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Integrated Research on Climate Change in Mountain Ecosystems: The CLIMET Project

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Introduction

Mountain ecosystems provide numerous services, such as regional freshwater supplies, but are potentially sensitive to climatic shifts because of their topographic complexity and strong environmental gradients. Like the Arctic and Antarctic regions, the higher elevations of many mountain systems have experienced relatively greater climatic change over the past several decades than lowland systems (Bradley et al, 2004). Studying climatic change impacts to relatively intact mountain protected areas offers the opportunity to better understand the mechanisms underlying ecological responses and to monitor rates of change without the confounding effects of land-use/land-cover changes that are typical of managed areas. As the regional landscapes around them change, mountain protected areas, such as national parks, become increasingly important to society as biodiversity reserves and engines of economic growth through tourism. What happens to mountain protected areas under future climate change matters more to regional human populations now than it did in the past.

Studying mountain ecosystems explicitly requires interdisciplinary and integrated approaches. A global change research programme was established in a variety of national parks of the US national park system in 1991 following an extensive competitive process that evaluated needs of multiple stakeholders from the national scale to the local park manager and community. Glacier National Park, Montana and Olympic and North Cascades National Parks, located in Washington, were among the first areas to be part of the national programme (see Figure 14.1). Research in each of these areas emphasized different ecosystem components and used different approaches to identify and understand mountain ecosystem responses to climatic variability and change to better equip managers for future decision-making. In 1998, the research programmes were merged to examine how different mountain ecosystems respond to climate change along a gradient of precipitation, landscape fragmentation and other factors from the Pacific Ocean to the Great Plains (Fagre and Peterson, 2000).

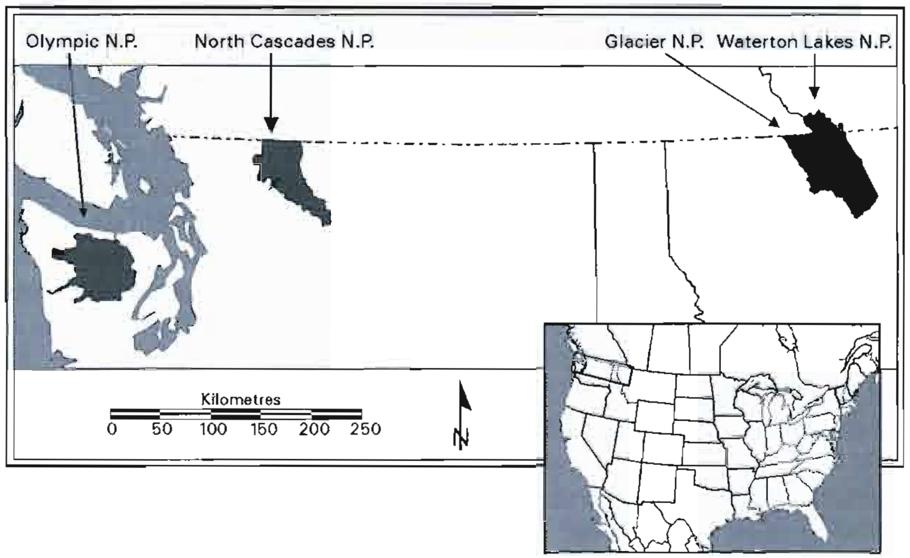

Figure 14.1 Location of CLIMET area

Note: Studies were focused on national parks along a longitudinal gradient from marine to continental climate

The Climate Landscape Interactions – Mountain Ecosystem Transect (CLIMET) uses an interdisciplinary approach to: first, document climatically-driven changes to natural resources; second, understand underlying mechanisms of change; and third, project potential future changes to mountain ecosystems. Guided by a common set of research questions and using standard protocols across all CLIMET locations, biophysical responses to climatic variability and change are explicitly identified, compared and used to inform specific management issues. We can expect non-linear responses in different regional settings with different sensitivities, with abrupt changes when thresholds are exceeded. For example, the response to a 10 per cent precipitation increase may hardly be detectable in the temperate rainforest of the western Olympic Peninsula, while the same 10 per cent precipitation increase may enhance vegetative productivity in the arid plains east of the North Cascade Range. Finally, regionally scaled assessments are relevant both to management policy for the Columbia River system that receives water from numerous mountain systems, and upon which millions of people depend, and to evaluation of future wildland fire risk, an issue that is receiving the highest priority in the CLIMET area and the American West.

Description of CLIMET area

The CLIMET project was developed to investigate the influence of climatic variability on a transect of three distinct mountain bioregions, with large mountain national parks as core research sites, from the Pacific Coast to the Rocky Mountains. CLIMET crosses three parallel mountain ranges along 1000km of the US–Canada border, centred on Olympic National Park (maritime climate), North Cascades National Park (intermediate) and Glacier National Park (continental climate). These are large, wilderness-dominated parks with minimal human disturbance and infrastructure. All are snow-dominated environments, have extensive coniferous forests, and numerous alpine glaciers and perennial snowfields. Precipitation gradients are steep with wet western aspects and dry eastern environments. Landscape fragmentation is extensive outside Olympic National Park, with forest removal occurring up to the park boundary. Glacier National Park, on the other hand, is embedded in a matrix of national forest wilderness-designated lands, Indian reservations, and, to the north, Canadian national and provincial parks. Most native flora and fauna still thrive in each national park, and hydrologic processes are unimpeded by dams or diversions.

The CLIMET integration approach

The design of the CLIMET project is built on the premise that interdisciplinary research is needed to address most issues in climate change science. This approach requires that scientists from different disciplines and with different perspectives work together in designing studies, collecting data and making interpretations. CLIMET uses the following integration approach to address climate change issues:

- develop a cadre of scientists, students and other cooperators with a common interest in the effects of climate change on natural resources;
- synthesize existing data on climate, biology and hydrology from the three CLIMET regions;
- collect data on climate, biology and hydrology in key watersheds in each of the three CLIMET regions;
- use appropriate modelling techniques to synthesize data and quantify the effects of climate change on natural resources;
- apply research results and inferences to specific resource issues by working with land managers, and by disseminating information to stakeholders.

Interdisciplinary cadre

The CLIMET research team consists of scientists from the US Geological Survey, US Department of Agriculture (USDA) Forest Service and many universities. Individuals on the team have expertise in forest ecology, paleoecology, hydrology and atmospheric science. Graduate students are key members of the team and provide leadership in empirical data collection. Annual meetings and frequent conference calls ensure information sharing and communication of ideas. One of the challenges of interdisciplinary work was maintaining effective communication among all cooperators. This was done through the usual means of workshops, conference calls and email, with emphasis placed on attention to the primary CLIMET objectives, consistent study protocols and meeting deadlines.

Data synthesis

Data sources were identified early in the project. We compiled all available data on climate, geology, hydrology, vegetation and ecological disturbance in the three CLIMET regions. These data were integrated within a GIS, allowing for data sharing and analysis of multiple data layers within and between regions. Data synthesis focused on two watersheds in each region – one on the west side and one on the east side – in order to represent contrasting climatic influences in wetter and drier environments. A central repository for all databases, as well as public posting of metadata, ensured the integrity and dissemination of project information.

New empirical data

Key data sets were collected within the watershed framework mentioned above. Specifically, we focused on the following watersheds: Glacier National Park – Lake McDonald, St Mary's Lake; North Cascades National Park – Thunder Creek, Stehekin River; and Olympic National Park – Hoh River, Dungeness River. These are all large watersheds, tens of thousands of hectares in area. Data were collected on various aspects of vegetation, ecological disturbance and hydrology in formats suitable for input to simulation models. Special emphasis was placed on developing and consistently implementing data collection protocols throughout the project. This was ensured by frequent discussions among scientists and field crew members, and by checking of data after each field operation.

Modelling framework

Ecosystem models provide insights on underlying mechanisms of ecosystem response to climatic variability and provide a look into possible futures. The Regional Hydro-ecological Simulation System (RHESSys) provides spatially explicit calculations of daily tree growth across the mountain landscape, mapped on an annual basis. Initial output from this model suggests that increased climatic variability will have as much influence on mountain forests as increases in annual average temperature or precipitation (White et al, 1998). The FIRE-BGC (BioGeoChemical) model emphasizes structural components of forest ecosystems and includes forest fires as a key disturbance factor. The model demonstrates that, in a warmer climate, forest landscapes will generate more frequent and severe fires than experienced historically even with increased precipitation (Keane et al, 1997). This nearly doubles smoke emissions in the future, reducing air quality in locations where clean air is highly valued.

Management applications

The BIOME-BGC model was recently used to examine the relative role of mountain ecosystems in providing ecological services. Cell-by-cell Pearson correlation coefficients of evapotranspiration versus precipitation, temperature and incident short-wave radiation indicate that precipitation explained spatial distributions of vegetation production and carbon stocks in vegetation and soil in drier areas, while temperature explained spatial variations in wetter areas (Fagre et al, 2005). Using BIOME-BGC and several climate change scenarios, we learned that reduced water supplies (outflows) are expected from mountain ecosystems across the region. However, the greatest effects were at mid-elevation sites, where most of the forests grow and where human settlement is increasing. Model output underscores the critical role of mountains in regional water supplies and our need to better understand ecosystem responses to climatic variability. Wildfire hazard will increase, but the amount and predictability of the regional water supply will be of even greater concern. The highest mountains where snow is stored may be even more critical in providing ecosystem services in the future.

Results of CLIMET research are also helping to inform resource management plans and other planning documentation in national parks in the region. This includes explicit consideration of climate change as a factor that affects natural resources, as well as potential means of adapting to altered environmental conditions. There is growing recognition that, from this point forward, most major decisions about natural resources must be made in the context of the effects of climate change on dynamic, non-equilibrium ecosystems.

Documenting environmental change

Glaciers

The CLIMET project has documented a variety of responses to long-term climatic change. One prominent indication of regional climatic change is glacial recession.

Figure 14.2 Paired photographs of glaciers clearly demonstrate their dramatic rate of shrinkage throughout the CLIMET area

Note: Shepard glacier, Glacier National Park, photographed by W. C. Alden in 1913 (*top*) and by B. Reardon in 2005 (*bottom*)

Among the most charismatic features of the three national parks, alpine glaciers offer numerous advantages for monitoring long-term changes in climate. For example, they are easily photographed and measured, and do not adapt to changing climate as plants and animals can. Responding almost solely to climatic patterns, glaciers provide a measurable signal of change within a few years to a decade.

Glacier recession at Glacier National Park reflects changes that are occurring throughout the CLIMET area and worldwide. Only 27 glaciers remain of the original 150 that existed when the park was founded in 1910. The largest glaciers cover less than 27 per cent of their original area and are expected to disappear by 2030 if current trends continue (Hall and Fagre, 2003). The area within park boundaries covered by ice and permanent snow decreased from 99km^2 in 1910 to 17km^2 by 1998 (Key et al, 2002). Surviving glaciers have thinned by hundreds of metres and may have less than 10 per cent of the ice volume that existed at the end of the Little Ice Age (see Figure 14.2).

The demise of these glaciers is driven by temperature increases of 1.6°C during the last century, three times the global average, but also is affected by timing and duration of multi-decadal droughts and pluvial periods. Temperature records have been regularly broken throughout the CLIMET study area, as warming continues (see Figure 14.3). Because the winter minimum temperatures have risen significantly, the glaciers and snowpack are warmer and initiate melting earlier in the spring, leading to a much longer melt season.

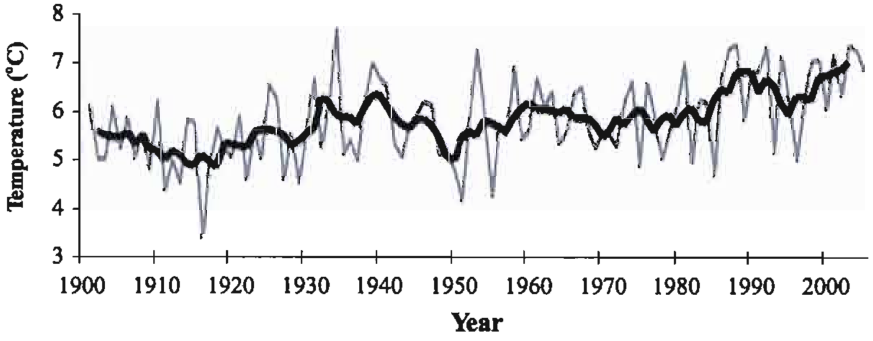

Figure 14.3 Annual mean temperature trend for western Montana, part of the CLIMET area

Note: The dark line is a five-year running average. Western Montana is currently 10°C warmer than 100 years ago

Source: Courtesy of Greg Pederson

A similar story of shrinking glaciers exists for the North Cascades National Park, which has most of the remaining glaciers in the conterminous US (Granshaw, 2002), and for the Blue Glacier in Olympic National Park (Conway et al, 1999). Monitoring of the South Cascade glacier in Washington has served as a benchmark for regional glacier mass balances (Bidlake et al, 2005) and shows significant reductions in ice volume. Finally, Fountain (2006) has compiled data on the declining area covered by glaciers for the CLIMET region. All the glaciers reflect downward trends in size, to varying degrees.

There are numerous consequences of disappearing alpine glaciers in western mountains, particularly in the more arid areas. Glaciers provide water in late summer when other sources are depleted, ensuring the survival of aquatic organisms that require cold water (Pepin and Hauer, 2002). Many aquatic biota are narrowly adapted to specific thermal conditions and will become locally extirpated when stream water temperatures rise. Conversely, disappearing glaciers provide new habitat for colonizing plants that, in turn, attract species such as bighorn sheep (*Ovis canadensis*). Finally, there is the aesthetic impact to tourists for whom vistas of alpine glaciers are highly valued. It is unknown whether this sense of loss will have any effect on visitation rates, but park interpreters report more questions from tourists about the disappearing glaciers than in the past, and some tourists state that they are visiting now, before the glaciers are gone.

Snow

The mountain areas of CLIMET are snow-dominated environments with most (70–99 per cent, depending on the elevation) of the annual precipitation arriving as snow. Thus, snow controls many essential ecosystem functions. Mote et al (2005) have shown a 50-year decline in mountain snowpacks over the CLIMET area, which ostensibly explains the shrinking glaciers. Average snowpacks in northwestern Montana also show the 50-year decline but have not significantly changed when the entire 84 years are considered (see Figure 14.4). This lack of a snowpack trend is despite a 10 per cent net increase in annual precipitation over the past century (Selkowitz et al, 2002). Thus, the ratio of rain to snow has increased with the 1.6°C increase in mean annual temperature, somewhat diminishing the role of snow in ecosystem processes.

Snowpacks have a strong periodicity associated with the Pacific Decadal Oscillation (PDO) (Selkowitz et al, 2002), a 20–30 year cycle of anomalous sea surface temperatures that affect regional climate patterns over the CLIMET study area (Mantua et al, 1997). The result is that multidecadal periods of greater or lesser snowpacks are a prominent pattern in CLIMET mountain ecosystems (McCabe and Dettinger, 2002). Superimposed on this strong oscillation of snowpack dominance is the long-term temperature increase of the past century that has resulted in earlier initiation of snowmelt and spring runoff (Stewart et al, 2005).

Periodic summer droughts have enhanced the effect of winter snowpack variability since 1540 (Pederson et al, 2004). Coupled with the PDO effect on winter snowpack, this pattern of extreme droughts helps explain changes in

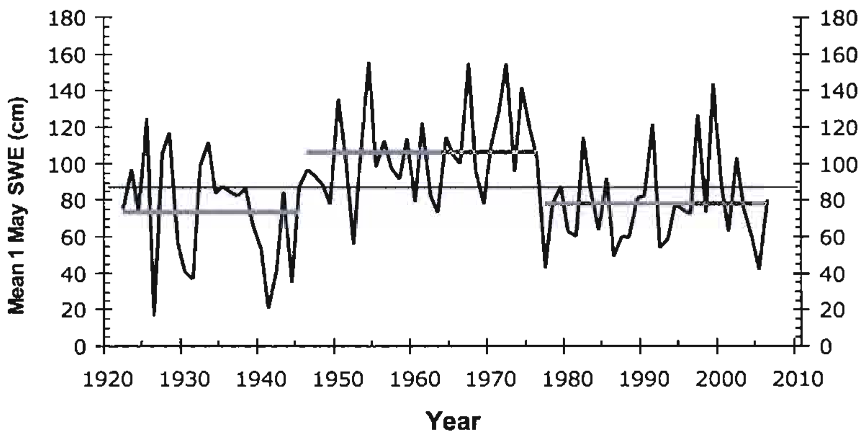

Figure 14.4 Mean snow water equivalent (SWE) of snow measured on 1 May each year in the Many Glacier area of Glacier National Park, Montana

Note: No significant change occurs over period of record but three distinct phases are tied to the Pacific Decadal Oscillation

Source: Courtesy of Greg Pederson

glacier mass balance, and glacier growth or shrinkage, over the past several centuries. Because snowpack is critical to regional water supplies, the effects of PDO and long duration droughts must be accounted for in comprehensive water management and forecasting in the face of climatic change.

Snow avalanches

Large-magnitude snow avalanches pose hazards to humans and infrastructure, but also shape ecosystem pattern and process by carving linear swaths out of the forest from ridge top to valley bottom. Avalanche paths create vegetation diversity, are utilized by wildlife, act as fuel breaks to large fires (Patten and Knight, 1994), and transport soil and nutrients from high elevations to valley bottoms (Butler et al, 1992). In alpine basins of Glacier Park, snow avalanches are more important disturbance processes than forest fires. Thus, changes to snow avalanche frequency may have profound effects on ecosystem dynamics and the state of natural resources.

Recent increases in rockfalls, floods and debris flows in Glacier National Park may reflect melting of permafrost in high-elevation topography and increases in extreme rainfall events. Historically, snow avalanches have caused extensive damage to the road bed and retaining wall of the Going-to-the-Sun road that bisects the park. In addition, for each day that the road is closed due to avalanches, the regional economy loses US$1.1 million (Fagre and Klasner, 2000). Thus, natural hazards linked to climatic change are of great concern to managers and the public. Weather patterns that trigger avalanches in Glacier National Park (Reardon et al, 2004) may become more frequent in a warmer climate and should be considered in future climate change scenarios.

Forest responses

Like glaciers and snow, the alpine treeline has responded to the century-long climatic change but in more complex ways. For instance, Butler and DeChano (2001) used repeat photography to show upward treeline elevation changes, but attribute some of these shifts to changes in fire management policy. Roush et al (2007) show a variety of treeline responses to a more benign climate, but found that geomorphology was a strong interacting factor in the resulting spatial patterns. Seedling establishment at one site in Glacier National Park above the existing treeline reflected PDO phases and was driven by positive feedbacks from snow and vegetation (Alftine et al, 2003). Bekker (2005) also reported PDO periodicity in tree establishment and growth along 'fingers' of trees invading open areas where consistent high winds made establishment difficult. These cyclical processes influence the pace and pattern of tree invasion into the alpine tundra. However, infilling of gaps in the extant patch forests and krummholz was more consistent, leading to a more sharply defined treeline and greater biomass (Klasner and Fagre, 2002; Roush et al, 2007).

Regeneration of conifers in high-elevation forest ecosystems has increased throughout western North America during the past century, particularly since the 1930s (Rochefort et al, 1994). This new establishment of trees is particularly prominent near treeline during periods of low snowpack, often associated with warm PDO regimes. Subalpine meadows also have filled in with invading trees throughout the CLIMET area (Peterson, 1998; Bekker, unpublished data) (see Figure 14.5), reflecting changes in snowpack magnitude and duration as well as other climatic trends.

Peterson and Peterson (2001) ascribe the different growth patterns of trees at different elevations to periods of variable snowpack; low snowpacks facilitated tree growth at upper elevations but inhibited growth at lower treeline, with the reverse being true for large snowpacks. Finally, McKenzie et al (2004) analysed tree-growth chronologies in western North America and found that the growth rate is increasing in many high-elevation forest ecosystems below treeline. This growth increase started after 1850, concurrent with the start of industrial activity and increased greenhouse gas emissions. These increased rates of tree growth contribute to greater biomass, stored carbon and fuel for forest fires.

Cascading consequences from these tree responses to climatic change include a reduction in habitat for alpine plants and animals as forests expand. Some animals, such as pikas (*Ochotona princeps*), are also directly affected by warmer temperatures in addition to forage and habitat responses (Beever et al, 2003). Pika populations have disappeared in several areas where they used to be common.

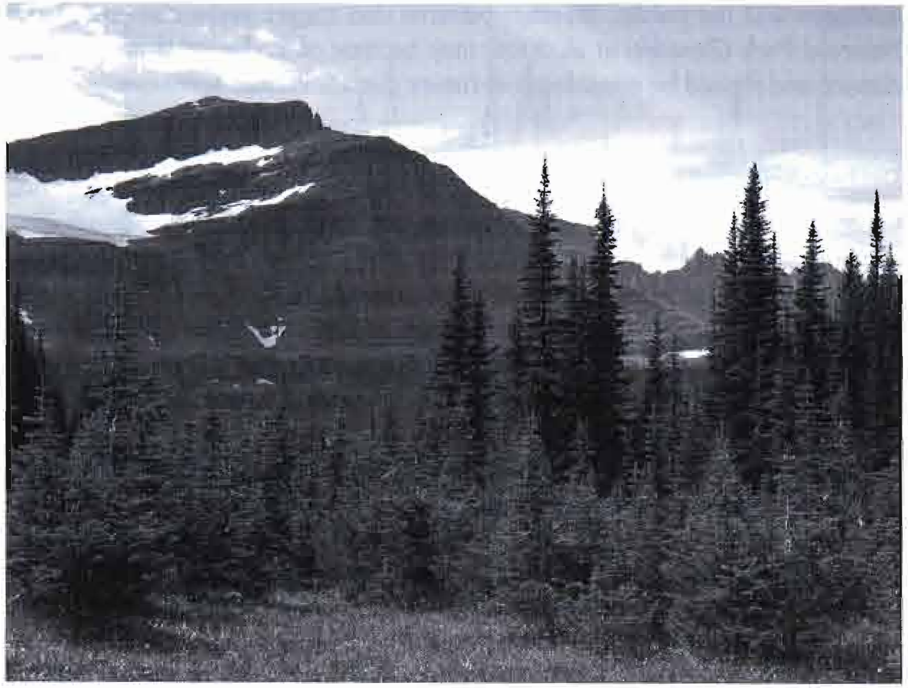

Figure 14.5 Invasion of young trees into subalpine meadows in Preston Park, Glacier National Park

Note: Many of the young trees are 20–50 years old and the large trees in the background are 250–300 years old. Warming temperatures and changing snowpacks have allowed the younger trees to become established during the last few decades.

Source: Daniel Fagre (2006)

Wildfire

Productivity, succession and large-scale vegetation patterns in the CLIMET area are controlled by ecological disturbance, especially fire. The area burned in any particular year is at least partially related to climatic variability, such as the PDO, and long-term climatic change. For example, years with fire area >80,000ha in national forests of Washington and Oregon are nearly four times more common during a warm PDO than during a cool PDO (Mote et al, 1999). This regional effect is moderated by synoptic-scale meteorology, particularly the effect of high-pressure ridges from eastern Washington to western Montana (Gedalof et al, 2002). Fire extent is also affected by long-term climatic change. A fire history for Glacier Park (Barrett, 1988) showed that fire frequency was lower during the height of the Little Ice Age, with a period of increased fires during the early 20th century related to warmer climate (Pederson et al, 2006).

Historical analogues help us estimate the potential for forest fires under future climate scenarios. Keane et al (1996) used FIRE-BGC to show that the resulting more-productive forest landscapes will generate more frequent and severe fires than the same landscapes experienced historically, even with the increase in annual precipitation (Keane et al, 1997). Because fire frequency has been altered by humans throughout the CLIMET area for the past century, fuel loads have built up to levels that could lead to fire intensities higher than might have been experienced in the past. A warmer climate will bring extended fire seasons and perhaps more large fires in much of the CLIMET area (McKenzie et al, 2004).

Management of forest fires is an important issue in the arid western US. In 2003, 13 per cent of the 4082km^2 of Glacier National Park was burned in three large fires and numerous smaller fires. Because forest fires are projected to become more frequent and intense under continued climate change, managers may be able to accomplish some goals, such as preserving threatened wildlife populations, by altering the management of fires. In 2003, efforts were successfully made to divert fires away from grizzly bear (*Ursus arctos horribilis*) habitat that contained huckleberry (*Vaccinium spp.*) plants necessary to ensure bear survival through the winter. The fires were also directed away from riparian areas so that trees could continue shading streams and prevent water from increasing in temperature. Fire has been used under controlled conditions to maintain some open meadow habitats. Finally, decisions about allowing some naturally started fires to burn and others to be controlled are being made with a complex set of considerations that include the volume of smoke emissions and consequent effects on human health.

Projecting future CLIMET responses to climatic change

The CLIMET project has made considerable progress in understanding and quantifying responses of mountain ecosystems to climatic variability and has developed models to better utilize this knowledge. One such model is based on an analysis of biophysical and climatic variables to develop predictions of how dominant tree species will respond to long-term climate change. Tree data are from 10,653 forest resource inventory plots in the state of Washington, occupying a longitudinal gradient from the crest of the Cascade Range to the western slope of the Rocky Mountains. For the majority of species, it is possible to fit variables from both moisture and temperature categories of predictors that indicate optimum responses. Douglas fir (*Pseudotsuga menziesii*) trees, for instance, are predicted to be most likely to occur where growing degree days are between 2500 and 3000, and soil drought days are between 100 and 150. Climatic conditions (for example, growing degree days) can be mapped from various climate-change scenarios to show where Douglas fir trees will grow in the future. When the predictor variables are spatially explicit, then changes in the geographic niches of species in response to climatic change scenarios can be quantified. This was accomplished for 13 species, at multiple spatial scales, providing a clearer picture of possible forests of the future.

A similar approach, using an environmental envelope of optimal climatic variables for major vegetation types, mapped the distribution of vegetation for each decade into the future in Glacier National Park (Hall and Fagre, 2003). These spatially explicit projections of future vegetation neither incorporate major disturbances, such as forest fires, nor account for plant competitive processes. However, they indicate where plant species are expected to occur in a warmer climate. Of particular concern to park managers is that this scenario indicates a conversion from forest to grassland, altering habitat for animal species and affecting potential fire frequency and magnitude.

In addition, FIRE-BGC was used to examine spatial attributes of ecosystem processes rather than the more common spatial analyses performed on structural components such as cover types (Keane et al, 1999). When fire is present under both current and future climate scenarios, patch density for vegetation compositional landscape maps decreased or remained stable, meaning that forest type did not change much. However, patch density increased for net primary productivity, indicating that fire increased the spatial heterogeneity of productivity. Areas where forest became more productive were mapped to indicate shifts in dynamic ecosystem outputs. The ability to 'see' and spatially analyse processes, in addition to visible structural components of ecosystems, provides a tool for understanding drivers of biodiversity in mountains and the potential effects of climatic change on natural resources.

Conclusions

The CLIMET project has addressed issues of both scientific and management significance by integrating monitoring and research studies across the three mountain bioregions. Combining field-based studies and modelling, common processes have been investigated with comparable techniques and at similar scales. In addition to elucidating the common drivers of ecosystem dynamics and changes to mountain natural resources, the relative importance of mountains to the regional landscapes has been identified.

The perspectives provided to the public by the CLIMET project would not be possible without the interdisciplinary and integrated approaches taken with diverse partners. The public's response is evident in the frequency with which these mountain protected areas are invoked as signals of climate change in the media, community symposia and legislative initiatives. The Waterton-Glacier International Peace Park, a world heritage site that includes Glacier National Park, has even been petitioned for endangered status based on the documented effects of climate change through the CLIMET project. Managers, too, have responded by incorporating climate change considerations in resource decisions and outreach to the public.

The CLIMET approach has been broadened to encompass the Western Mountain Initiative, a group of mountain research programmes that has been continuously monitoring and investigating various mountain processes since 1981. Additionally, the Consortium for Integrated Research in Climate Sciences in Western Mountains has been formed to expand on CLIMET concepts and incorporate almost all mountain systems in the western US (www.fs.fed.us/psw/cirmount/). These efforts are providing decision-makers and a variety of stakeholders with the knowledge and tools needed to navigate the challenges of a greenhouse climate.

References

Alftine, K. J., Malanson, G. P. and Fagre, D. B. (2003) 'Feedback-driven response to multidecadal climatic variability at an alpine forest-tundra ecotone', *Physical Geography*, vol 24, pp520–535

Barrett, S. W. (1988) *Fire history of Glacier National Park: McDonald Creek Basin: Final Report*, West Glacier, Glacier National Park

Beever, E. A., Brussard, P. F. and Berger, J. (2003) 'Patterns of apparent extirpation among isolated populations of pikas (*Ochotona princeps*) in the Great Basin', *Journal of Mammalogy*, vol 84, pp37–54

Bekker, M. F. (2005) 'Positive feedback between tree establishment and patterns of subalpine forest advancement, Glacier National Park, Montana, U.S.A.', *Arctic, Antarctic, and Alpine Research*, vol 37, pp97–107

Bidlake, W. R., Josberger, E. G. and Savoca, M. E. (2005) 'Water, ice, and meteorological measurements at South Cascade Glacier, Washington, balance year 2003', *US Geological Survey Scientific Investigations Report 2005-5210*, US Geological Survey, Reston, VA

Bradley, R. S., Keimig, F. T. and Diaz, H. F. (2004) 'Projected temperature changes along the American Cordillera and the planned GCOS network', *Geophysical Research Letters*, vol 31, L16210, DOI:10.1029/2004GL020229

Butler, D. R. and DeChano, L. M. (2001) 'Environmental change in Glacier National Park, Montana: An assessment through repeat photography from fire lookouts', *Physical Geography*, vol 22, pp291–304

Butler, D. R., Malanson, G. P. and Walsh, S. J. (1992) 'Snow-avalanche paths: Conduits from the periglacial-alpine to the subalpine depositional zone', in Dixon, J. C. and Abrahams, A. D. (eds) *Periglacial Geomorphology*, London, John Wiley and Sons

Conway, H., Rasmussen, L. A. and Marshall, H. P. (1999) 'Annual mass balance of Blue Glacier, U.S.A.: 1957–97', *Geografiska Annaler*, vol 81 A, pp509–520

Fagre, D. B. and Klasner, F. L. (2000) 'Application of snow models to snow removal operations on the Going-to-the-Sun Road, Glacier National Park', in Birkeland, K. (ed.) *A Merging of Theory and Practice; Proceedings of the International Snow Science Conference*, Big Sky, Montana

Fagre, D. B. and Peterson, D. L. (2000) 'Ecosystem dynamics and disturbance in mountain wildernesses: Assessing vulnerability of natural resources to change', in McCool, S. F., Cole, D. N., Borrie, W. T. and O'Laughlin, J. (eds) *Proceedings of USDA Forest Service RMRS-P-15, Wilderness Science in a Time of Change*, vol 3, Fort Collins, Rocky Mountain Research Station

Fagre, D. B., Running, S. W., Keane, R. E. and Peterson, D. L. (2005) 'Assessing climate change effects on mountain ecosystems using integrated models: A case study', in Huber, U. M., Bugmann, H. K. and Reasoner, M. A. (eds) *Global Change* *and Mountain Regions: A State of Knowledge Overview*, Berlin, Springer

Fountain, A. (2006) 'Glaciers Online: Glaciers of the American West', http://glaciers.research.pdx.edu/ accessed 6 November 2006

Gedalof, Z., Mantua, N. J. and Peterson, D. L. (2002) 'A multi-century perspective of variability in the Pacific Decadal Oscillation: New insights from tree rings and coral', *Geophysical Research Letters*, vol 29, pp2204–2207

Granshaw, F. D. (2002) *Glacier Change in the North Cascade National Park Complex, Washington State USA, 1958 to 1998*, Masters thesis in geology, Portland, Portland State University

Hall, M. P. and Fagre, D. B. (2003) 'Modeled climate-induced glacier change in Glacier National Park, 1850–2100', *Bioscience*, vol 53, pp131–140

Keane, R. E., Ryan, K. C. and Running, S.W. (1996) 'Simulating effects of fire on northern Rocky Mountain landscapes with the ecological process model FIRE-BGC', *Tree Physiology*, vol 16, pp319–331

Keane, R. E., Hardy, C. C., Ryan, K. C. and Finney, M. A. (1997) 'Simulating effects of fire on gaseous emissions and atmospheric carbon fluxes from coniferous forest landscapes', *World Resource Review*, vol 9, pp177–205

Keane, R. E., Morgan, P. and White, J. D. (1999) 'Temporal patterns of ecosystem processes on simulated landscapes in Glacier National Park, Montana, USA', *Landscape Ecology*, vol 14, pp311–329

Key, C. H., Fagre, D. B. and Menicke, R. K. (2002) 'Glacier retreat in Glacier National Park, Montana', in Williams, R. S. Jr. and Ferrigno, J. G. (eds) *Satellite Image Atlas of Glaciers of the World, Glaciers of North America: Glaciers of the Western United States*, Washington DC, United States Government Printing Office

Klasner, F. L. and Fagre, D. B. (2002) 'A half century of change in alpine treeline patterns at Glacier National Park, Montana, U.S.A.', *Arctic, Antarctic, and Alpine Research*, vol 34, pp49–56

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. and Francis, R. C. (1997) 'A Pacific interdecadal climate oscillation with impacts on salmon production', *Bulletin of the American Meteorological Society*, vol 78, pp1069–1079

McCabe, G. J. and Dettinger, M. D. (2002) 'Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate', *Journal of Hydrometeorology*, vol 3, pp13–25

McKenzie, D., Gedalof, Z., Peterson, D. L. and Mote, P. (2004) 'Climatic change, wildfire, and conservation', *Conservation Biology*, vol 18, pp890–902

Mote, P. W., Keeton, W. S. and Franklin, J. F. (1999) 'Decadal variations in forest fire activity in the Pacific Northwest', *11th Conference on Applied Climatology, American Meteorological Society*, pp155–156

Mote, P., Hamlet, A., Clark, M. and Lettenmaier, D. (2005) 'Declining mountain snowpack in western North America', *Bulletin of the American Meteorological Society*, vol 86-1-39, DOI: 10.1175

Patten, R. S. and Knight, D. H. (1994) 'Snow avalanches and vegetation pattern in Cascade Canyon, Grand Teton National Park, Wyoming, U.S.A.', *Arctic and Alpine Research*, vol 26, pp35–51

Pederson, G. T., Fagre, D. B., Gray, S. T. and Graumlich, L. J. (2004) 'Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA', *Geophysical Research Letters*, vol 31, L12203, DOI:10.1029/2004GL0197770

Pederson, G. T., Gray, S. T., Fagre, D. B. and Graumlich, L. J. (2006) 'Long-duration drought variability and impacts on ecosystem services: A case study from Glacier National Park, Montana USA', *Earth Interactions*, vol 10, pp1–28

Pepin, D. M. and Hauer, F. R. (2002) 'Benthic responses to groundwater–surface water exchange in two alluvial rivers', *Journal of the North American Benthological Society*, vol 21, pp370–383

Peterson, D. L. (1998) 'Climate, limiting factors, and environmental change in high-altitude forests of western North America', in Beniston, M. and Innes, J. L.(eds) *The Impacts of Climate Variability on Forests*, Heidelberg, Springer

Peterson, D. W. and Peterson, D. L. (2001) 'Mountain hemlock growth responds to climatic variability at annual and decadal scales', *Ecology*, vol 82, pp3330–3345

Reardon, B. A, Fagre, D. B. and Steiner, R. W. (2004) 'Natural avalanches and transportation: A case study from Glacier National Park, Montana, USA', in *Proceedings of the International Snow Science Workshop*, 19–24 September, Jackson, Wyoming

Rochefort, R. M., Little, R. L., Woodward, A. and Peterson, D. L. (1994) 'Changes in the distribution of subalpine conifers in western North America: A review of climate and other factors', *Holocene*, vol 4, pp89–100

Roush, W. J., Munroe, J. S. and Fagre, D. B. (in press) 'Development of a spatial analysis method using ground-based repeat photography to detect changes in the alpine treeline ecotone, Glacier National Park, Montana', *Arctic, Antarctic, and Alpine Research*, vol 39, pp297–308

Selkowitz, D. J., Fagre, D. B. and Reardon, B. A. (2002) 'Interannual variations in snowpack in the Crown of the Continent Ecosystem', *Hydrological Processes*, vol 16, pp3651–3665

Stewart, I., Cayan, D. and Dettinger, M. D. (2005) 'Changes towards earlier streamflow timing across western North America', *Journal of Climate*, vol 18, pp1136–1155

White, J. D., Running, S. W., Thornton. P. E., Keane, R. E., Ryan, K. C., Fagre, D. B. and Key, C. H. (1998) 'Assessing simulated ecosystem processes for climate variability research at Glacier National Park, USA', *Ecological Applications*, vol 8, pp805–823

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