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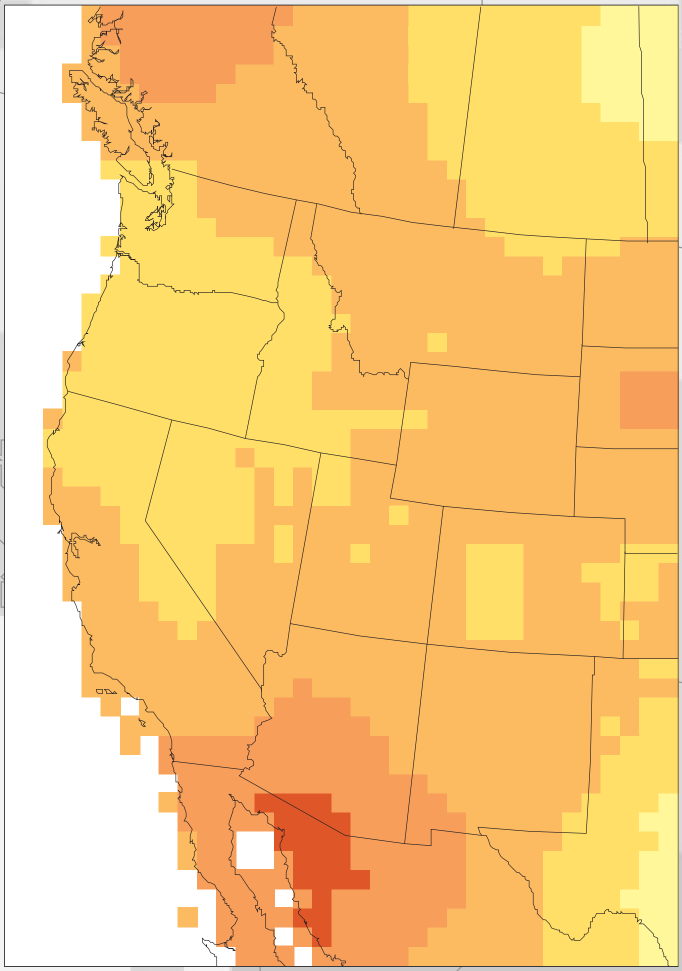
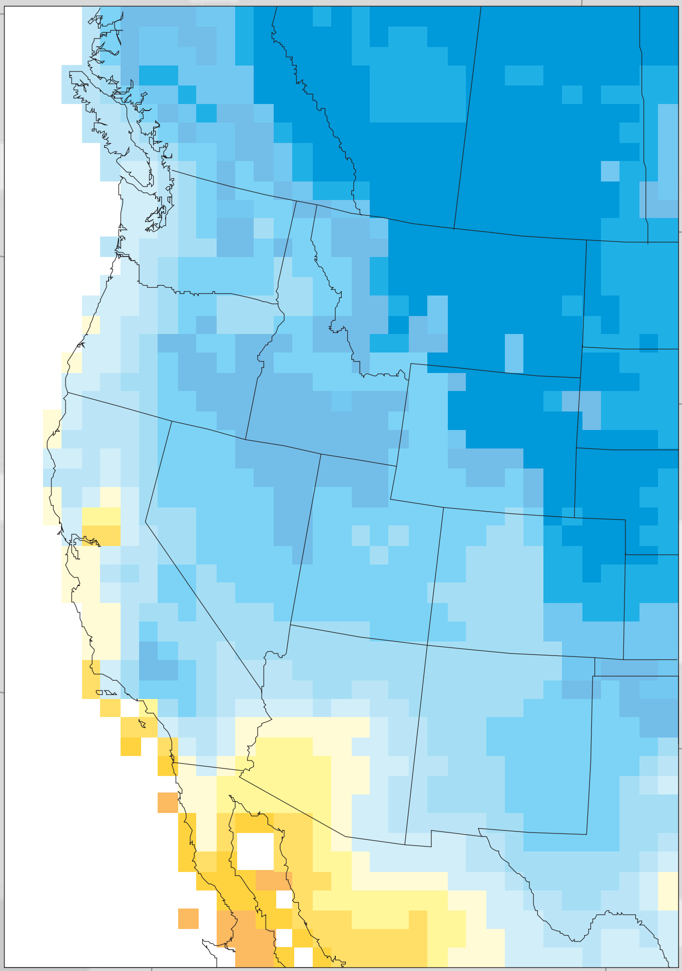
A Strategy for Assessing Potential Future Changes in Climate, Hydrology, and Vegetation in the Western United States





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Cover. The left-hand illustration depicts climate anomalies for July temperature calculated by subtracting simulated present-day climate conditions from simulated conditions under a 2×CO_2 climate—see figure 3*J*. The right-hand illustration depicts simulated present-day lake surface temperatures—see figure 4*A*.

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ACRONYMS USED IN THIS REPORT

Acronym	Meaning
AGCM	atmospheric general circulation model
BATS	biosphere-atmosphere transfer scheme (Dickinson and others, 1993)
GENESIS	global environmental and ecological simulation of interactive systems
GHG	greenhouse gases
INSTAAR	Institute for Arctic and Alpine Research (Boulder, Colo.)
NCAR	National Center for Atmospheric Research (Boulder, Colo.)
RegCM	regional climate model

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ABSTRACT

Historical and geological data indicate that significant changes can occur in the Earth's climate on time scales ranging from years to millennia. In addition to natural climatic change, climatic changes may occur in the near future due to increased concentrations of carbon dioxide and other trace gases in the atmosphere that are the result of human activities. International research efforts using atmospheric general circulation models (AGCM's) to assess potential climatic conditions under atmospheric carbon dioxide concentrations of twice the pre-industrial level (a "$2\times CO_2$" atmosphere) conclude that climate would warm on a global basis. However, it is difficult to assess how the projected warmer climatic conditions would be distributed on a regional scale and what the effects of such warming would be on the landscape, especially for temperate mountainous regions such as the Western United States. In this report, we present a strategy to assess the regional sensitivity to global climatic change. The strategy makes use of a hierarchy of models ranging from an AGCM, to a regional climate model, to landscape-scale process models of hydrology and vegetation. A $2\times CO_2$ global climate simulation conducted with the National Center for Atmospheric Research (NCAR) GENESIS AGCM on a grid of approximately 4.5° of latitude by 7.5° of longitude was used to drive the NCAR regional climate model (RegCM) over the Western United States on a grid of 60 km by 60 km. The output from the RegCM is used directly (for hydrologic models) or interpolated onto a 15-km grid (for vegetation models) to quantify possible future environmental conditions on a spatial scale relevant to policy makers and land managers.

INTRODUCTION

Although there remains considerable debate on the issue of global warming, computer models suggest that the increasing atmospheric concentrations of carbon dioxide and other "greenhouse" gases (GHG) released by human activities will cause global warming during the next century. In addition, instrumental measurements suggest that the Earth's climate has warmed during the past few decades, perhaps reflecting the initial phase of "greenhouse" warming (Houghton and others, 1996). Geologic studies of past periods of global warmth and simulations of these past climates by numerical models suggest that the degree of warming can vary greatly across the globe and that precipitation regimes are affected differently in different regions (Lauritzen and Anderson, 1995; Dowsett and others, 1994; Thompson and Fleming, 1996; Poore and Sloan, 1996). Given the complex nature of regional responses to global warming and the fact that natural climate variability is a complicating factor, better tools are needed to assess the impacts of a range of likely future climate variations on the Western United States and elsewhere. Climate change will directly affect water availability and quality, agriculture, forestry, power production from dammed rivers, and the storage of toxic materials. Entire ecosystems will be affected, as will a wide variety of public lands, including Native Lands, National Parks, National Forests, and range lands managed by the Bureau of Land Management. Thus, it is important that policy makers, land managers, and other interested parties understand the sensitivity of these ecosystems to potential climate change.

In this report, we present examples of the sensitivity of water and vegetation resources to a possible scenario of future climate in the Western United States.

STRATEGY

The Western United States has a diverse array of regional climates due to physiography and the interplay of air masses originating from different source areas (Mock,

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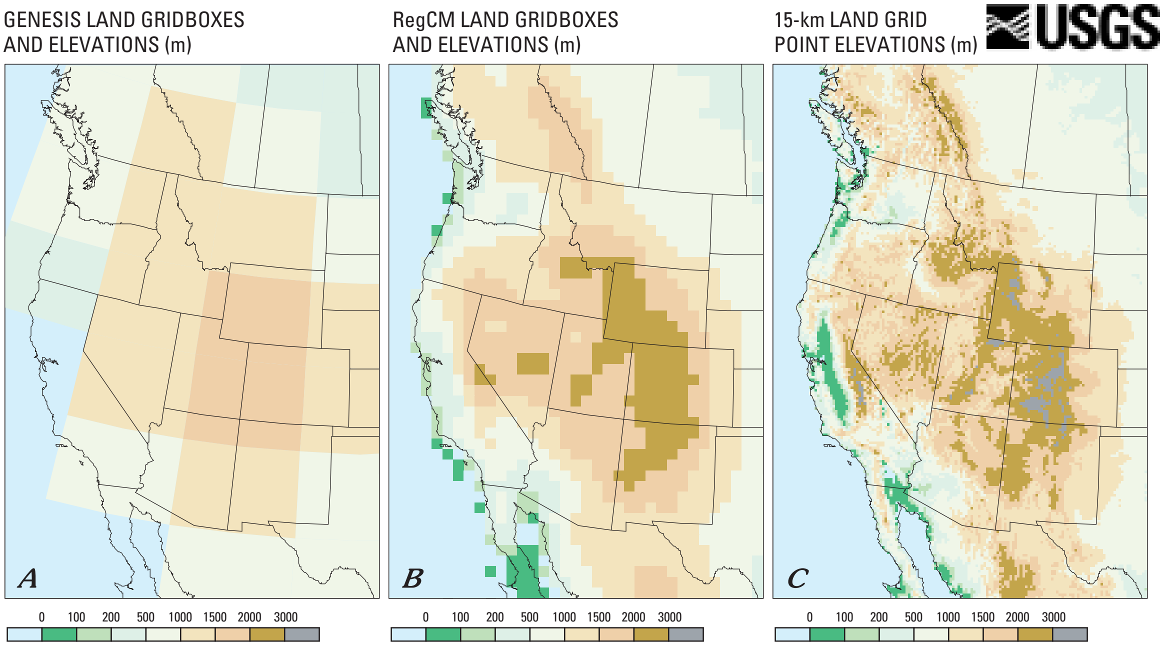

Figure 1. Maps illustrating spatial and topographic resolution of the two climate models—*A*, the GENESIS global atmospheric general circulation model (AGCM) and *B*, the regional climate model (RegCM)—relative to actual topography in the Western United States. The latter, shown in *C*, is displayed by elevations on a 15-km grid, sampled from the 5-minute ETOPO5 data set (Edwards, 1992). The GENESIS map (*A*) shows how the complex topography of the Western United States is greatly smoothed and reduced in elevation in this model. The RegCM map (*B*), in comparison with the map of observed topography (*C*), shows how many physiographic features in the real landscape that have an important mesoscale climatic influence, such as the Sierra Nevada, Colombia Basin, and Snake River Plain, are explicitly represented in the model. Some features, such as the Cascade Range and the individual basins and ranges, are still not well represented by RegCM.

1996; Thompson and others, 1993). To deal with this complex situation, we used the sequential application of a hierarchy of climate and landscape models to simulate the regional-scale responses to climate change of streams, lakes, and natural vegetation (table 1). At the top of the hierarchy of models, an atmospheric general circulation model (AGCM) is used to simulate global climate in response to specified large-scale boundary conditions (e.g., sea-surface temperatures and atmospheric CO_2 concentration). AGCM's incorporate the physics of atmospheric circulation and the interactions of the atmosphere with the Earth's surface. AGCM's are generally run at a rather coarse resolution (on the order of several degrees of latitude and longitude) to balance the level of detail with computing requirements. Many simulations of trace-gas-induced change have been conducted with AGCM's (Houghton and others, 1996). Most model simulations generally support the conclusion that global mean temperature will rise over the next century; however, the models disagree on the magnitude and spatial distribution of large temperature and precipitation changes. These problems are, in part, due to imperfect representations of atmospheric physics (e.g., cloud processes) and the coarse resolution of the models.

For our study, we use a $2\times CO_2$ climate simulation (Giorgi, Shields-Brodeur, and Bates, 1994) conducted with the GENESIS AGCM, developed at the National Center for Atmospheric Research (NCAR), to provide estimates of environmental sensitivity to global warming. The output from these simulations is on a rectangular grid of 4.4° of latitude by 7.5° of longitude—a coarse resolution for regional-scale analyses. To achieve finer resolution, we used results from a companion simulation conducted with the NCAR regional climate model (RegCM) with a 60-km by 60-km grid (Giorgi, Shields-Brodeur, and Bates, 1994). The RegCM simulation was initialized and driven with boundary conditions derived from the GENESIS simulation.

The landscape of the Western United States is dominated by a great number of mountain ranges, with the highest peaks reaching more than 4,000 m in elevation. The coarse resolution of the GENESIS AGCM portrays the topography of the Western United States as dome-like, with a very flat slope with a maximum elevation of less than 3,000 m centered over Utah and Colorado (fig. 1*A*, table 1). At the 60-km resolution of the RegCM (fig. 1*B*), the basin-and-range topography begins to emerge and the Sierra Nevada, Rocky Mountains, and intermountain plateaus are discernible.

Table 1. Overview of scientific strategy used in this report.

[Δ, delta or "change in;" GHG, greenhouse gases; AGCM, atmospheric general circulation model; BATS, biosphere-atmosphere transfer scheme (Dickinson and others, 1993)]

Components of a projection strategy	Components utilized in this report	Components of potential future reports
Climate-system boundary condition changes (i.e., projected changes in the large-scale controls of the climate system).	2×CO_2.	ΔCO_2, Δ other GHG; Δ tropospheric aerosols, land-surface cover.
Global-scale climate simulation (e.g., AGCM, global scope, coarse spatial resolution (hundreds of kilometers)).	GENESIS, version 1 (4.4° of latitude × 7.5° of longitude).	Higher resolution ACGM's (approaching hundreds of kilometers); fully coupled land-surface hydrology, vegetation, and oceans.
Procedures for downscaling to regional and local scales (i.e., to tens of kilometers).	RegCM (60-km resolution, BATS surface-physics package, interactive lakes).	Higher resolution regional climate models; interactive land-surface hydrology and vegetation.
Environmental system process models (e.g., vegetation, hydrology).	Plant taxon probability surfaces (empirical, equilibrium vegetation model); evaporation climatonomy watershed model; lake thermal model.	Dynamic vegetation models; comprehensive watershed simulation models.
Projected responses.	Projected plant taxon distribution changes; projected monthly streamflow changes; projected changes in lake temperature and ice-cover duration.	Projected plant taxon distribution changes, plus changes in carbon balances, ecosystem structure and function; projected changes in variability of streamflow, sediment yields, ground-water yields, water quality, etc.

However, compared with the actual topography at 15-km resolution (fig. 1*C*), much of the detail is still missing.

We use output from the RegCM simulation to drive hydrological and vegetation models to quantify fine-scale environmental responses to global climate change. We are not predicting the exact nature of future climatic changes in the Western United States; rather, our objective is to demonstrate how the effects of large-scale simulations of global climatic change can be portrayed on a spatial scale that is meaningful to society.

CONTINENTAL TO SUBCONTINENTAL CLIMATE MODELING

COMPARISON OF MODEL SIMULATIONS WITH OBSERVED PRESENT-DAY CLIMATE

Figure 2 illustrates present-day mean January and July temperature and precipitation in the Western United States as simulated by GENESIS (figs. 2*A*–2*D*) and RegCM (figs. 2*E*–2*H*), compared with observed values that have been interpolated onto a 15-km grid (figs. 2*I*–2*L*). In the observed climate, January temperatures are above freezing only in southern portions of California, Arizona, New Mexico, Texas, and along the Pacific Coast. Extremely cold winter temperatures occur largely on the northern Great Plains. Due in large part to its coarse depiction of topography, GENESIS for January simulates relatively warm winter temperatures across much of the interior Western United States; extremely cold temperatures are restricted to the far-northern Great Plains in Canada. In contrast, the RegCM simulation provides a spatial temperature pattern that better matches the observed present-day pattern. The location of the freezing line in the RegCM simulation is very close to that of the observed data, and cold temperatures on the northern Great Plains are more accurately depicted. For July temperatures, the results are similar: GENESIS simulates the general, broad pattern of July temperatures, but the Western Cordillera is not evident. The RegCM simulation provides an acceptable pattern of warm temperatures in the Southwest and cooler temperatures along the Western Cordillera mountain chain from northern Mexico to British Columbia.

Precipitation in the Western United States is presently dominated by two distinctly seasonal features of atmospheric circulation. Winter precipitation, associated with low-pressure cells and westerly wind patterns (jet stream) off the Pacific Ocean, is the dominant feature along the Pacific Coast and into the northern Rocky Mountains (fig. 2*K*). In contrast, summer rainfall, associated with convective storms from monsoonal flow originating from the subtropical Pacific Ocean and Gulf of Mexico, occurs in the southern and eastern portions of the West (fig. 2*L*). The wet-west/dry-east pattern of January precipitation is present in the GENESIS simulation (fig. 2*C*), although the spatial distribution does not closely match observations (fig. 2*K*). The RegCM simulation of January precipitation is a better match with the observed pattern, although, as with GENESIS, the simulated precipitation is too high in the Great Basin and the Southwest. The results for July show that both models simulate too much precipitation throughout the Rocky Mountains and that the RegCM captures the gross features of observed precipitation.

SIMULATION OF A POTENTIAL 2×CO_2 CLIMATE

The GENESIS 2×CO_2 simulation used a 50-m-thick “slab ocean” and atmospheric CO_2 concentrations prescribed at 680 ppm—twice the level used in the present-day simulation (Giorgi, Shields-Brodeur, and Bates, 1994). The model simulated 20 years before achieving an equilibrium climate. A $3^1/_2$-year RegCM simulation was conducted

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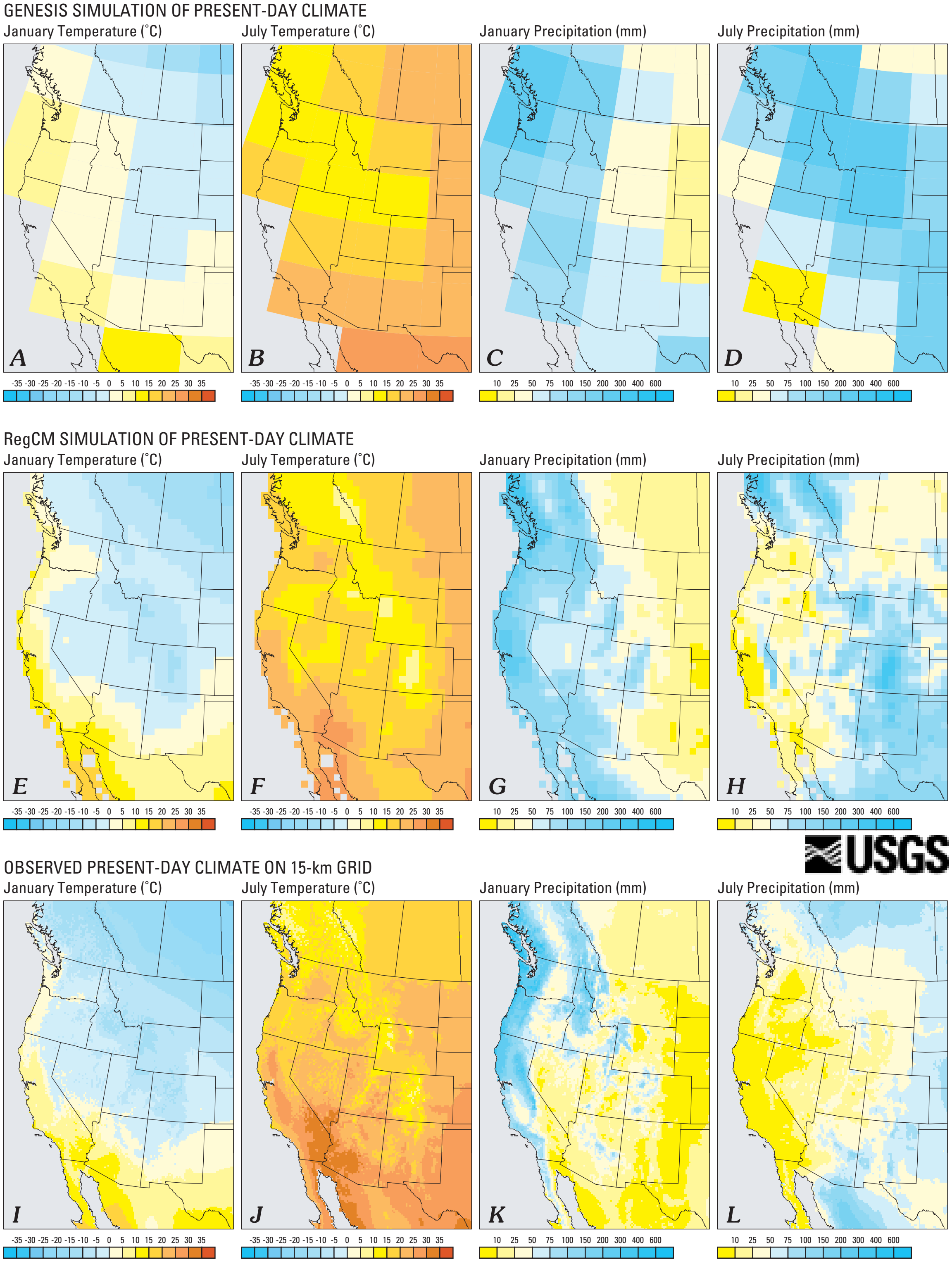
Figure 2 (facing page). Maps showing comparison of present-day climate (average or mean January and July temperature and precipitation) as depicted by *A–D*, GENESIS; *E–H*, RegCM; and *I–L*, observed conditions. Observed present-day climate data (*I–L*) is interpolated onto a 15-km grid from climate stations using a locally weighted trend-surface regression approach (e.g., Lipsitz, 1988). The GENESIS maps (*A–D*) show, in part, how the crude depiction of topography in the model (see fig. 1*A*) is translated into the simulation of temperature and precipitation. Because of the reduction in overall elevation in the smoothed representation of topography in the model, lower values of January temperatures are not simulated correctly and the overall representation of topography as a broad dome centered over Wyoming, Colorado, and Utah spreads out areas of higher precipitation relative to those of the observed present-day climate. The RegCM maps (*E–H*), on the other hand, show that this higher resolution model, even though forced by the coarse-resolution GENESIS, produces simulations that are closer in overall appearance to observed climatic patterns (*I–L*).


GENESIS SIMULATION OF PRESENT-DAY CLIMATE
January Temperature (°C)
July Temperature (°C)
January Precipitation (mm)
July Precipitation (mm)
A
B
C
D
RegCM SIMULATION OF PRESENT-DAY CLIMATE
January Temperature (°C)
July Temperature (°C)
January Precipitation (mm)
July Precipitation (mm)
E
F
G
H
OBSERVED PRESENT-DAY CLIMATE ON 15-km GRID
January Temperature (°C)
July Temperature (°C)
January Precipitation (mm)
July Precipitation (mm)
I
J
K
L
-35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35
10 25 50 75 100 150 200 300 400 600
USGS

using the last 3$^1/_2$ years of the GENESIS run as boundary conditions. The coarse-scale fields of GENESIS are interpolated to the finer scale boundary of the RegCM to provide forcing or inputs for the regional simulations. Giorgi, Shields-Brodeur, and Bates (1994) provide complete details and analyses of these simulations. Figure 3 shows a comparison of the simulated January and July temperatures and precipitation for the present-day climate (control simulation) (figs. 3*A*–3*D*) and 2×CO_2 climate (figs. 3*E*–3*H*). Figures 3*I*–3*L* show the climatic differences (anomalies) between these two simulations. The anomaly maps for January and July temperatures (figs. 3*I* and 3*J*) indicate general and substantial warming of the region for the 2×CO_2 simulation. January temperatures are as much as 5°C warmer on the northern Great Plains and 3°C or more warmer in parts of Oregon and Idaho, whereas the southwestern deserts warm by only 1°C to 2°C. The spatial pattern for July is quite different—British Columbia and the Sonoran Desert warm by 4°–5°C, whereas the northern Great Plains and the Oregon/Idaho region warm by 3°C or less.

The anomaly maps for precipitation (figs. 3*K* and 3*L*) indicate that, for the 2×CO_2 simulation, winter precipitation is greater than in the modeled present-day climate (control simulation) over the Pacific Northwest and along the Pacific Coast to southern California. Scattered areas of increased winter precipitation also are located over portions of the Great Basin, northern Mexico, and parts of the Great Plains. January precipitation values that are less than those modeled for the present-day climate are located over the Sonoran Desert, the Four Corners region, eastern Oregon, and most of Utah, Wyoming, Montana, Alberta, and the northern Great Plains in the United States. July precipitation for the 2×CO_2 climate is generally greater than that modeled for the present-day climate in the northern half of the region and is less than that simulated for the present-day climate in the southern half of the region. In the 2×CO_2 simulation, arid summer conditions are simulated for the Southwestern United States, California, and most of the Great Basin, as well as for portions of the northern Great Plains of the United States.

These simulations demonstrate the potential complexity of climate change in the Western United States. The amount of warming and the changes in precipitation in the 2×CO_2 simulation (figs. 3*I*–3*L*) vary greatly with geography and with season, with most regions of the Western United States receiving a mixture of winter and summer precipitation that is quite different from that of the present-day simulation.

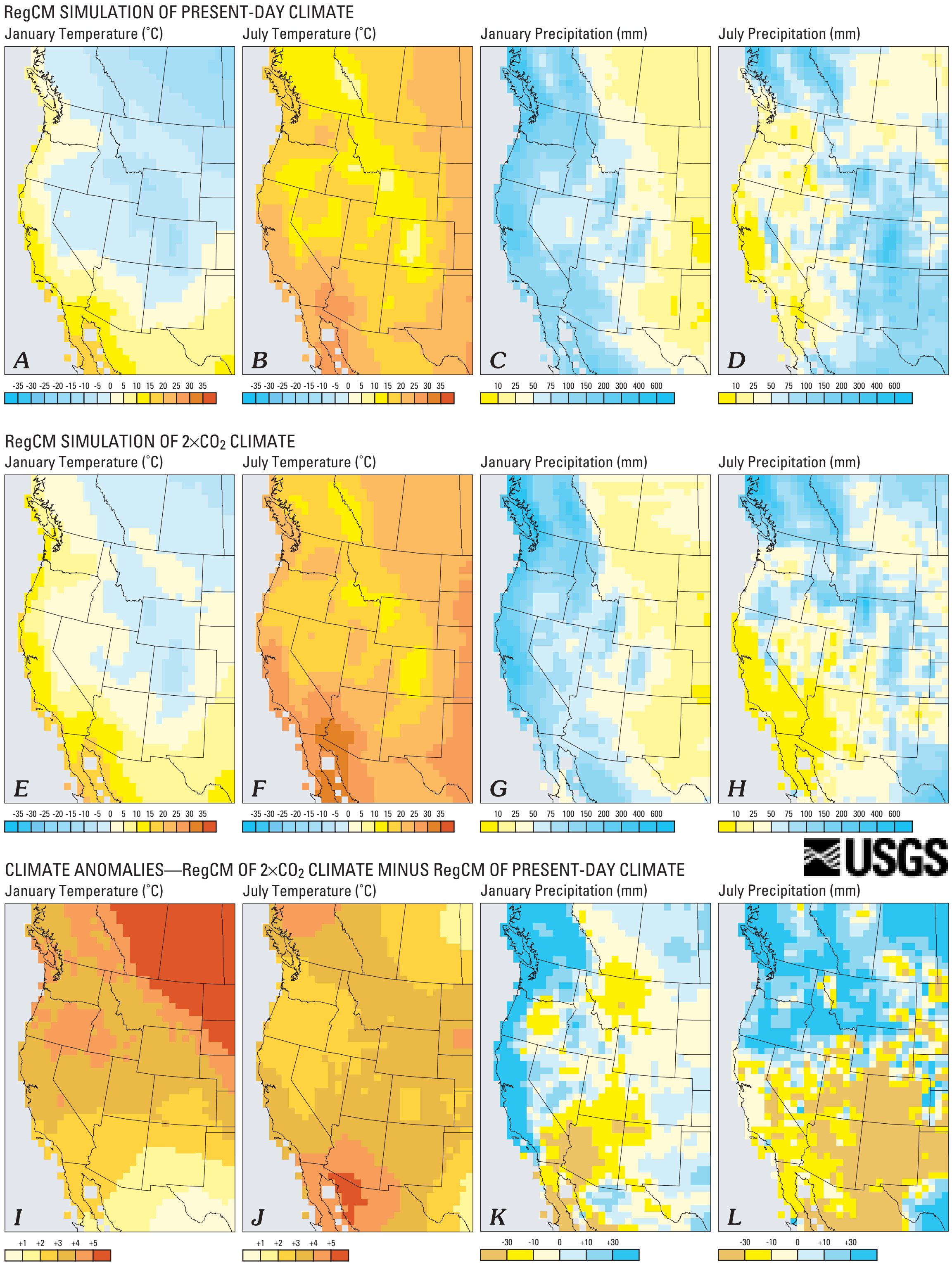
SIMULATED CHANGES IN SURFACE HYDROLOGY

The quantity and quality of water in lakes, reservoirs, streams, and rivers are directly affected by climate and climatic change. Water quantity is determined by net moisture, which, on average, is the difference between what is supplied by precipitation and what is lost to evaporation. Water quality, which is closely associated to water quantity, and climatic fluctuations can affect the temperature and biological and chemical properties of both lakes and rivers.

REGIONAL LAKE RESPONSES

A physically based model of lake temperature and evaporation (Hostetler and Bartlein, 1990) is used to assess the regional and local sensitivity of lakes to climate change. In this experiment, daily averaged meteorological parameters (air temperature, humidity, wind speed, solar radiation, and atmospheric radiation) derived from the RegCM 3-year present-day (control) and 2×CO_2 simulations were used as inputs to the lake model. In response to these initial conditions, the model computes daily average temperature profiles (i.e., the temperature at each meter of depth within the lake), mixing and stratification, evaporation, and, if applicable, ice and snow thickness.

Figure 3 (facing page). RegCM simulation of January and July temperature and precipitation for the present-day climate (*A*–*D*), for the 2×CO_2 climate (*E*–*H*), and the difference (anomalies) between the 2×CO_2 climate and the present-day climate (*I*–*L*). The RegCM present-day climate simulation (*A*–*D*) used the GENESIS simulation of present-day climate (see figs. 2*A*–2*D*) as lateral boundary conditions or inputs, whereas the RegCM 2×CO_2 climate simulation (*E*–*H*) used the GENESIS 2×CO_2 simulation for lateral boundary conditions. The climate anomalies (RegCM of 2×CO_2 climate minus RegCM of present-day climate) are shown in *I*–*L*. The temperature anomalies show greater warming in winter than in summer, with the maximum warming in winter in the interior of the continent (*I*). Precipitation anomalies reveal increases of precipitation in the 2×CO_2 simulation relative to the present-day climate along the West Coast in January (*K*), and in a broad region extending from the Pacific Northwest to the Great Plains in July (*L*), with generally drier conditions simulated elsewhere in the interior. A hint of a stronger summer monsoon in the 2×CO_2 climate is also apparent.


RegCM SIMULATION OF PRESENT-DAY CLIMATE
January Temperature (˚C)
July Temperature (˚C)
January Precipitation (mm)
July Precipitation (mm)
A
B
C
D
-35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35
10 25 50 75 100 150 200 300 400 600
RegCM SIMULATION OF 2×CO2 CLIMATE
January Temperature (˚C)
July Temperature (˚C)
January Precipitation (mm)
July Precipitation (mm)
E
F
G
H
-35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35
10 25 50 75 100 150 200 300 400 600
USGS
CLIMATE ANOMALIES—RegCM OF 2×CO2 CLIMATE MINUS RegCM OF PRESENT-DAY CLIMATE
January Temperature (˚C)
July Temperature (˚C)
January Precipitation (mm)
July Precipitation (mm)
I
J
K
L
+1 +2 +3 +4 +5
-30 -10 0 +10 +30

Regional lake simulations were conducted by sequentially running a lake model at each grid point for the 3-year period, thereby producing a gridded set of simulated lake parameters for the domain. The results presented here are for a hypothetical lake with a surface area of 0.5 km^2 (about 125 acres) and a maximum depth of 5 m (about 16 ft), a size that is typical of many of the smaller lakes throughout the West. The distributions of average annual lake-surface temperatures (figs. 4*A*, 4*E*, 4*I*) reflect the topographic and climatological variations simulated across the Western United States by the RegCM. Simulated water temperatures were generally coldest over mountain ranges and the eastern High Plains and warmest in the Southwest and along the Pacific Coast. Temperatures are warmer over the entire domain for the $2\times CO_2$ simulation (fig. 4*I*), with the greatest warming occurring over the western High Plains northward into the Canadian prairies. Even though lake evaporation increases for the $2\times CO_2$ climate, the net moisture (precipitation minus evaporation) computed over lakes is generally higher (fig. 4*J*) than that calculated for the present-day climate. This increase in net moisture on an annual basis is simulated despite decreases in precipitation and increased temperatures in January and July for the $2\times CO_2$ climate, indicating that precipitation is increased in months not illustrated in this report. The increased warmth for the $2\times CO_2$ climate results in a reduction in the number of days that lakes are ice covered in winter (fig. 4*K*) and the number of days per year that the lakes fully mix (turn over) (fig. 4*L*). Interpreting these regional patterns at a specific lake is complicated by lake-specific factors such as the actual size of the lake, the shape of the lake basin, and water chemistry.

Where present-day lake temperatures are relatively warm, deep lakes usually mix or turn over during the winter when water temperatures cool to near 4°C and the lake becomes more susceptible to convective and wind-driven mixing. Shallow lakes usually mix more than deep lakes. In warm lakes, it has been demonstrated that increased warming results in more stability and, hence, less opportunity for turnover. Because water chemistry, nutrient flux, and biological activity depend on turnover for mixing and redistribution of important nutrients, warmer waters could reduce or eliminate turnover and thus degrade water quality and biological productivity.

The short growing seasons in colder areas today limit lake productivity—in these areas, warmer water temperatures, reduced seasonal ice cover, and little change or slight increase in the number of mixing days associated with the $2\times CO_2$ climate would lead to enhanced lake productivity. Water quality and quantity would not be adversely affected by higher water losses to evaporation because net moisture values are generally more positive for the $2\times CO_2$ climate than they are for the simulated present-day climate.

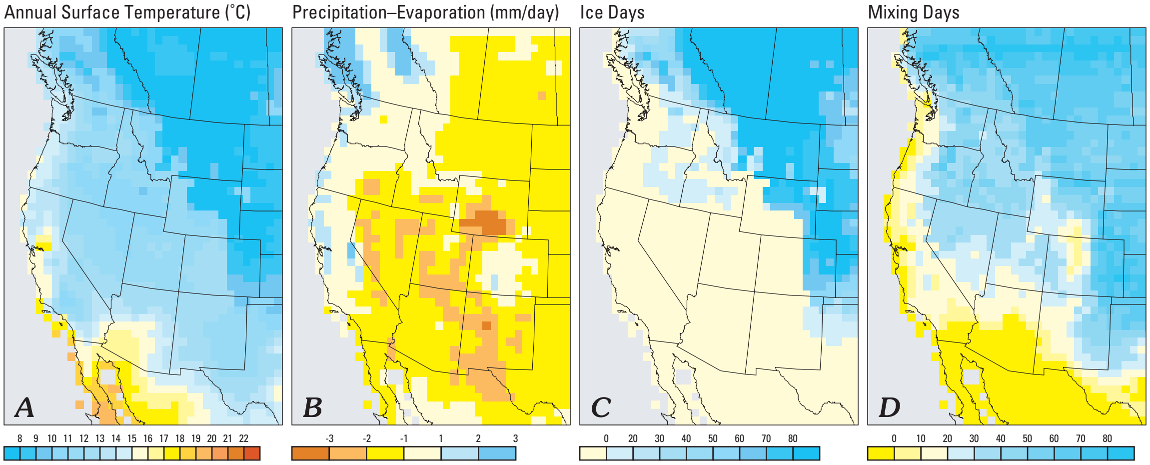
LAKE-SPECIFIC RESPONSES

The lake model described above was applied to Yellowstone Lake, Wyoming, and Pyramid Lake, Nevada—two large lakes of contrasting climatic setting (Hostetler and Giorgi, 1994). For both lakes, 3-year meteorological inputs for the lake model were derived by averaging the output for the four RegCM grid points closest to the lake. Actual depth and areal coverage data for each of the lakes were used in the model runs, which are summarized below.

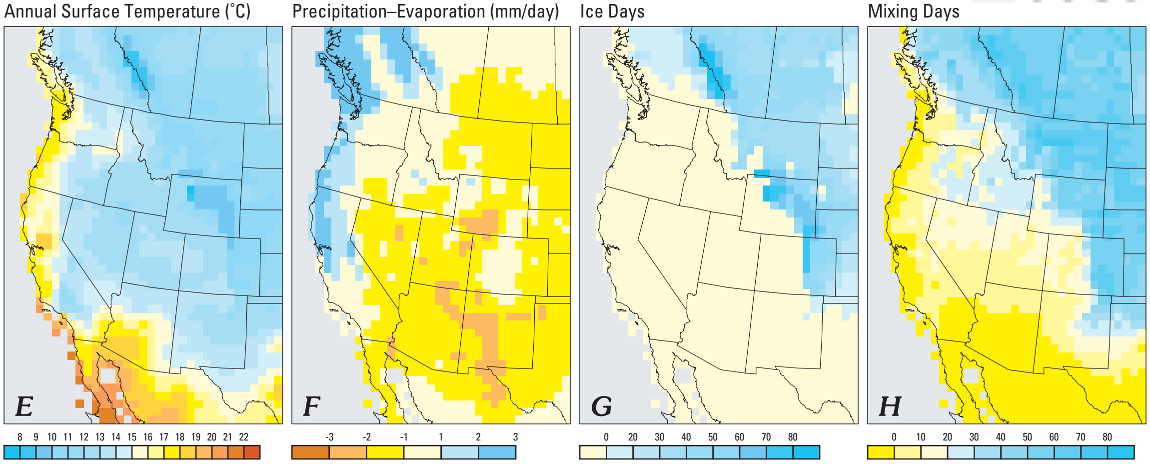
Yellowstone Lake lies within Yellowstone National Park in northwest Wyoming and is the largest (surface area 360 km^2, maximum depth 98 m), high-altitude (2,537 m) freshwater lake in North America. More than 100 tributaries provide water to the lake, which is drained by the Yellowstone River. The lake is relatively cold, covered by ice during winter, and usually turns over before ice forms and after ice melts. The lake is the native habitat of the Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), which is important both as a source of food for wildlife and as a game fish. The 3-year average surface temperature for ice-free periods is 11.6°C for the simulated present-day

Figure 4 (facing page). Maps showing lake conditions under RegCM-simulated present-day climate (*A–D*), lake conditions under RegCM-simulated $2\times CO_2$ climate (*E–H*), and lake responses (lake conditions under RegCM-simulated $2\times CO_2$ climate minus lake conditions under RegCM-simulated present-day climate) (*I–L*) for hypothetical lakes (here, a lake with surface area of 0.5 km^2 and depth of 5 m). Lake conditions calculated by physically based model of lake temperature and evaporation by Hostetler and Bartlein (1990). Annual surface temperatures for lakes are substantially greater across the region under the $2\times CO_2$ climate than under the present-day climate, with lake temperatures as much as 5°C warmer on the northern Great Plains (*I*). Annual precipitation minus evaporation is enhanced across much of the region under the $2\times CO_2$ climate, but drier-than-present-day conditions are simulated for parts of the southwestern deserts and the Great Plains (*J*). Ice days are, in general, reduced under the $2\times CO_2$ climate (*K*). The total number of days of full-depth mixing shows a complex pattern of response—with increases over most of the Great Plains and in parts of Mexico, the Southwest, and along the Pacific Coast (*L*).

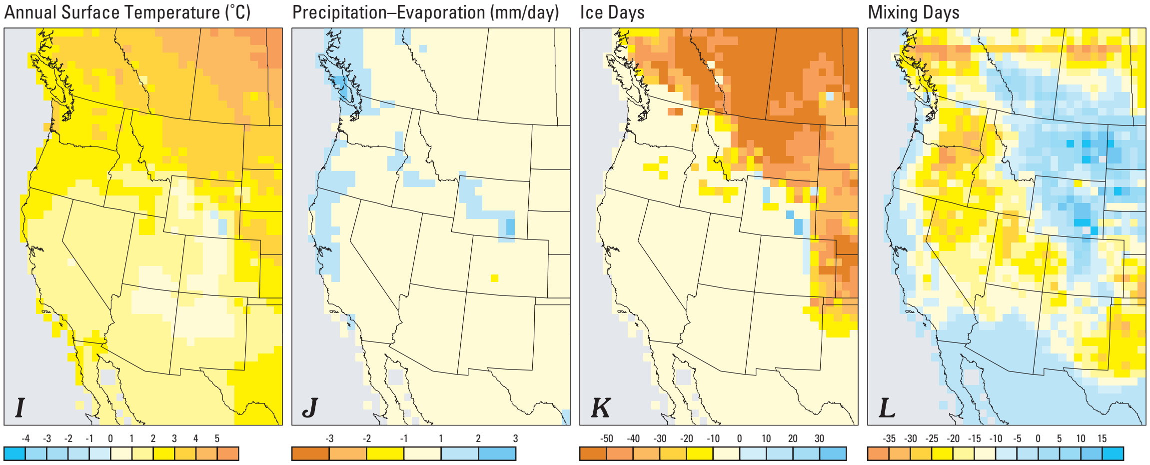
LAKE CONDITIONS—RegCM-SIMULATED PRESENT-DAY CLIMATE



LAKE CONDITIONS—RegCM-SIMULATED 2×CO_2 CLIMATE



LAKE RESPONSES—RegCM-SIMULATED 2×CO_2 CLIMATE MINUS RegCM-SIMULATED PRESENT-DAY CLIMATE



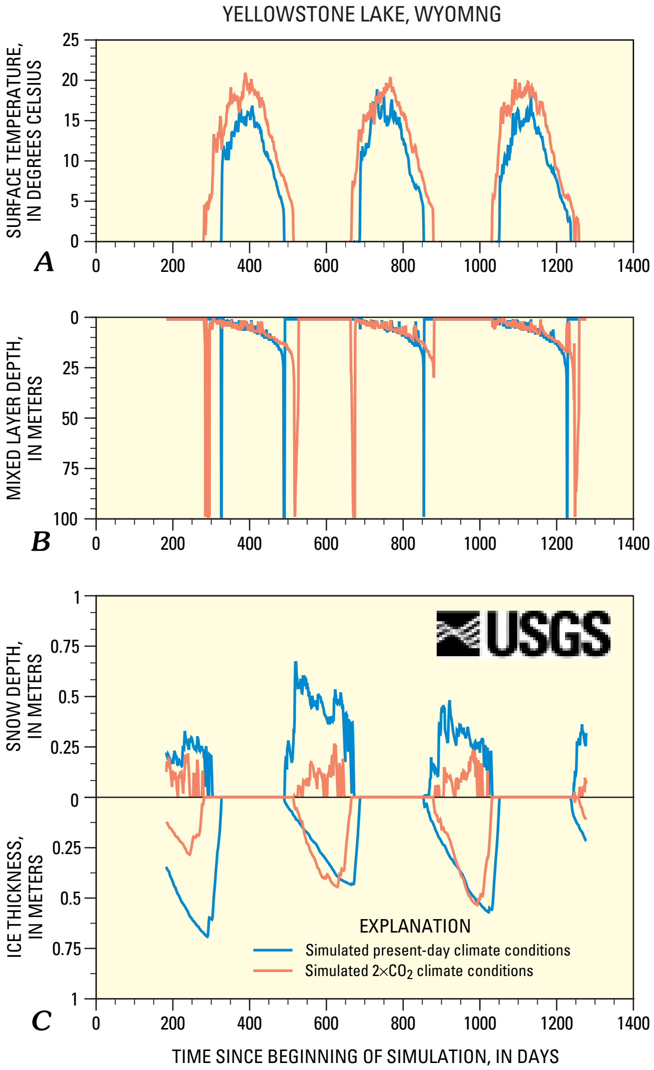


Figure 5. Present-day climate (blue) and 2×CO$_2$ climate (red) simulations for physical characteristics of Yellowstone Lake, Wyoming, during four winters and three summers. Physical characteristics modeled are *A*, surface temperature; *B*, mixed layer depth; *C*, snow depth and ice thickness. When compared to simulated present-day climate conditions, the simulated 2×CO$_2$ climate results in warmer summer water temperatures (+1.6°C), longer ice-free periods (as illustrated by the times of mixing in this dimictic lake), less snow depth in the winter, and generally thinner winter ice. (A dimictic lake has two turnovers or periods of mixing per year.)

(control) climate and 13.2°C for the 2×CO$_2$ climate (fig. 5*A*). The lake changes from being predominantly ice covered (196 days of ice cover) under the simulated present-day climate to being predominantly open (152 days of ice cover) under 2×CO$_2$ climate conditions. The resulting longer growing season, together with increased water supply to the lake (Hostetler and Giorgi, 1994), would lead to increased productivity of the Yellowstone cutthroat trout under the 2×CO$_2$ climate.

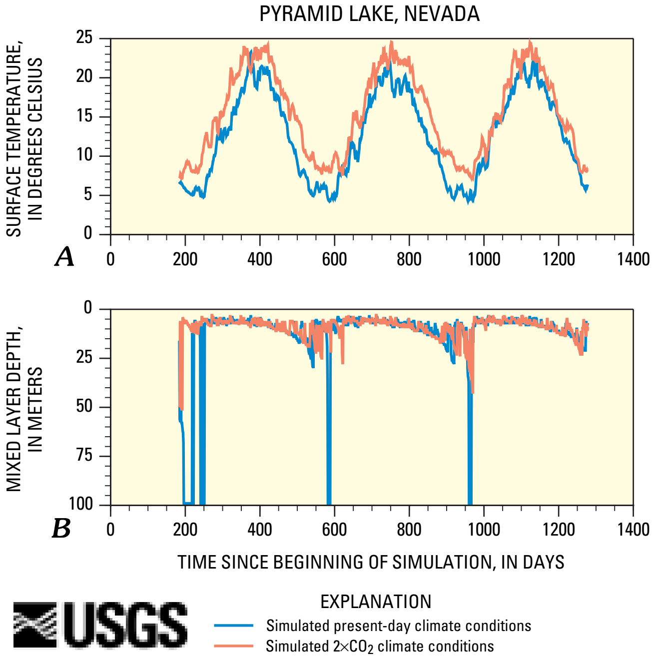


Figure 6. Present-day climate (blue) and 2×CO$_2$ (red) simulations for physical characteristics of Pyramid Lake, Nevada, during four winters and three summers. Physical characteristics modeled are *A*, surface temperature; *B*, mixed layer depth. The simulated 2×CO$_2$ climate results in warmer summer water temperatures than under simulated present-day climate conditions (+2.8°C). Part B of the figure shows that, for this lake, warmer water-surface temperatures (predicted by simulated 2×CO$_2$ climate conditions) have led to a cessation of the overturning process, which would affect the chemistry and biology of the lake. (This has changed the lake from a monomictic lake—one with one yearly turnover or period of mixing—into a lake with no turnovers or pe-

In contrast to Yellowstone Lake, Pyramid Lake is a warm, monomictic (i.e., ice free, with one period of turnover annually), closed-basin (no river outflow) lake located at an altitude of 1,065 m in the high desert that lies within the Paiute Indian Reservation in the lee of the Sierra Nevada. The lake is the native habitat of the Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) and the cui-ui sucker (*Chasmistes cujus*), which are important economic and cultural resources for the Paiute Tribe. The average surface temperature of Pyramid Lake over the 3-year present-day (control) simulation is 12.7°C, compared to 15.5°C under the 2×CO$_2$ climate simulation. The depth of the mixed layer of Pyramid Lake varies seasonally, with turnover occurring in January. Under modeled present-day (control) conditions, turnover of the lake occurred in January for each of the 3 years of simulation (fig. 6); however, under the 2×CO$_2$ climate simulation, turnover did not occur in any of the 3 years as a result of warming in the upper 30 m of the lake's waters. The average annual evaporation rate

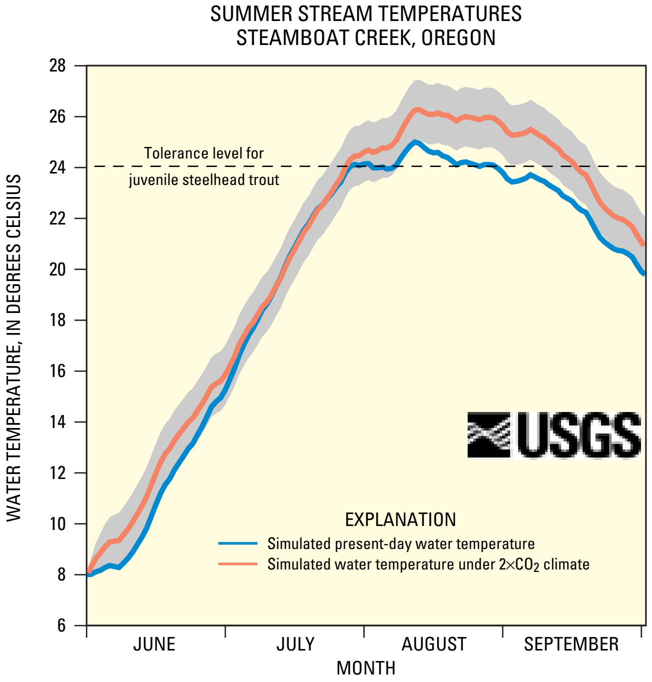


Figure 7. Simulated summer stream temperatures under present-day climate (control, in blue) and simulated temperatures under 2×CO_2 climate (red) of Steamboat Creek, Oregon. The dashed horizontal line at 24°C on the “water temperature” axis indicates the summer temperature tolerance limit of juvenile steelhead trout (*Oncorhynchus mykiss*). Under the 2×CO_2 climate simulation, the statistical model of Hostetler (1991) suggests that the length of time within the year when the tolerance limit is exceeded is more than twice as long as under simulated present-day climate conditions (control). Shaded area surrounding 2×CO_2 temperature curve indicates one standard deviation (σ) from the mean.

computed for the 2×CO_2 climate (1,595 mm) is 14 percent higher than that calculated for the modeled present-day climate. However, as in the case of Yellowstone Lake, increased precipitation in the 2×CO_2 climate simulation resulted in a net increase in moisture over the lake. The lack of turnover under the 2×CO_2 simulation would result in reduced productivity, which could have large negative effects on the fish populations in the lake.

STREAMFLOW

Streamflow models are still under development, generally stream-specific, and not yet capable of being applied on a regional scale. In addition, in some areas a substantial portion of river water is derived from ground water, and ground-water flow models are difficult to implement in the Western United States where complex topography and geology determine recharge areas and subsurface flow patterns. Nonetheless, it is still possible to demonstrate the potential sensitivity of specific streams to climate change, such as at Steamboat Creek, Oregon, which lies in a forested watershed on the western slope of the Cascade Mountains. Steamboat Creek and its tributaries provide important spawning and rearing habitats for native steelhead trout

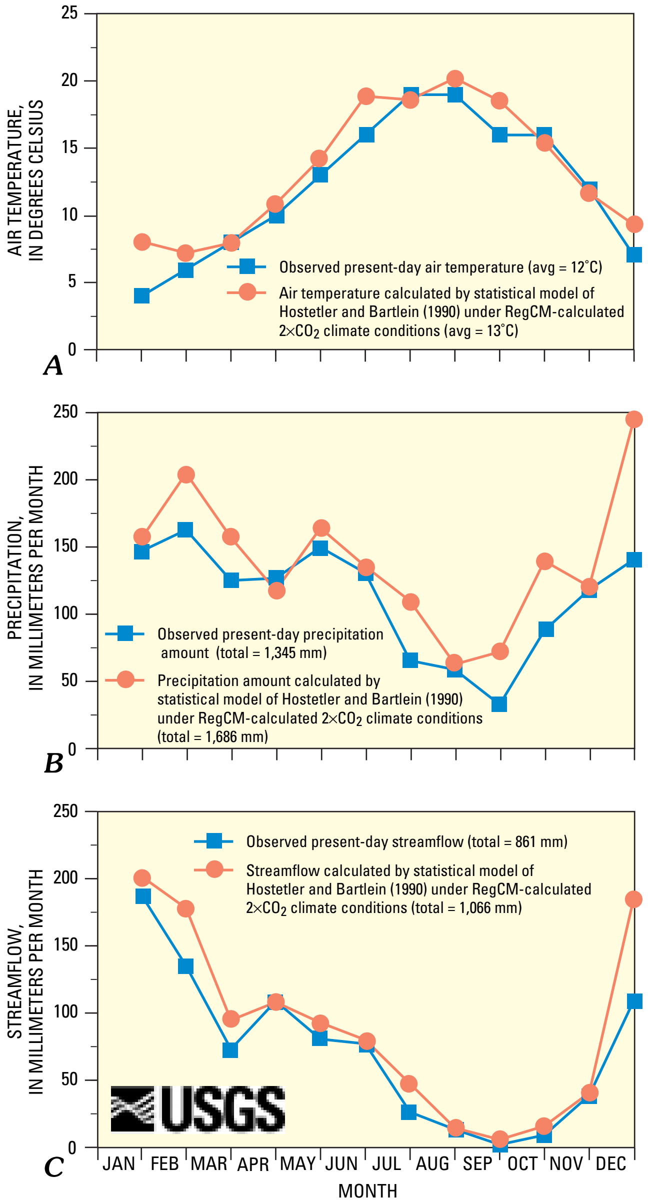


Figure 8. Comparisons of present-day (control, in blue) and 2×CO_2 (red) air temperature (*A*), precipitation (*B*), and streamflow (*C*) simulations of Steamboat Creek, Oregon. In this case, the simulated annual air temperature of the drainage rises only 1°C. However, the simulated air temperature during the summer period of minimum flow is 3°C higher in the 2×CO_2 simulation than in the control simulation. The 2×CO_2 simulation has higher precipitation levels than in the control simulation—hence, streamflow increases under the 2×CO_2 simulation and shifts slightly seasonally. The change in streamflow lags the temperature and precipitation changes by a month or more, probably due to the time required for soil moisture to respond to changes in climate.

(*Oncorhynchus mykiss*). During part of July and August, present-day average maximum stream temperatures are often near the upper limit of tolerance (24°C) for juvenile steelhead trout (fig. 7).

A statistical model of stream temperature (Hostetler, 1991) provides quantitative estimates of the change in summer water temperatures in this stream in response to climate simulated by RegCM. Although the annual average air temperature of the Steamboat Creek drainage was only about 1°C warmer for the simulated $2\times CO_2$ climate than for the control case (RegCM-simulated present-day conditions) (fig. 8), it was as much as 3°C warmer during the minimum flows of the summer. Precipitation increased 25 percent annually for $2\times CO_2$ climate relative to simulated present-day conditions. As a result of this increase in precipitation and change in air temperature, streamflow increased and is shifted slightly seasonally (fig. 8*C*). During summer, the effect of higher air temperatures on water temperatures was not offset by increased flow and maximum stream temperatures—stream water temperatures calculated for the $2\times CO_2$ climate exceeded the tolerance level of steelhead trout for a period more than twice as long as the simulated present-day average (fig. 7). Relatively small changes in climate could thus lead to significant degradation of spawning habitat. The potential for natural warming implies that, if the steelhead trout's habitat is to be maintained, land-use decisions in the Steamboat Creek basin will need to be based on extensive analysis of the effects of both natural climate variability and human modifications.

SIMULATED CHANGES IN PLANT DISTRIBUTIONS

The geographic ranges of plant species are controlled by climate change—in this section, we explore potential changes in the distributions of selected western plant species due to future climate change. Following the methods described in Lipsitz (1988) and Bartlein and others (1994), we interpolated present-day climatic data onto a 15-km equal-area grid of the Western United States to provide a fine-scale basis for the exploration of potential changes in plant distributions (fig. 9). The differences between the RegCM-simulated present-day climate and the RegCM-simulated $2\times CO_2$ climate were applied to this target grid to provide inputs into vegetation models simulating potential changes in plant distributions that would occur when comparing present-day and potential future climates.

PRESENT-DAY CLIMATE AND PLANT DISTRIBUTIONS

Bartlein and others (1994) prepared an equal-area 25-km grid of 30-year climate "normals" for North America. January and July temperature and precipitation data from this grid were used in the analyses presented below. GSMAP software (Selner and Taylor, 1992) was used to digitize maps of tree distributions (Little, 1971, 1976) and to determine which of the 32,211 points in the North American climate grid were within the geographic range of the each taxon and which were outside of this range. The presence/absence data were matched with temperature and precipitation data to determine the present-day relationships between plant distributions and climate (Thompson and others, in press). The distributions of 16 common western trees and shrubs (table 2) are analyzed for the present study. Scatter diagrams (fig. 10) illustrate the climatic tolerances of four of these plants in terms of seasonal temperature and precipitation. For example, Sitka spruce lives where January mean temperatures are above –10°C and mean July temperatures are below 20°C. In contrast, Douglas fir lives under a wide variety of temperature regimes, and the frost-sensitive species, California white oak and Joshua tree, live where mean January temperatures are above freezing. Sitka spruce is largely limited to sites with very high levels of January precipitation and relatively low levels of July precipitation. Douglas fir lives in a range of seasonal precipitation regimes, whereas California white oak lives in areas with high winter precipitation and pronounced summer drought. Joshua tree lives in very dry climates where winter precipitation tends to exceed that of summer.

COMPARISON OF PRESENT-DAY AND POTENTIAL FUTURE RANGES

The relationships illustrated in figure 10 can be analyzed statistically to produce derived presence/absence response surfaces (e.g., Bartlein and others, 1986) that determine the probability of occurrence for each plant for a given combination of seasonal temperature and precipitation characteristics. These statistical relationships can then be used with observed climate data to estimate the present-day range of the species. The relationships can also be used with climate-model output to simulate the potential future range of the plant. Figure 11 shows the simulated present-day and potential future ranges of the four plants discussed above. In the left-hand illustration of each row (figs. 11*A*, 11*E*, 11*I*, 11*M*) is shown the observed present-day range of the plant on the 15-km target grid. For comparison, the next illustration to the right (figs. 11*B*, 11*F*, 11*J*, 11*N*) shows the probability of occurrence of the species produced by response-surface analysis of the observed present-day climatic and plant-distribution data. In most cases, the present-day range is aligned with approximately the 0.4 probability of occurrence. The third illustration from the left (figs. 11*C*, 11*G*, 11*K*, 11*O*) illustrates the simulated probability of occurrence for the same taxa under the $2\times CO_2$ climate simulation interpolated onto the 15-km target grid. The right-hand illustrations (figs. 11*D*, 11*H*, 11*L*, 11*P*) illustrate changes in the distribution of each species at the 0.4

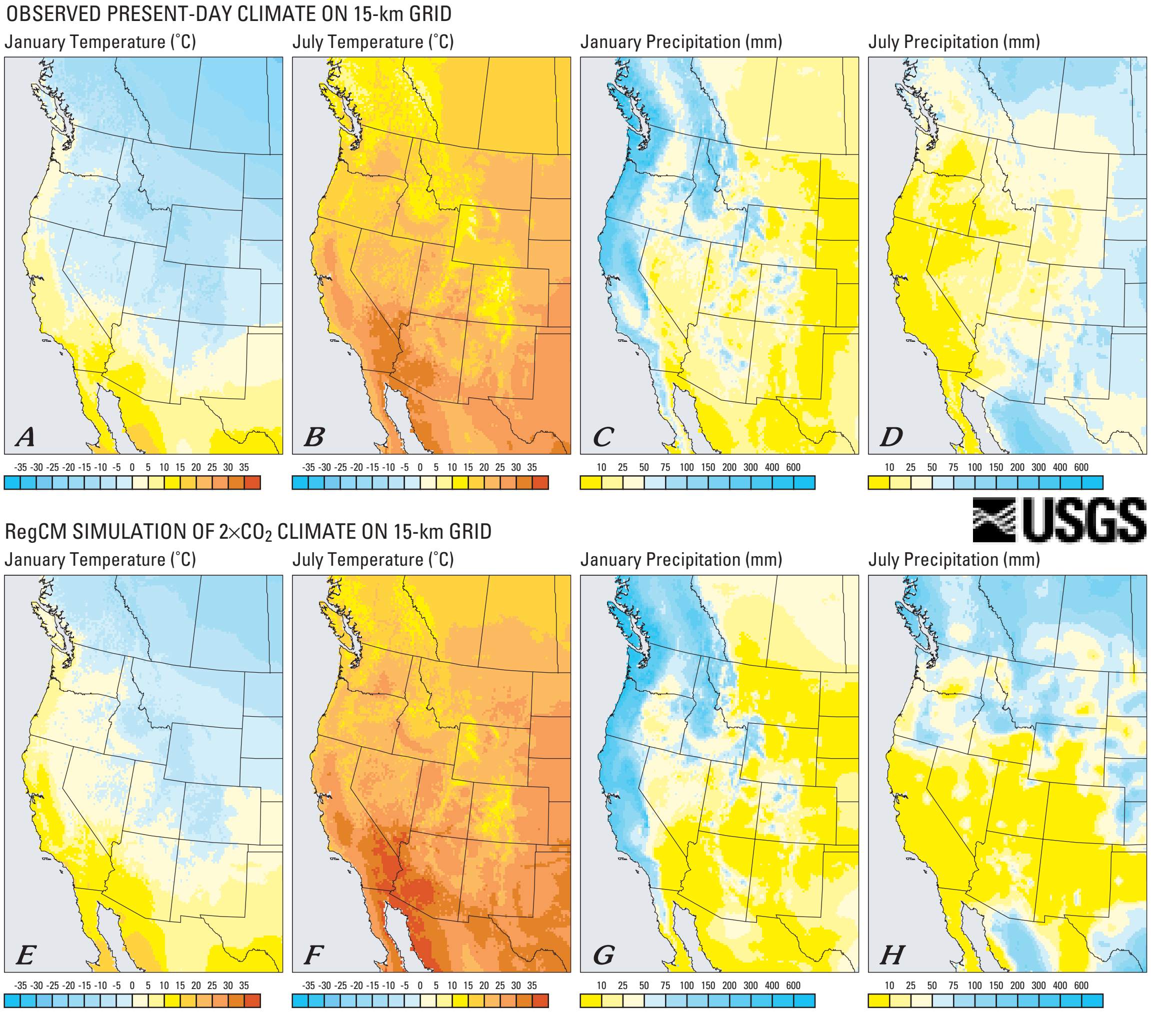


Figure 9. Observed present-day (*A–D*) and simulated 2×CO_2 (*E–H*) climates illustrated on 15-km grid. These latter values were formed by interpolating the RegCM climate anomalies (see bottom row of fig. 3) onto the 15-km grid and adding interpolated values to present-day values.

probability level between the present-day simulated distribution and the distribution calculated for the 2×CO_2 climate. In this case (i.e., the right-hand illustrations of the figure), green represents areas occupied by the species under both the present-day and 2×CO_2 climate simulations, red represents range lost by the species between the present-day and 2×CO_2 simulations, and blue represents new areas that could potentially be colonized by the species under the 2×CO_2 climate simulation. In the examples presented here, all of the four species could potentially increase their total coverage, although not necessarily within or adjacent to their current range.

Figure 12 illustrates potential range changes that could occur under the 2×CO_2 climate simulation. Here the habitats of plants along the Pacific Coast from northern California to British Columbia (Sitka spruce, western red cedar, western hemlock) are reduced slightly, but new habitat develops in the northern interior (figs. 12*A*, 12*B*, 12*C*). Incense cedar nearly dies out in its current range in California and Oregon, but potential habitat opens up in the present-day steppe environment of the Four Corners region (fig. 12*D*). Under this scenario, major forest trees and range shrubs (Engelmann spruce, Douglas fir, lodgepole pine, and big sagebrush) die off across much of their present-day range without much replacement habitat becoming available (figs. 12*E*, 12*G*, 12*M*). Ponderosa pine would lose much of its western range and find new potential habitat east of its present-day limits (fig. 12*H*). California white oak and Oregon white oak could potentially grow under a 2×CO_2 winter-wet summer-dry climate in the Southwest (figs. 12*I*, 12*J*). Gambell oak and pinyon pine would die off in the Southwest, but could potentially find new range in the northern interior (figs. 12*K*, 12*L*). Joshua tree and creosote bush, two shrubs adapted to arid conditions, would considerably expand their spatial

Table 2. Common and scientific names of plant species with simulated present-day ranges and potential ranges under a simulated 2×CO_2 future climate.

[The 15-km grid used in this study has 23,961 cells in western North America. "Present number" and "2×CO_2 number" are the number of those cells occupied by the species at the 0.40 level of probability for the present-day and potential future climate simulations, respectively. "Percent of present coverage" represents the percentage increase or decrease of the taxon under the future climate scenario compared to the present-day simulation (present-day range = 100 percent)]

Common name	Scientific name	Present number	2× CO_2 number	Percent of present coverage
Sitka spruce	*Picea sitchensis*	493	1,033	210
Western red cedar	*Thuja plicata*	1,010	1,143	113
Western hemlock	*Tsuga heterophylla*	945	1,185	125
Incense cedar	*Libocedrus decurrens*	517	1,103	213
Engelmann spruce	*Picea engelmannii*	3,387	566	17
Douglas fir	*Pseudotsuga menziesii*	4,898	2,474	51
Lodgepole pine	*Pinus contorta*	4,350	1,508	35
Ponderosa pine	*Pinus ponderosa*	2,319	3,147	136
Oregon white oak	*Quercus garryana*	626	1,330	212
California white oak	*Quercus lobata*	447	3,322	743
Gambel oak	*Quercus gambelli*	753	959	127
Pinyon pine	*Pinus edulis*	974	935	96
Big sagebrush	*Artemisia tridentata*	5,733	2,356	41
Joshua tree	*Yucca brevifolia*	187	1,482	793
Creosote bush	*Larrea divaricata*	3,891	6,235	160
Saguaro	*Cereus giganteus*	626	806	129

coverage relative to today under the 2×CO_2 simulation (figs. 12*N*, 12*O*). Saguaro, a frost-limited, dry-adapted plant of the Sonoran Desert, would largely die off in its present-day range, but could potentially find new range farther east and at higher elevations (fig. 12*P*).

If dispersal rates and (or) human intervention allowed these plants to reach their new potential habitats, how large would the changes be in the coverage of each species? Joshua tree and California white oak have potential future ranges under the 2×CO_2 simulation that would cover more than seven times their current total area (table 2). Incense cedar, Oregon white oak, and Sitka spruce would expand to more than twice their current areal extents; and creosote bush, ponderosa pine, and saguaro would have somewhat greater-than-present-day coverage, although generally not within their current range limits. Western hemlock and western red cedar could occupy modest amounts of new range near their present-day limits, whereas Gambell oak and pinyon pine would have slightly larger and slightly smaller coverages, respectively—but these species would have to disperse hundreds of kilometers northward to reach their new habitats. Douglas fir, big sagebrush, and lodgepole pine would have half or less of their present-day extents, whereas Engelmann spruce would have less than one-fifth of its present-day areal coverage. Could some of the forest trees have potential habitat north of the 15-km target grid under the 2×CO_2 climate simulation? This is probably not the case—if potential habitat existed north of the target grid, it would be logical to assume that the species would be surviving in cool habitats in higher elevations on the northern edge of the grid. Inspection of the output (fig. 12) indicates that this is not the case. The surviving trees are instead located in the lower elevations in this region.

DISCUSSION OF CHANGES IN PLANT DISTRIBUTIONS

The range changes simulated to occur between today and the 2×CO_2 climate would dramatically affect ecosystems across the Western United States. Similarly large shifts in plant distributions have been simulated for a potential 2×CO_2 climate in Europe (Dahl, 1990; Huntley and others, 1995; Sykes and others, 1996). The plant species modeled

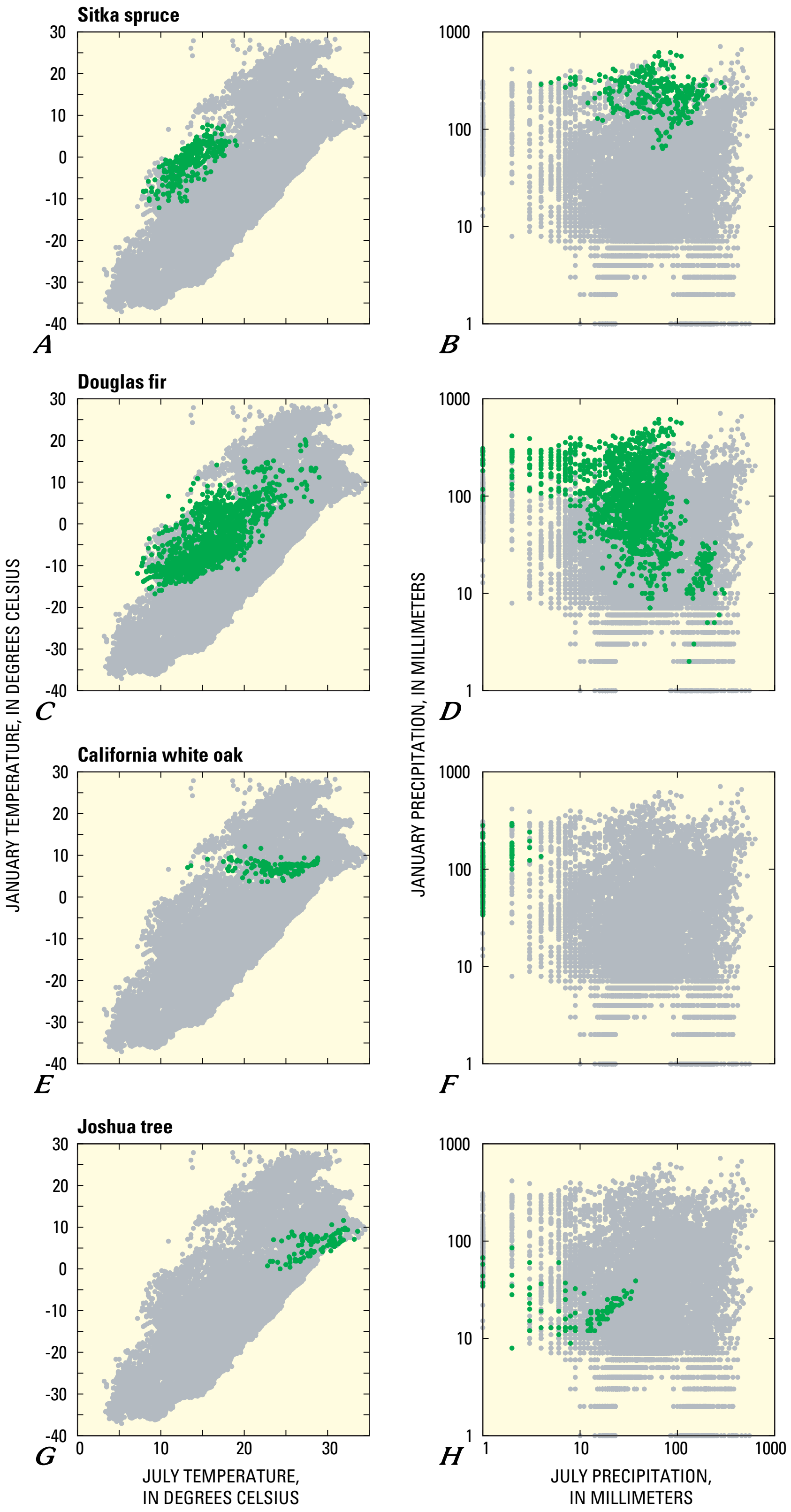


Figure 10. Bivariate scatter plots of January vs. July temperature (left column) and January vs. July log precipitation (right column) showing presence/absence data (green and gray, respectively) for four plant species in western North America. These illustrations depict the unique climatic adaptations of various tree species in western North America. Sitka spruce (*A*, *B*), a tree of the moist Pacific Northwest coast, lives in some of the wettest winter climates on the continent under January temperatures between –10°C and +10°C and July temperatures between 5°C and 20°C. Douglas fir (*C*, *D*) lives under a broad band of seasonal temperatures and precipitation conditions. California white oak (*E*, *F*) is restricted to environments west of the Sierra Nevada in California and lives under a fairly wide range of July temperatures but a very narrow band of January temperatures. This tree receives essentially all of its moisture in the winter and lives under pronounced summer drought. Joshua tree (*G*, *H*), an arborescent yucca of the Mojave Desert, lives in places where summers are extremely hot and winters are rarely below freezing. It survives in very arid environments.

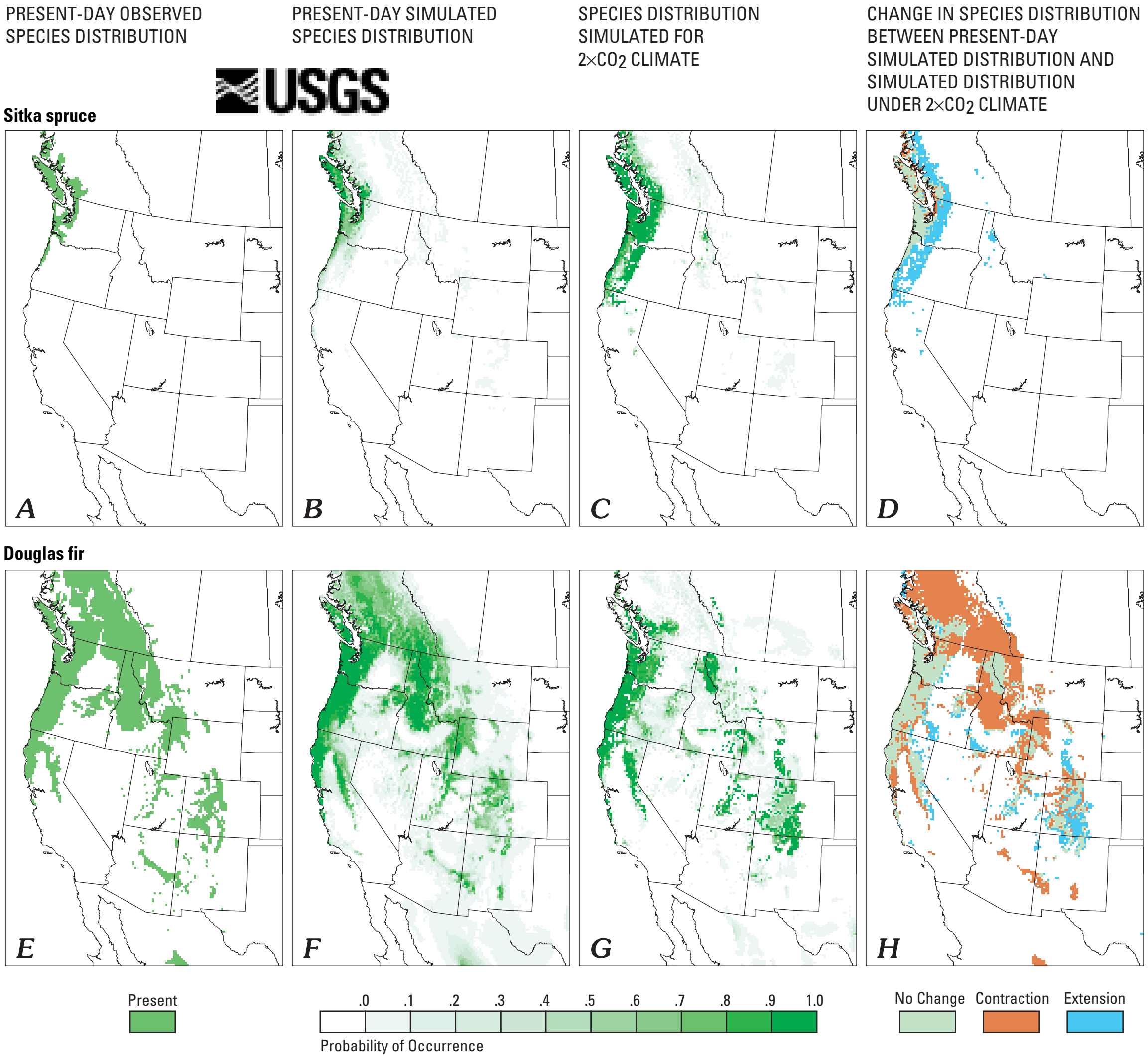
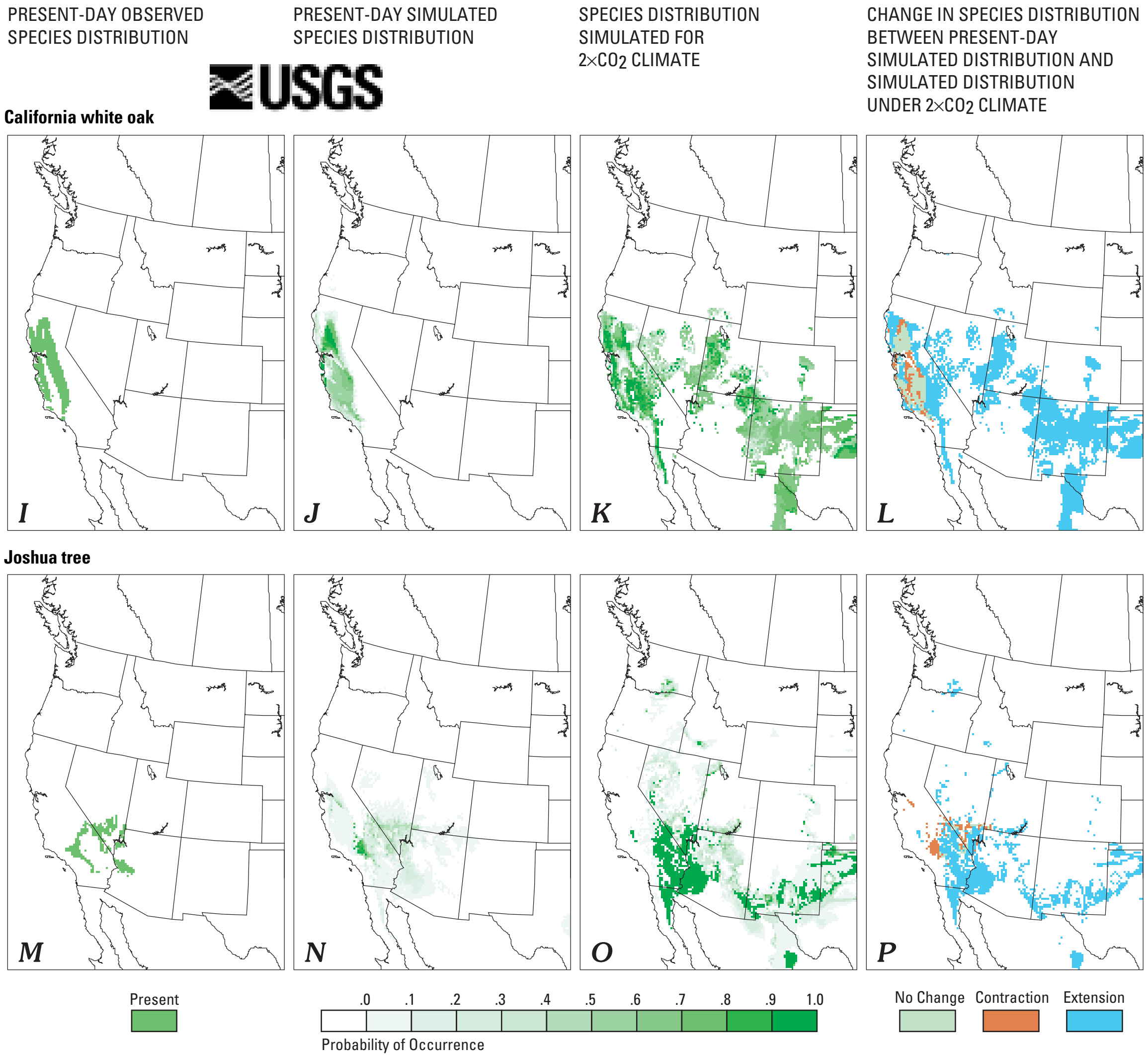


Figure 11 (above and facing page). Maps of plant-species distributions showing, by column from left to right, observed present-day distributions (*A*, *E*, *I*, *M*) (Little, 1971, 1976), simulated present-day distributions at 0.4 probability of occurrence (*B*, *F*, *J*, *N*), simulated distributions for 2×CO_2 climate at 0.4 probability of occurrence (*C*, *G*, *K*, *O*), and changes in species distribution between simulated present-day distribution and simulated distribution under 2×CO_2 climate (*D*, *H*, *L*, *P*). Species shown are Sitka spruce (*A*–*D*), Douglas fir (*E*–*H*), California white oak (*I*–*L*), and Joshua tree (*M*–*P*). Comparison of the simulated present-day distributions with observed present-day distributions demonstrates that the presence/absence response surface methodology captures the overall distribution pattern of all of the species. Comparison of the simulated present-day distributions and the simulated 2×CO_2 distributions illustrates the potential range shifts that could occur if species were able to migrate rapidly enough to reach their new potential habitats during the transition from the present-day climate to a 2×CO_2 climate. The right-hand columns of maps (*D*, *H*, *L*, *P*) show these shifts more directly—green represents sites where species live today and where they could continue to live under the simulated 2×CO_2 climate; red indicates sites where species live today but could not survive under the simulated 2×CO_2 climate; blue represents sites where species cannot live today but could potentially live under the simulated 2×CO_2 future climate.

here exhibit individualistic responses to climatic change, as has been demonstrated in the response of western plants to warming following the end of the last Ice Age (Thompson, 1988; Betancourt and others, 1990; Thompson and others, 1993). In the latter case, warming was relatively gradual and plants had thousands of years to disperse from their old ranges to new ones. In contrast, the anticipated onset of "greenhouse" warming may occur in only a few decades, and it is unknown whether or not displaced plants and animals could migrate to new habitats this rapidly. Many widespread taxa would lose much of their current range under the 2×CO_2 climate, whereas other presently uncommon taxa could greatly expand their ranges (table 2). Similar post-Ice-Age patterns have been documented in packrat midden plant



assemblages, illustrating the transition from Pleistocene to Holocene vegetation in the American Southwest (Thompson, 1988). For example, pinyon pine (*Pinus edulis*) was relatively rare during the last Ice Age, whereas papershell pinyon pine (*Pinus remota*) was common (Van Devender, 1990), a situation that reversed during the transition from Pleistocene to Holocene conditions.

The economic impacts of projected changes in vegetation for the 2×CO$_2$ climate could be substantial. Many forest trees, such as Engelmann spruce and lodgepole pine, could be driven to the edge of extinction. The habitats of National Parks, Bureau of Land Management (BLM) lands, and Native American lands would be strongly affected by these and other associated changes (e.g., Bartlein and others, 1997). Land managers could be faced with deciding if they should be protecting the land or the ecosystems presently occupying the lands. The hierarchy of climate and process models used here provides detail and geographic scope unavailable from the current generation of AGCM’s and employs embedded physics and process models that enhance the regional depiction of climate change. Analyses such as this provide a means for land-resource managers to identify and assess elements of ecosystems that are sensitive to climatic variability and climate change.

CONCLUSIONS

The use of a hierarchy of atmospheric and process models enables us to assess the effects of global climate change at the scale of landscape-scale processes. In this example, regional climate, hydrology, vegetation, and wildlife resources are affected by simulated global climate change. However, not all possible simulated or actual future climates would necessarily have the same environmental effects. Our strategy does provide a methodology for quantifying the response to a range of possible climatic changes on national lands and resources and may serve to identify regions and processes that are most vulnerable to these changes.

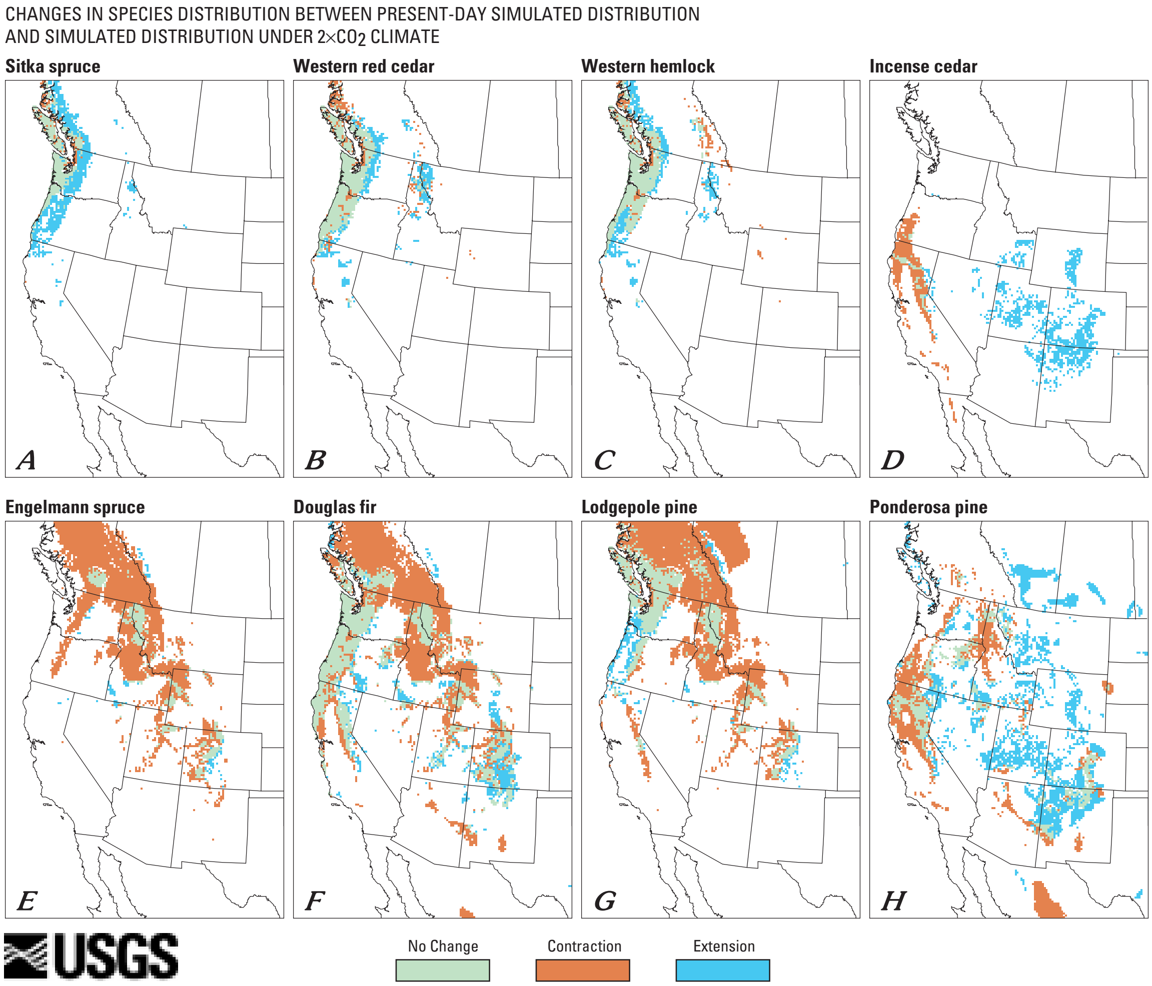


Figure 12 (above and facing page). Maps showing potential changes in distributions between simulated present-day distributions and simulated distributions under 2×CO_2 climate that could occur for 16 tree species in western North America. Green represents sites where a species lives today and where it could continue to live under the simulated 2×CO_2 climate. Red indicates sites where a species lives today but could not survive under the simulated 2×CO_2 climate. Blue represents sites where a species cannot live today but potentially could live under the simulated 2×CO_2 future climate. All species show some change in potential distribution, although, in some cases, these changes are relatively small (such as those for Sitka spruce (*A*), western red cedar (*B*), and western hemlock (*C*), each of which has a general expansion of their ranges in the Pacific Northwest and into the Northern Rocky Mountains). In other cases, there are large changes in the potential distributions of some taxa (i.e., Gambell oak (*K*), incense cedar (*D*), and pinyon pine (*L*)). Some taxa with rather restricted distributions at present become widespread (i.e., Joshua tree (*N*)), whereas others with widespread present-day distributions become restricted under a 2×CO_2 climate scenario (i.e., lodgepole pine (*G*) and Engelmann spruce (*E*)). The changes illustrated by these maps are specific to the particular set of climate simulations used here but are probably representative of the kinds of general changes that may occur.

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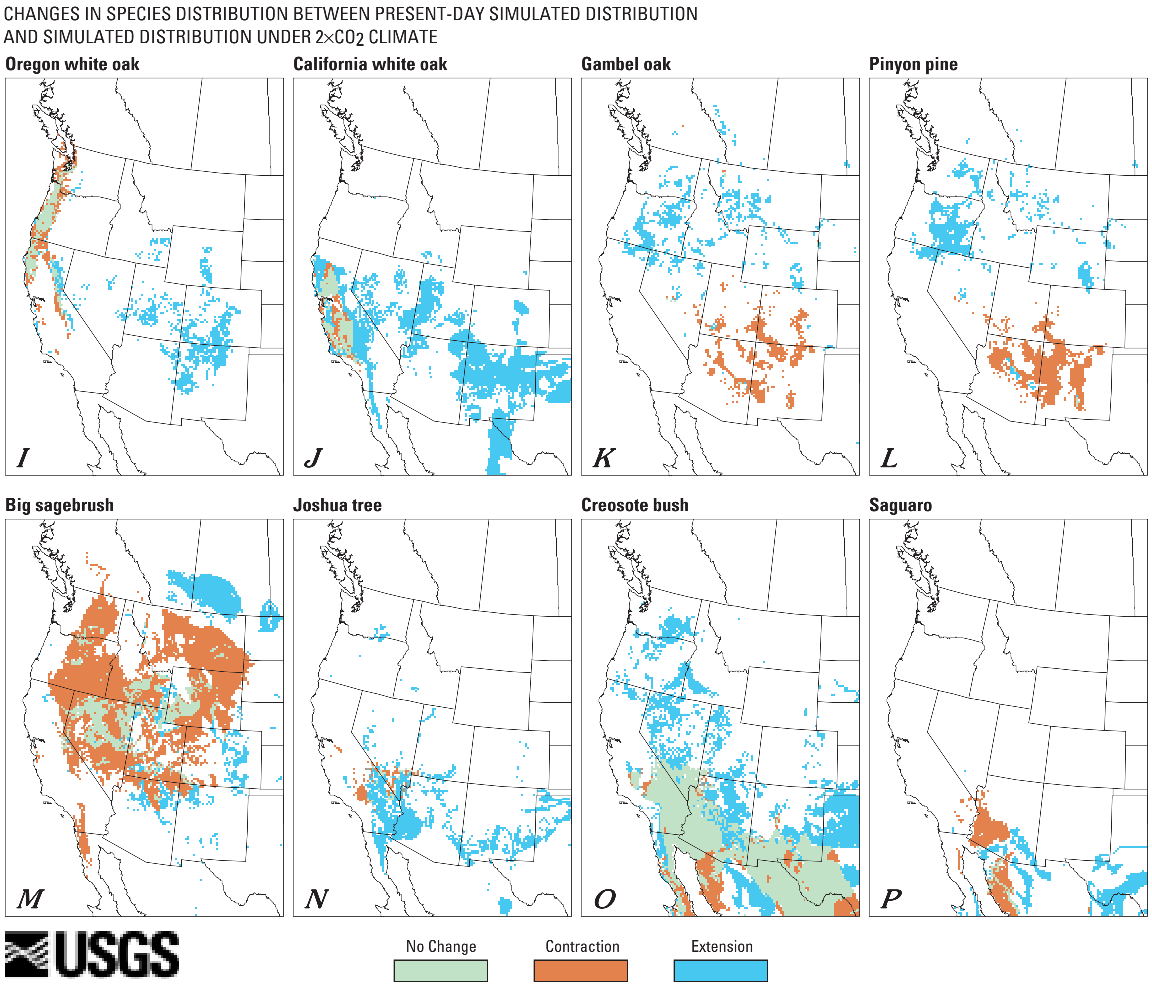

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