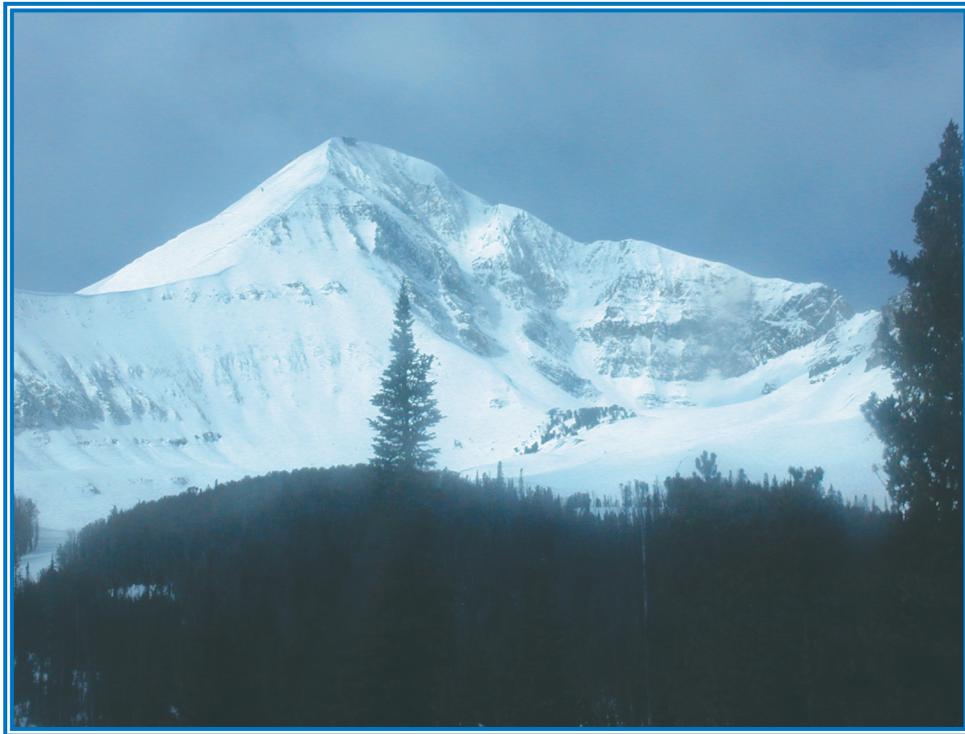


Prepared in cooperation with the
National Park Service and the
U.S. Department of Agriculture
Forest Service

Rocky Mountain Snowpack Chemistry at Selected Sites for 2001

Open-File Report 03-48



U.S. Department of the Interior
U.S. Geological Survey

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By George P. Ingersoll, M. Alisa Mast, David W. Clow, Leora Nanus,
Donald H. Campbell, and Heather Handran

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U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
meters (m)	3.28084	feet
kilometers (km)	0.6213712	miles
centimeter (cm)	0.3937003	inches
liter (L)	0.2641721	gallons

To convert from microequivalents per liter to milligrams per liter for major ions, divide microequivalents by factors indicated for each ion:

To obtain milligrams per liter,	For	Divide by
	hydrogen (H ⁺)	1,000
	calcium (Ca ²⁺)	49.9
	magnesium (Mg ²⁺)	82.26
	sodium (Na ⁺)	43.5
	potassium (K ⁺)	25.57
	ammonium (NH ₄ ⁺)	55.44
	chloride (Cl ⁻)	28.21
	sulfate (SO ₄ ²⁻)	20.83
	nitrate (NO ₃ ⁻)	16.13

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = 1.8 (^{\circ}\text{C}) + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Because regional-scale atmospheric deposition data in the Rocky Mountains are sparse, a program was designed by the U.S. Geological Survey, in cooperation with the National Park Service, U.S. Department of Agriculture Forest Service, and other agencies, to more thoroughly determine the chemical composition of precipitation and to identify sources of atmospherically deposited contaminants in a network of high-elevation sites. Samples of seasonal snowpacks at 57 geographically distributed sites, in a regional network from New Mexico to Montana, were collected and analyzed for major ions (including ammonium, nitrate, and sulfate), alkalinity, and dissolved organic carbon during 2001. Sites selected in this report have been sampled annually since 1993, enabling identification of increases or decreases in chemical concentrations from year to year. Spatial patterns in snowpack-chemical data for concentrations of ammonium, nitrate, and sulfate indicate that concentrations of these acid precursors in less developed areas of the region are lower than concentrations in the heavily developed areas. Results for the 2001 snowpack-chemistry analyses, however, indicate increases in concentrations of ammonium and nitrate in particular at sites where past concentrations typically were lower. Since 1993, concentrations of nitrate and sulfate were highest from snowpack samples in northern Colorado that were collected from sites adjacent to the Denver metropolitan area to the east and the coal-fired powerplants to the west. In 2001, relatively high concentrations of nitrate (12.3 to 23.0 microequivalents per liter ($\mu\text{eq/L}$) and sulfate (7.7 to 12.5 $\mu\text{eq/L}$) were detected in Montana and Wyoming. Ammonium concentrations were highest in north-central Colorado (14.5 to 16.9 $\mu\text{eq/L}$) and southwestern Montana (12.8 to 14.2 $\mu\text{eq/L}$).

INTRODUCTION

The Rocky Mountain region, containing an expansive system of National Parks, National Forests, and wilderness areas where snow is the primary source of water, is surrounded by mostly arid and semiarid lands. Recent population growth, water use, and energy development are increasingly affecting the quantity and quality of water resources in the Rocky Mountains.

Identifying changes in water quality and processes leading to degradation of water quality is important because alpine and subalpine environments in the region are sensitive to changes in chemical composition of the water. Thin alpine and subalpine soils and dilute water bodies in mountain ecosystems typically have limited capacity to neutralize or buffer acidity that may result from airborne contaminants such as nitrogen and sulfur. Atmospheric input of these and other chemicals to these sensitive areas may harm plant and wildlife populations (Corn and others, 1989). Precipitation that transports contaminants from the air can affect the chemistry of mountain watersheds and alter the chemical balance of these ecosystems (Cogbill and Likens, 1974).

Although several watershed-scale studies have addressed the problem of anthropogenic chemical deposition in small headwater basins in the Rocky Mountains (Turk and Campbell, 1987; Caine and Thurman, 1990; Baron, 1992; Reuss and others, 1993; Campbell and others, 1995; and Williams and others, 1996), regional-scale atmospheric deposition data are sparse. In the past, data from National Atmospheric Deposition Program (NADP) (2001) sites provided the only regional estimates of atmospheric deposition (Nilles, 2000). The NADP network is extensive nationwide, but coverage for high-elevation areas (greater than 2,000 meters [m]) in the Rocky Mountains is limited. Although 10 high-elevation NADP sites monitor wet atmospheric deposition in Colorado, few sites are operated at high-elevation areas in Montana, Wyoming, and New Mexico, where snowpacks persist with negligible melt through the snowfall season. These high-elevation snowpacks may accumulate 2 to 3 times the annual precipitation measured at lower elevations where regular monitoring is more feasible.

Thus, a snowpack-chemistry-monitoring program designed to determine the quality of regional snowfall and to identify sources of atmospherically deposited contaminants in the Rocky Mountains was developed.

Snowfall provides about 50 to 70 percent of the annual precipitation in headwater basins of the Rocky Mountains from early October to late March (Western Regional Climate Center, 2001). Snowpacks that accumulate during the winter and spring contain an integrated record of chemicals deposited from the atmosphere during these seasons. Because snowmelt supplies most of the freshwater in mountain lakes, streams, and wetlands, monitoring the water quality of snowpack is important to understanding the long-term health of these systems.

In the mid-1980's, U.S. Geological Survey (USGS) scientists began monitoring mountain snowpack and lake chemistry in western Colorado (Turk and Campbell, 1987; Campbell and others, 1991; Turk and others, 1992). The network of snowpack sites grew from a few sites in Colorado in the 1980's to more than 52 sites in four States in 1993. The current network of 57 sites extends about 1,500 kilometers (km) from northern New Mexico to northern Montana and is maintained by the USGS, in cooperation with the National Park Service, U.S. Department of Agriculture (USDA) Forest Service, and other agencies. This monitoring network requires only one annual visit to each of the snowpack-sampling sites.

Acknowledgments

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SAMPLING METHODS

The validity of a regional assessment of snowpack chemistry depends on the collection of representative snow samples that integrate atmospheric deposition for several months during the snowfall season. Since 1993, the USGS has applied consistent methods for sampling physical and chemical characteristics of regional

snowpacks (Ingersoll, 1999). A variety of chemical constituents are measured in a single, composite sample that indicates the quality of air masses present during snowfall events that contribute to the annual snowpack. The snowpack-chemistry network makes it possible to interpret precipitation chemistry data temporally and spatially and supports the identification of geographic patterns and likely sources of airborne contaminants.

Network Design and Sampling Locations

The network of snow-sampling sites in Montana, Wyoming, Colorado, and New Mexico was selected in protected National Forests or National Parks near the Continental Divide at locations with limited human activity or emissions from local residential, commercial, or industrial activities. Sites generally were located 10 km or more from local, potential air-contamination sources in order to see if regional emissions are detectable hundreds of kilometers from their sources. Most Colorado and New Mexico sites are at elevations ranging from 2,700 to 3,400 m; Wyoming and Montana sites typically are lower at about 1,800 to 2,700 m. At these locations, the seasonal snowpack accumulates throughout the winter, and substantial snowmelt does not occur until spring runoff begins in March or April. The seasonal snowpacks sampled melt entirely each summer, so resampling snowfall from previous years is avoided. As latitude increases along the Continental Divide, the elevation at which seasonal snowpacks persist generally decreases. Snow that survives snowmelt from year to year, referred to as firm, typically is present only in the highest alpine areas, well above tree line and above sampling locations in this network.

Severe weather in the Rocky Mountains during late winter and spring and logistical constraints restrict travel at high elevations. Limited access to remote, snow-covered areas requires careful selection of sampling locations. Because no construction of permanent structures or maintenance is necessary using USGS snow-sampling methods, sites may be selected in the most optimal locations without affecting wild areas in National Parks and National Forests. The only disturbance at the sites is the digging of a small snowpit, which is backfilled just after sample collection. Wind and subsequent snowfall events usually restore smooth, untracked snowscapes soon after site visits. Sampling locations are free from avalanche activity and are reasonably accessible to sampling crews. These criteria exclude much of the terrain at the highest elevations of the Rocky Mountains.

Samples were collected in small clearings in forests, on cooler, north-facing slopes whenever possible, and where the snowcover appeared to be free of human influence or other disturbances such as excessive tree litter or animal activity. Each layer sampled was inspected for visible contaminants. Scoured or drifted snowscapes were avoided because such areas may not represent a cumulative seasonal snowpack that contains layers from all snowfall events. Sites were located at least 30 m away from plowed roadways to minimize contamination from vehicular traffic; previous work has shown this distance to be sufficient (Ingersoll, 1999).

When possible, snow-sampling sites were collocated near snow-telemetry (SnoTel) instrument sites where measurements of snow-water equivalence (SWE) were reported daily. SnoTel sites, operated by the USDA, Natural Resources Conservation Service, reported other meteorological information describing snowpacks that was useful in choosing sampling locations for the study. Snow depths, total annual snowfall accumulations, air temperature, and total precipitation also were reported daily and historically from a wide network of SnoTel sites throughout the Rocky Mountains (Western Regional Climate Center, 2001).

Timing of Sample Collection

Samples were collected at about the annual maximum snow depth but before the onset of spring snowmelt. Scheduling field sampling of annual snowpacks near maximum accumulation was based on 30-year-averaged, maximum-SWE values reported at SnoTel sites at elevations similar to the sampling sites. Biweekly SWE values reported at SnoTel sites for the 30-year base period, 1961–90, were used to forecast times when snowmelt might begin. Collection dates were scheduled 2 or 3 weeks before the 30-year-averaged, maximum-SWE period in order to collect samples before episodes of earlier than usual melting. On average, this represented about 80 to 90 percent of total seasonal snowfall and thus provided a good indicator of atmospheric deposition for a substantial part of the year. Obtaining snow samples before melt begins is crucial to preserving the chemical record of the snowpack because the liquid water flowing downward through the snowpack in early stages of snowmelt tends to be more concentrated than snowmelt that occurs later in the process (Campbell and others, 1995; Harrington and Bales, 1998).

Methods of Sample Collection

Snowpits were prepared with a smooth, freshly cut, vertical, shaded face that extended from the ground surface upward throughout the entire depth of the snowpack (fig. 1). Before snow samples were collected, physical measurements of the snowpack were made. Temperature profiles were recorded at 10- or 20-centimeter (cm) intervals to ensure temperatures below 0°C were present among the snow layers. Snow-crystal size, type, and hardness of all homogeneous layers were measured to document the metamorphism of the snowpack through the winter. Further observations of ice layers, evidence of melt, saturated wet snow, and soil moisture beneath the snowpack were recorded to verify that snowmelt had not begun and that the snow to be collected maintained the seasonal atmospheric deposition in an ice phase.

Snow samples were collected carefully to prevent contamination. The top 5 cm of snowpack was discarded to exclude snow possibly contaminated by activities involved with transport to and preparation of the snowpit. The bottom 10 cm of the snowpack near



Figure 1. Snowpit face just before sampling the full snowpack at Buffalo Pass in Colorado.

the ground also was not sampled to avoid contamination from soils or other terrestrial materials. Powder-free, vinyl laboratory gloves were worn, and clean plastic shovels and scoops were used to collect a complete vertical snow column representing all layers for each sample.

Workers in the snowpits took precautions to avoid inclusion of potential contaminants such as soils, tree litter, animal waste, or perspiration when filling sample containers. The snow samples were removed and placed in 8-liter (L) polytetrafluoroethylene bags that were prerinsed with high-purity deionized water. These containers were sealed to prevent contamination, frozen to reduce chemical reactivity prior to laboratory analyses, and transported to a USGS research laboratory in Boulder, Colo., for analysis. Laboratory methods and quality-assurance procedures for major-ion analyses are described in Ingersoll (1999), Mast and others (2001), and Turk and others (2001). Laboratory blanks, field blanks, and field replicates composed about 20 percent of analytical processing. Ionic charge balance was calculated by dividing the sum of cations (hydrogen ion, calcium, magnesium, sodium, potassium, and ammonium) minus the sum of anions (alkalinity, chloride, nitrate, and sulfate) by the total cations and anions in solution. Alkalinity was calculated as the difference in total concentrations of bases and acids, and only positive values for alkalinity, indicating bicarbonate anion concentration, were included with the sum of anions in charge-balance calculations.

Snowpack Chemistry of Selected Sites

The 2001 snowpack samples were collected at 57 long-term sites in the network including 50 sites that have been sampled annually since 1993. The additional seven sites have been sampled for 4 to 8 years since 1993. In a few cases, the snowpack had warmed to near-melting levels throughout, but no substantial snowmelt had begun before samples were collected. During 2001, typical water contents measured and estimated in the annual snowpacks in the study area ranged from about 0.15 m in the drier areas to about 1.0 m in the deepest snowpacks. Direct measurements of SWE were not made in all snowpacks sampled during 2001. At sites where SWE was measured, strong positive correlations existed between snow depth and SWE ($r > 0.9$, $p = 0.05$). Snow depths in the 2001 snowpack ranged from 48 to 309 cm.

In 2001, concentrations of major ions and dissolved organic carbon, ionic charge balances, and laboratory pH are listed in table 1. Ionic-charge balances, a

measure of the quality of chemical analyses, were mostly positive, and the mean was +9.6 percent. Other ionic balances calculated for precipitation chemistry of comparable ionic strength in a separate network yielded similar deviations (National Atmospheric Deposition Program, 1993). One explanation for some of the positive bias of the ionic balances (table 1) is that organic acids that are possibly associated with the dissolved organic carbon (DOC) and other organic acids (such as acetate and formate) that have been detected in snow in the region in earlier work (Turk and others, 2001) were not included in the calculation. If these organic acids were included in ionic-balance calculations, it could decrease positive ionic balances by approximately 3 to 5 percent. The reason for the remaining percentage of positive bias of the ionic balances is unknown.

Ammonium (NH_4^+) concentrations ranged from 1.9 $\mu\text{eq/L}$ at Red Mountain Pass in Colorado (51) to 16.9 $\mu\text{eq/L}$ at Niwot SnoTel in Colorado (48). The highest levels of NH_4^+ were measured at Apgar Lookout (1), Lionshead (8), Monida Pass (9), West Yellowstone (15), Brumley (33), and Niwot SnoTel (48) (table 1, fig. 2).

Nitrate concentrations ranged from 5.3 $\mu\text{eq/L}$ at Granite Pass in Montana (6) to 23.0 $\mu\text{eq/L}$ at Monida Pass in Montana (9) (fig. 3). Sulfate concentrations ranged from 4.1 $\mu\text{eq/L}$ at Chief Joseph Pass in Montana (4) and Togwotee Pass in Wyoming, to 14.3 $\mu\text{eq/L}$ at Niwot SnoTel in Colorado (48) (table 1 and fig. 4). Regionally, concentrations of nitrate (NO_3^-) generally were highest near Yellowstone in northwestern Wyoming and southwestern Montana, and in northern Colorado (table 1 and fig. 3). Collectively, the snowpacks in northern Colorado that are adjacent to the Denver metropolitan area to the east and the coal-fired powerplants to the west had some of the highest overall concentrations of nitrate (fig. 3) and sulfate (SO_4^{2-}) (fig. 4). Concentrations of nitrate and sulfate at west-central Montana sites such as Mount Belmont (10) and Spring Gulch (14), and Apgar Lookout (1) in northwestern Montana, were higher than average in 2001. The highest concentrations of nitrate in seasonal snowpacks in the Rocky Mountain region were at Monida Pass (9), Dry Lake (37), Divide Peak (18), and Niwot SnoTel (48). The highest concentrations of sulfate were detected at Niwot SnoTel (48), Brumley (33), Divide Peak (18), and Old Battle (24).

Although flow directions of surface winds in the Rocky Mountains are variable and fluctuate on an hourly basis, prevailing westerly winds dominate in

Table 1. Concentrations of major ions, alkalinity, dissolved organic carbon; laboratory pH; and ionic charge balances from analyses of the 2001 snowpack [Hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and alkalinity (Alk) are in microequivalents per liter; dissolved organic carbon (DOC) values expressed in milligrams per liter. Ionic balances are percentages; <, less than]

Site number shown in figs. 2-4	Site name	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	Alk	DOC	Ionic balance
1	Apgar Lookout, Mont.	5.10	7.9	4.9	1.4	2.2	0.7	11.7	0.5	10.4	13.6	-6.7	1.0	8.0
2	Big Mountain, Mont.	5.05	8.9	2.0	0.8	1.4	0.3	4.3	<0.3	5.9	8.4	-9.3	0.5	10.7
3	Big Sky, Mont.	5.35	4.5	3.9	0.8	0.9	0.4	4.2	<0.3	4.2	6.6	-3.0	0.5	15.2
4	Chief Joseph Pass, Mont.	5.26	5.5	4.4	0.8	1.0	1.2	2.7	<0.3	4.1	5.5	-5.6	1.2	23.8
5	Daisy Pass, Mont.	5.25	5.6	3.4	0.8	0.9	0.9	4.8	<0.3	4.8	7.5	-4.0	0.8	14.4
6	Granite Pass, Mont.	5.39	4.1	5.4	1.6	1.7	1.0	3.6	<0.3	4.9	5.3	-2.8	0.9	26.0
7	Kings Hill, Mont.	5.15	7.1	6.9	1.6	1.3	2.2	7.3	<0.3	9.6	10.0	-6.9	1.4	14.7
8	Lionshead, Mont.	5.17	6.8	4.4	0.8	1.2	0.8	14.2	1.0	7.7	15.7	-6.9	0.8	7.2
9	Monida Pass, Mont.	5.11	7.8	6.4	0.8	2.7	0.4	13.6	2.5	5.5	23.0	-9.1	0.6	1.1
10	Mount Belmont, Mont.	5.18	6.6	8.9	2.4	2.2	3.7	5.3	1.5	11.0	12.5	-4.3	2.2	7.7
11	Noisy Basin, Mont.	4.99	10.2	2.9	0.8	1.4	0.5	4.2	<0.3	6.6	8.8	-10.5	0.7	13.1
12	Red Mountain, Mont.	5.50	3.2	8.4	2.4	1.3	0.9	5.4	<0.3	6.0	9.4	-2.0	1.1	16.7
13	Snow Bowl, Mont.	5.12	7.6	2.5	0.8	1.0	1.1	2.6	<0.3	5.2	5.6	-6.5	1.0	18.1
14	Spring Gulch, Mont.	5.17	6.8	7.4	0.8	1.3	0.0	5.8	3.9	9.1	13.7	-5.8	0.9	-9.5
15	West Yellowstone, Mont.	5.01	9.7	4.9	1.2	1.6	0.5	12.8	1.2	7.8	19.0	-11.1	0.8	4.7
16	Brooklyn Lake, Wyo.	5.48	3.3	7.2	1.2	1.5	1.0	4.5	<0.3	6.0	10.7	-1.9	0.9	5.7
17	Canyon, Wyo.	5.23	5.9	2.5	0.8	1.0	0.3	6.0	<0.3	4.3	9.3	-5.1	0.4	9.6
18	Divide Peak, Wyo.	5.22	6.0	14.9	3.2	6.9	0.6	6.3	1.6	12.5	20.1	-7.3	0.7	5.2
19	Elkhart Park, Wyo.	5.07	8.5	3.9	0.8	1.2	0.3	3.5	<0.3	5.8	10.2	-8.7	0.7	6.5
20	Four Mile Meadow, Wyo.	5.25	5.6	6.4	2.4	1.8	0.6	5.9	<0.3	4.9	10.0	-7.2	0.6	20.8
21	Garnet Canyon, Wyo.	5.33	4.7	5.9	1.6	2.1	1.2	8.3	<0.3	7.2	10.0	-5.6	0.7	16.1
22	Gypsum Creek, Wyo.	5.17	6.8	7.4	2.4	1.8	1.6	3.7	<0.3	6.1	11.7	-5.9	1.2	14.1
23	Lewis Lake Divide, Wyo.	5.35	4.5	2.9	0.8	1.1	0.2	10.5	<0.3	5.4	9.7	-4.0	0.4	13.9
24	Old Battle, Wyo.	5.06	8.7	8.9	2.4	4.8	0.7	7.0	1.5	12.1	16.0	-10.2	0.7	4.7
25	Old Faithful, Wyo.	5.19	6.5	3.9	0.8	1.5	0.4	10.5	<0.3	6.0	12.7	-8.0	0.7	11.5
26	Rendezvous Mountain, Wyo.	5.39	4.1	2.9	0.8	0.9	0.4	6.8	<0.3	5.9	7.0	-3.5	0.5	10.3
27	South Pass, Wyo.	4.99	10.2	5.9	0.8	1.8	0.4	5.0	<0.3	9.9	14.3	-12.4	0.7	-0.1
28	Sylvan Lake, Wyo.	5.12	7.6	1.5	0.0	0.8	0.3	7.1	<0.3	5.0	8.6	-6.7	0.4	11.9
29	Teton Pass, Wyo.	6.17	0.7	20.9	10.7	3.9	2.9	11.7	3.1	9.3	12.5	27.6	1.4	-1.7
30	Togwotee Pass, Wyo.	5.37	4.2	4.2	0.8	1.1	0.4	3.6	0.5	4.1	7.2	-3.9	0.6	9.9
31	Twenty-one Mile, Wyo.	5.18	6.6	3.4	0.8	1.1	0.4	8.2	<0.3	4.3	12.3	-6.2	0.4	10.5

Table 1. Concentrations of major ions, alkalinity, dissolved organic carbon; laboratory pH; and ionic charge balances from analyses of the 2001 snowpack [Hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and alkalinity (Alk) are in microequivalents per liter; dissolved organic carbon (DOC) values expressed in milligrams per liter. Ionic balances are percentages; <, less than]—Continued

Site number shown in figs. 2-4	Site name	pH	H^+	Ca^{2+}	Mg^+	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	Alk	DOC	Ionic balance
32	Berthoud Pass, Colo.	5.07	8.5	5.6	1.0	3.0	1.6	4.0	2.3	6.0	12.2	-7.9	0.9	7.3
33	Brumley, Colo.	5.18	6.6	11.9	2.4	5.1	1.4	14.5	1.1	13.7	15.2	-4.5	1.0	16.6
34	Buffalo Pass, Colo.	4.98	10.5	6.9	1.6	2.7	0.4	6.5	<0.3	11.1	13.0	-11.6	na	8.5
35	Cameron Pass, Colo.	5.21	6.2	5.9	0.8	1.9	0.5	6.4	<0.3	8.1	11.7	-6.1	0.5	4.5
36	Deadman Pass, Colo.	5.21	6.2	8.8	1.7	1.9	1.3	6.8	<0.3	9.0	14.5	-4.9	0.9	6.3
37	Dry Lake, Colo.	4.78	16.6	7.4	1.6	1.8	0.7	6.5	<0.3	10.3	20.6	-20.8	0.3	5.6
38	Dunckley Pass, Colo.	5.66	2.2	12.4	2.4	2.0	2.3	5.6	<0.3	8.0	12.5	2.4	0.7	8.0
39	Elk River, Colo.	5.00	10.0	11.4	1.6	3.9	0.9	5.1	1.0	10.4	17.8	-11.0	0.6	6.0
40	Fremont Pass, Colo.	5.31	4.9	5.4	1.6	1.4	0.6	2.8	<0.3	4.5	8.6	-5.1	0.5	12.1
41	Grand Mesa, Colo.	5.39	4.1	12.9	2.4	2.1	1.1	7.4	<0.3	9.8	14.8	-4.7	0.7	9.8
42	Lake Irene, Colo.	5.08	8.3	6.4	1.6	2.2	0.4	5.5	<0.3	8.4	13.0	-9.7	0.5	6.6
43	Loch Vale, Colo.	5.17	6.8	10.9	2.4	2.3	2.8	6.0	1.0	10.0	14.5	-7.1	1.9	10.0
44	Loveland Pass, Colo.	5.83	1.5	13.4	3.2	2.4	0.5	5.9	2.1	6.1	9.2	3.3	0.2	13.0
45	Lynx Pass, Colo.	5.22	6.0	8.4	1.6	1.7	0.9	8.4	<0.3	6.1	15.8	-6.2	0.7	10.5
46	Molas Lake, Colo.	5.25	5.6	7.4	0.8	1.4	0.5	3.0	<0.3	5.5	10.7	-4.4	0.6	7.0
47	Monarch Pass, Colo.	5.40	4.0	6.9	1.6	1.0	0.6	5.7	<0.3	5.4	9.7	-2.2	0.9	13.4
48	Niwot SnoTel, Colo.	5.11	7.8	9.9	2.4	2.9	1.1	16.9	1.4	14.3	20.0	-6.7	1.0	6.9
49	Phantom Valley, Colo.	4.88	13.0	8.7	1.6	2.5	0.8	6.4	0.6	11.3	18.8	-15.8	0.8	3.6
50	Rabbit Ears Pass, Colo.	5.08	8.2	6.7	1.2	2.7	0.3	5.7	<0.3	9.8	13.8	-9.4	0.4	2.5
51	Red Mountain Pass, Colo.	5.43	3.7	8.9	1.6	1.4	1.3	1.9	<0.3	5.0	9.1	-1.4	0.9	14.3
52	Slumgullion Pass, Colo.	5.68	2.1	11.4	3.2	2.2	1.8	2.2	1.0	5.1	7.3	3.5	1.0	15.1
53	Sunlight Peak, Colo.	5.37	4.3	8.9	1.6	1.8	0.6	6.4	<0.3	7.3	12.3	-1.7	0.4	9.2
54	University Camp, Colo.	5.01	9.8	7.9	2.4	1.9	1.7	9.2	0.9	11.3	15.1	-9.5	1.5	9.3
55	Wolf Creek Pass, Colo.	5.17	6.8	7.4	1.6	1.4	2.0	5.2	<0.3	8.9	11.0	-5.9	0.9	10.1
56	Hopewell, N. Mex.	5.02	9.5	7.9	0.8	2.4	0.7	6.3	1.1	8.0	14.3	-12.0	0.5	8.3
57	Taos Ski Valley, N. Mex.	5.15	7.1	7.7	1.0	1.6	1.0	7.3	<0.3	10.7	12.8	-6.3	0.8	4.4
Summary statistics:														
	minimum	4.78	0.7	2.0	0.80	0.80	0.00	1.9	<0.3	4.1	5.3	-20.8	0.2	-9.5
	maximum	6.2	16.6	20.9	10.7	6.9	3.7	16.9	3.9	14.3	23.0	27.6	2.2	26.0
	mean (median for pH)	5.18	6.6	7.1	1.6	2.0	0.9	6.6	1.5	7.6	12.2	-5.8	0.8	9.6
	standard deviation	na	3.8	3.6	1.4	1.1	0.7	3.3	0.9	2.7	4.0	6.1	0.4	6.0

Notes: (1) Percentages for ionic balances are mean values of individual annual calculations of charge balance of [(total cations - total anions)/(total cations + total anions)] x 100.

(2) Positive alkalinities are included in total anions; negative alkalinities are excluded.

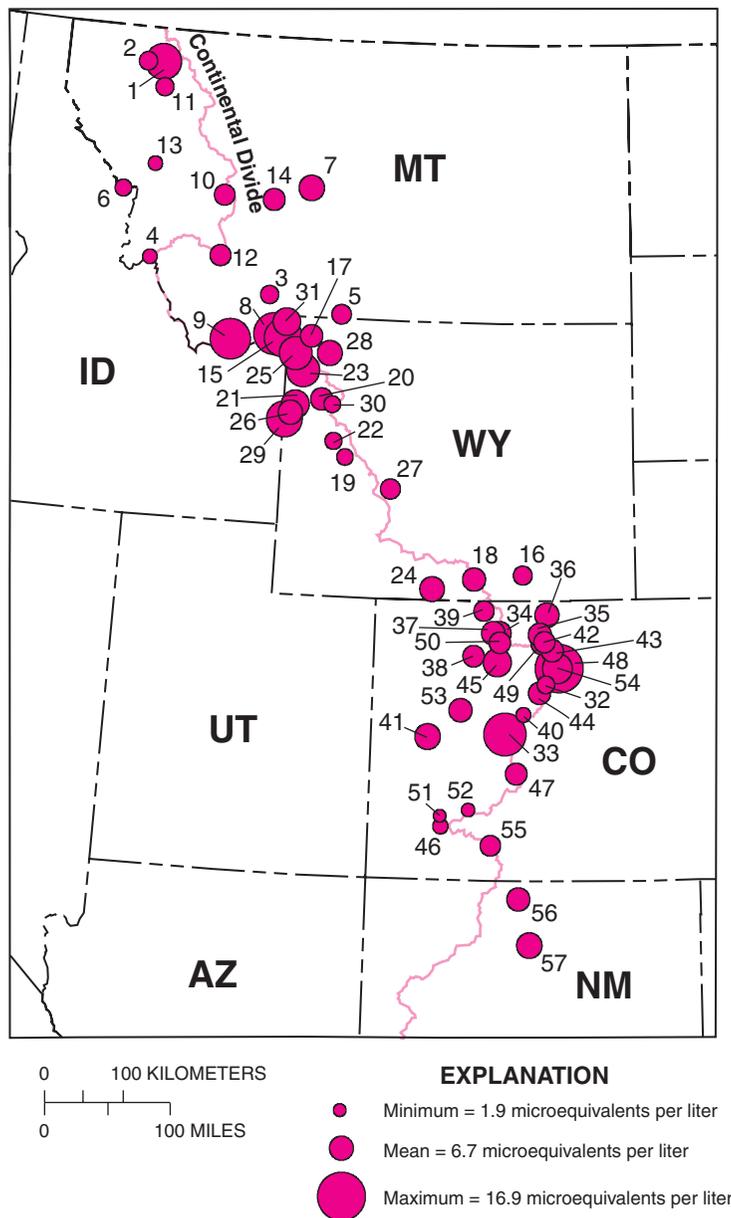


Figure 2. Snowpack ammonium ion concentrations, 2001, Rocky Mountain region.

this region during winter (Banta and Cotton, 1981; Barry, 1992). Springtime snowstorms in Colorado often originate from other directions with an easterly influence. The Dry Lake (37) and Buffalo Pass (34) sites are located downwind (east) from local coal-fired powerplants (Turk and Campbell, 1997) and 140–160 km upwind (west) from the Denver metropolitan area. Concentrations of nitrate and sulfate (byproducts of fossil-fuel combustion) in snowpacks at these two sites were as much as 3 times as high as levels in

snowpacks elsewhere in Colorado (Ingersoll, 1995; 1996). Divide Peak (18) and Niwot SnoTel (48) are located within potential influence of the powerplants and the Denver metropolitan area as just mentioned, but the sites at Brumley (33) and Monida Pass (9) (where elevated concentrations of either nitrate or sulfate were measured) are not. The lowest pH values (and highest acidity) measured in 2001 snowpacks were at Dry Lake (37), Buffalo Pass (34), and Phantom Valley (49). Patterns in chemistry of the 2001 snowpack indicate

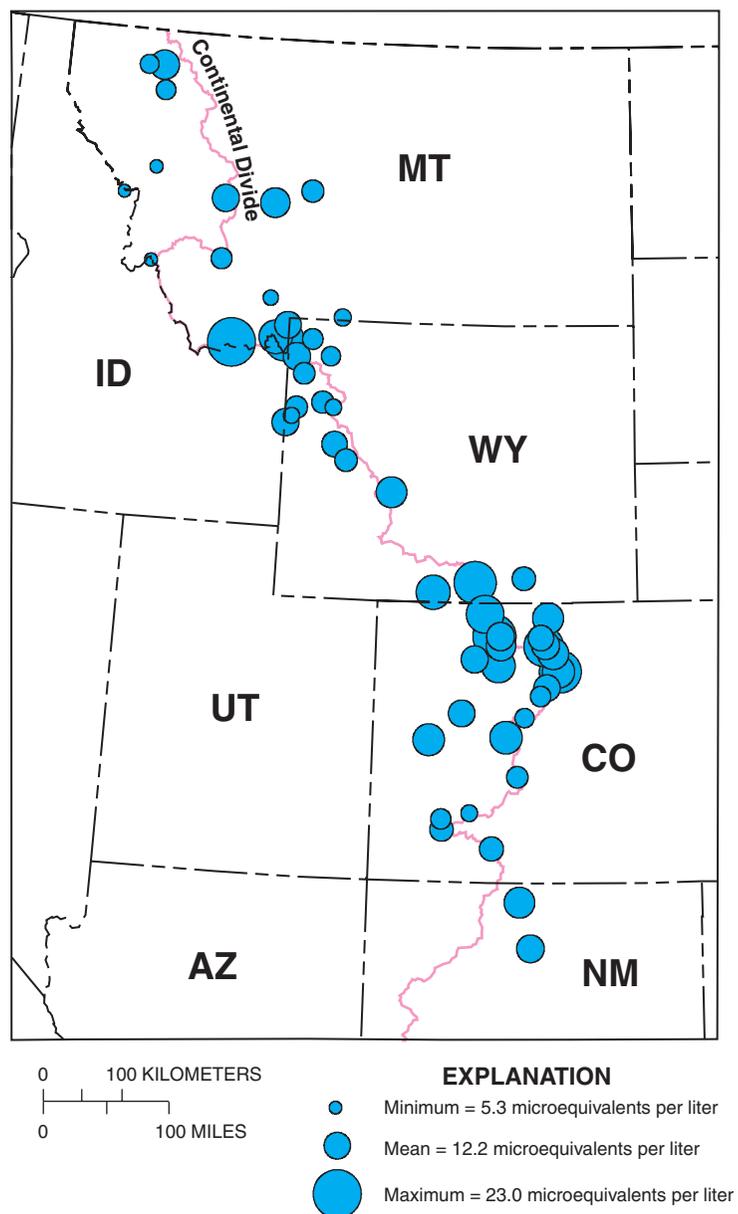


Figure 3. Snowpack nitrate ion concentrations, 2001, Rocky Mountain region.

that emissions other than those from the nearest large sources may be affecting the concentrations of these major ions deposited in snowpacks.

Snow depths were shallower in 2001 compared to snow depths in 2000 at about 75 percent of the sites. Hypothetically, if the amounts of atmospheric deposition during snowfall are similar during both years, concentrations of ammonium, nitrate, and sulfate would be expected to be inversely proportional to

snow depth, and a shallower snowpack would be more concentrated. This relation was observed at some sites during 2001, and it is estimated that many sites in the region in 2001 received a similar amount of atmospheric deposition as was observed in 2000 despite less SWE in 2001 snowpacks. Estimates of nitrogen loading based on measured SWE in Montana and Colorado (and estimated SWE in Wyoming and elsewhere throughout the region) and higher nitrate concentrations measured in 2001 at all but two sites in the region (as compared to

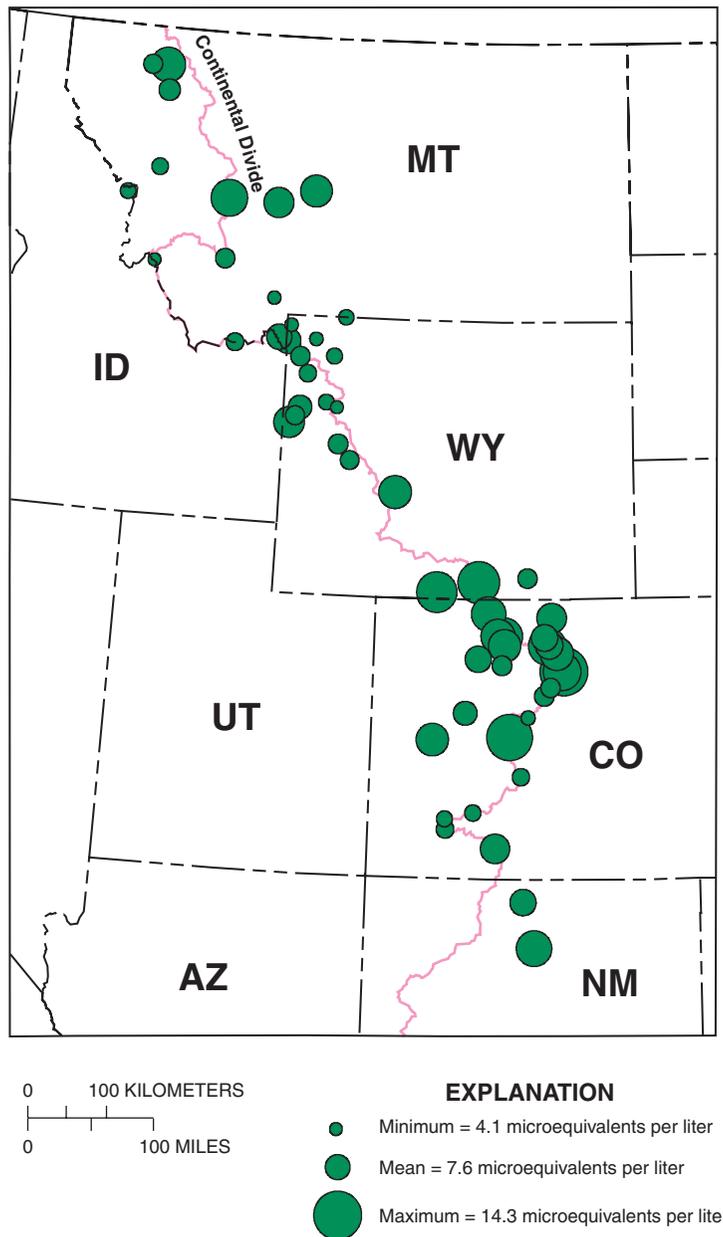


Figure 4. Snowpack sulfate ion concentrations, 2001, Rocky Mountain region.

2000 snowpacks) support this finding. Thus, even with less total SWE, similar or greater amounts of nitrogen may have been atmospherically available to many sites in the Rocky Mountain region during the 2001 snowfall season.

Although nationwide sulfur dioxide emissions have decreased in the past decade, nitrogen oxide emissions have not (U.S. Environmental Protection

Agency, 1999; Nilles and Conley, 2001). Increases noted for concentrations of nitrogen-bearing ions such as ammonium and nitrate in the 2001 snowpacks are consistent with this finding. In the mountains of northern Colorado near Denver, increasing evidence indicates that excess nitrogen entering aquatic and terrestrial ecosystems is causing nitrogen saturation. Heuer and others (2000) determined that nitrogen concentrations measured during 1992–97

in precipitation at NADP sites that are within about 200 km of Denver were consistently higher than concentrations at NADP sites farther from Denver. Other work has shown similar increases in nitrogen deposition to mountain ecosystems within this distance of about 200 km from Denver (Williams and others, 1996; Campbell and others, 2000). These findings are consistent with the regional spatial patterns of snowpack nitrate shown in figure 3. However, patterns in nitrate concentrations in 2001 snowpacks coupled with thinner snowpacks regionally also indicate a possibility that increased nitrogen for potential deposition may be available not only at locations near the largest sources such as powerplants and large population centers, but also in areas away from those large emissions sources such as Apgar Lookout (1) and Monida Pass (9).

SUMMARY AND FUTURE CONSIDERATIONS

Samples of seasonal snowpacks at 57 geographically distributed sites, in a regional network from New Mexico to Montana, were collected and analyzed for major ions (including ammonium, nitrate, and sulfate), alkalinity, and dissolved organic carbon during 2001. Sites selected in this report have been sampled annually since 1993, enabling identification of increases or decreases in chemical concentrations from year to year. Spatial patterns in snowpack-chemistry data for concentrations of ammonium, nitrate, and sulfate indicate that concentrations of these acid precursors in less developed areas of the region are lower than concentrations in the heavily developed areas. The results for the 2001 snowpack-chemistry analyses, however, indicate increases in concentrations (of ammonium and nitrate in particular) at sites where past concentrations typically were lower. Snowpacks in northern Colorado that are adjacent to the Denver metropolitan area to the east and the coal-fired powerplants to the west typically have had the highest overall concentrations of nitrate and sulfate in the network since 1993. In 2001, relatively high concentrations of nitrate (12.3 to 23.0 microequivalents per liter) and sulfate (7.7 to 12.5 $\mu\text{eq/L}$) were detected in Montana and Wyoming. Ammonium concentrations were highest in north-central Colorado (14.5 to 16.9 $\mu\text{eq/L}$) and southwestern Montana (12.8 to 14.2 $\mu\text{eq/L}$).

This study of the chemistry of regional snowpacks establishes regional ranges of ammonium, nitrate, and sulfate concentrations in high-elevation areas along the Continental Divide from northern New Mexico to northern Montana. Using established sampling and analytical protocols for all sites throughout the network

each year, a reliable, long-term record of the effects of atmospheric deposition on snowpack chemistry in the Rocky Mountain region is being built. As this snowpack-chemistry network continues to be monitored and more years of data are collected, confidence in apparent trends will increase. Established background concentrations at sites minimally affected by airborne contaminants are substantiated by successive years when consistently low constituent concentrations are detected. Similarly, identification of sites where concentrations are considerably higher than other network sites, can be done with greater confidence.

If reductions in emissions of sulfur dioxide from developed areas and power-production facilities continue nationally, downward trends in regional concentrations of sulfate deposition should be reflected in annual snowpack chemistry. Such results would be particularly meaningful in areas where costly emissions-reductions programs are enacted, such as at coal-fired powerplants or large urban centers. Monitoring the present trend of nitrogen emissions and the occurrence of nitrogen saturation in some mountain ecosystems also is important for protection of these wilderness areas. Continuation of this snowpack-monitoring network will support future evaluation of trends in atmospheric-deposition chemistry, modeling of estimated deposition if new emissions sources are to be permitted, and quantification of progress made toward emissions reductions.

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