EFFECTS OF STORM TRAJECTORIES ON SNOWFALL CHEMISTRY IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO

George P. Ingersoll[1]
Kathy A. Tonnessen[2]
Donald H. Campbell[1]
Ben R. Glass[1]
Andres O. Torizzo[1]

ABSTRACT

Snowfall samples from snowstorms lasting 1 to 4 days were collected near the Bear Lake snow telemetry (SnoTel) site in Rocky Mountain National Park, Colorado (ROMO), during the 1998-99 snowfall season to determine if storms moving in from different directions affect the chemistry of precipitation in the park. Storm pathways to Bear Lake during snowfall events were estimated using the HYSPLIT4 backward-trajectory model developed by the National Oceanic and Atmospheric Administration. Deposition of acidic ions of nitrate and sulfate in snowfall during the study varied substantially (two- to threefold) depending on storm trajectory because air masses traversing the park originated from different surrounding areas, including some having large sources of emissions of nitrate and sulfate. Concentrations of nitrate and sulfate in samples were lowest when storms reached ROMO from north and east of the park and were elevated when air masses traveled from the west where a number of power plants are located. Concentrations were highest in storms reaching ROMO from the south, a region with urban areas including Metropolitan Denver.

INTRODUCTION

Most of the terrain in Rocky Mountain National Park (referred to as the park or ROMO) is over 2,800 meters (m) in elevation, where deep annual snowpacks generally accumulate (Barry 1992; National Atmospheric Deposition Program 2000) and substantial total ionic loading may occur from atmospheric deposition. Alpine ecosystems are sensitive to chemical inputs due to limited soils and vegetation and more exposed rock. Thus, loadings of acidic compounds such as nitrate and sulfate in annual snowpacks are most likely to affect alpine soils and water bodies. Research in other high-elevation catchments in north-central Colorado indicated that nitrate levels in snowmelt runoff and in alpine streamflow were higher than in downstream subalpine areas (Heuer and others 1999). Other research indicates atmospheric inputs of nitrogen to the Rocky Mountains of Colorado have increased in recent years, and watersheds in and near the park area may be threatened by excesses of nitrogen occurring as a result of local or regional emissions (Williams and others 1996).

Regional and local emissions sources contribute to deposition of nitrate and sulfate which adversely affect ecosystem health in the park (Turk and others 1987; Campbell and others 1991). Numerous agricultural, industrial, and residential emissions that affect air and water quality in ROMO exist along the Colorado Front Range, in the greater Denver area, and in the surrounding area of northern Colorado (USEPA 2000). Two powerplants are located about 120 kilometers (km) west of ROMO, and the greater Denver area, with over one million residents, is located about 50 km southeast. Other work has documented acid deposition from emission sources in western Colorado (Ingersoll 1995; Turk and others 1997), and the greater Denver area (Musselman and others 1996). Existing monitoring networks allow interpretations of probable sources of chemical deposition by using a limited number of high-elevation (>2,400 m) sampling sites in and around the park. Although extensive research on acid deposition in northern Colorado has been done (Denning and others 1991; Campbell and others 1995; Baron 1992; Hasfurther and others 1994), the sources of nitrate and sulfate deposition entering the park are uncertain due to variability in storm tracks and snowfall regimes.

Paper presented at the 69th Annual Meeting of the Western Snow Conference, 2001.
[1]US Geological Survey, Mail Stop 415, Denver, CO. 80225
[2]National Park Service/RM-CESU, School of Forestry, University of Montana, Missoula, MT. 59812

Techniques that use snowpack chemistry to help identify nearby emission sources have been successfully demonstrated in many locations in the Rocky Mountain region in Colorado (Lewis and others 1984; Turk and others 1992; Turk and Campbell 1997) and Yellowstone National Park (Ingersoll 1999), and in the Sierra Nevada (Berg and others 1989). Because most annual precipitation in the park is snow (Western Regional Climate Center 2000), sampling snowfall provides a good method of estimating the contribution of different emission source areas. In this paper we combine snowfall-event chemistry with simulated storm trajectories to estimate origins of air masses during individual storm events that result in differing chemical concentrations of nitrate and sulfate deposited to the park.

Background

The U.S. Geological Survey has monitored the chemical composition of seasonal snowpacks in Colorado since the mid-1980's. Snowpack surveys allow us to map spatial trends in chemistry influenced by local versus regional sources of air emissions of nitrate and sulfate (Turk and others 2001). At sites where atmospheric deposition is affected by local emission sources, concentrations of acidic precursors were higher than at locations more distant from the source (Ingersoll 1995).

Study Area

The study site at Bear Lake is located in a high-elevation (2,900 meters) watershed on the eastern slope of the Continental Divide in Rocky Mountain National Park, Colorado (Figure 1). The selection of the bulk-deposition sampling site was chosen to represent a location that was near the center of the park, was safe and quick to access, and where substantial annual snowfall was expected. The sampling site was located in a small clearing below treeline in the subalpine zone where uniform snowfall was likely and effects of wind redistribution were minimized. At 2,900 m elevation subfreezing (average) temperatures were expected to cause most winter precipitation to fall as snow.

METHODS

Sample Collection

To examine the differences in chemical concentrations of nitrate and sulfate between distinct storms, portable bulk collectors were deployed at the Bear Lake site before and after individual snowfall events during the 1998-99 snowfall season. If a snowstorm was predicted, local observers would monitor weather conditions from nearby areas of the park and prepare to deploy clean collectors. At the onset of a new storm, two 60-liter Nalgene sample collectors with open 0.1134-square-meter orifices were positioned side-by-side on portable tripods 1 to 2 m above the snow or ground surface and then allowed to collect all wet and dry deposition. Collectors were fastened to the temporary tripods and secured with cables at adjustable elevations above the snowpack to minimize contamination. The bulk collector site also was located near a snow-telemetry (SnoTel) site where near-real-time data describing hourly precipitation amounts could be accessed remotely (Western Regional Climate Center 2000). This remotely accessed observation of precipitation allowed assessment of storm amounts for determination of timing of sample collection and documentation of periods of continuous precipitation. Bulk samples were retrieved after sufficient snowfall occurred (yielding ~1,000 milliliters of snowmelt) and after precipitation from individual storm events ceased. Snowfall-accumulation periods indicated from the hourly SnoTel record at Bear Lake were used to determine discrete times to run backward-trajectories of air masses passing over the sample collectors.

Analytical Methods

All sample containers were prerinsed in high-purity (18 megohm/cm electrical resistance) deionized (DI) water; collectors were capped and sealed for transport to and from sampling sites. After collectors were exchanged, samples were processed in U.S. Geological Survey laboratories in Lakewood and Boulder, Colorado, for measurement of sample mass and analyses of nitrate and sulfate ions. Snow samples were melted in the sealed containers used for collection, weighed, filtered (0.45 micron), and refrigerated pending analysis by ion chromatography. Additional information regarding detection limits, quality control, and other analytical methods used for chemical analyses of snowfall is available in other reports (Ingersoll 1995, 1999).

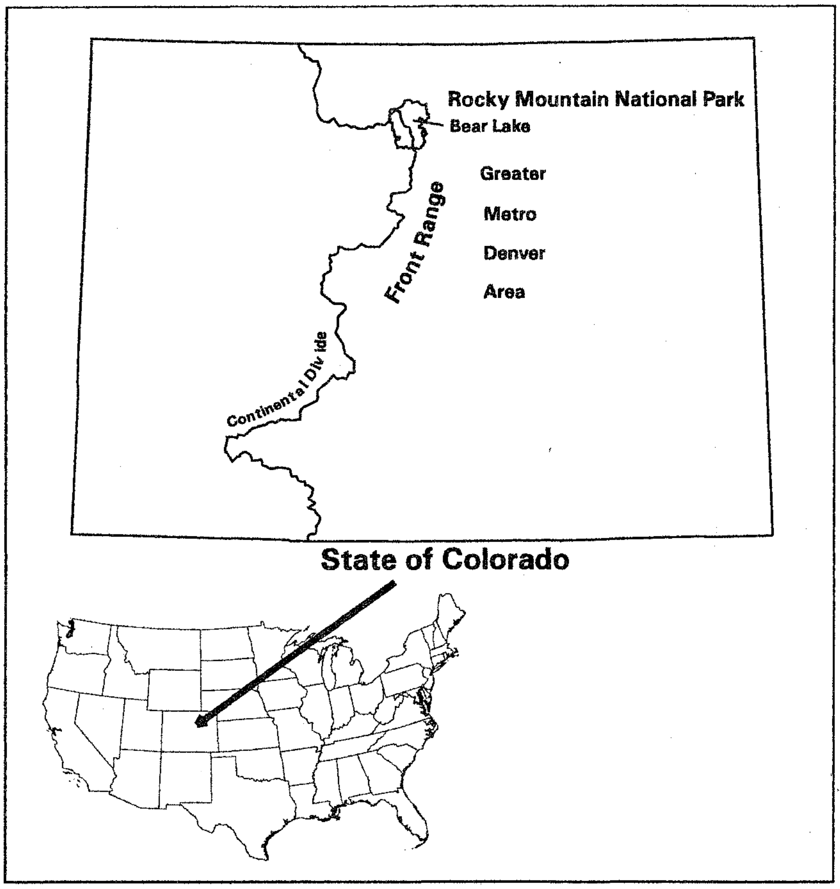

Figure 1: Study area and Bear Lake sampling site in north-central Colorado, USA.

Storm Trajectory Modeling

The HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4) Model (NOAA Air Resources Laboratory 1997) was run remotely using the Internet to estimate backward trajectories of air masses that passed over Bear Lake during snowfall events that were successfully sampled. Archived meterological data from the National Weather Service used in weather forecasting models also were accessible on the National Oceanic and Atmospheric Administration website (http://www.arl.noaa.gov/ready/hysplit4.html). Two archived datasets are provided to run the HYSPLIT4 model: Eta Data Assimilation System (EDAS) and FNL (known as "fill-in" archives for periods when EDAS archive output is unavailable). These gridded, archived data describing weather parameters including horizontal wind components, temperature, height, and pressure are input to HYSPLIT4 to similate the paths taken by air masses at a given latitude, longitude, elevation, and time. Model runs were selected for 96-hour backward trajectories from the geographic coordinates for the snowfall sampling site at Bear Lake (latitude 40.32° N, longitude 105.67° W). By starting the backward trajectories at the beginning of a storm, and continuing model runs until the end of the precipitation event, locations where air masses moving into the sampling site have been may be estimated. Removal of atmospheric pollutants is assumed to occur at a greater rate during precipitation events, and occur in lower levels of the atmosphere.

Three altitudes (500, 1,000, and 3,000 m) above ground level (AGL) were selected to represent the atmosphere above the study site during storm events. These three separate levels of the atmosphere were chosen because the most moisture- and snowfall-producing meteorology occurs within this lower half of the troposphere (Schlesinger 1997). At roughly each of these three altitudes different processes occur that affect snowfall chemistry. Winds driving storm systems commonly occur at the uppermost level, 3000 m AGL, and transport of emissions occurs at greater rates and across greater distances (several hundred kilometers per day). At about 1000 m and 500 m AGL clouds form and pollutants are washed out by precipitation. However, air masses from all three levels are mixed in the turbulence created by the mountainous terrain near Bear Lake.

RESULTS AND DISCUSSION

Backward trajectories of air masses have been used to estimate sources of nitrogen emissions in the Eastern United States (Russell and others 1998; Evans and others 2000) to classify general directions of storms before passing over a certain location. In this study clusters of backward trajectories similarly were used to divide approximations of storm directions into cardinal compass directions. Generally, storms reaching Bear Lake were classified as from the north, east, south, or west. However, there were large variations in the air mass directions for individual snowfall events that were sampled. Four storms with roughly constant directions during the snowfall events, and yielding sufficient precipitation, were chosen in an attempt to distinguish between geographically separate source areas (Table 1).

Table 1: Snowfall sample characteristics

Sample Collection Date	General Simulated Storm Trajectory	Nitrate Concentration (microequivalents per liter)	Sulfate Concentration (microequivalents per liter)	Precipitation collected (centimeters)
1/21/99	West	6.7	5.7	0.7
2/20/99	West	10.0	11.7	0.4
4/16/99	North	6.3	4.6	1.3
4/29/99	South	17.6	15.2	4.2

Previous work that analyzed bulk-deposition patterns across Colorado estimated source areas of nitrate and sulfate using biweekly sampling (Lewis and others 1984). Analysis of National Atmospheric Deposition Program (NADP) wet-deposition data indicated similar concentrations of nitrate and sulfate on both sides of the Continental Divide (Heuer and others 2000). Other work in Colorado compared precipitation chemistry between bulk-deposition and NADP wetfall-sampling sites located less than 2 km apart. This study showed a larger influence on atmospheric deposition of nitrate and sulfate from emissions along the Colorado Front Range including the Denver Metropolitan area (Ingersoll and others, 2000).

NADP data for wetfall chemistry including concentrations of nitrate and sulfate were collected in ROMO in 1999. Existing NADP sites collected wetfall in east-central sections of the park, adjacent areas to the south, and distant locations to the west. However, since the NADP sampling was done weekly, chemistry from individual snowstorms was combined with other wetfall during the week sampled, and dryfall was not sampled. Thus, determination of the snowfall chemistry for a storm lasting a fraction of a week was not likely. Overall, mean concentrations of nitrate and sulfate for the snowfall season in samples collected at Bear Lake were slightly higher than the annual mean concentrations at two nearby NADP sites. This difference may be due to the added dry deposition collected during periods when the snowfall collectors were open to the atmosphere while precipitation was not occurring before samples were collected. NADP wetfall collectors close and open in response to precipitation events.

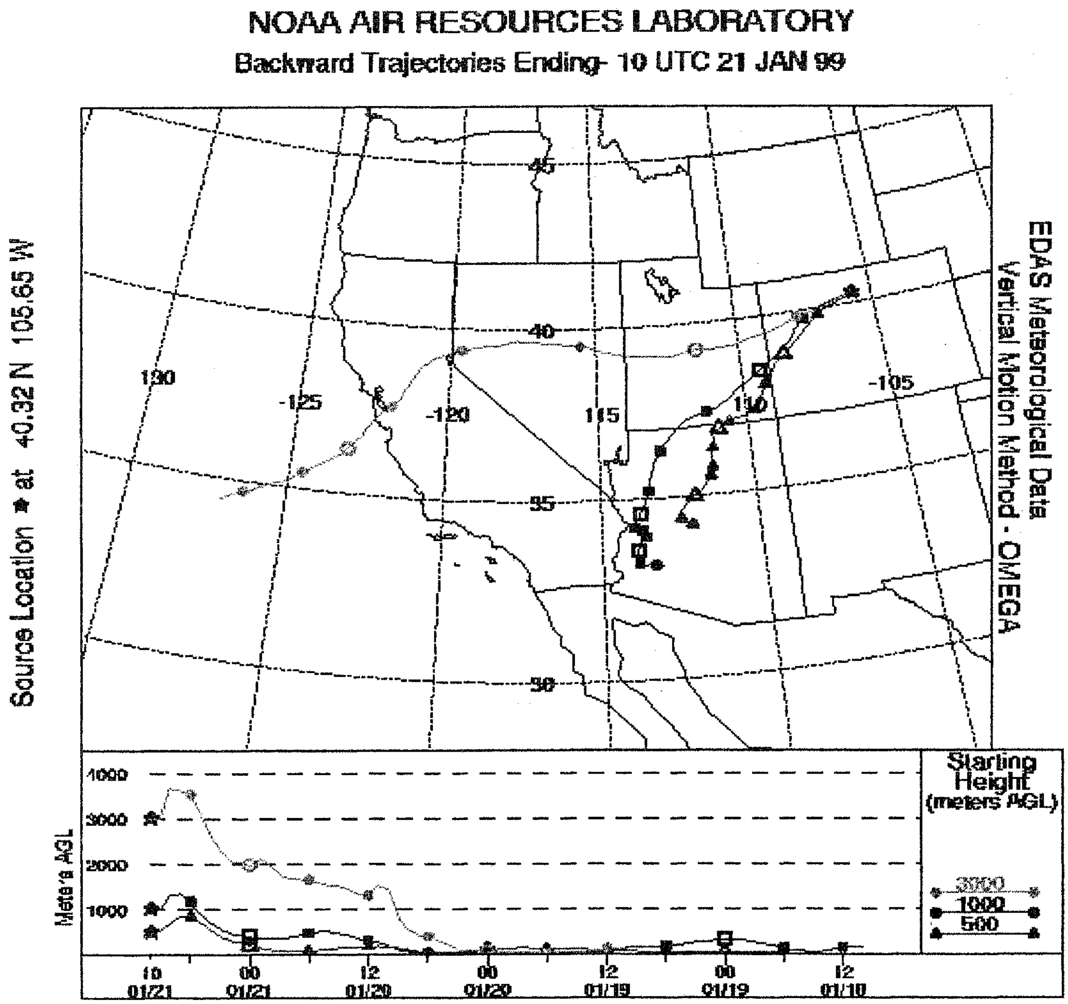

Figure 2: HYSPLIT4 model output of backward trajectory during snowfall event sampled January 21, 1999. EDAS and FNL archived data used are from the National Weather Service (http://www.arl.noaa.gov/ss/transport/archives.html). Greenwich Mean time (expressed as UTC) is 6 hours later than Mountain Standard Time. The Source Location indicated by the star symbol is the Bear Lake sampling site at 40.32 degrees north (N) latitude and 105.65 degrees west (W) longitude. Western longitudinal values are degrees expressed as negative. Symbols shown along trajectories represent 6-hour time intervals; open symbols are shown every 24 hours at 0000 UTC. Starting heights of backward trajectories are plotted in meters above ground level (AGL).

The snowfall event sampled on January 21, 1999 (Figure 2), was a typical winter snowstorm with generally westerly winds and light precipitation (0.7 cm). Plots shown in this discussion for each of the four snowfall samples were selected to be representative of the multiple trajectories simulated every 4 to 6 hours during sample collection, so plot times are earlier than sample-collection times in Figures 2-5. Wind data collected at the Niwot Ridge Long-term Ecological Research (LTER) station at an elevation of 3,018 m, and about 25 km south of Bear Lake, indicated mostly westerly winds at ground level during the storm. The backwardward trajectories shown represent general directions simulated every 4 hours during sample-collector deployment. All three levels of air masses (500, 1,000, and 3,000 m AGL) tended to originate in western and southwestern areas of the United States. As all three levels of simulated air masses converged in Utah and entered Colorado, the trajectories aligned more closely and traversed western Colorado. Most air parcels arriving at the Bear Lake site did not pass over the Metropolitan Denver area or the Colorado Front Range. The powerplants in northwestern Colorado were mostly missed by the storm. Nitrate and sulfate concentrations detected in the snowmelt of 6.7 and 5.7 microequivalents per liter, respectively, were low relative to those of the other samples shown in table 1, to other snowfall samples collected at Bear Lake, and to other observations of snowpack chemistry in Colorado (Ingersoll 1995).

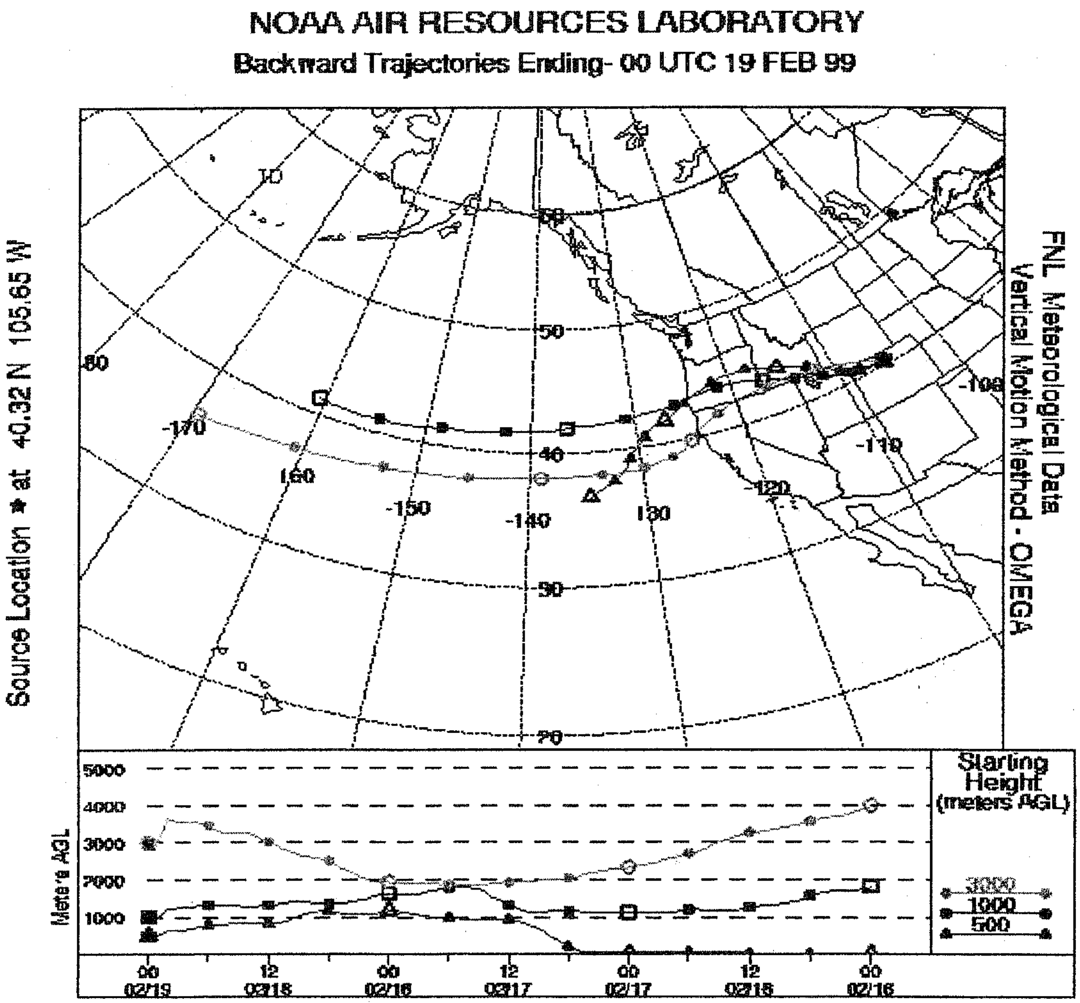

Figure 3: HYSPLIT4 model output of backward trajectory during snowfall event sampled February 20, 1999.

The next snowfall event listed in Table 1 (sampled on February 20, 1999, Figure 3), also was a typical wintertime snowstorm with generally westerly winds and light precipitation (0.4 cm). Wind data collected at the Niwot Ridge station indicated mostly westerly with occasional southerly winds at ground level during the storm. The backward trajectories were nearly constant in direction out of the west. All three levels of air masses (500, 1,000, and 3,000 m AGL) mostly passed through the Pacific Northwest or northern California and Idaho. As all three levels of simulated air masses converged in northern Utah or southwestern Wyoming and entered Colorado, the trajectories aligned very closely and traversed northwestern Colorado. Along this path the air masses passed over an area near large coal-fired powerplants in northwestern Colorado. According to these backward trajectories, air parcels arriving at the Bear Lake site did not pass over the Metropolitan Denver area or the Colorado Front Range. Nitrate and sulfate concentrations detected in the snowmelt of 10.0 and 11.7 microequivalents per liter, respectively, were moderate relative to those of the other samples listed in table 1, slightly below average compared to other snowfall samples collected at Bear Lake, and moderate compared to other observations of snowpack chemistry in Colorado.

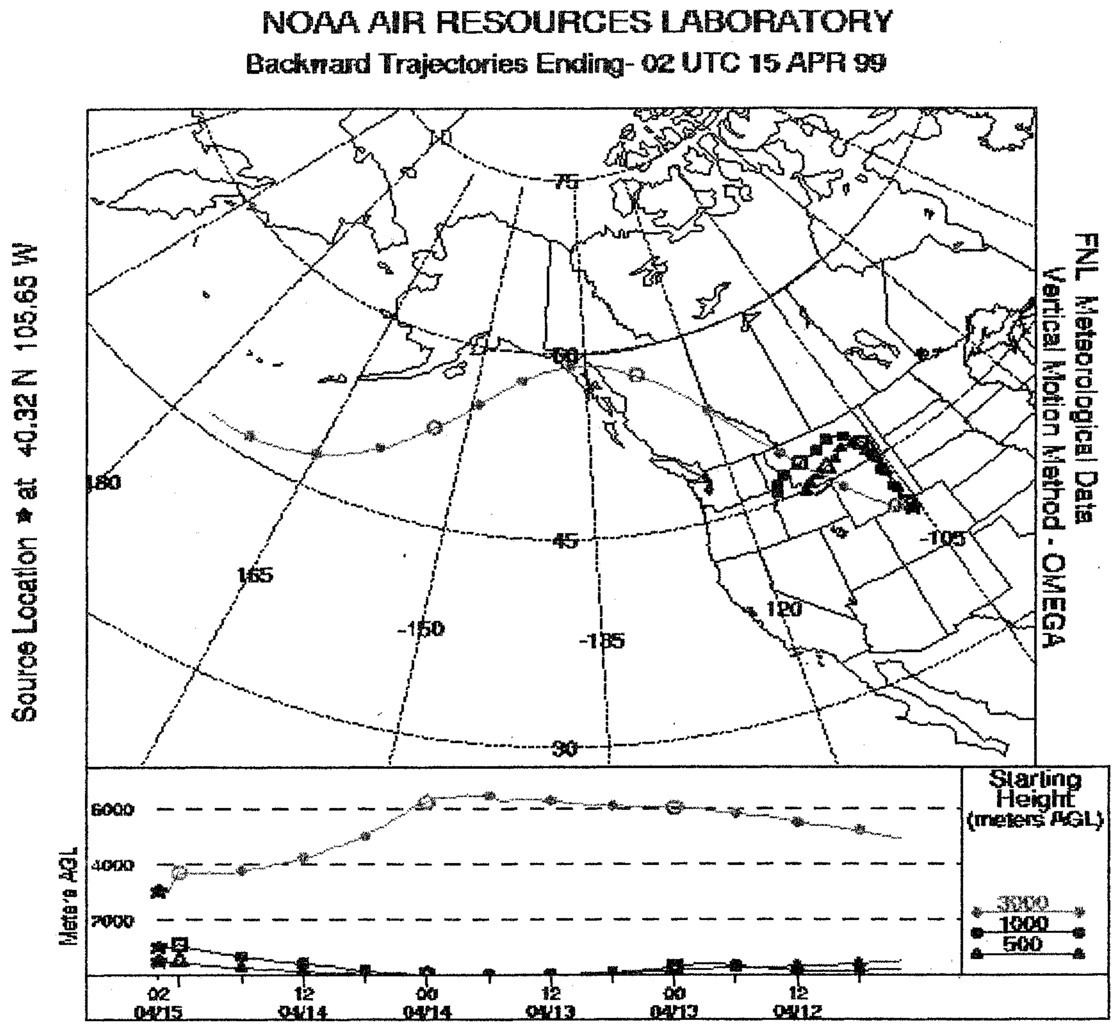

Figure 4: HYSPLIT4 model output of backward trajectory during snowfall event sampled April 16, 1999.

The snowfall event sampled on April 16, 1999 (Figure 4) occurred during a northerly snowstorm with light precipitation (1.3 cm). Wind data collected at the Niwot Ridge station indicated mostly northerly and north-northwesterly winds at ground level during the storm. The backward trajectories at 500 and 1,000 m AGL were closely aligned out of the north; at 3,000 m AGL the simulated airflow came from the northwest. All three levels of air masses passed through either Idaho or Montana before reaching Wyoming enroute to the Bear Lake site. As all three levels of simulated air masses converged in northern Colorado, the trajectories indicated a direct path to the sampling site. These backward trajectories indicated the storm system arriving at the Bear Lake site did not pass over either the powerplants in northwestern Colorado or the Metropolitan Denver area. Nitrate and sulfate concentrations detected in the snow samples were the lowest of the four samples discussed at 6.3 and 4.6 microequivalents per liter, respectively. These concentrations also were low relative to other snowfall samples collected at Bear Lake and to other observations of snowpack chemistry in Colorado.

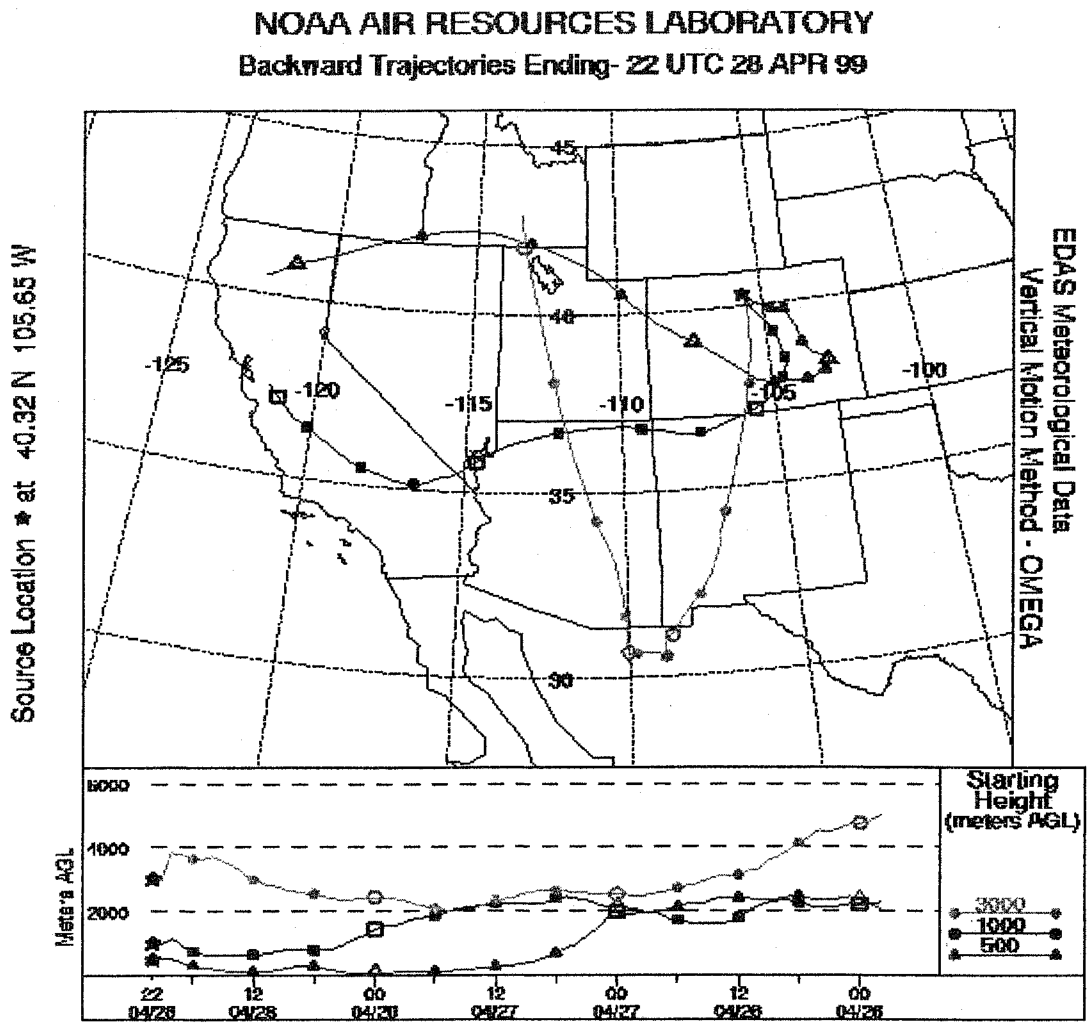

Figure 5: HYSPLIT4 model output of backward trajectory during snowfall event sampled April 29, 1999.

The final snowfall event (sampled on April 29, 1999, Figure 5), was a springtime, upslope storm with heavy precipitation (4.2 cm). Wind data collected at the Niwot Ridge station indicated mostly southerly winds at ground level during the storm. The backward trajectories at all three levels generally were aligned out of the south or southeast once arriving in Colorado, but the simulated airflow came from a variety of States in the Western United States before reaching the Bear Lake site. Finally, the trajectories converged and followed a path north and northwestward over developed areas along the Colorado Front Range and the Metropolitan Denver area to the sampling site. These backward trajectories suggest that the storm system arriving at the Bear Lake site did not pass over the powerplants in northwestern Colorado but traversed much of eastern Colorado where other powerplants are located. Additionally, urban, suburban, industrial, and agricultural development is prevalent along the eastern slope of the Colorado Front Range. Nitrate and sulfate concentrations detected in the snow were the highest of the four samples discussed at 17.6 and 15.2 microequivalents per liter, respectively. These concentrations also were high relative to other snowfall samples collected at Bear Lake and were high compared to other observations of snowpack chemistry in Colorado.

Using this technique in the Front Range area of the Rocky Mountains of Colorado presented several difficulties. Periods were encountered lasting from several days to weeks with minimal snowfall, which limited the number of samples. When measurable snowfall occurred and a collection time was determined by local observers who closely monitored current weather conditions, the samples collected generally did not have enough volume of water or were not representative of a single storm. Some storm events lasted several days with periods of negligible snowfall while multiple weather systems from different directions traversed the park. This complicated efforts by observers to clearly distinguish the end of a snowfall event from one direction and collect a sample before the start of the next storm from another direction.

Evaporative losses were not measured in the study but likely had a negligible effect on snowfall chemistry because the samples were collected and processed within a few days of storm events. Bulk sample volumes may have underestimated total precipitation amounts because of possible snowfall-catch inefficiencies of the simple design of the sample collectors. If future studies are attempted and estimating total ionic loading is a primary goal, then more elaborate shielding of collection devices and more accurate measurement of snowfall precipitation should be considered. Although bulk precipitation amounts collected after some of the storms sampled were at least 7 or 8 cm, other storms delivered less than the minimum amount necessary for analysis. NADP wetfall amounts in the area for this period similarly ranged from about 1 to almost 10 cm.

Interpretation of multiple trajectories should be carefully considered, especially when air masses at different altitudes move in nearly opposite directions. In this area of complex topography, meteorology is complicated not only by the steep terrain but also by the interaction between regional weather-producing influences including prevailing westerly winds aloft and opposing upslope flows from southerly, easterly, or northerly directions. During winter, snowstorms traversed the study area generally from the west, but easterly storms also were observed, especially in late winter or early spring. Occasionally two storm systems reached the ROMO area from different directions. For the four snowfall-event samples analyzed in this paper, local observations of storm directions, and measurements of surface winds agreed favorably with the backward-trajectory estimates.

SUMMARY AND CONCLUSIONS

General trends in concentrations of nitrate and sulfate in snowfall from distinct snowstorms were noted at a high-elevation site in the Rocky Mountains of Colorado. Bulk atmospheric deposition was collected for four distinct snowstorms during winter and spring in 1999. Storm pathways to Bear Lake during snowfall events were estimated using the HYSPLIT4 backward-trajectory model developed by the National Oceanic and Atmospheric Administration. Deposition of acidic ions of nitrate and sulfate in snowfall during the study varied substantially (two- to threefold) depending on storm trajectory. Snowfall-chemical concentrations of nitrate and sulfate at the Bear Lake sampling site were highest when air masses from the south traversed the developed areas along the Front Range of Colorado. Moderately elevated concentrations of nitrate and sulfate were detected when air masses traveled from the northwest where two powerplants are located. Lowest concentrations were observed when storms came from east or north of the study site and did not pass over the Metropolitan Denver area or other highly developed urban and industrial areas to the south. These results of substantially variable snowfall chemistry indicate the importance of storm direction on concentrations of nitrate and sulfate deposited to the sensitive ecosystems in Rocky Mountain National Park. This sampling technique may be more effective at identifying sources of atmospheric pollutants from particular storms than existing monitoring networks.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding provided by the National Park Service, Air Resources Division, Denver, Colorado. We appreciate the permission granted by the Rocky Mountain National Park research staff to locate sampling collectors near Bear Lake. Thanks also are expressed to Mary Kay Watry and others on the staff at Rocky Mountain National Park for their extended efforts to sample snowfall events at Bear Lake. We also thank Greg Alexander, Ron Antweiler, Terry Brinton, Dave Clow, Heather Handran, Dawn Jewell, Alisa Mast, Leora Nanus, David Roth, and Howard Taylor for analytical work and other support. The authors also thank the manuscript reviewers for their useful comments and suggestions.

REFERENCES

Baron, J., ed. 1992. Biogeochemistry of a subalpine ecosystem: Loch Vale watershed. Springer-Verlag, New York. 247 p.

Barry, R.G. 1992. *Mountain weather and climate*; 2d ed. Routledge, London. p. 226-259.

Berg, N.H., McGurk, B.J., Marks, D., Melack, J.M., and Dawson, D. 1989. Evaluation of methods for measurement of snowfall and collection of snow for chemical analyses. Report for California Air Resources Board Contract A6-078-32.

Campbell, D.H., Clow, D.W., Ingersoll, G.P., Mast, M.A., Spahr, N.E., and Turk, J.T. 1995. Processes controlling the chemistry of two snowmelt-dominated streams in the Rocky Mountains. *Water Resources Research* 31: 2811-2821.

Campbell, D.H., Turk, J.T., and Spahr N.E. 1991. Response of Ned Wilson Lake watershed, Colorado, to changes in atmospheric deposition of sulfate. *Water Resources Research* 27: 2047-2060.

Denning, A.S., Baron, J., Mast, M.A., and Arthur, M. 1991. Hydrologic pathways and chemical composition of runoff during snowmelt in Loch Vale watershed, Rocky Mountain National Park. *Water Air and Soil Pollution* 59: 107-123.

Evans, M.J., Shallcross, D.E., Law, K.S., Wild, J.O.F., Simmonds, P.G., Spain, T.G., Berrisford, P., Methven, J., Lewis, A.C., McQuaid, J.B., Pilling, M.J., Bandy, B.J., Penkett, S.A., Pyle, J.A. 2000. Evaluation of a Lagrangian box model using field measurements from EASE (Eastern Atlantic Summer Experiment) 1996. *Atmospheric Environment* vol. 34: 3483-3863.

Hasfurther, V., Kerr, G., Parks, G., and Wetstein, J. 1994. Chapter 9, Hydrology, in Musselman, R.C., The Glacier Lakes Ecosystem Experiment Site, USDA Forest Service. General Technical Report RM-249, Fort Collins, Colorado.

Heuer, K., Tonnessen, K.A., and Ingersoll, G.P. 2000. Comparison of precipitation chemistry in the Central Rocky Mountains, Colorado, USA. *Atmospheric Environment* 34: 1713-1722.

Heuer, K.; Brooks, P.D.; Tonnessen, K.A. 1999. *Hydrological Processes* 13: 2203-2214.

Ingersoll, G.P. 1995. Maximum-accumulation snowpack chemistry at selected sites in northwestern Colorado during spring 1994. U.S. Geological Survey, Open-File Report 95-139, 14 p.

Ingersoll, G.P. 1999. Effects of snowmobile use on snowpack chemistry in Yellowstone National Park, 1998. U.S. Geological Survey Water-Resources Investigations Report 99-4148. 23 p.

Ingersoll, G.P., Tonnessen, K.A., Campbell, D.H., Glass, B.R., and Torizzo, A.O. 2000. Comparing atmospheric-bulk-deposition chemistry to wetfall chemistry in and near Rocky Mountain National Park, Colorado. p. 142 In *Proceedings 93rd Annual Conference, Air and Waste Management Association,* Salt Lake City, Utah.

Lewis, W.M., Jr., Grant, M.C., and Saunders, J.F., III. 1984. Chemical patterns of bulk atmospheric deposition in the State of Colorado. *Water Resources Research.* 20: 1691-1704.

Musselman, R.C., Hudnell, L., Williams, M.W., and Sommerfeld, R.A. 1996. Water chemistry of Rocky Mountain Front Range aquatic ecosystems. USDA-FS Research Paper RM-RP-325, 13p.

National Atmospheric Deposition Program/National Trends Network Home Page. http://nadp.sws.uiuc.edu (accessed January 2000).

Niwot Ridge Long-term Ecological Research (LTER). 2000. http://culter.colorado.edu (accessed January 2000).

NOAA Air Resources Laboratory, 1997. HYSPLIT4 Backward-trajectory model developed by the National Oceanic and Atmospheric Administration, Silver Spring, MD. Web address: http://www.arl.noaa.gov/ready/hysplit4.html (accessed June 2001).

Russell, K.M., Galloway, J.N., Macko, S.A., Moody, J.L., Scudlark, J.R. 1998. Sources of nitrogen in wet deposition in the Chesapeake Bay Region. *Atmospheric Environment* 32: 2453-2465.

Schlesinger, W.H. 1997. Biogeochemistry: an analysis of global change. Academic Press, San Diego.

Turk, J.T. and Campbell, D.H. 1997. Are aquatic resources of the Mount Zirkel Wilderness Area in Colorado affected by acid deposition and what will emissions reduction at the local power plants do? U.S. Geological Survey Fact Sheet. FS-043-97 4 p.

Turk, J.T., and Campbell, D.H. 1987. Estimates of Acidification of Lakes in the Mount Zirkel Wilderness Area. Colorado, *Water Resources Research* 23: 1757-1766.

Turk, J.T., Campbell, D.H., Ingersoll, G.P., and Clow, D.W. 1992. Initial findings of synoptic snowpack sampling in the Colorado Rocky Mountains. U.S. Geological Survey Open-File Report 92–645, 6 p.

Turk, J.T., Taylor, H.E., Ingersoll, G.P., Tonnessen, K.A., Clow, D.W., Mast, M.A., Campbell, D.H., Melack, J.M. 2001. Major-ion chemistry of the Rocky Mountain snowpack, USA. *Atmospheric Environment* 35: 3957-3966.

USEPA AIRSData Home Page. http://www.epa.gov/air/data/index/ (accessed June 2000).

Western Regional Climate Center. 2000. http://www.wrcc.dri.edu (accessed January 2000).

Williams, M.W., Baron, J., Caine, N., Sommerfeld, R.A., and Sanford, R., Jr. 1996. Nitrogen saturation in the Rocky Mountains, *Environmental Science and Technology* 30: 640-646.