American Geographical Society

Alpine Areas in the Colorado Front Range as Monitors of Climate Change and Ecosystem Response
Author(s): Mark W. Williams, Mark V. Losleben, Hillary B. Hamann
Source: *Geographical Review*, Vol. 92, No. 2, Mountain Geography (Apr., 2002), pp. 180-191
Published by: American Geographical Society
Stable URL: http://www.jstor.org/stable/4140969
Accessed: 13/10/2008 16:55

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=ags.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

American Geographical Society is collaborating with JSTOR to digitize, preserve and extend access to *Geographical Review*.

http://www.jstor.org

ALPINE AREAS IN THE COLORADO FRONT RANGE AS MONITORS OF CLIMATE CHANGE AND ECOSYSTEM RESPONSE*

MARK W. WILLIAMS, MARK V. LOSLEBEN, and HILLARY B. HAMANN

ABSTRACT. The presence of a seasonal snowpack in alpine environments can amplify climate signals. A conceptual model is developed for the response of alpine ecosystems in temperate, midlatitude areas to changes in energy, chemicals, and water, based on a case study from Green Lakes Valley–Niwot Ridge, a headwater catchment in the Colorado Front Range. A linear regression shows the increase in annual precipitation of about 300 millimeters from 1951 to 1996 to be significant. Most of the precipitation increase has occurred since 1967. The annual deposition of inorganic nitrogen in wetfall at the Niwot Ridge National Atmospheric Deposition Program site roughly doubled between 1985–1988 and 1989–1992. Storage and release of strong acid anions, such as those from the seasonal snowpack in an ionic pulse, have resulted in episodic acidification of surface waters. These biochemical changes alter the quantity and quality of organic matter in high-elevation catchments of the Rocky Mountains. Affecting the bottom of the food chain, the increase in nitrogen deposition may be partly responsible for the current decline of bighorn sheep in the Rocky Mountains. *Keywords: alpine, bighorn sheep, biogeochemistry shift, climate change, nitrogen, water acidification.*

Many an alpine area is susceptible to environmental damages that may affect ecological health and regional economies (Dozier and Williams 1992). Moreover, small changes in the flux of energy, chemicals, and water in high-elevation catchments may invoke large changes in climate, ecosystem dynamics, and water quality. Climate change and ecosystem response may be reflected much earlier in alpine areas than in downstream forested ecosystems (Williams and Tonnessen 2000).

A decade ago, researchers began to evaluate the response of mountain ecosystems to changes in climate (Beniston 1994; Messerli and Ives 1997). Alfred Becker and Harald Bugmann suggest that the strong altitudinal gradients in mountain regions provide unique, and arguably the most useful, opportunities for detecting and analyzing global change processes and phenomena, because:

- Meteorological, hydrological, cryospheric, and ecological conditions change greatly over relatively short distances. The boundaries between these systems experience shifts due to environmental change and thus may be used as indicators of such changes.

* Tim Bardsley and Chris Seibold provided field and laboratory assistance. Funding assistance was provided by National Science Foundation grants DEB 9211776 and DEB 9810218 to the Niwot Ridge Long-Term Ecological Research site, by the Division of Environmental Geochemistry and Biogeochemistry of the National Science Foundation, by the Air Resources Division of the National Park Service, and by National Aeronautics and Space Administration, Earth Observing System grant NAGW–2602.

DR. WILLIAMS is an associate professor of geography and a research fellow at the Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado 80309–0450, where MR. LOSLEBEN is a professional research associate. DR. HAMANN is a visiting scholar in the Hulbert Center for Southwest Studies, Colorado College, Colorado Springs, Colorado 80903.

The Geographical Review 92 (2): 180–191, April 2002
Copyright © 2003 by the American Geographical Society of New York

- The higher parts of many mountain ranges are not directly affected by human activities. These areas include national parks and other protected environments. They may serve as locations where the environmental impacts of climate change, including changes in atmospheric chemistry, can be studied directly.
- Mountain regions are distributed globally, from the equator to the poles and from oceanic to highly continental climates. This global distribution allows us to perform comparative regional studies and to analyze the regional differentiation of environmental change processes as characterized above (2001).

In this article we focus on the role of snow in the alpine component of temperate mountain ecosystems. High-elevation ecosystems at midlatitudes are characterized by a six-to-nine-month period of continuous snow cover, with freezing temperatures and snow possible even throughout the summer growing season. The harsh environmental conditions characteristic of these environments suggest that organisms in alpine ecosystems are on the razor's edge of tolerance (Williams, Brooks, and Seastedt 1998). Consequently, organisms and the biogeochemical processes mediated by them may be sensitive to small environmental changes in climate and other parameters.

The presence of a seasonal snowpack in alpine environments may amplify climate signals. Mountain areas of the world have been termed "water towers for the 21st century" because of the storage and release of liquid water from the seasonal snowpack (Bandyopadhyay and others 1997, 134). Although the areal extent of alpine ecosystems is limited, snowpacks in these areas are the major source of stream runoff and groundwater recharge over wide portions of the midlatitudes. The contribution of mountain watersheds to the total surface runoff may be more than 80 percent in arid and semiarid regions such as the western United States and central Asia. The presence of snow in high-elevation areas may cause unexpected changes in streamflow in response to changes in climate at lower elevations (Williams and others 1996a). In addition to changes in water quantity, the quality of water may be changed if pollutants are added to snow and rain in alpine areas.

Our objective is to evaluate a conceptual model of how alpine ecosystems in temperate midlatitude areas respond to changes in energy, chemicals, and water. We illustrate the model's workings with a case study from Green Lakes Valley–Niwot Ridge, a headwater catchment in the Colorado Front Range of the United States, emphasizing how changes in the quantity and quality of snow may affect the quality of water (Figure 1). We build on current and past research activities conducted at this long-term study site (for an overview, see Bowman and Seastedt 2001).

The Study Site

The Colorado Front Range rises directly west of the Denver–Boulder–Fort Collins metropolitan area. The setting means that high-elevation basins in this portion of the Continental Divide are located just beyond a large metropolis, with nearby agricultural activities. Green Lakes Valley (40°3′N, 105°35′W) is a 700-hectare, east-

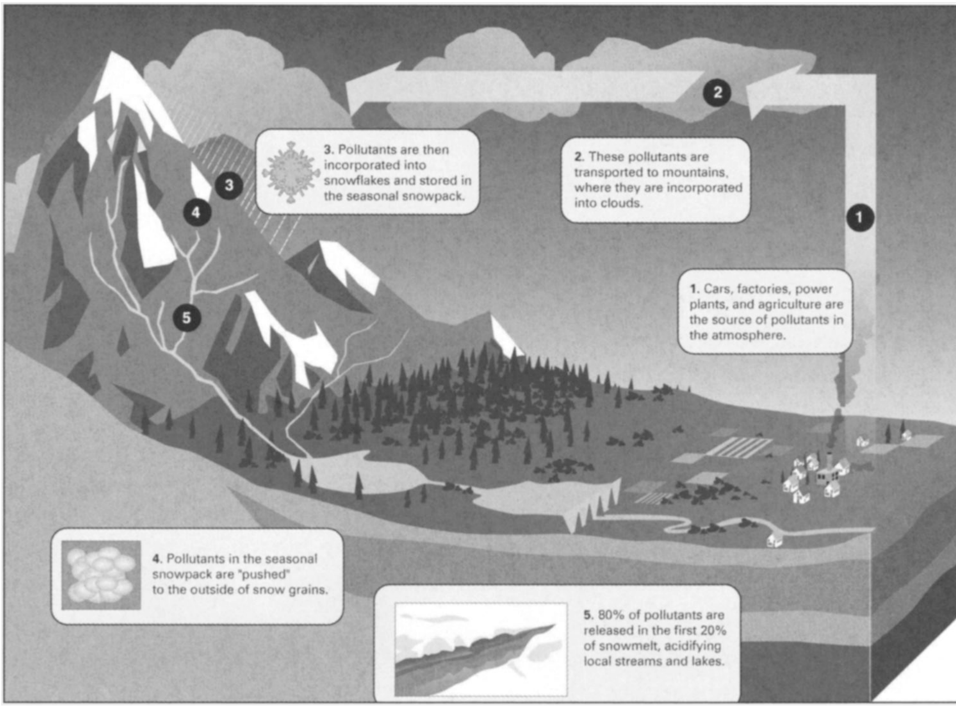

FIG. 1—Conceptual model of the importance of snow in moderating changes in energy, chemical, and water in seasonally snow-covered catchments. Small changes in the quantity and quality of snowfall may cause large changes in the quality of stream waters because solutes are stored in the seasonal snowpack for many months before they are released in the form of an ionic pulse.

facing headwater catchment that ranges in elevation from 3,250 meters to about 4,000 meters at the Continental Divide (Figure 2). The catchment appears to be typical of the high-elevation environment of the Colorado Front Range and includes Niwot Ridge, where research has been conducted since the early 1950s (Caine and Thurman 1990). This is both a UNESCO Biosphere Reserve and a Long-Term Ecological Research network site. The Green Lakes Valley is a water source for Boulder and is owned by the city. Public access is prohibited; hence the Green Lakes Valley is not affected by grazing or recreational activities, as are other high-elevation sites in the Front Range.

The climate of our study site is characterized by long, cool winters and a short growing season (one to three months). Since 1951 the mean annual temperature has been 3.8°C and the annual precipitation has been 1,000 millimeters (Williams and others 1996a). About 80 percent of the annual precipitation occurs as snow. Streamflows are markedly seasonal, varying from less than 0.05 cubic meters per second during the winter months to more than 3.0 cubic meters per second at maximum discharge during snowmelt just below Lake Albion, at the lower end of the valley. The surface waters are dilute, with acid-neutralizing capacities generally less than 200 micro equivalents per liter at all sampling sites (Caine and Thurman 1990).

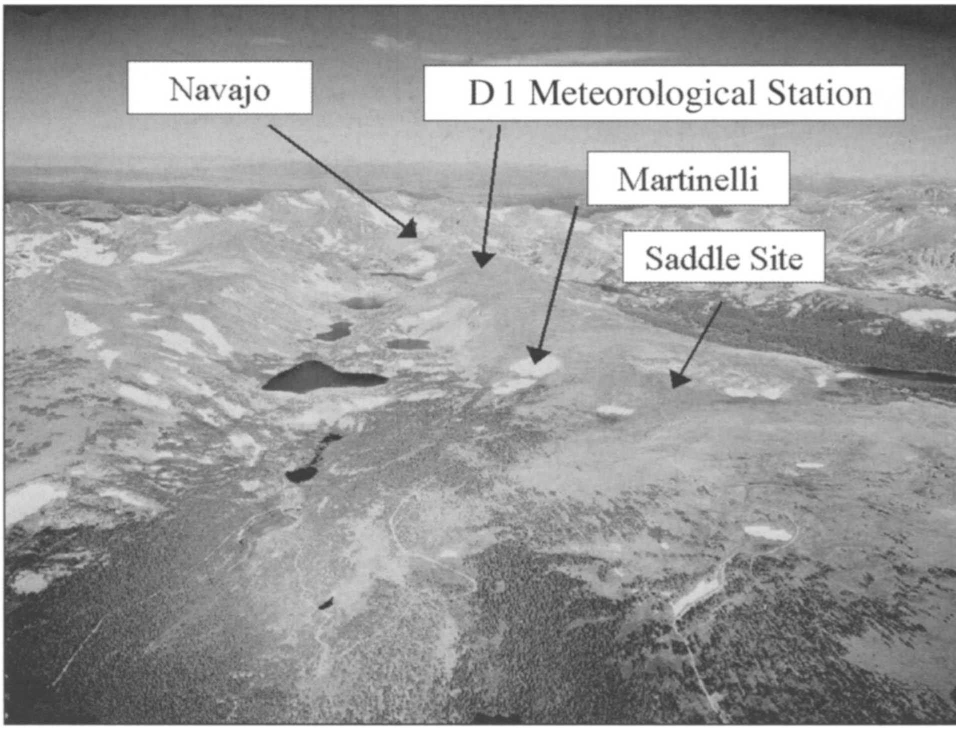

FIG. 2—Aerial photograph of Green Lakes Valley, Colorado. Discharge and stream chemistry are presented from the 42-hectare Navajo and the 8-hectare Martinelli catchments. The climate station at D1 is on Niwot Ridge; snow lysimeters and a National Atmospheric Deposition Program collector are at the Saddle Site on Niwot Ridge. (Reproduced courtesy of the Niwot Ridge Long-Term Ecological Research Archives)

Several research facilities are located on Niwot Ridge, an alpine tundra ecosystem that extends eastward from the Continental Divide and forms the northern boundary of the Green Lakes Valley watershed. Climate data have been collected since the early 1950s at the D1 climate station on Niwot Ridge, at 3,750 meters. The Long-Term Ecological Research network operates a high-elevation tundra laboratory at the Niwot Ridge Saddle, located below D1 at 3,500 meters. Also in the saddle is a subnivean laboratory where snowpack meltwater samples are automatically collected before contact with the ground (Williams and others 1996b).

METHODS

Precipitation amounts were collected at D1 by an unshielded Belfort recording gauge from 1951 to 1964 and with an Alter-type shield from 1964 to the present; the shielded and unshielded gauges were run concurrently for two years and the pre-1964 data adjusted. The accuracy of monthly precipitation totals is approximately 20 millimeters. Missing data were treated using regression analyses and with other nearby climate stations as presented by David Greenland (1989). Here we update information originally provided by Mark Williams and others (1996a).

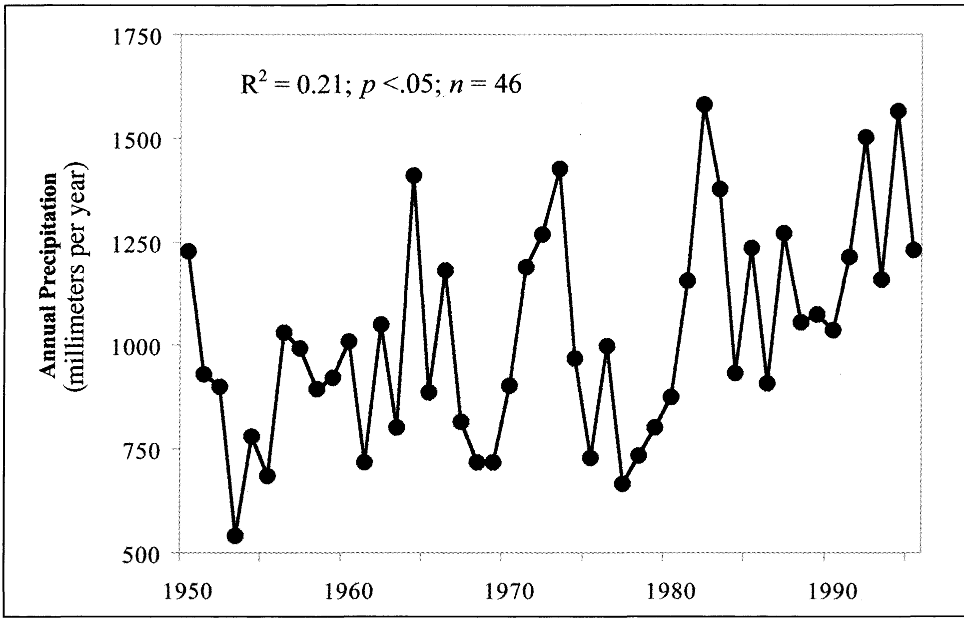

FIG. 3—Precipitation data from the D1 (3,750 meters) climate station on Niwot Ridge, Colorado. Annual precipitation has increased significantly since 1951.

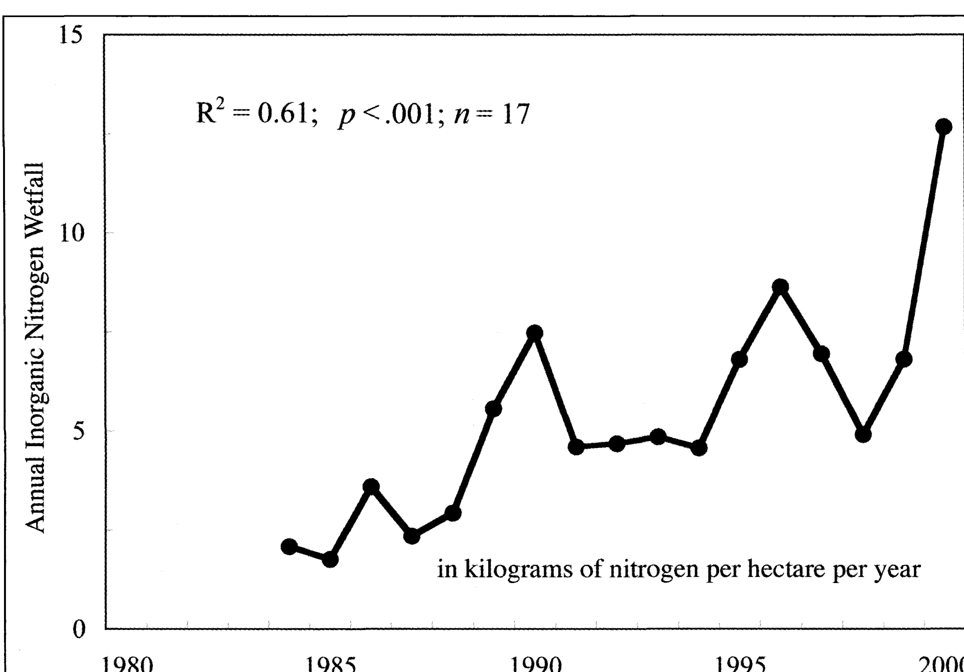

FIG. 4—Precipitation quality from the National Atmospheric Deposition Program station at the Saddle Site on Niwot Ridge, Colorado. The annual deposition of inorganic nitrogen in wetfall is increasing.

Wet deposition was sampled on the Niwot Ridge saddle (3,500 meters) as part of the National Atmospheric Deposition Program (NADP), which operates about 200 wet-precipitation collectors throughout the continental United States (NADP/NTN 1984–2000). Snow and stream-water samples were collected for chemical analysis, as documented in Williams and others (1996a). For our study, snowpack meltwater samples were collected in 1-square-meter snow lysimeters before contact with the ground, following protocols elaborated by Williams and others (1996b). Meltwater discharge was measured continuously in tipping buckets, and daily grab samples were analyzed for concentrations of major solutes. Analytical analyses for major solutes from stream water, snow, and meltwater followed previous practices (Williams and others 1996a, 1996b).

Results

QUANTITY OF PRECIPITATION

The amount of annual precipitation at D1 is increasing (Figure 3). Mean annual precipitation for the period 1951–1996 was 1,023 millimeters, with a standard deviation of 254 millimeters. A linear regression shows the increase in annual precipitation amount from 1951 to 1996 to be significant ($R^2 = 0.21$, $p < .05$), at a rate of 8.2 millimeters per year and an increase of about 300 millimeters since the 1950s. Most of the precipitation increase has occurred since 1967 (a period during which the same gauge and screen were used), at a rate of 16 millimeters per year.

QUALITY OF PRECIPITATION

Annual deposition of inorganic nitrogen in wetfall at the Niwot Ridge NADP site from 1984 to 1996 almost doubled, from 1.95 kilograms per hectare per year in 1985–1988 to 3.75 kilograms per hectare per year in 1989–1992 (Figure 4). Values have remained near or above 4.0 kilograms per hectare per year since the mid-1990s. A simple linear regression with time shows a significant increase in deposition of inorganic nitrogen in wetfall, at the rate of 0.42 kilograms per hectare per year ($R^2 = 0.61$; $p < .001$, $n = 17$). Earlier and comparable measurements extend the record back to 1982 and suggest that the increase in deposition of inorganic nitrogen in wetfall began in the early 1980s (Reddy and Caine 1988). Previous analysis of the NADP record by Williams and others for a shorter time period shows that about half of the increase in nitrogen deposition is from increasing concentrations of nitrogen in wetfall and about half from increasing amounts of annual precipitation (1996b).

STREAM–WATER CHEMISTRY

Aquatic resources in high-elevation catchments of the Rocky Mountains may be negatively affected at current levels of inorganic nitrogen deposition in wetfall. Acid-neutralizing capacities have been decreasing in Green Lake #4 since the mid-1980s (Caine 1995; Williams and Tonnessen 2000). We illustrate the potential problems caused by nitrogen deposition with acid-neutralizing-capacity measurements in 1996 from the 42-hectare Navajo sampling site on North Boulder Creek. Initial nitrate concentrations during snowmelt runoff were greater than 30 micro equivalents per liter (Figure 5). These stream-water values of nitrate were about three times greater than snowpack values (which were close to 10 micro equivalents per liter). Stream waters became episodically acidified, with acid-neutralizing-capacity values below 0 micro equivalents per liter. As nitrate values fell below 20 micro equivalents per liter, acid-neutralizing-capacities values recovered and became positive. Acid-neutralizing-capacity and nitrate values were then decoupled in the fall months.

IONIC PULSE

The release of nitrate from storage in the snowpack in the form of an ionic pulse may partially explain the elevated concentrations of nitrate at the Navajo sampling site. Field and laboratory experiments have demonstrated that initial stages of snowmelt often have ionic concentrations many times higher than averages for the whole snowpack: an ionic pulse (Johannessen and Henriksen 1978; Colbeck 1981). To illustrate, in 2000 the maximum concentrations of ammonium, nitrate, and sulfate in snowpack meltwater were about three to six times those of bulk concentrations in a co-located snow pit (Figure 6). Thus the storage and release of pollutants may be enhanced by the ionic pulse.

Variations in climate may change the magnitude of the ionic pulse. In 1999 the maximum concentrations of the same solutes in meltwater were about twenty times those of bulk concentrations in the snowpack (Figure 6). Thus the magnitude of the ionic pulse was three to seven times greater in 1999 than in 2000.

Air temperatures were above average in 2000, and melt rates were higher than normal, conditions that may have decreased the magnitude of the ionic pulse as solutes were released from storage in the winter snowpack. Thus the magnitude of the ionic pulse may be influenced by small changes in climate.

The difference in the magnitude of the ionic pulse in 1999 and 2000 was also evident in stream-water concentrations. Here we illustrate that difference with ammonium concentrations measured in stream waters at the 8-hectare Martinelli catchment. We chose ammonium for the illustration because it had the largest change of any solute. The initial snowpack concentrations of ammonium differed little in 1999 and 2000. Because of the warm climate, the thin snowpack, and the small amount of snow in April, snowmelt started about twenty days earlier in 2000 than in 1999. The maximum ammonium concentrations in 2000 were 6 micro equivalents per liter and quickly decreased to less than 2 micro equivalents per liter (Figure 7). In contrast, concentrations of ammonium in stream waters in 1999 were as high as 35 micro equivalents per liter at the start of snowmelt runoff. The differences in climate between 1999 and 2000 may have resulted in stream-water concentrations of solutes that were seven times higher in 1999 than in 2000.

Discussion

The role of snow in the climate of alpine areas and feedbacks with ecosystem responses has received little attention. The results of our case study at Green Lakes

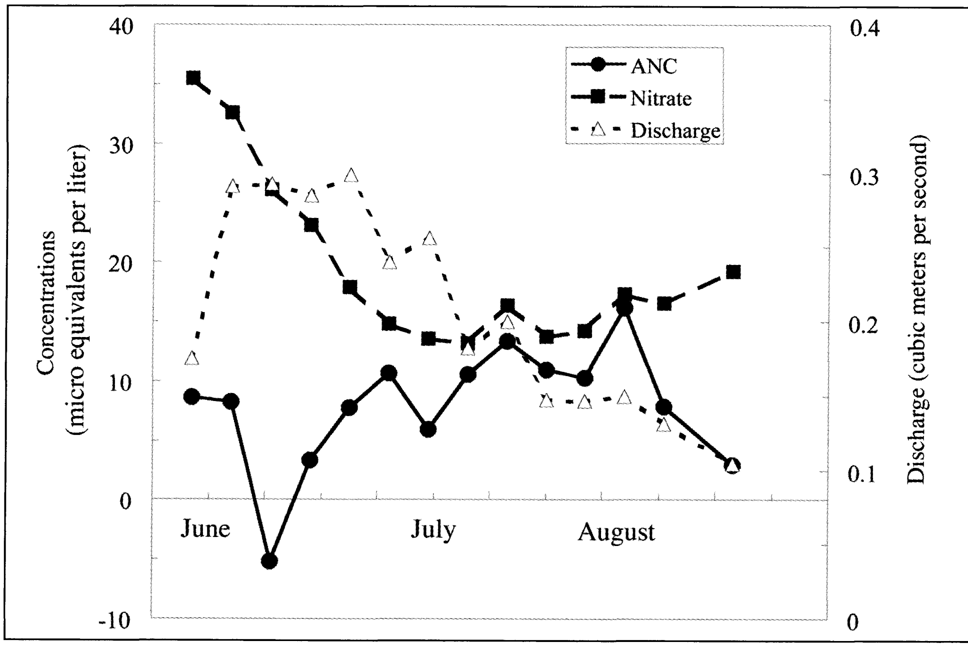

FIG. 5—Time series of acid-neutralizing capacity (ANC) and nitrate from the 42-hectare Navajo sampling site in Green Lakes Valley, Colorado.

Valley–Niwot Ridge suggest that small changes in energy, chemicals, and water in alpine basins may cause large changes in ecosystem response (Figure 1). Warming in lowland areas may result in the advection of water vapor to high-elevation sites. Orographic affects may then result in an increase in annual precipitation. In turn, an increase in precipitation may result in an increase in annual deposition of pollutants, even with no increase in the concentrations of pollutants in the precipitation. These pollutants are stored in the seasonal snowpack for six to nine months, to be released over a period of weeks during snowmelt runoff. Furthermore, release of solutes from the seasonal snowpack in the form of an ionic pulse increases the concentration of pollutants in surface waters. Thus small changes in the flux of energy, chemicals, and water in alpine catchments are amplified because of the storage and release of pollutants from the seasonal snowpack in the form of an ionic pulse (Figure 1). In turn, release of the solutes from the snowpack in the form of an ionic pulse may cause episodic pollution of stream waters at relatively low amounts of pollution.

SNOWFALL AND ANNUAL PRECIPITATION

Thomas Karl and others document a correlation between snow cover and air temperature (1993). In North America, although precipitation has been increasing, snow cover has been decreasing and temperature increasing. Mark Serreze and others suggest that the Pacific Northwest, Arizona, and New Mexico are the most climatically sensitive regions of the western United States, based on changes in the amounts

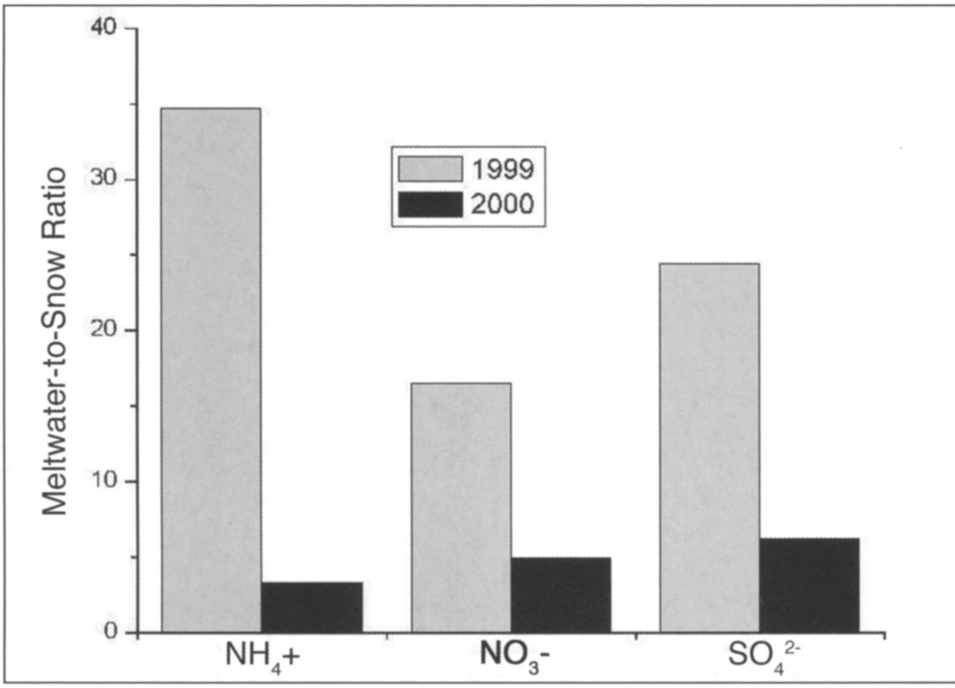

FIG. 6—Ratios of maximum concentrations of ammonium, nitrate, and sulfate in snowpack meltwater before contact with the ground to bulk concentrations from a co-located snow pit sampled concurrently, in 1999 and 2000. Solutes are released from the snowpack in the form of an ionic pulse. The magnitude of the ionic pulse was greater in 1999 than in 2000 because of small changes in climate.

of snow water relative to total winter precipitation (1999). Timothy Kittel and others report positive trends in precipitation in the northern and central Rocky Mountains of 30 percent and 33 percent per century, respectively, and increasing temperatures of +0.7 and +0.9°C per century (2002). Mark Losleben and Nick Pepin suggest that, with a future of increasing warm-phase El Niño–Southern Oscillation conditions, snowpack depths will decline on both the eastern and western slopes of the Oregon Cascades but will not have much effect in the Colorado Rockies or the central to northern Sierra Nevada of California (2003).

Although temperature is by far the easiest parameter to predict in global-warming scenarios, the relationship between temperature and snowpack is extremely complex (Houghton and others 2001). This is because snow falls only below a particular temperature threshold. Above the threshold, liquid precipitation acts to ablate snow. Thus the response of snowpack to temperature is nonlinear.

The role of snow in response to changes in climate deserves more attention. The increase in precipitation amount at Niwot Ridge does not follow the pattern predicted by Karl and others (1993). The climate patterns at Niwot Ridge are consistent with a conceptual model of climate change in high-elevation mountain areas proposed by Roger Barry (1990) and modified by Williams and others (1996a). Warm-

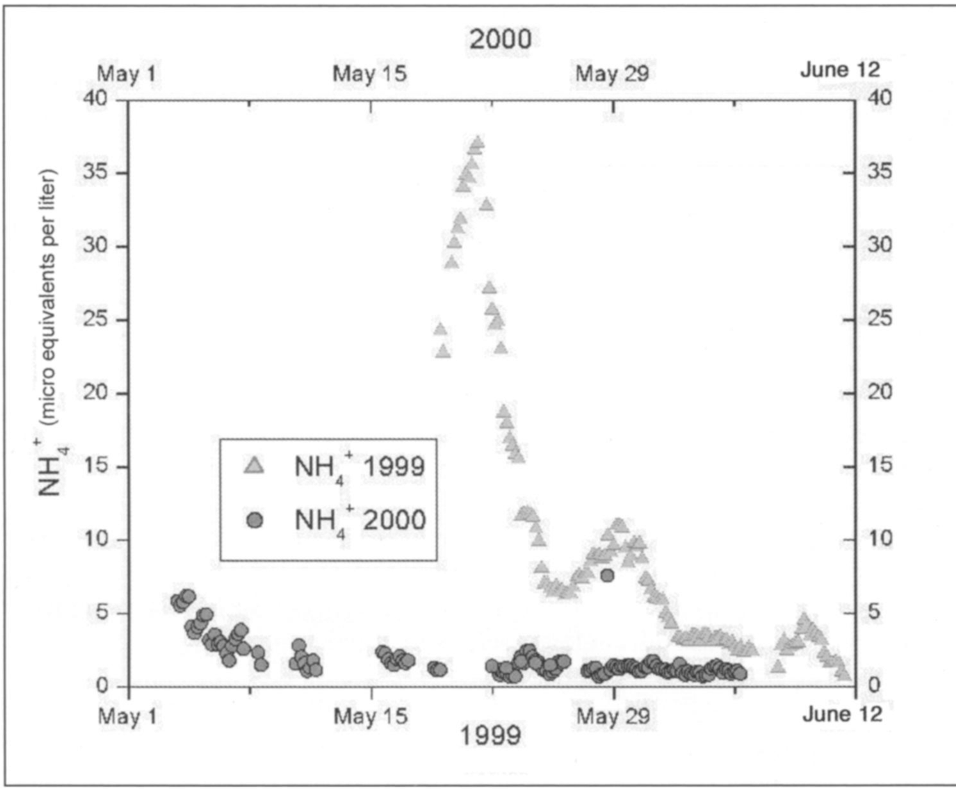

FIG. 7—Ammonium concentrations in stream waters from the 8-hectare Martinelli catchment, Colorado, in 1999 and 2000. The large ionic pulse in 1999 appears to have been a partial cause of the sevenfold increase in ammonium concentrations in stream waters, as compared with 2000.

ing at lower elevations may result in the advection of increased water vapor to higher elevations and increased orographic precipitation as snow. Late-lying snow on the ground may provide the moisture source for increased cloud cover during the summer months, resulting in a decrease in direct shortwave radiation. In the short term (a decadal time scale), the feedback loop may be positive in high-elevation areas above the tree line; in turn, atmospheric cooling lowers saturation vapor pressure and increases precipitation. The key factor here are the precipitation as snow in the spring and early summer and the resulting feedback with local climate (Williams and others 1996a). We recognize that other processes may explain these observations and suggest that such processes represent a fertile ground for further research.

EFFECTS ON THE ECOSYSTEM

Our results suggest that streams and lakes in high-elevation systems may be particularly sensitive to changes in energy, chemicals, and water. Recent analyses of high-elevation lake-sediment cores from the Rocky Mountains, reported by Alexander Wolfe and others (2002), highlight the vulnerability of alpine ecosystems to nutrient enrichment from atmospheric deposition. Algal productivity, attributable to nutrient enrichment from atmospheric deposition of nitrogen, have increased; and current levels of nitrogen deposition in the Rocky Mountains are sufficient to alter both the quantity and quality of organic matter in alpine lakes, in addition to inducing pronounced changes in the composition of algal flora.

Although changes in algal flora may not seem important, nitrogen deposition affects the bottom of the food chain and thus may lead to unexpected effects on large mammals near the top of the food chain. Mark Williams has been working with researchers from the State of Wyoming Department of Game and Fish to establish the cause of a decline in bighorn sheep (Hnilicka 2001; Polakovic 2001). The herd, which used to number about 1,250, declined by 30 percent in two years during the early 1990s and never recovered. Tests on the herd near the Wind River Range in Wyoming showed five parts per billion of selenium in forage favored by bighorn sheep, 75 percent lower than the minimum requirement for a healthy immune system. The lack of selenium may be causing white-muscle disease, a form of muscular dystrophy. Muscles deteriorate, fail to support the skeleton, and make the bighorn lambs easy pickings for mountain lions. Moreover, fewer lambs survive in wet years. We speculate that the combination of increasing nitrogen deposition and more available water in wet years results in lower selenium in the forage of bighorn sheep.

Alpine Ecosystems as Warning Beacons

Alpine ecosystems may be early indicators of climate change. Small changes in energy, chemicals, and water are magnified in alpine ecosystems relative to lower-elevation ecosystems. An increase in regional precipitation, with no change in ambient chemical content, leads to a disproportionate increase in chemical loading from wet deposition in high-elevation catchments because of orographic precipitation. Any increase in the solute concentration of snowfall is magnified several-fold in the first fractions of snowpack meltwater by an ionic pulse. A change in energy flux causes a corresponding change in the intensity of the ionic pulse and may either extend or shorten the period of snowmelt runoff. Interactions among these variables have the potential to magnify small increases in the amounts and chemical concentrations of precipitation to very large increases in the chemical content of snowpack meltwater. In turn, the changes in the chemical content of surface waters may rapidly affect local biota, which are at the edge of their environmental tolerance. The problems caused by nitrogen deposition may thus be widespread throughout the Rocky Mountains.

References

Bandyopadhyay, J., J. C. Rodda, R. Kattelman, Z. W. Kundzewicz, and D. Kraemer. 1997. Highland Waters: A Resource of Global Significance. In *Mountains of the World: A Global Priority,* edited by B. Messerli and J. D. Ives, 131–155. New York: Parthenon Publishing Group.

Barry, R. G. 1990. Changes in Mountain Climate and Glacio-Hydrological Responses. *Mountain Research and Development* 10 (2): 161–170.

Becker, A., and H. Bugmann, eds. 2001. *Global Change and Mountain Regions: The Mountain Research Initiative.* Stockholm: Royal Swedish Academy of Sciences, IGBP Secretariat.

Beniston, M., ed. 1994. *Mountain Environments in Changing Climates.* London and New York: Routledge.

Bowman, W. D., and T. R. Seastedt, eds. 2001. *Structure and Function of an Alpine Ecosystem: Niwot Ridge, Colorado.* New York: Oxford University Press.

Caine, N. 1995. Temporal Trends in the Quality of Streamwater in an Alpine Environment: Green Lakes Valley, Colorado Front Range, U.S.A. *Geografiska Annaler: Series A, Physical Geography* 77a (4): 207–220.

Caine, N., and E. M. Thurman. 1990. Temporal and Spatial Variations in the Solute Content of an Alpine Stream, Colorado Front Range. *Geomorphology* 4 (1): 55–72.

Colbeck, S. C. 1981. A Simulation of the Enrichment of Atmospheric Pollutants in Snow Cover Runoff. *Water Resources Research* 17: 1383–1388.

Dozier, J., and M. W. Williams. 1992. Hydrology and Hydrochemistry of Alpine Basins. *Eos, Transactions of the American Geophysical Union* 73 (3): 33.

Greenland, D. 1989. The Climate of Niwot Ridge, Front Range, Colorado, U.S.A. *Arctic Alpine Research* 21 (4): 380–391.

Hnilicka, P. 2001. Telephone interview with M. W. Williams, March.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dia, K. Maskell, and C. A. Johnson, eds. 2001. *Climate Change 2001: The Scientific Basis.* Cambridge, England, and New York: Cambridge University Press.

Johannessen, M., and A. Henriksen. 1978. Chemistry of Snow Meltwater: Changes in Concentration during Melting. *Water Resources Research* 14 (4): 615–619.

Karl, T. R., P. Y. Groisman, R. W. Wright, and R. R. Heim Jr. 1993. Recent Variations of Snow Cover and Snowfall in North America and Their Relation to Precipitation and Temperature Variations. *Journal of Climate* 6 (7): 1327–1344.

Kittel, T. G. F., P. E. Thornton, J. A Royle, and T. N. Chase. 2002. Climates of the Rocky Mountains: Historical and Future Patterns. In *Rocky Mountain Futures: An Ecological Perspective,* edited by J. S. Baron, 59–82. Washington, D.C.: Island Press.

Losleben, M. V., and N. Pepin. 2003. Mountain Snowpack, Lowland Winter Precipitation, and Variability in Three Western U.S. Mountain Ranges. Unpublished manuscript.

Messerli, B., and J. D. Ives, eds. 1997. *Mountains of the World: A Global Priority.* New York: Parthenon Publishing Group.

NADP/NTN [National Atmospheric Deposition Program / National Trends Network]. 1984–2000. NADP/NTN Annual Data Summary, Precipitation Chemistry in the United States. Colorado State University, Natural Resource Ecology Laboratory, NADP/NTN Coordination Office.

Polakovic, G. 2001. Deaths of the Little Bighorns: A Mysterious Illness Is Weakening Lambs in the Rockies, with Many Falling Prey to Predators: Researchers Say Pollution May Be the Cause. *Los Angeles Times,* 29 August, §A, 1.

Reddy, M. M., and N. Caine. 1988. A Small Alpine Basin Budget: Front Range of Colorado. In *International Mountain Watershed Symposium: Subalpine Processes and Water Quality,* edited by I. G. Poppoff, C. R. Goldman, S. L. Loeb, and L. B. Leopold, 370–385. South Lake Tahoe, Calif.: Tahoe Resource Conservation District.

Serreze, M. C., M. P. Clark, R. L. Armstrong, D. A. McGinnis, and R. S. Pulwarty. 1999. Characteristics of the Western United States Snowpack from Snowpack Telemetry (SNOTEL) Data. *Water Resources Research* 35 (7): 2145–2160.

Williams, M. W., and K. A. Tonnessen. 2000. Critical Loads for Inorganic Nitrogen Deposition in the Colorado Front Range, U.S.A. *Ecological Applications* 10 (6): 1648–1665.

Williams, M. W., P. D. Brooks, and T. Seastedt. 1998. Nitrogen and Carbon Soil Dynamics in Response to Climate Change in a High-Elevation Ecosystem in the Rocky Mountains, U.S.A. *Arctic and Alpine Research* 30 (1): 26–30.

Williams, M. W., M. V. Losleben, N. Caine, and D. Greenland. 1996a. Changes in Climate and Hydrochemical Responses in a High-Elevation Catchment, Rocky Mountains, U.S.A. *Limnology and Oceanography* 41 (5): 939–946.

Williams, M. W., P. D. Brooks, A. Mosier, and K. A. Tonnessen. 1996b. Mineral Nitrogen Transformations in and under Seasonal Snow in a High-Elevation Catchment, Rocky Mountains, United States. *Water Resources Research* 32 (10): 3161–3175.

Wolfe, A. P., S. S. Kaushal, J. R. Fulton, and D. M. McKnight. 2002. Spectrofluorescence of Sediment Humic Substances and Historical Changes of Lacustrine Organic Matter Provenance in Response to Atmospheric Nutrient Enrichment. *Environmental Science and Technology* 36 (15): 3217–3223.