Rocky Mountain Snowpack Chemistry at Selected Sites, 2003

By George P. Ingersoll, M. Alisa Mast, Leora Nanus, David J. Manthorne,
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In Cooperation with the
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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
cubic meter (m^3)	35.31	cubic foot (ft^3)

To convert microequivalents per liter (μeq/L) 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^+)	1000
	calcium (Ca^{2+})	49.90
	magnesium (Mg^{2+})	82.26
	potassium (K^+)	25.57
	sodium (Na^+)	43.50
	ammonium (NH_4^+)	55.44
	sulfate (SO_4^{-2})	20.83
	nitrate (NO_3^-)	16.13
	chloride (Cl^-)	28.21

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

$$°F=(1.8\times°C)+32$$

Vertical coordinate system is referenced to the North American Vertical Datum of 1988 (NAVD88). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

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Abstract

Chemical composition of the Rocky Mountain snowpack during water year 2003 was determined from samples collected at 74 sites extending from New Mexico to Montana. Snow samples were collected near the end of the 2003 snowfall season from a snowpack that was below average in every sampled basin but one, based on March 1 snow-water equivalent data. Significant snowfall during March increased snow-water equivalent values to near-average or greater in some basins, but for most of the basins below-average snow-water equivalent values on April 1 indicated that the region-wide drought continued.

Regional patterns in the concentrations of major ions including ammonium, nitrate, sulfate, mercury, and the stable sulfur-34 isotope ($\delta^{34}S$) differed from the previous year, 2002, which was affected by more severe drought conditions. At sites reported during both water years 2002–03, snowpack ammonium concentrations for 2003 were higher than concentrations in 2002 at most sites in the region. Nitrate concentrations were lower in 2003 than in 2002 at nearly all network sites, particularly at sites in Colorado and New Mexico. Sulfate increased across the region at about one-half of the sites reported for both years, whereas mercury concentrations decreased at slightly more than one-half of the sites in 2003. Ratios of $\delta^{34}S$ exhibited a similar regional pattern as observed in 2002 with ratios generally increasing northward from New Mexico and southern Colorado to northern Colorado, Wyoming, Idaho, and Montana.

Introduction

Snowfall that accumulates in seasonal snowpacks provides about 50 to 70 percent of the annual precipitation in headwater basins of the Rocky Mountains (Western Regional Climate Center, 2004). As these snowpacks accumulate during the winter and spring, chemicals deposited from the atmosphere are stored until snowmelt begins in spring. Because snowmelt supplies most of the runoff in mountain lakes, streams, and wetlands, monitoring the water quality of snow is important for quantifying atmospheric deposition to these systems.

In the Rocky Mountain region, population growth, water use, and energy development are increasingly affecting the quantity and quality of water resources at higher elevations. Alpine and subalpine environments in the region are sensitive to changes in chemical composition of the water because thin soils and dilute water bodies in these mountain ecosystems typically have limited capacity to buffer acidity that may be deposited with airborne contaminants such as nitrogen and sulfur. Atmospheric input of mercury to these sensitive areas may affect aquatic and wildlife populations. Human health also may be at risk because mercury has been associated with fish-consumption advisories for surface-water bodies in the study area (U.S. Environmental Protection Agency, 2001; 2004a).

Although several watershed-scale studies have investigated atmospheric 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; Williams and others, 1996; and Burns, 2002), regional-scale atmospheric deposition data are sparse (Nanus and others, 2003). The National Atmospheric Deposition Program (NADP) provides nationwide estimates of atmospheric deposition (Nilles, 2000; *National Atmospheric Deposition Program, 2004*). Coverage for high-elevation areas [greater than 2,400 m] in the Rocky Mountains, however, is limited. Although 12 NADP sites monitor atmospheric deposition above 2,400 m in Colorado, few sites are operated in high-elevation areas of Idaho, Montana, Wyoming, and New Mexico, where snowpacks also persist with negligible melt through the snowfall season. These high-elevation snowpacks are important because they may accumulate 2 to 3 times the annual precipitation measured at lower elevations where regular monitoring is more easily accomplished and more common.

Purpose and Scope

To gain a better understanding of atmospheric deposition at high elevation in the Rocky Mountains, the U.S. Geological Survey (USGS), in cooperation with the National Park Service, U.S. Department of Agriculture (USDA) Forest Service, and other organizations established a network of a minimum of 50 snow-sampling sites in the Rocky Mountain region. Sites in the network have been sampled annually since 1993. This report presents the snowpack chemistry for the network for 2003, and for comparison to previous years (Ingersoll and others, 2003, 2004; Mast and others, 2001; Turk and others, 2001).

Study Area

Snow-sampling sites in Montana, Idaho, Wyoming, Colorado, and New Mexico generally are located near the Continental Divide in national forests or national parks. Sampling sites were chosen at locations with limited human activity or emissions from local (residential, commercial, or industrial) activities to enable detection of regional emissions that may affect atmospheric deposition hundreds of kilometers downwind. Sites were located at least 30 m from plowed roadways to minimize contamination from vehicular traffic. As latitude increases along the Continental Divide, the elevation at which seasonal snowpacks develop generally decreases.

Colorado and New Mexico sites range in elevation from about 2,700 to 3,400 m; sites in Idaho, Wyoming, and Montana typically are lower at about 1,800 to 2,700 m. At these elevations, snowpacks accumulate throughout the winter, and substantial snowmelt does not occur until spring runoff begins in March, April, or May. As evidenced by SNOTEL data, snowpit observations, and summertime visits, the seasonal snowpacks melt entirely each summer at sites in the network so resampling snowfall from previous years is avoided.

Acknowledgments

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Study Methods

The USGS has developed methods for measuring physical and chemical properties of seasonal snowpacks. Detailed descriptions of sample-collection and analytical methods are reported in previous publications (Ingersoll and others, 2002; Mast and others, 2001; Turk and others, 2001).

Data Collection

Snowpack samples were collected at 74 sites in 2003 including 50 long-term sampling sites in the network that have been sampled annually since 1993. An additional 24 sites were added after 1993 to expand the geographical coverage of the network in Colorado, Idaho, and Montana. Where feasible, snow-sampling sites were collocated with snowpack-telemetry (SNOTEL) instrument sites where measurements of snow-water equivalence were recorded daily by the USDA, Natural Resources Conservation Service (Natural Resources Conservation Service, 2004). Sampling occurred from late February to early April prior to maximum annual snow depth. Samples were collected from snowpits (fig. 1) in small clearings in forests where uniform snow cover appeared to be free of human disturbance, excessive tree litter, or animal activity. A single depth-integrated, composite snow sample was collected from each snowpit.

Analytical Methods

Concentrations of major ions and trace constituents were determined from snow melted in 8-L Teflon bags in USGS laboratories in Boulder and Lakewood, Colorado. Method detection limits were 1.0 µeq/L for alkalinity, 0.2 to 1.7 µeq/L for major ions (ammonium, 0.5; calcium, 1.7; magnesium, 0.7; sodium, 0.9; potassium, 0.8; , 0.5; chloride, 0.5; sulfate, 0.3; nitrate, 0.2), 0.15 milligrams per liter (mg/L) for dissolved organic carbon, and 0.4 ng/L for mercury. Analytical laboratory methods and quality-assurance procedures for analyses of major-ion and mercury concentrations, and stable sulfur isotope ratios are described in Ingersoll and others (2002), Mast and others (2001), and Turk and others (2001). Further information including interlaboratory comparisons of USGS standard reference samples can be found at *http://bqs.usgs.gov/srs#contacts*.

Quality Assurance

Quality-assurance samples included laboratory blanks, field blanks, and field replicates composed about 20 percent of sample processing depending upon constituent. Four laboratory blanks were analyzed to test sample-processing equipment and deionized water (DI) for contamination. Eight field blanks were collected at snow-sampling sites by rinsing sampling tools with DI water into Teflon bags after collecting

Figure 1. Snowpit being prepared for sampling.

snow samples. Major-constituent concentrations in laboratory and field blanks were less than or equal to 1 μeq/L except for calcium at Grand Mesa, Colorado, which was 1.5 μeq/L. Total mercury concentrations in blanks ranged from <0.4 to 1.4 ng/L compared to the detection limit (0.4 ng/L).

Eleven replicate snow samples were collected at snow-sampling sites for evaluation of sampling and analytical precision. Ten samples were collected from the same snowpit face as the original sample and one sample was collected from a second snowpit less than 10 m away from the original snowpit. Results for quality-assurance samples are shown in tables 1 and 2.

Ionic charge balance of each major-ion analysis was calculated by dividing the sum of cations (hydrogen ion, calcium, magnesium, sodium, potassium, and) minus the sum of anions (alkalinity (> 0.0), chloride, nitrate, and sulfate) by the total cations and anions in solution. Ion balances calculated for the 2003 snow chemistry all were positive with a mean of +21.3 percent, indicating an excess of measured cations over anions in solution. This effect is inversely proportional to total cation plus anion concentrations in solution in these very dilute waters and is strongly influenced by small changes in concentrations near detection limits. Ionic balances calculated for precipitation chemistry of comparable ionic strength in a separate network operated by the NADP yielded similar deviations (National Atmospheric Deposition Program, 2001). For example, at the Buffalo Pass snow-sampling site, located near the NADP site CO97, cation-anion ratios in snowmelt were similar to those in wetfall collected during winter and spring at the NADP site (National Atmospheric Deposition Program, 2005). Cation-anion ratios from 10 other NADP sites around the region located near snow-sampling sites also were similar to those of snowmelt. One explanation for the excess cations in the ionic balances (table 3) is that organic acids were not included in the calculation for snowpack- or NADP-wetfall chemistry. Organic acids such as acetate and formate have been detected in snow in the region in earlier work, with mean concentrations of 1.2 μeq/L and 0.6 μeq/L (Turk and others, 2001).

Snowpack Chemistry

Water Content

When snow samples were collected during February, March, and April, snowpack water contents, referred to as "snow-water equivalent (SWE)," were below 30-year averages for 1971–2000 throughout most of the Rocky Mountain region (as measured at SNOTEL sites representative of basins where snow-sampling sites were located). Snow depth at sampling sites ranged from 67 to 375 cm; SWE ranged from about 19.5 to 128.8 cm. The majority of measured SWE values ranged from 20 to 80 cm. Snow depths at most sites in 2003 were greater than snow depths in 2002; however, the 2002 snowfall year was affected by more severe drought conditions. On March 1, 2003, the SWE at SNOTEL sites was below average in every basin sampled in the region except one. By April 1, 2003, SWE increased to the 30-year average or greater in few basins, but the drought persisted at many sampling sites. Compared to 30-year averages, SWE accumulations on April 1, 2003, were 80–111 percent in Montana, 88–98 percent in Idaho, 88–105 percent in Wyoming, 74–110 percent in Colorado, and 89–118 percent in New Mexico (National Resources Conservation Service, 2004).

Chemistry

Chemical data for 2003 (alkalinities, laboratory pH, concentrations of major ions, dissolved organic carbon, total mercury, stable sulfur isotope ratios, and ionic charge balances) are presented in table 3. Snow-sampling sites shown alphabetically by State in table 3 also are referenced by their site numbers in figures 2–6. Site numbers appear in parentheses directly after the first mention of site names in the following text.

Snowpack ammonium concentrations for 2003 were higher than concentrations in 2002 at most sites in the

Table 1. Quality-assurance replicate sample results for ammonium, sulfate, nitrate, in microequivalents per liter; mercury, in nanograms per liter; and sulfur-34 (del-34S).

	Ammonium				Sulfate			
Sampling site	Sample	Replicate	Difference[1]	Percent difference[2]	Sample	Replicate	Difference[1]	Percent difference[2]
Apgar Lookout	6.9	7.7	0.8	10.8	4.4	4.4	0.0	0.0
Cameron Pass	4.2	4.5	0.3	8.1	6.0	4.9	-1.1	-18.5
Granite Pass	2.3	1.8	-0.5	-21.7	1.6	1.6	0.0	0.0
Green Ridge Snowpit	4.1	3.5	-0.6	-14.4	4.0	4.6	0.6	16.2
Gypsum Creek	7.2	7.3	0.1	1.5	10.0	6.5	-3.5	-35.3
Hopewell	5.4	5.8	0.4	6.3	7.3	7.2	-0.1	-1.5
Lake Irene Forest	4.6	4.3	-0.3	-5.5	6.9	6.1	-0.8	-11.0
Lake Irene Meadow	4.9	4.0	-0.9	-17.1	5.5	4.7	-0.8	-15.5
Rabbit Ears 1 vs 2	8.2	6.4	-1.8	-22.4	8.6	8.1	-0.5	-5.6
Red Mountain Pass	2.5	2.3	-0.2	-8.7	3.2	4.5	1.3	41.1
Snow Bowl	2.7	2.7	0.0	0.0	2.4	2.7	0.3	9.5

	Nitrate				Mercury			
Sampling site	Sample	Replicate	Difference[1]	Percent difference[2]	Sample	Replicate	Difference[1]	Percent difference[2]
Apgar Lookout	6.9	7.1	0.2	2.2	1.3	1.4	0.1	7.7
Cameron Pass	8.9	8.6	-0.3	-3.0	2.2	1.5	-0.7	-31.8
Granite Pass	2.4	2.1	-0.3	-10.5	3.3	6.8	3.5	106.1
Green Ridge Snowpit	10.7	12.6	1.9	17.6	1.6	1.6	0.0	0.0
Gypsum Creek	6.7	6.6	-0.1	-1.2	2.2	2.0	-0.2	-9.1
Hopewell	12.1	11.8	-0.3	-2.5	2.6	2.3	-0.3	-11.5
Lake Irene Forest	10.2	9.6	-0.6	-5.3	4.1	5.0	0.9	22.0
Lake Irene Meadow	9.8	8.7	-1.1	-11.8	1.7	1.0	-0.7	-41.2
Rabbit Ears 1 vs 2	12.3	12.0	-0.3	-2.4	2.8	1.7	-1.1	-39.3
Red Mountain Pass	6.0	8.6	2.6	43.0	0.7	6.4	5.7	814.3
Snow Bowl	3.3	3.5	0.2	7.4	2.4	3.6	1.2	50.0

	Sulfur-34	
Sampling site	Sample	Replicate
Apgar Lookout	no data	no data
Cameron Pass	no data	no data
Granite Pass	no data	no data
Green Ridge Snowpit	no data	no data
Gypsum Creek	no data	no data
Hopewell	no data	no data
Lake Irene Forest	no data	no data
Lake Irene Meadow	no data	no data
Rabbit Ears 1 vs 2	7.4	7.3
Red Mountain Pass	no data	no data
Snow Bowl	no data	no data

[1] Difference = replicate – sample.

[2] Percent difference = [(replicate – sample)/sample] × 100.

Table 2. Quality-assurance laboratory- and field-blank results for ammonium, sulfate, nitrate, in microequivalents per liter and mercury, in nanograms per liter.

Site name	Sample type	Ammonium	Sulfate	Nitrate	Mercury
Grand Mesa	field blank	0.7	0.0	0.0	<0.4
Hopewell	field blank	0.5	0.0	0.0	no data
Red Mountain Pass	field blank	<0.5	0.0	0.0	0.4
Arapaho Creek	field blank	<0.5	0.0	0.0	<0.4
Phantom Valley	field blank	<0.5	0.0	0.3	<0.4
Monida Pass	field blank	<0.5	0.0	0.0	0.8
Gypsum Creek	field blank	0.8	0.0	0.0	<0.4
Elkhart Park	field blank	0.6	0.0	0.0	0.4
USGS laboratory	lab blank	<0.5	0.0	0.0	1.4
USGS laboratory	lab blank	<0.5	0.0	0.0	1.0
USGS laboratory	lab blank	<0.5	0.0	0.0	1.0
USGS laboratory	lab blank	<0.5	0.0	0.0	1.3

network. Concentrations of ammonium ranged from <0.5 µeq/L at Slumgullion Pass, Colorado (68) to 22.6 µeq/L at Lionshead, Montana (9), with a mean of 6.4 µeq/L (fig. 2, table 3). Concentrations tended to be lowest at sites dominated by mountain forests with less agricultural land use and highest near areas of more agricultural activity in lower elevation plains. Large-scale feed-lot and crop-fertilization operations such as those located in southwestern Idaho or northeastern Colorado do not exist in the steeper, forested terrain common to national parks and national forests in other areas of the region. The second highest ammonium concentration was found at West Yellowstone, Montana (19) (14.0 µeq/L), about 20 km east of Lionshead. This pattern of high ammonium concentrations in southwestern Montana is consistent with previous years. The Lionshead site (9) is located near a mountain pass where prevailing westerly winds funnel airmasses over the Continental Divide from west to east (Thompson and others, 1993). Storms originating out of the southwest may travel over large agricultural areas of Idaho, where large-scale application of fertilizer occurs, before reaching the two sites. The West Yellowstone site (19) also is very near the West Entrance of Yellowstone National Park, and near one of the largest snowmobile recreation areas in the area, where elevated ammonium concentrations have been related to snowmobile emissions (Ingersoll, 1999).

Sulfate concentrations increased in 2003 at about one-half of the sites when compared to 2002, in contrast to observed sulfate-concentration decreases in 2002 across the region at 77 percent of sites compared to 2001 snowpacks (Ingersoll and others, 2004). Concentrations of sulfate in 2003 ranged from 1.6 µeq/L at Chief Joseph Pass, Montana (4), and Granite Pass, Montana (7), to 11.3 µeq/L at Divide Peak, Wyoming (24), where the 3rd highest 2003 regional concentration of nitrate was observed (16.2 µeq/L), with a mean of 5.7 µeq/L (fig. 4, table 3). It is unclear what effect the severe drought of 2002 had on the differing sulfate concentrations as compared to 2003. Sulfate concentrations at all but 3 of 21 sites in Idaho and Montana were equal to or below the average concentration for 2003 for the region (5.7 µeq/L), consistent with results from previous years.

The five highest concentrations of sulfate detected in the region occurred in southern Wyoming and northern Colorado at Divide Peak, Wyoming (24) (11.3 µeq/L); Buffalo Pass, Colorado (43) (11.0 µeq/L); Mills lake, Colorado (59) (10.3 µeq/L); Brooklyn Lake, Wyoming (22) (10.2 µeq/L); and Dry Lake Colorado (46) (10.0 µeq/L). These five sites are within about 200 km of at least three large electric utilities, and possibly were affected by emissions from coal-burning powerplants located in southern Wyoming and northern Colorado, and sources from the Denver Metropolitan Area (Turk and Campbell, 1997). Substantial emissions of nitrogen oxides and sulfur dioxide have been reported in 1999 from several powerplants still operating in this area (U.S. Environmental Protection Agency, 2004b). Prevailing westerly winds dominate in this region, especially during winter (Banta and Cotton, 1981; Barry, 1992), but springtime upslope snowstorms in Colorado often originate from other directions with an easterly influence. Because these five sites generally are located between local coal-fired powerplants to the west, north, and east, westerly, northerly, or upslope storms could all deliver precipitation originating from airmasses contaminated by upwind sources. It also is noteworthy that 9 of 10 of the lowest pH values in the network (4.97–5.09) occurred at sites in this general area.

Concentrations of nitrate ranged from 2.2 µeq/L at Granite Pass, Montana (7), to 18.3 µeq/L at Lionshead, Montana (9), with a mean of 8.8 µeq/L (fig. 3, table 3). In previous years, many of the highest concentrations of nitrate were detected at several sites in Colorado and northern New Mexico, and the lowest nitrate concentrations occurred at sites

Table 3. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34 ; and ionic charge balances from analyses of the 2003 snowpack samples from Colorado, Idaho, Montana, New Mexico, and Wyoming.

[Alkalinity (Alk[2]), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) is expressed in milligrams per liter. Mercury (Hg) is expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "-", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]

Site number	Site name	Alk[2]	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	Ionic bal-ance[1,2]
1	Apgar Lookout, Mont.	-7.5	5.06	8.9	3.0	<1.0	<2.1	<0.8	7.3	1.1	4.4	7.0	0.5	1.4	-	21.1
2	Big Mountain, Mont.	-5.8	5.24	5.8	2.5	<1.0	<2.1	<0.8	4.0	0.8	2.7	4.6	0.4	1.3	-	21.0
3	Big Sky, Mont.	2.7	5.74	1.8	9.5	2.5	4.8	<0.8	4.6	3.0	3.8	4.9	0.5	1.8	-	23.3
4	Chief Joseph Pass , Mont.	-5.5	5.24	5.8	2.0	<1.0	<2.1	<0.8	2.1	0.6	1.6	2.3	0.3	1.8	-	37.5
5	Daisy Pass, Mont.	-3.3	5.41	3.9	3.0	<1.0	<2.1	<0.8	7.2	0.9	3.6	5.4	0.3	1.4	-	17.9
6	Granite Park, Mont.	-2.3	5.52	3.0	2.0	<1.0	<2.1	<0.8	3.6	0.6	1.7	3.4	0.2	3.5	-	20.4
7	Granite Pass, Mont.	-3.0	5.23	6.0	2.7	1.6	<2.1	<0.8	2.1	0.8	1.6	2.2	0.5	5.1	-	46.0
8	Kings Hill , Mont.	-0.6	5.51	3.1	7.0	2.5	2.3	1.2	7.1	1.1	5.9	8.5	0.8	5.4	9.5	19.8
9	Lionshead, Mont.	2.5	5.73	1.9	9.0	2.5	2.3	1.6	22.6	1.7	9.7	18.3	0.6	4.4	-	10.4
10	Monida Pass, Mont.	18.5	6.31	0.5	16.0	3.3	3.2	0.8	9.1	2.3	3.6	7.6	0.4	0.9	-	1.5
11	Mount Belmont, Mont.	-1.3	5.37	4.3	7.5	2.5	<2.1	2.3	8.9	1.0	5.7	7.4	1.8	4.7	-	28.9
12	Noisy Basin, Mont.	-4.4	5.22	6.0	2.5	1.6	<2.1	<0.8	5.3	0.8	3.4	6.0	0.4	1.3	-	20.0
13	Oldman Lake, Mont.	-3.6	5.14	7.2	3.5	1.6	<2.1	0.8	3.6	1.2	2.8	3.8	0.4	1.8	-	36.3
14	Preston Park, Mont.	-1.9	5.40	4.0	4.0	1.6	2.4	1.6	3.8	1.2	3.6	3.9	0.8	3.1	-	33.5
15	Red Mountain, Mont.	-0.5	5.54	2.9	6.5	1.6	2.5	<0.8	5.2	0.9	3.8	5.3	0.6	4.3	-	30.2
16	Snow Bowl, Mont.	-6.4	5.18	6.6	2.0	<1.0	<2.1	<0.8	2.7	0.8	2.5	3.4	0.4	3.0	-	25.6
17	Spring Gulch, Mont.	-1.1	5.47	3.4	8.0	4.1	<2.1	10.1	3.9	1.4	4.0	7.1	3.1	3.3	7.4	40.3
18	Snyder Lake, Mont.	-6.0	5.21	6.2	2.0	1.6	<2.1	<0.8	4.8	0.8	2.5	4.9	0.3	2.8	-	28.2
19	West Yellowstone, Mont.	0.4	5.61	2.5	9.0	2.5	2.9	1.5	14.0	2.0	7.4	12.3	0.6	2.1	-	18.5
20	Banner Summit, Idaho	6.7	5.64	2.3	7.5	1.6	6.7	<0.8	3.4	1.5	3.3	3.1	0.3	3.3	-	19.0
21	Galena Summit, Idaho	-0.9	5.69	2.0	8.5	5.8	3.0	0.8	3.6	1.2	3.2	3.7	0.6	2.4	6.4	49.1
22	Brooklyn Lake, Wyo.	1.5	5.56	2.8	16.0	4.1	4.0	1.8	7.9	2.1	10.2	11.3	1.4	16.3	7.3	18.4
23	Canyon, Wyo.	-1.6	5.57	2.7	5.5	2.5	<2.1	<0.8	7.7	0.9	4.6	7.1	0.3	1.3	-	18.3
24	Divide Peak, Wyo.	-7.8	5.16	6.9	10.5	2.5	3.6	1.6	8.5	1.2	11.3	16.2	1.1	1.9	-	7.8

Table 3. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34 ; and ionic charge balances from analyses of the 2003 snowpack samples from Colorado, Idaho, Montana, New Mexico, and Wyoming.—Continued

[Alkalinity (Alk^2), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^+), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) is expressed in milligrams per liter. Mercury (Hg) is expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "-", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]

Site number	Site name	Alk^2	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	Ionic balance^{1,2}
25	Elkhart Park, Wyo.	1.0	5.59	2.6	8.5	4.1	3.2	0.9	8.7	1.3	6.9	7.7	0.6	1.1	-	24.7
26	Four Mile Meadow, Wyo.	5.8	5.78	1.7	10.0	2.5	2.4	1.3	7.2	1.0	4.1	6.8	0.9	2.9	-	17.5
27	Garnet Canyon, Wyo.	18.1	6.14	0.7	21.0	4.9	4.0	3.1	8.6	1.1	6.8	6.2	0.7	4.3	-	13.5
28	Gypsum Creek, Wyo.	10.6	6.12	0.8	16.5	3.7	6.4	0.8	7.3	2.0	8.2	6.7	0.6	2.1	-	12.7
29	Lake, Wyo.	-3.9	5.43	3.7	4.0	1.6	<2.1	<0.8	5.9	0.8	3.7	6.4	0.5	2.1	-	17.3
30	Lewis Lake Divide, Wyo.	-2.5	5.46	3.5	3.5	<1.0	<2.1	<0.8	8.5	0.8	3.8	6.2	0.3	1.3	-	17.7
31	Old Battle, Wyo.	-1.9	5.29	5.1	10.0	2.5	2.5	2.3	7.9	1.1	8.7	11.6	0.7	2.1	-	17.4
32	Old Faithful Fire Road, Wyo.	8.8	5.91	1.2	13.5	3.3	7.2	<0.8	10.7	3.2	7.9	8.9	0.4	1.8	-	11.1
33	Rendevous Mountain, Wyo.	7.1	5.64	2.3	11.0	4.9	3.3	<0.8	7.3	1.4	5.3	5.1	0.3	1.6	-	20.8
34	South Pass, Wyo.	1.6	5.76	1.7	8.5	2.5	2.5	1.0	6.2	0.7	5.3	4.6	0.7	2.9	-	29.6
35	Sylvan Lake, Wyo.	-3.8	5.41	3.9	3.0	<1.0	<2.1	<0.8	5.8	0.7	3.2	5.3	0.4	1.3	-	16.4
36	Teton Pass, Wyo.	24.1	6.20	0.6	24.0	5.8	5.0	3.0	9.2	2.5	7.4	8.5	1.6	7.8	-	5.7
37	Togwotee Pass, Wyo.	2.8	5.74	1.8	9.0	2.5	2.2	1.0	5.7	1.0	4.2	5.8	0.6	2.5	-	23.1
38	Twenty-one Mile, Wyo.	0.1	5.59	2.6	7.0	1.6	2.4	0.8	8.9	1.6	5.3	9.0	0.5	2.4	-	18.5
39	Arapaho Creek, Colo.	-12.3	5.04	9.1	5.0	2.5	<2.1	1.2	4.8	1.0	4.6	12.7	0.8	2.4	-	10.7
40	Bear Lake, Colo.	1.1	5.42	3.8	11.5	2.5	<2.1	1.8	8.0	0.9	6.1	9.1	1.2	4.7	-	23.2
41	Berthoud Pass, Colo.	-4.7	5.28	5.2	9.0	4.9	4.6	3.1	6.1	4.2	4.2	10.7	1.6	3.5	-	26.7
42	Brumley, Colo.	-7.1	5.19	6.5	8.0	2.5	<2.1	2.9	4.3	1.4	4.2	9.5	2.1	2.6	-	23.0
43	Buffalo Pass, Colo.	1.7	5.83	1.5	19.5	4.1	2.9	1.0	7.5	1.3	11.0	13.1	0.5	2.7	3.6	14.9
44	Cameron Pass, Colo.	-9.9	5.07	8.6	5.0	2.1	<2.1	<0.8	4.4	0.7	5.4	8.7	0.5	1.9	-	14.5
45	Deadman Pass, Colo.	-6.5	5.25	5.6	7.0	2.5	<2.1	2.5	5.4	0.9	5.8	8.3	1.5	1.2	-	20.9
46	Dry Lake, Colo.	-9.4	5.06	8.7	11.0	3.3	<2.1	5.3	6.8	1.5	10.0	16.9	1.0	2.1	6.6	10.7
47	Dunckley Pass, Colo.	13.2	6.13	0.7	23.0	4.9	<2.1	1.9	6.9	1.0	6.5	10.5	0.7	1.9	-	9.1

Table 3. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34 ; and ionic charge balances from analyses of the 2003 snowpack samples from Colorado, Idaho, Montana, New Mexico, and Wyoming.—Continued

[Alkalinity (Alk[2]), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) is expressed in milligrams per liter. Mercury (Hg) is expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "-", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]

Site number	Site name	Alk[2]	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	Ionic balance[1,2]
48	Elk River, Colo.	-6.5	5.26	5.5	13.0	3.3	3.2	2.0	7.0	1.0	7.6	13.6	1.0	3.1	-	21.1
49	Fremont Pass , Colo.	-0.4	5.66	2.2	12.5	3.3	<2.1	1.5	3.5	1.1	4.2	8.5	0.6	3.5	-	24.7
50	Grand Mesa, Colo.	1.6	5.61	2.5	20.0	6.6	2.9	5.5	8.1	1.7	7.5	13.3	2.1	5.2	-	30.9
51	Green Ridge, Colo.	-0.5	5.63	2.4	11.5	4.1	<2.1	2.2	3.8	1.1	4.3	11.7	0.8	1.6	-	16.8
52	Lake Irene Forest, Colo.	-6.5	5.14	7.4	8.2	3.7	<2.1	3.8	4.5	1.7	6.5	9.9	1.4	4.1	-	20.8
53	Lake Irene Meadow, Colo.	-8.3	5.08	8.3	4.0	1.6	<2.1	<0.8	4.4	0.5	5.1	9.3	0.3	1.0	-	10.5
54	Loch Vale Forest, Colo.	0.3	5.21	6.2	12.5	3.3	2.5	2.0	6.9	2.4	8.5	10.4	1.0	2.9	7.3	21.3
55	Loch Vale Meadow, Colo.	6.4	5.82	1.5	14.5	2.5	<2.1	<0.8	6.1	0.6	5.9	9.5	0.2	0.9	5.9	4.5
56	Lone Pine, Colo.	-12.0	5.09	8.1	6.0	1.6	<2.1	<0.8	4.8	1.0	5.4	11.1	0.3	2.7	-	8.3
57	Loveland Pass, Colo.	-0.3	5.67	2.1	12.5	3.3	2.6	0.9	5.0	2.5	5.2	9.4	0.6	3.6	-	21.7
58	Lynx Pass, Colo.	-11.4	4.99	10.2	5.5	1.6	<2.1	<0.8	4.6	0.8	4.9	12.5	0.3	0.8	-	9.2
59	Mills Lake, Colo.	3.9	5.55	2.8	20.0	4.1	2.7	1.9	8.5	1.5	10.3	14.8	1.1	4.8	-	13.4
60	Molas Lake, Colo.	9.7	5.77	1.7	20.5	4.1	10.1	6.5	4.0	10.3	5.7	10.6	1.2	3.1	6.0	12.8
61	Monarch Pass, Colo.	-2.5	5.30	5.0	12.0	4.1	<2.1	1.7	5.1	1.4	5.0	10.5	0.7	3.0	5.7	24.6
62	Ned Wilson, Colo.	9.7	6.20	0.6	21.5	3.3	<2.1	<0.8	5.4	1.0	6.1	9.3	0.4	4.8	-	8.5
63	Niwot SNOTEL, Colo.	-6.4	5.22	6.0	7.0	1.6	<2.1	0.8	10.5	1.0	8.1	12.0	0.8	1.5	-	10.6
64	Phantom Valley, Colo.	-9.1	5.10	7.9	8.5	1.6	<2.1	1.2	6.6	0.7	7.5	12.8	0.8	2.0	-	10.2
65	Rabbit Ears, Colo.	-10.6	5.04	9.3	7.7	2.9	<2.1	2.3	7.3	1.0	8.4	12.1	1.1	2.3	7.4	15.8
66	Red Mountain Pass, Colo.	-0.7	5.63	2.5	11.2	2.5	<2.1	1.1	2.4	1.1	3.8	7.3	0.7	3.6	4.7	23.1
67	Ripple Creek NADP, Colo.	17.7	6.39	0.4	26.4	4.1	<2.1	<0.8	4.6	1.0	5.7	11.0	0.4	1.7	-	0.2
68	Slumgullion Pass, Colo.	15.1	5.80	1.6	16.5	5.8	3.7	13.4	<0.5	5.7	4.7	6.8	4.0	11.9	5.1	11.7

Table 3. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34 ; and ionic charge balances from analyses of the 2003 snowpack samples from Colorado, Idaho, Montana, New Mexico, and Wyoming.—Continued

[Alkalinity (Alk[2]), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) is expressed in milligrams per liter. Mercury (Hg) is expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "-", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]

Site number	Site name	Alk[2]	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	Ionic balance[1,2]
69	Sunlight Peak, Colo.	-6.3	5.21	6.2	10.0	4.9	<2.1	2.0	6.3	1.2	6.4	12.6	1.6	2.9	5.7	18.6
70	Tower, Colo.	-2.2	5.57	2.7	14.0	3.3	<2.1	0.8	7.4	1.0	9.5	11.2	0.7	2.5	-	13.0
71	University Camp, Colo.	-1.5	5.22	6.0	10.5	2.5	<2.1	1.1	7.6	1.0	6.7	10.0	0.7	2.1	-	22.3
72	Wolf Creek Pass, Colo.	2.3	5.70	2.0	18.5	3.3	4.0	3.8	4.4	1.9	9.9	10.9	1.1	4.0	-	18.1
73	Hopewell, N. Mex.	10.5	6.15	0.7	24.7	3.7	<2.1	1.1	5.6	1.3	7.2	11.9	0.6	2.5	-	7.2
74	Taos Ski Valley, N. Mex.	-3.4	5.44	3.6	9.5	2.5	<2.1	<0.8	5.5	1.0	6.3	9.0	0.6	2.0	4.2	12.9
	Summary Statistics															
	minimum	-12.3	4.99	0.4	2.0	1.6	<2.1	0.8	<0.5	0.5	1.6	2.2	0.2	0.8	3.6	0.2
	maximum	24.1	6.39	10.2	26.4	6.6	10.1	13.4	22.6	10.3	11.3	18.3	4.0	16.3	9.5	49.1
	mean[3]	-0.1	5.5	4.0	10.2	3.1	3.7	2.4	6.4	1.5	5.7	8.8	0.8	3.0	6.2	19.0
	standard deviation	7.6	na	2.6	6.2	1.2	1.8	2.4	2.9	1.3	2.3	3.5	0.6	2.3	1.5	9.4

[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 values are excluded.

[3] The median value for pH is shown.

in Wyoming, Idaho, and Montana. The 2003 concentrations show that same general pattern, but when compared to 2002 data, nitrate in 2003 decreased at all Colorado and New Mexico sites and at most sites in Wyoming and Montana. Nitrate concentrations were among the lowest in the region at the two Idaho sites: Banner Summit (20) (3.1 μeq/L) and Galena Summit (21) (3.7 μeq/L) during both 2002 and 2003.

Nitrate and sulfate concentrations generally were lower in less developed areas of the region such as in central Idaho and northwestern Montana than in more developed areas such as northern New Mexico, Colorado, and southern Wyoming. For example, at several sites in Glacier National Park, Montana, including Apgar Lookout (1), Oldman lake (13), Preston Park (14), and Snyder Lake (18), concentrations of nitrate and sulfate were below the 2003 average for sulfate (5.7 μeq/L) and nitrate (8.8 μeq/L) and observed for the region. In contrast, most concentrations of sulfate and nitrate were above the 2003 average at six sites in Rocky Mountain National Park, Colorado, including Lake Irene Forest (52); Lake Irene Meadow (53); Loch Vale Forest (54); Loch Vale Meadow (55); Mills Lake (59); and Phantom Valley (64).

Total mercury detected is reported for all mercury concentrations in these results. Mercury concentrations in 2003 snowpacks ranged from 0.8 ng/L at Lynx Pass, Colorado (58), to 16.3 ng/L at Brooklyn Lake, Wyoming (22), with a mean of 3.0 ng/L (fig. 5, table 3). The second highest concentration of mercury was at Slumgullion Pass, Colorado (68) (11.9 ng/L). Mercury concentrations were somewhat more complex in spatial variability than observed in ammonium, nitrate, and sulfate. The highest two concentrations were observed adjacent to sites with considerably lower concentrations, such as Divide Peak, Wyoming (24, near Brooklyn Lake) (1.9 ng/L), and Red Mountain Pass, Colorado (66, near Slumgullion Pass) (3.6 ng/L). Substantially lower concentrations were observed in 2003 at sites Granite Pass (7) (5.1 ng/L) and Snow Bowl (16) (3.0 ng/L) in northwestern Montana, where mercury concentrations in snowpacks were elevated in 2002 (11.1 and 11.0 ng/L, respectively). Similarly, moderately to substantially lower concentrations also were observed at sites in Northern New Mexico in 2003 (Hopewell (73) (2.5 ng/L); Taos Ski Valley (74) (2.0 ng/L) when compared to concentrations observed in 2002 (3.6 ng/L and 11.9 ng/L respectively).

These results are in fair agreement with other determinations of mercury including snowpack- and other precipitation-mercury concentrations in 2003 or recent years. Mercury concentrations detected in snowpacks in the study area during 2002 were within a similar range (0.4 to 11.9 ng/L) compared to the 2003 snowpack concentrations. Referencing other work, mercury concentrations in snowpacks generally may be compared to weekly mercury concentrations in precipitation at sites in the National Atmospheric Deposition Program (NADP) Mercury Deposition Network (MDN) (National Atmospheric Deposition Program (NRSP-3) Network, 2004), and in other USGS studies (Mast and others, 2003). Two sites were operated in the MDN near high-elevation snowpack sampling sites at Lake, Wyoming, and Buffalo pass, Colorado, where concentrations of total mercury measured from October 2002 through April 2003 ranged from 3.1 to 8.8 ng/L and 1.8 to 11.4 ng/L, respectively.

Stable sulfur isotope ratios ($\delta^{34}S$) were determined for a subset of 15 sites in the network (fig. 6, table 3). Ratios $\delta^{34}S$ ranged from 3.6 to 9.5 per mil with a mean of 6.2 per mil and indicated a regional pattern with the lightest $\delta^{34}S$ ratios generally in northern New Mexico and southern and central Colorado, and the heaviest ratios in northern Colorado, Wyoming, Idaho, and Montana. The light $\delta^{34}S$ ratios of 4.2 to 6.0 at sites in northern New Mexico, and southern and central Colorado indicate sulfate in atmospheric deposition at the southern end of the study area may have been derived from different sources than the rest of the study area where ratios range from 5.9 to 9.5 per mil. An exception to this pattern was Buffalo Pass, Colorado (43), with a ratio of 3.6 per mil. Results for $\delta^{34}S$ ratios from this study are fairly consistent with previous work (Mast and others, 2001).

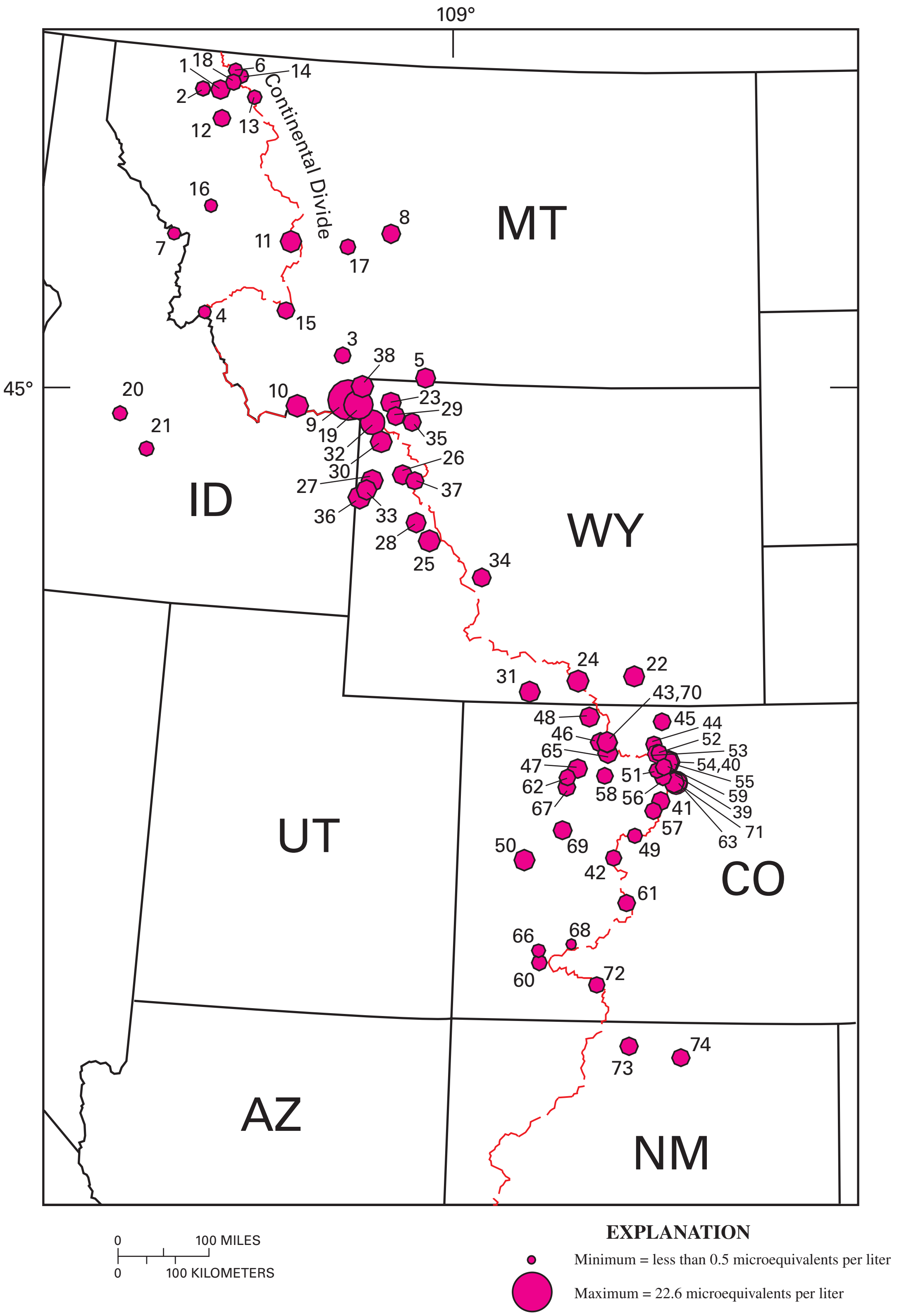

Figure 2. Relative ammonium ion concentrations in snowpacks, 2003.

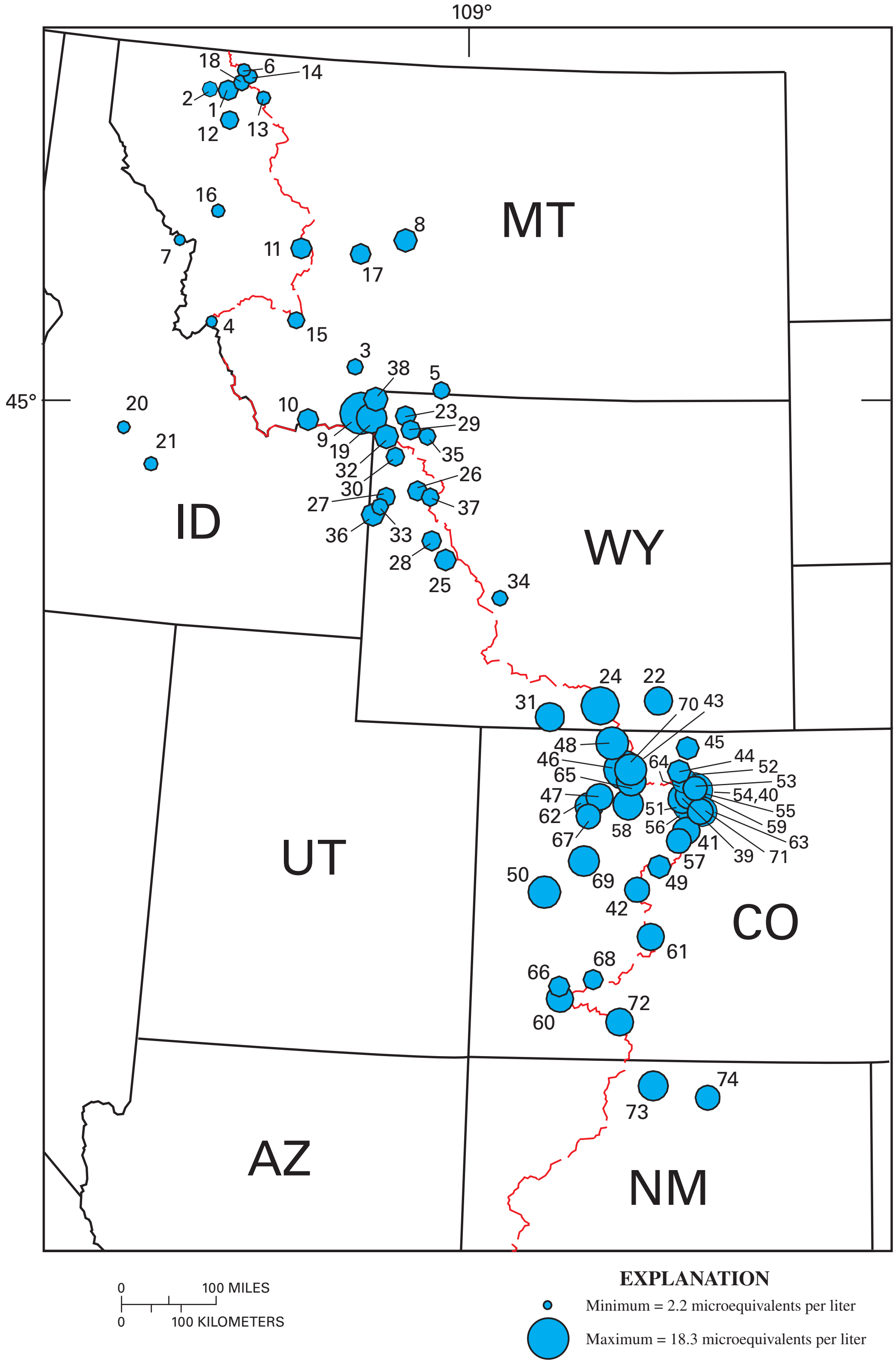

Figure 3. Relative nitrate ion concentrations in snowpacks, 2003.

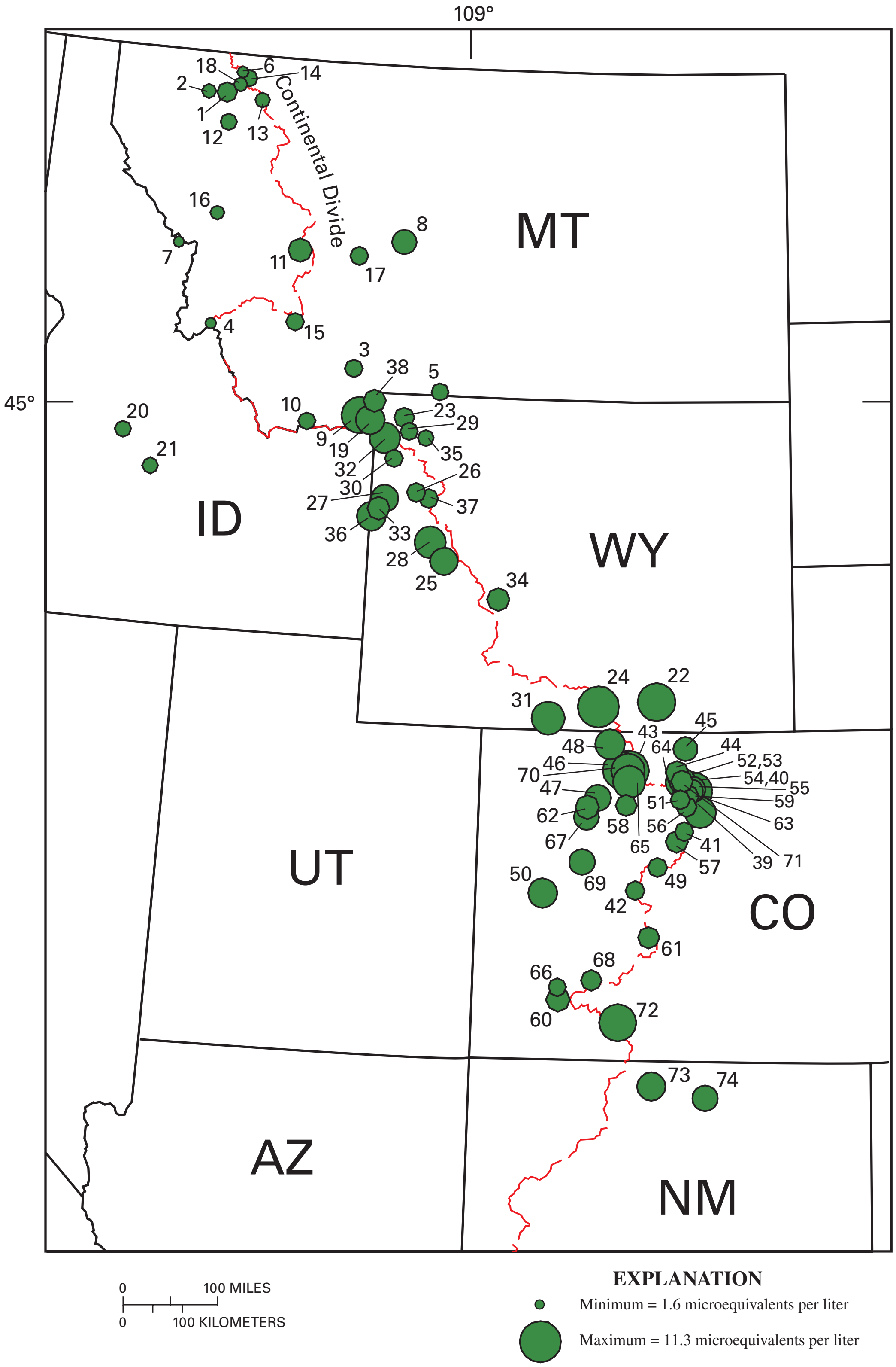

Figure 4. Relative sulfate ion concentrations in snowpacks, 2003.

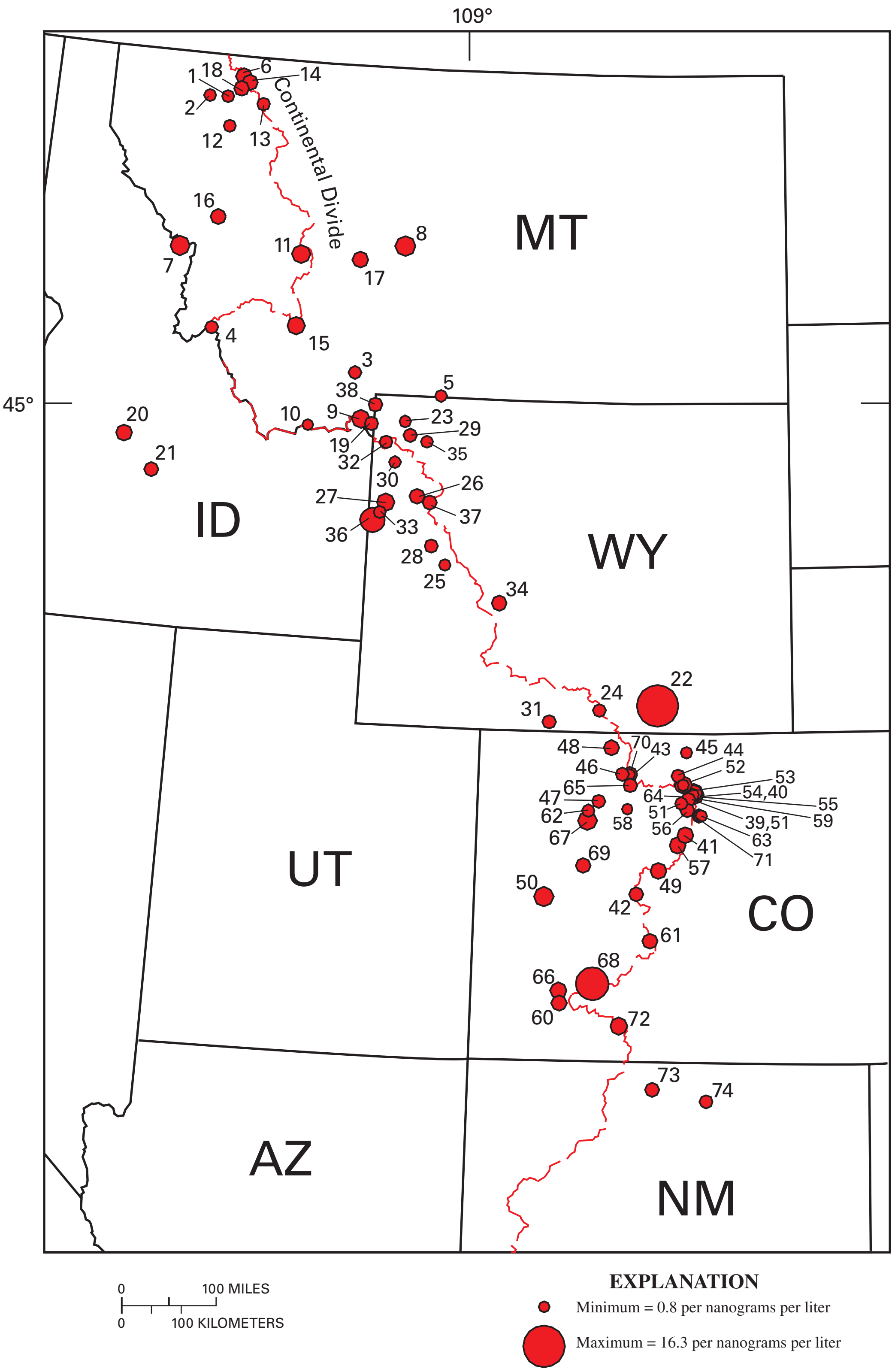

Figure 5. Relative total mercury concentrations in snowpacks, 2003.

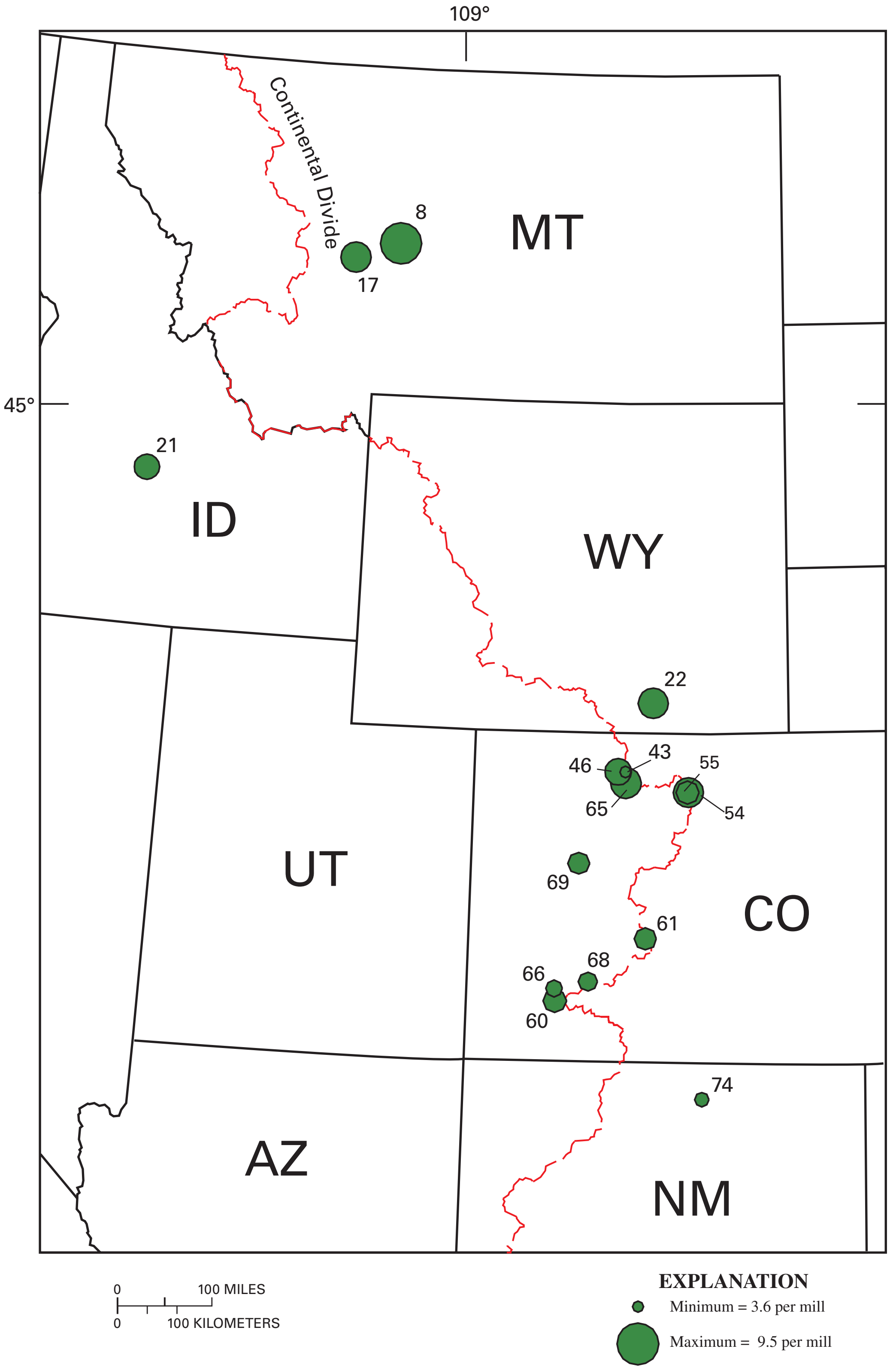

Figure 6. Relative stable sulfur isotope ratios in snowpacks, 2003.

Summary and Conclusions

To gain a better understanding of atmospheric deposition at high elevation in the Rocky Mountains, the U.S. Geological Survey, in cooperation with the National Park Service; U.S. Department of Agriculture, Forest Service; and other organizations established a network of a minimum of 50 snow-sampling sites in the Rocky Mountain region. Sites in the network have been sampled annually since 1993.

The 2003 snowfall season was drier than normal with snow-water equivalent (SWE) below the long-term average throughout most of the Rocky Mountain region. On March 1, 2003, the SWE in annual snowpacks was below average in every basin sampled in the region except one. By April 1, 2003, after much of the network samples had been collected, the SWE equaled or exceeded the 30-year average in few basins as the drought persisted. Compared to 30-year averages for 1971–2000, SWE accumulations on April 1, 2003, were 80–111 percent in Montana, 88–98 percent in Idaho, 88–105 percent in Wyoming, 74–110 percent in Colorado, and 89–118 percent in New Mexico.

Snow samples were collected near the end of the 2003 snowfall season in a network of 74 geographically distributed sites extending from New Mexico to Montana. The 2003 snowpack chemistry in the region differed from the previous year. Ammonium concentrations in snowpack in 2003 were higher than concentrations in 2002 at most sites in the network. Sulfate concentrations in 2003 were higher than concentrations in 2002 at about one-half of the sites reported for both years. Nitrate concentrations were lower in 2003 compared to 2002 at nearly all network sites, particularly at all sites in Colorado and New Mexico. Mercury concentrations detected in 2003 were in a similar range as in 2002. Sulfur-34 isotopic ratios had a similar regional pattern with ratios generally increasing northward from north New Mexico and southern Colorado to northern Colorado, Wyoming, Idaho, and Montana.

Data presented in this report reflect changing atmospheric deposition identified in constituent concentrations in snowpacks across the Rocky Mountain region. If reductions in emissions of sulfur dioxide from developed areas and power-production facilities continues to occur nationally, as seen in recent years, downward trends in regional concentrations of sulfate concentrations should be reflected in annual snowpack chemistry. National programs to reduce emissions such as sulfur dioxide are not in place for ammonium, so increasing concentrations of ammonium may be seen in the future. Continued monitoring of ammonium, nitrate, sulfate, and mercury concentrations in Rocky Mountain snowpacks will be important as the region becomes increasingly developed.

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