorbing ~80% of water use in the region, it is the major source for diversion to other uses. That diversion is occurring. Ruefer commented in the Water-managers Workshop that irrigated acreage in Nevada is declining. N.E. Stauffer, Chief of Hydrology and Computer Application for the Utah Division of Water Resources, comments similarly for irrigated land in Utah. Atencio (2000) describes the efforts of Santa Fe County, NM to acquire 588 acre-feet of water rights, owned by a farming operation (Top of the World Farms) near the Colorado border, that would be carried south by the Rio Grande to the burgeoning population of the Santa Fe area.

How far such changes will go is, of course, difficult to predict. If urban/industrial use doubles by 2050, the additional amount would constitute a reduction of one fourth (20% of the current 80%) in the contemporary agriculture usage. Additional allocation for Native American reservation rights, and for in-stream environmental and recreational values may well reduce agricultural allocations further. Clearly substantial adjustments will occur, probably including engineering changes to facilitate the changing allocations.

Potential Climate-change Effects

The 20th-century climate and streamflow evidence for most of the RMGB region, and the GCM projections for the 21st all point to increases in precipitation, temperature, and water resources in the coming century. The southeastern portion of the region appears not to have experienced such increases during the 1900s, but does not show any evidence of decreases. Thus, while any changes may be possible, the most plausible 21st-century scenarios fall in a span ranging from no change in climate and associated water resources up through a range of precipitation and temperature increases capped by the GCM projections, and with equivalent increases in water resources. It is possible that changes occurring in the northwestern and southeastern portions of the region would be extremes along a northwest-southeast continuum.

In addition, analyses of the 20th-century precipitation and streamflows show that as the means have increased, the variability has also increased with rising probabilities of what are now considered extreme events, and conceivably new extremes above what has been experienced in the historic era. Consequently, the scenarios address both rising means and increasing variability of precipitation and water resources.

Scenario 1: Regional Increase in Precipitation and Temperature

Scenario 1 is based in part on the observed 5-20% increase in precipitation and the 12-33% increases in streamflow over most of the RMGB region during the 20th century.

It is based further on the hypothesis that this increase is greenhouse-gas induced; and on the projection that atmospheric CO_2 concentration will double in the 21st century as a result of a CO_2 increase that will be six times the increase of the 1900s. On these bases, Scenario 1 is posed as: 21st-century precipitation, and associated water resources, will increase 50-100% over the mean levels at the end of the 20th century. The increases of the 1900s achieved a significant fraction of the lower part of this range, and the range encompasses most of the HadCM2 projected, annual precipitation increase (54-119%), and roughly two-thirds of the CGCM1 increase (59-184%) projected in Table 3.8.

Also posed as part of Scenario 1, mean, annual temperatures will rise in the 21st century by 2.0°-3.5°C (3.6°-6.3°F) above mean temperatures of the last years of the 1900s. The upper value in this range is the projected increase of HadCM2, and the range appears plausible in light of the 0.2°-2.0°C (0.36°-3.6°F) increases of the 20th century.

Since these projections fall in the lower range of GCM outputs, Scenario 1 may be conservative. The selection of a conservative range has no real basis in logic or evidence other than the uncertainties surrounding the GCMs.

As a first approximation, 50-100% increases in precipitation could produce an equivalent increase in water resources by the end of the 21st century, and ease or eliminate competition for

Table 4.6

Hypothetical Water Availability to Major Water Users Assuming 21st Century 50-100% Increase in the Water Resource

Hypothetical Resource Amounts and Uses	21st-century Increase[1] 50%	100%
Year 2000 RMGB Resource	100maf	100maf
Year 2100 RMGB Resource[2]	150maf	200maf
Year 2100 Urban/Industrial Use[3]	-40maf	-40maf
Unchanged 2000 Agricultural Use[3]	-80maf	-80maf
Year 2100 Evapotranspiration[4]	-20maf	-20maf
Remainder Above 2000 Resource	10 maf	60maf

[1]Units are in million acre feet (maf).
[2]Based on 50-150% increase over 2000 resource.
[3]Based on 80:20% agriculture:urban/industrial use in 2000, and 2X increase in the 2000 population by year 2100.
[4]Based on Nash and Gleick (1993) projection that a 4°C temperature increase would require 15-20% increase in the 2000 precipitation to maintain 2000-level Colorado River streamflow.

the resource discussed in the preceding sections of this chapter. Since urban/industrial use at present is a relatively small fraction (ca. 20%) of total use, a 50-100% increase in water resources could readily accommodate a doubling largely-urban population, allocate as much water to agriculture as is presently the case, accommodate other growing demands such as in-stream values and Native American rights, sustain increased evapotranspiration loss, and, depending on the level of increase, leave an increased amount for downstream users outside the region. Some purely hypothetical but proportionate numbers illustrate the point (Table 4.6).

This is of course overgeneralized. It makes no allowance for possible 21st-century adjustments in the year 2000-pattern such as conservation. Agricultural use may continue to decline for socio-economic reasons even if shortages ease. Table 4.6 may also include an overly generous allowance for evapotranspiration. Thus if anything, the speculation on the new margins after deduction for all uses could be conservative.

Moreover, the changes, if they occur, are likely to be expressed in altered seasonality of streamflow. These, and the detailed effects on human use, cannot be projected at present and there is an urgent need for modeling efforts to explore, hypothetically, the range of possible behaviors of the region's hydrology. Until such efforts are undertaken, some hydrologic implications, again hypothetical, can only be speculated upon.

As discussed previously in this chapter, numerous authors are projecting that temperature increases alone will change stream hydrographs, and there is evidence that it is occurring. As rain changes to montane snow later in fall and early winter, it will increase fall and winter streamflow above current levels with water that now builds snowpacks. Earlier springs will change snow to rain earlier than is now the case, and further reduce the amount of precipitation currently building snowpacks. Warmer temperatures are also likely to raise the lower snow line above current elevations, further reducing the magnitude of the snow cover. The net effects of temperature increases <u>alone</u> are projected to reduce snowpacks, smooth out seasonal hydrographs with increased fall and winter flows, reduce spring peaks, and prolong late-spring-summer-early-fall low flows. An associated result would be reduced water quality during the warm-season, low-flow period.

However, a 50-100% increase in precipitation could strongly elevate the levels of these altered seasonal flows, even if they remained in the same relative ratios to each other under the altered hydrographs. Despite a snowpack season shortened at both the fall and spring ends, and reduced at lower elevations, greatly increased winter precipitation could produce a greater volume of snow at the higher elevations. This could be an even stronger possibility if GCM outputs (Table 3.8) are correct in projecting by far the greatest precipitation increases during the winters.

This scenario raises the distinct prospect of increased flooding frequency. Floods tend most often to occur in the RMGB region under two sets of circumstances. Over most of the region they tend to occur in springs following exceptionally high winter snowfalls and snowpacks; and most often when these conditions are followed by early, warm springs especially if accompanied by heavy, warm rainfall. An above-average snowpack, its spring melt telescoped into a short period by warm temperatures, overloads stream channels geomorphically structured to carry the normal range of variation in flow and timing. Water overflows out onto the floodplain.

Since, as commented above, most homesteading and population growth in the West have occurred near water, many urban areas are at risk. In the spring of 1984, water flowed down sandbagged, downtown State Street of Salt Lake City following a record winter snowfall and overflow of City Creek flowing out of the Wasatch Mountains. In 1997, the Truckee River, which flows out of the Sierra Nevada Mountains through the city of Reno, overflowed its banks following a high-precip winter, and flooded the downtown area.

Flooding also occurs in the southern portion of the RMGB in late summer during the monsoon season. Convective rainstorms are sudden, intense, and localized. In July 1999, 3 in (7.6 cm) of rain fell in Las Vegas in 2 hours —that is three-quarters of the locale's mean, annual precipitation. The city experienced severe flooding.

It is doubtful that western streams could carry run-off events that would significantly exceed the current extremes without widespread damage. The water managers emphasized that they now contend with major year-to-year variability, Rick Wells commenting that streamflows vary between wet and dry years by a factor of 10. Mark Waage stated that variability in water resources is now so high that it would be difficult to detect alterations due to climate change.

But this implicitly draws inappropriate parallels between contemporary variability and change in future probability distributions as mean precipitation levels increase. The precipitation and streamflow analyses in this study have shown that, as the annual means have increased, the standard deviations around those means have also increased. Thus the probability distributions of annual flows both widen and shift to higher ranges with rising means. As a result the number of years with flow levels now producing floods would increase, as would the magnitudes of the flooding extremes on the right-hand tails of the probability curves. As Miller (1997) appropriately comments:

> It may, therefore, be helpful to think of global warming as gradually shifting the mean, variance, and shape of probability distributions of annual, seasonal, or daily streamflow. The actual sequence of streamflows over the coming decades will be random draws from these gradually shifting probability distributions …. Any projected change in mean flow implies a shift of the entire probability distribution.

The question also arises as to whether the western engineering infrastructure could control the region's hydrology—both in terms of reservoir capacity and dam stability—if the precipitation increases of Scenario 1 were to occur. The Teton Dam blew out on June 5, 1976 and eliminated three small Idaho towns. With sufficient warning the towns had been evacuated, but 11 people lost their lives nevertheless (Reisner 1987). The collapse was substantially the result of faulty engineering, but it was preceded by an above-average snowfall winter and accelerated spring run-off.

In June 1983, again following an above-average snowpack and warm spring rain, there was a distinct risk that Glen Canyon Dam on the Colorado would blow out (Behan 2001). For a 3-day period, maximum-capacity spillway releases could not prevent rise of already over-capacity Lake Powell. The dam was vibrating and losing massive blocks of concrete. Had the dam broken out and released an explosive torrent from the second largest reservoir on the Colorado, it would have unleashed a domino effect of all eight dams down the river, and driven by the growing flood augmented by release of each reservoir.

Utah's Wasatch Front, including Salt Lake City, along the base of the Wasatch Mountains where the majority of the state's urban development has occurred, could face a significant flooding risk from the Great Salt Lake. The level of the lake is determined by the balance between its input sources—66% from tributary streams, 31% from precipitation on its surface, 3% from groundwater—and loss from evaporation. The lake reached a postsettlement high point of 4,212 ft (1,284 m) above sea level in 1873. From that point, the lake receded, with some year-to-year variation, to a low point of 4,193 ft (1,278 m) in 1963 due to progressively increasing irrigation withdrawals from tributary streams and annual precipitation levels generally below the 20th-century average.

By the 1960s, irrigation withdrawals had largely stabilized and variations in the lake level have since been primarily correlated with annual precipitation. Between 1963 and 1986, precipitation averaged 10% above the 20th-century average, exceeding it in 19 of 23 years. In 2 years, 1982-83 and 1983-84 when precip exceeded the norm by 31 and 35%, the lake rose 9 ft. By spring 1987, the lake level had risen to 4,212 ft, similar to the previous, historic maximum. Had it not been for the irrigation withdrawals, the 1987 lake level would have far exceeded the previous, historic high point. However, 1987 ushered in a 4-year drought and the lake level receded. Since, precipitation of the 1990s and early 2000s returned to normal or below, and the lake level has resumed its approximate long-term average around 4,200 ft (1,280 m).

The lake's rise in the 1980s caused substantial economic loss. By 1987 the lake was edging against the western limits of Salt Lake City. It threatened to overflow the northern, western, and southern Interstate Highway accesses, and the beds of the latter two had to be raised. The lake level was only 1 ft below the 4,213-ft (1,284 m) elevation of Salt Lake International Airport, a short distance southeast of the lake. The city verged on isolation from several directions. An economic analysis by the Office of Energy and Resource Planning in the Utah Department of Natural Resources (Anon. 1999) placed the Capital/Operation and Maintenance Expenditures sustained by private, state, and federal institutions in the high-water year (1987) at $282,883,000.

If these changes occurred over a 23-year period in which annual precipitation averaged 10% above normal at the Salt Lake City weather station, it is obvious that the consequences of a 50-100% increase as postulated in Scenario 1 could seriously impact the entire Wasatch Front. Again, perhaps to overemphasize the point, all of this is hypothetical. But it has a basis in the science of the issue, and in early empirical evidence that the changes could be starting.

Finally, one additional variant of Scenario 1 needs mention. In a separate modeling effort with the Canadian Coupled Model, Fyfe and Flato (1999) project zero snowpacks in the northern Rockies by approximately 2070. As Mearns comments in Chapter 3, the Canadian model projects the most extreme temperature changes. However, if these authors' forecasts turn out to be correct, the climate changes will generate rather different water scenarios than the one sketched above. The uncertainties surrounding the differences between the Hadley and Canadian model projections emphasize further the importance of in-depth investigation of the question, as discussed below.

Scenario 2: Same as Scenario 1, But No Precip Increase in Southeast RMGB

Scenario 2 poses the same changes for the northwestern three-fourths of the region as Scenario 1 poses for the entire region. The potential socio-economic impacts would be expected to be the same, again for that portion of RMGB.

But the fact that the historical climate and streamflow analyses have been equivocal on any changes during the 20th century in the southeastern fourth of the region (SR, ECR, and perhaps WCR subregions) argues for leaving open the possibility that precipitation in this portion might not increase, or conceivably could decrease. Temperature increase is retained as part of Scenario 2 which would likely increase evapotranspiration. The net effect would be xerification of this portion of the region including reduction in water resources. The socio-economic effects, and coping needs, for this southeastern fourth would be the same as those to be discussed next under Scenario 3. As a result the RMGB would experience two patterns of impacts rather than one, and would need to employ two different sets of coping strategies.

Scenario 3: Increased Temperature, Same Or Less Precipitation For Region

Prior to this assessment, much of the early, speculative writing on climate-change impacts in the arid West assumed a xerifying effect, probably because the region is already arid to semi-arid, and any temperature increases would intensify the aridity. Some models of changing vegetation distribution project northward movement of the southwestern U.S. hot deserts into what is now the less severe Great Basin desert or shrub steppe (Neilson 1999). With the historical climate analysis of Chapter 3 now showing precipitation increase during the 1900s, and the GCMs projecting significant increase during the 21st century, Scenario 3 is accorded lower probability than Scenarios 1 and 2 as discussed above. But because uncertainties remain about the latter, it is appropriate to engage in some hypothetical consideration of the consequences of Scenario 3, especially in connection with water resources.

As commented several times in this chapter, the region's water resources are fully allocated under the current precipitation levels. Demands for the resource now exceed availability, and will increase substantially in the decades ahead. With a growing population, and no change in precipitation, those demands will grow over time and intensify pressures and needs for adjustment. If elevated temperatures increased evapotranspiration, and/or if precipitation were to decline, these pressures would be significantly exacerbated and major adjustments would be even more inevitable.

Coping Strategies

Obviously, which coping strategies become relevant will depend on which scenario becomes a reality. Scenario 3 and that portion of 2 addressing the southeastern quarter of the RMGB region portend no change or even decrease in water resources. A set of strategies focused on conservation, more efficient use, and exchanges between rights holders would become important. Scenario 1 and that portion of 2 addressing the northwestern three-quarters of the region project large increases in precipitation, the prospect of flooding in many areas, and consequently the need for flood planning, abatement, and control.

But these major changes in Scenarios 1 and 2 are projected for the latter part of the 21st century, and the early decades of the century are still likely to experience water shortage, at least on a per capita basis, given the surging population growth of the region (Table 4.5). The result could be the paradox of needing to conserve water in the first half of the century, and controlling floods in the second half.

Miller (1997) comments appropriately:

> Some would argue that the impacts of climate change are so far in the future that they pale in significance relative to more pressing concerns. However, the risk should not be ignored. In large part, climate change provides further reason to take actions that will improve resilience to the droughts and floods that arise from ongoing climate variability. However, climate change adds new twists to the uncertainties facing water users, water managers, and those who value preservation of environmental resources …. It is not too early to begin thinking about how to improve our capacity to manage those uncertainties and to respond efficiently and fairly to a range of possible streamflow changes, as well as to the effects of ongoing climatic variability.

The subject of water management is obviously a huge one, and cannot be discussed at any length here. But a few points relevant to the RMGB region bear mention, first regarding conservation, improved efficiency, and allocation to a growing and changing population; and secondly, what steps would be appropriate at this point to address the uncertain prospects of future flooding problems.

Coping strategies for Scenario 3, and Scenario 2 for the southeastern portion of the region, address the basic problem of adjusting increasing water demand to the current resource level, or possible decline. As discussed above, agriculture is the major (80%) water user in the RMGB, and its water is looked upon by water managers as the major source for accommodating the newer demands. As a first approximation, we suggested above that a two-fold increase in the RMGB population, and continuation of today's per capita use, would increase municipal/industrial water demand on the order of one-fourth of the current agriculture usage. A number of economic, institutional, and conservation measures could both facilitate this exchange and conceivably reduce its magnitude.

As several of the participants in the Water-managers Workshop commented, market forces can effect exchanges in willing-seller/willing-buyer situations. Brian Hurd pointed out that municipal/industrial water rights are priced an order of magnitude higher than rates paid by agriculture. With farmers operating on slim profit margins, there are clear economic incentives for them to sell their rights to urban/industrial users at the latter's price scale. In some cases, state water laws might need to be modified to facilitate the exchanges, particularly traditional concepts of beneficial use.

But some exchanges will not take place without social costs. The proposed sale, mentioned above, of agricultural water rights by a farming operation (Top of the World) in the San Luis Valley of northern New Mexico to Santa Fe county violates a long-standing policy against transferring water rights from the upper Rio Grande basin to the middle basin (Atencio 2000). The neighboring San Luis Valley farmers, who do not wish to sell, fear that the proposed sale would be a first step in the eventual transfer of the Valley's entire water resources and an end to their way of life. Transfer of the Top of the World Farms' rights would only accommodate Santa Fe's growth for 5 years.

A proposed dam on the Bear River in northern Utah would divert water, now supporting migratory bird habitat in the national Bear River Migratory Bird Refuge situated on the river's path to the Great Salt Lake, to the population centers along the state's Wasatch Front (Israelson 2000, Moulton 2000). The resulting reservoir would inundate farmland and displace families, to their obvious consternation.

A number of conservation measures could reduce the needed magnitude of these exchanges to some degree unless there is a major reduction in the resource. Within the agriculture sector, two strategies would reduce its water use. One is conversion to more efficient irrigation techniques. A related second would be conversion to crops which require less water. At present, hay is the dominant crop category in the RMGB portion of seven of the eight primary states in the region, and is second in the eighth state (Idaho). Hay crops require large amounts of irrigation water, and their replacement by more water-efficient crops could significantly reduce agricultural water demand, both by reducing acreage used for forage crops, and hastening conversion to more efficient irrigation methodologies that would serve the newer crops. Some of these changes are already occurring in California.

Certain institutional changes would likely facilitate greater water-use efficiency in the agriculture sector. One is fair-market pricing of agricultural water. As Grant Salter commented in the Water-managers Workshop "The best way to conserve water is to raise the price." The highly subsidized, low rates paid by agriculture, which Brian Hurd cites, do not provide incentives for water-use efficiency. A further institutional disincentive is the use-it-or-lose-it doctrine in some state water laws.

The urban/industrial sector can also employ a number of conservation measures. Some are the newer, water-efficient plumbing technologies, but a major potential lies in the patterns of water use in the region. Per capita use of "culinary" (i.e. potable) water in the region is one- third higher than the national average, and in some states (e.g. Nevada and Utah) is nearly twice as high, according to U.S. Geological Survey data:

1990 U.S. Per Capita Culinary Water Use (Anon. 1997) in Gallons per Day

Nevada	-	344
Utah	-	308
Wyoming	-	260
Mtn. States	-	243
Montana	-	226
New Mexico	-	226
Colorado	-	213
Idaho	-	201
U.S. Average	-	184

Some 60-70% of this use is for lawns and gardens (Norman Staufer, Pers. Comm.), and provides a considerable leeway for conservation through alternative landscaping practices.

Metropolitan Denver was pressed by water shortage in 1990. But by instituting conservation measures that included recycling sewage water, it was able to accommodate a 10% population increase by 1999 without any additional water (Marston 2000).

In total, there appear to be a number of actions that could facilitate conservation and reduce the magnitude of needed water-rights transfers from agriculture to urban/industrial and other uses. How much transfer would be needed depends, of course, on whether and what climate change occurs. If precipitation remains the same or declines, transfer will undoubtedly be needed to accommodate a two-fold population increase. As commented above, even if the precipitation increases of Scenarios 1 and 2 occur, some adjustment will probably still be needed in the early decades of the 21st century.

If the major precipitation increases projected by the GCMs (Table 3.8) and expressed in Scenarios 1 and 2 begin to eventuate by mid 21st century, the needed coping strategies will obviously be flood control through engineering measures. One need will be greater hydrologic storage, something water managers now report to be inadequate. Whether or not the contemporary antipathy to dams and reservoirs will continue in 40-50 years remains to be seen. But a partial solution would be the growing practice of underground aquifer storage. Las Vegas today has the largest aquifer recharge program, via deep-well injection, in the world.

Riparian corridors and flood plains would be at risk. As commented above, much of the early settlement in the arid West occurred in these sites because of the presence of water. As Rick Wells commented in the Water-managers Workshop, development is continuing in them because they are esthetically attractive. It is not too early for municipalities to engage in some contingency planning on possible ways of limiting, zoning, or discouraging by whatever means, further development in these potentially high-risk zones if climate developments in the near future indicate that the scenarios are materializing.

However, given the hypothetical nature of the GCM projections and scenarios, we do not at this time advocate any extensive engineering efforts. But we do recommend three, extensive, prescient actions that would provide necessary background information relevant to any policy actions needed in the future if Scenario 1 or 2 became reality. The first is a concerted hydrologic modeling effort that used a number of climatological scenarios to simulate hydrologic responses in terms of magnitude and seasonality of streamflow. There is a substantial literature on this subject (e.g. Nathan and Bowles 1997, Wilby et al. 1999, Sankarasubramanian et al. 2001), but it should be done systematically for the streams in the RMGB region. The information should be systematically reproduced and widely distributed.

A second effort should be systematic appraisal of reservoirs and dams in the region to evaluate their abilities to accommodate the run-off scenarios developed in the above modeling efforts. There has been an extensive effort to assess dam safety in the West in recent years (cf. Swain et al. 1998), but it needs to be done systematically for all of the RMGB dams. Any potential deficiencies and appropriate remedial actions need to be noted and the information again systematically recorded and widely distributed.

Finally, in view of the potential consequences of climate change, not only for the water-limited West but also the downstream users of major rivers that originate in but flow beyond the RMGB region, there is a critical need for an effective water-resources monitoring program. This would include:

(1) More high-elevation weather stations and snow courses throughout the West.

(2) Long-term hydrologic and water-quality monitoring on streams of all sizes and at all elevations. This is contrary to the U.S. Geological Survey trend of getting out of the stream-monitoring effort the agency has had underway for many years.

(3) Comprehensive monitoring of groundwater levels and quality.

(4) Water-quality monitoring, especially at low flows.

(5) Status of wetlands, riparian zones, and springs.

Information from such programs would provide valuable input for modeling efforts, and, by providing empirical evidence of scenario reality within 2-3 decades, would equip policy makers with early information needed for decision making.

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APPENDIX 4.1

WATER RESOURCES IMPACTS OF REGIONAL CLIMATE-CHANGE AND VARIABILITY SURVEY

Connely Baldwin and Upmanu Lall

This survey is an integral and important part of the Rocky Mountain/Great Basin Regional Climate-Change Assessment. It is one of 20 regional assessments that form a major part of the National Assessment due for submission to Congress on 1 January 2000. Due to the importance of water resources in our region, we have turned to you for your help in assessing the current stresses and potential impacts of climate variability and change on the water sector. We recognize that you deal with climate variability every day in your work with the water-resource system, and have the responsibility to assess the potential impact of change in variability that could profoundly affect the water-resource system. Thus, we have undertaken this survey to elicit your views and opinions. Please respond to as much of the survey as possible. Feel free to add additional comments.

1. What are your key water-management responsibilities?
2. What are your major tasks in carrying out those responsibilities? For example:

   Responsibility: Managing reservoir releases for irrigation water.

   Task: Set operating policy on a daily/weekly basis.

Responsibility: Maintaining adequate water quality in the stream.

Task: Monitoring, regulation and permitting on a semi-annual basis.

3. What are the major stresses and problems you face in carrying out your responsibilities? For example:

   Population growth and increasing demand.

   Climate variability and change.

   Changing demand between users (e.g., urban v. agriculture).

4. How significantly does climate variability impact your operations?

   a. Is there a recent climatic event or series of years that had a significant impact on your operation (example, the 1982-83 El Niño and subsequent wet period)?
   b. What actions did you (or your agency) take to capitalize on, or remediate, the effects?
   c. What would you do differently if a similar event recurred?
   d. Do you have any estimates of the dollar value of the impact (either positive or negative)?

5. For each item you listed in 4, how would climate variability at each of the following time scales affect that item?
   a. 1-day extreme rainfall.
   b. Seasonal extreme high or low snowfall.
   c. Length of multi-year severe wet period or drought.
   d. Length of extreme cold period or heat-wave (days to weeks).
   e. Change in seasonality (timing) of precipitation.
   f. Change in seasonality of runoff.
   g. 7-day low flow.

6. Climate varies at all of the time scales noted above without any human influence. The potential influence of increased atmospheric carbon dioxide may exacerbate or reduce climate variability. Recent research has indicated some past and potential changes in climate on the time scales noted in Question 5 that can be used to gauge the ability of the current water-resources system to adapt to climate change. A corresponding scenario for each of these items is noted below. (1) How you would respond to these scenarios operationally in your area of responsibility? (2) What would have to happen institutionally to allow operational coping strategies to be effective? (3) How would these scenarios change the way you do business with others? (4) Would planning and design issues be affected in a different manner? (5) Note that while many of these same concepts are used in planning and design, the magnitude of variation suggested here may exceed any historical or anticipated event.

   a. 1-day extreme rainfall – Karl and Knight (1998) note that over the past century some areas of the country have experienced an increase in the amount of rainfall received from the most extreme rainfall events in each month of the year. How would an increase in the intensity of the most extreme rainfall event in each month of the year affect your operation?
   b. Seasonal high snowfall – Consider the recurrence of the wet years of the early-to-mid 1980s. General circulation models indicate that El Niño events may recur more frequently, which has been linked to high seasonal snowfall in some areas of the region (Baldwin, 1998).
   c. Length of multi-year severe drought – Consider a 25-year drought. Woodhouse and Overpeck (1999) found that two historical continental-scale droughts lasted for 20 and 25 years covering a greater area than the drought of the 1930s.
   d. Length of extreme heat waves (days to weeks) – Consider an increase in the length of heat waves. IPCC (1998) indicates that for a given rise in temperature, the number of very-hot days will increase significantly.
   e. Change in seasonality of runoff – Consider an advance in the timing of peak spring runoff by 1 to 2 months. Recent unpublished reports by Strzepek (1998) and Lall (1998) indicate that a

change of this magnitude is plausible and may be occurring.

f. 7-day low-flow – The combination of higher evapotranspiration with earlier spring runoff considered in item e, may result in lower summer flow. Consider a longer period of low summer flow. Nash and Gleick (1993) found that inflow to Lake Powell could decrease a significant amount on an annual basis.

7. Your general views and opinions of climate-change are important for the regional assessment, since water resources are the linchpin for our regional assessment.

a. Do you believe that increased levels of carbon dioxide and other greenhouse gases have affected climate during this century?

b. Do you believe that there will be sufficiently strong climate changes in the future induced by rise in the greenhouse gases, that will create problems for your operations 10-25 years from now which override the problems associated with current levels of climate variability?

c. If so, what do you believe will be the most important change in climate?

d. If you responded no to Item b, what leads you to believe as you do? Is it because of concerns regarding the models and the science? Is it because your operation has not been demonstrably changed?

e. If you think climate will change but will not affect your operations, why? Is it because of the resilience of your system or invulnerability to climate change?

8. Are you willing to participate in a case study that would help us further the assessment? For example, do you have any models of your operation that you would be willing to run using climate-change scenario input? Are there any existing analyses or data you would be willing to contribute? We have a limited amount of time in which to complete the assessment, but would like to do some quantitative analysis so your help in this area would be greatly appreciated.

Thank you for completing this survey.

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APPENDIX 4.2

ABSTRACTS OF PRESENTATIONS AT WATER-MANAGERS WORKSHOP

Questionnaire Respondents

Mark Waage

Denver is located in a rainshadow at the foot of the Rocky Mountains' east slope. Some 75% of the Colorado population resides east of the Continental Divide while a similar percentage of the state's water is west of the divide.

The Denver Water Department delivers water to a million customers, half from the Platte River and half from the west slope via three large, underground aqueducts. Most of the water comes from snowmelt. The Department is in charge of the water-collecting system, and long-range planning. The current plan includes consideration for pricing, conservation, reuse, hydropower, fishing, whitewater recreation, endangered-species issues, and wild and scenic rivers.

Major operational stresses are population growth, especially in the suburbs, and extreme year-to-year-variability in the resource. The system is not capable of handling high flows although it has enough storage to cope with 1 year of short flow. However, in a dry year, if users do not have water rights that date back to 1873, they will no longer have water by mid summer. The system can stretch out the resource through 3 dry years, but at the end of that period, the reservoirs are empty. In the current environmental and political climate, it is not possible to develop new storage (i.e. reservoirs). The Department now attempts to ride out droughts without instituting restrictions.

Implications of a shorter snowpack period:

(1) If precipitation comes as rainfall, cannot predict effect.

(2) Early run-off would mean reduced stream flows during a longer growing season. This would throw the water-rights system "out of whack."

Variability of the water resource is now so high that it would be difficult to detect changes due to climate change. Climate change is simply not at present on their planning radar screen. Consequently it would be difficult to make institutional changes for climate change at present.

Jade Henderson

The Bear, Snake, and Green River basins are in this region. His responsibilities are:

(1) Regulate scarcity between prior rights and inter-state compacts.

(2) Adjudicate new uses.

(3) Mediate disputes.

(4) Monitor dam safety including reservoir inspections.

Aridity and seasonality are the foundation of western water law. All of his responsibilities are carried out in the context of "operating with scarcity."

Major stresses on his operations are:

(1) Shutting off users in dry years.

(2) Rapid subdivision growth in his region, and more rapid growth in downstream states (e.g. the lower Colorado for which the Green in his region is a headwater).

(3) Increasing pressures from endangered-species issues and adjudication of Native American water rights.

(4) A burgeoning economy that is increasing water demand.

What would ease pressures:

(1) More storage, but this (more dams and reservoirs) is not politically possible at present.

(2) Better public education about flooding.

Preoccupation with current stresses, especially year-to-year variability of the resources, has prevented much consideration of the implications of global warming.

Don Glaser comment: Native American uses preceded state seniority rights. The federal government usurped Indian rights, and are now resurrecting these and assigning them to the states to resolve.

Grant Salter

The Weber Basin Water Conservancy District, a Bureau of Reclamation project, manages the allocation for two river systems in northern Utah. The system has a 2-year carry-over to tide over a 1-year drought.

Major stresses include maximizing upstream carry-over for flood control, and urban population growth which changes the demands for water. In the 1940s, 90% of jobs in the West were associated with agriculture. Today it is 2%. The Conservancy District will be out of water by 2015 at present rate of population growth and no reduction in other demands.

Needed changes:

(1) The Conservancy needs to stop allocating water to the city of Provo, and let the latter get its water from the Jordanelle dam.

(2) The state needs to provide more education to land owners on environmental concerns and proper land use.

(3) The best way to conserve water is to raise the price.

Don Glaser comment re institutional changes: The idea of beneficial use is a historic term in western water law. In the early years of establishing water rights, most allocations were single-use (irrigation) projects. Consequently excess capacity often cannot be used for nonagricultural uses. These stipulations need to be changed to accommodate shifting demands. Institutional parameters surrounding flood-plain management also need change.

Rick Wells

He is responsible for long-range planning and daily operations of five reservoirs in two river basins involving the Boise, Payette, and Upper Snake Rivers. They are managed primarily for irrigation and flood control with secondary purposes including power production, river and reservoir recreation, and fish and wildlife purposes including endangered salmon. Competition for water is growing, not so much for consumptive use, but for environmental and esthetic values including whitewater recreation, bald eagles in riparian cottonwoods, and salmon.

His major tasks are scheduling reservoir releases and maintaining targeted streamflow rates in various river reaches. This involves scheduling releases from multiple reservoirs to meet multiple objectives and minimize conflicts as much as possible.

The principal stresses result from public complaints regarding reservoir operations. The policies guiding operations are fairly clear, but many people do not approve of them, feeling that they benefit other interest groups. There is a widespread lack of knowledge in the general public regarding hydrology, the variability of weather and its impact on operations, and the constraints and limitations of the reservoir systems.

Climate variability is the whole story. Variation in streamflow between wet and dry years is ~10x. Wet years bring complaints from non-irrigation interests charging that they are too conservative in making early reservoir releases and that they favor irrigation interests. Potential economic loss from flooding is increasing each year as a result of development in the flood plains. In recent years many expensive homes have been built near the Boise River because of the esthetic values of the river and riparian corridor.

Seasonal high snowfall brings the threat of flooding. A change in the seasonality of precipitation could cause trouble. The reservoir operating curves are statistically based, and the more atypical the precipitation and run-off distribution the more likely the risk of flooding or failure to fill the reservoir system.

It is unlikely that any climate changes within the next 10-25 years would override the problems that occur with existing climate variability.

John Redlinger

The Bureau of Reclamation in the Boulder City office is in essence the water master for the lower Colorado River, administering it according to the Law of the River. The Colorado is the most regulated and legislated river in the U.S.

The system has storage capacity of 60 million acre feet (maf), four times the average, annual flow (15maf). Lake Powell is a large upper sponge while Lake Mead is a lower. There is no significant amount of storage below Parker Dam.

Until 1992, there was sufficient water for demands. But the demand has increased, and it is now an overallocated system. California is using 5.2 maf although it is allocated only 4.4. By 2020, population growth in the lower basin will cause frequent shortage for Arizona.

The major concern is long-term droughts, not daily or monthly variations.

Jeanne Ruefer

Mean precipitation of Nevada is 9 in, of which 10% runs off to streams and 90% is lost to evapotranspiration (ET): 8-10″ ET in southern Nevada, 2-3″ in the north. In the state, 77% of water use goes to agriculture. Agricultural use is declining, but state demand is rising because of population growth.

Major stresses are:

(1) Unpredictability.

(2) Limited storage capacity.

(3) Population growth and associated increase in demand.

(4) Public suspicion of government agencies.

(5) Shortage of funding for data collection.

(6) Tribal claims.

Implications of climate change:

(1) If precipitation were to increase, there would be less need for drought planning and more for flood planning.

(2) A 25-year drought would mean the end of agriculture in Nevada, serious impact on tourism, and consequent severe impact on the state economy. It would be necessary to establish an office of water conservation.

(3) An altered run-off season would require basic reconsideration of the Nevada water-use pattern. Water rights are currently keyed to the irrigation season.

(4) If the climate changes, we won't know it until it's over.

Policy Issues

Briane Adams

Briane Adams chairs the national water assessment, one of the five sectoral assessments that cut across the 19 regional assessments. At the national level, concerns for the effects of climate change on water resources are much the same as the concerns for the RMGB region: flooding; droughts; snowpack; groundwater; lake, river, and reservoir levels; and water quality. They are considered in the context of such other stresses as land-use change, consumption of resources, fire, and air and water pollution. A general sense has emerged that American society across the nation as a whole would likely be able to adapt to most of the impacts of climate change on human systems but the particular strategies and costs are not known.

Donald Glaser

Don Glaser was Executive Director of the Western Water Policy Review Advisory Commission from September 1996 – April 1998. The Commission was impaneled in 1992.

In the West, water is defined by the Bureau of Reclamation and its 100-year-old law. Western water laws were enacted by the states, and their administrative agencies were formed, between the 1870s and early 1900s. In the 1960s-1970s, new, national environmental laws (e.g. NEPA, Clean Water Act, Endangered Species Act) were laid on top of the existing water laws and administrative structures.

Most western rivers are fully appropriated and allocated. Groundwater is being overdrafted in most of the West. Aquatic ecosystems are in decline and are far removed from their "natural state." Large Indian-reserve rights, not previously quantified, are now being adjudicated on already overappropriated water.

The West is now experiencing the most rapid demographic change ever. In the coming decades, California and Utah will have the highest birth rates. California will have a continuing inflow of people from Latin America and Asia, and will continue to export people to the entire western area. The High Plains states will continue to lose people to the West. By 2025, the West will be the most populous and urbanized region of the country with 8-10 major urban centers. Rural areas are diversifying faster than urban with a net decline in traditional western culture and lifestyles.

Traditionally, precipitation has been a defining feature of the West. But equally important has been government ownership. The federal government developed the water supply. It has also retained ownership of the upland, forested, and mountain areas. Homesteading was attractive only where there was water, and consequently riparian zones are largely on private lands. This has forced landuse and economic development into riparian zones. Land-management practices now define riparian zones.

Climate change is likely to increase pressure to dike and build levees around riparian zones. Increasing development in the riparian zones will reduce effectiveness of watersheds.

Institutional changes are likely to follow two models. One is top-down governmental regulation that sets standards and criteria. The other is local decision making at the watershed level. The West is likely to function with a combination of both. The West has had good success in solving point-pollution problems. But there are increasing problems in solving nonpoint-source discharges (e.g. feed lots).

Upmanu Lall and Connely Baldwin

The North American Water Quality Assessment of the U.S. Geological Survey established a nationally consistent description of water quality, identifies long-term trends in water quality, and identifies major factors affecting condition and trends. It monitors the status of the Snake River and streams in the Great Salt Lake watershed. Geological sources affecting water-quality are important to document, but difficult to control.

Variations in flow affect water quality. At low flows, water temperatures increase, algal blooms develop, and nutrients become more concentrated, all reducing water quality. High flows can improve water quality but create engineering problems. Examples of flow variations affecting water quality:

(1) The Weber Basin treatment plant was forced to shut down due to heavy sedimentation associated with high flows.

(2) High temperatures in the Middle Snake River stimulated vegetative growth and lowered dissolved oxygen levels.

(3) The nitrate concentrations of Griffin Springs vary with climatic conditions (wet vs. dry).

Weather conditions affect streams at different time scales:

(1) One-day extreme precipitation creates sediment problems.

(2) Seasonality of flow and 7-day low flows affect life cycles of aquatic organisms.

(3) Multi-year droughts have serious effects on aquatic habitats and water temperatures.

Larry MacDonnell

[Editorial note: Dr. MacDonnell was Executive Director of the Western Water Policy Review Advisory Commission prior to Donald Glaser's directorship. He is a former faculty member of the University of Colorado School of Law. His written statement for the water-managers' workshop was so well prepared, and western water law is such an important context for assessing climate-change effects and considering coping strategies, that we have chosen to reproduce that statement verbatim.]

OVERVIEW OF WESTERN WATER LAW

Larry MacDonnell

Basic Tenets of Western Water Law

Water law provides the rules governing human intervention in the hydrologic cycle. It is concerned primarily with allocation of the resource for human use, but it increasingly includes rules or guidance regarding the manner of intervention to reduce harmful effects on other values provided by water in the cycle.

Allocation of the resource for human use in the American West is governed by appropriation or physical capture of the resource and its application to a beneficial use. The legal right (regarded as a property right) is to divert and use some portion of water in accordance with the priority of the right. Those first to have appropriated and used water are senior to those who later appropriate water. Seniors are entitled to satisfy the full extent of their beneficial use before juniors, if the supply of water is limited. Water rights may be lost by non-use. Certain attributes of a water right, such as the point of diversion or the purpose or place of use, may be changed without loss of priority so long as no injury to other water rights results.

Allocation of groundwater use is governed by a variety of regimes, including prior appropriation, reasonable use, overlying landownership and special management areas.

[Insert from oral presentation: In a 1963 opinion (Arizona vs. California), the U.S. Supreme Court decreed the Reserve-rights Doctrine stating that the establishment of reservations by the federal government implied access to water by the reservations. This applies not only to Indian reservations but other reservations of land such as national parks and forests. Quantification of tribal rights is currently underway, with approximately one-third now completed. These rights are being adjudicated on already over-appropriated water resources.] Water necessary to fulfill the primary purposes for which federal reservations of land have been established is reserved from appropriation under state law as of the date the reservation is established. Reserved rights may be quantified in state stream-adjudication proceedings.

All western states except New Mexico now have rules by which some portion of water in a source may be left instream for protection of fisheries or other purposes.

Comparison among States in the RMGB Region

All study states follow the prior appropriation doctrine for allocation to human use of water resources. Colorado and Montana use courts to decree the existence of water rights, created by actions of the appropriator. The other RMGB states require application to a state engineer or equivalent administrative body for a permit to appropriate. Reviews include consideration of the public interest.

All study states recognize to varying degrees the hydrologic linkage between surface water and tributary groundwater and attempt to allocate and administer water rights accordingly.

Colorado, New Mexico, Nevada, and Utah generally support voluntary transfers of water rights on a willing-seller/willing-buyer basis and allow changes of use (subject to the no-injury requirement). Idaho allows temporary transfers through state-sanctioned water banks. Oregon and Wyoming allow changes of use but do not favor transfers outside the original place of use. Montana allows temporary leasing of water rights for new uses.

Colorado, Idaho, Oregon, and Utah allow state-agency appropriations of water for instream-flow use. Montana reserves water from appropriation for a period of time. Nevada allows instream-flow appropriations, probably by riparian landowners.

Pressures for Change in Western Water Law

Because of growing awareness of the finite supply of water, states are paying increased attention to administration of water rights (ensuring that users hold valid rights; that appropriators divert in priority; that diversions and use are in accordance with their right; that they have a reasonably efficient means of diversion; that abandoned or unused water rights are extinguished). This is not reflective of changes in law but in the matter in which existing law is being enforced. As scrutiny of the manner in which appropriators use water increases, as the cost of using water increases, as technologies for using water improve, and as financial assistance for making water-use improvements becomes available, users are becoming more efficient. Pressures on the resource also are driving efforts to improve and change system management of water, more efficiently utilizing storage capacity, for example, or altering patterns of storage and release.

There appears to be an increasing amount of litigation and/or negotiation between states regarding conflicts over uses of shared streams. Improved administrative mechanisms for better managing interstate and international streams are likely to develop. Finally, enormous amounts of time and money are gong to adjudicate water rights in several western states (Idaho, Washington, Arizona, New Mexico) to clarify priorities and uses. Such processes are cumbersome and leave many critical issues unresolved, suggesting the need for change.

Increasing use of groundwater is motivating some changes in state groundwater laws, primarily to accommodate adverse impacts on surface water users but also to reduce conflicts between groundwater users. Additional change in this area to allow better management of groundwater seems likely.

Growing interest in water transfers has prompted some changes in state law (California, for example). Additional changes to facilitate transfers in a manner consistent with protection of “third party” interests also seem likely.

Some tribal reserved rights have now been quantified through litigation or stream adjudications. Negotiated settlements have gained favor as a means of quantifying tribal water rights in recent years. Nevertheless, many tribal rights remain unquantified. Moreover, uncertainty exists regarding whether tribal rights can be transferred for use off-reservation.

Recognition of instream values of water since the 1960s has prompted virtually all western states to create some legal mechanism(s) by which such flows can be given legal protection.

These first-generation programs likely will evolve over time to allow protection of instream flows for more benefits (beyond, for example, just protection of fisheries) and to allow more interests to play an active role in protection of such flows. The public trust doctrine, particularly as expressed in California, represents a significant change in the prior-appropriation law. To date, no other state has extended this doctrine to existing rights and uses.

Virtually all of the important legal changes affecting the use of western water resources have come from the federal level. Thus the Clean Water Act regulates discharges of pollutants from point sources into streams. The National Environmental Policy Act requires careful evaluation of the adverse environmental effects of all major federal actions (including those relating to development and use of water resources and stream corridors) and consideration of alternatives. Federal Energy Regulatory Commission relicensing of hydroelectric power facilities now requires equal consideration of fish and wildlife values along with economic values. Federal agencies must insure that their actions are not likely to further jeopardize the continued existence of a protected species of plants or animals under the Endangered Species Act. Individuals are prohibited from a "take" of protected species, including harm caused by alteration of the essential habitat.

Implications for Western Water Law of Climate-induced Changes in Water Availability

The priority system will automatically distribute changes in water availability among appropriators according to their seniority. If changes adversely affect appropriators, they bear the burden of responding. At present the water-rights system favors stability over flexibility. Pressures to make it easier to transfer water rights, for example, may grow as more junior appropriators with high-economic-value uses find it necessary to secure their supply by acquiring another user's more senior priority right. Pressures also may grow to place measurement requirements and efficiency standards on existing users to spread the available resource to more users. Certainly there will be continuing efforts to more fully and carefully define the extent and nature of existing appropriations, and their use will be even more actively administered.

State instream-flow protection programs effectively have very junior priority claims to water. If climate changes result in lowered flows, senior out-of-stream diverters will have priority. To maintain streamflows, some senior out-of-stream diversions will have to be purchased and retired or diversions will have to be reduced through some means. Conceivably, interest in asserting the public trust doctrine as a way of protecting public values could grow.

The issues already noted regarding stream adjudications and interstate and international disputes could be exacerbated by climate-induced alterations in water availability.

Accommodation of federally mandated protection of environmental values such as endangered aquatic species with state-authorized water uses could become even more difficult. The extent of the constitutionally protected property right in a water right may very well become the subject of litigation.

The prior-appropriation doctrine is well equipped to handle changes in water resources, whether increase or decrease.

Natural-environmental values are most vulnerable. They tend to get "what's left over."

Brian Hurd

The impacts of climate change on consumptive users of water resources are likely to be mitigated by market exchanges between low- and high-valued uses. For example municipal water costs in the West are commonly in the range of $200-400 per acre foot (AF). Agricultural water charges are commonly in the range of $10-20/AF. Water for senior rights is commonly higher valued than junior rights.

Western water basins appear to be more sensitive to climate change than eastern ones. If precipitation and water resources decline, nonconsumptive uses are likely to exceed consumptive uses, percentage-wise.

Chapter 5

CULTIVATED AGRICULTURE AND RANCHING

Frederic H. Wagner and Connely Baldwin

CULTIVATED AGRICULTURE

Introduction

Although intensive in portions of northern Utah, southern Idaho, and in eastern Oregon, cultivated agriculture is not a major form of land use or contributor to the economy of the Rocky Mountain/Great Basin region (RMGB) as a whole. Less than 10% of the region is in farms (Fig. 5.1a), and the percentage in cultivation of those portions of the eight states that make up most of the RMGB region ranges from 1% in Nevada and New Mexico to 10% in Montana, and is 5% for the entire region.

Four crops—hay, potatoes, wheat, and barley in that order of importance—produce 88% of crop income in the region, according to U.S. Department of Agriculture statistics. Hay is by far the most important in every state, making up 41% of the region's total crop value, except in Idaho where it is exceeded by potatoes. Potatoes are second at 22%, largely because of the extensive production in Idaho which contributes roughly 27% of national potato value. Wheat, significant in every state, is third with 17% of the region's crop value. Barley at 8% is fourth.

While typically low in nitrogen and organic matter, arid-land soils are generally mineral rich, especially with phosphorus, and can be productive if given water. But the prevalence of rugged topography, extensive areas of highly saline soils, and aridity are inimical to very much crop production in the region. Between a third and half of the cultivated crops are irrigated (Fig 5.1b), relying on water resources that are already overallocated and under growing demand. Dryland crops are producing at the limits of their moisture tolerances over much of the region. And growing seasons are relatively short, by national standards, owing to the generally high elevations (>3,000 ft or 915 m) and associated low temperatures.

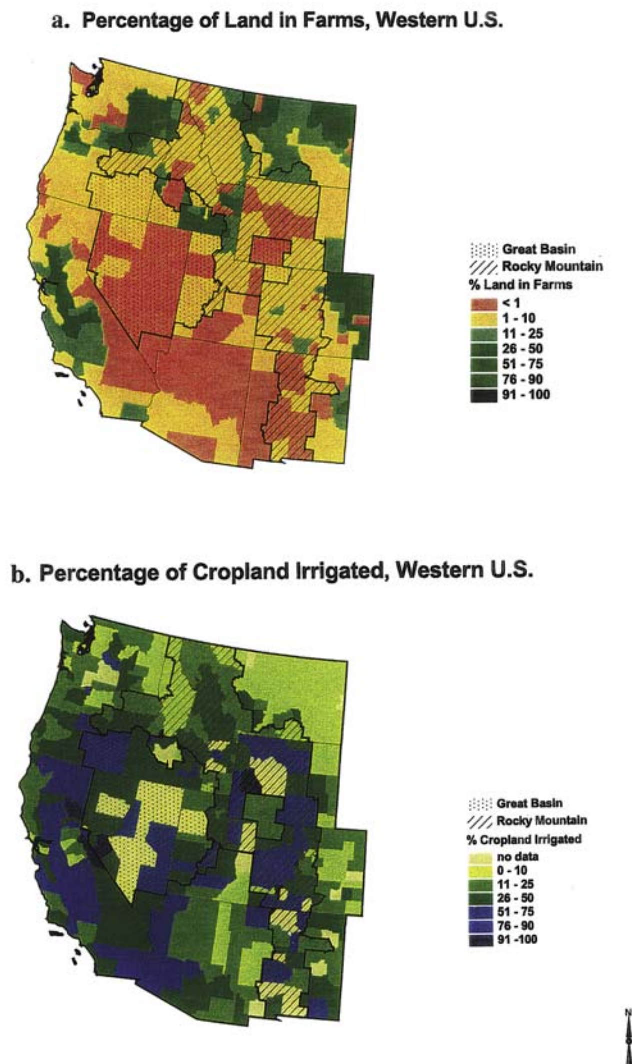

Figure 5.1. Percentage of land area in farms (a) and of cropland irrigated (b) in the western U.S. and in the Rocky Mountain/Great Basin region. From U.S.D.A. National Agricultural Statistics Service.

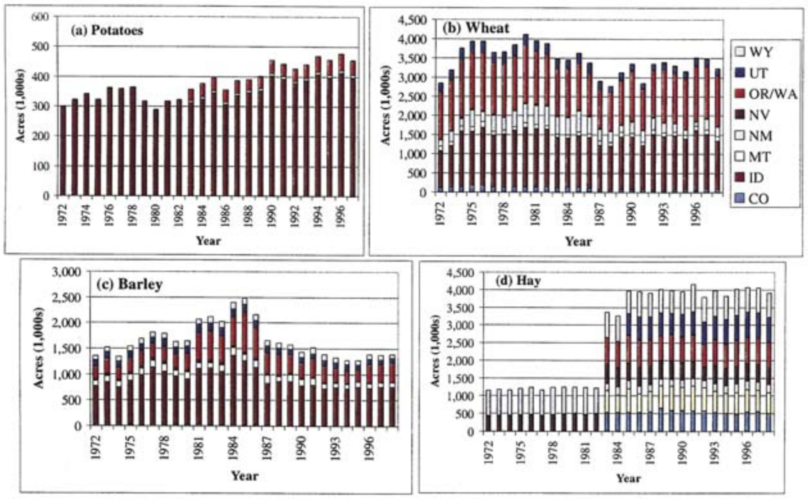

Figure 5.2. Annual acreages of potatoes, wheat, barley, and hay harvested from 1972-1998 in nine states with portions of their areas in the Rocky Mountain/Great Basin region. Data were not available for all states in all years.

Thus, RMGB agriculture is sensitively poised within the region's physical environment to be affected by any climate change. We have therefore explored in some depth the potential effects of different climate-change scenarios, focusing on the four crops that produce nearly 90% of the region's commodity value.

Scenario-based Projections

Sampling Units and Data Sources

Where the spatial sampling units in the analyses of Chapters 3 and 4 were the VEMAP quadrangles and their aggregates in the eight subregions, the crop-reporting districts (CRDs) of the U.S.D.A. National Agricultural Statistics Service are the data source on crop yields analyzed here. Each state is subdivided into CRDs, and annual crop yields and climatic data are reported on the Internet (cf. http: //www.nass.usda gov:81/iped, USDA-NASS Crop County Data). The 20th-century, annual climate statistics and crop-yield data for the four crops in each of the region's CRDs that reported harvesting 1,000 acres (404.9 ha) or more of the crops were tabulated. The one exception was an Idaho CRD that reported only 0.4 acre (0.16 ha) of potatoes. Data series varied in length up to 27 years (1972-1998). Only series 13 years and longer were used.

The yields of both winter and spring varieties of wheat and barley were aggregated in order to assess the combined effects on them. However, most of the wheat grown in the region is winter wheat, while most of the barley is produced by spring varieties (Anon. 1997). Grain yields are reported as bushels per acre, hay as tons per acre, and potatoes as hundred-weight per acre.

Data meeting the above criteria were available as follows:

wheat, 23 CRDs in nine states

barley, 23 CRDs in nine states

hay, 16 CRDs in seven states

potatoes, 10 CRDs in five states

The 1972-1998 data for the 72 crop-CRDs constitute the analytic domain. Since two or more crops were reported in many of the CRDs, the actual number of different CRDs in the domain is 24 distributed among the nine states. These statistics were used to analyze existing trends in the region's agriculture; and they were used to quantify a model to be described below, that projects 21st-century production of the four crops on the basis of climate-change scenarios.

While per-acre-yield statistics were reported for the entire 27-year sampling period, the data were not complete for acres of each crop harvested (Fig. 5.2) and total production for each year in the 24 CRDs. Hence the trends discussed below are based on shorter time series.

Scenario 1: No Climate Change

Agriculture in the RMGB region is changing under the influence of a number of factors. Any climate changes affecting farming will function in the context of, and their effects will be modified by, these factors. Hence it is necessary first to examine the nature of the changes.

Table 5.1 summarizes the changes in acres harvested, per-acre yield, and total production for the four crops in the years with consistent reporting in the 24 CRDs. Grain acreages declined significantly in the region during the 1980s and 1990s. Hay acreages remained essentially unchanged while potato acreage increased 23%. Since potato acreage is an order of magnitude below wheat acreage, and its increase does not compensate for the decline in wheat and barley, the total harvested acreage in the 24 CRDs declined 18% during the last two decades of the 20th century.

The decline has been due in part to the region's rapid population growth with its expansion of urban, industrial, recreational, and infrastructure development into farmland. Early European settlements developed where there was both water and arable land to support the new immigrants. As these settlements have grown into cities, they have expanded into croplands.

During the same period, the per-acre yield of the four crops increased, evidently due to genetically improved varieties, more effective machinery, and more efficient cultivation practices. These improvements partially offset the declining acreages, resulting in increased total production in wheat, hay, and potatoes. Total production declined only in barley for which acreage harvested declined 44%.

Under continued 20th-century climatic, economic, and land-use conditions, these trends would be likely to continue in the 21st. In the absence of stringent zoning restrictions, population increases as high as 100% by 2050 are likely to continue urban expansion into farming areas. Property values almost certainly will rise providing strong incentives for farmers to sell their land.

As discussed in Chapter 4, that same population increase is likely to double the demand for urban/industrial water at the expense of agricultural use and irrigated acreage. While there was no decline in acreage of the two primarily irrigated crops, hay and potatoes, during the years shown in Table 5.1, decline is almost certain in the 21st century as agricultural water rights are purchased and subsidized water prices give way to market forces. Thus, a complex of forces tending to reduce cultivated acreage during the 1900s would be likely to continue at even higher intensities in the 21st century if the climatic patterns of the 20th were to continue.

It is also reasonable to expect agricultural research, particularly in biotechnology, to continue increasing per-acre yields as occurred during the 1900s (Table 5.1). But the 20th-century increase in total production was largely offset economically by falling commodity prices, so that the agriculture industry in the region achieved little if any economic growth during the century. Similarly, significant growth in the 21st is problematic.

Moreover, agriculture's small fraction of the region's total economy declined during the 1900s as the urban/industrial economic sectors burgeoned. The number of individuals employed in services (e.g. legal, financial, health, telecommunications, education, software), construction, transportation, and government in the three-state counties surrounding Yellowstone National Park increased by approximately 129,000 between 1970 and 1994. Employment in logging, mining, and ranching increased by approximately 5,000 (Riebsame et al. 1997). On the Colorado Plateau, 12,115 new businesses in such sectors as services, retail trade, construction, financial services, and wholesale trade, developed between 1980 and 1994 while there were only 172 new agriculture-related businesses (Riebsame et al. 1997).

In sum, with continuation of 20th-century climate patterns in the 21st, RMGB agriculture would almost certainly continue to decline as a fraction of the region's total economy, and quite possibly in absolute terms.

Scenario 2: Increased Temperatures, No Precipitation Change

Rising temperatures without precipitation increases would be likely to exacerbate the above pressures. Evaporation off of streams, lakes, and reservoirs would increase and intensify competition for limited water resources. The national Agriculture Sector Assessment (McCarl 1999) concludes from its modeling efforts that warmer temperatures would lengthen growing seasons and, along with increased

Table 5.1
Percentage Change in Acres Harvested, Per-acre Yield, and Total Production of Wheat, Barley, Hay, and Potatoes During the Last Two Decades of the 1900s in 24 CRDs

		Percentage Change		
Crop	Years Reported	Acres Harvested	Per-Acre Yield	Total Production
Wheat	1980-1997	-25	+44	+26
Barley	1985-1997	-44	+36	-22
Hay	1985-1997	+5	+27	+33
Potatoes	1983-1997	+23	+26	+60

water-use efficiency from CO_2 enrichment, offset any negative effects from increased evapotranspiration. But this is based on model simulations using GCM inputs that include increased precipitation.

At the least, increasing competition for, and cost of, water would in all likelihood effect some decline in the irrigated crops, especially hay and potatoes among the four under consideration here. In addition, the national Agriculture Sector Assessment projects that the temperature increases posed by the GCMs would reduce potato yields because higher fall and winter temperatures would inhibit tuber formation (Melillo and Reilly 2000). The national assessment also projects increasing need for, and cost of, pesticide use: 5-15% for potatoes but mixed results for wheat (-15 to +15%).

In total, there is no basis for projecting increases in agriculture during the next century in a semi-arid, water-limited region if temperatures were to increase without accompanying increases in precipitation. The net effect would almost certainly be negative, although the magnitude of effect cannot be projected at present.

Scenario 3: GCM Projections of Temperature and Precipitation Increases

General approach. To explore the potential effects of the third climate-change scenario—the Hadley and Canadian GCM projections in Chapter 3, Table 3.8—on RMGB agriculture, we have developed a model to simulate crop yields at the end of the 21^{st} century, given the GCM inputs. We considered the use of mechanistic models that incorporate data on plant physiology, soils, and climate to project crop yields on the basis of climate variables. But we lacked the necessary data for the crops across the full extent of the region that would enable us to quantify the relevant functions.

We chose instead to use stepwise, multiple-regression tests using per-unit-area crop yields as the dependent variables. We quantified the functions with the CRD, 20^{th}-century climate and yield data, and eliminated certain climatic variables which the stepwise procedures showed were not significantly related to yields. We then used these models to project 21^{st}-century yields on the basis of the GCM climate-change projections discussed in Chapter 3.

This approach has several advantages. It is more direct and empirical than mechanistic models, and does not have the uncertainties surrounding the accuracy of the more numerous physiological functions. A second advantage of this approach is that the analyses of the 20^{th}-century data provide some indication of whether crop yields of the 1900s responded to the climatic trends shown in Chapter 3. And as a third advantage, this approach facilitated independent comparison with the results of the national Agriculture Sector Assessment (McCarl 1999) based on model simulations of crop yields.

One potential problem with the regression approach is whether the forms of the functions calculated from the historical data project into the range of the climate-change scenarios. We conducted several tests of the functions' linearity, and found them linear through the historic climate range. Hence we have assumed their continued linearity into the scenario range, but this remains a hypothesis with an unknown level of associated uncertainty. If there are any growth-limiting temperature thresholds—e.g. heat stress, vernalization of winter wheat, etc.—within the scenario range, these are not provided for in the models.

The model. We calculated 72 multiple-regression tests—one on each of the 72 crop-CRD combinations listed above. In each, 20^{th}-century per-acre crop yield in the CRD was the dependent variable, with independent variables to be described below. Each test then became a model with which we projected 21^{st}-century yields on the basis of climate-change scenarios, also to be described below.

We chose a stepwise, multiple linear-regression model that uses the Akaike Information Criterion (AIC) to determine which independent variables were significantly related to crop yield in each CRD during the years of the data series. AIC is defined as

$$AIC = 2\ 1(\theta) - 2\ k$$

where θ is the parameter vector, 1() is the likelihood function, and k is the number of parameters in θ. By fitting a separate model to each CRD, we were able to compare results between adjacent CRDs, determine whether the independent variables were consistent among them, and thus test the robustness of the model.

Independent variables. With the stepwise regression tests, we examined the following independent variables:

(1) Climate variables:

(a) Annual mean temperatures for each of the four seasons (winter, DJF; spring, MAM; summer, JJA; fall, SON).

(b) Annual precipitation for each of the four seasons. The years were subdivided into these four seasons to be compatible with the seasonal projections of the GMC scenarios shown in Table 3.8.

(c) Annual growing degree-days.

(d) Annual frost-free season length.

(e) Annual minimum temperatures.

Preliminary tests showed that using all five provided very little additional explanatory power over using just the first two (a and b), so we only used the latter.

(2) Changes in area harvested: As discussed above, and shown in Fig. 5.2, the area harvested for each crop changed over time. These trends may have resulted from changes in the quality of land used: e.g. expansion of urban development into prime farmland and/or cultivation extended into less favorable land. They may also involve changes in the crops planted on the same acreages. They occurred in each of the states, and widely among the CRDs.

For these reasons, it seemed desirable to make some provision in the tests for the changes in order to partition out the variance in yields associated with them. Consequently, we used the number of acres harvested each year in each CRD as an independent variable.

(3) Chronological trends in yields. As discussed above, the data clearly show rising per-acre yields in each of the four crops over the years of record. Ideally, this source of variance should be partitioned out to more clearly measure the variances associated with climatic variables. A number of authors have used a variety of detrending procedures for this purpose (cf. Thompson 1969, Waggoner 1983).

However, any such calculations for the RMGB data would also partition out any trends associated with 20th-century climate change. Moreover, there were no data on the form of the technological trends: whether linear, nonlinear, or stepwise. Consequently we chose not to detrend the yield time series, and used the uncorrected yield data.

(4) Several other variables likely associated with climate parameters, possibly in nonlinear ways, may affect crop yields. But we had no data on these for the CRDs, and could not encorporate them in our models. We mention them here to point out that they could produce some variance in the yield data and weaken any correlations. These are:

(a) Changes in seasonality and/or variability of precipitation and temperature.

(b) Nonlinear correlations between soil moisture and precipitation.

(c) Changes in timing or length of growing season.

(d) Variations in the severity of weed infestations, insects, and disease.

It seems likely that the first three, and possibly the fourth, covary with the climate parameters. They would therefore be subsumed, though perhaps imperfectly, in the climate correlations.

(5) Direct effects of CO_2 enrichment on stomatal closure, water-use efficiency, and growth of root systems. This effect would likely be linear as the CO_2 atmospheric content has increased during the 1900s. But as commented above, they cannot be separated from other factors that have produced yield increases during the period.

Methodology for 21st-century projections. In order to project potential crop yields for the end of the 21st century that would be forced by the climate patterns simulated by the GCMs, we used those patterns (cf. Table 3.8) as inputs into the models for each CRD structured with the 20th-century climate and yield data. Since the USDA-NASS yield and precipitation data are reported in English units, and the temperatures in degrees F, we converted the Table 3.8 data into English and Fahrenheit units. These are shown in Table 5.2.

Because of the highly empirical nature of our tests without provision for a number of climate-related variables that could affect yields, as discussed above, and the relatively small samples of years for some of the CRDs (e.g. 14-16) we chose a conservative comparison of 20th-century yields with those implied by the GCM values. Rather than compare the mean yields for the 1900s in each CRD with the yields projected by our models for the GCM climate scenarios, we calculated two standard errors on each side of the means (± 2 SE) and used these ranges as 20th-century bases for comparison.

We calculated yields hypothesized by the GCM scenarios in Table 5.2 with the regression equations. Since both GCMs projected a range of precipitation values (termed "Low Est." and "High Est." in Table 5.2), we calculated both "Low" and "High" yields for the 21st-century values which provided a range of yield values for each season and each CRD. We then compared the projected 21st-century Low-High range for a given CRD with its ± 2 SE range for the 20th century. Where the projected range was mostly higher than the 20th-century range, we concluded that yields of that crop in that CRD would increase if the 21st-century scenarios became reality. If the two ranges overlapped significantly, we concluded that modelled climate changes of the scenarios would not significantly change yield levels above those of the 20th century. If the projected range was below the 20th-century range, we concluded that projected 21st-century climate changes would reduce yields.

Results of the 20th-century tests. The 20th century regression results and 21st-century projections for the four crops in all CRDs reporting 1,000 acres or more of crops harvested are both summarized in Table 5.3. Each line of the table represents a CRD, and they are arrayed in descending order of acres harvested for each crop (Column 3).

Table 5.2

Mean Seasonal Changes in Temperature and Precipitation Projected by the HadCM2 and CGCM1 Models for the Period 2080-2100[1]

	Temperature (°F)		Precipitation (in/month)[2]			
			HadCM2		CGCM1	
Season	HadCM2	CGCM1	Low Est.	High Est.	Low Est.	High Est.
Winter	8.1	14.4	2.4	3.6	2.4	4.8
Spring	4.5	10.8-12.6	0.0	0.6	1.2	1.2
Summer	7.2	9.0	0.0	0.6	-0.9	0.6
Fall	6.3	10.8	0.6	1.8	0.6	3.6

[1]Metric and centigrade units of Table 3.8 have been converted to English and Fahrenheit units.
[2]Future precipitation was projected by the GCMs as ranges (Table 3.8). The low and high values of the ranges are shown here as "Low Est." and "High Est." although with units converted as described above.

The results of the regression tests of 20th-century yields and climatic variables are shown in the right-hand seven columns of Table 5.3. The far right column lists the coefficients of determination (R^2s) for the combined independent variables (predictors) that were significantly correlated with annual yields in the CRDs. The six columns to the left of the R^2 column list the climatic variables (predictors) that had significant partial correlations with

Table 5.3

Tabular Results of the Stepwise Regression Analysis of Climate Variable Effects on 20th-century Yields and of Projected 21st-century Yields Based on Global Circulation Model Scenarios

Key:

(1) Each line records results for a single U.S.D.A. Crop Reporting District (CRD) in a single state.

(2) Columns 11-16 record the independent variables or predictors (climate variables by season) that were significantly correlated with crop yields in the CRDs during the period 1972-1998. (mam=March, April, May; jja=June, July, August; etc.)

(3) Column 17 (R^2) records the coefficients of determination expressing the proportion of variance in crop yield associated with variance in predictors for each CRD.

(4) Columns 5 and 6 record ±2 standard errors (Low and High) around the mean yield for the years of record for each CRD. Units are: bushels per acre x 10 for wheat and barley, hundred weight per acre x 10 for potatoes, and tons per acre x 10 for hay.

(5) Columns 7-10 record the 21st-century yields projected by the regression model with inputs of the GCM climate-change projections in Table 5.2. # Low and High refer to the ranges of precipitation in Table 5.2. Units are the same as above in (4).

(6) Color codes denote 21st-century projected changes in each CRD based on comparison of GCM ranges with historical ranges: green represents increased yields based on minimal or no overlap between higher GCM ranges and historical; yellow represents significant overlap between GCM and historical ranges, thus no change; red represents GCM ranges below historical without significant overlap, with implied yield declines.

Barley

St.	CRD	Ac. Harv. (1,000)	POR Years	Hist. Range Low	Hist. Range High	HadCM2 Scen. Range Low	HadCM2 Scen. Range High	CGCMI Scen. Range Low	CGCMI Scen. Range High	Predictor Variables Chosen						R^2
ID	90	527	27	584	634	801	1590	1041	2189	pcp.djf	pcp.mam	pcp.jja	tmp.son	tmp.mam		0.70
WA	90	255	27	569	621	376	900	463	1193	pcp.son	pcp.mam	tmp.jja				0.74
ID	80	158	27	816	873	1070	1768	1347	2382	pcp.djf	pcp.mam	pcp.jja	tmp.son	tmp.djf	tmp.mam	0.80
ID	10	151	27	505	561	423	825	650	1224	pcp.mam	tmp.mam	tmp.jja				0.57
WY	10	81	27	774	850	774	1054	706	1185	pcp.mam	pcp.jja					0.21
MT	70	66	27	553	613	591	935	527	1204	pcp.jja	tmp.son	tmp.mam				0.46
OR	30	63	27	601	654	358	717	459	947	pcp.son	pcp.mam	tmp.mam	tmp.jja			0.54
UT	10	62	27	664	720	853	1439	1071	2160	acres.harvested	pcp.son	pcp.mam	tmp.son	tmp.mam		0.59
ID	70	60	27	811	868	890	1110	1062	1445	pcp.mam	tmp.mam					0.45
OR	80	59	27	686	769	771	1116	968	1597	acres.harvested	pcp.mam	tmp.mam				0.51
MT	10	51	27	568	614	624	947	646	1303	acres.harvested	pcp.son	pcp.mam	pcp.jja	tmp.mam		0.67
UT	50	47	27	757	825	1014	1956	1186	2635	pcp.djf	pcp.mam	pcp.jja	tmp.son	tmp.mam		0.56
WY	30	18	27	455	508	473	661	418	809	pcp.jja	tmp.mam					0.20
CO	70	13	27	777	844	964	1546	1151	1917	acres.harvested	pcp.mam	tmp.son	tmp.jja			0.63
NV	10	12	27	740	847	992	2266	1200	3707	acres.harvested	pcp.son	pcp.mam	tmp.son	tmp.mam		0.51
UT	70	10	27	759	808	831	1560	731	1726	acres.harvested	pcp.son	pcp.djf	pcp.mam	pcp.jja	tmp.jja	0.75
NM	30	8	18	569	642	578	2323	370	2887	pcp.djf	pcp.jja	tmp.djf	tmp.mam			0.61
UT	60	8	27	640	686	768	1243	815	1739	acres.harvested	pcp.son	tmp.son	tmp.djf			0.73
CO	10	6	27	307	340	41	339	0	440	acres.harvested	pcp.son	tmp.jja				0.56
NM	90	6	18	615	689	765	1402	791	1732	acres.harvested	pcp.son	tmp.jja				0.47
NV	30	3	22	622	716	724	2161	1090	3746	acres.harvested	pcp.son	pcp.mam	tmp.son	tmp.mam	tmp.jja	0.75
NV	80	1	22	564	673	715	938	877	1356	tmp.mam						0.48
WY	40	1	27	541	611	351	663	94	725	pcp.mam	tmp.djf	tmp.jja				0.36

Hay

St.	CRD	Ac. Harv. (1,000)	POR Years	Hist. Range Low	Hist. Range High	HadCM2 Scen. Range Low	HadCM2 Scen. Range High	CGCMI Scen. Range Low	CGCMI Scen. Range High	Predictor Variables Chosen							R^2
OR	80	519	16	266	288	258	454	297	534	pcp.djf	pcp.mam	tmp.son	tmp.djf				0.59
MT	70	333	16	238	260	238	296	249	339	acres.harvested	pcp.mam						0.62
CO	10	295	16	152	162	114	210	108	272	acres.harvested	pcp.son	tmp.son	tmp.jja				0.62
MT	10	284	16	243	300	132	285	0	293	acres.harvested	tmp.mam						0.82
WY	30	284	27	142	151	141	214	133	239	pcp.djf	pcp.mam	pcp.jja					0.39
CO	70	255	16	257	294	257	294	257	294	NONE							0.00
NV	30	238	27	168	188	195	312	232	438	pcp.mam	pcp.jja	tmp.mam					0.43
WY	40	234	27	135	149	140	264	125	377	acres.harvested	pcp.son	pcp.mam	pcp.jja				0.45
UT	10	219	14	321	334	259	313	242	309	acres.harvested	tmp.jja						0.66
NV	10	210	27	308	331	342	455	425	619	acres.harvested	pcp.mam	tmp.mam					0.57
WY	10	198	27	271	290	291	676	266	803	acres.harvested	pcp.djf	pcp.jja					0.34
UT	50	182	14	398	407	364	569	361	659	acres.harvested	pcp.son	pcp.djf	pcp.mam	tmp.jja			0.90
UT	60	139	14	315	325	248	347	243	406	acres.harvested	pcp.son	pcp.mam	tmp.jja				0.90
UT	70	113	14	403	406	459	575	502	716	acres.harvested	pcp.son	pcp.djf	pcp.mam	pcp.jja	tmp.son	tmp.mam	0.98
WA	90	42	14	383	406	186	355	0	307	pcp.mam	tmp.mam	tmp.jja					0.47
NV	80	35	27	350	369	370	411	391	478	acres.harvested	tmp.mam						0.63

Potatoes

St.	CRD	Ac. Harv. (1,000)	POR Years	Hist. Range Low	Hist. Range High	HadCM2 Scen. Range Low	HadCM2 Scen. Range High	CGCMI Scen. Range Low	CGCMI Scen. Range High	Predictor Variables Chosen							R^2
ID	90	232	26	256	266	319	481	338	621	acres.harvested	pcp.son	pcp.djf	tmp.mam				0.86
ID	80	92	26	326	344	426	718	535	1045	acres.harvested	pcp.son	pcp.djf	pcp.mam	pcp.jja	tmp.djf	tmp.mam	0.83
ID	70	26	26	356	386	407	519	499	704	pcp.mam	tmp.mam						0.47
OR	80	22	15	269	1020	2084	6098	3796	11795	acres.harvested	tmp.son	tmp.djf	tmp.mam				0.61
OR	30	14	15	299	1292	0	107	0	0	pcp.son							0.36
WA	90	9	15	548	573	555	665	591	669	acres.harvested	pcp.son	pcp.djf	pcp.jja				0.80
NM	30	5	15	279	307	279	307	279	307	NONE							0.00
MT	10	4	15	272	289	272	289	272	289	NONE							0.00
MT	70	4	15	297	310	315	396	356	472	acres.harvested	pcp.mam	tmp.mam	tmp.jja				0.88
ID	10	0.4	26	188	243	231	386	263	615	tmp.mam							0.22

Wheat

St.	CRD	Ac. Harv. (1,000)	POR Years	Hist. Range Low	Hist. Range High	HadCM2 Scen. Range Low	HadCM2 Scen. Range High	CGCMI Scen. Range Low	CGCMI Scen. Range High	Predictor Variables Chosen							R^2
WA	90	887	27	565	621	688	1126	951	1704	pcp.son	pcp.mam	tmp.djf	tmp.mam				0.62
ID	90	641	27	519	581	784	1739	1069	2464	pcp.djf	pcp.mam	pcp.jja	tmp.son	tmp.mam			0.67
ID	10	369	27	575	635	699	981	968	1457	pcp.mam	tmp.mam						0.53
OR	30	343	27	554	620	357	848	561	1228	pcp.mam	tmp.mam	tmp.jja					0.54
NM	30	313	27	219	254	255	843	255	1100	pcp.son	pcp.djf						0.34
ID	80	241	27	758	808	1018	1637	1193	2031	acres.harvested	pcp.son	pcp.djf	pcp.mam	pcp.jja	tmp.mam	tmp.jja	0.88
UT	10	134	27	371	408	489	788	524	1090	acres.harvested	pcp.jja	tmp.son	tmp.djf	tmp.mam			0.79
ID	70	98	27	778	854	908	1679	1224	2206	acres.harvested	pcp.mam	pcp.jja	tmp.mam	tmp.jja			0.69
OR	80	73	27	700	805	825	1920	1170	2643	acres.harvested	pcp.djf	pcp.mam	tmp.mam				0.59
MT	70	71	27	413	472	499	837	485	1149	pcp.jja	tmp.son	tmp.mam					0.47
CO	70	58	27	230	268	250	415	250	578	acres.harvested	pcp.son						0.48
CO	10	54	27	220	245	103	292	48	326	acres.harvested	pcp.jja	tmp.djf	tmp.jja				0.56
UT	50	47	27	335	375	349	602	349	814	acres.harvested	pcp.mam	pcp.jja	tmp.mam				0.70
MT	10	39	27	447	498	476	701	486	932	pcp.mam	pcp.jja	tmp.mam					0.45
UT	60	38	27	217	252	287	583	384	961	pcp.son	pcp.mam	tmp.mam					0.61
NV	10	17	27	692	765	772	1319	772	1514	acres.harvested	pcp.djf						0.43
NM	90	12	27	438	512	354	725	182	738	tmp.mam	tmp.jja						0.20
WY	40	5	26	214	245	22	214	0	234	acres.harvested	tmp.son	tmp.djf	tmp.jja				0.55
UT	70	4	27	425	465	326	723	206	801	acres.harvested	pcp.djf	pcp.mam	pcp.jja	tmp.son			0.72
WY	10	3	27	524	625	524	625	524	625	NONE							0.00
NV	30	3	21	528	618	528	618	528	618	acres.harvested							0.38
WY	30	2	26	249	358	670	1837	776	2491	pcp.djf	tmp.mam	tmp.jja					0.42
NV	80	1	21	540	605	602	740	661	957	acres.harvested	tmp.mam						0.40

Note: POR = Period of record; Ac. Harv. = Acres Harvested; CRD = Crop Reporting District

Key to Colors:
Range of Scenarios Above Historical Range
Range of Scenarios Surrounds Historical Range
Range of Scenarios Below Historical Range

the crop yield. The CRDs showing "NONE" in these columns had no significant correlations between the independent variables and crop yield.

As discussed above, the stepwise regression tests evaluated nine independent variables (precipitation and temperature in each of the four seasons, and acres harvested). Of the 72 crop-CRD tests, 68 showed significant correlations between crop yield and one or more of the independent variables. The latter are summarized in Table 5.4.

Table 5.4

Summary of Seasonal Climatic Variables (Predictors or Independent Variables) with Significant Partial Correlations with 20th-century Crop Yields[1]

Crop	Wheat	Barley	Hay	Potatoes	All Combined
#CRDs	23	23	16	10	72
Predictors and number of times appearing	tmp.mam 15	pcp.mam 16	acres 11	tmp.mam 6	tmp.mam 42
	acres 12	tmp.mam 15	pcp.mam 10	acres 5	pcp.mam 40
	pcp.mam 11	pcp.son 10	tmp.mam 6	pcp.son 4	acres 38
	pcp.jja 9	pcp.jja 10	pcp.jja 5	tmp.dif 3	pcp.jja 25
	tmp.jja 7	tmp.son 9	pcp.son 5	pcp.mam 3	pcp.son 24
	pcp.dif 7	acres 10	pcp.dif 6	pcp.jja 2	tmp.jja 22
	tmp.son 5	tmp.jja 9	tmp.jja 5	pcp.dif 2	pcp.dif 20
	tmp.dif 4	pcp.dif 5	tmp.son 3	tmp.jja 1	tmp.son 18
	pcp.son 5	tmp.dif 4	tmp.dif 1	tmp.son 1	tmp.dif 11

[1]Lower-case letters denote seasons: mam-March, April, May; jja=June, July, August, etc.

The number of significant variables among the CRDs varied between 1 and 7, with a median of 3, per CRD. Spring precipitation and temperature were the two most frequently significant variables, ranking in the top three for all crops except potatoes in which spring precipitation was replaced by fall precipitation (Table 5.4). The third most frequently correlated variable was acres harvested which ranked in the top three in all crops but barley. Summer variables were among the middle third of the frequency of relationships, while winter variables were least often correlated.

Four of the 72 tests showed no significance between 20th-century climate variables and crop yield. These include one CRD each in wheat and hay, and two in potatoes.

Results: 21st-century projections. The changes in yield of the four crops projected by the models using the GCM climate-change scenarios (Table 5.2) are shown in Columns 5-10 of Table 5.3. Columns 5-6 ("Hist. Range") report the ± 2 SE ranges around the 20th-century mean yields in each CRD. Columns 7-8 and 9-10 show the 21st-century Low-ppt.-High-ppt. ranges in yields projected by the regression models with inputs of the Hadley and Canadian GCM climate-change projections (Table 5.2), respectively. The CRD lines are color-coded so that light green indicates possible increase, yellow indicates possibly no change, and pink indicates possible reduction in 21st-century yield above/below 20th-century levels.

The trends represented by the color-codings are summarized in Table 5.5. These project increases in yield in more than half (58%) of the CRDs, 35% with no change, and 7% with yield declines. Percentagewise, the crop least affected would be hay, 63% of the 16 hay CRDs projecting no change or decrease in yield. Among the other three crops, 64% of the CRDs project yield increases.

That hay appears less responsive to climate change than other crops is probably explainable on several grounds. Most obviously, hay is largely irrigated in the RMGB and consequently less sensitive to variations in precipitation. Moreover, hay crops are biennial or perennial. In arid and semi-arid ecosystems, annual plants are typically more sensitive to annual variations in precipitation than are perennials (MacMahon and Wagner 1985). The other three crops are annuals.

Table 5.5

Summary of Trends in Yields in the CRDs by 2100 Projected by the Regression Model with Inputs of the GCM Scenarios (Table 5.2)

	No. CRDs and Trends in Yield by 2100		
Crop	Decrease	No Change	Increase
Potatoes	1	2	7
Hay	3	7	6
Barley	0	10	13
Wheat	1	6	16
Totals	5	25	42
Percentages	7%	35%	58%

Beyond these differences, our models probably understate the likely response of hay to climate change. They simulate future per-acre yields on the basis of current cropping practices which under present climates include two hay cuttings per year typically, and occasionally a third. Warmer temperatures and longer growing seasons would in all probability permit three cuttings routinely, and quite probably four or more. If irrigation water were available for the longer season, climate change like those projected by the Table 5.2 scenarios, could conceivably increase hay yields by 50% or more.

Comparison with national Agriculture Sector simulations. McCarl (1999) reported the results of the national Agriculture Sector Assessment for the entire U.S. based on simulation models of crop yields and projection of the Hadley and Canadian GCMs for 2030 and 2090. He subdivided the nation into regions, and his "Mountain" region—including Idaho, Montana, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico—corresponds well with the RMGB region. His models were parameterized with crop data generally from the 1961-1990 period. Thus it is of interest to compare his projections, based on different methodology, with ours.

McCarl (1999) calculated percentage increase from average yields of the 1900s to projected values for 2030 and 2090. Hence it has been necessary to compare mean yields of the four crops in our 1972-1998 sampling periods for the region with mean projected yields for 2090 based on the Table 5.2 GCM projections, and calculate percentage change. This was carried out as follows.

We calculated mean 20th-century yields in the CRDs for each crop reported in Table 5.3, and weighted them according to the areas harvested (Column 3 in Table 5.3) in each CRD. We calculated mean, projected yields for 2090 for the region by averaging the values in Columns 7-10, again weighted by the areas harvested in the CRDs. These calculations produced an RMGB area-weighted mean yield for the 1972-1998 sampling period, and four 2090 projected mean yields (Hadley "Low" and "High," Canadian "Low" and "High" estimates) for each crop. We then calculated the percentage change between the 1972-1998 mean yields and each of the four projected 2090 yields. These are shown in Table 5.6 under "Regression-projected."

McCarl's (1999) percentage-increase values by 2090 for the four crops, based on the same GCM projections as our tests, but subdivided by irrigated and dryland cropping for the two grains and potatoes, are shown under "Simulation-projected" in Table 5.6.

The two sets of calculations are similar in some respects, do not agree in others. Both approaches project yield increases in the two grains that are of similar orders of magnitude. Our regional calculations project greater increases in the "High" estimates then in the "Low," possibly in response to the higher precipitation scenarios in both models (Table 5.2). The national-assessment modeling projects little, if any, increase in irrigated grains. But it simulates major increases in dryland grains, again perhaps responding to the increased precipitation scenarios. We did not subdivide the RMGB data in this way because most of the small grain in the region is dryland grain. But in total, both approaches imply significant increases in production for most of the region's wheat and barley, with major increases in response to the higher precipitation scenarios.

Projected hay yields show small to moderate increases in both modeling approaches. But these again do not provide for extended growing seasons and more cuttings per year. If the future

Table 5.6

Comparison of Mean Percentage Change in Crop Yields by the Year 2100, Based on the GCM Scenarios, as Projected by the Regression Models and McCarl's (1999) Simulation Model

	Regression-projected % Change				Simulation-projected % Change			
	HadCM2		CGCM1		HadCM2		CGCM1	
Crop	Low Est.	High Est.	Low Est.	High Est.	Irrig.	Dryl.[1]	Irrig.	Dryl.[1]
Wheat	14%	123%	47%	214%	15%	86%	-3%	68%
Barley	6%	97%	31%	169%	40%	319%	-17%	277%
Hay	-10%	43%	-11%	72%	30%		16%	
Potatoes	28%	120%	56%	223%	-16%		-30%	-17%

[1]McCarl simulated changes in irrigated and dryland small grains separately. He combined both in his hay and potato simulations.

climate is warmer and wetter, hay production per unit area will in all probability increase.

The one crop in which there are major differences between the two modeling efforts is potatoes. The national assessment only projects yield declines, whether irrigated or not. Our regression approach projects substantial increases with scenarios of both GCMs. As commented above, the national assessment describes inadequate tuber formation under higher temperatures. Provision for this in the models may produce simulations of lower yields. Our empirical approach indicated only yield increases during years with high temperatures in our sampling period. Evidently those temperature ranges did not inhibit strong yields. This raises the questions of whether the temperature-inhibition functions in the simulation models correctly represent the relationships; and/or whether the relationships are not linear and the temperature ranges projected by the GCMs exceed the high temperatures of our 1972-1998 sampling period and do inhibit yields. The matter needs clarification either with existing expert information on potato growth, or research focused on the question.

Conclusions on 21st-century projections. Except for the potato question, two independent models project substantial increases by 2100 in per-acre yields of RMGB crops considered here if the GCM scenarios become reality. Coupled with likely increases produced by agronomic research, yield increases of 50-100% are conceivable. (Yields in these crops rose 26-44% in the latter decades of the 1900s, Table 5.1.)

How this would affect the agriculture economy of the region needs some analysis. The increased production could well reduce commodity prices to some degree. But if the region received the precipitation and water-resource increases discussed in Chapter 4, there could be some easing of water prices and consequent benefit to the irrigated portion of RMGB agriculture. Warmer temperatures, increased precipitation, and adequate irrigation water could also provide conditions for alternative, higher-valued crops. In total, it is entirely probable that the region's agriculture itself would benefit from the projected climate changes unless they simultaneously fostered conditions for plant and insect pests, and crop-disease organisms.

It is not as clear that these benefits would significantly enhance the overall economy of the region. The area under cultivation might increase somewhat with more favorable climate and adequate irrigation water, although the majority of land in the RMGB is public land and not suitable for cultivation. And the urban/industrial expansion into farmland, with associated reduction in cultivated acreage, is likely to continue, given the rapid population growth. Four of the five fastest growing states in the nation during the 1990s—Colorado, Idaho, Nevada, and Utah—are in the RMGB region, according to the 2,000 census. Moreover, increased crop yields would have the effect of reducing prices.

Thus, while a 50-100% increase in per-acre yields could benefit RMGB agriculture and provide stability for rural communities during the 21st century, its total production would not be likely to significantly increase its small proportion of the region's total economy as the largely urban/industrial sectors increase by an equivalent or greater amount.

LIVESTOCK INDUSTRY

Introduction

While cultivated agriculture is carried out on only 5% of the RMGB area, most of the nonurban area of the region is grazed by privately owned livestock, primarily cattle. Sheep ranching was a major industry in western U.S. in the first half of the 20th century, but declined after its peak in the 1940s. Today, the economic value of sheep, lambs, and wool sold in the region is only 3% of all domestic-animal value, while cattle and calves make up 93% of the total, according to statistics published by the U.S.D.A. Economic Research Service. Hence this analysis will focus only on cattle ranching.

Although cattle are grazed over most of the region, the sale of cattle and calves in the eight primary RMGB states is still only about one-third of total agricultural income in the region, and approximately 15% of cattle sales nationally. Thus ranching is not a major contributor to the region's economy. But it is part of the historic culture and character of the

West, and its perpetuation is now being looked upon as a bulwark against pell mell real-estate development which accords ranching a whole new set of values.

The prevalent husbandry practices in the region are termed cow-calf operations. Ranchers maintain herds of cows which are bred in May or June. Calves are born typically on the home ranch or on winter range in February and March, moved onto high-elevation summer range with their mothers, then sold in October to feedlots where they are matured and fattened for slaughter. Annual, gross income for RMGB ranchers with cow-calf operations is determined primarily by the number and weights of the calves sold. These depend on the calving rates of the cows, and rates of weight gain by the calves between birth and sale in the fall. There are variations on this pattern, but most are basically similar. All of these variables depend on the nutritional condition of the animals, and that ultimately on the amount and quality of the forage.

Thus in its dependence on the natural forage produced by the native vegetation and supplemental forage crops produced on cultivated land, and in turn the sensitivity of those vegetation types to climate variation, the welfare of the cattle industry is closely tied to the region's climates, and any change therein.

The ranching operations in the region typically center on home ranches with limited (e.g. hundreds) acres of private land. The cattle are transported to extensive (thousands of acres) high-elevation national forest or U.S. Bureau of Land Management (BLM) lands for grazing between spring and fall. They may winter on low-elevation BLM lands, and/or on the home ranch where they are fed supplemental forage produced there or purchased on the open market.

While some small, often part-time, ranchers raise small numbers of animals on their own land, most of the major, economically viable operators must graze their animals seasonally on public lands (Starrs 1998) for which they pay grazing fees. In fact, their animals graze on several times as many acres of public land, and derive several times as much forage, as on private land. Consequently, the effects of climate change on the RMGB ranching industry would depend not only on the effects of that change on private-land forage conditions, but also its effects on the 80% of the region that is in public land. And the effects would depend importantly on policy responses of the public agencies responsible for managing the resources on that land. In order to conduct this assessment, we have not only gathered data from files and the literature, but also consulted with ranchers and agency officials for their likely policy responses to climate-change effects if these become reality. The analyses that follow are based in part on a March 13, 2000 workshop on ranching in Boise, Idaho, in which the following participated:

Barbara Curti, Nevada Farm Bureau and RMGB Steering Committee Member

Martha Hahn, BLM Idaho State Director and RMGB Steering Committee Member

Sherman Janke, Sierra Club, Bozeman, MT and RMGB Steering Committee Member

Hardy Redd, Utah rancher and RMGB Steering Committee Member

Robin Tausch, U.S.D.A. Forest Service, Reno, NV

Dale Toweill, Idaho Dept. of Fish and Game, and RMGB Steering Committee Member

Frederic Wagner, CoCordinator and RMGB Assessment Team

Booth Wallentine, Utah Farm Bureau Federation and RMGB Assessment Team

Others who contributed valuable information and comments include:

BLM Utah State Office:

- Sally Wisely, State Director
- Douglas Koza, Deputy State Director for Resources
- Ronald Bolander, Threatened and Endangered Species Specialist
- George Diwachak, Environmental Scientist
- George Ramey, Senior Rangeland Management Specialist

U.S.D.A. Forest Service Intermountain Regional Office:

- Jack Blackwell, Regional Forester
- Bob Hamner, Range Management Program Leader
- Liz Close, Director of Recreation

Bill Burbridge, Director of Biophysical Resources

Bob Swinford, Director of Communications

Robert Mrowka, Biodiversity Conservation and Species Viability Coordinator

Office of Energy and Resource Planning, State of Utah Department of Natural Resources:

Thomas Brill, Natural Resource Economist

Bruce Ratzlaff, Policy Analyst

Gale Sowards, Natural Resource Analyst

Other individuals who have provided valuable data and insights are:

Kate Kitchell, BLM District Ranger, Boise, ID

George Wanlass, southern Idaho rancher

Leon Pack, BLM Denver Office

Ken Ashby, President of Utah Farm Bureau and Utah farmer

Status and Trend of the Industry

The cattle industry has struggled for some decades in the face of several sets of pressures. One is economic. While not as extreme as the plight of the sheep industry, cattle ranching has been in difficult economic straits in the Intermountain West. A number of authors cite low net returns on assets (ROA), formulated as:

ROA = net annual return/total asset value

A commonly cited figure is 2-3% ROA (cf. Winder 1999). Authors point out that ranchers could double their income by selling their assets and investing the proceeds in bonds or, until low interest rates of the early 2000s, certificates of deposit. Many reportedly stay in the business because they value the lifestyle (Starrs 1998). These difficulties result from ranching in an arid to semi-arid environment with low rates of forage production and low carrying capacities coupled with significant operating costs, and in recent years from low commodity prices.

A second set of pressures is the changing policies of the public agencies prompted in part by their efforts to achieve sound land management, and in part by their response to broadened public values and constituencies associated with the public lands. Agencies require ranchers to reduce the number of animals they graze on the public lands to correct for past excessive grazing pressures and improve land health, protect threatened and endangered (T and E) species, improve water quality, and promote biodiversity. And recreationists, environmentalists, and hunters become antagonistic to livestock use on public lands even to the point of buying up vacated grazing allotments to retire them from livestock use and protect environmentally sensitive areas, T and E species, and wildlife habitat. Such purchases have been made by state wildlife agencies (George W. Ramey, Pers. Comm., 2001) and environmental organizations like The Nature Conservancy.

A third set of pressures is similar to those affecting cultivated agriculture, and is associated with the population growth and changing socio-economic profile of the West. Suburban sprawl crowds in on ranching areas and rising water prices increase operating costs for ranchers who irrigate their own hay crops. Ranchland is purchased by real estate developers, and by affluent individuals who build upscale rural retreats. Decker (1998) describes a decline in the number of ranches in Ouray County, Colorado from 70 to 40 between the 1970s and the present, with some of that decline going to elegant second homes situated on large blocks of land.

As western economies and affluence grow, the increasing land values are incentives for ranchers to sell their lands. At the same time, the high land prices and low profitability of ranching are disincentives for new people to acquire land and enter the ranching business. Many in the younger generations of ranching families, discouraged by the difficult economic straits, move to cities for more rewarding forms of employment.

The net effect of these pressures and changes is a decline in ranching in the West and widespread concerns about the survival of a lifestyle which historically was a major contributor to the region's economy, has been a major determinant of its image and personality, and has been a force for social stability in this historically rural region. One measure of this decline is the trend in annual number of grazing permits and annual number of AUMs (an animal unit month is equivalent to one cow with or without calf, or five sheep, grazing for 1 month) allotted on its lands by the Bureau of Land Management in nine western states since it began partial record keeping in 1953, and more comprehensively in 1974. (Washington and New Mexico are not included in what would otherwise be the 11 western states.) Total AUMs declined 45% between 1953 and 2000 (Fig. 5.3). At –87%, sheep AUMs declined most precipitously, but cattle AUMs declined 24% over this same period. The number of grazing permits declined by 37%. Part of this resulted from larger ranchers buying out smaller operators' permits, but part is due to the purchase and retirement of permits from use. The net effect is that only two-thirds as many ranchers grazed only slightly more than half as many animals in 2000 as in 1953.

However, in the past 10-20 years, new perspectives have been developing among the socio-economic groups contending for influence in the rural West. The realization is growing that farming and ranching are impediments against loss of open space, against pell mell suburban sprawl, and against rural, leap-frog real-estate development that intrudes on the largely unpopulated, wilderness character of the region. That character is a major component of the quality of life for both rural and urban residents, and along with ranching is a major attraction for the tourist influx that contributes to the region's economy.

As a result, a number of policy initiatives are developing to strengthen the economic

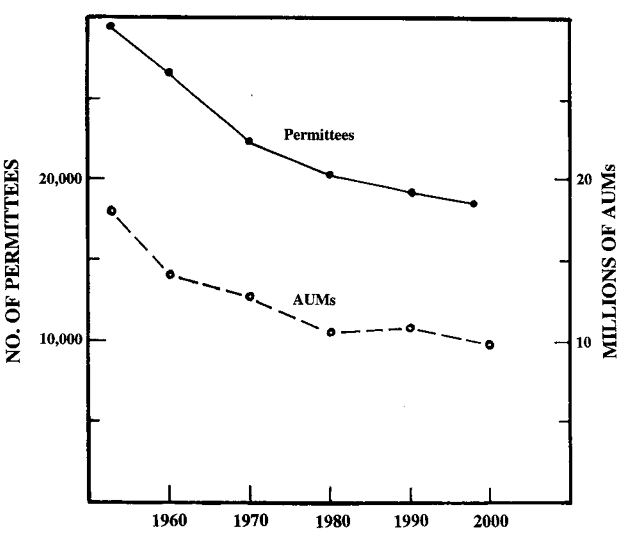

Figure 5.3. Trends in annual number of rancher permittees grazing livestock on U.S. Bureau of Land Management lands in nine western states (New Mexico and Washington not included), and in number of animal unit months (AUMs) of stock grazed by these permittees, between 1953 and 2000.

condition of the ranching community. One is a tax provision termed "conservation easements." In return for placing his/her land in a permanent easement, including all subsequent owners, a rancher is given a charitable income-tax deduction equivalent to the difference between the appraised agricultural value of the land and what he/she could realize by selling the land to a developer (Decker 1998). The arrangement also has the advantage of keeping the land value low, and thereby reducing the estate taxes which the rancher's heirs must pay upon his/her demise.

While the easements provide clear economic advantages, they do not supply the continuing cash flow that ranchers need to supplement their thin profit margins. A number of organizations are purchasing "development rights" from ranchers: paying them cash for the difference between the agricultural value of the land and what a developer would pay to acquire it. Some of these are private groups of local residents—Huffman (2000) describes such a Colorado Cattlemen's Agricultural Land Trust. Some are governmental—Decker (1998) discusses Great Outdoors Colorado, a state agency that receives its funds from the tax proceeds of the state lottery with which it purchases ranchers' development rights. Sherman Janke (Pers. Comm., March 13, 2000) states that the Montana legislature has appropriated funds to buy development rights.

Whether or not these measures can succeed in preserving the ranching industry in the Intermountain West is of course unknown. Some observers simply predict that public-land ranching will be a thing of the past in another 50 years. But Decker (1998) comments "It is ironic that urban money has preserved the rural countryside and its traditional way of life." It is within these dynamics that climate change would or would not affect the industry and the broader economy of the RMGB region.

Scenario-based Projections of Climate-change Effects

Scenario 1: No Climate Change

The difficulties currently besetting the ranching industry are substantially the result of the current arid- to semi-arid climate which results in low forage production and low livestock carrying capacities. The difficulties are exacerbated by the rapid, largely urban population growth with its increasing demand for water and competing demands for use of the public lands.

Without climate change, these pressures would continue and in all probability the industry would continue its slide unless the newer efforts at shoring up the ranchers' economies are widely successful. The disappearance of ranching could entail rural, socio-economic instability with the demise of local businesses, and local schools and other infrastructure. Whether or not ranching survives, the direct effects on the overall RMGB economy would not be great because it is such a small part of that economy. It is conceivable that the disappearance of ranching could have an additional indirect effect. If the private land of the Intermountain West filled up with suburban sprawl that so changed the character of the region from what now attracts tourist influx, the result could be a decline in tourism and a further negative impact on the RMGB economy.

However, as will be discussed in the next chapter, and contrary to widespread impression, tourism makes only a limited direct contribution to the economy of the Intermountain West. A major factor driving economic growth in the region is the immigration of what several authors term "amenity migrants"—affluent individuals from outside the region who are attracted by the quality-of-life characteristics and bring or start their own businesses. In many cases, these individuals are the purchasers of the private lands and builders of up-scale homes, and in the process make contributions to the local economies that exceed any losses that might occur with diminution of direct tourism income. The net effect of all these changes is that decline of ranching would not noticeably affect the economy of the region as a whole.

Scenario 2: Temperature Increase, No Precipitation Change

Temperature increases without accompanying increases in precipitation would intensify aridity in lower elevations by increasing evapotranspiration. The result would be lower forage production. It is possible that primary production would be increased by longer growing seasons at high elevations where there is more precipitation. But any gains at higher elevations could well be offset by losses in the lower-elevation ranges plus rising prices for water and open-market forage.

There is little basis for projecting any improvement in the economic status of the ranching business in the RMGB under elevated temperatures without increases in precipitation. The net effects would likely be increased pressures on an already beleaguered industry.

Scenario 3: GCM-projected Increases in Temperature and Precipitation

Effects of increased precipitation. Studies worldwide have shown close correlations between year-to-year variations in vegetative (primary) production and yearly variations in precipitation in arid and semi-arid areas (Le Houerou and Hoste 1977, Wagner 1980, MacMahon and Wagner 1985). Similarly, it is well established that mean vegetative production in different areas is commonly correlated with mean precipitation levels in the same areas. As a result, areas with higher precipitation can support more livestock than more arid ones.

While we could not find studies showing correlations between annual precipitation and calf performance in the RMGB, there are numerous reports for the Great Plains. Hurtt (1951) reported that calf weight gains in one Montana study declined by a third during the drought years of the 1930s. Reed and Peterson (1961) reported that the percentage of cows weaning calves in these same years declined to 73% compared with 87% in the "more normal" years. The authors attributed these differences to variations in milk production by the cows. In an 8-year study during the 1950s, Houston and Woodward (1966) found correlations between annual precipitation and daily calf weight gains, weaning weights, and percent calf crop, again in Montana.

It is entirely probable that the precipitation and temperature increases projected by the GCMs (Table 5.2) would benefit the cattle industry in the region if they eventuated. Increased precipitation would be expected to increase forage production and allow an increase in numbers of animals on the range and, depending on stocking rates, improved calf performance. The warmer temperatures would in all probability lengthen the growing seasons, and permit longer grazing seasons on high-elevation ranges, especially the national forests.

The overall result would be increased forage production on natural ranges, reduced need for forage supplements, and reduced costs either of hay purchased on the open market and/or of water for irrigating home-ranch forage crops.

There could be some negative effects. The above would depend on plant-community composition, very likely to change under altered climates (cf. Chapter 9), retaining a significant component of nutritionally favorable plant species. A major shift from herbaceous to woody vegetation would cancel any benefits of increased precipitation. A number of authors (cf. Kurihara et al. 1999) are suggesting that warmer temperatures and increased precipitation could change herbaceous vegetation from a predominance of cool-season (C_3) grasses to warm-season (C_4) species which are less nutritious. One Idaho rancher, George Wanless, has suggested that climate changes might accelerate weed invasion and increase labor costs for weed control. He also stated that calves are more susceptible to diseases such as pneumonia and scours under the stress of variable climate.

Subject to these caveats, it is a reasonable hypothesis that an increase in temperatures and precipitation would increase forage production and carrying capacities for cattle on both private and public lands in the RMGB.

Public-agency policy constraints. Of the 80% of the RMGB area in public land, 96% of that total is managed by two federal agencies: 39% is in national forests and managed by the U.S.D.A. Forest Service, and 57% is in what has been termed the unappropriated public domain managed by the U.S. Bureau of Land Management. Federal legislation stipulates grazing by privately-owned livestock on these lands, but it also prescribes multiple use and conservation of these lands for other values. The two agencies are bound by law to manage the land for an array of uses, and decisions on any one must be balanced by responsibilities for the others.

Thus whether or not climate change prompted decisions favoring the livestock industry would depend on other management priorities, climate-related and otherwise. For these reasons we have discussed these questions at considerable length with administrative personnel in the Idaho and Utah state offices of the BLM, and in the office of the Intermountain Region of the Forest Service which administers 16 national forests in the states of Wyoming, Idaho, Nevada, and Utah. There was considerable similarity of response, and these generalize as follows:

(1) The federal lands of the RMGB region are now fully subdivided into grazing allotments. Even if climate changes increased production of range forage, there would be no basis for increasing the number of allotments or subdividing them. Hence, there would be no significant potential for increasing the number of ranching businesses that depended on public-land use. Since Intermountain ranching is so heavily dependent on the public lands, there would be little if any prospect for significant expansion of the industry.

(2) Both BLM and Forest Service officials commented that if it were compatible with other uses and demands on the public lands, consideration might be given to allowing existing permittees to graze some additional animals. However, they commented that in the event of increased forage production, hunting interests might request that this be allocated to increased numbers of wild ungulates, particularly elk.

(3) All agency officials concurred that the first consideration in responding to climate change would be assuring healthy functioning of the land: stable watersheds, high water-quality standards, protection of threatened and endangered species, and perpetuation of wildlife habitat. Idaho BLM Director Hahn commented that second- and third-order effects of climate change might well be of greater concern than immediate effects. In her view, increased precipitation makes desert roads more fragile, and roads become the channels for serious landscape gullying during high-rainfall years. High precipitation also increases growth of ground-fuel vegetation and the frequency of range fires that permanently alter the vegetation (cf. Chapter 9).

BLM District Ranger Kitchell remarked that "climate change might give us a chance to catch up." As many as 50% of the allotments have been experiencing excessive grazing use for years. BLM has been pressing Idaho ranchers to reduce the number of animals for up to 20 years, but has been thwarted by political intervention. A more productive range under improved climatic conditions might permit range improvement without reduction in animal numbers. But the implication is that there would be no increase in stocking rates on those allotments.

Conclusions on Livestock-industry Effects

Under current climatic patterns, ranching in the RMGB region is in difficult straits. Whether it will survive as a way of life and economic sector in the region is uncertain. Survival might depend on the effectiveness of the new initiatives to improve the ranchers' economic status. Increased temperatures without increased precipitation (Scenario 2) would in all probability exacerbate the industry's problems.

The increased precipitation and temperatures of Scenario 3 would be likely to increase forage production, vegetative growing-season lengths, and ultimately livestock carrying capacities. Increased precipitation, with attendant reduction in the frequency of drought years, as discussed in Chapter 3, would reduce the number of years like 2000 when ranchers were required by the agencies to remove their animals from the public lands weeks or months ahead of the normal late-summer or fall removal dates. These actions were taken because of the drought conditions, lower forage production, and inability of the vegetation to withstand a grazing season of normal length without significant damage to the range resource.

As a result, animals had to be returned to home ranches where ranchers were forced to feed more supplemental forage than in the average or more favorable year. For ranchers without irrigated hay, the forage was purchased on the open market with elevated prices because of the increased demand. Such years increase costs, reduce herd performance, and make profits difficult if not impossible. Some ranchers were even forced to sell off their herds. The higher precipitation levels of Scenario 3 would reduce costs, and produce more consistently favorable herd performance.

Additional economic benefits to the industry would be reduced hay costs associated with lower need and demand. They would also include lower water prices, both because there would be less need and because of the increased availability of the resource (cf. Chapter 4). Several participants at the March 13 ranching workshop agreed that all of these changes would increase the ranchers' property values.

In sum, unless there would be drastic change in the vegetation composition of the region associated with increased fire frequency and widespread invasion of exotics, it is probable that Scenario 3 climate change would strengthen the economic status of the RMGB livestock industry, even with no favorable changes in public-agency policies. Workshop participants agreed that there might be some need for changes in husbandry practices such as newer, better-adapted livestock breeds and new grazing rotation systems. But all agreed that the livestock industry is adaptable. And Steering Committee member Barbara Curti stressed the need for continuing emphasis on research to provide the knowledge base that would guide husbandry practices facilitating adaptation to these changes.

These comments focus on strengthening the status of the existing industry. It does not follow that there would be significant expansion of ranching. Since the public-land ranges are now fully allotted, there would be no space for new allotments, for increases in the number of ranching operations, and thus increases in the magnitude of the industry. Whether or not the agencies would allow ranchers to run more cattle on improved existing allotments is uncertain, depending on the contingencies discussed above.

Thus, while the Scenario 3 climate changes could well strengthen the economic status of the industry as structured today, that strengthening would have very little direct effect on the region's overall economy because it is such a small component at present. But in strengthening the industry's economy, Scenario 3 climate change could have a more pervasive influence on the region than the minor effect of enhanced commodity production on the region's economy. If by strengthening the industry's economic status climate change increased the probability of its survival, that change could contribute to the preservation of an historic way of life in the region, and of its open, wilderness character. These traits contribute to the quality of life for both rural and urban residents of the region, and are major attractions for the tourist influx that contributes to the region's economy. And in helping sustain the livestock industry, Scenario 3 climate change could help in maintaining rural, social stability.

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Chapter 6

OUTDOOR RECREATION AND TOURISM

Frederic H. Wagner

INTRODUCTION

Spectacular scenery, challenging topography, an equable climate, and predominance of public land that has maintained a largely natural landscape with minimal commercial development make the Intermountain West a Mecca for outdoor recreation and its economic expression in tourism. Several economic analyses of outdoor recreation range from the economic analyses of individual recreational activities to entire litanies of pursuits that are tributes to human creativity and ingenuity in seeking emotional and stimulating experiences with nature. A composite list of these includes:

Warm-season terrestrial: Sight seeing, picnicking, hiking, camping, mountain biking, off-road vehicle driving, horseback riding, hunting, bird watching, spelunking, mountaineering, rock climbing.

Winter terrestrial: Downhill and cross-country skiing, snowboarding, snowshoeing, snowmobiling, ice skating, winter camping.

Water based: Swimming, power boating, sailing, kayaking, canoeing, jet skiing, water skiing, wind surfing, whitewater rafting, sport fishing, snorkeling, scuba diving.

Aerial: Flying, fixed-wing gliding, hang gliding, paragliding, hot-air ballooning.

These activities contribute to economies of local communities, states, or regions when tourists from outside those economies travel into them to pursue their outdoor-recreation activities, and in the process spend money on food, lodging, travel, and purchase of equipment and access. For purposes of this assessment, such outdoor-recreation-oriented influx and expenditures are termed "outdoor tourism" to distinguish them from tourism for such other purposes as business travel, attending conventions, shopping, family visits, spectator sports, and in Nevada, gaming.

The purpose of this chapter is to explore the potential effects of climate change on the above forms of outdoor recreation, and ultimately on their outdoor-tourism contributions to local, state, and regional economies of the Rocky Mountain/Great Basin (RMGB) region. Betz et al. (1999) comment that outdoor recreation is one of the few ways in which humans will experience climate change directly because it involves direct interaction with the natural environment. They suggest further that locations whose economies are highly dependent on outdoor tourism are likely to experience the greatest effects, whether positive or negative. Given the volume of outdoor recreation and tourism in the RMGB region, it is an obvious sector for assessment.

ECONOMICS OF OUTDOOR RECREATION AND TOURISM

National Expenditures on Outdoor Recreation

A growing literature reports increasingly sophisticated analyses of the economics of outdoor recreation. Some studies focus on how climate change would affect individual recreation activities such as trout fishing (Ahn 1997), wildlife hunting and viewing (Cooper and Loomis 1991), skiing (Dessel and Hinckley 1998), boating (Duk 1997), camping (Wall 1997), etc. But several analyses have assessed the potential, total economic effects of climate-change scenarios on the entire gamut of outdoor activities in the U.S. (Betz et al. 1999, Loomis and Crespi 1999, Mendelsohn and Markowski 1999).

The latter authors base their analyses on a number of assumptions. The metric of use is the "user-day." "Consumer surplus" is defined as the amount the user is willing to spend on an outdoor-recreation activity over and above his/her normal daily expenditures. By affecting both the favorability of conditions for an activity, and the quality and availability of a resource for an activity (e.g. snow for skiing, beaches for seaside recreation, water for boating and fishing), climate is considered to affect both the number of user days and the consumer surplus.

The essence of recreation (sometimes termed the "leisure experience") is the experience that results from engaging in an activity, not the activity itself. Each activity has its own environmental requirements and weather sensitivities. Those that are achievable in a variety of recreation-resource and climatic settings are "robust" experiences. Those that are attainable only under very limited circumstances are "nonrobust." The latter are considered most susceptible to climate change and are least susceptible to substitution.

Using questionnaire data, the authors evaluated the influence of different climate patterns on consumers' demand for the individual activities. Based on these assumptions, they developed linear and log-linear regression models with which they projected trends in recreation activity and expenditures in response to a range of climate-change scenarios by the year 2060.

As baselines, Mendelsohn and Markowski (1999) cited national expenditures for 1990 on the order of $2.5 billion for skiing, and $76.3 billion for boating, camping, fishing, golfing, hunting, and wildlife viewing. Thus expenditures for warm-season recreation far exceed outlay for winter activities. With a set of temperature- and precipitation-increase scenarios, the authors' models projected increased effort and expenditures on boating, fishing, and golf; and reduction in camping, hunting, skiing, and wildlife viewing.

But the net effect on all activities by 2060 was 7-9% increase in expenditures associated with 2.5°C (4.5°F) increase in temperature and 7% increase in precipitation. If the temperature increase were 5°C (9°F) and precipitation increased by 15%, the net effect on expenditures for all activities was projected at 40-65% increase. Loomis and Crespi (1999), projecting aggregate trends for 17 activities, obtained results quite similar to those of Mendelsohn and Markowski. The overall increases were significantly due to the increase in recreation activities and expenditures during the warm season, in response to prolonged summers resulting from increased temperatures.

These are national figures and do not necessarily reflect potential changes in the RMGB region. The studies are summarized here to elucidate the complexities of analyzing trends in climate-change effects on outdoor recreation and especially tourism, and to provide context for assessing potential effects in the RMGB.

Implications of National Studies for RMGB Assessment

Several implications of the national outdoor-recreation analyses provide focus for assessing climate-change effects in the RMGB. First, the national recreation expenditures do not equate to national, outdoor tourism and therefore cannot be considered additions to the American economy. It is a reasonable, economic assumption that if not spent on outdoor recreation, the funds would be spent elsewhere in the national economy. The expenditures in total can only be considered additions to the economies of the outdoor recreation businesses (equipment manufacturers, hotels, restaurants, etc.).

Only that portion, probably quite small, expended by visitors from outside the U.S. could be considered additions to its economy. (In Utah, 3.9% of total nonresident visitations are international visits. Teton National Park officials report that 8-10% of their visitors are from outside the U.S.) By the same token, any effect of climate change on outdoor-recreation expenditure in the U.S. could not be considered a climate-change effect on the national economy except for any effect on inflow and expenditures of foreign tourists.

The same reasoning applies to the effects of climate change on outdoor tourism in RMGB region, the constituent states, and local economies. Climate change would affect the outdoor-tourism contributions to the economies of the three entities to the extent that it would affect the inflow and expenditures of tourists into them. Hence this assessment requires estimates of the magnitudes of their economies, of their outdoor tourism, and how the latter would be affected by various climate-change scenarios.

As a second implication of the national studies, outdoor recreation and tourism are not monoliths. Some activities, and presumably their associated tourism, are affected positively by a given weather pattern. Others are affected negatively. Hence a given climate change would have mixed effects on the tourism contribution to a given economy. And the economies of communities catering strongly to a given outdoor activity could be affected quite differently from those of communities primarily oriented to other outdoor pursuits.

Third, the magnitudes of the projected changes in individual and total recreational activities in the national studies are not necessarily those of the RMGB region. The combinations of activities must vary regionally, and there may be a wider range of recreational options in the West. There may also be regional differences in recreationists' responses to specific weather patterns. However, there are no comparable studies in the RMGB of weather effects on the individual recreational pursuits. Hence it is necessary to use the national values where applicable as hypotheses at least of the directions of effect if not the magnitudes.

ECONOMIC VALUE OF OUTDOOR TOURISM IN THE RMGB

Current Value

The potential effects of climate change on the outdoor-tourism contribution to the RMGB economy can potentially be evaluated at the level of the region's economy, that of the eight primary states in the region, and the economies of local communities. Conceptually, the needed parameters would appear to be (1) some measure of current, total economies of these three categories of areas (e.g. the gross state products (GSPs) of the states); (2) measures of current outdoor-tourism expenditures in each; and (3) projections of how specified climate-change scenarios would affect (2). However, there are additional factors that need to be included in such an analysis, and the needed data are often not available.

One source of complexity is the indirect effects on economies. Several authors (cf. Rasker and Glick 1994, Rasker 1996, Power 1996) describe what Snepenger et al. (1995) term a "tourism destination life-cycle model" that is in essence a form of economic succession for local communities in the Intermountain West. Early in the history of the region, local economies at Stage 1 in the succession were heavily dependent on extractive uses of natural resources. With the rapid expansion of tourism after World War II, those communities closely situated to attractive outdoor-recreation amenities—spectacular scenery, proximity to state and national parks and other public lands, quality fishing and hunting, skiing developments, etc.—attracted increasing numbers of tourists. And the ensuing proliferation of tourist-support businesses came to dominate the local economies in this second stage of the succession. National park gateway communities like West Yellowstone and Gardiner, Montana, and Moab, Utah are examples.

In the most recent changes in the succession (Stage 3), many tourists who travel from outside the West to see the above amenities perceive additional quality-of-life traits—less pollution, crime, and traffic congestion; less stressful living conditions, lower cost of living, all in addition to the esthetic attractions of the surroundings—and move to small western towns and establish permanent residence. Variously termed "footloose entrepreneurs" (Rasker and Glick 1994), "equity migrants" (Rasker 1995), "travel-stimulated entrepreneurial migrants" (Snepenger et al. 1995), or "amenity migrants" (Rey 2001), some of these individuals bring their own businesses which they may operate from their homes via the internet, FAX, and telephone. Others start new businesses. The process is particularly facilitated if a town has or is close to an airport capable of accommodating commercial airline flights.

Another class of amenity migrants are retirees who bring into the local economies income from their retirement pensions, prior investments, and savings. Rasker (1995) and Power and Barrett (2001) term this "nonlabor income" and report that over a third of the personal income in the Intermountain West is from this source.

The arrival of these new residents builds demand for support services: construction businesses, retailers, schools, insurance companies, medical services, etc. All of this together fuels massive economic growth that typifies the changes taking place in many of the smaller towns in the U.S. West. At this stage of the economic succession, extractive uses of the natural resources, and even tourism, become minor contributors to the local economies. R. Rasker (Pers. Comm., July 8, 2001) estimates that the combined contribution of resource extraction and tourism to the economy of the Greater Yellowstone Ecosystem is now on the order of 9% despite its massive flow of tourists. Towns in this category include Aspen and Telluride, Colorado, and Jackson, Wyoming.

The implication for climate-change assessment is that the effect of any change on the outdoor-tourism contribution to local economies would depend on where the communities are in the successional sequence. Economies of communities in the first stage that have no significant tourist attractions would be largely uninfluenced by climate-change effects on outdoor recreation. In the second successional stage, tourism contributes directly by adding tourism expenditures into what otherwise would be limited local economies. Analyses of this dynamic are fairly straight-forward, and it is at this stage of the economic succession that climate-change effects, whether positive or negative, are most likely to be significant and quantifiable.

In successional Stage 3, tourism assumes a more complex economic role by attracting amenity migrants who, perceiving the quality-of-life characteristics of an area, immigrate and vastly expand the economies. This effect is more difficult to evaluate economically as would be any climate-change effects if there were any of significance. Intuitively, those effects would not appear to be significant.

Another complication in evaluating outdoor tourism is that most states and communities have estimates of economic expenditures on total tourism, but except for skiing do not separate out what is here being termed outdoor tourism. Hence precise estimates of outdoor tourism cannot be made here.

Given these complexities and limitations, the following case studies and analyses give some indication of at least the current magnitudes of tourism contributions to western economies, and subsequently what effects climate change might have on those economies.

Moab, Utah, a small town with population slightly over 9,000, is a gateway community for two national parks and a state park. It is situated in a spectacularly scenic region popular for hiking and backpacking, mountain ("slick-rock") biking, and camping. It is also on the banks of the Colorado River with companies providing river float trips in breath-taking scenery. According to Kemp (2000), 44% of the employment in Grand County (in which Moab is the only town of significant size) in 1999 was "tourism related." This value must indicate the magnitude of outdoor tourism's contribution to the Grand County economy, an economy in Stage 2 of the economic succession. This heavy dependency on tourism is likely to continue, and its economy is likely to be affected by whatever effect climate change might have on tourism.

Park City, Utah is situated at the base of the largest ski area in the state, and was an important venue for the 2002 Winter Olympics. Its population approaches 27,000, and a throng of skiers obviously make a major contribution to the community's economy in winter. Some 41% of the 1999 employment in Summit County (in which Park City is located) was "tourism related" (Kemp 2000). However, Park City is a diversified town with a number of small businesses, numerous art galleries and artists, convention facilities, up-scale restaurants, music festivals, a golf course and tennis courts, second homes and time-share condominiums, all of which attract a significant warm-season tourist flow. Thus much of the 41% tourism-related employment does not serve skiing and other outdoor tourism. A major decline in skiing in the immediate future would have a material impact on Park City's economy. But the community is well on its way to Stage 3 in the economic succession, and at some point in the future will no longer have as strong dependency on skiing, or be as subject to climate-change effects.

As discussed above, the Greater Yellowstone Ecosystem encompassing parts of Wyoming, Montana, and Idaho is one of the West's major tourist attractions. Yellowstone and Grand Teton

National Parks each attract more than 3 million tourists each year. The area has three major and several smaller ski areas. It supports a plethora of outdoor activities including wildlife viewing, hiking, climbing, rafting, fishing and hunting, snowmobiling, cross-country skiing in addition to a flow of simple sight seeing. Yet according to economist Ray Rasker (Pers. Comm., July 8, 2001), tourism and extractive use of the natural resources contribute only 9% of the total economy of the region, with tourism contributing perhaps no more than half that amount. The area has made the full transition to succession Stage 3, and any climate-change effects would only modify the current 4-5%.

While the economic contribution of tourism to the economies of local areas varies substantially between them, the contributions to state economies appear consistently to fall in a small range. The 1999 gross state product for Utah (the most recent year posted by the U.S. Department of Commerce Bureau of Economic Analysis on its website) was $62.6 billion. In that same year, the total travel and tourism expenditure in the state was $4.25 billion (Kemp 2000, Utah Div. of Travel Development web site), or 6.8% of the GSP. Some fraction of this total was not outdoor tourism. Hence expenditure on the latter contributed less, perhaps significantly less, than 6.8% of GSP.

Published statistics on expenditures by nonresident skiers indicate the value of one component of outdoor tourism. Nonresident skiers in Utah have been spending in the range of $400-500 million annually (Deseret News Archives). These values range from 0.6-0.8% of GSP. The 1999 Colorado GSP was $153.7 billion. In the 1996-97 ski season, 8,161,885 Colorado "destination skiers" spent an average of $189 per visit (Anon. 1997). These values combined total to $1.543 billion, or almost exactly 1% of Colorado's GSP.

In total, outdoor tourism in the RMGB states evidently contributes less than 6-7% of GSP, quite possibly less than 5%. And the magnitude of economic effect from climate change on the state and regional economies, positive or negative, would be to modify those numbers.

Trends in RMGB Outdoor Tourism

What effects climate change would have on outdoor tourism in the RMGB by the latter part of the 21st century would depend on the magnitude of tourism in the region by that point in time, and the interaction of climate change with factors shaping the trends toward that magnitude. Several trends in outdoor activities have been evident in the latter decades of the 20th century that could suggest at least the directions of change by 2100.

One measure is the trend in visitations to national parks in the region. Annual visitation statistics compiled by the Intermountain Field Office of the National Park Service for the period 1979-2000, and available on the Park Service Web site, are shown in Fig. 6.1 These show rapid increase from 1979 to about 1991, and then reduced growth or near cessation in the last 9 years.

Most of the 1979-2000 increase occurred in winter. January visitations increased by 139% over that period while August visitations increased only 15% over the same 22 years. Moreover, summer visitations actually declined slightly during the 1990s, June and July experiencing their highest attendance in 1994, and August in 1993. This is partially reflected in Fig. 6.1. Over the first half of this 22-year

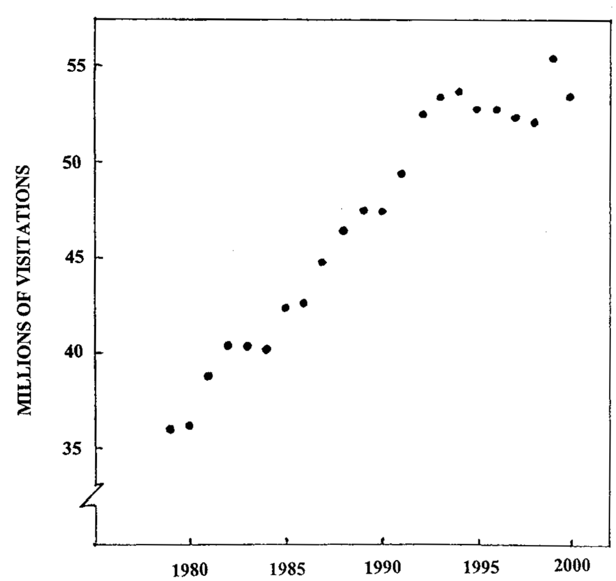

Figure 6.1 Annual number of visitations to national parks in the National Park Service's Intermountain Region.

period, summer visitations outnumbered winter attendance by factors of 5-6, and the summer numbers largely determined the annual trends. But by the end of the 1990s winter visitations had increased sufficiently to affect the trends shown in Fig. 6.1.

What factors shaped these trends can only be speculated on. The major increase in winter visitations could reflect the increasing retirement-age component of the population whose freedom to travel at times other than summer is unconstrained by children in school and employment commitments. Why summer visitation should have leveled off is also uncertain. The 1990s were a period of rapid economic growth, and some outdoor-recreation specialists generalize that economic strength stimulates outdoor recreation and tourism. But the decade was also one of declining unemployment which may have reduced travel time for the population as a whole.

Annual numbers of skier visits provide another index of trend in outdoor tourism. Colorado with 22%, and Utah with 5.7-6.0%, of national skier visits set the pace for the RMGB region. Their annual numbers from 1961 to the present are shown in Fig. 6.2. Nonresident skiers comprise about two-thirds of Colorado

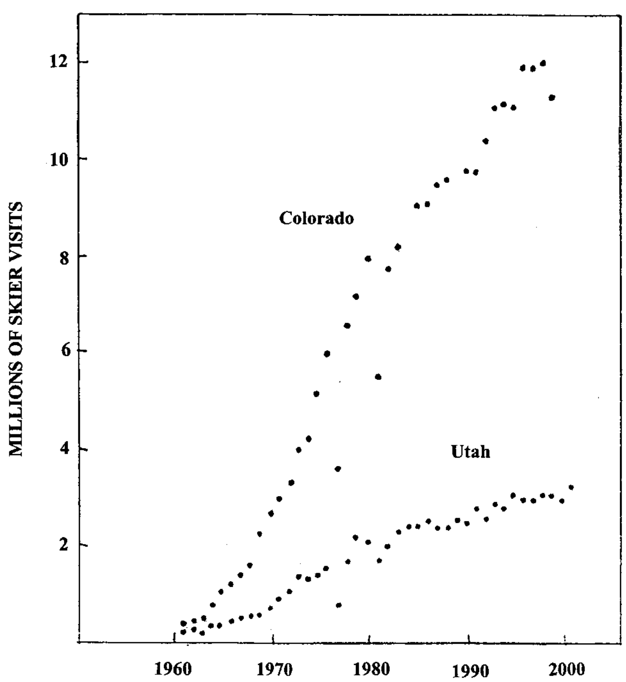

Figure 6.2. Annual number of skier visits to Colorado and Utah ski areas.

skier visits (Anon. 1999), and 54-60% of Utah skiers (Utah Office of Planning and Budget, Demographic and Economic Analysis). Numbers of skiers in the two states have increased continuously since 1961, growing most rapidly in the 1970s and early 1980s. But the growth slowed in the latter 1980s, including periods of 3-4 years with no increase. Skier numbers in Idaho's Grand Targhee Resort peaked in 1991-92 and have dropped 10-12% in the years since. The trends in these states coincide with a cessation of growth in skier numbers nationally in the latter 1980s (United Ski Industries Association). Over the U.S. as a whole, skier numbers have essentially not increased since 1987.

In Utah, the number of nonresident skiers stopped growing in about 1991. The continued increase in total numbers has been driven by growth in resident skiers of approximately 40% between 1991 and 2001. As a result of these disparate trends, nonresident skiers in Utah, as a proportion of total state numbers, declined from 60% in 1991 to 54% in 2001. Consequently, the continued increase in resident skiers can be considered to make an increasing contribution to the economics of local services, ski-equipment businesses, and local ski areas like Park City, but not to the state's economy. And given the lack of growth in nonresident skiers since 1991, skiing in total has not significantly increased its contribution to the state's economy since that year.

What forces have produced these trends is again subject only to speculation. The slowing growth of skier numbers could be partially due to the population's aging. But costs have also risen, and Colorado Ski Country USA (Anon. 1999) surveys show that median household income of Colorado nonresident skiers rose from $55,600 in 1993-94 to $87,200 in 1997-98. Conceivably, the increasing costs are gradually excluding individuals of less-substantial income. Costs are still within the means of resident skiers who do not incur the expenses of travel, lodging, and meals borne by the nonresidents. The cost issue could interact with climate change, as will be discussed below.

POTENTIAL CLIMATE-CHANGE EFFECTS

Scenario 1: No Climate Change

Warm-season Activities

It is reasonable to assume that without significant climate change in the 21st century, the forces currently shaping the trends in outdoor recreation and tourism in the RMGB region would continue to drive those trends. The projected doubling of the regional population (Table 4.5), while not necessarily increasing outdoor tourism (as defined above) for the region as a whole, will likely enhance tourism and economies of individual states and local communities. Continued increase of the national population and rise in foreign visitations can be expected to enhance tourism and the economy of the region. However, if the slow growth in summer national-park visitation reflects slow increase in tourism generally, increase in the 21st century may be more modest than the rate of population growth.

U.S.D.A. Forest Service recreation specialists (D.J. Chavez, Pers. Comm., Sept. 27, 2000) also point out that tastes in outdoor recreation activities vary among ethnic groups and age classes. As the region's ethnic composition and age distribution change, so too will distribution of demands for recreational services and facilities. As an example, the recreational preferences of the fast-growing Latino component of the population often tend toward multi-family activities in well-developed facilities like picnic grounds. This contrasts with the more individual and small-group activities in wilderness settings that have characterized the recreational preferences of many Anglo individuals in recent decades.

Without increased precipitation, the population growth will also exacerbate the competition for overused water resources, as discussed in Chapter 4. Since, as described in that chapter, in-stream flow values that support recreation (e.g. fishing, kayaking, rafting) receive lower priorities than agriculture and urban-industrial uses in water allocation, there may be growing constraints on water-based recreational activities.

In total, there is likely to be some increase in tourism in the region under continuation of current climate patterns, to the economic benefit of the region as a whole. But the relative distributions of different recreational activities, seasonal patterns of use, and locales of activities may change from the present patterns to the benefit of some states and communities, and to the detriment of others.

Winter Season

As with summer tourism, the growing national and regional populations, and the increasing national park visitations of the past two decades probably portend increasing winter tourism in the RMGB region. And the more rapid rise of winter park visitations may presage more rapid growth at this season during the 21st century.

The growing water shortage may also constrain growth in water-based recreation in winter as suggested above for summer. It may also affect growth in the skiing industry. As will be discussed below, ski resorts are increasingly depending on, and installing equipment to produce, artificial snow. This requires additional water for which prices are rising in response to increasing demand, and also entails the costs of snow-making equipment. These elevated costs will in all probability be passed on to skiers at a time when rising costs may already be limiting growth of this form of outdoor recreation. In some cases the additional water may not be available.

Thus it is likely that, without significant climate change, some forms of outdoor recreation and tourism in the RMGB region will continue to increase. This could include some forms of snow-based activities like cross-country skiing and snowmobiling. It may also include downhill skiing, but projection of trends is uncertain because of rising costs and potential water shortages.

Scenario 2: Higher Temperatures, No Precipitation Change

Warm-season Activities

Scenario 2 is essentially the same as those used by Loomis and Crespi (1999) and Mendelsohn and Markowski (1999) in their national analyses. It is reasonable to hypothesize that many of the trends they projected would occur in the RMGB region. These authors projected increase in many summer recreational pursuits because of lengthened summer seasons and more favorable weather produced by warmer temperatures.

The national park visitation rates may again serve as indicators of more general trends in seasonal tourism that could change with rising temperatures. The magnitude of visitations to four of the southern-most parks in Texas and Arizona, and to four parks at higher latitudes and altitudes are quite different (Fig. 6.3), no doubt due largely to the fact that the four northern parks—Zion, Rocky Mountain, Yellowstone, and Glacier—are among the crown jewels in the National Park System and attract large numbers.

But it is the comparative trends that are of interest. Visitations to the four southern parks peak in March, and reach their annual lows in July and August. Visitations to the four northern parks hit their low in December and January, and fall below the numbers at the southern parks for the 6-month period November-April. It is likely that the November-April tourist attraction to the southern parks reflects the more favorable climatic conditions at those latitudes while the June-August low results from avoidance of summer heat. The concurrent, low November-April attendance at the northern parks almost certainly results from tourists' reluctance to visit them under severe weather patterns, and to travel under potentially hazardous driving conditions.

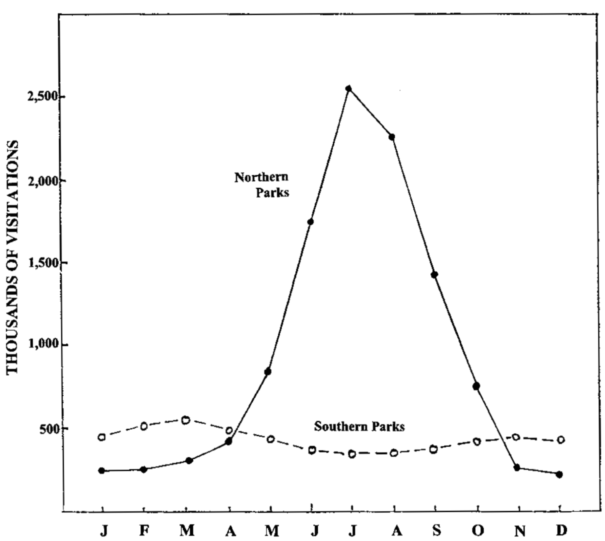

Figure 6.3. Monthly number of visitations to four southern (Big Bend, Guadalupe Mountains, Oregon Pipe Cactus, Saguaro) and four northern (Zion, Rocky Mountain, Yellowstone, Glacier) national parks during 2000.

Increasing temperatures would lengthen the warm season in the north, and could encourage more tourism in the current November-April low season. Since, as discussed above, winter visitations to national parks are already increasing rapidly, rising temperatures could well accentuate this trend. Further temperature increases in the southwestern states, where summer highs already reach 108-110°F, could also evoke more summer travel to the higher elevations and cooler temperatures of the RMGB. Significant numbers of Phoenix-area (Sun City) residents now spend summers in Rexburg, Idaho, Logan, Utah, and other northerly small- and medium-sized towns in the RMGB region.

Because of the semi-arid to arid climate of the RMGB, Scenario 2 conditions could affect one subset of warm-season recreational activities somewhat differently from the effects projected by the national analyses. Mendelsohn and Markowski (1999) project increases in water-based activities, especially boating and fishing. But in the Intermountain West, the existing oversubscription of water resources, likely to be magnified by rapid population growth, would almost certainly be accentuated by higher temperatures that increased evapotranspiration. In all probability, water-based recreation would be constrained.

Winter Season

A number of studies have explored the potential effects of rising temperatures on the ski industry from a national perspective (cf. Cline 1992, Hutchins 1999, Loomis and Crespi 1999, Mendelsohn and Markowski 1999). All conclude that climate warming would be detrimental to the industry. Postulated major effects include reduced and seasonally shortened snowpacks, less favorable conditions (e.g. rain producing wet, low-quality snow), all of which would be likely to reduce skier numbers and expenditures. Warmer temperatures would also be likely to increase the need for, and cost of, increased production of artificial snow to compensate for the deficiencies of natural snow.

Fyfe and Flato (1999) modeled the effects of climate change on snowpacks in the northern Rocky Mountains during the 21st century. Their simulations showed shrinking snowpacks during the first two-thirds of the century with complete disappearance by 2070. They based their simulations in part on the Canadian Coupled Global Circulation Model which projects higher temperature increases than the British Hadley Circulation Model (Table 3.8). As discussed in Chapter 4, some authors are adopting more conservative projections (e.g. Mote et al. 1999), suggesting that rain will change to snow later in the fall-spring precipitation season, and snow will revert to rain earlier in the spring. The result would be a shorter snowpack season, reduced but real snowpacks, and earlier spring melt and run-off. As discussed in Chapter 4, hydrographs of a number of western rivers are showing advances in peak, spring run-off possibly indicating that these changes are beginning to occur.

Financial return for ski resorts is importantly a function of the length of the skiing season. Ted Seeholzer, owner-operator of the Beaver Mountain Ski Area in northern Utah, states that he must have a minimum of 100-105 days of skiing in order to realize a profit in a year (Wagner and Baron 1999). Lower-elevation areas, like Seeholzer's (7,200-8,800 ft, 2,194-2,682 m), are at greater risk of reduced snowpacks, shortened snowpack seasons, and loss of economic viability. Regressions of his recorded opening and closing dates on time for the period 1978-2000 are variable, but do show delay in average opening dates of 8 days (December 8-16) over the 22-year period, and advance in the average spring closing dates of 14 days (April 11-March 29). The results are variable and the opening-date test is not statistically significant, but the test for the closing dates is significant at p=0.02 (Fig. 6.4).

At the higher-elevation areas (e.g. 8,000-11,000 ft, 2,439-3,353 m) snow depths are greater, and lower temperatures delay the dates of spring melt. Ski areas typically close in spring, not because of unfavorable snow conditions, but because of declining skier interest. Major concern for higher-elevation areas is the timing of first snow falls that provide sufficient snow for the season openings.

Area operators wish to open as early as possible, both because it lengthens the season, and in order to cater to pent-up desires of skiers who have been anticipating, during summer and fall, the resumption of skiing (Best 2001). Moreover, destination skiers are more likely to travel to a resort later in the season if they can be told in fall telephone calls that snow conditions are already excellent. In total, early snows and season openings build momentum toward strong skier response and more profitable seasons.

Most ski areas now make artificial snow to smooth out variability in early-season snows and opening dates. Virtually all eastern and midwestern resorts make sufficient snow to cover their entire areas in order both to control opening dates and to restore snow cover in cases of midseason thaws (Hutchins 1999). Western areas, at higher elevations and with more dependable snow, have been less aggressive at installing snowmaking equipment. But by 2001, all but three of Colorado's 27 resorts covered some portion of their areas, the Keystone area being the highest at 52% of its terrain (Best 2001). Until 2001, ten of Utah's 14 areas had installed equipment capable of covering anywhere from 2-75% of their areas. In that year the Snowbasin resort installed computerized equipment capable of covering its entire area in preparation for the 2002 Winter Olympics.

Water needed for snowmaking ranges from 140,000-210,000 gallons (52,990-79,485 dekaliters) per acre-foot of snow (Hutchins 1999). Bryan Strait, assistant manager of Utah's Park City Mountain Resort, states that his area uses 4

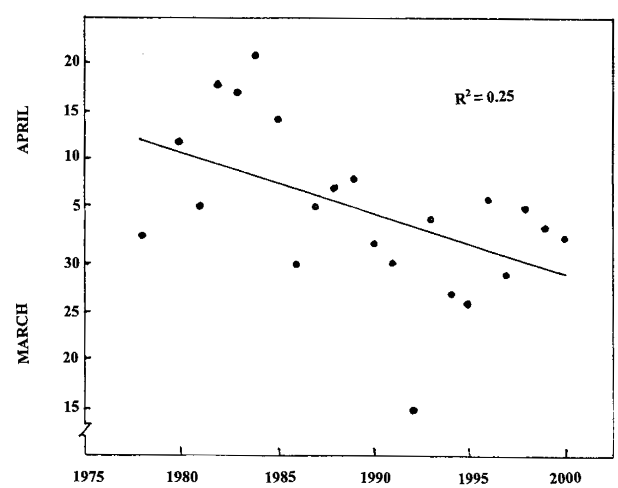

Figure 6.4. Spring closing dates for the Beaver Mountain Ski Area in northern Utah for the period 1978-2000.

million gallons (1,514,000 dl) per day during snowmaking (Pers. Comm., Aug. 19, 1999). Total-season water use in some areas may reach several hundred million gallons (Hutchins 1999). While some areas have access to groundwater, many draw their supply from high-elevation mountain streams. Best (2001) comments that the Keystone resort in Colorado may at times take half the flow of the state's Snake River. All of this is taken within the competitive western water situation with its rising prices.

A further complication for snowmaking is the temperature requirement for the process. Artificial snow can only be made at temperatures at or below 28°F (-2°C) over a period of several hours. In general, the quality of snow improves, and the water need declines, at progressively lower temperatures. It is possible that, if temperatures rose sufficiently, there would be periods when snow could not be made to maintain skiable conditions and skiers would not come out to pursue their sport.

Snowmaking also requires large amounts of electrical energy to force compressed air and water up to the high-elevation spray guns. Energy costs may reach tens of thousand of dollars per day during snowmaking and total hundreds of thousands to low millions per season.

In total, snowmaking becomes a major expense for ski resorts. Utah operators report varying percentages of their total operating costs, ranging from 2% for one resort that covers 7% of its ski area to 20% for a resort that covers 75%. But the industry considers it a needed investment. As Best (2001) states:

> … snowmaking has become almost as essential to the ski industry as ski lifts. They call it insurance, and for ski areas, it's an attempt to divorce their financial fate from whims of weather.

The snowpack changes projected by Fyfe and Flato (1999) would obviously spell the end of the ski industry and associated tourism in the RMGB region by the mid or latter 21st century, if they became reality. But even less-extreme Scenario 2 climate changes would impact the economy of the ski industry by (1) shortening ski-season lengths, (2) increasing costs of artificial snowmaking, and (3) coping with declining water resources associated with increasing evapotranspiration. Three out of seven Utah resort operators stated on questionnaires that there is not now enough water to allow significant increases in machine-made snow.

If, as suggested above, rising costs of skiing have been responsible for slowing the increase in skier numbers in recent years, the added operational costs of snowmaking associated with warmer temperatures would almost certainly be passed on to the customers and raise skier costs further. When asked if his area could operate profitably on artificial snow alone, Deer Valley Resort (Utah) manager Bob Wheaton commented (Pers. Comm., Jan. 5, 2000) that it probably could but with significantly altered operations, higher fees, and different skier expectations. Vice President for Operations Mike Goar of the Solitude Mountain Resort (Utah) stated (Pers. Comm., Oct. 7, 1999) that he makes artificial snow early in the season to ensure that he can open at the same time as the other, in some cases larger, areas. But at present fee structures, he operates at a loss when skiing is supported only on artificial snow.

In general, warmer temperatures and increased reliance on artificial snow would in all probability increase ski-area operating costs and result in higher fees for skiers. The net effect would add to the existing deterrence to growth in the industry, and conceivably be a force for reduction. The lower-elevation areas would be at greatest risk of losing profitability.

A related economic effect of decline in the ski industry could be falling private-property values. Ski areas with significant amounts of private property commonly attract purchase of both custom-designed and speculation homes by well-to-do skiers. Building lots may be priced at $1 million, and some speculation houses carry $7.5 million price tags. Aspen and Vail, Colorado, Jackson, Wyoming, Park City and Deer Valley, Utah and Sun Valley, Idaho are examples. Resort operators comment that if skiing—the original attraction for the economic development, and major contributor to the local economies for 4-6 months of each year—fails, it will almost certainly lead to sharp declines in property values even if extensive summer tourism could be developed.

In sum, a significant decline in skiing, or certainly its complete demise, would mean serious economic loss to the resorts, and to the economies of communities heavily dependent on skiing and not likely to move into Stage 3 of the economic succession. But because skiing is not a major part of the states' total outdoor tourism, or contributor to theirs and the region's economies, the economic impacts at these levels would not be great. Meanwhile increases in the remainder of outdoor tourism, as projected above, would still be expected to contribute positively to the region's economies at all levels under the conditions of Scenario 2.

Scenario 3: Higher Temperatures and Precipitation

Warm-season Activities

The warm-season increases in tourism projected for Scenario 2 could reasonably be expected for Scenario 3. The warmer temperatures of 3 would similarly extend the length of the vacation season, and produce climatic conditions conducive to a variety of outdoor activities. While some recreation specialists report that rainy weather is a deterrent to outdoor recreation, a 50-100% precipitation increase (Table 3.8) in the region's current semi-arid-to-arid annual precipitation levels (e.g. 8-16 in, 20.3-40.6 cm) would still not deter active tourist attraction to the region's outdoor amenities. This is especially true since the greater part of precipitation occurs now, and would be expected to continue occurring, between fall and spring.

One major difference between the effects of Scenario 3 and those of Scenarios 1 and 2 would be on water-based activities. As discussed in Chapter 3, if the precipitation increases projected by the latter 21st century (Table 3.8) occur, they would alleviate the region's water shortage and ensure adequate water resources to support the water-based sports, even allow increases. These could contribute further to the projected increase in warm-season tourism.

Winter Season

The potential effects of Scenario 3 on skiing are more difficult to project than those of Scenario 2 because of the increased precipitation. If the Fyfe and Flato (1999) projections eventuate, then the sport and its associated tourism will not survive. But if the temperature increases were less extreme, the increased precipitation could produce more dependable, mid-season snow, at least at higher elevations. The warmer temperatures would still be likely to reduce season length, and the survival probability of lower-elevation resorts would still be low. But once rain changed to snow at the high elevations, mid-season snowfall could exceed current levels. And the increased water resources could ease the problem of water shortage for snowmaking, and the associated costs.

There is a pressing need for simulation-modeling efforts that project snowpack seasons and magnitudes at different elevations, given a range of temperature and precipitation levels. These would give a better sense of the probabilities surrounding the future of skiing and the ski industry in the RMGB under Scenario 3 climate change.

Beyond the potentially negative effects on skiing, the increases in winter tourism projected for Scenario 2 would also be likely for Scenario 3. Even with decline in skiing, the net effect would be increased contribution of tourism to local, state, and regional economies. The increases might be considerable for local economies in successional Stage 2 that are now heavily dependent on outdoor tourism. But they would not be expected to have significant effects on state and regional economies, given the limited contributions of outdoor tourism to those economies.

CONCLUSIONS

The outdoor amenities of the Rocky Mountain/Great Basin region are powerful tourist attractions for residents of the region, persons from elsewhere in the U.S., and for international tourists, all of whom engage in a wide variety of outdoor activities. The tourist flow into local RMGB communities, the individual states, and the region as a whole has been increasing since World War II, probably for a variety of reasons that include population growth, greater mobility, increasing standards of living, and changing age and ethnic makeup of the U.S. population. In some outdoor pursuits, winter tourism is increasing faster than summer activities.

However skiing, which began increasing in the 1960s, virtually stopped growing nationally in the latter 1980s. Growth has continued up to the present in Colorado and Utah, but at slowing rates and only among resident skiers in Utah.

Outdoor tourism is economically important to many local communities in the RMGB. But despite the visibility of large flows of travelers and facilities built to accommodate them, outdoor tourism's contribution to the economies of the region as a whole and the individual states is not great, perhaps 5% or less.

Several national-level analyses and information sources converge on the view that temperature increases would enhance public participation in outdoor-recreation activities and associated tourism, thereby accelerating the current rates of increase. Extending the length of summer would be an important contributing factor, and moderate winter temperatures could strengthen the already high rate of increase in winter tourism. Skiing would likely be an exception. Most analyses project a decline, if not total demise, of downhill skiing by the mid or latter part of the 21st century.

If temperature increase were not accompanied by precipitation increase, the loss of water to increased evapotranspiration and the accentuated competition for limited water resources associated with a rapidly increasing regional population would likely diminish summer, water-based activities. But if temperature increase were accompanied by significant increase in precipitation, as projected in Table 3.8, there would likely be adequate water to support current uses and an expanded population, as discussed in Chapter 4, and enough to support extensive, water-based recreational activities. The additional precipitation might mitigate, to some degree, the temperature-related pressures on the skiing industry.

In their analyses of the climate-change effects on outdoor recreation nationally, Mendelsohn and Markowski's (1999) models project 7-9% increased expenditures by 2060 on "leisure activities" in response to 5°C (9°F) temperature increase (the approximate increase projected by the Hadley model for the RMGB, Table 3.8) with no precipitation change. Their models project 40-65% increased expenditures on outdoor recreation with 5°C temperature rise and 15% precipitation increase. The projections are based on the aggregate effects on seven outdoor activities including a significant negative effect on skiing.

As discussed above, these projected national trends in expenditures on recreation activities do not equate to increases in tourism per se, nor are the analogous parameters necessarily similar in the RMGB. But they and similar simulated values by Loomis and Crespi (1999), using different models and different aggregates of recreation activities, give some indication of what at least the direction of effect of climate change and related tourism might be in the region. It should be emphasized that whatever the appropriate percentages are for the RMGB, they are the proportionate increases in the very low percentage contribution (perhaps 5% or less) of outdoor tourism to the state and regional economies. For example, a 10% increase in tourism in a state in which tourism contributed 5% to its GSP would constitute an increase of 0.5% to the GSP.

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Chapter 7

NATURAL ECOSYSTEMS I. THE ROCKY MOUNTAINS

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INTRODUCTION

Background and Purpose

This assessment of climate-change effects on Rocky Mountain terrestrial ecosystems is prepared from information generated by a workshop focused on terrestrial systems of the Rocky Mountains, and held in Boulder, CO, on 29-30 September 2000 at the National Center for Atmospheric Research. It is a compilation of this workshop's discussion along with material from earlier workshops.

Because individual participants brought different disciplinary and geographic knowledge of the Rocky Mountains to this workshop, they were asked to provide insights on aspects of Rocky Mountain ecosystem sensitivity to climate change for which they had expertise. Specific future climate scenarios were provided in advance to provide some structure for the members' considerations. Modified versions of those scenarios are discussed later in this report.

The purpose of this chapter is to sum up the best thinking on possible impacts of future climate change on Rocky Mountain terrestrial ecosystems. To a large extent, this document consists of acknowledged suppositions derived from "first principles" logic superimposed on years of experience in this region. Ideas contributed to this report are derived from perspectives covering a wide range of spatial and temporal scales. In this sense, this document is complementary to the Thompson et al. (1998) assessment of "… Potential Future Changes in Climate, Hydrology, and Vegetation in the Western United States" that is based on a common data set and a fixed scale. This report has not benefited from in-depth data analyses of particular issues such as hydrologic or vegetative responses to past climate changes. Nor does it fully utilize the rich ecological literature available for this region. No aspect of this report is, by any means, complete or authoritative. Rather, it aggregates the judgment of a score of people with long experience in the Rocky Mountain region who, by sharing their joint experience

Figure 7.1. The Rocky Mountain Province and surrounding physiographic provinces according to Hunt (1967) extended to the southern New Mexico border between the Rio Grande and edge of the Great Plains. Published with permission of W.H. Freeman and Company.

and cautiously evaluating the evidence, make prudent extrapolations for the future.

The group considered it important to consider regional problems with landuse change, fire suppression, exotic-species invasions, habitat loss of threatened and endangered species, outbreaks of forest pests, and air and water pollution. These issues are ongoing, all too tangible realities, threatening the integrity of Rocky Mountain ecosystems now. Climate change, by comparison is presently an uncertain threat. Nevertheless, workshop participants hewed to the task of focusing on climate change itself, and were unanimous in their opinion that significant change will result from the interaction of climate change with present environmental issues if the projected changes occur.

This report is divided into 12 main sections starting with a brief description of the physical geography of the region and its sources and patterns of variation. Next are sections on hydrology, geomorphology, vegetation as an aggregation of plant cover, and individual species responses as members of the flora and fauna. After brief consideration of timbering, livestock production, and recreational activities in the region, the report terminates with an agenda for needed research and a summary.

REGIONAL GEOGRAPHY

Domain

The geographical domain of this analysis is the Rocky Mountain Province (Hunt 1967) within the conterminous U.S. (Fig. 7.1). This Province is bounded by the Great Plains to the east, and by the Sierra-Cascade, Columbia Plateau, Basin and Range, and Colorado Plateau Provinces to the west. Technically, the Rocky Mountains terminate at their southern limit in northern New Mexico near Albuquerque and the mountains that continue southward to the Texas border are, in fact, part of the Basin and Range Province (Hunt 1967). For the purpose of this report, the Rocky Mountain domain extends to the Texas border to include the mountains east of the Rio Grande.

The Wyoming Basin is included in this domain according to Hunt (Fig. 7.1) along with many smaller valleys and basins lying between the scores of distinct mountain ranges comprising this cordillera. Except for parts of Montana, where several disjunct mountain ranges extend outward into the plains, the eastern boundary is relatively distinct where abrupt increases in slope and changes in lithology mark the junction of the Great Plains with a more-or-less continuous series of mountain flanks. This report does not include the Black Hills which are considered part of the Great Plains. The western boundary is more arbitrary where this Province abuts other provinces containing other mountain systems (Fig. 7.1).

Regional Heterogeneity

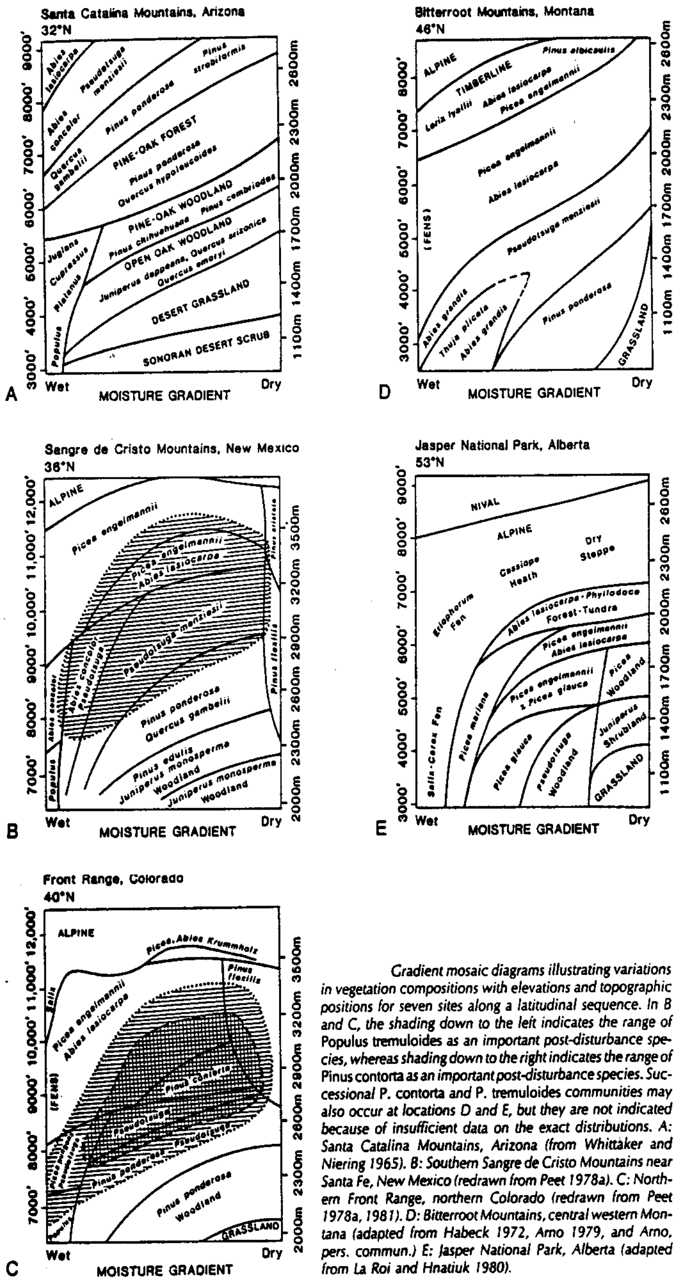
The heterogeneity of the Rocky Mountain Province can best be described in hierarchical terms. At the largest scale, this region extends 17° in latitude, or about 1,900 km (1,181 mi), from the Texas-New Mexico border to Canada. A latitudinal range of this extent imposes not only latitudinal variation in mean temperature at a prescribed elevation, but also significant effects on growing-season length, frost-free periods, and photoperiods. In addition, significant variability in the climatic regime exists within the Rocky Mountains (Bryson and Hare 1974). The northwestern portion of the Province is dominated by a Pacific maritime influence with mild winters and relatively high levels of precipitation for a given elevation. The Central Rocky Mountains are characterized by a relatively even precipitation regime, although winter snow often exceeds summer rain. The Eastern Rocky Mountains generally experience a more continental climate similar to that of the Great Plains, with significant precipitation from summer convective thunderstorms. The Southern Rocky Mountains are more generally aligned with the bimodal regime of the Colorado Plateau, with spring droughts and abundant late-summer thunderstorm activity associated with monsoonal flows from the Gulf of Mexico.

At a smaller spatial scale, the elevational dimension of this Province generates an even stronger axis of heterogeneity than does latitude. Base elevations of the mountain ranges of the Rockies extend from only a few hundred meters in the northwestern Rockies to elevations of greater than 1,200 m (3,937 ft) in the Central Rockies. Maximum elevations in the central Rockies reach 4,000 m (13,123 ft), and individual mountain-range relief varies from a few hundred meters to almost 3,000 m (9,842 ft).

Steep temperature and precipitation gradients result from these elevational extents that, in turn, enforce strong altitudinal gradients in the occurrences of plants and animals. Such variation in occurrence of dominant plants is often characterized in terms of elevational "zones." Boundaries between these zones vary with latitude but typically zonation starts with vegetation describable as a grassland or desert system at the mountain base, and then changes to woodland, then to several forest types, and finally to alpine tundra at the highest elevations (Fig. 7.2). The changes in dominant plant zones and associated animals vary more with elevation at any latitude, than they do along the entire latitudinal gradient of 1,900 km (1,181 mi). The exact locations of these zonal boundaries vary with slope aspect, with boundaries occurring at lower elevations on north-facing slopes than on south-facing slopes (Fig. 7.2).

As a third component of complexity, local and regional variations in geology lead to distinct landforms, soils, and geomorphological processes. The Rocky Mountains is a collective term for a large number of distinct geologic events. Accordingly, individual mountain ranges within the Rockies may be block-faulted uplifts, thrust-faulted overthrusts, broad synclinal folds, or of extrusive or intrusive igneous origin. Broad exposures of rocks ranging from igneous and metamorphic pre-Cambrian basement rocks to Cenozoic or Tertiary volcanics to Tertiary sediments or Quaternary alluvium all occur and interact with regional climate to form distinct soils. At yet a smaller scale, the presence or absence of Pleistocene glaciation is another source of variation. Where glaciation has occurred along the latitudinal axis of the Province, it dominated at higher elevations and in valleys. Glaciated terrains typically have steeper valley walls but more gently graded valley floors than do areas shaped by fluvial erosion.

At a scale of 100s to 1000s of meters, topographic variation imposed by geological structure and geomorphological processes create



Gradient mosaic diagrams illustrating variations in vegetation compositions with elevations and topographic positions for seven sites along a latitudinal sequence. In B and C, the shading down to the left indicates the range of Populus tremuloides as an important post-disturbance species, whereas shading down to the right indicates the range of Pinus contorta as an important post-disturbance species. Successional P. contorta and P. tremuloides communities may also occur at locations D and E, but they are not indicated because of insufficient data on the exact distributions. A: Santa Catalina Mountains, Arizona (from Whittaker and Niering 1965). B: Southern Sangre de Cristo Mountains near Santa Fe, New Mexico (redrawn from Peet 1978a). C: Northern Front Range, northern Colorado (redrawn from Peet 1978a, 1981). D: Bitterroot Mountains, central western Montana (adapted from Habeck 1972, Arno 1979, and Arno, pers. commun.) E: Jasper National Park, Alberta (adapted from La Roi and Hnatiuk 1980).

Figure 7.2. Gradient mosaic diagrams for portions of the Rocky Mountain cordillera extending from 32°N in Arizona (not part of the Rocky Mountains but illustrative for this purpose) through 53°N (part of the Rocky Mountains but beyond the limits of this assessment). This figure was created by Peet (1988) and is published here with the permission of Cambridge University Press. Mosaic diagrams illustrate the distribution of vegetational units in terms of elevation (Y axis) and moisture availability (X axis). The moisture axis represents a number of factors including slope aspect and position with mesotopography of the mountainous landscape. For the purposes of this paper, the X axis may be viewed as a north- to south-facing slope gradient. Note the downward shift of analogous zonal boundaries with elevation. Peet's original caption is retained here to add further information to this figure.

patterns in resource availability for the biota (Fig. 7.3). South-facing slopes are warmer than north-facing slopes; steep slopes shed more water than do shallow slopes, ridges are intrinsically drier than drainages, lower portions of catchments benefit from vadose water more than do upper portions of catchments, water is distributed and stored differently when slopes parallel the dip slope of sedimentary rocks than when they cut across them. Thus, at the scale of hundreds to thousands of meters, topographic variation leads to differential vegetation, animal habitat and, sometimes, propensity for fires or disease outbreaks.

Topography is not the only source of variation at this scale of 100s to 1000s of meters. Historical imprints left by past disturbances mark ecosystems at this and even larger scales. For example, a slope favoring subalpine fir might be occupied by lodgepole pine because of a fire that took place 100 years previously. That imprint will last until succession allows fir to reestablish itself, or yet another disturbance event intervenes. Of course, some of the most obvious historical imprinting has been left in these mountains by clear-cutting and roads associated with forest management (Fig. 7.3).

This recognition of heterogeneity is important because it highlights the difficulty of generalizing at any scale in this region. Assessments of any potential environmental change are made more difficult by the extremes in spatial heterogeneity in mountainous regions than they are in regions of more gentle topography. Similarly, designs of experiments or monitoring systems and models of impacts derived from climate-change projections have to be made in the context of this multiscale heterogeneity. It is essential to match the scale of the phenomenon in question to the appropriate scale of heterogeneity in this and all mountainous regions.

About 25% of the nation's surface water emanates from the Rocky Mountain region (Stohlgren 2000, Chapter 3), providing water supplies to arid and semi-arid regions of at least equal size to the east and west. Most of this water arrives as snow in the winter and is key to natural resources and economic activities of the region. Thus, the distribution of snowfall and consequent pattern of hydrologic river, tunnel, and aqueduct arteries is another layer of critical geographic variation superimposed on the others outlined above.

The social-economic fabric of this region reflects the variability of its natural geography. The region encompasses parts of seven western states, each with its markedly differing political legacies and styles. The most productive portions of the region are generally privately held. But the majority of the area is publicly owned, containing 15 National Park System units, 16 national forests, and hundreds of other agency, state, and conservation lands. The region has historically supported livestock, mining, timbering, and tourism industries but major nodes of industrial production and information/services such as Albuquerque, Colorado's Front Range strip, Salt Lake City, and Boise have grown up in the region (Riebsame 1996). These urban centers extend tentacles of influence along roads and highways into foothill and riparian zones and around recreational facilities at higher elevations. Parts of the Rocky Mountain region are growing 2-3% per year (Stohlgren 2000) while other parts are demographically and economically stagnant.

The Rocky Mountain region includes extensive wilderness areas, nevertheless the hand of humankind has fallen heavily on this region. Despite our American mythology and contemporary wishful thinking, human effects were profound and ubiquitous throughout the Holocene up to the EuroAmerican period (Wagner and Kay 1993). It is possible that many elements of the continent's megafauna were

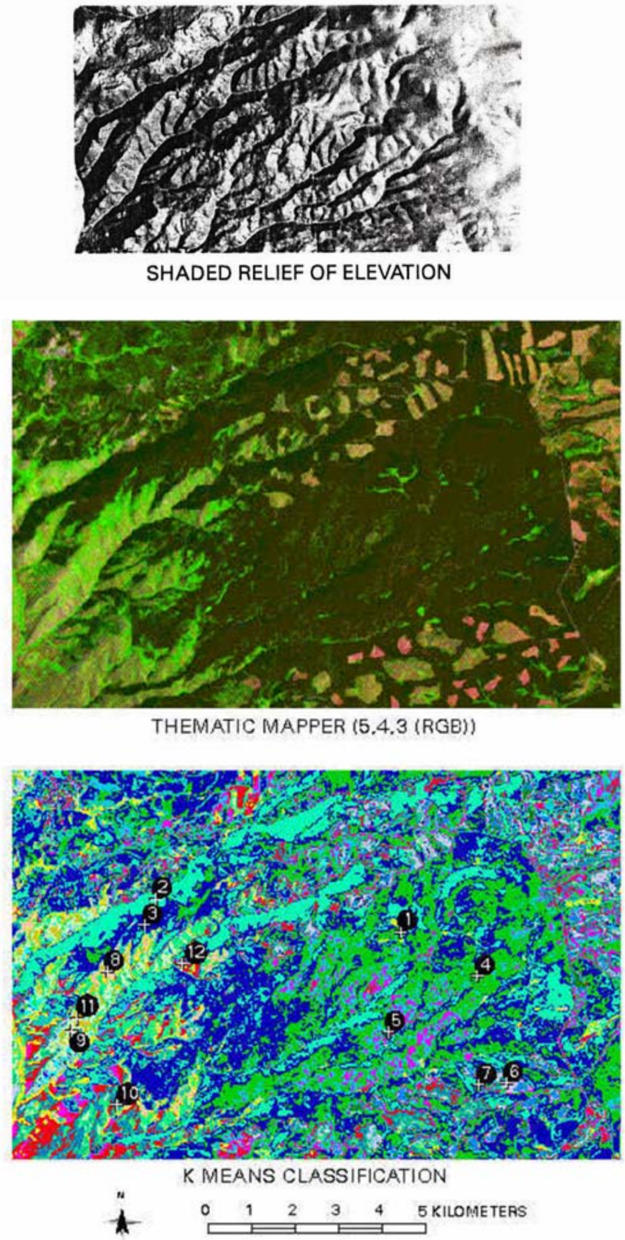


Figure 7.3. (A) Shaded relief visualization of topography for a 12,500 ha (30,888 ac) area centered on the Savage Run Wilderness Area of the Medicine Bow Mountains, south-central Wyoming. The right edge of this image is approximately centered on a broadly arching ridge of these mountains at 3,000 m (9,840 ft) and extends down in elevation to the left to about 2,200 m (7,216 ft). Terrain incision by streams flowing from east to west (right to left) deepens downslope. These west-running drainages create strong topographic patterns with distinct north-slope-south-slope contrasts. (B) A Landsat Thematic Mapper-derived Image of the areas. The TM bands 5/4/3 have been presented as red/green/blue. The dark green, triangular area in the center is the wilderness area. The areas on the right half of the image surrounding the wilderness area have been mostly clear-cut. Some of the vegetation to the left of the image is non-forest. (C) The same area as A but with spectral differences enhanced to show vegetational patterns. Numbered crosses are centered on examples of the following and cover types: (1) non-forested riparian, (2) coniferous forest on mesic, north-facing slopes dominated by Engelmann spruce, subalpine fir, and lodgepole pine; (3) coniferous forest on dry-mesic sites dominated by the same species as 2; (4) lodgepole pine forests on comparatively flat terrain, on broad ridgetops, or on south-facing slopes; (5) rock outcrops, exposed soil, open woodlands with limber pine or lodgepole pine, and the margins of clear-cuts; (6) post-harvest vegetation developing after clear-cutting in the 1980s; (7) post-harvest vegetation developing after clear-cutting prior to the 1980s; (8) aspen, typically in moist environments or on the margins of coniferous forests at lower elevations; (9) foothill meadows and forblands; (10) foothill shrubland dominated by big sagebrush and bitterbrush; (11) foothill shrubland dominated by mountain mahogany, and (12) on image-processing and landcover classification.

hunted to extinction by Clovis people who arrived about 11,500 BP (Martin 1984). Whether this overkill hypothesis is correct or not, the fact that many species of large mammals were lost in a wave of extinctions about this time is incontestable (Pielou 1991). Ecologists can surmise that the loss of both herbivorous and carnivorous species from ecosystems of that time must have had severe "top-down" effects on vegetation and other members of the fauna.

The role of Native Americans in shaping ecosystem structure and function prior to the Euro-American period is inadequately known and hotly contested. There is evidence in some areas like the Northern Rocky Mountains that Native Americans curtailed the sizes of large ungulate populations, particularly elk (Kay 1998), which transmitted effects to forage species and carnivorous elements of those ecosystems (Keigley and Wagner 1998). Native Americans probably also influenced fire regimes in the Rocky Mountains (Wagner and Kay 1993). How these impacts were geographically distributed and varied over this period is poorly known but throws into doubt our concept of what "normative conditions" were as comparisons with the present (Callicott et al. 1999).

Whatever impacts Native Americans might have had, they were dwarfed by the actions of EuroAmericans. Beginning in the mid-19th century, all the lands of the region became managed in one fundamental way or other through mining, grazing, logging, recreation, road construction, fragmentation, fire suppression, near elimination of beaver and grizzly, diminution of cougar and golden eagle populations, probably futile persecution of the coyote, and the temporary extirpation of gray and Mexican gray wolves. Even the most remote wilderness areas are, at the least, affected by altered air and precipitation quality. As we assess the potential impacts of climate change, we recognize that no place in the Rocky Mountain region is without the influence of human action.

CLIMATE CHANGE OVER THE ROCKY MOUNTAIN REGION

Historical Climate Change

Contemporary and future climate change is best viewed in the context of historical climate change in this region. Reconstructions of general climate changes across the entire western U.S. for the last 18,000 years and the climatology underlying those changes are provided by Thompson et al. (1993). This is an excellent foundation source for the larger area encompassing the Rocky Mountain region. Considerable paleoecological work of high quality has been done in the Rocky Mountains themselves (for reviews see Thompson 1988, Thompson et al. 1993, and for more recent work see Whitlock and Bartlein 1993, Feiler et al. 1997). But inferences about climate in these publications are usually stated in relative terms (cooler-warmer, wetter-dryer); numerical values for temperature and precipitation over the last 22,000 years are difficult to obtain.

Temperature differences between the present and the most recent glacial maximum (22,400 to 12,200 yr BP) have been estimated as 9°C (16.2°F) by Fall (1988) for Colorado, as 7° to 13°C (12.6-23.4°F) by Mears (1981) for the Wyoming Basin, and as ~10-15°C (18.0-27.0°F) in the Greater Yellowstone Ecosystem (GYE)

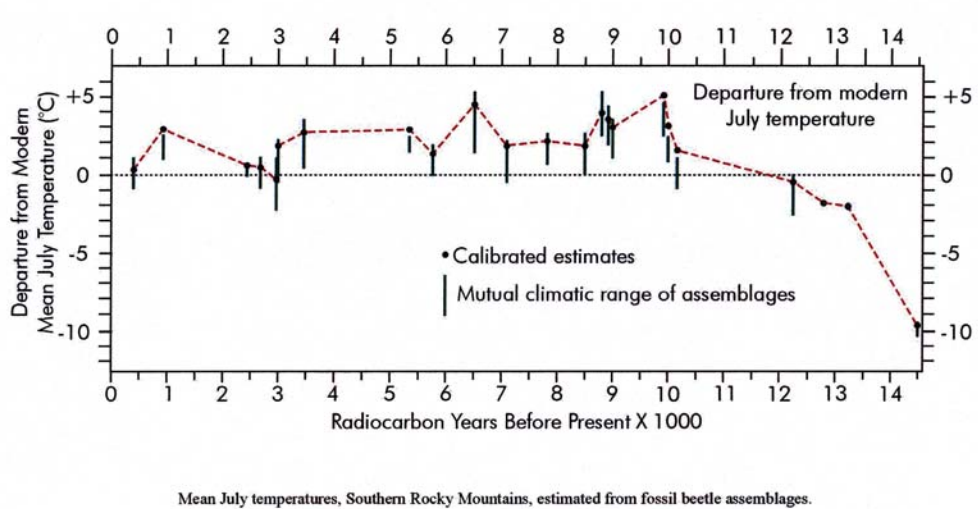


Figure 7.4. Mean July temperature departures from modern values for the Southern Rocky Mountains for the last 14.5k yr estimated from fossil beetle assemblages (Elias 1996).

(Porter et al. 1983). Based on fossil insect evidence, Elias (1996) estimated that mean July temperatures were 9-10°C (16.2-18.0°F)colder than today during the last glacial maximum (Fig. 7.4), and that mean January temperatures may have been as much as 23°C (41.4°F) colder than today. With closure of the most recent Ice Age, rapid deglaciation was complete by 14,000 to 15,000 yr BP in the southern part of the cordillera (Fall 1988) and by 10,000 to 11,000 yr BP in the Yellowstone Plateau area (Whitlock 1993). During this late glacial period, pollen studies suggest that temperatures were 3-4.5°C (5.4-8.1°F) cooler than the present and the treeline had ascended to about 500 to 700 m (1,640-2,296 ft) below the modern treeline (Fall 1988). However, the fossil insect evidence (Fig. 7.4) suggests that modern summer temperature levels were reached as early as 12,000 yr BP in the Rocky Mountain region (Elias 1996).

With the beginning of the Holocene (12,000 BP), conditions generally warmed but fluctuated irregularly across this region as well as the rest of the globe. Terms such as the "Medieval Warm Epoch" (MWE) supposedly characterizing the 11th-13th Centuries, and "Little Ice Age" characterizing the period 1550-1850 A.D. have been applied to climatic deviations that may not have behaved in the same way at the same time or with the same amplitude in other areas including the Rocky Mountains. Thus, we are advised by Bradley (2000) to refer to the MWE as the "Medieval Climatic Anomaly" and view the Little Ice Age as possibly having a longer time span than that normally applied and demonstrating different conditions than inferred elsewhere.

Based on pollen evidence, temperatures were warmer than present for the southern Rockies from 9,000 to 4,500 yr BP when upper treeline may have been 300 m higher than it is presently (Fall 1988). Fossil insect evidence indicates that warmer-than-modern summer temperatures existed in this region as early as 10,000 yr BP (Fig. 7.4), and persisted until about 3,500 yr BP (Elias, 1996). The pollen evidence suggests that regional temperatures cooled below current levels 4,500 to 3,100 BP (Fall 1988), warmed slightly between 3,000 to 2,000 yr BP, then cooled again during the Little Ice Age between 1550 and 1850 AD. Temperatures have been warming slowly since the end of the Little Ice Age. In general, precipitation regimes varied with temperature, becoming wetter in warm periods and dryer in cold periods.

There is evidence that temperature changes in recent millennia may sometimes have been rapid (Fall 1988, Graumlich 1993, Hughes and Graumlich 1996, Elias 1996, Schuster et al. 2000), sometimes as much as 10°C (18.0°F) in a few years (Grootes et al. 1993, Alley et al. 1993, Alley 2000). According to Schuster et al. (2000), climate changes during the Holocene in the topographically complex and latitudinally extended Rocky Mountains have been abrupt—sometimes decadal in scale—bi-directional and unpredictable.

In summary, the Rocky Mountain region has experienced wide swings in temperature, perhaps in the order of 10°C (18.0°F) for summer temperatures, and poorly documented precipitation variation throughout the Holocene. These changes are of amplitudes equivalent to those forecast for the next century.

It has been the common wisdom that the rates of change for projected new climates will be faster than those experienced in the past. In fact, the past millennia have been highly variable. But any generalizations turn on whether these were random or oscillatory variations around relatively unchanging, or slowly changing, mean secular trends over time scales of a century or more. As discussed in Chapter 3 (cf. Fig. 3.19), the proxy temperature evidence for North America shows abrupt interannual and decadal variation from 1000-1998, but superimposed on a gradually declining net trend to about 1900. Since 1900, instrumental data show a rise, still with abrupt short-term variations, to mean levels far above anything experienced in the preceding millennium. More data and synthesis of existing data are needed to adjudicate the rate of change over defined ranges.

Present and Future Climate Change

The Global Perspective

The dominance of opinion on the evidence for global warming has been reinforced in recent months by the continuing trend of increasing global surface temperatures, e.g. (http://www.ncdc.noaa.gov/ol/climate/research/1999/ann/triad_ann99_pg.gif), new data on heat accumulation in the oceans (Levitus et al. 2000), on river and lake ice melting (Magnuson et al. 2000), by a number of world-wide biological indicators (Hughes 2000), and by the weight of reaction of the scientific community (National Assessment Synthesis Team [NAST] 2000), Intergovernmental Panel on Climate Change (IPCC)). In fact, on 26 October 2000, the IPCC increased its estimate of the upper limit of possible global temperature change for this century to 6°C (10.8°F) (http://www.ipcc.ch/).

Scientific opinion that at least some of this warming is related to human influence on the atmosphere has recently been strengthened by model and statistical results by Andronova and Schlesinger (2000), Delworth and Knutson (2000) and Crowley (2000). Concern that climate changes might be more rapid and step-like than previously thought has also been heightened in the scientific community as illustrated by the 97(4) special issue of the Proceedings of the National Academy of Science published in February 2000. While general climate models generally concur in predicting further global climate change as a result of the balance of changing radiative forcing factors, there remains considerable disagreement as to the magnitude of the change, and especially how changes will be distributed on different parts of Earth's surface (Kerr 2000). In addition, it is becoming increasingly apparent that changes in landcover/landuse might mitigate or augment mesoscale climate changes in significant, but still unrealized, ways (Couzin 2000).

The Western United States Perspective

In spite of serious uncertainties about regional climate change, Chapter 8 of the NAST 2000 report (Smith et al. 2000) makes the following summarizing statements about the 20th Century climate change for the "western United States." It is important to note that this chapter covers all of the southwestern United States and only includes the Utah, Colorado, and New Mexico Rockies:

- "In the 20th century, temperatures in the West rose 2°F to 5°F (*1.1 to 2.8°C*).
- The region generally became wetter, with some areas having increases of greater than 50%. A few areas, such as Arizona, became drier and experienced more droughts. But, the length of the snow season in California and Nevada decreased by about 16 days from 1951 to 1996."

Prognoses based on selected scenarios for the coming century made in the same chapter include the following:

- "During the 21st century, temperatures will increase throughout the region, at a rate faster than that observed, with two GCMs projecting increased temperatures of about 3°F *(1.7°C)* to over 4°F (*2.2°C*) by the 2030s and 8°F (*4.4°C*) to 11°F (*6.1°C*) by the 2090s.
- The two GCMs also estimate increased precipitation, particularly during winter, and especially over California. However, parts of the Rocky Mountains are estimated to get drier and one of the two models has most of the region getting drier in the 2030s. And there is a slight chance the climate over much of the West could become drier for certain time periods during the 21st century.
- Under the GCM scenarios, runoff is estimated to double in California by the 2090s, but the climate models also suggest there could be more extreme wet and dry years in the region."

As noted, these statements only applied to the southern Rockies. The part of the Rocky Mountain Province occurring in Wyoming and central Montana (Fig. 7.1) is putatively covered by the NAST chapter for the Great Plains, but in fact is not discussed (Joyce et al. 2000). The Rocky Mountains of Idaho and western Montana are putatively covered in the NAST chapter on the Pacific Northwest (Parson 2000) but where "interior forests" are discussed, they are lumped with mountains much farther west.

Moreover, these projected increases are based on GCMs (general circulation models) that do not resolve topography even at the scale of the Rocky Mountain cordillera, that have limited capacity to project precipitation trends, and whose outputs differ among themselves to varying degrees (cf. Table 3.8). Only two GCMs out of a possible ten or so were chosen to make these projections. Some models are better at some processes and some at others. Moreover, these models are designed for making global estimations and are being pushed beyond their bounds of design or resolution to make regional projections. NAST itself makes clear the limitations of GCMs for projecting climate changes at the regional level (MacCracken et al. 2000). Contributors to this report view the specificity of the projections reported by NAST with some reservation, but do consider that some extent of warming is not only possible, but likely.

The Rocky Mountain Regional Perspective

In reviewing evidence for 20th-century climate trends in the Rocky Mountain region specifically, it should be noted at the outset that it is particularly difficult to detect trends in the western United States in general and the Rocky Mountain region in particular because of wide swings in short-term climate at several scales. As discussed above, weather varies widely on an inter-annual basis at any particular station. Stohlgren (Chapter 3) analyzed data for Estes Park, CO over the 1931-1993 period. During that interval, annual temperature varied from the average by +/- 0.6°C and precipitation varied by +/-29.6%. In addition to inter-annual variations, sub-decadal and decadal variations occur in relationship with both the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillations (PDO) as discussed in Chapter 3. Further complicating the analysis, the precipitation patterns for the northern half of the Rocky Mountain region (north of 40°N) oscillate inversely to the southern half (cf. Cayan et al. 1998, Dettinger et al. 1998, and discussion in Chapter 3).

In the face of this apparent climatic noise, four types of analyses pertaining to changes within the last 100 years are available: temperature and precipitation data over the last 100 years, streamflow data for undammed Rocky Mountain region streams, glacier recession rates, and upper treeline changes.

Trends in 20th-century climates in the Rocky Mountain/Great Basin region were analyzed by Baldwin in Chapter 3. His results show increases in mean, annual minimum temperatures of 0.62°C (1.12°F), 0.40°C (0.72°F), and 0.54°C (0.97°F) for the Northern, North-central, and West-central Rockies respectively, all significant at $p<0.01$, during the 20th century. The trends in minima were not significant at $p=0.05$ in the East-central and Southern Rockies (Table 3.5). Mean, annual maxima increased significantly only in the Northern Rockies, at 0.67°C (1.21°F) per 100 years. Trends in annual, average temperatures were the same in the five subregions (Fig. 3.20). Baldwin's analyses also showed that 20th-century annual precipitation rose significantly in the Northern and North-central Rockies, but not significantly in the West-central, East-central, and Southern subregions (Fig. 3.23).

Kittel had similar results with slightly different subdivision of the Rocky Mountain chain. He found significant, positive trends for mean, minimum temperatures, and for annual and seasonal precipitation in his Northern and Central Rockies subdivisions. There were no such trends in the Southern Rockies (Figs. 3.22, 3.26).

Collectively, these results indicate temperature and precipitation increases from approximately the latitude of northern Utah northward to the Canadian border. And combined with Kittel's evidence of more pronounced trends in the Canadian Rockies, they are consistent with poleward increases in temperature change, and more pronounced increases in nighttime minima. In Chapter 4, Baldwin et al. analyzed streamflow timing in three streams of the West-central and North-central Rockies. They found the contemporary dates of peak run-off have advanced 10-15 days over those of 1950-1970. Dettinger (2000) reported similar advances in streams of the northern-U.S. Rockies that he attributed to "… spring temperatures which have warmed significantly since 1945 … in this region …"

A warming climate will increase evapotranspiration (PET). Without a commensurate increase in precipitation to balance a higher PET for an area, a regional decline in annual stream discharges could reasonably be expected. In Chapter 4, Baldwin et al. analyzed trends in 20th-century flow in four streams with headwaters in the Rocky Mountain system. Three showed significant increases in flow over the period (Fig. 4.2), and a fourth showed increase but the test fell short of significance. A fifth, the San Juan in southern Colorado, was well short of significance. Lettenmaier et al. (1994) similarly recorded flow increases in streams of the northern-U.S. Rockies, and Kittel et al. (2002) reported similar increases in streams of the Canadian Rockies. However the Chapter 4 analyses found no trends toward increase in 20th-century flows of the Colorado River and its tributaries, largely in Colorado.

We conclude that the evidence points to increase in the flows of a number of streams, during the 20th century, in the western and northern portions of the Rocky Mountain system. These are portions of the Intermountain West in which precipitation increases over the same period have been documented. However, streams of the southern Rockies, where no precipitation increase has occurred, show no net trends in streamflow during the 1900s.

These levels of temperature change are less than the 1.1 to 2.8°C (1.98-5.04°F) increase reported for the western U.S. by the NAST Report (Smith et al. 2000). Precipitation increases occurred only in the northern regions. The rates of temperature increase, where they occurred, were linear in form over this 100-year period. Thus, they may represent changes related to continued warming at the end of the Little Ice Age—although temperature trends in the early part of the 1900s were downward (Kittel et al. 2002)—or they may be related to the onset of the Industrial Revolution around the mid-19th century, or both factors may have been involved. The present increase in atmospheric CO_2 content becomes noticeable in ice core records by 1850. The combined radiative forcing function of CO_2 and other greenhouse gases, along with slight increases in solar forcing (Lean et al. 1995) and the counter-balancing effect of increasing aerosols, accelerated to their present levels of annual increase around 1980 (Shine et al. 1990, Schimel et al. 1996). However, Mann et al. (1998) reported evidence of earlier temperature increases for the northern hemisphere.

In this region, hydrographs primarily reflect melting of the winter snowpack. A shift from precipitation as snow to rain together with warming temperatures would be expected to accelerate the timing of stream runoff.

Two other sets of observations provide supporting evidence for subregional warming in the Rocky Mountain region. The first is evidence for accelerated melting of glaciers in Montana and Wyoming (Fagre and Peterson 2000, Schuster et al. 2000). The second set of observations are changes in krummholz tree growth to more erect forms (Hessl and Baker 1997a) and in-filling between krummholz patches by tree regeneration (Hessl and Baker 1997b). Moir et al. (1999) also recorded trees in-filling subalpine meadows.

One well-documented example of climate change in the region is actually one for cooling in the Front Range area of Colorado. Chase et al. (1999) and Stohlgren et al. (1998b) have shown that the foothill-plains areas at the base of the Front Range have cooled since the early 1930s, probably because of increased latent energy in the area due to irrigation and other landuse changes. This is an example of how landcover can modify climate at the mesoscale.

In summary, these lines of evidence support the probability that the northern portions of the Rocky Mountains have warmed slightly, particularly at night and in the winter, over the last 100 years. And they point to increases in precipitation in the same region.

Climate Scenarios for Possible Future Change

The National Assessment Synthesis Team (NAST 2000) has prepared scenarios for consideration at the national level for the latter decades of the 21st century (MacCracken et al. 2000), and with appropriate caveats for smaller areas, particularly the Rocky Mountains. Downscaling these models is problematic as there is typically wide variation in temperature for areas as small as the Rocky Mountain region, and even greater variation in precipitation. General circulation models (GCMs) necessarily operate at relatively coarse spatial scales that do not represent ground and atmospheric conditions well at the scale of hundreds of kilometers.

Beyond the typical constraints and limitations associated with these models, the Rocky Mountains must be considered a particularly difficult area for downscaling. The extraordinary heterogeneity discussed above is homogenized by these models, with the entire Rocky Mountain region exhibiting less relief than is typical for an individual small range within the region. While relatively sophisticated downscaling techniques were employed to increase the spatial resolution of the projections, in many cases these represent extrapolation, rather than interpolation, and the base simulations fail to capture topographic features known to have significant influence on the climate of the Rocky Mountains (Mock

1996, Bartlein et al. 1997). Nor can these models take into account mesoscale landcover/landuse effects such as demonstrated by Stohlgren et al. (1998) for the Colorado Front Range, which are changing faster in the Rocky Mountains than in many other areas of the country.

A climate-change scenario by Thompson et al. (1998) exemplifies these kinds of problems. These authors demonstrated a scenario based on the NCAR GENESIS AGCM (atmospheric circulation model) for a $2xCO_2$ global climate at 4.4° lat. by 7.5° long. Output from this global model was scaled down by the NCAR RegCm regional climate model to a grid of 60 x 60 km (37.3x3.7.3 mi). Output from that grid was further interpolated onto a 15 km (9.3 mi) grid on the basis of topography for driving hydrologic and vegetation models. Methodological problems notwithstanding, results from this approach are the state-of-the-art and their results must be taken seriously, if with some reserve.

Thompson et al. showed model output for January and July mean temperatures and precipitation totals distributed to 15 km grid units and mapped present versus potential anomalies at 60 km. This latter output shows the northern Rockies warming by 3°C (5.4°F) and the southern Rockies by 1-2°C (1.8-3.6°F) in January, and all of the Rockies warming by 3°C (5.4°F) in July. It also shows a complex pattern of precipitation change for January, with most areas increasing by 0 to 10 mm (0-0.39 in) except for Montana, western Colorado and northern New Mexico which decrease by 10-20 mm (0.39-0.78 in). In general, this model projects an increase in July precipitation by 0 to 30 mm (0-1.18 in) north of 41°N and decreasing by 30 mm (1.18 in) south of 41°N.

As a basis for deliberations in this workshop, Assessment Team members posed a set of climate-change scenarios for consideration of possible effects on Rocky Mountain ecosystems (Table 7.1). Selection of these scenarios began with the model projections set forth in Table 3.9, but with three modifications: (1) The Hadley projections were used as a base because they are more conservative than those of the Canadian model. (2) Because the historical climate analysis of Chapter 3, and that of Kittel et al. (2002), showed more pronounced 20th-century temperature and precipitation change in northerly subregions of the Rockies than in the southerly and eastern subregions, scenarios for the Northern, North-central, and West-central subregions (cf. Fig 3.18) were given 1°C (1.8°F) higher temperature projections and slightly higher precipitation increases than the East-central and Southern Rockies subregions. (3) Some authors have suggested that increased temperatures in the West might elicit summer-precipitation increases through strong, northward extension of summer monsoons. Hence, scenarios are posed with increased summer precipitation in Table 7.1.

Snowpack, a central variable in ecosystem function in this region, was adjusted to reflect temperature changes combined with precipitation seasonality. For example, the first scenario for the northern group is warmer but also wetter (Table 7.1). This was considered to

Table 7.1

Scenarios for Assessment of Ecosystem Sensitivity to Climate Changes Within Rocky Mountains

Subregion[1]	Scenario	°C Mean Temperature Increase[2]	mm/day Precip. Change	Snowpack
Northern, North-central, West-central Rockies	1 Winter	+4.5	+2.0 to +3.0	No change
	Spring	+2.5	0.0 to +0.5	
	Summer	+4.0	0.0 to +0.5	
	Fall	+3.5	+0.5 to +1.5	
Northern, North-central, West-central Rockies	2 Winter	+4.5	0.0 to +0.5	Reduced to none
	Spring	+2.5	+0.5 to +1.5	
	Summer	+4.0	+2.0 to +3.0	
	Fall	+3.5	0.0 to +0.5	
East-central and Southern Rockies	1 Winter	+3.5	+1.0 to +1.5	Reduced
	Spring	+1.5	-1.0 to -0.5	
	Summer	+3.0	-1.0 to -0.5	
	Fall	+2.5	-0.5 to +0.5	
East-central and Southern Rockies	2 Winter	+3.5	-1.0 to -0.5	Reduced to none
	Spring	+1.5	-0.5 to +0.5	
	Summer	+3.0	+1.0 to +1.5	
	Fall	+2.5	-1.0 to -0.5	

[1]Subregions are same as those shown in Fig. 3.18.
[2]Temperature increases are expected to result more from elevations in night-time minima than from day-time maxima.

lead to no net change in the snow pack. But with warmer temperatures and less winter precipitation, a reduction or elimination of the snowpack was posed. Both scenarios for the southern Rockies led to declines or elimination of the snowpack.

The climate changes shown in Table 7.1 are working values prepared to aid in estimating ranges of ecological responses. The values are not a formally derived set of climate-change projections for the Rocky Mountain region.

HYDROLOGIC RESPONSES TO CLIMATE-CHANGE SCENARIOS

General Patterns of Change

The importance of changes in seasonality and amount of water resources in the arid and semi-arid western states was noted by the compilers to the NAST report (Smith et al. 2000), and discussed in Chapter 4 of this report. Any permanent changes in the amount, timing and form of precipitation; the spatial and temporal extent of snowpack; the temporal variation in stream discharge, or the timing and total volume of stream discharge would affect every aspect of the Rocky Mountains and much of the regions surrounding them. The importance of snowpack to life in and around the Rocky Mountains cannot be overemphasized. It is an important determinant of the mesoscale climatology of the region, a control of vegetation and animal life at the landscape scale, as well as being the primary source of ground and surface water (Liston 1999).

Based on the stream hydrograph data presented above and general principles, some general predictions can be deduced:

(1) If winter precipitation changes to rain, or if precipitation seasonality shifts from winter to summer, then:

(a) Temporal extent and volume of snowpack will decrease, and mountain catchments will discharge more water more evenly through winter and spring.

As a result:

· Peak flows will be lower and earlier in the year.

· Lower hydrographic peaks will influence aquatic communities, geomorphic processes, and water management strategies.

· Water available for mountain vegetation will decline earlier in the growing season.

(b) Geomorphic processes will shift from cryoturbation (snow and ice abrasion) and avalanche-related processes to fluvial erosion and deposition processes.

(c) Glacial melting will accelerate.

(2) If annual or growing-season precipitation is less than the water demand created by higher temperatures, then:

(a) A larger percentage of incoming water will be lost to evaporation and transpiration (ET). As a result:

· A smaller percentage of water will be available for runoff to downstream ecosystems and socio-economic uses.

· Vegetation will undergo moisture stress for longer periods of time, with the result that

· Vegetation will be more combustible for longer periods.

(b) Fluvial erosion rates will decline.

(c) Glacial melting will accelerate so that glacial contribution to streamflow, especially in late summer, may increase in the short term, but decrease in the long term.

(3) If global warming intensifies the hydrologic cycle in general, then:

(a) Cloudiness would increase and it would produce:

· Increased orographic precipitation.

· Reduced solar radiation in the mountains which would:

· Steepen precipitation gradient between mountains and lowland.

· Reduce night-time reradiation, particularly at high elevations, and reduce night-time cooling.

· Daytime cooling and night-time warming.

(b) More water available for streamflows.

Thompson et al. (1998) projected how some hydrologic features of the Rocky Mountains would react to their climate-change projections. They projected that Yellowstone Lake might experience the following: average temperature would increase from the present 11.6° to 13.2°C (20.9-23.8°F); ice cover would decrease from the present 196 days to 152 days; concomitant longer periods of mixing would appear throughout the water column and less snow cover and ice thickness would result during the winter.

Several hydrologic simulation models have been exercised for altered climate conditions for well-parameterized Rocky Mountain catchments. Perhaps the first was a relatively simple simulation by Revelle and Waggoner (1983) in which they forecast a reduction in streamflow throughout the United States of 40-70%. Later, Running and Nemani (1991) simulated a climate projection with FOREST-BGC coupled with MT-CLIM for the Swan Range area of Montana. Their model indicates that an increase in air temperature of 4°C (7.2°F) and an additional 10% precipitation would net a decrease in snowpack duration by 19-69 days, depending on location in the landscape, and a decrease in outflow by as much as 30%. Nash and Gleick (1991) used a "conceptual model" to simulate effects of temperature and precipitation change on stream discharge in several sub-basins of the Colorado River. Flows would decrease with temperature increases and vary as anticipated with higher or lower amounts of precipitation. According to this model, flows would be more sensitive to precipitation changes than to temperature changes. Rango and van Katwijk (1990), using a non-distributed snowmelt model (SRM), simulated snowmelt runoff scenarios for two Rocky Mountain catchments. Simulating a 3°C (5.4°F) warming, with or without a 10% change in overall precipitation, leads to a simulated outcome of 20-40% decrease in runoff in months of peak water demand.

These hydrologic results confirm intuitive conclusions that soil-moisture availability, water yield, time of peak flow, and amount and duration of snowpack would be affected by the annual cycle of water-budget variables as would be expected from first principles. The amounts to which these variables would change and their timing change are dependent on details of the models and assumptions about intervening events such as forest disease or fire on the catchments being simulated. It is important to discriminate between probable trends for Rocky Mountain hydrology in general, and outcomes for actual catchments in particular.

A Case Study: The Loch Vale Simulation

Baron et al. (2000) examined the sensitivity of hydrologic and ecologic components of the Loch Vale headwater catchment in Colorado using RHESSys (Regional Hydrologic-Ecological Simulation System) with a TOPMODEL hydrological component. This area has undergone cooling in the past 40 years (Chase et al. 1999), so they ran the simulations at –2° (-3.6°F), +2° (+3.6°F), and +4°C (+7.2°F) in conjunction with –10% and +10% precipitation and various degrees of direct CO_2 effects on water-use efficiency. These simulations are quite similar to the range of scenarios presented in Table 7.1. In general, cooling led to greater snowpack, slightly less runoff, evaporation, and transpiration. The +4°C (+7.2°F) simulation projected a snowpack reduced by 50% and a runoff peak advanced by 4-5 weeks. These results are particularly useful in their representation of high-elevation catchments where evapotranspiration effects of plants are less important to the water budget. Forested catchments might be expected to show a lesser yield at higher temperatures because of higher evapotranspiration losses.

These simulation results support some of the projections made by other model simulations described above. In summary, more data synthesis of past trends and responses to climatic deviations as well as more simulation exercises of this type are needed to fully explore the range of response that might be expected within the range of scenarios tabulated above. If climate changes of sufficient magnitude do occur, there is every reason to think that hydrologic responses will result in this semi-arid region.

GEOMORPHIC RESPONSES TO CLIMATE-CHANGE SCENARIOS

Geomorphic responses to climate change have been overlooked among the "key issues" listed in Smith et al. (2000) for the western United States, but consideration of them is important to the ecosystem orientation of this assessment. Such processes logically follow on hydrology inasmuch as the movement of water is intimately linked with the many processes by which materials are moved.

Geomorphology (sometimes termed earth surface processes) is the science addressing the form of the land surface and the processes underlying those forms (Summerfield 1991). It is the branch of geology that describes and predicts how processes like weathering and fluvial, glacial, colluvial (mass movement in response to gravity), and aeolian erosion reshape the surfaces provided by tectonic uplift, vulcanism, and sedimentary aggradational processes. Climate is a fundamental variable controlling the relative importance of surface processes. As climate changes, the net sum of processes will change as well. In fact, many of the principles of geomorphology such as "open systems," "disequilibrium," "entropy," and "multiple controlling factors" are shared with ecologists and soil scientists.

Consideration of climate change is very much part of geomorphology (Eybergen and Imeson 1989, Bull 1991) although it is primarily used in retrospective analysis. In this respect, there is a close relationship between geomorphology and paleoecology. But, surface processes are pervasive in mountainous environments—the kind of environment being assessed here. These processes have influences on soil formation, plant longevity, and even the welfare of animal population conditions. For example, deer, mountain goat, grizzly bear, and even wolverine activities have been shown to be greater around avalanche tracks than surrounding terrain covered with older vegetation (Krajick 1999). Erosion dominates over aggradation for the most part in mountainous landscapes although alluvium deposition and reworking are critical processes in mountain valleys. Erosion is brought about by glacial, fluvial, and colluvial processes. Changes in snow distribution by wind (Hiemstra et al. 2000) and increases or decreases in rain will alter the rates of all of these forms of erosion and consequent deposition within and beyond mountain landscapes. This is a large topic with a rich literature (e.g. Menounos and Reasoner 1997) that can only be highlighted in passing here.

The tools are available to predict how climate warming might accelerate glacial retreat and enhance deposition of glacial debris, reduce freeze-thaw (cryoturbation) activity at high altitudes, reduce snow avalanches and debris torrents down steep mountain slopes, accelerate fluvial incision of channels in some cases, and aggradation in others (e.g. Eybergen and Imeson 1989, Bull 1991, Hiemstra et al. 2000). All of these processes are dependent on the altitude, local climate, slope steepness and form, and the lithology of the terrain in question. Thus, generalization is only possible in the broadest terms. Inclusion of geomorphic processes in any detail would require specification of local conditions.

Workshop members did not have the expertise to provide professional opinions on how climate change might influence dominating, recurrent surface processes in the Rocky Mountain region so that any such analysis is inappropriate here. However, changes in geomorphic regimes should be incorporated in more holistic analysis of climate-change effects in a more thorough assessment effort.

VEGETATION

Vegetational Zonation: A Construct for Generalization About

Climate-change Effects

In this assessment, the plants of the region are differentiated as "flora" and as "vegetation." Flora is the total species list of a designated area. Vegetation is the plant cover of the area. Floras are inclusive listings of all the taxa in an area regardless of the ecological importance or environmental preferences of any taxon. Vegetation is described in terms of the physical structure imposed by the plant cover in terms of form (evergreen or deciduous trees, shrubs, herbs, etc.), and in terms of the identities of dominant species. A focus on plants as vegetation is imperative because vegetation defines the primary energetic and biogeochemical functions of the landscape in which it occurs, influences hydrologic budgets and geomorphic processes, provides fuel for fire and substrates for pests, and, to a large extent, determines habitat for animal and microbial life.

There are three primary axes of variation in the distribution of vegetation in the Rocky Mountains: elevation, geology and climate. As described earlier, dominant plant species tend to sort out along complex environmental gradients associated with elevation, forming loosely structured "zones" or "bands." The zones have transitions between them termed ecotones, and the elevational position of the ecotones vary with latitude and moisture gradients associated with the effects of slope-aspect (Fig. 7.2). We emphasize that vegetation zones are mental constructs providing a convenient structure for general discussion over broad areas. Closer inspection of vegetation in any particular place reveals that vegetation is better described in some places and at some scales as gradients, and in other places and scales as complex patch mosaics.

Three points to note in Fig. 7.2 are that:

(1) Where the zones have the same character (e.g. alpine zone), their boundaries move down in elevation with increasing latitude;

(2) The effect of slope-aspect increases with latitude; and

(3) The nature of the zones themselves changes with latitude through the addition and loss of dominant species.

The first point indicates that temperature is a strongly controlling factor, and that the cooler temperatures associated with higher elevations can compensate for the higher mean annual temperatures of lower latitudes. The second point reflects the influence of topographic shading on direct solar radiation, with increasingly significant effects at higher latitudes.

The third point is more complex. In part such latitudinal changes stem from insufficient elevation effects to compensate for very large latitudinal effects on temperature, but also in part from differences in climate regime (seasonality of precipitation and temperature and differences in climate variability) which do not vary smoothly with latitude. For example, given similar mean annual temperatures and precipitation amounts, the Pacific maritime, Great Basin, and Arizona monsoon climates support different vegetation adapted to the peculiarities of those regimes.

Zonal generalizations about vegetation assume a dominance of climatic variables and minor role for edaphic (soil) variables. A caveat is appropriate here. The Rocky Mountains were rejuvenated in the Pliocene and sculpted by ice in the Pleistocene so that many, but not all, slopes are steep, surfaces relatively young, and soils relatively immature in the region. Consequently the physical and chemical properties of Rocky Mountain soils are strongly determined by soil parent material—underlying rocks—and less modified by climate as would be the case in older terrains. Due to the high level of variability in geology of these soil parent materials, the properties of the immature soils are also quite variable, producing sometimes dramatic spatial heterogeneity throughout the Rocky Mountains. This spatial variability of soil properties, in turn, constrains the possible migration of plant species in response to changes in climate.

This last caveat notwithstanding, the zonal structure of Rocky Mountain vegetation provides a convenient conceptualization for discussing vegetation change resulting from warming and altered precipitation patterns. It provides a general language for making vegetation-change projections based on simplistic, first-order logic and on the expert opinions of the workshop participants. The most general projection that can be made for a warmer, dryer scenario is that all of the boundaries will move upward in elevation in response to warming. If such were to occur, forested zones could be eliminated from low mountains as the lower treeline ascends past the summit, and alpine zones could be extinguished from medium-sized mountains as the upper tree line ascends over the summit in climatological terms (but see discussion of treeline below). A corollary of this upward shift is that as any zone moves upward, the space that it occupies decreases because the amount of land area diminishes rapidly with elevation.

A second, general projection can be made with a scenario involving more precipitation, particularly in the summer. In such a case, a bi-directional change of zones both upward and downward—a spreading of the forested zone (Stohlgren et al. 1998a, 1998b)—would likely occur.

The third most general projection is that if the upward shift of forested zones is the dominant result, it will tend to cause shifts in the character of the zones. Pine-oak woodland and pinyon-juniper zones would become more widespread in the montane zones of the southern Rockies, while Douglas-fir, lodgepole pine, and ponderosa pine would infiltrate upper montane and subalpine zones in the northern Rockies. Everywhere, this movement upward would be achieved at the expense of area occupied by Engelmann spruce and subalpine fir. These very general projections are consistent with predictions made with continental-scale models for vegetation change in response to a $2xCO_2$ climate (Neilson and Chaney 1995, Neilson et al. 1998).

Application of Climate-change Scenarios to Vegetation at the Regional Level

Climatic Variables Affecting Plant Function

The zonal structure of Rocky Mountain vegetation provides a conceptual framework for discussing vegetation change resulting from warming and altered precipitation patterns, but is too simplistic to capture the variability of response to be expected. The current (and probable future) climatic controls on the distributions of the dominant species of these zones are: (1) soil moisture availability during the growing season as compared to evaporative demand, (2) the length of growing season and temperature or heat, and (3) the climatic variability, specifically including frequency of spring droughts and growing-season frost. The future-climate scenarios included in our analysis (Table 7.1) are insufficiently detailed with regard to these basic drivers. Soil- moisture calculations require integrating the difference between precipitation and potential evapotranspiration, while considering the soil-moisture holding capacity. Clearly, such calculations cannot be completed on the given scenarios, or in the absence of soils data, and much simpler methods will have to suffice.

The Jensen-Haise equation (1963) relates potential evapotranspiration to air temperature in a simple function

$$PET = 0.245 \times 10^{-4} \times R_s(0.025\ T_a + 0.08)$$

where PET = potential evapotranspiration (mm/day), R_s = shortwave radiation (KJ m^2/day), and T_a = average daily air temperature in degrees C. Depending on the levels of radiation (assumed unchanged although cloudiness might increase), it is possible to estimate the increase in PET for a given increase in temperature as has been done for the discussions in the following sections.

The frequency of occurrence of droughts and frosts cannot be determined from the scenarios and have to be estimated very generally. Nor can this informal analysis take into account the possible direct effects of increased CO_2 on water-use efficiency of all the plants involved. Interestingly, the scenarios considered appear to accentuate the existing differences in climate between the northern and southern Rocky Mountains (Dettinger et al. 1998), thereby requiring separate treatments.

East-central and Southern Rocky Mountains

In the East-central and Southern Rocky Mountains, the scenarios call for increasing temperatures (+1.5 to +3.0°C) and variable precipitation (-45 to +90 mm/yr). Under Scenario 1 (increased winter precipitation, decreased growing-season precipitation), the increase in summer temperature of +1.5 to +3.0°C is likely to increase PET on the order of 0.5 to <1 mm/day depending on the actual temperature. Given the projected decrease in growing season precipitation of -0.5 to -1.0 mm/day, the net effect is a growing-season decrease in the water budget of -1.0 to -2.0 mm/day. Even if offset by the most favorable precipitation estimates (+90 mm in winter), the net effect is a significant decrease in soil-available water, or an increase in soil drought. In addition, thinner or rockier soils will be unable to store the additional winter precipitation, leading to no net increase in soil-available water against a very significant increase in PET. The result will be a very significant drying. Only those species that can disperse upward in elevation will be able to secure the necessary cooler-wetter conditions. The degree of change in climate would probably be too significant to allow vegetation change to be ameliorated by latitudinal migration except in isolated cases. The net effect would likely be significant decreases in productivity, losses of area in forested ecosystems, and some local losses of native species.

Under Scenario 2 (+1.0 to +1.5 mm/day increased precipitation in summer), the situation is much more favorable. While on an annual basis the increase in PET will far outstrip the increase in precipitation, water balance should actually be more favorable in the summer season, resulting in increased available soil water during parts of the growing season than at present. A reasonable expectation is that total water available over the course of the year will still decline significantly, but the impact will be much less than under Scenario 1. Water available to plants will depend much less on soil-water holding capacity and more on growing-season precipitation. The summer precipitation regime will more closely match the current Arizona monsoon regime that presently dominates the Southern Rocky Mountains. Despite the less severe conditions, high-elevation subalpine ecosystems are likely to be lost from the Southwest.

Northern and Western Rocky Mountains

In the Northern and Western Rocky Mountains, the scenarios are significantly different from those of the Southern Rockies. Both scenarios (1 and 2) call for an increase in precipitation from 225 to 495 mm/yr. However, similar to the Southern Rocky Mountains, the difference in seasonality between Scenarios 1 and 2 leads to large differences in projected vegetation change.

Under Scenario 1, winter precipitation and temperature both increase, with relatively little expected impact on snowpack. Given this scenario, high-elevation sites which already achieve maximum soil-water holding capacity (field capacity) will enter the growing season with roughly the same amount of water as at present; lower-elevation sites not having excessively thin or rocky soils may achieve higher rates of soil-water recharge and enter the growing season with higher soil moisture than at present. During the growing season, the slight increase in precipitation (0.0 to +0.5 mm/day) is sufficient to offset most of the effect of higher temperatures, and possibly have a net, positive change at high elevations. The expected result is possibly higher soil-moisture availability on sites with sufficient water-holding capacity, offset by a slightly unfavorable shift in PET versus precipitation. The result would be a slight drying at high elevations (due to soil storage limitations) and relatively little change at mid elevations. Under these circumstances, relatively more drought-tolerant species such as Douglas-fir might expand into higher elevations while maintaining populations in their current elevation zone. Intermountain basins will experience milder, wetter winters with hotter, drier summers, possibly benefiting early-season crops and exacerbating late-season irrigation demands on water.

Under Scenario 2, precipitation increases predominantly in the spring and summer (+1.0 to +3.0 mm/day), with winter precipitation increasing only slightly. Accompanied by a significant increase in temperature, especially in winter (+4.5C), the result is a significant reduction in snowpack with frequent winter rain events. Despite the loss of snowpack, mid- and high-elevation forests are likely to enter the growing season with relatively high soil moisture availability due to winter rain with low PET conditions. In addition, increased summer precipitation will be significantly more than that required to offset the increased PET due to increased temperatures, leading to higher soil-water availability during the growing season. Even in the absence of increased water-use efficiency due to higher CO_2 concentrations, vegetation in the Northern Rockies would experience more favorable conditions for growth. Given milder winters, the growing season may lengthen, and in combination with increased moisture, increases in productivity should occur.

Given similar scenarios, Romme and Turner (1991) and Bartlein et al. (1997) project forest vegetation in the Greater Yellowstone area similar to what now occupies western Montana and northern Idaho. However, the shift to a summer maximum precipitation regime is a significant change for many parts of the Central Rockies, and shifts in species composition more similar to those characterizing the Arizona monsoonal or Pacific maritime areas might occur. Accordingly, ponderosa pine, Gambel oak, and quaking aspen may all increase their importance and move into the Central Rocky mountains. Under these conditions, the diffuse boundary between mixed-grass prairie and sagebrush steppe in the Wyoming Basin might move westward from its present location between the Bighorn and Medicine Bow Mountains (Driese et al. 1996)

Intrazonal Changes in Response to Climate Change

Complexities at Subzonal Scales

The zonal view of vegetation is convenient, particularly for generalizing over 1,900 km of latitudinal variation for collective assemblages. It is not a particularly good way to examine the distribution of individual species (e.g. Stohlgren et al. 1997). But intrazonal variation, and even the possible breakdown of zones as presently defined may also occur with climate changes. The zones graphed in Fig. 7.2 are not as monolithic as they appear. These are conceptual diagrams, not views of mountain slopes. Some of the variability denoted by the horizontal axis—the moisture gradient—can occur at relatively fine scales of tens to hundreds of meters. Depending on their lithology and geomorphologic processes, mountains may have expansive planar slopes or may be dissected into fine-grained sub-catchments. Depending on topographic grain, xeric sites on south-facing slopes or rocky ridges may be as much as kilometers or as little as tens of meters away from mesic sites on north-facing slopes, or from hydric sites in the bottoms of these sub-catchments. More subtle vegetational changes in response to climate change are likely to occur at this scale of tens to hundreds of meters than at the zonal scale.

An example of the complex grain at relatively small pattern scale is exhibited in Fig. 7.3. The upper panel of this figure is a shaded relief image of the topography for an area in the Medicine Bow Mountains of 12,500 ha (30,888 ac) centered on an unlogged wilderness area. As explained in the caption, the elevation decreases from upper right to lower left and terrain becomes increasingly dissected as elevation drops to the left. Three environmental factors are illustrated here. First, elevation and its attendant macroclimatic properties decrease from upper right to lower left. Second, the terrain is dissected by downcutting streams running from right to left with the extent of dissection increasing downslope. Third, the east-west-running stream channels create sharply contrasting north- and south-facing slopes. Thus, the topography of this area creates some complex variations in microclimate and soil properties at a relatively fine scale of tens to hundreds of meters.

The second panel in Fig. 7.3 is a Landsat-TM derived image for the same area. The relatively undisturbed, non-forested vegetation of the wilderness area extends from the darkly colored wilderness area to the lower left corner. The shadows cast by north-facing slopes make them appear darker than the rest of the image. This topographic variation is better revealed in the third panel in which more detailed separation of the spectral signals of this image are exhibited as colored polygons, each polygon representing a different vegetation type. Some of the variations in the unlogged area stem from elevational differences, some from topographic effects. The drainage incisions have produced more-or-less linear features paralleling the direction of the stream channels. The second panel indicates that the wilderness area is surrounded in the right two-thirds of the figure by a system of clear-cut plots. The patterning described above applies to non-logged areas. The patchwork surrounding the wilderness area patterning illustrates another form of spatial heterogeneity that, along with roads, is a dominant aspect of much of the Rocky Mountains.

The complex pattern demonstrated in Fig. 7.3, both logged and non-logged, is the kind of environment in which intrazonal changes may occur. Some crude projections can be made on intrazonal change but they are locally specific and replete with caveats. For example, different properties of the vegetation will change at different time scales. Clearly, mature trees have experienced considerable climate change already over their 100- to 500-year life spans as is evidenced in variations in their tree rings and correlations with past climate changes. These adult trees can endure a considerable amount of climatic variation and persist. More problematic is seedling establishment and sapling growth (Stohlgren et al. 1998a). Regeneration is highly variable in the West and climate effects are more likely to affect regeneration processes than mortality processes so that while forests may appear to be unaffected in terms of responses by adult trees, changes in reproduction may have already taken place that may not be seen for decades without very careful demographic studies. While climate-driven processes can be slow and subtle, changes could be accelerated by disturbances, extinctions, or invasions of exotic species. In contrast to forests, response times in mountain meadow species will generally be faster than for forests (see discussion below).

It is within intrazonal changes that the different precipitation scenarios come into play. The situation is further confounded by considerations of increased water-use efficiency (WUE) brought about as a direct effect of higher

CO_2 itself. Comprehensive models of climate effects on vegetation performance take this into account although little is known, in fact, about the long-term effect of CO_2 in this respect. For an assessment as generalized as this one, the direct CO_2 effect is not considered.

A warmer scenario with more precipitation in the winter, or with less precipitation in the summer, would intensify the summer drought period. Given the site preferences of species today, those members of a given zone occupying xeric sites would expand their area of occupation at the expense of those occupying more mesic sites within that zone. For example, ponderosa pine might give way to limber pine, Douglas-fir to ponderosa pine, subalpine fir to Douglas-fir at low elevations, or to lodgepole pine at higher elevations in landscapes like that shown in Fig. 7.3. Lodgepole pine, a widespread dominant from 38.5° lat. (central Colorado) northward (excepting the Utah mountains) would lose some ground it presently occupies to competition from other species at a specific elevation because its relatively high, spring frost tolerance would no longer provide a crucial advantage in competition with other species. These kinds of shifts are projected by Neilson and Chaney (1995, 1998) on a broad areal basis. The point here is that these shifts can interplay in relatively small areas at the same time.

A warmer scenario, or even no temperature change, but with a shift in precipitation to summer, would favor other species in competitive interactions across the landscape. Under these circumstances, white fir and trembling aspen could expand their area of occupation in middle-elevation landscapes at the expense of the pines, while ponderosa pine and Gambel oak could expand their share of landscapes at lower elevations. The same kinds of shifts in relative importance of species over a landscape could be predicted on a smaller scale for dominant species composing the alpine zone.

Embedded within the forest matrix, meadows dominated by graminoids and forbs occur in valleys, dry slopes, and sites of past fires at all altitudes (Peet 1988 [Fig. 7.2], Debinski et al. 1999). The vegetative structure of meadows varies over short distances along xeric-mesic gradients (e.g. vegetation Type 1 in Fig. 7.3). Because of the shorter life-spans of the herbaceous and shrubby species, composition of meadow vegetation could change more rapidly than that of the surrounding forests under altered climatic conditions (Harte and Shaw 1995). Under the right conditions, these meadows are highly invasive by trees and could disappear. In dry meadows, that change could result under warmer, wetter conditions; in wetter meadows, tree invasion could be fostered by shortened periods of saturated soil moisture. Under still drier conditions, these meadows could expand in area but would also undergo large shifts in composition. For example dry slopes occupied by sagebrush could expand to cover other slopes and dominate more area at the expense of grasses and forbs at intermediate altitudes. All of these possible dynamics would be very much altered by fire (see later section).

Debinski et al. (2000) found that mesic meadows (meadows at the midpoints of moisture gradients) support the highest plant diversity and they also show the largest inter-annual and seasonal variability in spectral response. Because spectral responses are linked with productivity, one might expect major changes in productivity along these moisture gradients under conditions of climate change. For this reason, mesic meadows may be important indicators of environmental change that could be detected with remotely sensed data.

The upper treeline, where trees give way to dwarfed krumholz forms, and ultimately to alpine tundra, is an area of intense study because it is an ecotone at which it would seem to be particularly easy to detect changes. There is a copious literature on treeline and its causal factors. Space does not allow lengthy review of this, and the focus here is on evidence for change in the Colorado Front Range.

While it is intuitive to infer that any increase in temperature would cause treeline to move upward, available evidence suggests that it has not occurred rapidly in recent years in the Front Range. Weisberg and Baker (1995a, 1995b) have extensively measured changes in growth form, seedling establishment, and leader extension in the krumholz zone. They found little seedling-establishment and sapling-density increase, but did find increased growth extension in the short krumholz trees. So far, there seemed to be no general expansion at the expense of tundra at that locale. Hessl and Baker (1997a, 1997b) also found no evidence of change in recent years.

Patterns of snow deposition, both too much and too little, wind-driven snow-crystal scour of coniferous needles, soil moisture and, in some places, inadequate soils, control treeline and may prevent rapid change. This is an issue that is very much site-bound and must be evaluated locally. If it is true that upper treeline will be intransigent to climate change, that has important implications for the generalizations about zonal "shifts" and how vegetation zones below treeline could be "compressed."

Nevertheless, the northward elevational decline of treeline, and the post-Pleistocene elevational shifts described above in the Historical Climate Change section remain as persuasive, circumstantial evidence that the overall positioning of the zone is climatically determined. And they are a reasonable basis for the hypothesis that treeline will ultimately rise with increasing temperatures.

Within the alpine tundra, snow distribution and depth of snow cover is a dominating influence on vegetative patterns (e.g. Walker et al. 1993), animal distributions, and ecosystem processes (e.g. Seastedt and Vaccaro 2001). Any scenario lessening the distribution, depth, or length of coverage in the snow cover will have short-term effects on tundra vegetation structure and function. For example, winter-time soil activity is relatively high under deep snow in the Front Range alpine tundra. A lessening of the snow cover would reduce rates of organic matter decomposition and nitrogen mineralization (Brooks et al. 1996, 1998). The impact of more snow is being experimentally tested at Niwot Ridge in the Colorado Front Range. Shifts in vegetation due to the imposition of an artificial snowfence have brought about changes in the vegetation that are obvious to any observer, and ecosystem functions are likely to reflect this as well.

A larger question is whether climate warming, particularly at nighttime, would be as great at altitudes over 4,000 m (13,120 ft) because of the lesser depth and mass of overlying atmosphere and its radiative properties. A counter-argument to this possibility is that the atmosphere is so well mixed that local elevation means little; advection processes are greater than local radiative processes. This argument is supported by recently quoted Chinese data from much higher elevations in the Himalayan Mountains. There they found not only "...a linearly increasing annual temperature trend of ~0.16°C per decade from 1955 to 1996, and an increasing winter trend of ~0.32°C per decade, they also report evidence that the rate of warming has increased with elevation." (Thompson et al. 2000).

A Case Study: The Greater Yellowstone Ecosystem:

Romme and Turner (1991) took several climate-change scenarios for the Greater Yellowstone Ecosystem of northwestern Wyoming and adjacent Montana and projected how the alternative scenarios would alter vegetation distribution and some of the signature plants and animals of the region. The methods used were relatively simple rule-based applications of GIS but the results seem plausible for an equilibrium outcome. This kind of simulation does not take into account the influence of intervening changes in disturbance patterns, influences of soil types, or lags in the migration rate of plants. These authors used three climate scenarios:

"1) Warm, dry--temperature and PET increase, precipitation decreases or remains unchanged, and WUE [water-use efficiency] increases only slightly; plants are subjected to elevated temperatures, CO_2 and drought stress.

"2) Intermediate—temperature and PET increase; precipitation decreases or remains unchanged, and WUE increases sufficiently to compensate for increasing PET; plants are subjected to elevated temperatures and CO_2, but there is no change in drought stress.

"3) Warm, wet—temperatures and CO_2 increase, precipitation increases, and WUE increases significantly; plants are subjected to elevated temperatures and CO_2, but to reduced drought stress."

Fig. 7.5 is a simplified synopsis of the outcomes of these projections in terms of vegetation zones now and with the three different scenarios. Starting at the top of Fig. 7.5, the first point is that the alpine zone can go no higher and its elevational range, and thus area, is greatly reduced according to all three scenarios. The whitebark pine zone, a species critical to grizzly bear habitat, increases in elevation and is reduced in elevational range and area. The forested zone in general increases in elevation and maintains the same range under Scenario 1, increases in upper elevational range in Scenario 2, and increases in both upper and lower elevational range in Scenario 3. Thus, with a warmer-wetter scenario, the forested zone expands above and below, reducing shrub and herbaceous areas at both ends of the elevational gradient. This has profound implications for grazing/browsing and other kinds of animals. Finally, the low-elevation, shrub/grassland zone increases in elevation and elevation range in Scenario 1, is about the same for Scenario 2, and decreases to only the lowest elevations in Scenario 3. This projection approach is relatively simple from a technical point of view and yet provides some insight on how vegetation, and

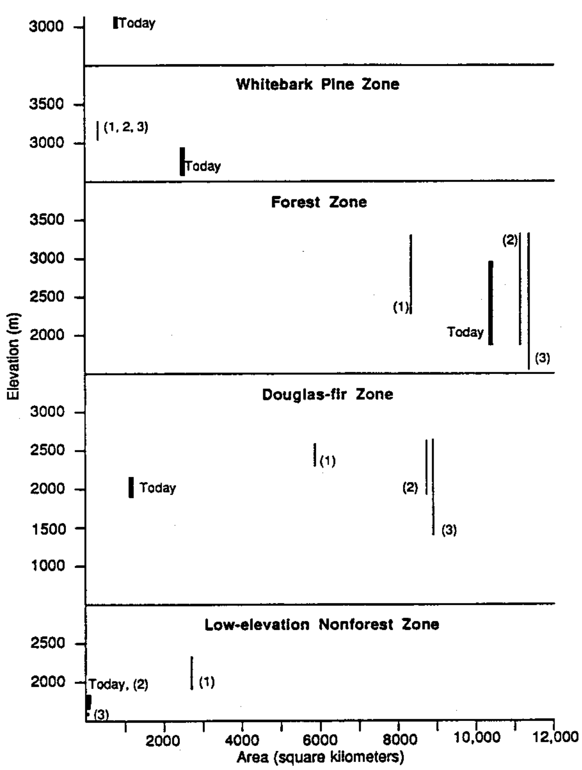


Figure 7.5. Present and projected elevational ranges of vegetation zones in Yellowstone National Park and the adjacent mountains along its eastern border. Scenario (1) is elevated temperature, CO_2, and drought stress. Scenario (2) is elevated temperature, but no change in drought stress. Scenario (3) is elevated temperature and CO_2, but reduced drought stress. From Romme and Turner (1991); see text for details. Published with permission of Conservation Biology.

thus animal habitat, might react to different kinds of climate change.

Others have modeled the possible redistribution of individual species, perhaps a more realistic approach from an ecological point of view although without an explicit elevational output such as used by Romme and Turner. Plants attain their distributions, in our opinion, mostly in terms of their unique environmental requirements and dispersal qualities, not as components of integrated vegetational types. For example, Thompson et al. (1998) and Bartlein et al. (1997) calculated climatic envelopes for nine species occurring in or around the Greater Yellowstone Ecosystem (GYE)—lodgepole pine, whitebark pine, Gambel oak, western larch, Douglas-fir, Engelmann spruce, ponderosa pine, western red cedar and big sagebrush. Based on the co-occurrence of species distributions with January and July temperatures, and January and July precipitation, they created response surfaces that then could be mapped over the region in terms of those variables under a $2xCO_2$ climate.

This approach assumes that species distributions are individualistic, in equilibrium with the current climate, and that competitive relations between them or dispersal limitations will not restrict redistribution. It also assumes that other climatic variables or combinations of the four determinant variables will not be more important than the ones used. It also cannot take into account how soil properties may create lags in establishment of different species, or how changes might be accelerated or delayed due to fire. These are equilibrium models, not temporally dynamic models. As such, they are not designed to consider processes affecting rates of change. Outputs by this method are small-scale maps of projected individual species distributions.

The combined research from both of these publications produced some very enlightening results for the eight target species. The projected distributions of lodgepole pine, Douglas-fir, and Engelmann spruce were mostly reduced along their margins. Whitebark pine was almost entirely eliminated from the region. Gambel oak expanded north to the Canadian border and southeast to south-central Wyoming. The projected western larch distribution was reduced in the northern part of its range but expanded to the southeast, centering on the Wyoming-Idaho border. Ponderosa pine range was reduced by this projection throughout much of its range in northern Idaho but became more prominent in much of central Montana and lower margins of western-Wyoming mountains where it is only sparsely found today. Western red cedar range was projected to shift from Idaho and western Montana farther east in Montana and in the Teton and Wind River Ranges of Wyoming, and the Overthrust Belt of Idaho and western Wyoming. Big sagebrush range contracted in the Great Basin, Columbia Basin, and eastern Wyoming and Montana according to this projection but expanded into eastern Colorado, Alberta, and Manitoba. The climate scenarios employed by Bartlein et al. (1997) and Thompson et al. (1998) most closely matched Scenario 2 (Table 7.1) as used in this report, and their projections are qualitatively in agreement with ours for that scenario.

More sophisticated vegetation distribution models than these are possible and needed to better evaluate possible outcomes for other parts of the Rocky Mountains. The individual species approach is preferable but considerations of competitive relations, dispersal pathways, and the interacting roles of potential changes in disturbance regimes also need to be considered.

Disturbance Regimes in Response to Climate Change

Disturbance Regimes

All ecosystems are subject to natural destructive disturbances by a host of agents: trampling, over-grazing, windstorms, floods, landslides, avalanches, insect or disease outbreaks, and fire. The frequency of occurrence of these disturbances depends on geographic location of a site and—particularly in the case of forest insects, disease, and fire—on the physiological condition and age of the forest, and on the weather. Thus, there is an important intersection between potential climate change and its resultant weather with disturbance in the Rocky Mountain region. For this reason, disturbance phenomena--their contemporary regimes and their relationships with weather--deserve careful consideration in this assessment.

The complex of factors responsible for a disturbance event—topographic location, geographic context, infection, ignition-event frequency, growth rate of a stand—all lead to a characteristic frequency of occurrence of the disturbance event, albeit with large variance. This is considered the "disturbance regime" for that location. These regimes may or may not have characteristic frequencies related to climate oscillations (Swetnam and Betancourt 1990, 1998, Swetnam and Lynch 1993, Parsons et al. 1999, Veblen et al. 2000). Meadows and shrublands also are disturbed by fire, but their recovery dynamics are typically more rapid than those of forests.

Fire

Fire has been part of the Rocky Mountain environment throughout the Holocene and probably before. Records dating back to 17k yr BP show a correspondence between fire frequency and climate change over the Holocene (Millspaugh et al. 2000). More recent tree-ring records demonstrate that fire frequency in the southwestern U.S. (including New Mexico) varied not only with ENSO cycles but with multi-decadal-scale variation in the amplitude and/or frequency of ENSO events (Swetnam and Betancourt 1998). Currently, larger fires and more numerous fires are associated with dry years related to La Niña following wet periods related to El Niño in the Rocky Mountains. The wet years lead to the accumulation of more fine fuels and the dry years lead to higher temperatures and drying of those fuels (Veblen et al. 2000). Farther north in the Rockies, the Pacific North America pattern plays a stronger role in creating fire weather. For example, in the Canadian southern Rockies mid-tropospheric surface-blocking events during large fires are teleconnected to upper-level troughs in the atmospheric circulation over the North Pacific and eastern North America (Johnson and Wowchuk 1993). Thus, the fire regime for any given location has to be viewed in an appropriate time frame. The regime at the decadal scale may vary at the interdecadal scale and at the millennial scale. These demonstrated relationships between fire and climate strongly suggest that a fire disturbance regime is likely to be shifted with the kinds of secular climate change projected for the future.

It is difficult to know what the natural fire regime for forests might be today. Fuel accumulation, and thus stand age, is dependent on a historical legacy of past disturbances. There were fire and insect outbreaks prior to European settlement, but the regime has been strongly impacted by human management effects since the late 19th century. Management, including cutting and grazing, but particularly fire suppression, has confounded the present situation (Veblen et al. 2000). Cutting and grazing may reduce fire probability, but suppression certainly increases the potential for more widespread and intense fire events.

Aside from the effects of fire suppression, human-caused ignition and the interactions of blowdowns and insect attacks on fire probability, it seems likely that all of the summer-dry scenarios for climate change could, at least in the short term, contribute to increases in fire probability. They would do so mainly by intensifying dry periods. The relative impact of increased fuel desiccation is likely to be greatest in mesic spruce-fir forests where summers currently are relatively moist compared to the intense summer drought typical of ponderosa pine and other low-elevation forest types. It is well documented that large areas of subalpine forest have burned during infrequent, exceptionally dry years that have occurred during the past several centuries (Romme 1982, Kipfmueller and Baker 2000). These historically documented patterns of extensive fires in the subalpine zone will in all likelihood be repeated under future conditions of more severe summer drought. In the longer term, shifts toward more xeric vegetation under summer-dry regimes could reduce productivity and fuel loading although that relationship is not documented. If the scenario for summer-wet conditions were sufficiently large, it would tend to reduce fuel flammability and could reduce fire frequency. Of course, vegetation productivity would also increase and species composition would be likely to change as well.

A key determinant of the probable influence of climatic trends on future fire regimes is the degree of year-to-year variability in moisture availability. Fire history studies in the Rocky Mountains have demonstrated that decadal and longer average weather conditions have less influence on fire regimes than do extreme oscillations occurring over 2- to 5-year periods (Swetnam and Betancourt 1998, Veblen et al. 2000).

A Case Study: The Colorado Front Range

Veblen et al. (2000) have recently published a detailed history of fire in ponderosa pine forests of the montane zone (~1,830--2,790 m) of the northern Colorado Front Range. Over 700 fire-scarred trees, mostly ponderosa pine, from 41 sites were sampled from which 525 sections yielded 909 cross-dated fire scars. Fire dates extended from 1,450 AD to the late 20th Century. The resulting record can be divided into three historical periods: pre-EuroAmerican settlement (pre-1850), early European settlement (1851--1920), and the fire suppression period (1920-present).

The first period was marked by frequent surface fires in the lowest elevation (c. 1900 m) ponderosa pine woodlands, near the ecotone with the Plains grassland. In higher-elevation forests (above ca. 2,400 m, 7,872 ft), where ponderosa pine co-occurs with Douglas fir, the pre-EuroAmerican fire regime was characterized by a much lower fire frequency and included extensive stand-replacing fires as well as some surface fires. The second period was marked by a much higher fire frequency in both the lower and upper montane zone, and the third period by very low frequency, small-sized fires.

Although increased ignitions by humans during the mid- and late-19th century probably contributed to the increased burning, this was also a period of increased year-to-year climatic variability. ENSO cycles became more marked in the latter half of the 19th century, concurrent with EuroAmerican settlement and probably increased fuel conditions favorable to the spread of fire. Tree-ring evidence shows that years of widespread fire tend to be preceded 2 to 4 years by above-average moisture during the El Niño years and to coincide with drought associated with La Niña years. With suppression through most of the 20th century, recent fire occurrence has been well outside the historical range of variability in this region. As a result of the exclusion of surface fires that formerly killed many tree seedlings, the lowest elevation ponderosa pine forests have increased in density.

In the upper montane zone, stands are typically even-aged as a result of abundant tree establishment following the widespread stand-replacing fires of the late 1800s. Both situations have resulted in a montane landscape of more homogeneous stand structure and increased fuel continuity that now has the potential for sustaining more extensive crown fires. This poses a difficult management situation. Managers must now take into account the relationship between buildup of fine fuels during El Niño periods together with subsequent high temperatures and fuel drying imposed by subsequent La Niña periods, all superimposed on large areas of extensive forests primed to burn through decades of fire suppression.

How will climate change influence this already complicated situation? It seems that any of the scenarios are likely to encourage burning in that warmer temperatures help to produce more fuel in wet periods and to dry fuels in dry periods. How interdecadal fluctuations in ENSO amplitude are altered in a new climate regime will be a very important consideration in this regard. A climate change bringing more precipitation during warm phases of those fluctuations might diminish fires, but more precipitation would also alter the vegetation to such an extent that past experience in these ponderosa pine forests and woodlands would have less value for predicting outcomes.

Insects and Disease

It is more difficult to specify general rules for how climate change might interact with the greater diversity of disturbances caused by insect outbreaks and diseases. The literature is extensive on each of these so the level of generalization must be more superficial than for fire.

Large areas of forest in the Rocky Mountains are attacked and trees killed by bark beetles and defoliating insects such as mountain pine beetle, Douglas fir beetle, spruce beetle, and western spruce budworm (Amman 1977, Frye et al. 1974, Schmid and Mata 1996, Veblen 2000). In the southern Rocky Mountains the mountain pine beetle (Dendroctonus ponderosae) primarily attacks live ponderosa and lodgepole pines. During epidemics, nearly 100% of overstory trees can be killed by mountain pine beetles over many square kilometers (Schmid and Mata 1996). Numerous mountain pine beetle outbreaks have occurred during the 20^{th} century throughout the southern Rocky Mountains (Roe and Amman 1970). It is widely believed that increased stand densities associated with fire exclusion in this century have increased the susceptibility of stands to outbreaks of mountain pine beetle (Roe and Amman 1970, Schmid and Mata 1996). However, there are no long-term studies (e.g. based on tree-ring records) of the frequency or duration of outbreaks to examine this hypothesis. Also this hypothesis ignores the fact that the larger trees (i.e. those most susceptible to beetle attack) were removed from stands that subsequently have experienced outbreaks. Occurrence of extensive outbreaks in the late 1800s and early 1900s (Roe and Amman 1970) indicates that not all outbreaks can be attributed to the stand structural changes resulting from modern fire exclusion.

The extensive research on mountain pine beetle has shown that the larval stage is vulnerable to low temperatures during winter, and hence the species is limited to lodgepole pine stands generally below ~ 3,000 m (9,840 ft, cf. Amman 1973). U.S.D.A. Forest Service biologist J.A. Logan (Pers. Comm.) suggests that rising temperatures would allow the species to move up to higher elevations where it would attack and eliminate whitebark and limber pines. The nuts of these species are important foods for the threatened grizzly bear in the North-central and Northern Rockies.

The Douglas-fir bark beetle (Dendroctonus pseudotsugae) can cause widespread mortality of Douglas-fir in the southern Rocky Mountains, and its epidemics appear to have arisen during and expanded following outbreaks of western spruce budworm (Schmid and Mata 1996). Outbreaks have been observed to last 5 to > 10 years, and intervals between outbreaks in the same areas may be on the order of 15 to 35 years (Hadley and Veblen 1993, Schmid and Mata 1996).

The spruce beetle (Dendroctonus rufipennis) in the southern Rocky Mountains mainly infests Engelmann spruce (Alexander 1987, Schmid and Mata 1996). Endemic spruce beetle populations infest fallen trees and scattered live trees, but during outbreaks can kill most canopy spruce over extensive areas. Spruce < 10 cm (3.7 in) in diameter usually are not attacked, nor are the subalpine fir, and their accelerated growth following the death of canopy trees can be used to date outbreaks (Veblen et al. 1991). Stands containing large (i.e. > 55 cm (21.7 in) diameter) spruce and especially those in valley- bottom sites are the most susceptible to outbreaks. Blowdowns or accumulated logging debris are usually the immediate triggers of outbreaks (Schmid and Frye 1977) which is an important distinction from outbreaks of mountain pine or Douglas fir beetle. Tree-ring records document the occurrence of regionally extensive outbreaks of spruce beetle in the mid-19th century and earlier prior to any significant impact of Euro-Americans on the subalpine forests of northwestern Colorado in the form of either logging or fire suppression (Baker and Veblen 1990, Veblen et al. 1991, 1994).

The western spruce budworm Choristoneura fumiferana) primarily defoliates Douglas-fir and white fir in the southern Rocky Mountains (Schmid and Mata 1996). Extensive defoliation by budworm over several years can produce high levels of tree mortality. Given the apparently greater susceptibility of stands with suppressed understories of Douglas-fir saplings, it is likely that fire exclusion during this century is creating a more homogeneous landscape of increased susceptibility to budworm outbreaks. Studies from Montana to New Mexico suggest that since the early 1900s budworm outbreaks have become increasingly severe and synchronous over larger areas (McCune 1983, Anderson et al. 1987, Swetnam and Lynch 1993, Hadley and Veblen 1993). Increased 19th century burning in the upper montane zone also would have created extensive areas of post-fire, even-aged stands that more or less synchronously become susceptible to budworm outbreaks (Hadley and Veblen 1993).

Weather profoundly affects the life cycles of insect pests as well as the capability of trees to respond to insect attacks, yet the effects of climatic variation on the occurrence of insect outbreaks are poorly understood (Swetnam and Lynch 1993, Logan et al. 1995). For example, mortality of mountain pine beetle is increased by cold winters so that, as commented above, cool temperatures are believed to be the major restriction on mountain pine beetle outbreaks at high elevations (Logan et al. 1995). Generally, warmer temperatures promote bark beetle outbreaks both through their favorable influence on the life cycle of the insect and through drought-related declines in the trees' abilities to withstand attack (Frye et al. 1974, Amman 1977).

Logan and Powell (2000) have written an especially interesting treatise on how bark beetles might react to climate change. Through careful analysis of heat requirements for life-history steps, they concluded that bark beetle responses to warming would be highly non-linear. Once warming passed a critical level (at a given elevation), the life-history processes would pass over a cusp and the population could enter an infestation phase. From their analysis it appears that as a specific elevational level gradually became warmer, the heat budget would build up and changes in beetle population levels would be small to nil. But after the heat budget reached a critical point, the population would pass across a cusp of life-cycle viability permitting completion of its life cycle at that elevation and thus allowing it to attack the trees at that elevation. This kind of analysis would be desirable for all of the insect pests of concern in this region as it integrates life history, physiology, stand conditions and climate in a way permitting better predictive modeling of possible outcomes to climate warming.

Although it has long been believed that drought pre-disposes Douglas-fir stands to outbreaks of western spruce budworm (Cates and Alexander 1982), recent research from New Mexico suggests that wet periods may favor outbreaks. For example, in northern New Mexico tree-ring records of outbreaks from 1690 to 1989 indicate a tendency for outbreaks to coincide with years of increased spring precipitation (Swetnam and Lynch 1993). This contrasts with findings for the northwestern U.S. and eastern Canada where shorter-term records indicate an association of budworm outbreaks with periods of moisture deficit (Swetnam and Lynch 1993). Although the mechanisms relating budworm population dynamics and tree susceptibility to attack are not clear, there is strong evidence that climatic variation influences the occurrence of budworm outbreaks. However, non-climatic changes in stand structures still play an equal or greater role.

Clearly, insect outbreaks are important modes of wide-spread disturbance in the Rocky Mountain region. The relationship between these insects and stand condition and weather are complex. Stand condition, in turn, is related to fire history and logging practices. Fitting individual species climatological envelopes to projected spatial distributions only provides a "potential" new range for that species. The complex dynamics of fire and insect epidemics must be factored in to generate projections that are ecologically satisfactory. The workshop participants cannot make meaningful projections on this complicated set of interacting forces. It can only point out the importance of the factors and point toward the need for better-directed research to develop such projections.

Among forest diseases, the exotic species white pine blister rust is of most general concern. This rust has decimated much of the western white pine range and more recently has infected the whitebark pine that is primarily restricted to high elevations. It is unknown whether the recent infection of this high-elevation species might have been enabled by a warming climate. As mentioned above, the loss of whitebark pine is of particular concern as a critical food resource for the threatened grizzly bear (Koteen 1999). Whitebark pine is also a nursery plant for subalpine fir, so that blister rust might influence vegetation dynamics indirectly (Callaway 1998).

BIOTA

Species-level Effects

In contrast to the previous section on vegetation, this section addresses the biotic resources of the Rocky Mountain region from a species-level point of view. Projecting how individual species might react to a change in climate is a complex process requiring a multifaceted set of considerations. Hughes (2000) has written on evidence for species changes world-wide and produced a causal linkage diagram of key processes from which Fig. 7.6 is abstracted. The top of Fig. 7.6 illustrates that increases in CO_2 and change in climate variables are linked while the first contributes to the second. CO_2 itself has a direct effect on plant physiology. Climate variables also have effects on phenology, distributions, and adaptations *in situ* (second tier of Fig. 7.6). The third tier illustrates how changes in physiology, phenology, distributions and adaptations collectively influence species interactions. Changes in interactions can cause further shifts in distribution and lead to extinction of some species (fourth tier). Shifts in distribution and extinction of species lead to changes in community structure and composition (fifth tier).

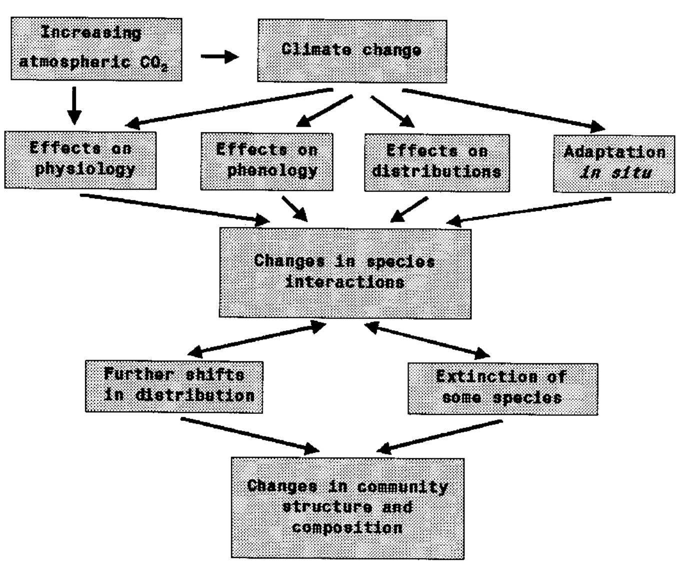


Figure 7.6. Projected causal sequences from atmospheric-CO_2 increases and climate change through effects on individual species, species interactions, and ultimate changes in community structure and composition.

Hughes' approach is a logical way to conceptualize potential climate impacts on individual members of the biota. While this cannot be done in this report, elements of this approach will be followed. In the following, the biota is divided into several groups based on the way the groups tend to be studied and managed.

Flora

There is no defined flora for the Rocky Mountains as described in this report although one could be compiled with considerable effort. Floras tend to be organized by states and none of the Rocky Mountain states fall entirely into the Rocky Mountain region. Ronald L. Hartman, Curator, Rocky Mountain Herbarium estimates that a flora for the region, as defined here, would be in the order of 5,000 to 5,500 vascular plant species (Pers. Comm.). For perspective, this is a moderate-sized flora, not quite equal to the flora of the entire state of California—a state with extraordinary environmental diversity and endemism. As is typical of any flora, most species are quite uncommon and a relatively few are dominants or occur with high fidelity in particular habitats or vegetation types (Stohlgren et al. 2000). A small number of species in this flora are listed as threatened and endangered by the U.S. Fish and Wildlife Service (see below).

Assessing the possible influence climate change might have on this flora as a whole cannot be made in this brief report even if the requisite information were available. The ranges of most species are not well known, much less their environmental requirements. Work is underway in developing environmentally-based distribution models for some species (Bartlein et al. 1997, Thompson et al. 1998, Fertig and Reiners 2001) but the number of species receiving this attention is a small fraction of the entire flora. Furthermore, there is evidence for low fidelity of species to environmental complexes and for large persistence in the face of environmental change (Stohlgren et al. 2000). The influence of landuse change and invasive exotics will probably be more important than climate change for the majority of the members of the Rocky Mountain flora. On the other hand, a more careful evaluation of restricted groups within the flora, such as members of alpine tundra, bog or wetland groups, might reveal some important trends in vulnerability to climate change.

Fauna

As with the flora, there is no single terrestrial faunistic list for the Rocky Mountains as defined here. The situation with animals is complicated by the migratory habits of many of the birds. A very crude estimate for Wyoming alone, provided by D. Keinath, Heritage Zoologist with the Wyoming Natural Diversity Database, is 370 species of birds, 24 species of reptiles, 12 species of amphibians, and 117 species of mammals for a total of 523 vertebrate species (Pers. Comm.). This faunistic list probably represents Idaho and Montana fairly closely but the numbers in the more southerly states of the Rocky Mountain region are undoubtedly higher because of the latitudinal enrichment effect and wider range of environmental conditions found in Utah, Colorado, and New Mexico. A crude way to arrive at an estimate for the entire region might be to double the numbers found in Wyoming for a total of about 1000 vertebrate species. Numbers would likely increase for all classes of vertebrates but the increase would probably be proportionally higher for amphibians and reptiles. The number of invertebrate species has to be orders of magnitude higher than for vertebrates.

Climate-change impacts on vertebrates and invertebrates would probably be associated with climate-change effects on their habitats. Habitats are based, in part, on vegetation discussed earlier but also on spatial proximity to other resources such as water or cover. For most vertebrates, enough is known about their habitats through development of habitat models for wildlife management and through the Gap Analysis Program to permit crude modeling at coarse scales for climate-change impacts on these species. Such models can be obtained through the National Gap Analysis Program (**http://www.gap.uidaho.edu/Projects/States/**). Much less is known about invertebrate habitat requirements except for certain pest species, but climate change would almost certainly affect these ectothermic species directly by operating through their physiologies.

A small proportion of the fauna is of exotic origin although most exotic invasives are invertebrates. An even smaller proportion of the fauna is threatened and endangered and will be discussed in the next section.

Threatened and Endangered Species

Conservation biology is a general term used for consideration of and planning for maintenance of species as part of the "biodiversity" of a defined area. There are two issues that need to be separated—biodiversity as a quantitative property of a designated area, versus the host of specific protection measures on behalf of threatened and endangered species. "Biodiversity" is often simplified to mean species richness—the number of species, usually within a taxonomic group like reptiles—occurring in a defined area. By this usage, higher species richness is synonymous with higher "biodiversity." This quantitative measure of an ecosystem variable is quite different from more highly focused concerns with threatened and endangered species whose populations are in a precarious state or are close to extinction.

Within the United States, individual State Heritage Programs maintain records on the status of species with respect to their vulnerability to extinction, but the responsibility for taking action as well as maintaining status records falls with the U.S. Fish and Wildlife Service. Species monitored for their viability status include vascular plants and vertebrate animals and a relatively few invertebrates such as butterflies and mollusks. Most invertebrates, non-vascular plants, and microbes are excluded from these listings. They are kept by state, and not in terms of the region in which they are found. In fact, many species, particularly animals, are found in more than one region. Thus, listings of endangered species of the Rocky Mountain region strictly delimited are not readily available.

The lack of systematic data on invertebrates is unfortunate for purposes of evaluating the ecological impacts of climate change. Although less is known about these groups on a species-by-species basis, given the fact that many invertebrates have short generation times and high reproductive rates, and sometimes have tight associations with members of the vegetation, the effects of regional climate change could take place quickly and dramatically among the invertebrates. Identifying key invertebrate species to monitor for such changes is strongly recommended.

State heritage programs list species status in more complex terms than those issued by the U.S. Fish and Wildlife Service, thus more complete information about endangered species can be found at the state level. The addresses for these programs are:

Montana—http://nris.state.mt.us/mtnhp/

Idaho—http://www2.state.id.us/fishgame/cdchome.htm

Wyoming—http://uwadmnweb.uwyo.edu/wyndd/

Utah—http://www.utahcdc.usu.edu/ucdc/

Colorado—http://www.cnhp.colostate.edu/

New Mexico—http://nmnhp.unm.edu/

The legal status of species is set by the only agency mandated by Congress to enforce laws protecting endangered non-marine species: the U.S. Fish and Wildlife Service. According to these listings, the Rocky Mountain states are home to 14-27 threatened and endangered animals and 2-22 vascular plant species (Table 7.2). Naturally, many, if not most, of these species occur in more than one state so the total animal species found primarily in the mountains is nine and the total plant species is six.

Compared with the total floral and faunal lists, the number of species listed as threatened or endangered in the Rocky Mountains is small. The nine animals listed are: Uncompahgre fritillary butterfly (Boloria acrocnema—one of the few invertebrates listed), Mexican spotted owl, Preble's meadow jumping mouse, woodland caribou, bald eagle (which has come close to delisting), grizzly bear, gray wolf, lynx, and jaguar. However, some of these species, like the grizzly, bald eagle, gray wolf, and lynx are signature species of the Rocky Mountains as well as of wildness in general in America. The bald eagle, grizzly bear, and gray wolf also play important functional roles in the ecosystems in which they are found. The list would be extended to ten if one wishes to differentiate the Mexican gray wolf from the gray wolf of the north. Petitioning for further listings by the U.S. Fish and Wildlife Service is anticipated for isolated populations of martens and flying squirrels on single mountain ranges or systems (G. Beauvais, Pers. Comm.). These are boreal-subalpine Holocene isolates for which climate change would be particularly endangering and as such, illustrate the problems for genetically differentiated populations of any taxonomic species.

Table 7.2

Numbers of Threatened and Endangered Plant and Animal Species in the Rocky Mountain States and (parentheses) in Mountainous Habitats Plus Wyoming Basin Within the RMGB Region[1]

State	Plant Species	Animal Species
Montana	2 (1)	14 (4)
Wyoming	2 (1)	15 (5)
Colorado	12 (7)	20 (7)
New Mexico	14 (1)	27 (4)
Idaho	3 (1)	21 (5)
Utah	22 (2)	21 (3)

[1]Source: U.S. Fish and Wildlife Service listings updated September 1, 2000.

The number of threatened and endangered plant species is only seven and none of them could be said to be signature species for the region. They include: Penland alpine fen mustard (Eutrema penlandii), North Park Phacelia (Phacelia formosula), water Howellia (Howellia aquatilis), Sacramento Mountains thistle (Cirsium vinaceum), heliotrope milk-vetch (Astragalus montii), Maguire daisy (Erigeron maguirei), and blowout penstemon (Penstemon haydenii).

The primary concern for most of these species is habitat loss and habitat fragmentation, both of which result primarily from management decisions and disturbances. For grizzly and gray wolf (and possibly jaguar) the primary cause of death is human "predation." Of course, human-caused mortality is also a function of access, which, in turn, is related to fragmentation. One concern related to climate change is the loss of area occupied by whitebark pine, due to restriction to even higher elevations. Such a loss would be a detrimental reduction in grizzly bear food resources, as commented above. This situation is already exacerbated by the loss of whitebark pine to white pine blister rust. Whether the spread of the rust is being augmented by subtle, ongoing changes in climate is unknown. There is a potential here for a three-way interaction. It is important to note that the grizzly's present range is highly restricted by human intervention. This species would be prospering in a wider climatic range extending well into the Great Plains if it were not for human predation.

A second climate-related concern is for the lynx. The lynx is a high-elevation predator dependent on deep and long-lasting snowpacks. Without snow, the lynx tends to be outcompeted by other predators like coyotes, foxes and bobcats, and can even be victim to direct attacks by the bobcat (Beauvais 1999). This relationship with snow is exacerbated by increasing penetration of mountainous areas in the winter by recreational snow machines. Where the snow machines create packed snow trails through the subalpine zone, predators like coyotes can enter a foraging area normally dominated in the winter by lynx, wolverine, and marten (Beauvais 1999). Any reduction in snowpack depth, spatial extent, or duration would be a particular threat to the lynx.

A third species of concern is the Uncompahgre fritillary butterfly. It currently lives on one mountain pass (Mt. Uncompaghre) in Colorado and is undoubtedly strongly affected by the local climate. If the region becomes warmer, the butterfly's principal host plant, the snow willow (Salix nivalis), could potentially be lost from the area. There is not much area for either the plant or the butterfly to move up the mountain if the climate were to warm.

Not enough is known about the environmental requirements of the seven listed plant species to comment on their possible status in the face of climate change.

Invasive Exotic Species

In some ways, the impact of exotic invasive plants, animals, and microbes may be greater in the Rocky Mountain region than will be climate change. This judgment will depend on an individual's viewpoint. The effort required by a farmer to adapt to temperature and precipitation may be less onerous than that required for coping with invasive pest species. In contrast, loss of snowpack will be more serious than weed invasions to a ski-area operator. The spread of invasive exotics has accelerated rapidly in the latter half of the 20th Century and the ultimate accommodation of exotics to the Rocky Mountain environment is yet to be seen. The ranges of many of these organisms have not yet found their limits. How impacts and ranges of invasives will react to climate change is less well known than for natives for which there is little information as well.

There are many information sources on invasive exotics but none are delimited to the Rocky Mountain region itself, and none are complete with regard to all taxa. A number of databases exist but each has its own taxonomic and geographic limitations. For an entry to these databases see: http://www.invasivespecies.gov/databases/main.shtml. One of these, "The Invaders Database" from the University of Montana, contains listings of exotic plants in Washington, Oregon, Idaho, Montana and Wyoming (http://invader.dbs.umt.edu/). This lists 447 total exotic species for Idaho, 82 of which are noxious. Similarly Montana has 489 total, 80 noxious, and Wyoming has 220 total, 48 noxious. This gives the magnitude of plant-species numbers involved. Most of these plant exotics are problems within agricultural parts of these states, some are very critical in rangeland ecosystems, but relatively few invade forests or tundra ecosystems. Numbers do not tell the entire story, however. The advance of only a single exotic into an ecosystem can radically alter its normal structure and function. The advance of just one species—leafy spurge on to the northern mixed-grass prairie or chestnut blight into the eastern deciduous forest—have had impacts of enormous ecological significance.

There is generally less known about the environmental limits of invasive species than there is for most members of the native flora and fauna, partly because there is little known about the historical distribution of exotics. Further, their potential distributions are, for the most part, still unrealized in the U.S. Were these known, it might be possible to model individual species responses to climate changes in the same way described for forest trees and other members of the flora and fauna (Scott et al. 1996, Bartlein et al. 1997, Thompson et al. 1998, Fertig and Reiners 2001). A concerted effort to identify those exotic species known, or suspected, to be the greatest threats to Rocky Mountain ecosystems; a series of long-term monitoring plots to detect their spread; and development of a database on their environmental limits, would be valuable starts toward projecting how their distributions and roles might change with an altered climate.

Spatial Relationships

Particularly when investigating how individual species might respond to climate change, it is important to be realistic about the heterogeneous nature of the terrain and land cover. Fig. 7.3 provides an example of that kind of complexity for both natural variability and management-imposed variability (Knight and Reiners 2000). The latter leads to increasing fragmentation through dissection of old forest into more isolated and smaller fragments in a matrix of younger forests, openings, and edge (Baker 2000). Especially under the latter case of human-disrupted landscape patterns, we cannot assume that species will interact freely or disperse according to translocation of suitable climatic environmental space somewhere else. Migration, dispersal, and gene exchange depend on topological relationships between points in environmental space. For example, habitat suitability might be related to patch size or core/edge relationships. Ability to migrate in response to climate change to translocated environmental conditions involves appropriate connectivity across landscapes that may or may not be satisfied in the increasingly fragmented landscape (Pitelka 1997, Malanson and Cairns 1997, Collingham and Huntley 2000). This means that a component of landscape ecology must be implemented in model building in order to predict species movements across landscapes.

Such consideration of spatial relations increases the complexity of the task before us. It is in this context that we begin to perceive the chaos that may be expected if climate changes to the degree and with the velocity predicted by some models. Ecosystems across the region may eventually reach some kind of accommodation with the new conditions, replete with the same form of temporal dynamics at multiple scales with which we are familiar. But, it is likely that a quasi-transition period over a period of rapid climate change will bring many surprises. Species will probably appear in new locations and become extinct in others asynchronously with their associates in present-day assemblages. Adaptations we postulate for heat or water stress by particular plants or animals may prove to be misplaced if and when changes actually occur. Over time the apparent new assemblages may be surprising, and temporary. We should be prepared to find that our understandings about how nature functions are incorrect.

NATURAL RESOURCES

Timber

If forested zones were to shift upward in response to temperature increases alone, the areas occupied by merchantable as well as non-merchantable forests would necessarily shrink. However, as illustrated in the Greater Yellowstone Ecosystem case, if warming were offset by more precipitation, particularly in the summer, the area occupied by forest might even expand upward and downward. Thus, the area for potential harvesting is scenario dependent. Quite unknown is whether there will be a lasting direct effect of CO_2 on water-use efficiency of long-lived plants.

Except for moist areas of Montana and Idaho, forest productivity in the Rocky Mountains is relatively low. As old-growth timber has already been largely cut in the Rockies, and as the forests tend to be used increasingly for recreational activities, forest harvest is tending to become less important over most of the region. Market forces and political agendas will probably have a greater influence on the future of timbering in this region than will climate change.

Livestock Production

Warmer and drier climate scenarios would suggest that rangelands would expand in the Rocky Mountains at the expense of forests. Of course, these expanded rangelands could be of lower productivity and of quite different character than the present ones. Scenarios for warmer and wetter conditions could have the opposite effect of reducing rangeland area in this zone as forests expand. To a certain extent, and for other reasons, this has already been the case with the expansion of juniper over large areas of former rangeland at the bases of mountains in this region (Goodloe 1993).

As with the timber industry, the future of livestock production in the Rocky Mountain region is likely to be controlled more by market forces and political attitudes about grazing on public lands than by climate change. These factors, together with impacts of invasive species, are likely to interact in ways too complex to address in this report.

Recreation

The Rocky Mountain region has been a locus for recreation since the arrival of the mountain men and women in the early 19th century. Hunting and fishing were the original, dominating recreational uses early in Post-EuroAmerican settlement, but other uses have grown over time. These include hiking, back-packing by foot and horse packing, camping, touring by automobile, skiing and, more recently, roving by all-terrain vehicles in the summer, and by snow machines in the winter. These recreational usages vary historically, geographically, and seasonally but the dominant trend has been an increase in all of them.

Recreation and tourism are primary activities in the region that represent significant financial interests and active political activity. Conflicts occur between recreational and non-recreational usages. Thus, management is going to be the primary determinant of how these activities are changed in the future. Climate change will likely play some role in altering the context of management conflicts but other drivers will be primary.

NEEDED RESEARCH

Research needs have been suggested throughout this assessment but are revisited here as integrated format. As a preface, it must be said that workshop members realize that examining ecosystem components or regional land uses in sequential order is a misrepresentation of how the ecosystems of the region actually work. Topography, lithology, climate, soils, vegetation, animals, hydrology, etc. all work together in space and time in complex ways. Textual presentation requires this kind of linearization of environmental elements, but one of the prerequisites for coordinated research on this problem would be designing a program that permitted and required integration of these components and phenomena. A principal research need is a holistic research design.

A physiographic region like the Rocky Mountains is, by virtue of its geographic extent alone, heterogeneous. The altitudinal variation superimposed on the horizontal extent intensifies the variability embodied in this area as a unit of study and integration. A research need is a programmatic design providing for informational management of this three-dimensional geographic variation. This can be achieved with a digital geographic database, probably in a GIS framework, with which knowledge gained in a local area can be extrapolated appropriately, and with which phenomena generated by broader functions such as mesoscale climate can be interpolated appropriately to local areas. If this region is to be dealt with as a whole, a geographic data center is necessary.

Related to gaining control of geographic variables is the requirement to maintain a time-varying perspective on systems at any spatial scale. Some temporal phenomena like diurnal and annual cycles are obvious, but virtually every phenomenon has its characteristic time scalar. Such scalars may range from hours for population turnover times of soil microbes to decades for fire return times, to centuries for generation times of Engelmann spruce. Thus, a temporally varying as well as spatially varying mind-set is mandatory for research in this region, particularly with respect to a time-varying phenomenon like weather and the possible secular change in climate variables.

Various phenomena occur at different spatial scales and their observation, representation, and modeling require different resolution (grain, or areal extent of data units) for appropriate research. An integrated program must maintain a sure understanding of which extents and grains are appropriate for different issues, and how to properly scale up or down as the case requires. This will require a relatively sophisticated scale-awareness of all involved in a concerted program.

In keeping with recognition of different scales of operation, the project will require projects that are extensive in scope (in both space and time) and intensive projects that are highly focused in scope. For this kind of research, results of intensive studies gain value as they may be properly extrapolated into the broader system, whether it is a site, catchment, elevational zone, mountain range, or the entire region.

Advances in prediction of climate change and its effects, or of any kind of perturbation, cannot be made without modeling. Modeling of virtually all processes of interest is needed and will play a role complementary to that of spatial database management, analysis, and extrapolation.

Some, but not all, kinds of data can be gathered by different forms of remote sensing. Remote sensing extends from animal and environmental telemetry to low-level aerial photography and lidar surveys, to high-level aerial photography and satellite-borne remote sensing. Remote-sensing technologies should be integrated into a research plan in order to gather necessary spatial data and used in such a way to integrate phenomena across spatial and temporal scales.

The extensive environmental literature on the Rocky Mountains has scarcely been touched by this assessment. Much is known that needs to be organized in literature search and database organization that will include a digital cross-referencing system. The same is true for data. A system archiving data with rigorous metadata standards is needed for this region. The data-archiving systems being developed for the Long-term Ecological Research Program or by the National Center for Ecological Analysis and Synthesis are possible models.

Some locations are better than others for characterizing ecosystem functions. Managed forests and rangelands have value because of their accessibility, presence of sites with known histories and age classes, and amenability to disturbance experiments. National Parks and USFS Research Natural Areas (RNAs) and national monuments are more limited in this regard but have special value as long-term records and management histories that are supposed to represent pre-EuroAmerican settlement. Of course, national parks have much greater extent than do RNAs. Wilderness areas feature the most pristine conditions of the region but are very limited for access, treatment, and even monitoring studies. An integrated research program on the Rocky Mountain region should take into account the special character of each of these management resources

A regional research program should include surveys for meaningful indicator phenomena that might provide signals of change for small amounts of effort. Indicator phenomena might include the presence or absence of species, changes in population properties such as abundance or age-class structure, alterations in interactive behavior of species with one another, nitrate concentrations in streamwater, as well as standard physical measurements of weather, snowpack, hydrology, etc.

Many of the components of a regional research program require technological methods that may be remote from organisms themselves. A program should not be based purely on measurements of physical properties and derivative model outputs. A program must have a philosophy that organismal-level ecological research—research that might be termed "natural history"—needs constant support. It is from research at that level that we will learn vital information about the biological elements that drive many of the broader processes.

The topics addressed in this assessment (climate-change effects on hydrology, vegetation, disturbance regimes, floral and faunal elements) are natural foci for an integrated research program. Not discussed in this assessment are other important topics that, in a sense, are a derivative of the set reviewed. These include potential feedbacks between landcover change and mesoscale climate, changes in the amount and chemical character of primary productivity, interactions between terrestrial and aquatic ecosystems, and biogeochemical functions such as net carbon exchange with the atmosphere or nitrogen cycling.

In much of this discussion, effects of climate change are described as moving from one state to another. Neither was the past, nor will be the future, anything like a steady state when viewed from a sufficiently large temporal window. Clearly periodic and aperiodic variations occur at multiple time scales. These sources of variation combined with the nonlinear dynamics characteristic of ecological systems, inabilities of species to respond to rapid climate change, and lack of adaptations to new climates and habitat conditions together add to the complexities of developing predictive models needed to project the effects of climate change on Rocky Mountain systems. Hence there is a critical need for further research on the biota itself, and on developing system-level models, both in the context of climate-change effects.

SUMMARY

The Rocky Mountain region is large in extent and complicated by its extensive altitudinal gradients and local variations in structural geology, lithology, climate, and history. This heterogeneity makes generalization about possible responses of ecosystems to climate change difficult. The Rocky Mountains have undergone climate changes of great amplitude through the Pleistocene and Holocene and may be experiencing a warming trend that is differentially manifested throughout the region. Whether this warming is linked to greenhouse-induced mechanisms is presently impossible to tell.

Scenarios for warming and drying, and warming with more moisture in, alternatively, the winter or summer, were devised to provide a framework for considering ecosystem responses. Because the Rocky Mountain region is basically semi-arid, changes in the water budget anywhere in its domain will be of more importance than temperature change *per se*. On the other hand, temperature and precipitation cannot be separated as they both have controlling influences on water budgets. Warming is likely to reduce snowpack depth, extent, and duration under any scenario, but stream discharge timing and volume will be affected differently by the different scenarios. It is possible that changes in precipitation amount and timing may be more important than changes in temperature for altering hydrologic regimes. Regrettably precipitation is difficult to model and high-elevation precipitation gages are so limited as to make validation of precipitation models at high elevations almost impossible.

Climate changes are likely to cause changes in geomorphic processes throughout the region but inadequate attention was directed to this area to produce any suggestions of trends in this regard. Soil responses likewise were not considered in this assessment.

Potential responses by vegetation, and thus habitat, to climate change are highly likely, but variable in time and space, given evidence for such changes in the past. This may be manifested as shifts in elevational location of entire vegetational zones, as breakdowns in zones and the boundaries between them, and most probably, as variations in the species composition and distribution of zonal elements across landscapes within zones. In the most general terms, a warmer, dryer scenario suggests translocations of zones upwards with loss of some higher zones off the tops of lower mountains. Of course for hydric systems, such a change would reduce the amount of watershed area nourishing them and they might be totally eliminated from the landscape. Warmer and wetter scenarios, particularly with higher summer precipitation, might lead to expansion of forested zones upward into the alpine zone and downward into the shrub or grassland areas now below the lower treeline.

The responses of vegetation to climate change will be highly influenced by changes in disturbance regimes, particularly of fire and insect outbreaks. The fire regime has already been altered beyond the range of natural historical variability by grazing, logging and, especially, fire suppression. It is becoming increasingly clear that fire occurrences and extents are related to intra-decadal oscillations in climate associated with ENSO and PDO. This climate relationship ensures that fire will be influenced by any of the scenarios, or intensification or buffering of the ENSO and PDO cycles themselves. There is evidence that insect outbreaks are also climate-related but other factors such as the distribution of forest stands by age class, and thus tree vigor, will modify climate effects.

Climate change will be implemented through alterations in species populations throughout the Rocky Mountain region. The flora (ca. 5,000-5,500 vascular plant species) and fauna (ca. 1,000 vertebrate species) are likely to react individualistically to changes in climate along with related changes in fire, insect outbreaks, landuse change, and further invasion or naturalization of exotic species. Predicting the responses of individual species requires considerable knowledge about those species but methods are in place to begin to do this. Some model results have been published for tree species and there is no reason why more cannot be done with other members of the flora and of the vertebrate fauna. Invertebrate species are less well known across most groups but a few, particular species such as the Yellowstone checkerspot butterfly (Euphydryas gillettii) which is diagnostic of wet meadows near riparian areas (Debinski 1994), would have great utility in this regard. Sheer numbers of invertebrate species prohibit investigations of all of them, but critical or diagnostic species might be especially useful for analysis and prediction because of their associative fidelity with plant species, physical conditions, or vegetation types.

Species deserving particular attention are threatened and endangered species, of which there is actually a relatively small number in this region (nine vertebrate and one invertebrate animal and seven vascular plants). Shifts in environmental gradients across Rocky Mountain landscapes are likely to lead to rapid growth in the numbers of recognizably threatened species.

Invasive exotic plant and animal species may be a threat to Rocky Mountain ecosystems equal, in some cases, to potential climate change. Exotic species are a present-day reality that must be considered regardless of climate change. They will vastly exacerbate our abilities to predict and manage for the anticipated chaotic shifts in future species composition and occurrences when superimposed on climate-change effects.

Considerable research has been published and is ongoing in the Rocky Mountain region focused on, or relevant to, climate-change questions. This assessment uncovers but a small part of the scientific resources available in this region. There is good potential for organizing a more coordinated method for integrating research bearing on climate change if that were a national goal. A series of research needs concludes this assessment. This list may help to conceptualize a coordinated research system to better help society to predict and recognize changes ongoing and looming in the future due to a changing climate.

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Chapter 8

NATURAL ECOSYSTEMS II. AQUATIC SYSTEMS

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INTRODUCTION

There is growing public awareness that concentrations of several greenhouse gases (e.g. carbon dioxide, methane, and chlorofluorocarbons) are increasing in the atmosphere and much of this increase is attributed to anthropogenic sources (Hansen and Sato 2001, Hansen et al. 2001, 2002). Relationships between ozone depletion, global warming, and linkages with El Niño-Southern Oscillation (ENSO) climate dynamics add further complexity. Several studies conclude that climate change over the last 100 years has exceeded the natural range of variability and has been caused at least in part by anthropogenic changes (Crowley 2000). The directionality, magnitude, rate, and causes of any future climatic changes are all topics of ongoing research.

For inland drainage basins in western United States, the relationship between warmer climate and altered precipitation is of utmost importance because of the arid to semi-arid nature of this Intermountain region, and the increasing need for fresh water by a rapidly growing human population. However, there remain persistent uncertainties regarding the linkages between global warming and changes in patterns of precipitation in general. The hydrologic and ecological implications of climate change are perhaps the least understood of the wide array of potentially important future impacts. The combined effects of warmer water and extreme floods and droughts that are considered likely in some forecasts will alter inland aquatic ecosystems over the next 50 years, especially because the demand for freshwater by human populations is growing regionally (Coutant 1981, Carpenter et al. 1992, Covich 1993, Grimm 1993, Grimm et al. 1997, McKnight and Covich 1997, Meyer et al. 1999, Murdoch et al. 2000, Postel 2000, Jackson et al. 2001, Poff et al. 2002).

A group of geologists, hydrologists, and ecologists met in February, 2000 in Salt Lake City, Utah to discuss different climate scenarios and examine some well-documented historic changes in climate. The group discussed the potential effects of climatic variability and change on aquatic ecosystems in the Rocky Mountains and Great Basin. This chapter is a synthesis of the material and views presented at the Salt Lake workshop and extensive review of the relevant literature discussing climate-change effects on aquatic ecosystems.

A major goal of this chapter is to summarize important points needed to understand ways in which large-scale, long-term dynamics of climate would affect inland aquatic ecosystems. A second goal is to provide examples and case studies that illustrate general relationships of how climate change has already affected aquatic species and ecosystems in the Rocky Mountain/ Great Basin (RMGB) region. A third goal is to identify gaps in current understanding that need more study in order to improve future forecasts regarding the expected consequences of climate change on freshwater ecosystems.

CURRENT AND FUTURE STRESSES AFFECTING RMGB AQUATIC SYSTEMS

As commented in the other chapters, climate-change effects will interact with other stresses now affecting the sectors, or those likely to affect them in the decades ahead. Several influential ones are now besetting aquatic systems in the RMGB region.

Human Populations and Transfers of Scarce Water Resources

Social changes will influence how any climatic changes affect freshwater ecosystems. Climatic effects can only be observed in conjunction with changes in land use that alter interconnected hydrologic, geomorphic, and biological responses to climatic variables. Thus, increased understanding of the effects of future climate change must be coupled with better understanding and integration of the likelihood of increased demands for high-quality freshwater resources. These demands for drinking water, irrigated agriculture, industrial coolants, and dilution of treated sewage and industrial effluents will continue to increase and add more stress to aquatic ecosystems.

Predicting responses of species and ecosystems to climatic changes is also complicated by complexity of the terrain in the region. Yet, assessing how future climatic change may alter aquatic ecosystems is especially important because of these close connections between aquatic habitats and rapidly growing human populations. Resource management by private owners, state and federal agencies, and research strategies for understanding and adapting to climatic changes will require enhanced coordination. This region relies on groundwater, large reservoirs, water diversions for irrigation, and many types of regulated river flows and interbasin water transfers to maintain reliable sources of water for human uses. The combined effects of these managed flows on natural aquatic habitats are extensive. Urban development, road construction, overgrazing, and irrigated agriculture have affected infiltration, overland flow, and evapotranspiration. These changes have altered the seasonal patterns of discharge, caused declines in some river flows, draining of wetlands, and loss of aquatic habitats (Hirsch et al. 1990, Postel 2000, Vorosmarty et al. 2000).

Under warmer climate conditions these regulated flows in some large rivers may be managed to reduce variability in seasonal discharge and water temperatures, and to minimize effects of any increased frequencies of floods and droughts (Meyer et al. 1999). In other rivers, the addition of adverse effects from climate change may further disrupt ecosystem dynamics. Dams already have altered natural flow regimes and affected the ability of native species to compete with non-native species (Poff et al. 1997, 2002). Effects of dams may already be greater than any expected effects from climate change. Currently dams are responsible for fragmenting fluvial ecosystems in much of the western United States and their impacts on river discharge is several times greater than impacts anticipated as a result of climate change (Graf 1999).

Although water resources are abundant in a few locations (near large rivers, deep lakes, and reservoirs), the recent rapid increases in human populations have already overappropriated water resources (Naiman and Turner 2000, Jackson et al. 2001). This region contains some of the fastest growing cities in North America. For example, urban and suburban growth in Las Vegas, Denver, Albuquerque, Salt Lake City and surrounding areas is dependent on water transfers from remote locations and reallocation from agricultural uses. Several towns (e.g., Clover Creek and Rush Valley) are using much of the available water supplies south of the Great Salt Lake so that groundwater use is increasing faster than recharge of aquifers. In other areas deeper drilling for well water is occurring to support expansion of irrigated farming and population growth. Very rapid growth of populations in the cities of the region continues to create increased demand for high-quality, freshwater resources. During the next century these demands will continue to increase.

Moreover, aquatic habitat degradation from eutrophication of rivers and reservoirs (from both point and non-point sources of nutrients), and atmospheric acid deposition may combine to lower water quality and reduce habitat availability for fish and wildlife as a consequence of rapid human population growth in urban centers. In rural areas the increased demand for water to irrigate crops (Postel 2000) and the potential for overgrazing rangelands (Armour et al. 1991, Trimble and Mendel 1995, Kauffman et al. 1997) will further stress drainage basins.

Thus, any effects from future changes in precipitation and temperature may be accelerated and accentuated by associated increased demands for freshwater from human population growth. These combined effects from climate change and human population growth will be difficult to distinguish. Trends in both climate change and landscape change can occur gradually so that detection and identification of each of these sources of change will be problematical.

Incursion of Nonnative Species

Throughout North America the present distributions of native aquatic species have been greatly modified through competitive displacement by introduced non-native species, and by habitat loss resulting from rapidly expanding human populations and homogenization of fish faunas (Rahel 2000). Recent studies report 92 introduced non-native fish taxa (foreign and native transplants) in the Great Basin, and 64 and 102 in the Upper Colorado River and the Lower Colorado River Basins, respectively (Fuller et al. 1999). These introduced fishes compete with native species and also disrupt food webs by having a major effect on invertebrate prey species. In the Intermountain West, many of the introduced forms are adapted to relatively warm water temperatures. They have usurped the lower, warmer stream reaches and restricted the native species to the higher-elevation, colder reaches. Increasing water temperatures would allow the exotics to move to higher elevations and further impact the natives.

Currently, many native species that occur in inland waters are listed as endangered, and rapid changes in climate may further degrade their habitats. Plans for managing these endangered forms need to consider how extreme climatic events, human population growth, and exotic species interact to affect their chances for survival. The additional stress on aquatic species and ecosystems induced by climate change may generate renewed interest in better managing rivers, lakes, wetlands, and floodplains for the preservation of threatened and endangered species. The potential for significant economic consequences resulting from global warming may lead to more large-scale, long-term planning and ecosystem management. This integrated approach could minimize local extinctions of already threatened forms. But much remains unclear about how this interdisciplinary integration may be accelerated to enhance management options.

Past and Current Climate Variability

Climatic variability influences water budgets of drainage basins and affects a diversity of streams, rivers, ponds, lakes, springs, and wetlands in the RMGB region (Winter 1981, 1989, Hostetler 1995, Hostetler and Giorgi 1995, Hostetler and Small 1999). Current and historic data demonstrate that these regional aquatic ecosystems are subject to large interannual variations in climatic variables, and have changed greatly over geologic time scales. These major shifts in precipitation, temperature, and wind have altered species distributions, ecosystem productivity, and foodweb structure.

The biotic responses to abrupt climatic shifts are especially well documented by paleoecological studies of lake sediments with relatively fine temporal resolution determined with various dating methods (Benson et al. 1990, Fritz 1996, Reheis 1999, Battarbee 2000, Saros and Fritz 2000). Shifts in species of plant and animal fossils are preserved in lake sediments throughout the region. For example, remains of different species of chironomid midges are used to interpret paleotemperatures. Diatom species reflect shifts in salinity and alkalinity that were altered by changes in temperatures, evaporation, and precipitation.

Fluctuating lake levels have occurred in many of these closed drainage basins over the last 50,000 years (Benson and Thompson 1987, Benson et al. 1990, Lall and Mann 1995). Increases in lake levels and the subsequent linkage among lakes were followed by decreases in lake levels and isolation of populations that were exposed to different salinities and temperatures so that organisms evolved adaptations to different aquatic environments over many thousands of years (Galat and Robinson 1983, Dickerson and Vinyard 1999a, Herbst 1999).

The region's aquatic systems are also highly variable on the shorter time scale of the contemporary climate. The area is largely semi-arid, and arid and semi-arid climates are among the most variable, globally. The region is also influenced by the El Niño-Southern Oscillation (ENSO) climate variability (Molles and Dahm 1990, Cayan and West 1993, Cayan et al. 1998, 1999). Currently, there are marked year-to-year variations in snow accumulation that are altered by ENSO patterns. For example, snowpack depths were 30% lower during the 1996 La Niña event than in the previous winter in the Jemez Mountains of northern New Mexico, the southernmost area of this Rocky Mountain/ Great Basin region (Baker et al. in press).

Spatial Variability

The great latitudinal, elevational, and geomorphic variability of the region produces a collage of aquatic habitats. Varying combinations of water temperatures, flow rates, sediment loads, nutrients, other dissolved materials, and water depths (habitat permanence) produce a wide range of habitat quality for aquatic species. Habitat quality, fragmentation, and connectedness within drainage networks influence distributions of fishes, associated food-web components, and ecosystem processes.

As is well known, distributional patterns of precipitation and temperature are influenced by the topographic relief of drainage basins. Fluvial and alluvial geometry, in turn, affects the weathering of basins and is responsive to climate change (Schumm 1977, Howard et al. 1994, Montgomery and Buffington 1997, Whipple and Tucker 1999, Whiting et al. 1999). The extensive, heterogeneous topographic relief of high mountains and broad valleys within this large geographic region results in complex temperature regimes, uneven precipitation, and exposure to high winds. Snow can occur during most any month at high elevations; and precipitation is characteristically different from north to south, and to some degree from east to west. The timing of snowfall and snow melt in this complex terrain varies across latitude and elevation resulting from differences in slope, aspect, geology, vegetational cover, and land use.

The hydrology reflects regional precipitation, evapo-transpiration, vegetative cover, catchment runoff, river regulation, and land use. The combination of high winds and complex terrain results in deep snow accumulation in some locations and snow removal in other locations. These topographic features create a complex mosaic of habitats with variously sized and shaped drainage basins. Many mountains are characterized by rain shadows and rapid runoff. Thus, because of the complex mountainous terrain there are multiple sources of landscape-level variability that alter local weather patterns within subregions.

Although considerable long-term data exist for temperature, precipitation, and wind for some areas (Baron 1992), there is a general lack of data from higher elevations and non-agricultural areas (Hirsch et al. 1990, Williams et al. 1996, Stokstad 1999). Aquatic ecosystems could be especially vulnerable to any increased frequencies of extreme events, as predicted in some climate-change scenarios, because this region is generally characterized by relatively low mean annual precipitation and by widespread occurrence of floods and droughts. Although there are several large rivers and thousands of permanent lakes (especially in the mountainous areas) that provide critical habitat for native species and for recreational uses, there are also less persistent habitats such as shallow ponds, vernal pools, and various types of wetlands that provide important habitat diversity. All of these aquatic habitats could be altered by persistent climatic shifts in precipitation, evaporation, wind, and temperature. Individual species will respond in different ways by altering population densities and community composition, and will likely be influenced by several physical and chemical variables.

Wetlands in the Rocky Mountains and Great Basin are relatively scarce except in riparian areas, and these species-rich habitats are likely to be sensitive to climatic change. Of the six physiographic types of wetlands defined by Winter (2000), the mountainous and the broad interior drainage basins that dominate this large semi-arid region are highly vulnerable to climate change because their groundwater sources are often limited or negligible. In general, the shallower the water depth and the more dependent the water source on direct precipitation, the more likely these wetland habitats will be vulnerable to climatic change (Winter 1989, 2000).

Over time, the aquatic biota of the Rocky Mountain/Great Basin region has evolved adaptations to survive in this climatic and habitat variability—in some cases broad tolerance ranges to cope with wide swings in water temperatures, depths, chemistry, etc.; in other cases genetic changes that best adapt organisms to local habitat conditions. The effects of climate change on the aquatic species, communities, and ecosystems will depend on their abilities to respond to changing conditions. Almost certainly, some species will be more adaptable than others, and community and ecosystem compositions will change.

As a consequence of the region's habitat variability and the many differences in geological terrain, drainage basins, water resources, and aquatic habitats, RMGB aquatic systems are likely to respond to climate changes at different rates (Hurd et al. 1999). Freshwater ecosystems may be altered by interannual changes in the frequencies and intensities of short-term extreme events. These events may reset the geomorphic template in fluvial ecosystems. Their frequency and intensity can result in very different impacts. For example, some populations of freshwater fishes or invertebrates in different microhabitats can adapt physiologically or behaviorally to changes in water temperatures or discharges that occur seasonally or over decadal time scales. Similarly, plant species and vegetative communities that cover the drainage basins may respond to climatic shifts at different rates and in different ways from aquatic species. But a sequence of severe droughts could cause widespread mortality and lead to wildfires and a major restructuring of drainage basins.

The challenges which the aquatic biota will face in adapting to climate change in an already variable environment will be exacerbated further by the newer stresses of human alterations of water resources—eutrophication, acidification, soil erosion and associated siltation, and water diversion and regulation—and by competition with intrusive, nonnative species. This complex of stresses makes assessment of climate-change effects highly problematic and raises a host of questions needing intensive research: How will changes in climate alter persistence and function of the current biota? Will species move to other habitats and can they disperse as conditions change? Will nonnative species compete more aggressively and displace native species? Will ecosystem functions change if the populations become fragmented and biotic composition changes? These and many other questions need to be answered if the effects of climate change on Rocky Mountain/Great Basin aquatic ecosystems are to be understood and predicted.

ASSESSMENT PROCEDURES

Subregional Scenarios

For purposes of this assessment of aquatic ecosystems, the RMGB region was divided into northern and southern subregions for three reasons. The first is the great latitudinal, and thus climatic, extent of the region. The second is the fact that the southern portion has a predominantly summer monsoonal precipitation pattern while the northern portion has a more Mediterranean seasonal distribution. And third, the evidence presented in Chapters 3 and 4 suggested that climatic changes predicted by general circulation models (GCMs), and resulting hydrologic changes, may have started to appear during the 20th century in the northwestern two-thirds of the region but not in the southeastern third.

The subregions are separated by an east-west line running approximately through central Utah and central Colorado. The southern subregion thus includes the southern halves of Utah and Colorado, and the northern New Mexico portions of the RMGB region. The northern subregion includes virtually all of the Great Basin, and those portions of the Rocky Mountain system north of central Utah and central Colorado.

This subdivision could draw attention to potential survival strategies of some species in response to rising temperatures. In the next century, if temperatures increase in the southern subregions, differences in orientation among rivers are likely to be important because drainage basins with a predominantly north-south directionality may provide some potential for northward movement by many aquatic species that require cooler-water habitats. Such movements could occur where dams, steep terrain, and the isolated locations of some reservoirs, lakes, and wetlands did not prevent species from moving into thermal refugia.

Different sets of scenarios are posed for the subregions (Table 8.1). Rising temperatures are posed for both, especially in winter. Increased precipitation is posed for both, primarily in winter in the north, and summer in the south. A number of authors are projecting increases in summer-monsoonal moisture in the southern portion of the Intermountain West. These climatic changes would be expected to reduce (northern) or eliminate (southern) montane snowpacks, alter stream temperatures and seasonal hydrographs; and in the south reduce soil infiltration and increase evaporation.

Table 8.1

Climate-change Scenarios and Hydrologic Responses for RMGB Aquatic Ecosystems

Scenario and Consequences	Northern Subregion	Southern Subregion
Precipitation	Increased winter precip., especially rain	Reduced winter rain, increased summer rain
Temperature	Warmer fall, winter, spring	Warmer winter, late summer
Expected Hydrologic Consequences	Reduced snowpacks	Snowpacks eliminated
	Earlier peak spring flows	Reduced peak spring flows
	Increased annual and base flows	Reduced annual and base flows
	Reduced summer flows	Reduced infiltration
	Increased flood magnitudes	Reduced flood magnitudes
	Increased baseflow temperatures	Increased evaporation

The Need for Model Development

Effective projections of the impacts of climate change on RMGB aquatic ecosystems can best be made with well-structured models. Developing models that simulate the effects of climate change on aquatic biotas is complicated by the fact that climate influences the organisms both by shaping the hydrology, and by affecting such environmental variables as water temperature and chemistry. The latter affect the organisms' physiologies, subsequently their population processes, and ultimately such biotic interactions as predation and competition which structure community composition. Hence the needed models will be complex structures that couple climatic inputs, hydrology, and biotic processes within aquatic systems. Such models do not presently exist, and thus cannot facilitate this assessment. But it seems useful to review some of the data needs and complexities that will affect development of such models.

Increasingly sophisticated models simulate global and regional scenarios related to directional changes in temperatures and precipitation (see reviews by Henderson-Sellers 1994, Leavesley 1994, 1999). Shifts in mean, annual global temperatures and precipitation remain difficult to forecast, especially at seasonal and regional levels (Mahlmen 1997, Reiners 1998, Ojima et al. 1999). But current general circulation models (GCMs) predict some increase in mean, annual global temperatures and changes in global precipitation over the next century. These directional changes are expected to alter regional patterns of evaporation and precipitation and thereby alter regional hydrology, especially the frequencies and intensities of floods and droughts (Arnell 1994, 1996, Lins and Slack 1997a, b, Easterling et al. 2000).

Statistical downscaling (SDS) models are being linked to GCMs and runoff models to generate regional and basin-level predictions of climate and precipitation runoff (Xu 1999a, 1999b). This approach appears to be more accurate than previous approaches because GCMs do not include effects of surface features and land-surface processes that influence runoff in mountainous basins (Wilby et al. 1999, Hay et al. 2000, Wilby et al. 2000). Other enhancements may come from use of artificial neural networks (ANN) for spatial interpolations of data used in SDS models (Snell et al. 2000). The combined applications of ANN and SDS are likely to provide more useful predictions to hydrologists and aquatic ecologists working in complex terrain if sufficient long-term data are available at enough locations within the region.

During the last several decades more attention has focused on models of how climate change beyond the range of natural variability can cause aquatic species (especially fishes) to respond to rapid and persistent shifts in temperature (e.g. Coutant 1981, Beitinger et al. 2000, Schlosser et al. 2000, Carline and Machung 2001, Isaak and Hubert 2001). Distributional and phenological changes of species are increasingly being documented. Some biological changes may be linked to extreme climate events (Easterling et al. 2000, Hughes 2000) that can trigger hydrologic and geomorphic responses which, in turn, modify the ecology of entire drainage basins. Because of these concerns, numerous studies have focused on how climate change may affect inland waters and associated biota (Gleick 1986, Molles and Dahm 1990, Hostetler 1991, Carpenter et al. 1992, Firth and Fisher 1992, Grimm 1993, McKnight et al. 1996, Cushing 1997, Meyer et al. 1999, Murdoch et al. 2000, Poff et al. 2002). These studies have identified important physical relationships among hydrologic and geomorphic variables that affect aquatic ecosystems. Researchers attempting to evaluate effects of future climate change on hydrology and precipitation confront challenges similar to those addressed by workers who are evaluating the effects of other on-going sources of disturbance on aquatic communities.

Studies dealing with distributions of biodiversity in aquatic ecosystems (Vannote and Sweeney 1980, Hawkins et al. 1995, Poff 1997, Vinson and Hawkins 1998, Lowe and Hauer 1999, 2000, McKee and Atkinson 2000) incorporate physical factors in their analyses including climate-driven variables such as temperature and discharge variability. Although variability in these physical variables is known to have seasonal and interannual effects on natural ecosystems, the understanding of how directional change or extreme variability in climate can alter biotic communities and ecosystem dynamics is still inadequate. A comprehensive approach is needed to integrate the more narrowly focused, short-term studies into a context of climate variability. For example, use of multivariate approaches to examine complex relationships between changing distributions of aquatic organisms and climate trends and variability is needed to succeed research that has previously been concerned only with eutrophication or ecotoxicology.

Several characteristics of aquatic systems complicate the development of climate-change models. One such complication is that species- and community-level dynamics are less predictable than the overall ecosystem functions of productivity, nutrient cycling, and decomposition. Rates of ecosystem functions are likely to respond to various combinations of climatic driving forces such as precipitation, temperature, and wind. Climatic variables may often drive mean rates of change in nutrient uptake, storage, and cycling. These climatic driving forces influence, but often do not control, population dynamics and some community relationships. The linkages among physical variables and biotic communities even for current climatic conditions are locally complex and not yet highly predictable. Streams, rivers, ponds, lakes, springs, and wetlands constitute broad continua of conditions where many aquatic species are adapted to wide ranges of conditions. Other species are more specifically adapted to narrow ranges of conditions, and must migrate within a bounded landscape in search of new locations if their environment changes.

Local terrain and other physical features greatly influence the composition of biotic communities so that species-specific responses to climate change remain uncertain. For example, models of energy balance and water balance for lake ecosystems are based on physical parameters. These models generally are useful for predicting when ice forms and melts on lakes (Magnuson et al. 2000, Prowse and Beltaos 2002) and when lake levels rise or fall (Winter 1981, 1989 Wurtsbaugh and Berry 1990). However, the consequences of having shallower, warmer waters or longer periods of open water and increased light penetration into a lake are not as predictable. Warmer waters generally stimulate faster rates of growth and production, but how these rates alter species-specific functions are not well known.

A related complication involves the size of a water body. As the size of a river, lake, or wetland increases, the hydrologic and ecological connections are more complex and some types of predictions are more uncertain. For example, snow melt and runoff from mountainous terrain are predictable with several types of hydrologic models (Band et al. 1996, Leavesley 1999, Baron et al. 2000). How the stream fishes respond to earlier peak flows or warmer summer waters, however, is not clear. In the RMGB region, deep lakes have predictable density and thermal stratification that result in more thermal refugia for organisms. However, stratification may result in biologically important differences in dissolved oxygen until the lakes again mix completely and increase exposure to atmospheric oxygen. Increased salinity can further accentuate stratification in lakes and large rivers so that species distributions become more variable over time and space and thus more difficult to predict competitive outcomes.

Larger, shallow-water ecosystems are often mixed by wind-driven currents and these create more spatial and temporal complexity. Such habitat complexity provides microhabitats for numerous species and increases food-web complexity. But again at the ecosystem level, these larger aquatic habitats may allow more predictable biotic responses to climate change in terms of major functional relationships. At the ecosystem level, size of lakes and rivers can influence the number of trophic levels in food webs or the complexity of energy flows through these food webs (Post et al. 2000). Species-level changes in microbes, phytoplankton, zooplankton, and fish within complex food webs, as responses to climate changes, are less predictable (e.g., Keleher and Rahel 1996, Rahel et al. 1996, Taniguchi et al 1998, Jager et al. 1999, Petchey et al. 1999).

As a third characteristic related to the latter two, aquatic-ecosystem responses are likely to be spatially and temporally linked at larger spatial scales. These interconnections can produce significant time lags associated with variable flow velocities among different standing- and flowing-water ecosystems. Although aquatic ecosystems have distinct boundaries and attributes, they are also linked to important sources of atmospherically and terrestrially derived inputs of water, nutrients, and toxins. In general, connected networks of rivers, streams and lakes integrate many physical and chemical aspects of their drainage basins that influence their biotic communities (Hynes 1970, Likens and Borman 1974, Power 1995). Standing waters of lake ecosystems have residence times, temperatures, and chemical attributes that reflect complex surface and groundwater dynamics within their drainage basins (Winter 1999, 2000, 2001). These ecosystems are also interconnected as chains of lakes and reservoirs within topographically controlled drainage networks (Hutchinson 1967, Hasler, 1975, Taub 1984, Baron 1992, Kling et al. 2000). Linkage by groundwater connections provides a continuum of internal interactions within a hierarchy of nested watersheds and varied rates of flow (Kratz et al. 1991, 1997, Winter et al. 1998).

Thus, any ecosystem-level or biotic-community-level responses to climate changes are likely to be complex and characterized by lags and thresholds that are challenging to model if only certain types of discrete systems are analyzed. Clearly, temporal and spatial scales are critical considerations in developing models for the aquatic systems of a region as large and diverse as the RMGB.

ASSESSMENT OF POTENTIAL EFFECTS

While we do not yet have models that permit comprehensive simulations of climate-change effects on RMGB aquatic ecosystems, we can make reasonable projections on the effects of changing climate variables on ecosystem components, based on the extensive aquatic literature for the region. These are proposed in the following sections, subdivided by climatic and hydrologic variables.

Precipitation and Hydrology

The major effects of precipitation on aquatic ecosystems are its influences on hydrology. The amount of precipitation determines the amount of water resources for the organisms, and its seasonality influences seasonal fluctuations to which the organisms adapt their life cycles. In the RMGB region, 85% of stream flow results from the melting and run-off of montane snowpacks (Dahm and Molles 1991, Barry 1992), and hence the stream hydrographs are intimately linked to the timing, form, and amount of montane precipitation, and to the timing of snowmelt. Any changes in seasonal distribution of precipitation, evaporation, or temperature are likely to affect the timing and amounts of flow.

The scenarios of Table 8.1 project higher temperatures and precipitation for both the northern and southern subregions, similar to the scenarios posed for the region in Table 3.8 of Chapter 3. Increased precipitation should add to the existing resources as long as the increase exceeds the higher evapotranspiration resulting from higher temperatures. Nash and Gleick (1993) concluded that a temperature increase of 4°C (7.2°F) would require a 15-20% increase in precipitation just to maintain annual run-off in the Colorado River basin at historical levels. Increased streamflow increases habitat and oxygen content, while reduction concentrates dissolved chemicals and facilitates increased temperatures.

This region has numerous seeps, springs, and groundwater-fed rivers and lakes. Habitat persistence is determined by the quantity of precipitation and by the ratio of infiltration to groundwaters and runoff to surface waters. These relationships of groundwater flows and runoff to surface waters and below-surface waters (hyporheic) are critical for defining types of biotic communities along a gradient of permanence and vulnerability to climatic changes (Winter 2000).

Current climate-change models for this region all suggest reduction in (or possible elimination of) snowpacks by 2080 to 2100. Spring peak flows during snow melt are forecasted to be lower and possibly earlier than currently observed, and reduction in snowpack would limit the quantity of snowmelt that provides the source of surface and groundwater for aquatic habitats. Any long-term change in the seasonal distributions of rain or snow (or rain on snow that results in rapid runoff and flooding) will likely alter aquatic ecosystems, especially where and when other environmental factors such as acid and nutrient deposition shift in their effects (Baron and Campbell 1997, Bowman and Steltzer 1994).

Earlier spring snow melt and increased frequencies of rain-on-snow events will greatly alter the timing of peak flows and patterns of species reproduction and survival. The timing and number of floods greatly alter wetland and floodplain habitats as well as nutrient transfers. More extreme floods and droughts would increase mortality of fishes and many types of invertebrates. More rapid runoff and higher peak floods would alter bank erosion and sediment transport. Increased sedimentation of fine particulates and infilling of rocky substrata (embeddedness) would limit fish spawning and result in loss of some species. Biotic communities would almost certainly change in species composition, dominance, and foodweb structure.

Precipitation and Water Chemistry

Retention of organic matter that provides food resources for detritivores will be altered under different seasonal patterns and magnitudes of flow alterations. During prolonged low-flow conditions, accumulation and decomposition of organic matter will lead to decreases in dissolved oxygen, especially if water temperatures are also increased. Lower dissolved oxygen and warmer waters will stress many species of fish and invertebrates and increase mortality, particularly in late summer.

Changes in water balances within catchments result from both shifts in precipitation, evaporation, evapotranspiration, and water diversions or inter-basin transfers. Together with geologic composition and land use, these hydrologic changes greatly alter salinity of inland waters. The Great Basin region is characterized by salt lakes and mineral-rich springs and soils that are derived from climatic changes and soil weathering during the Pleistocene (Lall and Mann 1995). Within the last several decades, increased salinization of soils and stream runoff has created water-quality problems in many areas of western North America. Changes in lake levels and persistence of riparian vegetation, playas, and other wetlands are all indicators of large-scale responses to hydrologic conditions that influence salinity, especially in closed basins with internal drainage. Closed basins accumulate salts in solution or in sediments over time. During periods of rapid evaporation, brines form that limit biotic diversity in closed basins with internal drainage. Open basins with out-flowing rivers transport salts out of the drainage area.

Changes in salinity along with other associated water-quality effects (warmer waters, decreased dissolved oxygen, and increased nutrients) have generally had major effects on biotic distributions in inland waters (Williams 1998, Murdoch et al. 1999, Koop and Grieshaber 2000). Physico-chemical variables restrict biotic distributions because of the physiological limitations among different species. Only a few species are well adapted for highly variable changes in salinity (i.e., euryhaline), and most species are limited to narrow ranges (stenohaline).

For example, as salinity fluctuates in response to variations in precipitation and evaporation, invertebrate communities in many deep lakes and shallow vernal pools change rapidly to exploit new conditions (Galat and Robinson 1983, Galat et al.1988, Stephens 1990, Wurtsbaugh and Berry 1990,Williams 1998). Shallow-water habitats that vary in salinity are often characterized by low species diversity but high productivity. These habitats provide essential food resources for wading birds and migratory waterfowl that consume large numbers of invertebrate prey (Wollheim and Lovvorn 1995, 1996). Such highly mobile consumer species disperse prey species among similar habitats that vary in temporal persistence. These prey species produce resistant stages or encapsulated eggs during their relatively short life spans that are well adapted for bird transport.

In total, changes in amounts and seasonal variations in aquatic environments associated with precipitation and temperature change would undoubtedly produce significant changes in aquatic biotas.

Temperature

General circulation models predict that climates will warm over the next 50 to 100 years at a rate much faster than in the recent past. The Rocky Mountain/Great Basin region is expected to be one of the warmer areas relative to global trends. Recently, these projections have included higher temperature increases (Houghton et al. 2001). Mean annual temperatures in many locations have increased during the last decade.

Because most aquatic species are ectothermic —a few species of aquatic birds and mammals are exceptions—and assume the body temperatures of their environments, an extensive history of research has examined the effects of temperature variations on aquatic ecosystems and individual species, and provides a basis for projecting global-warming effects.

General System Effects

Temperature is biologically important for aquatic organisms because it directly affects metabolic rates, growth, and reproduction. The potential impact of rapidly changing water temperatures is great in inland waters because the fish and invertebrates living in these waters lack physiological abilities to regulate their body temperatures. They rely on behavioral thermal regulation by moving into specific microhabitats with different thermal regimes. Depending upon their location and their mobility, many species can seek out different water temperatures where they attempt to optimize their growth and reproduction. Generally, species that are restricted to narrow ranges of temperatures (stenotherms) can persist only in relatively stable environments such as spring-streams or very deep lakes. Species with wider ranges of temperature tolerances (eurytherms) are more commonly found in shallow streams, lakes and ponds. Aquatic species differ greatly in their thermal preferences and tolerances: cold stenotherms are well adapted to waters just above freezing and are often limited by distinct upper thresholds while warm stenotherms are limited by lower and upper thresholds in water temperatures. These physiological differences led Magunson et al. (1979) to propose that various species use locations with particular thermal regimes as a resource within their habitat just as food types and sizes are essential resources within a species' niche.

If the warming trends of the 20th century continue, species already at the southern limits of their temperature tolerances will experience warmer waters than they can tolerate, especially during late summer. Thus, at southern margins of distribution, the maximal temperatures will likely affect some species. At the northern edges of distributions, there may be changes in lengths of growing seasons, and shifts in patterns of growth and reproduction. Warmer waters create constraints for aquatic species because metabolic demands for dissolved oxygen increase but solubility of oxygen decreases. In general, these constraints are likely to increase for some species, especially if temperature increases are extreme (Vannote and Sweeney 1980, Sarvivo, V.S. 1983, Cox and Rutherford 2000a, b).

Effects on Fishes

The thermal niches of fishes are well studied and widely used to determine how different species interact and compete for certain locations within their physiological niche requirements (Magnuson and DeStasio 1996). Coldwater fish species such as trout and salmon are the dominant components of food webs throughout the Rocky Mountain/Great Basin region. Any decline in coldwater fish abundance will have a cascade of ecological effects. These species are also especially well studied in terms of their thermal tolerances (De Staso and Rahel 1994, Taniguchi et al. 1998, Poff et al. 2000). Some of the earliest work on the effects of water temperature on trout distributions emphasized the limiting effects of cold water because growth and recruitment can be severely reduced at high elevations and latitudes. Later studies considered variable temperatures and related factors such as dissolved oxygen (Scarnecchia and Bergersen 1987).

Because of their intolerance to warm water temperatures, coldwater fishes are likely to be restricted to higher elevations if climate warming occurs. Reduction in the geographic distribution of coldwater fishes and fragmentation of remaining populations into isolated, high-elevation enclaves is anticipated as an important effect of climate warming. Based on current regional distributions of trout during the summer, Keleher and Rahel (1996) used a Geographic Information System approach to project loss of geographic range under different warming scenarios for the Rocky Mountains. Increases of 1, 2, 3, 4, and 5°C (1.8, 3.6, 5.4, 7.2, and 9.0°F) in mean July air temperatures were projected to reduce the geographic area containing suitable habitat by 17, 36, 50, 62, or 72% respectively.

Other studies used a 21°C (37.8°F) maximum water temperature as the current limit of distribution of trout in the North Platte River drainage basin, and found similar projections for reductions in stream lengths that would contain thermally suitable habitat (Rahel et al. 1996). The potential for habitat fragmentation was evaluated in the North Platte drainage where the present-day distribution of trout habitat that extends over 4,000 km (1,488 mi) of interconnected, thermally suitable streams would be broken up into many smaller, isolated enclaves with a 3°C increase in summer water temperatures (Rahel et al. 1996).

In addition to reduced suitable habitat, it is likely that climate warming will cause coldwater fishes to be replaced by warmwater species such as minnows and suckers. Laboratory experiments demonstrate competitive dominance of trout over minnows in cold water (4-20^{o}C, 7.2-36^{o}F) , while minnows begin to compete successfully from 22 to 24^{o}C (39.6-43.2^{o}F) and dominate at 26^{0}C (46.8^{o}F, Taniguchi et al. 1998). Physiological adaptation by trout to warmer waters is unlikely because they are currently excluded from warmer waters at low elevations, at least in part by competition with warmwater species.

Even among the coldwater species of trout, climate warming may favor non-native species such as brook trout, brown trout, or rainbow trout at the expense of native species such as cutthroat or bull trout in some habitats within the Rocky Mountain region. In laboratory studies, brook trout tolerated warm water temperatures better than Colorado River cutthroat trout in terms of survival and bursts in swimming speeds associated with successful predation. When matched for body size, brook trout and Colorado River cutthroat trout were equal competitors for food and space at 10^{o}C (18^{o}F), but brook trout were superior competitors at 20^{o}C (36^{o}F, De Staso and Rahel 1994). In this area it is likely that warming would favor nonnative salmonids over native cutthroat trout and bull trout.

In other locations within this region various subspecies have different thermal tolerances. The temperature preferences and current distributions of the federally listed native species are increasingly well documented. For example, the native Colorado greenback cutthroat trout possibly can expand its range to upper and lower elevations under warmer water conditions wherever non-native fishes can be eliminated (Young and Harig 2001). The Lahontan and Bonneville cutthroat trout may also be able to increase their geographic ranges under warmer climates if non-native species of trout are restricted from competing with the natives.

Studies of the projected long-term increases in mean, annual air temperatures from GCMs in other regions provide some insight regarding the effects of warmer air temperatures on groundwater and on groundwater-fed streams relative to trout distributions during summer. Meisner (1990) concluded that habitat restrictions are likely in some low-elevation and low-latitude waters, where fishes such as brook trout (*Salvelinus fontinalis*) are limited by their upper thermal physiological limits for growth and reproduction. Although not yet examined, lethal effects on young-of-the year might also occur as a result of extremely warm temperatures during late summer. These "bottlenecks" for survival limit persistence of those species that require cold waters. There may be some thermal refugia in deeper springs and groundwater-fed rivers, and in deep, stratified lakes where cooler waters are spatially distributed (Eaton et al. 1995, Eaton and Scheller 1996). The size and extent of these local refugia may be very limited and may increase vulnerability to predators and diseases.

However, Meisner (1990) pointed out that climate warming could result in some positive effects in populations at high altitudes and/or latitudes. Naturalized populations of introduced brook trout in western North America could increase their range of suitable habitats if higher water temperatures occur. The difficulty is that they may expand into habitats of native species such as the endangered Colorado greenback cutthroat trout (Young 1998, Behnke 1992).

Effects on Invertebrates

Aquatic invertebrates which provide food for fishes and wading birds in upper trophic levels are also known to have distinct thermal requirements. Water temperatures clearly alter individual growth and reproductive rates. The timing of reproduction and allocation of energy into egg production are influenced by water temperature. For example, aquatic insects are among the most widely distributed invertebrate groups. They live over a wide range of thermal regimes with some species adapted to very warm waters such as thermal springs (Pritchard 1991). But in North America, most aquatic insect species are found in cold or intermediate ranges of temperature (see Ward and Stanford 1982, Sweeney et al. 1992, Hershey and Lamberti 2001 for reviews). Similarly, a few species of freshwater crustaceans can tolerate high water temperatures while many more occur in cooler waters. Some amphipod crustaceans occur in relatively warm waters. For example, *Hyalella azteca* lives in waters up to 33-34^{o}C in Devil's Hole, Nevada while *Gammarus lacustris* lives in cold alpine waters.

Gammarus lacustris occurs over a wide geographic range including altitudinal and elevational differences in annual thermal regimes, and varies greatly in such reproductive traits as egg size and number (France 1992, Wilhelm and Schindler 2000). If montane-lake waters warm, *G. lacustris* reproduction is predicted to shift along a continuum from a few large eggs to many small eggs. Warming of high-elevation lakes will result in a shorter life cycle and increased egg production in *G. lacustris* which could increase density of this species (Wilhelm and Schinder 2000). Such an increase could alter interactions with amphipod food resources in the benthic and planktonic communities as well as predators such as fish.

Generally, many aquatic species track seasonal temperatures to optimize their survival. For example, field studies show that *Hyalella azteca* has a 20°C threshold for induction and termination of reproductive resting stages. These crustaceans move from warmer, shallow waters to cooler, deeper water as individuals mature (Panov and McQueen 1998). Other species are restricted to cooler waters (*Gammarus minus* occurs only in waters below 20°C, see Covich and Thorp 2001 for review). Zooplanktonic crustaceans such as *Daphnia pulex* and *D. galeata* are likely to respond by altering their foraging, food-web dynamics, and life histories. One hypothesis being tested is that warmer waters will provide an environment that favors smaller zooplankton over larger species because of metabolic constraints on swimming and bioenergetics (Achenbach and Lampert 1997, Beisner et al. 1997).

If extreme temperatures occur more frequently in the future, the effects of climate change will likely alter many shallow-water aquatic communities through increased physiological stress due to both warmer and more fluctuating temperatures (Sarvivo 1983, Lagerspetz 2000). In addition, reduced volumes due to higher evaporation and evapo-transpiration rates could result in rapid loss of habitat (Winter 1989, 1999). Increased temperatures reduce the solubility of dissolved oxygen while simultaneously increasing metabolic rates and physiological demands for more dissolved oxygen by aquatic invertebrate species. In addition, rates of microbial growth and decomposition also increase and require more dissolved oxygen. Over time, the indirect effects of increased temperatures on growth and reproduction can be as important as the direct effects of high lethal temperatures because mortality results in fewer individuals surviving to reproduce.

Biotic distributions are likely to shift in response to climatic changes but how food-web dynamics and ecosystem productivity will be altered is not known. A decline of species diversity can generally be predicted in sites where there is a persistent increase in high temperatures or in those with highly fluctuating temperatures (Hogg and Williams 1996). These two sets of environmental extremes create major barriers to dispersal for most aquatic species.

Effects on Riparian Vegetation

Light, temperature, and flow regimes affect which plants can compete for space along stream banks. Native riparian plants provide shade (as well as leaf litter and woody organic inputs) that influence water temperatures. A diverse community of trees along streams can alter the invertebrate community by the timing, quantity, and quality of litter inputs to the stream, and can reduce bank erosion and maintain substrates suitable for fish spawning and benthic prey (Kennedy et al. 2000). The frequency and magnitude of flooding greatly influences seed germination and recruitment of new individuals into these populations. Changing hydrologies associated with climate change will almost certainly alter the distributions and compositions of these zones, and consequently their influences on stream ecosystems.

Conclusions and Needs for Further Study

Currently, aquatic ecosystems within the heterogeneous landscapes of the Rocky Mountains/Great Basin region support a high diversity of species (Cushing 1997, Grimm et al. 1997, Hauer et al. 1997, Leavesley et al. 1997, Melack et al. 1997, McKnight and Covich 1997). Many biotic communities have undergone post-Pleistocene changes in species composition along riparian zones, wetlands, floodplains, springs, rivers, and lakes. The most recent post-glacial changes shifted from a wet, pluvial climate to an arid or semi-arid climate throughout most of the region. This series of natural climatic changes has created a mosaic of different habitats occupied by a very diverse biota (Herbst and Blinn 1998, Dickerson and Vinyard 1999b, O'Brien and Blinn 1999, Kulkoyluoglu and Vinyard 2000, Shepard et al. 2000).

Climate change will almost certainly alter these systems, in many cases very fundamentally. And some of the changes can be predicted, at least qualitatively, with a high level of probability. For example, in the two subregions considered, climatic forecasts of 2 to 4°C (3.6-7.2°F) increases in temperatures over the next century are likely to result in different impacts on freshwater ecosystems from north to south. Some of the future changes in aquatic ecosystems resulting from this warming can be anticipated, especially for the southern subregion. These effects will likely include an earlier spring peak flow driven by more rapid snowmelt. Warmer springs are expected to extend the growing seasons of some species of fishes and invertebrates and alter food-web dynamics. Warmer water temperatures in streams and their combined input to lakes and reservoirs may alter lake stratification by mid to late summer. Warmer surface waters (epilimnion) and slightly warmer bottom waters (hypolimnion) of stratified lakes will likely alter phytoplankton and zooplankton community structure and productivity by increasing metabolic rates and shifting competitive and feeding relationships.

Higher water temperatures may well shift the distributions of cold-water species northward and to higher elevations. At the same time those temperatures are likely to favor warm-water species, many of which are nonnatives, and which are likely to compete more stringently with species that are now threatened or endangered.

Moreover, climate change is likely to interact with several current trends that will either continue to change incrementally or could shift in unexpected ways in the next century as human population growth and management decisions change. Thus climatic change is likely to have several cumulative and possibly synergistic effects as warmer waters, more extreme precipitation (droughts and floods), and increased demand for water resources by a growing human population combine their influences. Warmer and more nutrient-rich waters (from various human effluents) will likely modify many different types of aquatic ecosystems by accelerating nutrient cycling and increasing primary and secondary productivity while at the same time impacting individual species. Increased erosion (from overgrazing, streambank erosion, and road construction) during extremely high peak flows will alter stream substrates and lead to changes in benthic communities and fish distributions.

However, firm quantitative predictions await the development of coupled hydrologic and ecosystem models, and increased information on many aspects of the RMGB aquatic ecosystems. Many locations lack basic data as a result of the uneven distribution of climatic monitoring stations and limited, long-term biotic sampling. Although studies exist for some locations near urban centers, limits on extrapolation among many different ecosystems within this very large region prevent definitive analysis.

To an unknown degree, constituent species have not yet been discovered and described. For example, Hershler (1998) collected aquatic snails in a survey of springs from 500 sites in the Great Basin. He found 58 new undescribed species of *Pyrgulopsis* that occur in a wide variety of thermal and saline spring-fed waters. Endemism is extreme and 22 of these new species are known from only a single site. Kulkoyluoglu and Vinyard (2000) collected 14 species of ostracodes from 24 springs and found nine species not previously reported for Nevada. Little is known of the population ecology of these species or how they might respond to warmer or drier climates in the future. Additional new species continue to be found (Hershler et al. 1999). Equally important are gaps in conceptualization and understanding of how these dynamic biotic communities and ecosystems function. Knowledge of local and regional biodiversity and of likely biotic responses to climatic change is limited. Careful monitoring of the few groups that are relatively well studied is essential.

In total, climate change as projected in Table 8.1 will in all probability fundamentally alter RMGB aquatic ecosystems. Some of those changes can be predicted qualitatively on the basis of existing research. But concerted research effort is needed to provide the additional information required for quantitative predictions of those changes.

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Chapter 9

NATURAL ECOSYSTEMS III. THE GREAT BASIN

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INTRODUCTION

Projecting potential changes in an ecosystem that would be induced by climate change can be approached in several ways, all of which have limitations. Changes in climate variables and atmospheric CO_2 concentration alter the existing interactions between those variables and the individual organisms within ecosystems. The individuals of a species react collectively in population responses which, in turn, affect community composition and, ultimately, ecosystem structure and function. Conceptually, climate-change effects on an ecosystem could be predicted with models that encorporated detailed data on the interactions between the component species and their climatic and CO_2 environments, and if given projected changes in those environments.

Several of the authors cited below describe very fundamental and unexpected changes in community and ecosystem structure that could only have been predicted with thorough knowledge of the interactions among the constituent species. These authors have emphasized the need for species-level models. Shaver et al. (2000) describe a wide range of experimental research designed to provide this type of understanding. But in reality, of course, we do not have the detailed ecological information on all or even most of the species in the Great Basin that would make it possible to structure such models. Given the number of species in the system, and the complex of interactions in which each is enmeshed, an extensive understanding of even the majority of species must lie some distance in the future.

Some climate-change effects have been modeled at more general levels of biotic organization based on sufficient knowledge of the environmental requirements of dominant species structuring the vegetation. A significant increase in precipitation could reasonably be expected to change a grassland or shrubland to woodland. Increase in temperature without precipitation increase would tend to shift vegetation to more xeric types. And temperature increase with adequate precipitation could promote northward movement of vegetation types constrained at the northern limits of their ranges by winter conditions and/or growing-season length. Nielson (1995, 1999, Nielson and Drapek 1998) has predicted such changes at global, national, and regional scales.

The geographic extent and topographic complexity of the Great Basin are a distinct advantage in projecting climate-change effects in the region, even while increasing the complexity of making such projections. The latitudinal, longitudinal, and altitudinal gradients are accompanied by climatic gradients and correlated vegetation gradients. Ecologists infer that these correlations are causal, and therefore provide insights into the environmental requirements of the species. Those insights in turn provide a basis for predicting how species distributions and composition would be altered by changes in climate variables.

Finally, the great number of packrat (Neotoma spp.) middens (Betancourt et al. 1990) distributed throughout the Intermountain West provide a unique resource for projecting climate-change effects in the region. The extensive paleoecological research conducted on these sites have made it possible to correlate biotic changes with climate changes over the past 40,000 years. The correlations are again assumed to be causal, and provide another basis for hypothesizing changes in the region's biota associated with future changes in climate.

This chapter will draw on all of these approaches in projecting potential changes in the Great Basin ecosystem induced by a set of climate-change scenarios. But it will begin with an overview of the contemporary structure and function of that system to set forth the complexities within which climate change would operate.

BIOGEOGRAPHY OF THE GREAT BASIN

The common stereotype of the Great Basin is the general area in western U.S. between the north-south Wasatch Mountains of central Utah and the Sierra Nevada and Cascades of California and Oregon-Washington. As such, it is commonly thought of as the western half of Utah and all of Nevada above a point ca. 91 km (50 mi) north of Las Vegas. The east-west distance across its center is ca. 725 km (450 mi).

However, as Trimble (1989) and West and Young (2000) discuss, scientists in different disciplines set different limits on the region. A hydrographic Great Basin encompasses a wedge-shaped area including the Utah-Nevada portion, a large section of south-central Oregon, and an area of southeastern California and northern Baja California. Its delineation is based on that area of the West in which all streams terminate within the area, none flowing to the ocean or into streams that flow to a coast.

A physiographic Great Basin is mapped as the Great Basin section of the geologists' Basin and Range Province. It includes the Utah and Nevada portions, but also extreme southern Nevada and parts of southern Oregon and southeastern California.

The Great Basin region addressed in this assessment approximately coincides with Trimble's (1989) biogeographic Great Basin. Its defining characteristics are a shrub-steppe vegetation functioning (1) in the semi-arid environment of the Sierra Nevada and Cascade Mountain rain-shadow; (2) a cool, temperate climate produced by moderate latitudes (37-47^{o} North) and altitudes (>1,200 m, West and Young 2000); and (3) precipitation largely occurring between spring and fall, much of it (60%) as snow. It is approximately the same as Shelford's (1963) "cold desert" and MacMahon's (1979) Great Basin Desert.

Mapped in Fig. 1.1, the region retains the Utah-Nevada portion as its central core, but it does not coincide exactly with either the hydrographic or physiographic Great Basins. It does not include the southern Nevada, southern California, and Baja California parts of the hydrographic because their elevations and latitudes are lower, and their vegetation type is the Mojave Desert. And it extends beyond the hydrographic by including that portion of the Snake River plains of southern Idaho south of the river, and the Columbia Plateau of eastern Oregon, both of which have drainages into the Columbia River system and ultimately the Pacific. It does not include the California and southern Nevada areas of the Basin and Range Province, again because of their lower latitudes and altitudes, and associated Mojave Desert.

Topographically, an east-west transect at 40^{o} N latitude across the Utah-Nevada area shows broad basins of glacial lakes Bonneville in the eastern fourth of the transect (lower elevations around 1,280 m or 4,200 ft) and Lake Lahontan in the western fourth (lower elevations approximately 900 m or 2,950 ft). The central half is a higher plateau corrugated by more than 200 north-south mountain ranges (Cronquist et al. 1972) with elevations of the intervening basins rising to 1,700 m (5,576 ft) or more. A few of the mountain ranges rise to more than 4,000 m (13,120 ft). According to West and Young (2000), montane elevations above 1,850 m (6,680 ft), the mean lower boundary of arborescent vegetation, occupy approximately 40% of the area, while foothills and basins covered with shrub steppe occupy 60%.

As their names imply, the Snake River plains and Columbia Plateau are less rugose than the Utah-Idaho portion of the Great Basin. But their topographies are rolling and dotted with mountain ranges so that the ecological diversity produced by altitudinal variation, so characteristic of western U.S., prevails in these subdivisions of the biogeographic Great Basin.

At recession of the last glacial stage, montane glaciers released melt water into the lowlands of the Great Basin, extending the area of Lake Bonneville to 51,282 km^2 (19,800 mi^2), nearly the size of contemporary Lake Michigan, and Lake Lahontan to perhaps half that size. The melt water also produced on the order of 90 smaller lakes (West 1983a) in the Intermountain basins. Much of this hydrology was interconnected, allowing dissemination and exchange of numerous aquatic animal species (Sigler and Sigler 1987). As the bodies of water shrank, salinized, and became isolated during Holocene xerification, these aquatic forms were left in disconnected ephemeral streams, spring ponds, and wetlands with the resulting evolution of endemic races and subspecies. Many of these are now endangered as European settlement has further altered these water bodies.

Few of the Intermountain basins now have permanent water. Lake Bonneville contracted to the 2,898 km^2 (1,800 mi^2) of the present Great Salt Lake area and the smaller Lake Utah. Lake Lahontan relics persist as 5-6 small lakes including Walker, Carson, and Honey Lakes, and the larger Pyramid Lake. Otherwise the basins are typically playas that are dry in most years. These may collect spring run-off in above-average precipitation years which then evaporates by mid to late summer. Over millennia of such flooding and evaporation cycles, the playa bottoms have become highly saline, often with crystalline sodium chloride flakes on the surfaces when dry.

Like elsewhere in the West, precipitation is positively correlated with elevation in the Great Basin. Annual precipitation ranges from 10.2-20.3 cm (4-8 in) in the more southerly and lowest-elevation basins to 40.6 (16 in) on the eastern foothills at the upper elevations of the shrub steppe. The mean, annual precipitation of 22.9 cm (9 in) for the state of Nevada, based largely on valley-bottom weather stations, is something of a metaphor or norm for the lower elevations of the Basin. The higher mountain tops may receive up to 127 cm (50 in) mean, annual precipitation (West 1983a).

These elevational correlations with soils and climatic variables produce gradients in the physical environments of each basin. To varying degrees, soil salinity and temperature are inversely correlated with elevation. Soil-particle size and diversity, precipitation, and distance to ground water are positively correlated.

These gradients in physical environments produce gradients in vegetation types adapted to the different conditions along them. The fauna, too, is arrayed in elevational gradients associated with the vegetation types and/or the physical environment. Each basin is thus, in a sense, an inverted pyramid of physical environments and biota. Since, as Wagner (1980) and Ayyad (1981) comment, arid-land vegetation is exceptionally sensitive to slight variations in physical environments, any climate change is likely to alter present altitudinal and latitudinal distribution and composition of the Great Basin vegetation. And faunal changes are likely to follow suit.

The following discussions treat the lower-elevation shrub-steppe and the higher-elevation arborescent vegetation zones, separately. The mean elevational boundary between the two is approximately 1,850 m (6,680 ft) according to West and Young (2000), but the separation occurs at higher elevation in the southern portion of the Basin, and lower levels in the north.

ECOSYSTEM STRUCTURE

Shrub-steppe Subsystem

Vegetation

The salt-desert shrub type. The vertical, vegetational zonation from the bottoms of the basins to the tops of the surrounding mountains is also expressed on a broader, geographic scale as subregional altitudinal variations and latitudinal differences modify temperatures and precipitation. West (1983b, c, d) distinguishes a lower-elevation and more southerly salt-desert shrubland from the more mesic sagebrush type, and subdivides the latter into sagebrush semi-desert and sagebrush steppe. At 0.17 and 0.18 x 106 km^2 (66,000 and 69,000 mi^2), the salt-desert shrub and sagebrush semi-desert occupy about equal areas. The sagebrush steppe is the more extensive of the three, exceeding the other two by a factor of 2.5. But much of the area occupied by this type is in parts of Wyoming, Idaho, and Oregon not included in the RMGB region. Hence its portion in the Basin must be of the same general magnitude as the other two.

The salt-desert shrub type occurs around the lower elevations of the basins, and is geographically extensive in the lower altitudes and more southerly reaches of the Lake Bonneville and Lahontan basins (West 1983b). Its perennials are typically halophytes, largely in the Chenopodiaceae. Diversity of the vegetation is extremely low, with single-species stands common. Few stands have more than 3-4 species of perennials most of which are shrubs generally 1 m (3.28 ft) or less in height, and half shrubs (suffrutescents) that die back to the root crown each fall and resprout in the spring.

The type itself occurs in a gradient from highly saline conditions with free NaCl at the surface on, and at the margins of, the playas and salt flats to better-formed, less saline soils at slightly higher elevations. At the lower extreme, salt flats may be occupied by single-species stands of iodine bush or pickleweed (Allenrolfea occidentalis), saltwort (Salicornia utahensis and S. rubrum), or saltgrass (Distichlis stricta). A zone of slightly higher elevation (~ 0.5 m and higher), but within 1 m of ground water (West 1983b), is dominated by shrubs of greasewood (Sarcobatus vermiculatus) up to 1 m in height, and with an understory of 2-3 half-shrub species such as Atriplex falcata, Kochia americana, and Sueda torreyana.

At the higher elevations of the salt-desert-shrub elevational gradient, soils are well formed with minor salinity but with high levels of Na^+ ions. The most conspicuous and diagnostic shrub species is 0.5 m-tall shadscale (Atriplex confertifolia). Trimble (1989:46) shows the species broadly distributed in western Nevada in the Lahontan basin and in western Utah in the Bonneville basin. While clearly the dominant species in the vegetation of these areas, Holmgren and Hutchings (1972) present evidence that it is something of an increaser species in western Utah under sheep grazing, and declines under protection from grazing.

Associated perennial species are largely half shrubs including winterfat (Ceratoides lanata), gray molly (Kochia americana), budsage (Artemisia spinescens), and several species of Atriplex including falcata, cuneata, and Gardneri. Depending on site conditions and disturbance histories, any of these species may occur in extensive, mono-specific stands. Thus in west-central Utah and east-central Nevada, Ceratoides lanata occurs as a broad band on the lower levels of the alluvial skirts around numerous mountain ranges. Perennial grasses enter the salt-desert-shrub gradient at its upper elevations as a minor-moderate component of the vegetation, including such species as Sporobolus airoides, Elymus elymoides, and E. cinereus.

But despite the slightly greater diversity of this upper zone, the overall aspect is still austere with low and sparse vegetation. In one study area in western Utah, Holmgren and Hutchings (1972) show the combined canopy cover of the 3-4 main species aggregating at well below 10%. Yet root:shoot ratio in this type are 3-5:1, the majority of the phytomass thus occurring below ground (Bjerregaard 1971, Caldwell and Camp 1974).

The sagebrush type. As commented above, West (1983c, d) subdivides the sagebrush type into a more xeric sagebrush semi-desert and a slightly more mesic sagebrush steppe. He (1983c) places the semi-desert in the Great Basin entirely in Utah and Nevada, and the steppe (1983d) in the western half of Wyoming, the southern two-thirds of Idaho, northwestern Nevada, and major portions of Oregon and Washington east of the Cascades. Only the southern fringe extends into the northern edges of Utah and Nevada.

Floristically the two vary according to the amount of perennial grasses and forbs in the understory. And since these variations occur across a continuum not only on a horizontal and latitudinal scale, but on a vertical, elevational scale within the two subtypes, I have chosen to treat them together as a single type. The overwhelmingly dominant and conspicuous species is big sagebrush, Artemisia tridentata, which occurs in shrubs up to 1 m in height. It is subdivided into three subspecies: tridentata in mesic, low elevation areas; wyomingensis across a wide range of elevations and at intermediate moisture levels; and vaseyana at intermediate moisture levels and higher elevations (West 1983c).

Associated shrubby species of comparable stature are Tetradymia canescens and T. glabrata, Grayia spinosa, Purshia tridentata, and Chrysothamnus nauseosus. West (1983c) lists 8 species of associated perennial grasses and 18 species of perennial forbs at three Great Basin sites, all in Nevada. At the upper elevational limits of big sagebrush on rocky foothills of the mountain ranges, and on rocky knolls and ridges, the species grades into black sage (Artemisia nova), a more compact shrub that is highly palatable to browsing herbivores. In turn, black sage merges into the slightly higher pinyon-juniper, pigmy-conifer zone.

The role of annuals. Unlike the "hot" deserts of southwestern U.S. in which a rich flora of native annuals coexists with the perennials, native annuals are extremely scarce or absent in the Great Basin shrub steppe. Wagner (1980) has hypothesized that the difference results from alternative evolutionary trajectories associated with the abundance and distribution of perennial root masses. In the southern deserts, root biomass is typically half or less of total phytomass (Barbour 1973, Wallace et al. 1974). In the Great Basin this percentage may rise to 80% or more, as described above. There are comparable differences in absolute root biomass. Wagner (1980) reports the root biomass in a Great Basin and a Sonoran Desert site at 27,499 and 10,929 kg/ha, respectively, or a difference of 2.5x.

Moreover, the vertical distributions of the root masses differ. Nearly half of the greater mass in the Great Basin vegetation is in the upper 20 cm of the soil profile while only a fourth of the lesser mass in the Sonoran Desert site is in this layer. Maximum root mass in the latter area is in the 20-40 cm depth. Thus the soil surface layers in the shrub steppe are permeated with fine, actively growing roots of the shrubs and half shrubs which may preclude any surface-soil niche into which a native annual flora, capable of coexisting with the perennials, could evolve.

However, there is today an abundant annual flora in the Great Basin vegetation made up of exotic species, the most common of which are:

Bromus tectorum, cheatgrass

Descurainia pinnata, tansy mustard

Halogeton glomeratus, halogeton

Lepidium perfoliatum, peppergrass

Malcolmia africana, malcolmia

Salsola kali, Russian thistle

Taeniatherum asperum, medusa-head

These are typically disturbance species that achieve significant growth only in perennial stands subjected to some measure of disturbance, or in areas where perennials have died or been removed.

They respond to different precipitation patterns. Some (e.g. cheatgrass) are winter annuals that germinate in fall with the first seasonal rains; grow slowly if at all during winter; undergo rapid growth, flowering, and seed set in spring and early summer; then die as the summer dry season sets in. Others (e.g. halogeton) require significant amounts of spring and summer moisture for expression in late summer. As a result, which species appear, and their abundances, vary markedly between years as annual precipitation patterns vary.

The annuals tend to be excluded or suppressed by relatively undisturbed stands of native perennials (Fig. 9.1). Cheatgrass is one of the most widely distributed of the exotic annuals —currently estimated to dominate 20% of the Intermountain shrub-steppe (Knapp 1996)—and is undoubtedly the most extensively studied and published (cf. Hironaka and Tisdale 1963, Mack 1981, Rickard and Vaughan 1988, Billings 1990, D'Antonio and Vitousek 1992, Knapp 1996, Novak and Mack 2001), particularly its relationship to big sagebrush.

The competitive interaction between cheatgrass and big sagebrush is a complex one, varying with the life-history stages of the two species (Booth 2002) and the physical environment (R. Tausch, Pers. Comm. March 14, 2000). At elevations above 915 m (3,000 ft), a healthy sagebrush stand, with or without an understory of perennial forbs and grasses, can block significant expression of cheatgrass growth, even though there may be an abundant cheatgrass seed supply (Fig 9.1, Reichenberger and Pyke, 1990). At lower elevations (<915 m) still within the sagebrush zone, as in the Lahontan Basin in southwestern Nevada, cheatgrass can invade and eventually exclude mature sagebrush plants. This occurs near the limits of sagebrush physical tolerance which may impair its competitive ability to block cheatgrass invasion.

Yet numerous authors have observed an inability of sagebrush seedlings to reinvade cheatgrass vegetation in a wide variety of sites. Rickard and Vaughan (1988) describe oldfields in south-central Washington, which have been dominated by cheatgrass for 40 years following wheat cultivation, that show no signs of sagebrush encroachment from the surrounding shrub-steppe vegetation. In northwestern Utah, Booth (2000) shows rapid soil-moisture depletion by the early spring flush of cheatgrass growth which may usurp moisture needed for sagebrush germination and/or seedling survival. However, the native perennial grass Elymus elymoides (formerly Sitanion hystrix) can invade cheatgrass, and once it has assumed dominance permits invasion and coexistence of sagebrush (Hironaka and Tisdale 1963, Booth 2000).

Thus the interactions of exotic annuals and native perennials vary depending on the species and physical environments. But with some exceptions, healthy stands of perennials tend to outcompete the exotic annuals, contrary to the common notion that the latter are highly aggressive. This superiority of perennials also holds true for nonnative perennial grasses, such as crested wheatgrass (Agropyron desertorum), which have been seeded widely over the Great Basin both to improve forage conditions for livestock, and to suppress exotic annuals. The ubiquity of the latter is not so much a function of their aggressiveness vis-à-vis the native vegetation, but of the ubiquity of disturbance.

Fauna

Despite the low vegetative diversity, and contrary to the widespread impression that biodiversity is generally low in arid lands, faunal diversity in the Great Basin shrub steppe compares favorably with that in more mesic, mid-latitude biomes (Wagner and Graetz 1981). The one exception is nesting passerine birds with few species, apparently because of the low vegetative structural diversity. Rogers et al. (1988) observed only six species along four 500 m (1,640 ft) transects traversed through sagebrush steppe in the springs of 1979 and 1980 in south-central Washington. Wiens and Dyer (1975)

Figure 9.1. Intact stands of native perennials in the Great Basin can exclude expression of exotic annuals. In the upper picture, sagebrush in the foreground prevents growth of exotic cheatgrass (Bromus tectorum) which flourishes when perennials have been removed by fire or other disturbance, as in area surrounding the truck. In lower picture, winterfat (Ceratoides lanata) in foreground blocks significant expression of tansy mustard (Descurania pinnata) which flourishes in the background in the absence of winter fat.

reported 4, 5, and 4 species in three shrub-steppe sites in southern Oregon. Fautin (1946) listed five species for a site in western Utah.

The number of nesting raptorial species that forage over the open shrub steppe commonly exceeds the number of passerine species. Hawk and owl abundance depends in part on the availability of nesting sites provided by proximity to trees at slightly higher elevations or in riparian corridors, and on topographic sites such as rocky cliffs and buttes. Most Great Basin areas have at least seven nesting species that forage over open shrub steppe, typically:

Buteo jamaicensis, red-tailed hawk

B. swainsoni, Swainson's hawk

B. regalis, ferruginous hawk

Circus cyaneus, northern harrier

Aquila chrysaetos, golden eagle

Bubo virginianus, great-horned owl

Athene cunicularia, burrowing owl

Rogers et al. (1988) list 12 species for the Arid Land Ecology Reserve (ALE) in southern Washington, and cite seven species of hawks alone for the Snake River Birds of Prey area in southern Idaho.

The characteristic shrub steppe galliform is the sage grouse (Centrocercus urophasianus). The species has been in decline for a number of years. There is concern for its survival and growing intention to list it as threatened or endangered.

Typical of arid and semi-arid regions of western U.S., the Great Basin shrub-steppe fauna contains significantly greater diversity of small rodents than more mesic areas east of the Rocky Mountains. Rogers et al. (1988) list 11 species for the shrub-steppe vegetation, plus the larger hoary marmot (Marmota flaviventris). They also list three species of lagomorphs: Lepus californicus and L. townsendii (black-tailed and white-tailed jackrabbits) and Sylvilagus nutalli (Nuttall cottontail). To this list the pygmy rabbit (S. idahoensis) may be added for much of the Great Basin shrub steppe.

Several species of carnivorous mammals occur in the shrub steppe, including coyote (Canis latrans), badger (Taxidea taxus), bobcat (Lynx rufus), kit fox (Vulpes velox), striped skunk (Mephitis mephitis), and long-tailed weasel (Mustela frenata). Many Great Basin areas have all of these species).

Pronghorn antelope (Antilocapra americana) are the characteristic year-round ungulates. Mule deer (Odocoileus hemionus), and in some areas elk (Cervus elaphus), summer in the mountain ranges, but winter on the foothills and out some distances into the valley bottoms.

The considerable faunal diversity, relative to other biomes at intermediate latitudes, extends to the reptiles (Tanner 1978). Rogers et al. (1988) list four species of lizards and four of snakes in the shrub-steppe habitats of the ALE Reserve. Fautin (1946) recorded five species of lizards and two of snakes in his western Utah study area. The insects are no less diverse, Knowlton (1974) reporting over 1,000 species in one area of north-western Utah. Wagner and Graetz (1981) compare this with 1,242 arthropod species on a North American grassland site and 696 invertebrate species in three Douglas fir (Pseudotsuga menziesii) sites in the Pacific Northwest.

While the emphasis here is on diversity, or more properly on species richness, it does not follow that there is a high degree of evenness within the fauna. In some areas, certain species far exceed the others in their guilds or trophic levels in numbers and/or biomass. The black-tailed jackrabbit fluctuates in numbers through a 20x range between high and low populations in one northwestern Utah area (Knowlton and Stoddart 1992). Yet its biomass at its population lows exceeds the aggregate biomass of all rodent species (Wagner 1971) in the area reported on by Knowlton and Stoddart (1992). As a result, jackrabbits constitute the major dietary item for coyotes even at the jackrabbit population low (Clark 1972).

Along with the coyote, several species of raptors prey on jackrabbits in the same area. But coyote biomass, and presumably food need, exceeds collective raptor biomass by a factor of 10 (Wagner 1971). Correspondingly, coyote predation on jack-rabbits exceeds that of all of the raptorial species combined.

As in other arid and semi-arid areas, predatory and parasitic species are a higher percentage of the total fauna in two Great Basin areas than they are in Arctic and eastern deciduous forest areas of the U.S. (Wagner and Graetz 1981).

Woodland and Alpine Subsystem

Vegetation

The pinyon-juniper zone. The elevational gradients of physical environments and vegetation discussed for the shrub steppe continue in slopes above the sagebrush zone. And with increased precipitation at rising elevations, the vegetation changes to woodland forms up to the highest altitudes where extreme conditions constrain plant growth to alpine tundra.

The first zone above the shrub steppe is variously termed the pinyon-juniper (P-J) zone, the pigmy-conifer zone or woodland, or the foothill woodlands (Cronquist et al. 1972). It occupies approximately 18% of the surface area of the Great Basin (West et al. 1998).

West and Young (2000) place the mean, lower boundary of P-J in the Great Basin at 1,850 m (5,576 ft). Its average altitudinal width is on the order of 351 m (1,150 ft), but may be twice this extent in some areas, and may narrow almost to the point of disappearing in some (Trimble 1989). Its precipitation range is typically 31-46 cm (12-18 in).

But these are averages that vary with latitude in the Great Basin and with slope-aspect. West et al. (1998) generalize that P-J forms broad belts encircling the mountain ranges of the middle latitudes in the Basin. In the northerly regions, the type fades on the north and east slopes of the ranges, and retains strong expression only on the southerly and westerly aspects. The reverse is true on the more southerly ranges, with strong expression only on the northerly and easterly exposures.

Over most of the Basin, the type consists almost entirely of two species of conifers that grow to 10-15 m (33-49 ft) heights at maturity or advanced age: single-needle pinyon (<u>Pinus monophylla</u>) and Utah juniper (<u>Juniperus osteosperma</u>). Pinyon predominates in the western and southwestern portions of the Basin, does not extend northward above the Humboldt River in northern Nevada. It is replaced by a second pinyon species, <u>P.</u> <u>edulis</u>, in a small, southeastern portion of the Basin. Utah juniper is replaced by western juniper (<u>J.</u> <u>occidentalis</u>) in the northwestern portion of the Basin (Cronquist et al. 1972).

Relative importance of the two species also sorts out by elevation (West et al. 1998). Juniper is the only species at 1,600 m (5,248 ft) at the lower margin of the P-J type. Its cover, as a percentage of the aggregate cover of the two species, declines progressively with increasing elevation until it essentially disappears at 2,600 m (8,528 ft). Pinyon appears as scattered plants at approximately 1,800 m (5,904 ft) and increases progressively with elevation to virtually sole occupancy at 2,600 m. Canopy cover of the two species is roughly similar at intermediate elevations (2,000-2,200 m, 6,560-7,216 ft), each ranging between 35 and 65% of the combined canopies on any given site. Again, at a given elevation, the percentage of juniper is slightly higher on southern and western exposures, that of pinyon higher on northern and eastern exposures.

West et al. (1978) found no strong correlation between soil types and latitudinal or elevational distribution of P-J. They concluded (West et al. 1998) that "… contemporary climate is much more dominant than soils or topography in delimiting the basinwide and elevational extent of these woodlands."

There is no distinct understory flora in the P-J zone, the prevailing species being those of the adjacent grasslands and shrub steppe (West 1988). Cool-season bunchgrasses and sagebrushes prevail in the northern and western part of the Basin; warm-season sod grasses and fewer shrubs characterize the understories of the more southerly woodlands. Understory cover and species richness tend to be lowest in the intermediate elevations where tree cover tends to be highest. They are higher in the lower and upper reaches of the zone where only one of the two tree species predominates, and total tree cover is lower (West et al. 1998).

Montane woodlands. With shrub steppe and P-J together occupying nearly 80% of Great Basin area, and additional area occupied by nonforested mountain tops, montane and subalpine woodland cover only a minor percentage of the Great Basin. And much of that woodland is floristically depauperate, comprised of only one or two species of conifers. The low diversity is attributed by most contemporary ecologists who have studied the region to the effects of glacial-era forces on the Basin's phytogeography, and the distances and isolation of its mountain ranges from major revegetation sources in the Holocene.

Altitudinal zonation of forest types in the Rocky Mountain system east of the Great Basin (Trimble 1989) might include, from lower elevations above the foothill P-J to the mountain tops:

(1) A montane zone containing individual species or combinations, depending on elevation and slope-aspect, that includes ponderosa pine (Pinus ponderosa), Douglas fir (Pseudotsuga menziesii), white fir (Abies concolor), and Rocky Mountain juniper (Juniperus scopulorum).

(2) A subalpine zone containing Engelmann spruce (Picea engelmannii).

(3) Species generally considered to be seral in either of these zones include lodgepole pine (Pinus contorta) and aspen (Populus tremuloides).

(4) What in essence are relictual species that may grow in small groves or as individual trees, often on rocky wind-swept ridges and mountain tops: bristlecone pine (Pinus aristata), limber pine (P. flexilis), and whitebark pine (P. albicaulis).

These species extend westward into the Great Basin from the Wasatch Mountains of central Utah, in Trimble's (1989) words, "only tentatively." Higher mountain ranges in western Utah and the eastern edge of Nevada may have as many as eight of these Rocky Mountain species, again in Trimble's words in "attenuated pockets of Rocky Mountain forest." But the 116th meridian in eastern Nevada marks the western extent of this vegetation beyond which the Rocky Mountain forms largely disappear, and the subalpine zone, where it occurs, is comprised largely of limber pine and bristlecone pine, now P. longaeva, in the Basin. Most Great Basin mountains lack spruce and fir (Wells 1983).

The two pines largely occur at higher elevations (e.g. >2,900 m, 9,512 ft), and intervening slopes between P-J and these levels may be cloaked in sagebrush, isolated P-J plants, and several species of deciduous shrubs. Hence the subalpine vegetation in many ranges is made up of species that more resemble those of the lower, dryer elevations.

The Sierra Nevada at the west edge of the Basin have typical montane and subalpine conifer forests including whitebark, ponderosa, and lodgepole pine, Douglas fir, and white fir, all in subspecies different from those of the Rockies. They also include Jeffrey pine (P. jeffreyi), a true Sierran species. For unknown reasons, these do not extend eastward into the Great Basin beyond, at most, the first tier of ranges adjacent to the Sierras. Hence, even in western Nevada, vegetation of the montane and subalpine elevations is similar to the impoverished form characterizing most of the Basin ranges.

Alpine zone. At the higher elevations of the tallest Great Basin mountain ranges —Cronquist et al. (1972) list 12 ranges as examples—trees phase out as wind abrasion and winter desiccation prevent their growth, and as snow accumulation through must of the growing season inhibits their establishment (Peet 1988).

Billings (1978) generalizes the Great Basin timber line at 2,744 m (9,000 ft). But Peet (1988) places it at elevations ranging from 2,800 m (9,184 ft) to 3,500 m (11,480 ft), stating that tree line lowers by 100 m (328 ft) with each additional degree of latitude. These numbers correspond to the 7° latitudinal span of the Great Basin and suggest that Billings is generalizing from tree-line elevations of the northerly portions of the Basin. Peet (1988) points out that even these are idealized zones, with tree lines on any given mountain range occurring at lower elevations on northern exposures than on southern.

On those ranges with true alpine tundra, the species have affinities with those of Rocky Mountain tundra, a situation similar to the affinities of the montane and subalpine vegetation. Hence tundra species richness is greatest in the ranges at the eastern portion of the basin, and fades to the west. As with the montane and subalpine zone, Sierran tundra species do not contribute significantly to the alpine zones of ranges at the western areas of the Basin, and consequently the species diversity is low. Typical components of the alpine vegetation on the more easterly ranges include species of sedges and grasses, and a number of forbs especially including the buckwheats (Eriogonum spp.). The zones have a high degree of endemism, mostly species evolved from Rocky Mountain precursors for which the isolation facilitated the changes.

Many of the mountain ranges—especially those with maximum elevations of 2,287 m (7,500 ft) to 3,049 m (10,000 ft)—have no tundra and are topped with sagebrush, other shrubby species, and grasses. The tops may be bare of trees and appear at a distance to be capped with tundra. But in fact the species are not tundra forms. And there may be scattered growths of limber and bristlecone pines on rocky tops. In short, Great Basin tundra and other mountain-top vegetation has, like the other Great Basin vegetation types, low diversity.

Fauna

The topographic and vegetative variety on the mountain ranges of the Great Basin provides an array of habitats and food sources that far exceeds those of the shrub steppe, and consequently produces a higher faunal diversity. Talus formations serve as habitat for pikas (Ochotona princeps) which occur from 1,740 m (5,707 ft) in the P-J woodland to as high as 3,354 m (11,000 ft) in various ranges.

The trees provide food for pinyon and stellar's jays (Gymnorhinus cyanocephalus, Cyanocitta cristata) which cache pinyon nuts, and Clark's nutcrackers (Nucifraga columbiana) which cache seeds of bristlecone and limber pine. Miller et al. (1999) comment on the large number of frugivores [e.g. western and mountain bluebirds (Sialia mexicana, S. currucoides), American robins (Turdus migratorius), cedar waxwings (Bombycilla cedrorum), and Townsend's solitaire (Myadestes townsendi)] in central Oregon. The trees provide nest sites for raptors, corvids (jays, magpies, and crows), and numerous smaller passerines. And they provide cavities for such hole-nesting species as woodpeckers, owls, mountain bluebird, and red- and white-breasted nuthatches (Sitta canadensis, S. carolinensis).

Behle (1978) identified 75 species of birds above 2,287 m (7,500 ft) in a sample of 14 mountain ranges, with an average of 43 species per range. The number of species per range varied from 19 to 64, and was closely correlated with his measure of habitat diversity. These numbers are an order of magnitude higher than the number of species in the surrounding shrub steppe described above. As with the vegetation, the species showed a close affinity with those of the Rocky Mountain system to the east, and little affinity with the Sierra Nevada avifauna.

Lawlor (1998) tallied 15 species of "small" mammals (including yellow-bellied marmots, Marmota flaviventris, and white-tailed jackrabbits, Lepus townsendii, and smaller, with bats excluded) in 16 Great Basin mountain ranges, again at elevations above 2,287 m. The mean number of species per range was 10. Most of the species were Rocky Mountain forms with little affinity for Sierran species.

Wilcox et al (1986) counted an average of 59 species of butterflies per mountain range, again at elevations above 2,287 m, in 18 Basin ranges.

While the Great Basin fauna is relatively diverse, all of the above authors considered the components they studied to be depauperate by comparison with their Rocky Mountain counterparts. Wilcox et al. (1986) commented on entire butterfly genera "diversely represented in the Rockies" that were absent from the Great Basin ranges. Brown (1978) pointed out that several mammalian species, truly boreal in the sense of their affinity with boreal forests across the continent, including the Rocky Mountain system, do not occur in Great Basin ranges.

Behle (1978) suggested that the relative avifaunal impoverishment resulted from the depauperate vegetation of the ranges. But the entire question of species diversity in the coniferous zone of the Great Basin ranges has elicited an extensive theoretical debate and literature exploring the possible operation of island-biogeography principles on species numbers. This will be explored below.

Diversity of faunas above timberline is quite low, probably associated with the low structural diversity of the vegetation, short growing seasons, and severe winter climates.

ECOSYSTEM FUNCTION

Environmental factors including climate change, alter biotas by affecting the rates of ecophysiological, demographic, community, and ecosystem processes. The following sections discuss a number of Great Basin climate-biota interactions, an understanding of which provides a basis for projecting the effects of climate change on the region's ecosystem.

Post-Pleistocene Changes

The extensive paleoecological investigations in the Great Basin have disclosed climate-related geographic and altitudinal shifts in the vegetation since the end of the Wisconsin glacial era that parallel correlations between contemporary altitudinal climatic and vegetation zonation. These provide some basis for hypothesizing future vegetation changes induced by possible climate changes. Moreover, knowledge of the Holocene vegetation changes has stimulated theoretical inquiries into the mechanisms producing the contemporary faunal diversity, and their implications for survival of animal species on Great Basin mountain ranges in the event of climate change.

At the full-glacial state (20,000-12,500 BF, Wells 1983), the higher mountain peaks—Wilcox et al. (1986) comment on "30 or more" ranges with peaks exceeding 3,000 m (9,840 ft)—were capped with alpine glaciers. Thompson (1990) states that alpine glaciers extended below 2,800 m (9,184 ft) "in many of the larger mountain ranges." Many of the valleys across the region contained pluvial lakes produced by snowmelt and higher precipitation than at present.

There are two schools of thought about the character of the vegetation at the end of the Pleistocene. Wells (1983) concludes that current Great Basin shrub-steppe species and P-J woodlands were distributed south of the Great Basin in the regions now occupied by the Sonoran and Mojave Deserts. In Wells' view, the mountain slopes and the valleys, as the lakes receded, were covered with a low-diversity subalpine forest comprised of bristlecone and limber pine, a prostrate juniper (J. communis), and in a few localized sites, Engelmann spruce. In Wells' view, this forest was essentially continuous across the Basin. Most of these inferences are drawn from fossil evidence in woodrat (Neotoma) middens.

Thompson (1990), placing more weight on the palynological evidence, inferred that sagebrush and "other steppe shrubs maintained their modern geographic ranges and perhaps even their upper modern limits …. [while moving] downslope by hundreds of meters and their geographic limits expanded in all directions …. [including] southward into the Mojave and Sonoran deserts …" Thus, in Thompson's view, steppe vegetation dominated the valleys, while woodlands of bristlecone and limber pine, and prostrate juniper occupied the mountain slopes. In this view, the woodlands, while occupying extensive areas of the lower elevations, were not continuous across the basin as Wells had inferred. But whichever school of thought is correct, it does appear that the area occupied by woodland at the end of the Pleistocene far exceeded the area occupied today.

With early Holocene warming to cool temperatures still 10°C below the present, the woodland zone began moving upslope according to both authors. And with temperature increases to the warm and dry climates of the middle Holocene, the pine woodlands moved to high elevations where they assumed essentially relict status. At the same time, single-needle pinyon moved north into the Basin somewhere around 2,000-6,000 BP and joined Utah juniper which had been a minor species, sparsely distributed during the glacial period. Both now came together on the lower mountain slopes to form the modern, extensive P-J zone.

As these changes were occurring, several species of Rocky Mountain conifers were spreading, in declining numbers, westward into the Great Basin. Beyond 116° longitude in eastern Nevada, a depauperate coniferous vegetation remains as scattered individual trees and small, thin groves of limber and bristlecone pine. Intervening and understory vegetation is grassland, sagebrush, and other shrubby forms. The challenge now is to hypothesize from this evidence of climate-related vegetation changes, how the contemporary vegetation might change in response to the climate changes projected for the future.

Brown (1971, 1978) proposed a stimulating hypothesis to explain the numbers of small mammalian species in what he called the boreal zones (wooded zones above 2,287 m, 7,500 ft). He accepted Wells' (1983) inference that coniferous woodland was continuous across the Great Basin at the end of the Pleistocene. He set as a premise that the number of small mammalian species was uniform across the region, given the continuity of habitat. With the contemporary coniferous vegetation shrunken to montane islands, the number of species he observed in his field work on each of 19 sampled islands varied between 3 and 13, with the total number of species on all 19 at 16.

Brown applied island-biogeography principles (MacArthur and Wilson 1963) to this distribution of species. He found a strong correlation between the log of species numbers in his sample areas, and the log of surface area above 2,287 m of the 19 areas. He considered the slope of the relationship, Z = 0.326 (Brown 1978), to be high and not representative of faunas at equilibrium between extinction of species and colonization from other areas.

Rather, he concluded that the mammalian faunas above 2,287 m on the Great Basin mountain ranges, which he termed "boreal," were relicts of a post-Pleistocene fauna that had been uniform and continuous across the Basin. As the boreal zones of the ranges moved up slope, became isolated from each other, and shrank in size with Holocene warming, varying numbers of species became extinct, the numbers being inverse to the size of the zones. The now hot and arid intervening basins became barriers to dispersal of species between the montane islands.

McDonald and Brown (1992) used this paradigm to predict the effects of global warming on mammalian species numbers on the Great Basin ranges. More recently, Lawlor (1998) has presented new evidence on species distribution in the Basin that prompts reconsideration of both Brown's paradigm and McDonald and Brown's model of species extinctions associated with global warming. These will be discussed below in the section on climate change.

Behle (1978) and Brown (1978) have examined the evidence on avian species distributions in the Great Basin mountain ranges to determine whether island-biogeography forces were producing the observed patterns. While Behle attributed the variations in species numbers to variations in habitat diversity, Brown noted that the numbers of year-round resident species per mountain range was correlated with the surface area of each range above 2,287 m, as in the case of his mammals. He concluded that the number of species per range was at or near island-biogeography equilibrium by virtue of significant vagility that permitted colonization from other ranges which off-set extinctions.

Wilcox et al. (1986) observed similar species-area correlations between sedentary and semi-vagile butterfly species in 18 Great Basin mountain ranges. Murphy and Weiss (1992) projected butterfly species extinctions in response to global warming as did McDonald and Brown (1992) with small mammals. These will be discussed below in the climate-change section.

Short-term Variability and Strengths of Trophic Couplings

Climate change can affect ecosystems by (1) directly altering first-order relationships between climate and system components, and (2) indirectly by altering second- and higher-order biotic relationships between other components and those directly affected. How pervasive the changes might be through the system would depend on how tightly its components are coupled, and therefore how completely the system would respond to effects on any of its parts.

Few, if any, ecosystems are so thoroughly understood that models can be developed to project the manifold effects of climate change throughout them. That certainly includes the Great Basin. But certain portions of the system are sufficiently understood to allow reasonable projections of climate-change effects on those portions.

Vegetation in arid and semi-arid ecosystems worldwide is under tight moisture constraints. Annual net primary production (NPP) is closely correlated with annual precipitation (Le Houérou and Hoste 1977, MacMahon and Wagner 1985). And as discussed above, slight variations in soils or topography that alter soil-moisture conditions produce abrupt changes in vegetation types (Ayyad 1981). In extreme desert systems, much of the fauna also fluctuates with annual variations in precipitation (Wagner 1980). The net effect is systems with tight climate-vegetation coupling, and strong links between climate and fauna directly or indirectly through the vegetation. Thus any climate change would have pervasive effects throughout the system.

The Great Basin shrub-steppe vegetation is also under tight moisture constraint. On the Desert Experimental Range in western Utah, NPP is closely correlated with annual precipitation (Wagner 1980). Some Great Basin animal species are similarly correlated. Hinds and Rickard (1973), in a long-term population study of the tenebrionid beetle Philolithus densicollis in southern Washington, found that the species, which has a 2-year life cycle, fluctuates with three weather variables: autumnal soil temperatures in both years of its cycle, and October precipitation in the year the eggs are laid. O'Farrell et al. (1975) observed annual population fluctuations of the Great Basin pocket mouse, Perognathus parvus, in the same area as Hinds' and Rickard's study, to be closely correlated with precipitation of the preceding October-April period. The weather affect on the beetles is apparently direct on the animals. O'Farrell et al. hypothesized that the effect on pocket mice is through the quantity and quality of the plant food supply, itself a function of annual precipitation.

However, major components of the fauna in the Great Basin shrub steppe fluctuate independently of the precipitation-driven annual vegetation changes. In a 29-year study Wagner (1981) and Knowlton and Stoddart (1992) have shown that black-tailed jackrabbits fluctuate through a smooth ~ 10 year cycle in northwestern Utah (Fig. 9.2) in which the cyclic highs may exceed the lows by two orders of magnitude. As described above, jackrabbit biomass at the cyclic low exceeds the aggregate biomass of the several rodent species. Yet Westoby (1973) calculated that vegetation consumption by jackrabbits at their population high was only 2% of NPP, and Clark (1979) calculated that consumption in the same area at the population high was only ~ 1% of vegetative standing crop. Thus, there does not appear to be a tight trophic coupling between jackrabbits and the vegetation. The major population constraint is imposed by predation from coyotes and a guild of raptors, all fluctuating in unison as a superpredatory species (Wagner 1981).

The white-footed deer mouse (Peromyscus maniculatus) has been shown to be the most numerous rodent species in several Great Basin areas (cf. Larrison and Johnson 1973, Stoddart 1987, Groves and Steenhoff 1988), outnumbering the other species combined. In 14 and 11 years of Peromyscus censuses on northwestern Utah and southern Idaho research sites, Stoddart (1987) found brief, approximately 2 year cycles (Fig. 9.3) resembling self-induced, time-delayed fluctuations like those modeled by May (1981). There was no correlation with annual variation in precipitation, and hence no strong link either to the climate directly, or indirectly to the vegetation as a food source.

Thus major components of the Great Basin herbivorous fauna, at least the vertebrates, fluctuate independently from the highly variable precipitation and correlated vegetation production. It follows that climate does not at present impose a significant direct constraint on these species, and there is no tight trophic coupling between them and the vegetation.

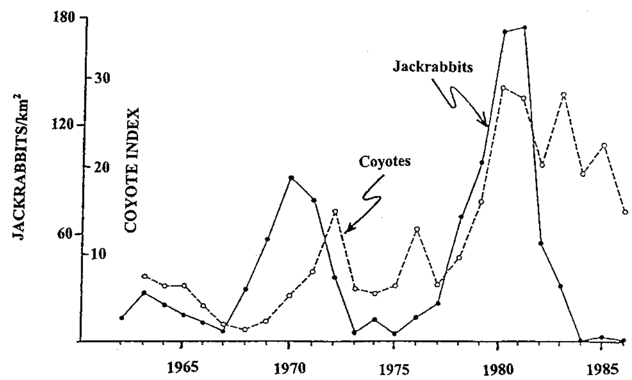

Figure 9.2. Between 1962 and 1986, in a shrub-steppe area of northwestern Utah, jackrabbits and coyotes oscillated through an approximate 10-year cycle, with the coyotes lagging approximately 2 years behind the jackrabbits. The coyote is the dominant predator on jackrabbits in the area, and jackrabbits are by far the major food item for coyotes.

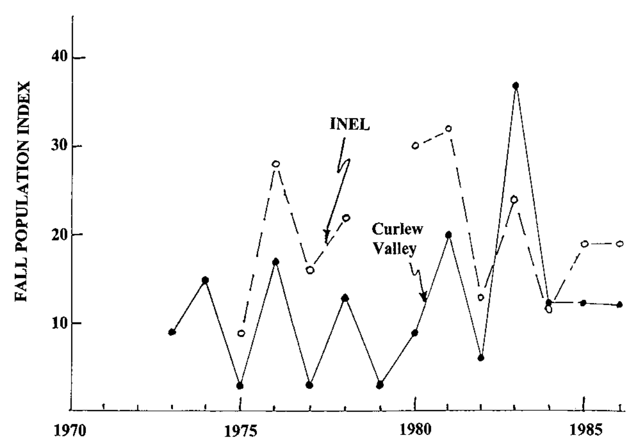

Figure 9.3. White-footed deermouse (Peromyscus maniculatus) populations in shrub-steppe areas of northwestern Utah (Curlew Valley) and southern Idaho (Idaho National Engineering Laboratory, INEL) fluctuate through an approximate 2-year periodicity similar to those induced by overcompensating, discrete-time logistic-population models (May 1981).

However, there is considerable evidence of close linkage between these mammalian primary consumers and a number of vertebrate predatory species. Wagner (1981) and Knowlton and Stoddart (1992) have shown that coyotes fluctuate with black-tailed jackrabbits in northwestern Utah and southern Idaho shrub steppe in what is apparently a predator-prey cycle. Egoscue (1985) observed fluctuations in kit fox populations in western Utah correlated with ups and downs in jackrabbit numbers.

Several authors have reported raptor fluctuations associated with changing jackrabbit numbers: Howard and Wolfe (1976) and Smith et al. (1981) in ferruginous hawks, and Kochert (1972) in golden eagles.

In sum, there appear to be two subsets of the Great Basin shrub-steppe system that function somewhat independently of each other. One is the climate-vegetation subset plus those primary consumers that are either subject to strong, direct climatic constraints or are linked to vegetative production through feeding dependencies. The second subset is an herbivore-carnivore component that is not tightly linked to the first because there is no strong trophic coupling between the vegetation and the herbivores in this subset. As a result, the two subsets are highly variable in time, but fluctuate somewhat independently of each other because they are functioning under separate, first-order environmental constraints. And the first subset would seem to be more subject to alteration by climate change, by virtue of its current climatic constraint, than the second.

However, these hypotheses are inferred from short-term fluctuations in the components of the system and what is known about trophic interactions between them. Habitat dependencies pose a separate set of interrelationships which, if affected directly by climate, or indirectly through some intermediate factor related to climate, could be the causal links between climate change and significant alteration of the shrub-steppe system. Stoddart (1972) and Westoby and Wagner (1973) observed higher densities of black-tailed jackrabbits in sagebrush and greaswood shrublands than in more-open vegetation of lower stature in a northwestern Utah study area. And Knick (1990) observed the same pattern for jackrabbits and Townsend's ground squirrels (Spermophilus townsendii) on the Snake River Birds of Prey Area in southern Idaho.

Welch (2001) terms sage grouse "obligate" sagebrush inhabitants, stating that optimum sagebrush canopy cover for nesting and brood rearing is 20-50%. He refers to pygmy rabbits (Brachylagus idahoensis) and sagebrush voles (Lagurus curtatus) as "obligate-like," stating that these species need 16-33% and 51-55% sagebrush canopy cover, respectively. Welch also classified Brewer's sparrow (Spizella breweri), sage sparrow (Amphispiza belli), and sage thrasher (Oreoscoptes montanus) as "near obligate" sagebrush species whose densities were a function of habitat structure.

Thus a major portion of the shrub-steppe fauna requires the shrubby vegetation for habitat. Any climate-change alteration in that habitat would significantly change the faunal component of the shrub-steppe ecosystem. This aspect will be explored at greater length below.

Nitrogen Cycling

Arid-land soils are characteristically nitrogen deficient (West and Klemmedson 1978), possibly due in part to a dearth of plant species with symbiotic nitrogen-fixing root nodules; and perhaps in part due to the high pH levels of the soils which promote rapid, bacterial denitrification and ammonification. Moreover, with the low standing crop of vegetation, desert systems have low, total nitrogen content by comparison with more mesic systems. These traits are characteristic of the Great Basin system.

Consequently, nitrogen is the second significant constraint on vegetative production after water in the Great Basin. James and Jurinak (1978) increased primary production of both native Great Basin shrub species (sagebrush and shadscale) and an introduced perennial grass (crested wheatgrass, Agropyron desertorum) with experimental amendments of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$.

Nitrogen is fixed in the Basin soils primarily by free-living blue-green algae, and by lichens that are symbiotic combinations of blue-green algae and fungi, both situated in surface, microphytic crusts (Rychert et al. 1978). Fixation largely occurs in a spring pulse when soils are still moist from seasonal precipitation and warmed by spring thaw. Once fixed, nitrogen is promptly lost through denitrification (Westerman and Tucker 1978), and to a lesser degree from ammonia volatilization (Klubek et al. 1978). Thus the plants have a short window of time during which there is a significant amount of mineral nitrogen which they can take up for growth.

As a consequence of this seasonal volatility, most of the nitrogen retained in a given system is in the perennial vegetation. And the nitrogen cycle is termed a "closed" cycle since the element is held in shrubs through their decades-long lives (Jones and Woodmansee 1979).

As discussed above, much of the Great Basin shrub steppe is being replaced by exotic annuals, particularly cheatgrass. Booth (2002) has shown that soil nitrogen content in cheatgrass stands is higher than in soils occupied by perennials, despite the fact that the microphytic crusts do not form in such stands. Hence the nitrogen cycle is now "open" as the annuals die each year, their tissues are mineralized, inorganic nitrogen is returned to the soil, and it is taken up again by the following year's cheatgrass crop.

With no microphytic crust and associated fixation in the cheatgrass stands, the source of the soil nitrogen is not clear. But the prevailing hypothesis is that it has been derived from mineralization of the dead perennials previously dominating the site. As such, the amount of nitrogen on a site is finite, and once mineralized is subject to loss from wind and water erosion, and to volatilization from periodic cheatgrass fires.

The loss may be a lengthy phenomenon. Perennial root tissue exceeds above-ground phytomass by a factor of 2-4x. Mineralization of this below-ground mass, not subject to fire, may be a protracted, multi-year process. But the net effect over time on Great Basin nitrogen budgets from the conversion of native perennials to exotic annuals may be a progressive loss of nitrogen fertility from the soils (West 1991).

The effects of climate change on this aspect of Great Basin ecosystem function will depend on the direct effects on existing nitrogen-cycling processes; and it will depend on whatever indirect effects climate change will have by influencing the ongoing conversion of native perennial vegetation to exotic annuals through the frequency of fires.

RECENT AND CURRENT STRESSES

The Great Basin ecosystem has been subjected to anthropogenic influences since the first humans arrived perhaps 12,000 years BP. These influences have intensified over time, and the system has been changed at accelerating rates up to the present. Climate change is likely to interact with these pressures, and could well intensify the rates of change further. Hence assessment of the effects must be made in the context of the influences that are already altering the system.

Livestock Grazing

Cattle ranching began in the Basin in the 1860s to support a growing mining effort. Large numbers of animals were brought in from California and Texas, and this eventually evolved into established ranching efforts by early settlers (Young and Sparks 1985). Since the land was largely either unappropriated public domain in those states that had just attained statehood (Nevada, Oregon), or was still U.S. territory, ranching was a highly mobile, open-range, uncontrolled enterprise. Sheep ranching only became a major land use around the turn of the century.

Given its aridity, forage production in the Basin was inevitably low by standards elsewhere and only some of the plant species were palatable to cattle: winterfat in the salt desert shrub; and limited amounts of perennial grasses in the latter, in the lower and dryer sagebrush zone, and somewhat greater amounts in the higher sagebrush, P-J, and upper-elevation zones. Sheep take larger amounts of browse in their foraging, and hence could use a broader fraction of the vegetation. But the aridity remained a constraint on the collective production of the entire vegetation. The valley bottoms served as winter range, while both cattle and sheep were moved into the mountain ranges for summer grazing.

Grazing pressures on public lands remained largely uncontrolled until passage of the Forest Reserve Act in 1891 which began the national-forest system in the mountain ranges, and the Forest Service Organic Administration Act of 1897 that established an agency to administer the forests. Grazing on the lower-elevation public lands was unconstrained until the Taylor

Grazing Act of 1934 and formation of the Bureau of Land Management in 1946 as successor to its precursor agency, the Grazing Service.

Consequently, livestock numbers reached their peak on national forests shortly after the turn of the century before their steady decline up to the present (Wagner 1978). Sheep and goat numbers on public-domain lands peaked about 1940 and have declined since. But cattle numbers on the lower-elevation lands increased until the 1970s before entering the decline shown in Chapter 5.

The range-ecological literature is virtually unanimous in the view that native ungulates were present in low numbers in the Intermountain West in pre-Columbian times, and consequently the vegetation had not evolved strong adaptations to withstand significant grazing pressures (Caldwell et al. 1981, Mack and Thompson 1982, Young and Sparks 1985, Milchunas et al. 1988, Knapp 1996). As a result, the herbaceous vegetation in the shrub steppe and P-J zones declined under the heavy grazing pressures applied by the introduced, domestic ungulates. Relieved of competition from the herbaceous species, sagebrush, shadscale, pinyon and junipers increased in density and distribution. And the changes were transmitted through the structure and function of the entire ecosystem. These were the first major ecological changes imposed on the Great Basin by European immigrants.

The Fire-cheatgrass Synergy

Shadscale and particularly sagebrush are extremely sensitive to fire. Unlike other shrub and half-shrub species in the Great Basin, they do not resprout from surviving roots following fire, and must restore growth from seed germination and seedling growth. Recovery of a sagebrush stand following fire may require 10-30 years (Houston 1982:107).

Hence the fact that early travelers in the Basin exclaimed over the endless vistas of sagebrush—the "Gray Ocean of Sagebrush" (Young and Sparks 1985) and "The Sagebrush Ocean" (Trimble 1989)—must imply that fire in the shrub steppe was an infrequent event. Indeed West (2000) estimates the pre-Columbian fire-return interval in the sagebrush steppe at 53-100 years. This low frequency was probably due to the wide spacing of the vegetation in this arid environment, and to the paucity of herbaceous ground cover, especially annuals, that could provide fuels capable of carrying fire.

To the contrary, dendrologic studies of P-J disclose a distribution of old trees on rocky hillsides that served as refugia from fire (Peet 1988). Younger trees today occur on finer-textured soils with moderate topography. Coupled with early photographs that show bare mountain slopes, P-J investigators now consider that fire frequencies were high in this type before European contact. Fires are thought to have been set largely by Native Americans (Gruell 1985, 1999, Peet 1988). The more abundant herbaceous ground cover at these higher elevations and precipitation levels are thought to have provided necessary fuels to carry fire. Tausch and Nowak (1999) comment on the landscape diversity that prevailed, comprised of a patchwork of successional stages and openings with associated floral and faunal diversity.

Since European settlement, the new residents have fought fire aggressively in the P-J zone. And with livestock grazing out the understory fuels, fire has become quite infrequent in P-J in the past 150 years. As a result, P-J canopies have closed to dense, even-aged stands, and the type has expanded downslope into the sagebrush zone and previous open areas. Tausch and Nowak (1999) generalize that the expansion has more than tripled the area occupied by woodlands in the Great Basin. The vegetation type is now highly vulnerable to intense and extensive stand-replacing fires.

Although numerous species of nonnative annuals have been introduced into the Great Basin, cheatgrass, in combination with fire, is by far the most influential in effecting drastic changes in the region's ecosystem. Its arrival has produced what Tausch (1999a) terms a threshold beyond which the region is experiencing fundamental, and potentially permanent ecological change.

The Central Asian species was first identified in North America in the Pacific Northwest in 1889 (Mack 1981), first in the Great Basin around the turn of the century (Billings 1990). It had generally spread throughout the sagebrush steppe by the 1930s (Mack 1981), but subsequently extended into the salt desert shrub, and upward into the P-J. The species is now ubiquitous within these zones as is its seed source.

In below-average and average precipitation years, reasonably intact perennial vegetation, whether shrubs or grasses, can suppress significant cheatgrass growth (Fig. 9.1). But in years with strongly above-average precipitation, the species can produce significant growth among the perennials. And in exceptionally moist years, others of the exotic annuals, which normally are less conspicuous than cheatgrass, also produce extensive growth (West 1994). Once senesced in early summer, the annual growth now provides a sufficient fuel base to carry summer fire, whether anthropogenic or lightning set, which eliminates shadscale, sagebrush, and P-J.

If there is a significant perennial grass understory, removal of the shrubs by fire on a site removes their competition with the grasses which are fire-resistant. The latter expand to convert the site to a native, perennial grassland (Blaisdell et al. 1982, West and Yorks 2002), which blocks significant cheatgrass growth. But if there are no perennial grasses, as in the more arid areas, or if they have been grazed out by livestock, removal of the shrub competition opens a site to massive growth of cheatgrass (Fig. 9.1) which now grows annually, even in dry years.

Sites converted to cheatgrass provide an annual, highly flammable fuel base. The fire-return interval is then 3-5 years (West et al. 1998) which effectively precludes recovery of the native vegetation. The result is in essence a permanent alteration of the ecosystem. Moreover, the process is a positive feedback one. As more area is converted to cheatgrass, the probability increases that lightning strikes will hit such areas and fire frequencies increase. Actual fire records indicate such a trend (Fig. 9.4). By one estimate, wildfires burned 3,000 square miles (7,692 km^2) in Nevada in the summer of 1999 (Christensen 2000a). Other estimates place the percentage of the Nevada sagebrush zone converted to cheatgrass at 20% (Knapp 1996) to 30% (J.A. Young quoted in Christensen 2000b).

Knapp (1995) analyzed in detail the seasonal climatic factors that predispose the Intermountain region to lightning fires in native vegetation not yet converted to cheatgrass monotypes, but containing seed sources of the annuals. Fires are most prevalent in years when climatic conditions (1) promote extensive annual growth that produces a fuel base, and (2) renders the vegetation highly flammable in summer. In the first case, abundant cheatgrass (a winter annual) growth is stimulated by above-normal precipitation in fall preceding a summer fire season; and by cool fall and winter temperatures that minimize soil-moisture loss, and retain it for the spring growth period. In the second case, flammability is enhanced by dry, warm springs and summers that reduce plant moisture content. Flammability is reduced in cool summers with above-average precipitation. Climate change will accelerate or slow the pace of vegetative change in the Great Basin according to how these seasonal variables change.

The conversion from salt desert shrub, sagebrush steppe, and pinyon-juniper to cheatgrass monotypes results in drastic biotic impoverishment (Billings 1990, Whisenant 1990, D'Antonio and Vitousek 1992). Not only does it constitute almost complete reduction in vegetative diversity, but as well the entire ecosystem superstructure supported by the vegetation. An extensive literature now reports a depauperate small-mammal fauna in cheatgrass compared with nearby sagebrush steppe. Rogers et al. (1988) trapped 3.2x as many small rodents in sagebrush-bunchgrass as in cheatgrass with standardized trapping procedures in their southern Washington area. Larrison and Johnson (1973), Halford (1981), and Groves and Steenhoff

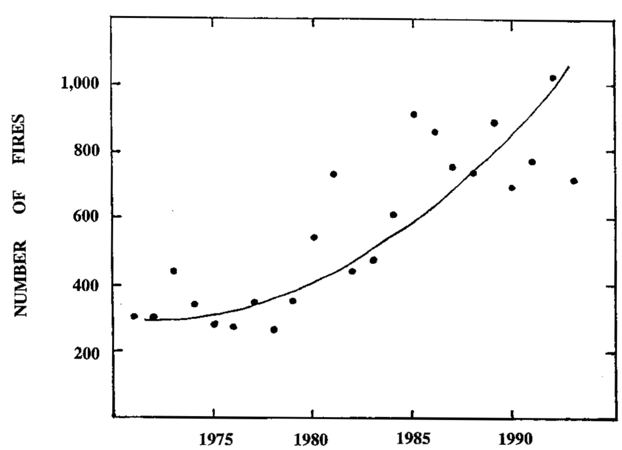

Figure 9.4. Number of range fires reported by the U.S. Bureau of Land Management in western Utah and all of Nevada between 1971 and 1993.

(1988) observed differences of similar magnitude in three areas across southern Idaho.

The latter authors, working in the vicinity of the Snake River Birds of Prey Natural Area (SRBOPNA), observed a significant decrease in the number of Townsend's ground squirrels (Spermophilus townsendii) in the burned areas. This species is staple prey for prairie falcons (Falco mexicanus), red-tailed and ferruginous hawks, and badgers (Taxidea taxus) in the area. Approximately 50% of the SRBOPNA has been burned off by range fires in recent years. Roberts (1991) observed a similar effect of cheatgrass conversion on black-tailed jackrabbit populations, a species important for golden and bald (Haliaeetus leucocephalus) eagles.

Similar changes have been observed in passerine bird assemblages. Rogers et al. (1988) observed nearly twice the number of passerine birds (41 vs. 23) per unit area in sagebrush-bunchgrass as in cheatgrass, and twice the number of species (6 vs. 3) in their southern Washington site. Vander Haegen et al. (2000) reported that vegetation fragmentation "… had detrimental effects on numerous shrubsteppe [passerine] species." And an extensive literature now describes the effects of habitat alteration on sage grouse populations (cf. Drut et al. 1994, Gregg et al. 1994, De Long et al. 1995, Connely et al. 2000).

The sweeping changes in the biota inevitably involve alteration of general ecosystem processes. Several authors have commented that the conversion of shrub steppe to cheatgrass reduces soil stability in several ways (Rickard and Vaughan 1988, Knapp 1996). One is the presence of the soil-stabilizing cryptogram crust in shrub steppe, and its absence in cheatgrass (Rickard and Vaughan 1988, Booth 2000). Further, some 69% of the cheatgrass root mass is in the surface 20 cm of soil while 41% is in this level in sagebrush grass, the remainder distributed at greater depths and providing stability for a significant soil column. And since cheatgrass dies at the beginning of summer, the system is without the stability provided by live plants for half of the year. If summer fire sweeps the dead annuals, the soil loses the limited mechanical protection provided by the dead vegetation, and is virtually without constraint of wind and water erosion.

The conversion may also be reducing the long-term nitrogen fertility of soils that already have low nitrogen content. The discussion above outlined how the nitrogen cycle of the cheatgrass type is more "open" than that of the shrub steppe, with more inorganic nitrogen in the cheatgrass soils (Rickard and Vaughan 1988, Booth 2002). Since there is no cryptogram crust in the cheatgrass, the greater nitrogen content cannot be produced by current fixation. The alternative is from mineralization of the dead, perennial plant tissues which, when alive, had served as a nitrogen pool. With the nitrogen now free in soils more susceptible to erosion, the long-term result would be gradual depletion of nitrogen from the system. This would be exacerbated by periodic fire in the seasonally dead cheatgrass, and resulting volatilization of nitrogen in the tissues of the annual.

The conversion to cheatgrass may also change the soils of the shrub steppe from a carbon sink to a significant source of CO_2 release. The following is a hypothesis under investigation by J.M. Stark at Utah State University as this is written. Stark hypothesizes that the bacterial breakdown of the extensive dead, perennial root material in the shrub steppe following fire releases CO_2 in the soil which then bonds with soil moisture to form carbonic acid. The latter may react with the underlying carbonate hardpan, characteristic of arid-land soils, to release CO_2. The hardpan is an extensive carbon sink underlying the soils of the Great Basin.

It is clear that the Great Basin ecosystem is experiencing fundamental change in response to existing stresses under current climates. The effects of climate change on the system will depend substantially on their interaction with the on-going changes.

CLIMATE-CHANGE ALTERATIONS OF THE GREAT-BASIN ECOSYSTEM

Perspective

Any Great Basin ecosystem response to climate change will constitute the collective response of the constituent species. They will respond according to how changing climate variables affect their physiological, demographic, and behavioral processes directly; and/or indirectly according to how the climate variables affect the species in the system with which they interact (e.g. predators, competitors, symbionts, habitat providers). If species are affected, their population densities are likely to change, and in the process alter the structure of communities in which they function. Changes in communities and their physical environments produce total ecosystem changes.

Species-specific predictions of how the Great Basin ecosystem would respond to particular climate changes would require thorough knowledge of the ecology at least of the major species among the several thousand occupying the region. And as discussed above, they would require models encorporating that knowledge into simulations of the interactions of those species with their physical environments and with other species in the system. While decades of research have produced an extensive understanding of Great Basin ecology, it is still not sufficient to structure detailed mechanistic, process-based models that could project climate-change effects at high probability levels.

A number of authors have developed generalized models that combine species into blocks or categories such as plant life forms (e.g. trees, shrubs, grasses) and project changes in these vegetation types. While these are useful heuristic exercises for developing hypothetical projections, Brown et al. (1997) describe "reorganization" of an arid ecosystem in response to a "modest" increase in summer precipitation over a 2-year period. Animal species composition changed drastically, some declining sharply or even disappearing, others increasing in abundance. The changes were thought to result from alteration of interspecific interactions, and could only have been predicted by models containing this level of mechanism in their structures.

de Valpine and Harte (2001) conducted artificial warming experiments on 11 Rocky Mountain forb species. Two responded positively in terms of abundance, size, flowering, and frost damage while four responded negatively. Köerner (2000) emphasizes that different plant species respond differently to elevated CO_2. Cerling et al. (1997, 1998, Ehleringer et al. 1997) point out that plants with C_3 photosynthetic pathways are favored by high levels of atmospheric CO_2 while C_4 plants are not. Shaver et al. (2000) comment that simultaneous CO_2 enrichment and increasing temperatures may have differing, sometimes antagonistic, effects on plant species. Raymond Angell (Pers. Comm., March 20, 2000) reports on the basis of his research that plant species in his experiments are adapted to certain amounts of precipitation at specific seasons. They do not function adequately if provided the same amounts of moisture, but at different seasons.

The common theme in all of these examples is that every species has its own unique environmental requirements. Each is persisting in a system because those requirements are met. But each has tolerance ranges for its environmental factors, and each may be well positioned near the optimum of its environmental-tolerance ranges, or may be barely subsisting on the margins of one or more of its ranges. For example Murphy and Weiss (1992) suggest that Edith's checkerspot butterflies (<u>Euphydryas</u> <u>editha</u>) subsist near San Francisco in an environment that is almost too arid for their survival, and would benefit from increases in precipitation.

In short, climate change would be likely to favor some species and affect others negatively. And Brown et al. (1997) conclude that generalized simulation models cannot be expected to incorporate such subtleties and diversities of interaction, even if the latter were fully known, and therefore cannot be used for making species-specific predictions. de Valpine and Harte (2001) conclude "Our study points to the potential importance of understanding ecosystem response to climate change in terms of species responses."

Neither is this level of understanding available for a significant fraction of Great Basin species, nor are there models that can project ecosystem changes for the Great Basin at the species level of resolution. Hence this assessment will follow two procedures. In the first it will review the kinds of species-specific responses to climate changes that have been observed elsewhere, and that could reasonably be expected to occur in the Great Basin in response to the climate-change scenarios under consideration here. Some of these changes have occurred in Great Basin species.

The second procedure is to hypothesize Great Basin community and system changes based on analogies with (1) the contemporary latitudinal and altitudinal distribution of the biota reflecting climatic gradients on both scales; and (2) correlated changes in both climate and biota that have occurred in past millennia, as shown by the extensive paleoecological record for the region.

Climate-change Scenarios

The discussions that follow hypothesize species and system responses to three climate-change scenarios:

(1) No change. Continuation of current climates.

(2) Increase in temperatures, no change in precipitation. This scenario is considered to place organisms both in a warmer environment and a dryer one since higher temperatures are likely to increase evapotranspiration.

(3) Increase in temperatures and precipitation. The scenarios proposed in Chapter 3 projected more precipitation in all seasons, but the greatest increase in winter. However, the historic weather analysis in Chapter 3 showed greatest increase in June in those subregions with statistical increases in precipitation during the 1900s. Hence both need to be considered.

Implicit in all three scenarios is increase in atmospheric CO_2, and in Scenarios 2 and 3 reduced snowpacks. The latter may range from shortened snowpack seasons and rising lower snowlines to complete disappearance in low-elevation mountains.

Species-specific Responses

Peters and Lovejoy (1992) and McCarty (2001) have summarized a number of responses like those under consideration here. Most are responses to increasing temperatures during the 20th century. A sampling of these, applicable to the Great Basin, follows.

Range Extension

Several authors have documented northward extension of the ranges of birds, mammals, and butterflies during the 20th century (McCarty 2001). Thomas and Lennon (1999) recorded 18.9 km (30 mi) northward movement of the northern range limits of "southerly' British birds over a 20-year period. Parmesan et al. (1999) examined records on the northern limits of 52 European butterfly species. Some 65% had extended the northern limits of their ranges northward in the past 30-100 years.

Parmesan (1996) also recorded distribution records of Edith's checkerspot butterfly along the western edge of North America from Mexico to southern Canada. The species exists in metapopulations, the occupancy of a given area consisting of scattered habitat patches of subpopulations that disappear periodically and are repopulated by dispersers from surviving subpopulations. Parmesan found that the extinction rate of subpopulations is higher at the southern extreme of its continental range than at the northern indicating more favorable conditions in the north and a mechanism by which the species range could extend northward. She also found higher subpopulation extinction rates in lower elevations than higher ones in mountainous regions.

Much of the Great Basin literature discusses range extensions in the region's species. Tausch et al. (1995) emphasize that Great Basin vegetation has been in continual geographic and altitudinal movement in response to climate changes for thousands of years. They sketch the northward advance of single-leaf pinyon across the Great Basin over the last 10,000 years. In the authors' view, there is no reason to assume that such movements are not taking place at present, and suggest that the vegetation we measure today is merely a snapshot of the trajectories currently underway. The effects of current anthropogenic climate change would be expected to modify these trajectories.

Similar changes are in all probability underway in the fauna, either in response to climate changes, or in response to climate-induced habitat changes. One species for which there is evidence is Grace's warbler (Dendroica graciae) which was first observed in the southeast corner of the Great Basin in 1963 (Trimble 1989). Species limited at the northern fringes or upper elevations of their ranges by winter conditions can be expected to move northward or upward with rising temperatures.

Species in mountainous areas that have dual seasonal ranges, occupying higher elevations in summer and lower slopes in winter, may change their seasonal migrations. Ungulates occupying higher levels of Great Basin mountains in summer are currently forced to move down to limited, lower winter range by the deep snows and low temperatures at high elevations. If these conditions are moderated by climate warming, the animals would be able to remain for most or all of the year in the more extensive, higher elevations and with increased populations. The result would in actuality be a shrinkage of range.

Changing Phenology

A number of authors have recorded advances in the dates of plant growth, insect emergence, arrival dates of migrating birds, and other life-history events of a wide variety of species during recent decades. Bradley et al. (1999) recorded phenological advances in 35% of 55 phenophases under observation in southern Wisconsin for 61 years. Brown et al. (1999) recorded a 10-day advance in nesting by Mexican jays (Aphelocoma ultramarina) in the Chiricahua Mountains of Arizona between 1971 and 1997.

Some of the changes are to the benefit of the species, but others are detrimental. Inouye et al. (2000) observed advancing spring arrival dates of American robins and emergence dates of yellow-bellied marmots at 2,945 m (9,660 ft) in the Colorado Rocky Mountains between 1975 and 1999. But because of increased snowfall during the period, there was not a synchronous melt of the snowpack. The authors reasoned that the food sources for the two species - - insects and plants - - were not sufficiently advanced for the species' survival.

Changing Demography

McCarty (2001) summarizes a number of cases in which rising temperatures have been reported to affect species' populations, both positively and negatively. His negative examples are largely marine associated with increasing water temperatures, and Antarctic. Positive examples are largely avian terrestrial ones in northern Europe, but likely to occur in some Great Basin species. Earlier nesting dates in some species are associated with increased clutch sizes and more favorable environments for survival of young. In multiple-clutch species, such as mourning doves (Zenaidura macroura), there would be time for more clutches, especially at the more northerly latitudes of the Basin, and at higher elevations.

Warmer temperatures may also benefit mammalian species or subpopulations occupying higher elevations. Bronson (1979) observed that golden-mantled ground squirrels (Spermophilus lateralis) at lower elevations in the Sierra Nevada have longer vegetative growing seasons which allow the young extended periods for feeding and growth before going into hibernation, and most females reproduce the year after their birth. At higher elevations, the short warm season allows the young animals less time for growth before forced hibernation. Most females do not produce young until 2 or 3 years of age, and bear fewer young. Higher temperatures and longer growing seasons could provide the high-elevation populations the benefits enjoyed by those at lower altitudes.

Higher temperatures might also allow increased survival of young ungulates in winter, typically a stressful season. The relationships between winter severity and overwinter mortality rates are well established for western mule deer and elk.

Species Extinctions

The possible effects of global warming on species extinctions in the Great Basin have elicited concerns among conservation biologists. McDonald and Brown (1992) combined implications of their island-biographic studies, as described above, with the consequences of upward movement of montane vegetation zones to predict mammalian-species extinctions in Great Basin mountain ranges. A number of authors are predicting upward movement of the wooded zones as temperatures increase. Since surface area is less at higher elevations than at low, the areas of the woodland zones, and the habitats they provide for mammalian species, would be expected to decrease with upward movement.

Brown (1971) had earlier shown a correlation between number of mammalian species and woodland area in Great Basin mountain ranges. Shrinkage of the habitat occupied by the contemporary species would be expected to exclude some of them. MacDonald and Brown (1992) actually estimated the percentage of existing species that would be likely to disappear on the different ranges, and the species most likely to be lost.

Lawlor (1998) pointed out that new evidence produced a different perspective on Brown's conclusions, and reduced the probability of extinctions. But at the March 14, 2000 regional workshop on climate change in the Great Basin ecosystem, Lawlor (Pers. Comm., March 14, 2000) generalized:

> Because coniferous forests will likely shift upward in elevation with climate warming, montane species of animals inhabiting high-elevation forest (e.g. many small mammals, butterflies) will experience shrinking habitats. Local extinctions will probably increase. Murphy and Weiss (1992) review these same patterns and conclude that some extinctions are likely in mammalian, avian, and butterfly species.

CO_2 Enrichment and Invasive Plant Species

A number of authors have examined the effects of CO_2 enrichment on different plant species and their implications for invasion of exotics. Johnson et al. (1993), Ehleringer et al. (1997), and Cerling et al. (1997, 1998) generalize that species with the C_3 photosynthetic pathway are strongly favored by higher levels of atmospheric CO_2 while C_4 plants are relatively insensitive to such levels.

Dukes and Mooney (1999) report that some exotic species are benefited by CO_2 enrichment while others are not. Smith et al. (1987) conducted greenhouse experiments on the effects of increased CO_2 levels on the growth of three Great Basin perennial grass species, and an annual, cheatgrass. All are C_3 species. All increased production and water-use efficiency. The authors speculated that the increased performance of cheatgrass under rising CO_2 levels would make it an even more pernicious pest than it is at present.

Ehleringer et al. (1997) comment that some of "… the most noxious and aggressive summertime weeds in temperate and subtropical regions…" are C_4 species. Since these are not favored by CO_2 increase, their aggressiveness is facilitated by disturbance.

Alward et al. (1999) measured a positive correlation between production of exotic and native forbs, and a Great Basin C_3 perennial grass Elymus elymoides, formerly Sitanion hystrix, and daily minimum temperatures. They observed a negative correlation between a perennial grass and perennial forb, both C_4 species, and daily minimum temperatures.

Community and Ecosystem Responses

Analogies with Elevational, Latitudinal, and Paleontological Gradients

The fire variable. While we do not have species-level models for predicting Great Basin community and ecosystem responses to climate change, given the inscrutable complex of factor effects and interactions within which the species function, hypotheses on such responses can be posed by analogy with existing correlations between vegetation distribution and altitudinal, topographic, and latitudinal climatic gradients, and with correlated vegetation and climate changes over geologic time. These suggest what might occur in the future to the extent that projected climate changes fall along contemporary gradients and/or simulate those of the past.

However, such projections need to be prefaced by discussion of the role of fire in changing the Great Basin ecosystem, and how its occurrence would be affected by climate change. Some ecologists in the region fear that at present rates, the Basin biota would be largely converted before the climate could change sufficiently to have a significant effect on the existing flora and fauna.

There is some evidence that climate affects fire probability differently in desert and mountain woody vegetation. As discussed above, Knapp (1995) generalized that a major prerequisite for high fire probability in the shrub steppe is above-average fall, winter, and early spring precipitation which stimulates lush cheatgrass growth and provides a dense fuel base. But Bessie and Johnson (1995), in modeling fire intensity (which correlated with area burned) and crown-fire initiation in 47 subalpine forest stands in the southern Canadian Rockies concluded:

> … forest fire behavior is determined primarily by weather variation among years rather than fuel variation associated with stand age …. The lack of any strong relationships between fuel variables …

The significant weather variables were hot, dry conditions that reduced fuel moisture content, and wind speed.

These authors' results accord with the general impressions of Great Basin ecologists and anecdotal observations of recent years. The view is widespread in the region that years with extensive range fires in the shrub steppe have summers following high fall, winter, and spring precipitation. The most recent was 1998 following the 1997-98 winter, an El Niño period with exceptionally high precipitation. The summers of 2000 and 2001 occurred in hot, dry years with below-average shrub-steppe fires in the Basin. But these were summers of extensive montane forest fires in the West, including those at Los Alamos National Laboratory in northern New Mexico in 2000. The year 1988, in which the extensive fires in Yellowstone and surrounding region occurred, was a record-setting drought year.

Thus the effect of climate change on patterns of wildfires, and associated conversion of ecosystems, are likely to depend on the nature of the climate change. And the implications of the scenarios under consideration here would appear to be as follows:

(1) Fire frequencies and vegetation conversion under Scenario 1, no change from present climate, could approach current rates of increase for two reasons. If the shrub-steppe fire frequency is a positive-feedback process, as discussed above, the prevalence of fire in the shrub steppe is likely to increase (cf. Fig. 9.4). And if the probability of major fires in pinyon-juniper has increased in recent decades as a result of increased density and maturation of the vegetation (Tausch 1999b), the extent and severity of fires in that type could increase. The combined result could be conversion of shrub steppe to cheatgrass, and P-J to perennial grasses and other herbaceous vegetation if there is an understory of these. If there is not, the type could also be converted to cheatgrass.

(2) The drying effect of Scenario 2, increased temperature with no precipitation change, could reduce the probability of shrub-steppe fires. But it could increase the fire probability in the montane/subalpine zone, and possibly in the P-J. Thus the shrub-steppe conversion rate would be reduced while much of the current wooded zones in the mountains would be converted to herbaceous vegetation.

(3) The potential effects of Scenario 3 with significant increase in precipitation at all seasons would appear to be mixed. Increased fall and winter precipitation would encourage cheatgrass growth, and hence fuel production in the shrub steppe. But wetter summers and fuels with higher moisture content could inhibit summer fires. The fuel production might be the overriding factor, and the net effect might be increased fire frequency in this zone. Higher precipitation would be expected to <u>reduce</u> fire frequencies in the wooded zones unless periodic droughts became more intense.

Spatial shifts in the elevational zones. Since the extent of fire conversion over the next century is uncertain, the potential extent of climate-change effects is equally uncertain. The only approach to hypothesizing the combined effects of the two is to pose major or complete alteration by each, and postulate that the actual changes will fall somewhere between these two extremes depending on the extent of fire conversion. Hence the attempt now is to explore potential climate-induced changes in the hypothetical situation in which there are no significant fire effects.

The discussion above generalized the sequential vegetational zonation in the Great Basin, from low to high elevations, as shrub steppe-pinyon/juniper-montane/subalpine woodland-alpine tundra. This sequence correlates positively with a precipitation gradient, and inversely with a temperature gradient, and the correlations are assumed to be causal. They exist:

(1) In the contemporary elevational zonation.

(2) In the latitudinal gradient in which these zones occur at progressively lower elevations northward with slightly more moderate temperatures and increased precipitation.

(3) At lower elevations on the north and east slopes of mountain ranges with their lower insolation and consequent more mesic conditions.

And (4), they occurred at lower elevations at the end of the Pleistocene with its cooler, moister conditions; and moved upslope with Holocene warming and xerification.

Two considerations need to be addressed before postulating hypothetical response of these zones to climate-change scenarios. The first is the question of what determines the upper and lower limits of the zones. Without firm ecophysiological guidance it is reasonable to assume that the lower limits are set by the minimum moisture conditions in which the zones can survive. This is the general view held by western ecologists. The upper limits of the zones have received less consideration, but a reasonable hypothesis would be competitive exclusion by the next higher zone: shrub steppe cannot compete with P-J and the latter with montane/subalpine forest. Timberline is generally considered to be set by severity of winter weather and wind conditions, and a short growing season limited by protracted snowpacks.

The second consideration is the lack of exact parallels between the spatial and temporal gradients of the contemporary environments and the paleoclimatic changes, themselves all similar in direction - - i.e. warm-dry to cool-moist (Tausch 1999a) - - and the conditions posed in the climate-change scenarios. The closest parallel is Scenario 1 with no climate change, but elevated CO_2 as one difference. Scenario 2 with increased temperature but no precipitation increase approximately parallels the contemporary downslope spatial and Holocene paleoclimatic gradients. While Scenario 2 does not have reduced precipitation, the warmer temperatures would have a xerifying effect. But Scenario 2 includes the same increase in CO_2 as Scenario 1.

Scenario 3, the preferred scenario (Table 3.8) with its increased temperature and precipitation, differs most from the contemporary and paleoclimatic gradients. And like Scenarios 1 and 2, it includes increased CO_2 levels.

Given these assumptions and caveats, the following spatial shifts in the elevational zones can be hypothesized in response to the three climate-change scenarios:

(1) Scenario 1, no significant climate change during the 21st century. This scenario specifies the 21st-century time frame and is modified with the adjective "significant" because, as Tausch et al. (1999b) emphasize, Great Basin systems and climates have been under continuous change for millennia, and undoubtedly are continuing to change. Shortening the time frame to the 21st century minimizes this ongoing change. Without anthropogenic change in temperatures and precipitation, any climate shifts will be restricted to the background changes currently underway which might be expected to be limited in scope and similar to changes that occurred during the 20th century. Some of that change was increase in density and downslope movement of P-J as a result of fire protection, and this would probably continue under a fire-free, no-climate-change hypothetical scenario.

Johnson et al. (1993) comment that CO_2 enrichment favors woody vegetation, and attribute its increase during the Holocene to postglacial rise in CO_2. Similarly, Nowak et al. (1994) documented a progressive shift from a higher proportion of herbaceous to a higher proportion of shrubby species during the past 30,000 years in the fossil record of a packrat midden in northwestern Nevada.

In total, the changes would be expected to be limited with the possible exception of continued P-J advance.

(2) Scenario 2, temperature increases with no added precipitation during the 21st century, would be likely to shift the zones to higher elevations and higher latitudes because of the net drying effect of such climate changes. With declining surfaces at higher elevations, the woodland zones would shrink as would the habitats provided for the animal inhabitants of those types. The result could be some of the small mammal, avian, and butterfly extinctions postulated by McDonald and Brown (1992), Murphy and Weiss (1992), Brown (1995), and Lawlor (Pers. Comm., March 14, 2000). Alpine tundra on those mountains in the Great Basin that support this type could largely disappear as would the faunas that are obligates of the type.

Some of the more mobile animal species that use several zones, like ungulates and their predators; and some high-elevation species that are currently forced to move to lower zones in winter, could be benefited by the changes.

The increased temperatures and aridity could induce northward movement into the southern Great Basin of what Neilson (1999) terms "southwest deserts." If the seasonality of the current precipitation remains the same —i.e. with a preponderance of winter moisture —the change would likely involve movement of the Mojave Desert type. But if there were a shift toward summer, monsoonal moisture, the change could involve Sonoran Desert species.

(3) Scenario 3, with its temperature and precipitation increase—as much as 50-100% increase, as set forth in Table 3.8—has no analog

either in the spatial or paleoclimatic gradients. The Great Basin would in all probability become more mesic with downward movement of the elevational zones. Pinyon-juniper, and perhaps the lower montane-forest types, would move downslope and some distance into the shrub steppe. Concurrently, subalpine forest would move up to occupy the alpine zone as in Scenario 2.

What changes would occur in the shrub steppe are uncertain. The contemporary precipitation range cited above for the zone spanned 4-8 in (10.2-20.3 cm) for the southern and lowest elevations, through the 9 in (22.9 cm) average for Nevada, to 16 in (40.6 cm) for the eastern limits of the Basin. A 50-100% precipitation increase would raise all but the lower portion of this range into the 12-18 in (31-46 cm) range of the contemporary pinyon-juniper zone. Elevated temperatures would increase evapotranspiration and thus raise the moisture tolerance range for P-J somewhat. But this would be somewhat compensated for by the higher plant water-use efficiency induced by elevated CO_2 levels. Thus, the magnitude of precipitation increase posed by Scenario 3 for the shrub steppe would still place it in much of the P-J range.

The nature of the changes could well depend on the seasonality of the precipitation increase. If there were a significant increase in summer precipitation associated with Scenario 3, and/or an increase in monsoonal moisture as Neilson (1999) projects, much of the shrub steppe could change to grassland, again as Neilson (1999) proposes. There would also appear to be some possibility that the southern limit of the shrub steppe would move southward into the northern portions of the Sonoran and Mojave Deserts.

In total, the Great Basin would in all probability become more mesic under Scenario 3 with woody vegetation extending out from the mountains, perhaps into grasslands that had replaced shrub steppe. And abetted by increased CO_2 enrichment, the region could conceivably be covered primarily with woody vegetation at all elevations much like what prevailed at the end of the Pleistocene.

Where the potential upward movement of vegetation zones under Scenario 2 raises concerns for habitat shrinkage and extinction of animal species (Murphy and Weiss 1992, Brown 1995), the woody-vegetation expansions of Scenario 3 would increase woodland habitat. And it would restore some or most of the habitat connectivity inferred for the end of the Pleistocene. The result could be reduced probability of extinctions, enhanced species exchanges between mountain ranges, and increased faunal evenness and diversity across the Great Basin, at least of woodland-inhabiting species. At the same time there would be major reductions in the shrub-steppe biota.

It is also reasonable to project increase in wetlands, now of course scarce in the region, and in riparian zones. The result would in all probability be an increase in biodiversity. Fleischman et al. (1999) observed high, butterfly species richness in undisturbed riparian habitats of the western Great Basin. Rogers et al. (1988) described an entire riparian avifauna on the Arid Land Ecology Reserve (ALE) in southern Washington "… that cannot successfully nest in the surrounding sagebrush-bunchgrass communities."

In total, the changes would take time, probably a century or more once the climate changes had significantly approached the levels projected by Scenario 3 for the end of the 21st century. Davis (1986) has discussed the lengthy time lags associated with changes of this magnitude, at least in tree species.

Changes in Soil Features and Nutrient Cycling

West et al. (1994) reported the results of a seven-person workshop in which the participants collaborated in hypothesizing the changes in soil physics and chemistry, and in nutrient cycling, likely to occur in arid- and semiarid-land soils under five climate-change scenarios. They used Delphi procedures to arrive at consensus on expected trends, and modeling to integrate the complex of factors and project the directions of soil changes of the four North American deserts including the Great Basin.

The authors examined the effects on 26 soil features. Two of their five scenarios were similar to the ones under consideration here: (1) no climate change, and (4) 2°C (3.3°F) increase in mean, annual temperature and 20% increase in mean annual precipitation. They had no scenario for increased temperature without change in precipitation.

The authors generalized:

> Whereas most mesic terrestrial ecosystems have huge stores of organic matter in soils and large standing crops of plants to buffer the effects of climatic variability, this is not so true of deserts and semideserts. Thus, even small changes in climate may intensify already high natural variability, and lead to permanent degradation of the productive potential of such lands …. Arid and semiarid lands may thus be among the first regions in which ecosystem dynamics become altered by global environmental change.

Structural and functional features, which their modeling efforts showed most likely to be altered under their Scenario 4 (above) were:

(1) Among those likely to increase:

- Formation of physical and chemical crusts
- Formation of subsurface vesicular horizons
- Soil carbonate pool
- Soil salinity
- Water erosion
- Litter decomposition

(2) Among those predicted to decrease:

- Biological crusts
- Soil organic matter
- Soil nitrogen pool
- Soil inorganic phosphorus
- Nitrogen fixation
- Water infiltration

In total, the changes would represent (1) reduction in soil fertility, C/N ratios, and microbial action; (2) enhanced physical changes, all resulting in soils less conducive to plant production; and (3) reduced resistance to erosive loss.

General Summary of Climate-change Effects

Projecting potential effects of climate-change scenarios on the Great Basin ecosystem is confounded by uncertainties surrounding the degree to which that system will be altered by fire by the time climate-change effects exert significant influence. Scenarios for the region (Chapter 3) are projected for the year 2100. Significant temperature and precipitation changes are likely to occur if one or the other scenario eventuates. But response of some species, particularly long-lived forms, are likely to lag behind the climatic changes (Davis 1986). Hence, significant change in major species, such as woody vegetation, would probably be decades away.

Meanwhile, fire is now occurring at what appears to be an increasing rate (Fig. 9.4), and one author estimates that 20% of the Nevada shrub steppe has already been converted to exotic annuals (Knapp 1996). Climate change could affect fire occurrence, the nature of the change depending on which of the scenarios became reality. Scenario 2 could reduce fire occurrence in the shrub steppe but increase it in the wooded zones of the mountains. The effects of Scenario 3 could be the reverse. Whichever scenario developed, the fire influence would increase over the 21st century as the full measure of climate change unfolded.

Thus there is considerable uncertainty as to how much of the contemporary, unburned biota would still be present in the latter half of this century when the climate had changed sufficiently to exert significant influence on the Basin's ecosystem structure and function. Consequently the changes posed here are provisional, depicting modification in a hypothetical system largely unaltered by fire. The actual nature of the system by the end of the present century would likely be at some unspecifiable point along a scale of increasingly extensive fire conversion, and an inverse scale of the extent of climate-induced change in the contemporary system.

Changes in the vegetation dominants that give the elevational zones their primary structure would vary with the direction of the climate change. The drying effects implicit in Scenario 2 would likely stimulate upslope movement of the zones with probable elimination of most of the alpine zone. Areas of all zones would shrink except for the shrub steppe. The latter might well be invaded along its southern margin by the more extreme southern deserts, Sonoran and/or Mojave.

The increasingly mesic conditions of Scenario 3 would in all probability elicit downslope movement of the zones except for upslope movement of the subalpine into the alpine.

Areas of all woodland zones would increase, while that of the shrub steppe would decrease and/or change to grassland if there were a significant increase in summer precipitation.

Analogous changes in the associated, subsidiary vegetation (e.g. shrubs and herbaceous) and fauna of the zones would be likely. But the species composition of the communities cannot be projected because the species-level ecological understanding is insufficient, and unexpected shifts in community structure like that described by Brown et al. (1997) are likely. Species would be expected to respond individually to the changes. Some would be benefited directly by the changing physical environment, others would be affected negatively. All would be affected indirectly in numerous ways by changing biotic influences: shifting competitive, predatory, parasitic, and symbiotic interactions.

Native, western North American species not presently in the Great Basin would in all probability extend their ranges into the region, as is now occurring elsewhere. Some of the existing species could very well disappear. The altered biotic relationships among the existing species could change their abilities to block intrusion of exotic species, both negatively and positively. In particular, invasive C_3 plant species favored by CO_2 fertilization, such as cheatgrass, could become more invasive.

In total, very fundamental and unpredictable changes in community structure would likely occur if the species became immersed in environments unlike any in which they evolved, and unlike those in which their evolutionary precursors evolved over the past 20,000 or more years.

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