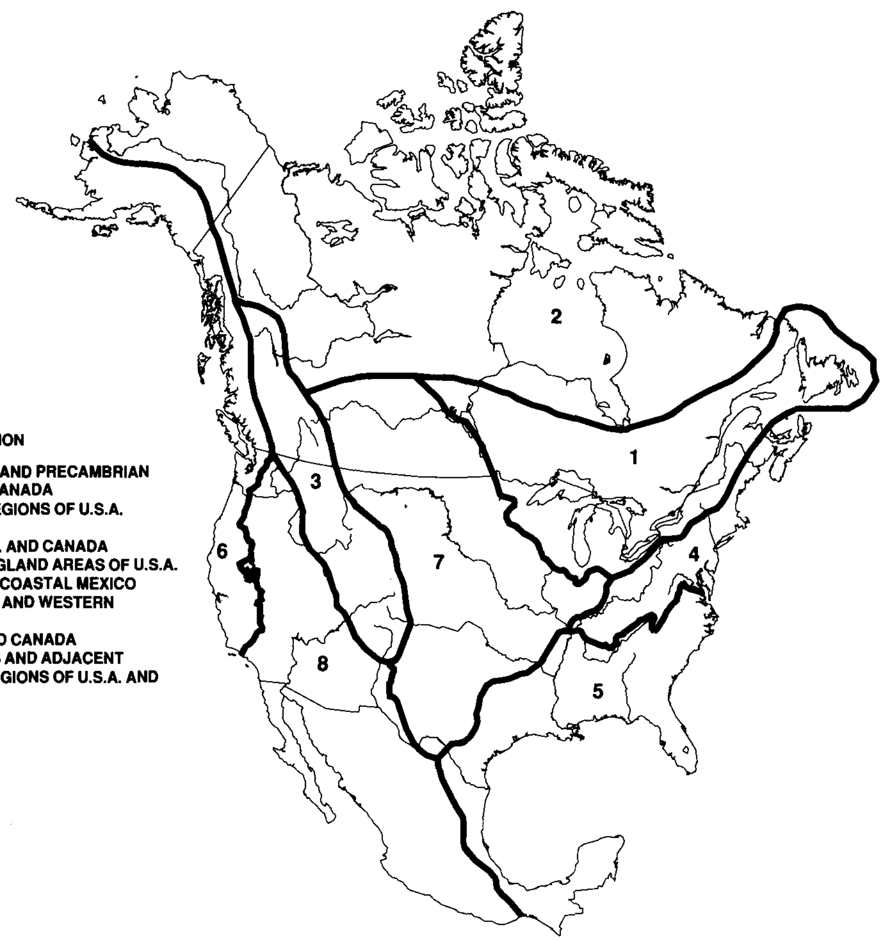
SYMPOSIUM REPORT

Regional Assessment of Freshwater Ecosystems and Climate Change in North America

October 24-26, 1994

Leesburg, Virginia



EXPLANATION

1. LAURENTIAN GREAT LAKES AND PRECAMBRIAN SHIELD OF U.S.A. AND CANADA
2. ARCTIC AND SUB-ARCTIC REGIONS OF U.S.A. AND CANADA
3. ROCKY MOUNTAINS IN U.S.A. AND CANADA
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7. GREAT PLAINS OF U.S.A. AND CANADA
8. BASIN AND RANGE REGIONS AND ADJACENT ARID AND SEMI-ARID REGIONS OF U.S.A. AND MEXICO

Organized by:
American Society of Limnology and Oceanography
North American Benthological Society

Sponsored by:
U.S. Environmental Protection Agency
U.S. Geological Survey

Acknowledgments

The symposium "Regional Assessment of Freshwater Ecosystems and Climate Change in North America" was organized by the American Society of Limnology and Oceanography and the North American Benthological Society through a steering committee composed of **Alan P. Covich** (co-chair), Colorado State University; **Diane M. McKnight** (co-chair), U.S. Geological Survey; **William Eichbaum**, World Wildlife Fund; **Nancy B. Grimm**, Arizona State University; **George Leavesley**, U.S. Geological Survey; **John Melack**, University of California Santa-Barbara; **David W. Schindler**, University of Alberta; and **Steven Schneider**, Stanford University. Ex-officio members of the Steering Committee were **Colbert E. Cushing** (NABS), Batelle-Pacific N.W. Laboratory; **John Eaton**, U.S. Environmental Protection Agency; **Harry Lins**, U.S. Geological Survey; and **C. Susan Weiler** (ASLO), Whitman College. The regional summaries were prepared by the regional working groups based upon discussion which included symposium participants. The synthesis working group for the symposium includes **David W. Schindler** (chair), **Steven R. Carpenter**, University of Wisconsin; **William Eichbaum**; **Stuart Fischer**, Arizona State University; **James Miller**, Rutgers University; and **Steven Schneider**. This report was compiled by **Diane M. McKnight** and **C. Susan Weiler**, February 28, 1995.

Primary support for the symposium, this report, and symposium issues of *Limnology and Oceanography* and *Hydrologic Processes* was provided by the **U.S. Environmental Protection Agency**, Environmental Research Laboratory-Duluth, and the **U.S. Geological Survey**, Water Resources Division, through Interagency agreement DW14936586 with the U.S. Geological Survey.

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Preface

The symposium and the resulting publications focus on the general theme of freshwater ecosystems and climate change in North America, and are jointly organized by the American Society of Limnology and Oceanography (ASLO) and the North American Benthological Society (NABS). The symposium occurred on October 24-26, 1994 in Leesburg, VA. The goals of this effort are to:

- evaluate current evidence for directional change in inland waters;
- examine potential important responses to climatic changes resulting from a hypothetical doubling of atmospheric carbon dioxide (or its radiative equivalent); and
- develop recommendations for experimental studies or augmentation of monitoring programs.

In order to make the linkage between climate change and freshwater ecosystems, a regional approach has been taken, with eight regions identified to encompass the North American continent. These regions include a range of inland waters. For several months prior to the symposium, working groups for each of the eight regions conducted preliminary assessments and considered regional climate change scenarios that have been put forward. The first day of the symposium began with thematic talks, and continued with overviews of each of the eight regions, and a poster session of contributed papers related to freshwater ecosystems and climate change. The second day of the symposium was devoted to open meetings of the Regional Working Groups for evaluation of the potential responses to regional climate change scenarios for a doubling of carbon dioxide in the atmosphere. On the third day of the symposium, talks on the implications for water resources and fisheries were presented and the Regional Working Groups as well as the Synthesis Working Group summarized their findings. The symposium closed with a presentation on environmental policy and climate change by Dr. Robert Hirsch, Chief Hydrologist for the U.S. Geological Survey.

This report is a preliminary summary of findings of the Regional Working Groups. The research papers from the thematic talks and the contributed session are planned for publication in a special issue of the *Limnology and Oceanography*, and the regional and synthesis working group reports will be published in a special issue of *Hydrologic Processes.*

Regional Summaries

Introduction

The purpose of this brief report is to present a preliminary overview of the findings from the symposium "Regional Assessment of Freshwater Ecosystems and Climate Change in North America" for the participants in the symposium, the membership of the two participating societies, ASLO and NABS, and for the sponsoring agencies the Environmental Protection Agency and the U.S. Geological Survey.

The eight regions identified for this assessment are presented on the cover of this report. In addition to geographic and hydrologic considerations, regional boundaries were set with the goal of compatibility of scale with meso-scale Global Circulation Models (GCM's). The region typically encompasses several ecoclimate regions and specific areas within a region are considered for in-depth analysis. The following summaries begin with a description of significant or unique geographic and climatological characteristics of each region and of major types of aquatic ecosystems found within each region. Most of the summaries briefly review the long term climatic patterns based on paleo records, and near term trends indicated by instrumental records.

The regional groups were tasked with considering responses to a doubling of atmospheric carbon dioxide (referred to here as 2X CO2 scenarios). Uncertainties in predictions from GCM's presented a major challenge for every regional working group, and in the summaries each group discusses their approach to this challenge. The possible consequences for aquatic ecosystems which may result from the 2X CO2 scenarios were identified from the literature and ongoing studies and are highlighted in the summaries. Also addressed are interactions between anthropogenic impacts on aquatic ecosystems and possible climatic effects. The caveat that the projected responses and interactions are speculative in nature applies to all the regions.

The summaries conclude with preliminary recommendations for data collection and research. These recommendations will be further developed in the final regional working group reports that will be published in the journal *Hydrologic Processes.*

Region 1. - Laurentian Great Lakes and Precambrian Shield

John J. Magnuson, Carl J. Bowser, Raymond A. Assel, Bart T. DeStasio, John R. Eaton,
Everett J. Fee, Peter J. Dillon, Linda D. Mortsch, Nigel T. Roulet,
Frank H. Quinn and David W. Schindler

Regional Description

This region is water-rich with low relief, cool to cold in winter and warm to cool in summer. A multitude and diversity of lakes and associated wetlands and streams dominate the area. Included are the Laurentian Great Lakes, smaller glacial lakes, streams, and wetlands south of the permanent permafrost to the southern extent of the Wisconsin glaciation. Lakes are emphasized in our analysis owing to the existing breadth and intensity of lake research. Physical and biological processes and conditions of these systems are sensitive to potential climate change, as are associated human values.

Paleo analyses of lake sediments and time series of weather data and ice phenologies indicate that the region is warmer and wetter now than several thousand years ago. Observed air temperatures, summarized from 1895 to 1993 for the Great Lakes - St Lawrence area, have increased about 0.8°C (spring) and 1.1°C (winter) with little change observed in summer and fall. Similarly annual precipitation has been increasing at a per-decade rate of 2.1%. Ice thaw dates on selected lakes indicate that late winter temperatures have warmed by about 2.5°C since the mid 1800s.

Potential Responses to CO_2 Doubling

2X CO2 scenarios from the Canadian General Circulation Models (GCM) generated warmer temperatures of 6°-10°C (winter) and 4°-5°C (summer). Scenarios for summer are dryer in western Ontario (-20%) but show little change or slight increases elsewhere. Scenarios for winter are wetter in western Ontario and northern Minnesota, Wisconsin and Michigan (+20%) but show little change or slight decreases elsewhere.

Two overarching considerations shaped our thoughts: 1) the wide array of expected changes, and 2) differences in expected responses within the region. Potential changes include changes in physical limnology; hydrology in respect to water levels, weathering, and residence times; solar radiation in respect to changes in cloudiness, dissolved organic carbon concentrations, and deep water oxygen concentrations; and distribution, growth, and persistence of fishes. Watershed- and lake-specific factors were identified as key considerations.

Various limnological models have been used to extend climate scenarios from the GCMs to physical limnological scenarios. With a doubling of carbon dioxide, these models generate stream temperatures that track air temperature, summer lake temperatures that are 1° to 7°C warmer in the epilimnion and 6°C cooler to 8°C warmer in the hypolimnion, deeper or shallower thermoclines by up to 4m, sharper thermoclines, and reductions in duration of ice cover by several months including the absence of ice cover at some latitudes. To the south, the loss of ice for some lakes in some years indicates that dimictic lakes would become monomictic and mix through the winter; summer stratification would become longer. To the north, some lakes that presently are monomictic and mix during summer would stratify in summer and become dimictic. Dimictic deep lakes would be less likely to mix completely. All of these changes would influence lake ecosystems.

Hydrologic scenarios with a warmer and dryer climate produce lower lake water levels which should change wetlands, alter spawning opportunities for fishes and substrates for littoral benthos, and increase demand for water for agriculture and other uses. For Lake Michigan various 2XCO2 scenarios produce a decrease in water level of 1.25 to 2.5m. For the Illinois shoreline of the Chicago area increased costs for dredging, extending water intakes, relocating beach facilities, and extending stormwater outfalls have been estimated at $280 million to $540 million. Other direct economic impacts include increased costs of shipping in the Laurentian Great Lakes and reduced production of hydroelectric power at Niagara Falls.

Lower runoff under a dryer and warmer climate would affect biogeochemical processes, such as slowing the weathering of silicate rocks and decreasing solute fluxes to lakes. Conversely, concurrent increases in water residence time would cause higher solute concentrations and greater internal alkalinity generation. Lower wetland water tables could decrease the extent of reducing environments, increase acidic flows, and decrease dissolved organic carbon (DOC) and trace metals in inflows. The decrease in DOC should increase water clarity, deepen the thermocline, increase benthic algae and invertebrates. Such logically predictable changes have been observed in the Experimental Lakes Area of western Ontario during the recent 20-year period of progressively warmer and dryer weather.

Fishes are aerobic ecotherms and would respond strongly to changes in temperature and oxygen concentrations. Generally, simulations driven by climate scenarios, both for large and small lakes, increase thermal habitat for warmwater, coolwater and even coldwater fishes if oxygen is not depleted in deep water. Scenarios also generate increased body growth if there is sufficient food to meet the higher metabolic demands at warmer temperatures. For some more extreme scenarios and latitudes, there is an increased probability that temperatures would reach lethal levels both for coolwater and warmwater fishes. Simulations also suggest that deepwater anoxia is more probable, which could eliminate coldwater fishes. Warmer groundwater and stream temperatures would cause habitat reductions and loss of some coldwater and coolwater fish populations.

Local lakes and streams do not necessarily exhibit coherent responses to the same climate changes and variability. Lakes integrate changes over different time scales because their water residence times are influenced by lake size and inflows differ. Specific spatial factors that alter hydrologic responses of lakes to climate changes are regional climate, geomorphic setting and substrates, mean depth, ratios of lake/drainage area, and lake volume/total basin storage. Differing hydrologic responses can interact with differences in ecosystem structure and function. The reduction in ice cover can decrease winterkill of fishes in a shallow forest lake, but increase winter mortality of whitefish eggs in bays of the Laurentian Great Lakes. This results not only from the physical differences between tiny lakes and great lakes, but also from differences between their species in life history and physiology.

Preliminary Recommendations

Five broad research needs were identified: 1) Long-term research and monitoring should be maintained and expanded at key locations; 2) models of aquatic system behavior should be improved and tested against long-term data and manipulative field experiments; 3) climate models should be improved to include outputs of wind and clouds and at temporal and spatial scales more suitable for subregional analyses; 4) heterogeneity of potential responses should be recognized and a predictive understanding of this heterogeneity should be developed; and 5) better understanding of the high-temperature tolerances of aquatic organisms and communities is needed.

Region 2. - Arctic and Subarctic North America

Wayne R. Rouse, Marianne S. V. Douglas, Robert E. Hecky, George W. Kling, Lance Lesack, Philip Marsh, Michael McDonald, Barbara J. Nicholson, Nigel T. Roulet and John P. Smol.

Regional Description

Region two comprises Arctic and Subarctic Canada and Subarctic Alaska. It extends across 30° of latitude (52°N to 82°N) and 80° of longitude (62°W to 142°W). With a total terrestrial area of approximately 6.1 x 10^6 km^2 it spans eight ecoclimatic regions.

As would be expected with such diversity, the climate is highly variable. Exclusive of the ice cap areas in the eastern Queen Elizabeth Islands, the annual mean temperature spans 21°C (+3° to -18°C), precipitation (in the few places it is measured) ranges from 460 to 60 mm, the frost-free period from 125 to <10 days, the median snow-free period from 245 to 80 days and the global solar radiation from 160 to 90 Wm^{-2}. The net radiation at the surface in turn varies from 53 to 3 Wm^{-2}. Thus while in the most southerly parts of Region 2 about 33% of solar radiation is realized as effective surface net radiant energy, this decreases to about 3% in the most northerly areas. Any climatic warming would result in an increase in the surface net radiation as a result of reduced longevity of the snow cover during the high sun season and this combined with warmer temperatures would substantially increase evaporation rates.

A conservative estimate would place the surface area of fresh water at about 350,000 km^2. This includes small ponds, large lakes and large rivers and represents a major fresh water resource within North America. Great Bear and Great Slave Lakes, two of the largest lakes in the world, feed the Mackenzie River system, one of the largest rivers in the world. Also included is all of the Yukon River system. Major freshwater ecosystems include ponds which freeze to the bottom in winter, lakes which do not freeze to the bottom, rivers and their deltas, and wetlands which are usually peatlands. The region is underlain by either continuous or discontinuous permafrost and is vegetated primarily by tundra or subarctic open forest.

Potential Responses to CO_2 Doubling

Global Climate Models (GCMs) generally concur in predicting that the mainland areas will experience temperature increases in the order of 4°C summer and winter for a 2X CO2 scenario, and the Arctic Islands will undergo a corresponding 3° and 8°C increase. Thus this region could experience the largest temperature increases of any area on planet Earth. GCM's show less agreement with respect to precipitation, although some increase is generally indicated. To help in understanding potential impacts of climate change we have adopted scenarios of higher temperature in the order of 4°C, and the possibility of more, the same or less precipitation.

The instrumental record indicates a temperature increase of 1.7°C in the Mackenzie Basin between 1895 and 1991. On a shorter time scale, between 1950 and 1989 there was a west-to-east trend in temperature increases ranging from 1.5°C in Alaska and the Yukon, 1.0°C in the Mackenzie, nil through the central Arctic Islands, to -0.5°C over the eastern Baffin Isands. Cause cannot be ascribed to these short-term changes because they are well within the recorded natural variability. Over a 30-year period, there has been a close correspondence between above-average daily temperatures and higher-than-normal precipitation. For the middle and upper Mackenzie and Yukon this applied to the mid-winter period only, but for most of the Arctic Islands the correspondence persisted for the period October through April. Thus the amelioration of very cold temperatures in these regions has the potential to increase precipitation.

Paleoclimatic reconstructions during the Holocene cast light on the magnitude of climate change or variability. There has been a fairly steady increase in temperature in the last 150 years of about 2°C. Late 20th century summer temperatures are as warm or warmer than any in the period from 1640 to 1980. All summertime dendroclimatic records indicate that temperature variations of substantial but somewhat lesser magnitude than those suggested by GCM results have occurred. Diatom records from high Arctic lakes indicate a strong warming trend in the last two centuries. The Holocene may have been the only non-glacial period with widespread permafrost. Indeed, the temperature of the permafrost in many western subarctic regions is close to 0°C and a small warming would promote substantial thaw. There is strong palynological evidence from the early Holocene that subarctic forests spread to the mainland Arctic coast into present-day tundra regions. Analysis of stable isotope ratios from ice cap cores on the Canadian Arctic Islands shows that melting over the entire ice cap surface occurs nine years out of ten, whereas at higher elevations in Antarctica and Greenland no melting at all occurs. From 1200 AD to the 1970's, several periods of persistent strong melting lasting 5 decades or more have occurred, and the period with the strongest magnitude of melt has occurred during the last 100 years. There appears to be some congruence in the instrumental, dendroclimatic, diatom, synoptic and ice-core indicators that suggests a substantial 20th century warming in most of this region.

Because of the region's size and the lack of broadly distributed information, we have focused on areas with substantial research knowledge including the ponds and lakes of the High Arctic; ponds, lakes and wetlands at the LTER site, Toolik Lake, Alaska; lakes and wetlands in the Mackenzie Delta; peatlands in the Mackenzie Valley; ponds and lakes in Keewatin, Mackenzie and Yukon regions of Canada; ponds, lakes and wetlands in the Hudson Bay Lowland and in northern Quebec. Unique limnological responses to climate warming would be many. Ponds and lakes would remain unfrozen for longer periods. The proportion of precipitation falling as rain rather than snow would increase. There would be a large increase in evapotranspiration and, unless matched by increased precipitation, ponds, lakes and wetlands would become drier or undergo completely summer drying. Surface and subsurface runoff would decrease with a more negative water balance and permafrost active layers would become deeper. Thermokarst would result from the melting of ice-rich permafrost. Existing lakes might drain and new lakes might be created.

General ecological responses would cover a wide range. With a longer ice-free season, cumulative primary production in lakes would increase unless offset by a greater turbidity which limits light penetration. Greater turbidity could be caused by increased bank erosion, slumping, or subsurface drainage through permafrost ice wedges, resulting in lake drainage. Generally, primary producers would be expected to undergo increased growth, but the response of secondary producers might vary, depending on magnitude of temperature increase and impact on food supply. In the open subarctic forested areas, under warmer and drier scenarios, trees would be encouraged to migrate into shallow lake and pond areas and into peatlands, leading to ecological change. Under warmer and wetter scenarios, lake and woodland environments would be preserved.

The most important variable affecting the carbon balance of peat lands is the water balance because it controls the size of the aerobic and anaerobic layers. A second variable is temperature. Productivity and decomposition rates are related to temperature once the general level of saturation has been accounted for. Thus both the thermal and precipitation changes which accompany climatic change act synergistically in controlling the carbon budget. Tundra lakes are recognized as an important source of carbon to the atmosphere and as with peatlands they also are responsive to water balance and temperature changes. An interesting case of water-balance synergism between river and lakes is presented. The multitude of lakes and ponds in the Mackenzie Delta are heavily dependent on ice damming during breakup of the Mackenzie River, whereby bank overflow renews their water supply to redress a general annual negative water balance. Warmer temperatures with more evaporation plus fewer ice dams or earlier occurrence of ice dams, would promote the disappearance of lakes and greatly influence the ecological and carbon status of the Delta.

Preliminary Recommendations

Future research plans must recognize the need for experiments and observations in several areas which include the following: 1) Measurement programs for representative peatlands, lakes and ponds, in the high arctic, low arctic and subarctic; 2) Continuous measurements of primary productivity and components of the carbon balance of lakes, ponds and peatlands over a period of several years to establish the interannual variability of net productivity; and 3) Studies into the biological histories of lakes and ponds and into the accumulation of carbon in peatlands. These should relate to the last few hundred years in order to put the measurements outlined above into context. There is a fundamental need for basic studies of all lake and wetland processes in terms of changes in temperature and the water-balance.

Region 3. - Rocky Mountains in the U.S. and Canada

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Steve Hostetler, George H. Leavesley, Peter R. Leavitt, Lyndon C. Lee,
Diane M. McKnight, and Jack A. Stanford

Regional Description

The Rocky Mountains in the U.S.A. and Canada encompass the interior cordillera of western North America from the Stikine Range in southern Yukon (63°N) to the Sangre de Cristo Range in northern New Mexico (35°N). The Rocky Mountain region is composed of multiple mountain ranges generally oriented in a north-northwest to south-southeast direction. Landscapes are a reflection of the very dynamic geologic, hydrologic and glacial processes that formed and sculpted the region. Complex sedimentary and igneous formations provide markedly different concentrations of solutes. Elevation gradients >3000 m are prevalent and exhibit distinct patterns of climate and vegetation. Alpine, subalpine, and montane valley life zones are dominant features. Temperatures tend to vary more along local elevation gradients than the latitudinal gradient.

Annual weather patterns are cold in winter and mild in summer. Cold fronts associated with low atmospheric pressure can result in snowfall any day of the year in alpine and subalpine areas. Winter temperatures and winds in the alpine are frequently severe. Precipitation has high seasonal and interannual variation and may differ by an order of magnitude among geographically very close locales, depending on slope, aspect, and local climatic conditions. The region's hydrology is characterized by the accumulation of winter snow and increased stream flows in the spring and early summer. During the 2-3 month "spring runoff" period, rivers frequently discharge >70% of their annual water budget and have instantaneous discharges 10-100 times greater than mean low flow.

The region contains the headwaters of many of the continents great river basins (e.g., Rio Grande, Missouri, Saskatchewan, Mackenzie, Yukon, Columbia, Colorado). Larger streams and rivers (4-7 order) of montane valleys are characterized by well-sorted alluvial gravels providing a high degree of connectivity between surface and subsurface ground waters. Extensive hyporheic habitats (10^2m scale laterally and 10^1m scale vertically) and associated communities often play a fundamental role in the structure and function of the river ecosystem. Although in glaciated valleys pothole wetlands are common, the most prevalent wetlands are associated with river margins, especially flood plains. These riverine wetlands are often surficial expressions of paleo-river channels and are hydrologically connected to the extant river via networks of hyporheic conduits. The tens of thousands of alpine and subalpine lakes of the region represent a broad array of climatic and geologic conditions and floral and faunal histories.

Potential Responses to CO_2 Doubling

Complex weather patterns characterized by high spatial and temporal variability make predictions of future conditions tenuous. However, general patterns are identifiable; north and western portions of the region are dominated by maritime weather patterns from the North Pacific, central areas and eastern slopes are dominated by continental air masses, and southern portions receive seasonally variable atmospheric circulation from the Pacific and Gulf of Mexico. Significant interannual variation occurs in these general patterns, possibly related to ENSO forcing. Uncertainties associated with prediction are increased by the planting of fish in historically fishless, high mountain lakes and wholesale introduction of exotic species of fishes and invertebrates into often previously simple food webs. Many of the streams and rivers suffer from the anthropogenic effects of extraction and regulation. Many of the large lakes receive increased nutrient, suspended sediment and contaminant loads from a growing human population.

Temperature changes could have significant effects on the distribution and abundance of plants and animals. Changes in timberline elevation are largely temperature dependent. Paleolimnological investigations have shown significant shifts in phyto- and zooplankton populations as small mountain lakes shift between being above or below timberline. Likewise, streamside vegetation has a significant effect on stream ecosystem structure and function. Change in stream temperature regimes will likely result in significant change in community composition of both lakes and streams as a consequence of bioenergetic constraints. Stenothermic species could be extirpated as appropriate thermal criteria disappear. Warming temperatures may geographically isolate cold-water stream fishes in increasingly confined headwaters. Heat budgets of large lakes may be affected resulting in a change-of-state from dimictic to warm monomictic in character.

Changing hydrologic regimes may significantly affect late summer stream flow, as well as the peak and duration of spring runoff. A significant change-of-state could occur if continuously flowing streams become intermittent and long-lived species are extirpated. Interaction between earlier spring warming and precipitation could result in an earlier and more extended runoff. Potential consequences of these hydrologic changes are manifold, affecting vertebrate and invertebrate life histories, physiochemical properties of lotic systems such as stream power, bed load, and concentration and flux of organic particulates and solutes.

Preliminary Recommendations

We concluded: 1) regional climate models are required to adequately resolve the complexities of the high-gradient landscapes; 2) extensive wilderness preserves and national park lands, so prevalent in the Rocky Mountain Region, may provide sensitive areas for differentiation of anthropogenic effects from climate effects; and 3) future research should encompass both short-term intensive studies and long-term monitoring studies developed within comprehensive experimental designs.

Region 4. - Mid-Atlantic and New England

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Carol L. Folt, Harold F. Hemond, Robert W. Howarth, John R. Mather,
Peter S. Murdoch and Michael L. Pace

Regional Description

Water-rich and, in places, densely populated by humans, this region extends along the East Coast of North America from Nova Scotia to Chesapeake Bay and westward to include much of the Ohio River drainage basin. Freshwater ecosystems are abundant and diverse, in part, due to the Wisconsin glaciation, the altitudinal relief of the Appalachian Mountains, and the presence of the Atlantic coast. For example, 11,500 lakes and reservoirs (surface area > 1 ha) occur in New England, New York, and New Jersey. South of the Wisconsin glaciation (all mid-Atlantic and interior states excluding New York), however, natural lakes are largely absent and replaced by reservoirs. Lotic habitats range from cold-water streams in the Appalachian Mountains to large turbid rivers along the Atlantic coastal plain. More than 480 estuaries (> 2 sq km), including the largest estuary in the United States, occur here, and this density is second only to that in the southeastern region of the United States. Finally, at least 6% of the land area is covered by wetlands and, of this, 92% is freshwater wetlands, predominantly red-maple swamps or, west of the Appalachians, riparian wetlands.

Despite the diversity and abundance of freshwater ecosystems, most have been and are currently influenced by the activities of humans. For example, the forested watersheds of many 'pristine' lakes located in northern New England and New York state were sites of intensive agriculture or silviculture in the 1800s. Today, the watersheds of many of these lakes have reverted to forest, but humans continue to influence these lakes via recreation, development, forestry practices, and atmospheric deposition. In the western portion of the region (KY, OH, WV, western PA), the cycle of extensive deforestation and reforestation has also occurred. Today, however, acid mine drainage and nonpoint pollution from agricultural activities degrade streams and some reservoirs. At present, coastal areas contain the highest human population densities in North America although some areas to the west are rural. Because population densities are forecasted to increase at the same time that climate is expected to be changing, an assessment of how climate change may interact with the direct impact of humans is essential.

The general climate, at present, is humid continental with warm to hot summers (mean July temperature = 20.1°-25°C) and cool to cold winters (mean January temperature = 5.0° to -9.9°C). The region receives abundant precipitation (1350 - 1500 mm/yr), and annual variability of precipitation is lower in the Northeast than any other region of the United States with extremes departing only about 10% from the mean. Air and water temperatures have warmed in at least parts of the region over the past 70-150 years. For example, in central New Hampshire, historical records of air temperature reveal an increase both annually (1.7°C) and in summer (2.2°C) over the last 150 years. Water temperatures in the Hudson River have increased 0.12°C per decade between 1920-1990.

Potential Responses to CO_2 Doubling

Climatic projections suggest warmer and drier conditions for much of this region under conditions of a 2X CO2 atmosphere. Temperature and precipitation projections generated from GCMs were used in a water balance model (Thornthwaite-Mather model) to estimate changes in evapotranspiration, water surplus, and runoff for the region. Annual temperature increases ranging from 3°-5°C are projected, with the greatest increases occurring in fall or winter. Annual precipitation projections vary spatially across the region. Convective summer storms, however, will probably become less frequent but more severe throughout the region. According to the water balance model, the projected increase in temperature will result in greater rates of evaporation and evapotranspiration (any possible antitranspirent effect of increasing CO_2 has not been included in the model), thus causing decreases in stream flow for most of the region. For example, a 12 to 32% reduction in annual stream flow is projected for the Delaware River Basin, and these reductions are more likely to occur in fall and winter. Additional factors likely to exacerbate climatically induced reductions in flow include dam construction and diversion of water between drainage basins to meet human water needs.

Large metropolitan areas, common to this region, generate distinctive climates which may, in some ways, represent a microcosm of global climatic change. For example, annual average temperatures in urban areas are 1°-3°C warmer than nearby rural areas of comparable topography. On some days, however, urban areas can be as much as 12°C warmer than nearby rural areas, and the magnitude of the urban heat island effect increases with population density. Consequently, average temperatures within the heat islands of many cities have risen by an order of magnitude more than the global temperature average over the last century. Runoff flowing from urban areas is warmed due to water flowing over hot pavement, and greater amounts of runoff flow from urban watersheds due to the impervious surfaces of asphalt and concrete. Consequently, some aquatic ecosystems located in urban areas may provide 'natural laboratories' for measuring how aquatic systems accommodate to climate change.

Humans and their direct impact on aquatic ecosystems are likely to increase in this region over the next 50-100 years. Thus, we chose to focus on ways in which climate change may interact with anthropogenic factors to affect freshwater ecosystems. Five examples of such interactions were identified to exemplify the types of effects that may occur. First, acidification events in streams and lakes may become more episodic and possibly severe. Nitrate, deposited on the watershed as both wet and dry deposition, may be washed out of watersheds during storm events. Thus, if rain events become less frequent, nitrate export would likely become more episodic, potentially resulting in greater acidification during episodes. Second, primary production in estuaries may be altered by climate change. For example, if freshwater discharges to estuaries decrease, stratification in estuaries may lessen, resulting in deeper mixing of phytoplankton and greater light limitation of production. Reduced freshwater discharges may also result in lower input of allochthonous carbon and nutrients, although changes in land use may be a more important control on such allochthonous fluxes. Third, the intensity of direct and indirect effects of inorganic and organic contaminants on lake and stream food webs may be enhanced by climatic change. Direct effects of temperature and toxicity on bioaccumulation and lethal and sublethal responses in different aquatic species may cause changes in food web structure. At the same time, changes in food web structure can affect the rates and degree of biomagnification of these toxins to consumers at the top of the food web. Fourth, fragmentation of riparian forests will expose streams to increased amounts of solar radiation, and this may exacerbate effects of climatically induced warming on lotic communities (e.g., fisheries, invertebrates). Finally, both climatic change and human modifications of the hydrologic budgets of wetlands may result in partial drying, altering their ability to filter or trap nutrients, heavy metals and other ionic constituents.

Preliminary Recommendations

Three recommendations regarding future research were identified: 1) developing and refining projections of climate variability such that the magnitude, frequency, and seasonal timing of extreme events can be forecasted, 2) describing quantitatively the flux of materials (sediments, nutrients, metals) from watersheds characterized by a mosaic of land uses, 3) and comparing climatically induced changes of community and ecosystem processes among habitats differentially impacted by humans.

Region 5. - Southeastern U.S. and Gulf Coast Mexico

Patrick J. Mullholland, G. Ronnie Best, Charles Coutant, George M. Hornberger,
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Regional description

This region, encompassing the Southeastern United States and Eastern Mexico generally has a humid, warm temperate to subtropical climate. Freshwater ecosystems are characterized by extensive land-water interfaces (e.g. abundant wetlands, high edge to volume ratios) and a high diversity of organisms (particularly fish, reptiles, amphibians, and invertebrates), including many endemic species. The region is experiencing extensive impacts from urbanization, from large surface water demands with concomitant management issues, and from the introduction of exotic species. The effects of changes in climate on freshwater ecosystems may be accentuated by these human-induced stresses. Over the past forty years there has been a general decline in mean air temperature, while precipitation and runoff have increased over some parts of the region.

Potential Responses to CO_2 Doubling

In the face of uncertainties about exactly how climate might change in the region, we considered the types of changes that might occur in aquatic systems assuming that mean temperatures are likely to rise and significant alterations of the hydrologic cycle are likely to occur. Results from GCM's suggest mean temperature increases of up to 3°-5°C for the region under a 2X CO2 scenario. Changes in precipitation and other elements of the hydrologic cycle are much less certain. Model results suggest that there may be an increase in precipitation over much of the region. Analyses based on the expectation that the hydrological cycle will be intensified indicate that the frequency of weather events may be altered; i.e., hurricane frequency may increase, rain events may be more clustered in time due to increases in convective storm activity, summer droughts may be more common.

There are several climate features of particular importance for the region and significant changes in freshwater ecosystems may occur as a result of changes in these climate features. Average annual air temperature defines (1) the habitat for coolwater species via the control of ground-water temperature, (2) the growing season for wetland vegetation, (3) organic-matter decomposition, and (4) the physiological balance between respiration and growth. Habitat for coolwater species, such as brook trout in the southern Appalachians, would be substantially reduced if temperatures of groundwater discharging to streams and reservoirs increase. A general warming in the region would lead to longer growing seasons, which might increase net primary productivity in wetlands. Organic-matter decomposition would be likely to increase with temperature, thus intensifying biogeochemical cycling and increasing emissions of CO_2 and CH_4. Summer air temperatures and radiative heating control runoff via effects on evapotranspiration rates and determine the maximum temperatures in open waters. Higher air temperatures would tend to increase evapotranspiration and thus reduce runoff, although increasing atmospheric CO_2 concentrations might counteract this by increasing plant stomatal resistance. Increases in summer maximum temperatures in impoundments, reservoirs, and larger rivers would reduce habitat for fish with low thermal tolerance limits (e.g., striped bass), increasing stress and susceptibility to pathogens and parasites. Increased demand for electricity in summer may result in increased waste heat discharges to many waters, thus exacerbating summer water temperature problems. Minimum winter air temperature establishes the range of subtropical species. Increases in winter air temperatures, particularly the winter minimum, might result in expansion of subtropical species northward from their present limits in Florida and Mexico. This expansion might include a number of nuisance species, such as the wetland plant *Melaleuca quinquenervia* or the walking catfish *Clarias batrachus*. Northward shifts in agriculture requiring warmer winters, such as citrus, might lead to the replacement of forests and to increased eutrophication.

The duration of summer drought periods is another critical climate feature of the region. Summer droughts limit habitat through reduction in dissolved oxygen concentrations, degrade water quality, and restrict the seasonal flooding of Florida wetlands, enhancing their susceptibility to fire. Increased surface- and ground-water demands by humans would exacerbate summer low-flow problems in rivers, reservoirs, and wetlands (particularly Florida wetlands). The size and duration of rain events control erosion and sedimentation stresses as well as nutrient inputs to freshwaters. Under scenarios of increased storm size and frequency, higher peak stream flows would likely increase sediment loads, leading to reduced habitat for stream fish and invertebrates (including many endemic species). Such an effect would be superimposed upon the already serious problems of increased sediment load and habitat loss (channel modification) due to urbanization. Similarly, greater runoff from urban and agricultural lands due to intensified precipitation events would increase the input of nutrients and toxic substances to freshwaters. Finally, winter/spring rainfall events define wetland hydroperiods (north of Florida), river-floodplain interactions, and the flushing of reservoirs and estuaries. Depending on overall changes in the water balance, wetlands might be expected to expand, although present and future land use might prevent such a response. If river flows increase, estuarine flushing rates would also increase. The resulting decreases in salinity and increases in stratification could lead to greater anoxia and reduced habitat. For example, shrimp production in the Gulf of Mexico has been shown to be inversely related to Mississippi River discharge.

Preliminary Recommendations

Continued work to improve predictions of climate change on a regional basis and our understanding of how climate variables affect aquatic ecosystems are essential if we are to manage successfully the aquatic resources of this region. Long-term records of climatic, hydrological, and ecological variables are invaluable in this regard. These records must be continued and they must be used in synthesis activities. Selected new data acquisition activities must be initiated in the region to provide the data that will be needed in the future. For example, long-term records of precipitation and runoff in forested catchments can be used to identify trends in evapotranspiration. Similarly, long-term records of the temperature of streams and near-surface ground waters may prove to be a sensitive indicator of ecologically important temperature changes. Populations of keystone (ecological) or temperature-sensitive species should be monitored in different habitats. Experimental studies on the effects of warming on organisms and ecosystems must be initiated. Studies aimed at identifying how flow management decisions affect ecological processes should be conducted. Erosion control strategies must be developed and tested further, and a better understanding of the relationships between land use, hydrological, and ecological characteristics must be developed.

Region 6. - Pacific Coast Mountains

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Regional Description

The Pacific Coastal Mountains and Western Great Basin spans 30 degrees of latitude from southern Alaska (64°N) to southern California (34°N) and range in altitude from sea level to 6200 m asl. Orographic effects combine with moisture-laden frontal systems originating in the Pacific Ocean to produce areas of very high precipitation on western slopes, and dry basins of internal drainage on eastern flanks of the coastal mountains. Seasonal temperature variation is moderated by the proximity of the ocean. In the southern half of the region most of the runoff occurs during the winter or early spring while in the northern part most of the runoff occurs in the summer, especially in the glacerized basins. Climatic anomalies such as ENSO events can produce very large interannual differences in runoff.

Numerous small to medium sized rivers and small, high elevation lakes occur throughout the region. Several large freshwater and saline lakes are also prominent, as is San Francisco Bay. To the north, glacerized basins increase and are especially common in Alaska. Human-caused impacts on the aquatic habitats of the region are considerable in the more populated southern coastal areas but are small in much of the northern portion and at high elevations. Extensive schemes to divert water for human uses have been constructed in California. Estuaries have been diked and filled, have received diminished freshwater inflows and have had multiple introductions of exotic species.

Potential Responses to CO_2 Doubling

Use of the outputs of climate models to formulate scenarios of climate change resulting from a doubling of atmospheric carbon dioxide to the region is problematic. Existing GCM's have too coarse a spatial resolution for the topographically complex terrain in the long, narrow region. Atmosphere-ocean interactions and important climatic anomalies such as ENSO events are not adequately incorporated. Predictions of changes in precipitation are equivocal for the western coast of North America. Moreover, nested mesoscale models have not yet been developed for use on a long-term climatic basis. Hence, climate models were deemed inappropriate for defining climate change for the region.

Instead, analyses of long-term historical climatic and hydrological records combined with paleoclimatic reconstructions are used to develop likely scenarios of climatic variations. Important features of these scenarios are an emphasis on changes in climatic variability rather than in average conditions, and inclusion of shifts in large-scale weather patterns that can produce anomalies such as ENSO events. Climatic scenarios derived from time-series data for the region include warming trends, changes in the frequency and intensity of ENSO and other atmospheric patterns.

Several consequences of the potential scenarios of climatic change are of special relevance to the Pacific Coastal Mountain region. An increasing fraction of rain in precipitation will alter the timing and volume of runoff, and will increase the atmospheric loading of solutes. Changes in the volume and timing of discharge will influence mixing dynamics in lakes and alter sediments transport and hydrodynamical conditions in streams. Modifications of temperature regimes will impact breeding and growth of important fish such as salmon. Changes in glacial mass balance will increase or decrease runoff and modify riverine temperatures with concomitant effects on aquatic vertebrates and invertebrates.

Approaches for evaluation of possible responses of aquatic ecosystems to potential consequences of climatic change range from mechanistic, quantitative models to empirical models to analyses of long-term data sets to qualitative hypotheses. All four approaches have been applied to the Pacific Coastal Mountain and Western Great Basin region. The incidence of meromixis in saline lakes and the associated reduction in nutrient supply and algal abundance were determined with a mechanistic model used in conjunction with historical records of stream discharge. By statistically relating meteorological factors controlling primary productivity in subalpine lakes to GCM outputs, increased productivity with global warming was calculated based on two of three GCM's used. Time-series spanning two to three decades indicate that lacustrine productivity can be significantly altered by (1) especially strong winds effecting deep mixing, (2) drought-enhanced forest fires, and (3) maximal and minimal snowpacks associated with ENSO events.

Preliminary Recommendations

Research and monitoring activities should include (1) further synthesis of historical and paleoclimatic records, (2) expanded monitoring activities at high elevations, (3) continued monitoring of existing sites with addition of rivers with unaltered flows, (4) continued and increased mass balance studies of glaciers and (5) applications of remote sensing to monitoring and experiments. Relevant variables amenable to remote sensing include snow covered area, water vapor profiles and fluxes, cloud cover, radiation and land cover. Additional areas ripe for further research include ecotones as indicators of climate change, and analyses of fire frequency and influence on optical and nutritional conditions in lakes.

Region 7. - Western and Northern Plains

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Regional Description

This region is characterized by relatively low topographic relief and steep gradients in precipitation (aridity increases from east to west) and in water temperature (summer-heat extremes vary from south to north). The northern boundary is delimited by a discontinuous permafrost line. Weather patterns are dominated by the interactions of several air masses: 1) westerly airstreams with moist air that moves eastward from the Pacific and in southern subregions lose most of their moisture as snowfall over western mountains; 2) warm, moist tropical airstreams from the Gulf of Mexico, which are the major source of moisture from the Western Plains; and 3) cold, dry Arctic airstreams from the north. Shifts among these air masses can rapidly change meteorological conditions. An east-to-west transition zone from forest to prairie spans the northern subregion. This transition zone is known to have moved eastward and then westward over the last ca. 800 years in response to climate change. Grasslands comprise the dominant terrestrial vegetation throughout the mid-continent as a result of low rainfall and frequent natural fires. Soils and runoff waters range from neutral to acid in the eastern plains and from neutral to alkaline in the western plains.

The climate-sensitive aquatic ecosystems in this region range from spring-fed streams and rivers with uniform, relatively cool waters and permanent flows to temporary habitats with highly variable flows and temperatures in numerous intermittent streams, ponds, and playas. The major natural aquatic ecosystems are large-river drainage networks with extensive distributions of ponds and wetlands. Historically, these large rivers had wide and braided channels, but most of these rivers have been greatly modified by dams, dikes, and channelization. The Mississippi River drainage covers most of the interior of this region. Shallow oxbow lakes, deflation basins, playas, and buffalo wallows are also typical habitats in the southern subregion. Glacial-originated, deep lakes and shallow pothole lakes are typical of the northern subregion. Riparian forests along some prairie streams and wooded sections along Ozark and Oachita Mountain streams influence water temperatures through seasonal shading.

Water balances and heat budgets are available for several well-studied lakes and wetlands, although flood-control storage reservoirs and water diversions complicate estimates of runoff and discharge. Many basins are among the continent's most agricultural productive zones and have fine-scaled, spatially explicit, long-term climatic records. Intensive data on runoff and sediment loads are also available throughout much of this region. Many aquatic ecosystems in this region receive runoff from fertilized drainages and localized, point-source nutrient additions from feed lots and urban centers. The shallow-water habitats tend to be eutrophic although many are highly turbid and have their aquatic productivity limited by light availability. Flood-plain dynamics in wetlands are a major control over nutrient cycling in this region. Channelization and dams have greatly altered rates of nutrient cycling and large-river productivity.

Data are available from streams with long records (>50 years) of discharge and from historic documentation of lake-level changes in potholes and lakes. Deep lakes with long sedimentary records and tree-ring chronologies provide high-resolution information on rapidly changing regional climates during the last 11,000 years. Detailed estimates of annual precipitation over the past 300 years have been reconstructed from tree-ring studies in some basins. Droughts and floods (such as the 500-year flood event of 1993) provide evidence of recent variability of freshwater ecosystems.

Potential Responses to CO_2 Doubling

Droughts and floods (such as the 500-year flood event of 1993) provide striking evidence of recent variability. The region's spatial heterogeneity in climatic variability has been intensively studied in highly instrumented catchments and from paleoecological records extending back 11,000 years. Past climate-driven changes in the frequency and intensity of extreme drought and/or temperatures are known to have significantly altered freshwater ecosystems in the plains by lowering lake and stream levels and by increasing salinity. Future climate changes are anticipated to have periods of highly variable precipitation regardless of the nature of the driving force, be it greenhouse warming, ENSO, or other meteorological phenomena. However future climate changes may alter this region's freshwater ecosystems, the cumulative effects of intensive land use will likely accelerate specific surface impacts on biotic communities and associated ecosystem processes.

By 2030, several GCM's project that this region could be on average 2° to 4°C warmer in winter and 2° to 3°C warmer in summer. GCM's also project shorter growing seasons as a result of less precipitation.

Many shallow-water habitats during late summer are already at extremely high temperatures and any additional increases in water temperatures or lowering of water levels are likely to be highly detrimental to native species. For example, streams in the southern Great Plains currently have some of the hottest free-flowing water on earth, with summer maxima of 38° to 40°C. Native fishes that survive in these waters are already near their lethal thermal limits. Increased extinction rates for these endemic species and isolated local populations are clearly likely if water temperatures exceed current maxima because of restricted routes for migration to cooler waters. Warming of groundwater and spring-fed streams is also a distinct possibility but modeling of these complex relationships has not progressed adequately.

Reduced water depths would be expected to increase penetration of UV-B radiation and to alter foodweb dynamics. Effects of reduced runoff of dissolved organic carbon and shifts in associated water color are also expected to alter UV-B penetration. Rapidly lowered water levels could reduce growing seasons for littoral and wetland vegetation by mid-summer. The resulting lower annual productivity would probably modify composition of grazer/detritivore foodwebs as well as shorten foodweb length. Warmer springtime temperatures could shift productivity of emergent and submerged macrophytes, perhaps offsetting shorter growing seasons with compressed life-histories. These alterations in primary productivity and temperatures are also expected to influence rates of decomposition and deoxygenation thereby restricting many species, especially fishes, to lower quality habitats.

Simulations of projected water level changes as a result of 2X CO2 atmospheric increases have suggested that semi-permanent prairie pothole wetlands will be sensitive to changes in evaporation and precipitation. These simulations provide a basis for estimating future declines in waterfowl production resulting from lower water levels.

Preliminary Recommendations

We conclude that sufficient data are available for several subregions to generate some likely consequences of increased warming and decreased precipitation. Because these climate-change effects will be compounded by changes in land use and policy shifts over the next several decades, we expect that some dramatic and clearly observable changes will be documented. Interpreting relationships among these various sources of ecosystem change will require maintaining current long-term data collection sites. An early assessment of the current data is needed to determine which subregions are lacking adequate data.

Region 8. - Basin and Range, Arid Southwest and Mexico

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Regional Description

The Basin and Range, Southwest and Mexico Region encompasses predominantly arid and semi-arid lands of western North America from the state of Oregon (48°N) in the United States to Oaxaca (18°N) in Mexico. Because the region transcends a wide latitudinal range, there are gradients in mean annual temperature (highest in south) and annual temperature range (highest in north). Gradients in seasonality of precipitation also are pronounced within the region, with summer rains predominant in southern and eastern sub-regions and winter rains in northern and western sub-regions; the Sonoran Desert (near the region's geographical center) experiences bimodal precipitation. The scarcity of surface water is a distinguishing feature of the region; mean annual precipitation ranges from <100 mm to 700 mm (except in the extreme southern portion); runoff comprises an average of less than 20% of precipitation, freshwater inputs to oceans are minor; and about 30% of the region's drainage is endorheic. Because water is so scarce, abuse of this resource (imprudent impoundment, flow diversion, groundwater withdrawal) via pressure from expanding human populations represents the greatest anthropogenic threat.

Most types of aquatic ecosystems are represented in the region, especially when higher elevations are included (because higher elevations are generally less arid than lowlands). Regional generalities are the paucity of natural lakes (those that exist tend to be terminal lakes), the prevalence of temporary waters (ephemeral and intermittent streams, tinajas, playas), large rivers all arise in more temperate high elevations and are regulated in lower reaches, and many aquatic ecosystems are isolated and support a high degree of endemism. Mexico, in particular, is ranked 5th globally in terms of its biodiversity. Despite their limited extent, riparian and hyporheic zones and marginal wetlands are especially important aquatic habitats within this arid/semi-arid region.

Potential Responses to CO_2 Doubling

Climate models poorly describe dynamics of the region's climate. GCM's are too coarse to deal adequately with mountainous regions such as the Basin and Range. Regional models suffer particularly in arid/semi-arid regions even if they accurately predict temperature, because even slight errors in precipitation estimation are amplified in runoff estimates. Physically based hydrologic models are appropriate for small areas (e.g., small drainage basins) but do not scale well to large regions. Time-series analysis of hydrologic data holds the most promise for understanding the climate-hydrology interaction; however, the drawback of this approach is that it assumes past climates are representative of future ones. This working group concluded that models, with the possible exception of time-series analyses, were of limited utility in generating climate change scenarios for the region.

There is no evidence for directional, greenhouse-induced change in climate, hydrology, or aquatic ecosystems of the Basin and Range, Southwest and Mexico region. However, there is abundant evidence of periodic phenomena, past climates that differed dramatically from current ones, and anthropogenic impacts (through water use) on aquatic ecosystems. Seasonal flow and flooding in both mountain and desert streams of the Southwest are responsive to ENSO forcing. The summer monsoon of the Southwest and Mexico varies in intensity in response to global-scale circulation phenomena and may have been enhanced during warmer Holocene time. As a rule, both lake levels and streams flows show tremendous interannual variability; chemical and ecosystem processes vary as a result of this fluctuation. Finally, many ecosystems have undergone dramatic changes or have disappeared entirely because of over-extension of limited water resources. All variable evidence suggests this is a threat that far outweighs that presented by CO_2-induced global warming.

Since neither global nor regional models are sufficiently complex to predict even the direction of change in precipitation, much less the hydrologic response for this region, we decline to select a scenario based on climate or hydrologic models. Instead, we selected for consideration the most potentially damaging scenarios of climate change. As aquatic ecosystems are likely to be most sensitive to reduced precipitation (this would threaten the existence of many aquatic systems that now are only marginally aquatic), we consider scenarios of: reduced overall precipitation; reduced summer precipitation; reduced winter precipitation. We also consider impacts of a change (enhancement or reduction) in the variability of precipitation and runoff.

In considering the impacts of selected scenarios, it is useful to place potential changes in driving and response variables into a context defined by the relevant temporal scales over which they operate. Changes in "mean climate" - physical variables such as annual precipitation, runoff ratio, lake level - occur on the scale hundreds of years. Species and ecosystem processes that can adjust to changes within that time period are likely to be robust in the face of such changes. Entire ecosystems, however, such as many small desert springs in Nevada, may be at risk if climate shifts to drier conditions - and the raw material for evolutionary change is almost certainly insufficient to permit adaptation of aquatic organisms to terrestrial conditions! Even if mean climate remains constant at the 10^2-year scale, greenhouse-forced changes may occur at the 10^1-year scale, in driving variables such as frequency or severity of El Nino episodes. This brings global events into play in determining interannual variability. Such interannual variability in precipitation-streamflow coupling in the Sonoran Desert influences transport of nitrogen to aquatic ecosystems and groundwater: floods that follow several years of drought carry higher loads than those occurring during wetter periods. Change at the 10^0-year scale, such as shifts in seasonality of precipitation and/or runoff, can have a profound impact on aquatic ecosystems particularly in this region where precipitation and streamflow are so distinctly seasonal. Finally, high flow events defined by aquatic ecologists as disturbances, although they may have recurrence intervals of 10^1 to $>10^2$ years, occur over periods of days or weeks and their impact is thus measured on the scale of 10^{-1} years. In the Basin and Range, Southwest and Mexico region, extreme variability is the norm and thus aquatic ecosystems and the organisms within them may be relatively robust to changes in climate expressed at these shorter time scales.

Within any of these time scales, extreme events or thresholds may occur that force the system into a new state. Ecosystem sensitivity may be viewed in terms of thresholds within the temporal framework outlined earlier. An ecosystem (or its components) that is altered by extreme events occurring within a year is sensitive at the lowest temporal scale, whereas a system that can persist despite shifts in seasonality, variability (such as flood events), and even 3-5 year low or high flows, may be sensitive only at the longest time scale. In the Great Salt Lake, Utah, trophic structure was profoundly altered by extreme low salinity (corresponding to high lake level) that allowed a predator intolerant of high salinity to invade. The process of invasion and ensuing changes in food web structure occurred over one or two years, thus this ecosystem component is sensitive to the interannual scale of variability in water inputs.

Preliminary Recommendations

For the Basin and Range, Southwest and Mexico region, research and monitoring activities should focus on: reconstruction and analysis of past climates and associated ecosystem characteristics; continuation and/or initiation of long-term studies to discriminate directional change vs. year-to-year variability; and studies of human-impacted ecosystems. The last could be accomplished via a comparative ecosystem approach wherein relatively unaltered ecosystems are compared with highly manipulated ones. Aquatic ecosystems may be most effectively managed in the context of global climate change if both the more pressing anthropogenic threats and the occurrence of extreme events are considered and incorporated into management plans.

Conclusions

Colbert E. Cushing

Despite the expected challenges associated with considering 2X CO2 scenarios from GCMs, some general patterns can be identified. Potential ecosystem responses in several regions were linked to changes in transpiration and evapotranspiration rates, and these, in turn, were further linked to interactions with stream-flow and water-temperature changes. And for some regions, catchment-wide interactions had overriding influences on changes at the stream- and lake-ecosystem level.

Climate changes ranged from fairly straightforward predictions of warmer and drier conditions in the Mid-Atlantic and New England region to one of complete unpredictability, even in the direction of change, in the Basin and Range, Arid Southwest and Mexico region. Oftentimes, it was valuable to consider the 2X CO2 scenarios in the context of historical and annual variations in climate, hydrology, and ecosystem characteristics.

Postulated responses of ecosystems and endemic organisms also varied widely, ranging from predictable detrimental impacts on species existing in warm waters already near lethal thermal conditions to dramatic increases in primary productivity and dependent food-webs in regions where increasing temperatures may extend ice-free conditions. Potential effects to endemic organisms were not always predicated on direct impacts, such as increased water temperatures, but often indirectly through links to changes in other ecosystem components. Examples of this are changing nutrient regimes resulting from increased or altered runoff patterns.

Regional Assessment of Freshwater Ecosystems and Climate Change in North America

October 24-26, 1994
Leesburg, Virginia

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