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

Snowpack Chemistry Monitoring Protocol for the Rocky Mountain Network; Narrative and Standard Operating Procedures

Administrative Report

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

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By George P. Ingersoll, Don Campbell, M. Alisa Mast, David W. Clow,
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Abstract

Since 1993, the U.S. Geological Survey, in cooperation with the National Park Service, the U.S. Department of Agriculture–Forest Service, and others, has operated the long-term Rocky Mountain Snowpack program. A network of more than 50 snowpack-sampling sites was designed to annually monitor atmospheric-deposition chemistry in high-elevation watersheds of the Rocky Mountains. The protocol used in the Rocky Mountain Snowpack program to sample snowpacks for chemical constituents and snow-water equivalent (SWE) is presented and critical elements of applied snowpack-sampling methods are discussed. Twenty-one standard operating procedures give instructions for consistent, long-term monitoring in the National Park Service Rocky Mountain Network. The Rocky Mountain Network consists of an inventory and monitoring network created by the National Park Service and implemented in Glacier National Park, Rocky Mountain National Park, and Great Sand Dunes National Park and Preserve.

To develop an understanding of optimal spacing distances between snowpack-sampling points in the Rocky Mountain Network, historical data from snowpack-sampling sites were evaluated. Differences in six key variables (SWE and concentrations of selected major constituents: ammonium, calcium, hydrogen, nitrate, and sulfate) between sampling sites at local scales are discussed to offer guidelines for determination of sample spacing, physical settings, and elevations for sampling sites. Results show that a preference should be given to establishing snowpack-sampling sites in forest clearings rather than in open meadows. Results also indicate that snowfall in meadows may not fully represent atmospheric deposition, and forest clearings offer more representative snowpack-sampling sites. Further, SWE and concentrations can be influenced by elevation differences of about 500 meters.

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Snowpack Chemistry Monitoring Protocol for the Rocky Mountain Network; Narrative and Standard Operating Procedures

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Narrative

1 Background and Objectives

Since 1993, the U.S. Geological Survey (USGS), in cooperation with the National Park Service (NPS), the USDA–Forest Service (USDA–FS), and others, operates the long-term Rocky Mountain Snowpack (RMS) program designed to monitor and interpret atmospheric deposition chemistry in high-elevation watersheds of the Rocky Mountains. Long-term (1993 to present) operation of the core network of more than 50 snowpack-sampling sites (figs. 1 and 2) has resulted in the development of a robust sampling protocol to produce consistent and high-quality data (Ingersoll and others, 2002). This protocol has successfully been applied in other mid-latitude and high-latitude mountain ranges in the Western United States and Alaska. The protocol used in the RMS program to collect snowpack samples for chemical analyses and for snow-water equivalent (SWE) measurement is presented in a format after Oakley and others (2003) for use in NPS lands in the Rocky Mountain Network (ROMN). The ROMN, an inventory and monitoring network created by the National Park Service (fig. 3), includes Glacier National Park (GLAC), Rocky Mountain National Park (ROMO), and Great Sand Dunes National Park and Preserve (GRSA). The purpose of this report is to provide three products: (1) a narrative of snowpack-sampling procedures, (2) a discussion about optimal sample spacing based upon snowpack samples collected in and near ROMN parks, and (3) a detailed set of 21 standard operating procedures (SOP) for annual snowpack sampling.

As the SOPs detailed in this report are used there is a possibility that changes will need to be made to the SOPs, perhaps due to new problems encountered in sample collection or processing. All SOPs have a section dedicated to such changes entitled "Change History." It will be the responsibility of the National Park Service to ensure such change history is documented in future editions of this report.

1.1 Introduction

Snowfall in the Rocky Mountains accumulates from October until March, April, or May, and provides about 50 to 70 percent of the annual precipitation in headwater basins of the Rocky Mountains (Western Regional Climate Center, 2008). Atmospheric contaminants such as nitrogen and sulfur compounds tend to be stripped from the atmosphere during precipitation as these snowpacks accumulate (Gray and Male, 1981). These annual snowpacks collect both wet and dry deposition and provide an excellent record of the deposition of airborne contaminants until snowmelt begins each spring. Because snowmelt supplies most of the freshwater in mountain lakes, streams, and wetlands, monitoring the water quality of snow is important to understanding the effects of atmospheric deposition on these systems. Although seasonal snowpacks do not represent several months of summertime precipitation, snowpack-sampling methodology enables efficient collection of a substantial fraction of annual precipitation in a single sample. The methodology also is adaptable for collection of samples for specialized analyses such as for trace metals, isotopic composition, and selected organic compounds.

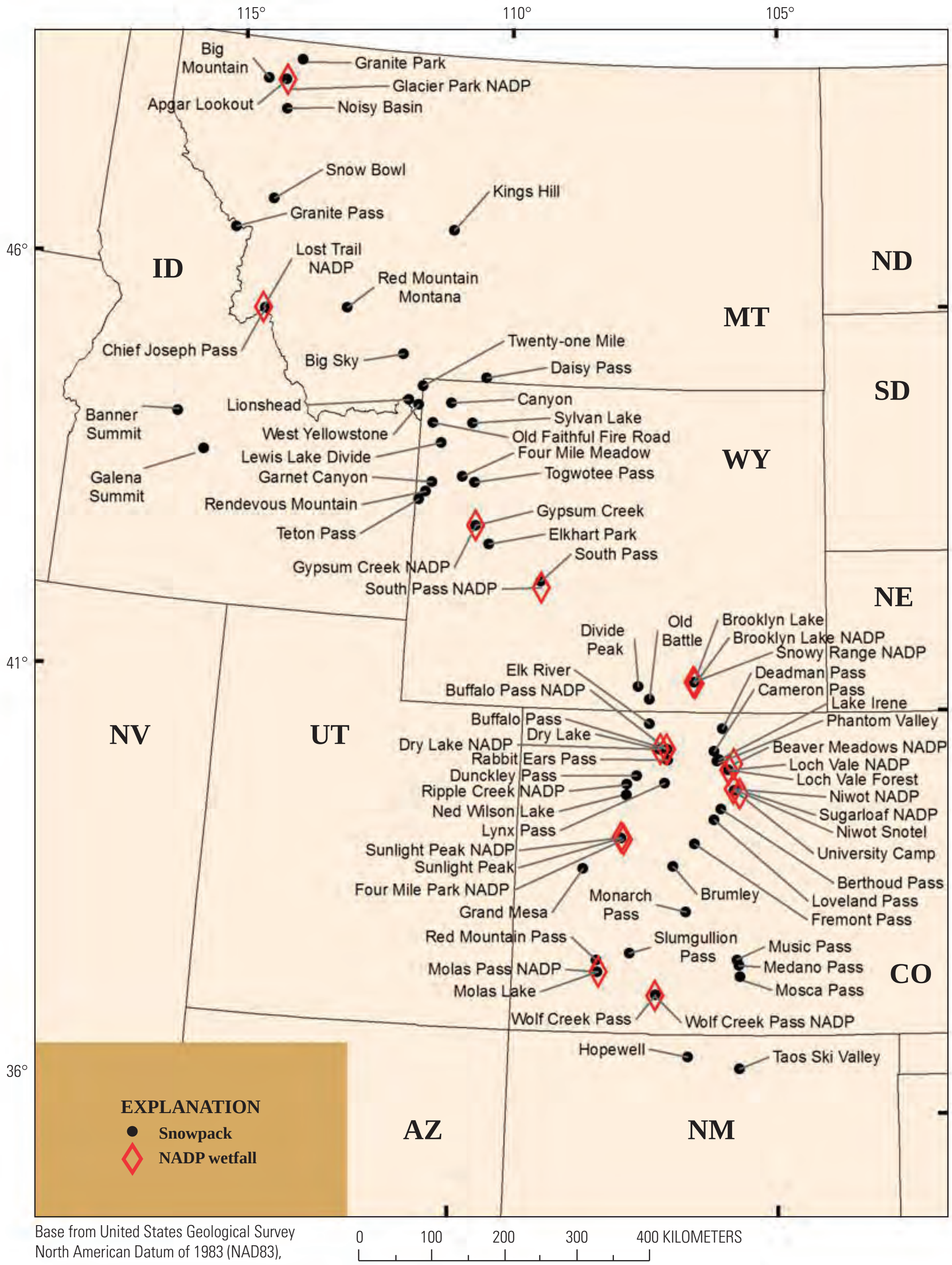

Figure 1. Selected snowpack and National Atmospheric Deposition Program (NADP) wetfall sites in the Rocky Mountain region, 2007.

1.2 Rationale and Justification

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 ecosystems typically have limited capacity to buffer acidity that may result from deposition of airborne compounds such as nitrate and sulfate. As annual snowpacks melt, atmospheric inputs of these ions to these watersheds may affect aquatic and terrestrial ecosystems. Concerns about adverse effects associated with nitrogen or sulfur deposition in North America historically have focused on eastern areas of the continent (U.S. Environmental Protection

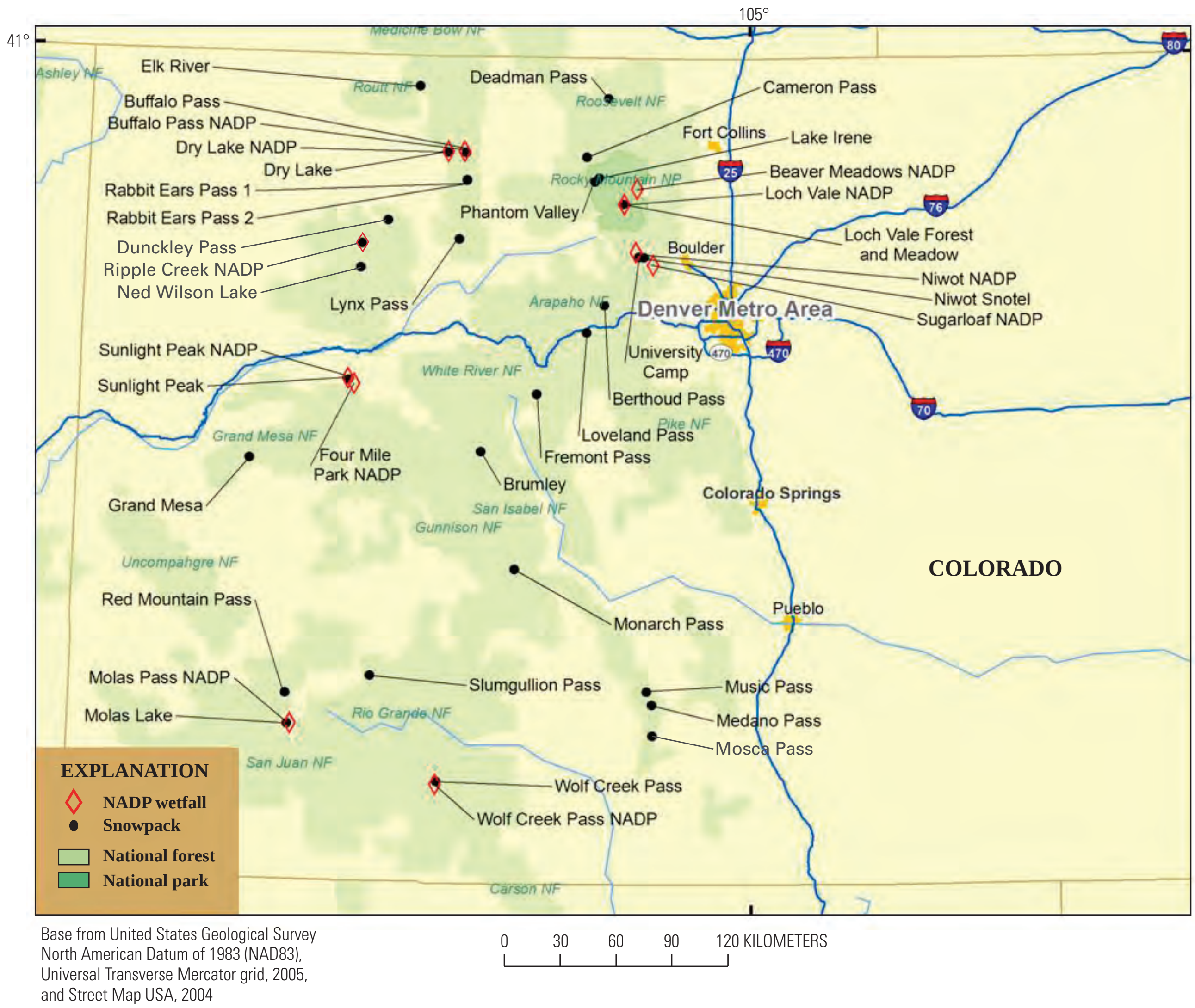

Figure 2. Selected snowpack and National Atmospheric Deposition Program (NADP) wetfall sites in Colorado, 2007.

Agency, 2008). Recent work, however, indicates watersheds in the Rocky Mountains of the Western United States, particularly along the Front Range of Colorado, are exhibiting nitrogen saturation (Campbell and others, 2000; Burns, 2002; Fenn and others, 2003a).

Although several watershed-scale studies have investigated atmospheric deposition of nitrogen and sulfur 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; Williams and Tonnessen, 2000), regional-scale atmospheric-deposition data are sparse (Nanus and others, 2003). The National Atmospheric Deposition Program (NADP) provides nationwide estimates of atmospheric deposition of nitrogen and sulfur (Nilles, 2000; National Atmospheric Deposition Program, 2005). Coverage for high-elevation areas [greater than 2,400 meters (m)] in the Rocky Mountains, however, is limited. Although atmospheric deposition has been monitored at 10 NADP sites at elevations above 2,400 m (North American Vertical Datum of 1988) since 1993 in central and northern Colorado, few sites are operated in other high-elevation areas of the ROMN (such as Montana, Wyoming, and southern Colorado), where snowpacks persist throughout the snowfall season. These high-elevation snowpacks are important because they accumulate two to three times the annual precipitation measured at lower elevations where regular monitoring is more easily accomplished. Estimates of mountain precipitation and chemical deposition primarily drawn from lower elevation monitoring stations do not include large areas of substantially heavier snowpack accumulation. As a result, estimates of regional deposition, which are typically based on lower precipitation amounts, can be lower than those including measurements of water content and chemistry from snowpacks at higher elevations. Also, if estimates of deposition

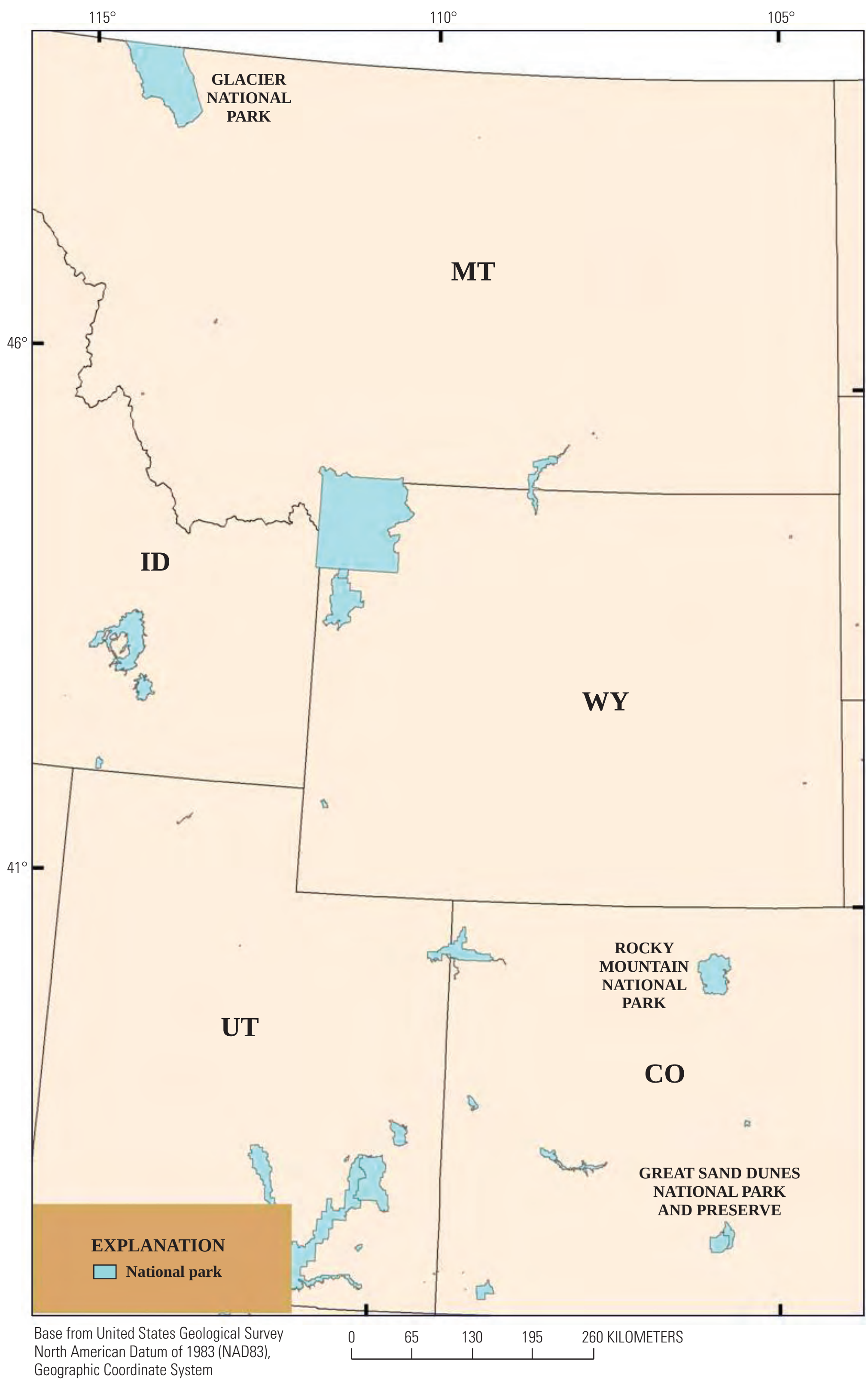

Figure 3. Map showing Rocky Mountain Network parks, 2007.

fall short of actual levels, detection of regional increases or decreases may become more difficult. Thus, seasonal snowpack chemistry in high-elevation areas of the ROMN is an important vital sign that justifies continued monitoring. This is especially true as contaminant emissions may be changing in the region (Baldwin, 2005; Bureau of Land Management, 2005; Fenn and others, 2003b, McGuire, 2006).

1.3 Historical Monitoring

Within the ROMN network, 7 sites have been selected for continued monitoring (table 1) as part of the larger RMS network. Additional information about these 7 sites and 35 other, mostly short-term, snowpack-sampling sites in ROMN parks is given in table A1 (only selected sites from tables 1 and A1 are shown in figs. 1 and 2). Snowpack-chemistry analyses obtained from these annual snowpacks offer reliable estimates of atmospheric-deposition chemistry for a substantial fraction of yearly precipitation and are comparable to results reported from the NADP network (Heuer and others, 2000; Clow and others, 2002).

Historical information from nearby snow-telemetry (SNOTEL) sites operated by the National Resources Conservation Service (2008) provided useful information both for locating sampling sites and timing sampling events (Western Regional Climate Center, 2008). Telemetry of hourly or daily measurements of snow-water equivalent (SWE) and air temperatures from remote SNOTEL sites near snowpack-sampling sites made it possible to remotely monitor the development of seasonal snowpacks over the internet. Remote sensors recorded the accumulation or ablation of snowpacks at SNOTEL sites throughout snowfall seasons of each year during this study. This technology was used to determine whether snowpacks were gaining or losing SWE so that sampling could be accomplished before substantial snowmelt began.

1.4 Measurable Objectives

The objective of the RMS program is to determine and understand long-term spatial and temporal patterns in SWE, and concentrations and deposition of selected major constituents (ammonium, calcium, hydrogen, nitrate, and sulfate) in snowpacks in the Rocky Mountain region. This information is to be used to measure watershed health, anthropogenic activities, and climate variability. To accomplish this, the program must contain sites that are representative of the region and must be operated in a consistent, efficient, and cost-effective manner that is complementary to the NADP network by representing higher-elevation sites that are not feasible for wet-deposition sampling techniques. The efficiency and cost-effectiveness results from requiring only a single snowpack sample to represent an entire season of chemical deposition. The principal focus of the RMS program is on nitrate, sulfate, and mercury concentrations and deposition in snowpacks, although the program lends itself to inclusion of other constituents of interest such as pesticides and other selected organic compounds.

Table 1. Location information and years sampled for selected snowpack-sampling sites in Rocky Mountain Network parks, 1993–2008.

[dd, decimal degrees; m, meters]

Snowpack-sampling site name	Latitude (dd)	Longitude (dd)	Elevation (m)[1]	Years sampled
Glacier National Park, Montana				
Apgar Lookout	48.51806	114.02000	1,579	1996–2004, 2006–2008
Rocky Mountain National Park, Colorado				
Lake Irene	40.41508	105.81925	3,255	1993–2008
Loch Vale Forest	40.28944	105.66750	3,216	1994, 1995, 1997–2008
Loch Vale Meadow	40.29028	105.66667	3,215	1993, 1996, 1999–2008
Phantom Valley	40.39804	105.84576	2,752	1993–2007
Great Sand Dune National Park and Preserve, Colorado				
Medano Pass	37.86389	105.47361	3,339	2006, 2007
Music Pass	37.92833	105.50500	3,484	2006–2008

[1]Above North American Vertical Datum of 1988.

2 Sample Design

2.1 Introduction

Fundamental considerations incorporated into the design of the RMS network of snowpack-sampling sites were target population, spatial design for regional representation, and sample population size. The most challenging aspects of this sample design were the sample spacing and the total number of sampling sites to be included in the RMS network. This section discusses the rationale for sample-site selection and offers quantitative comparisons for justification of sample spacing and the number of sample sites, in addition to sample frequency and timing.

2.2 Target Population

The target population consists of mountain snowpacks from selected locations in or near national parks and wilderness areas where snowmelt runoff dominated annual hydrology. The chemical analyses of snowpack samples are indicators of recent air quality conditions and are of particular interest to Federal land managers. In addition, increasing urban and suburban development in the region and the associated demand for power production may cause potential increases in air emissions near national parks and wilderness areas.

2.3 Spatial Design and Sample Population Size

Although optimizing regional representation of atmospheric deposition is a key objective, RMS sampling sites were limited to mountainous areas of the region where seasonal snowpacks persist through the winter months. That stipulation ruled out much of the region at elevations below 2,000 to 2,400 m, especially in Colorado. Because of the large areal extent of the Rocky Mountain region and the variety of lower-elevation and semiarid landscapes found adjacent to mountainous areas, evenly spaced geographic representation is not possible. In addition to choosing sample sites in targeted protected areas or in underrepresented geographic areas (target sites), other sites in the region were located relative to local or regional contaminant sources to evaluate effects of changing emissions (Mast and others, 2005). This distribution of RMS sites has made it possible to observe regional gradients in concentrations of major constituents such as the greater density of high nitrate concentrations in snowpack samples in Colorado compared to other states in the Rocky Mountain region (Ingersoll and others, 2007; fig. 4).

Specific locations to be sampled in the Rocky Mountain regional network were selected based on additional criteria. After target sites were selected in national parks and wilderness areas, additional sites were chosen to represent spatial gaps between established monitoring locations (such as wetfall sites operated by the NADP, fig. 1) and to maximize regional representation. When possible, sites were collocated with SNOTEL sites so that the hourly SWE and air temperature data could be used in the analyses. Local sources of emissions or other anthropogenic disturbances such as roadways or buildings were avoided by a horizontal distance of at least 30 m and typically 100 m or more. Sites were chosen where snowpacks accumulated uniformly in small clearings in forested areas, yet where limited forest litter was deposited. Finally, all sites were determined to be safely accessible (Ingersoll and others, 2002). Because these combined constraints influenced site selection, a particular maximum distance between sites was not considered.

Factors influencing the number of sites selected include the appropriate distance (spacing) between sites, topography, elevation, and cost. Because of the considerable topographic relief found in much of the ROMN, substantial differences in seasonal precipitation amounts may occur over short distances. For example, in Rocky Mountain National Park, differences in elevations of 300 to 500 m over a horizontal distance of 1 or 2 kilometers (km) are common. Snowfall may yield substantially greater amounts of SWE at higher elevations than at lower elevations (Western Regional Climate Center, 2008). In such cases, differences in atmospheric deposition may be substantial even when concentrations of major constituents are similar. When the RMS network was established in 1993, few data for precipitation chemistry for mountainous terrain were available to evaluate spacing distances between sites. Using long-term, snowpack-chemistry data available in 2006, comparisons were made to evaluate the effects of spacing of sites at local scales. At regional scales, optimal distances between sites were estimated using geostatistical techniques. Due to factors such as varying topography, land ownership, and resource limitations, many of the RMS program sites are many tens of kilometers apart and users of snowpack data must be aware that this distribution of sites adds spatial uncertainty. Distances between sampling sites with similar concentrations of major constituents ranged from 10 to 85 km depending on the constituent. Further details and results of the geostatistical treatment of site spacing in the RMS network are discussed by L. Nanus (written commun., 2008).

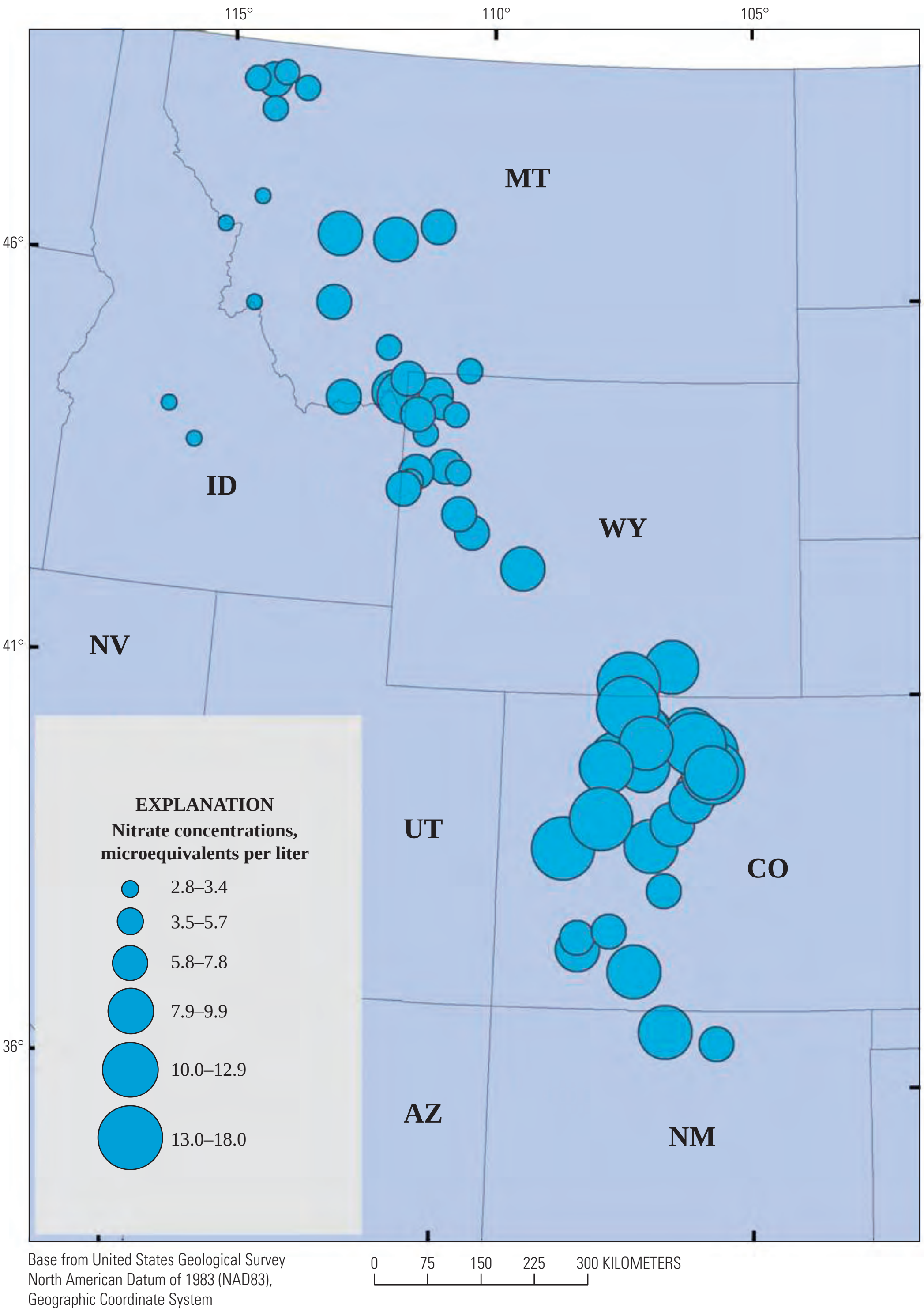

Figure 4. Dissolved nitrate concentrations (as NO_3^-) at snowpack sites in the Rocky Mountain region, 2004.

One method for the determination of distance needed between sampling sites at local scales is to evaluate differences in precipitation and concentrations of major constituents based on empirical data. If such data indicate little difference in precipitation amounts and concentrations between two adjacent sites, then one site may be redundant. For this report, historical SWE data and snowpack-chemical data were evaluated in and near ROMN parks for differences in SWE and concentrations between sites at varying distances, physical settings, and elevations. To compare replicate and adjacent samples, percent differences between replicate measurements and concentrations were calculated. To compare values for snowpack sites located in different physical settings (forest or meadow) and different elevations, one-sided Wilcoxon rank-sum and signed-rank tests (Wilcoxon, 1945) were used.

2.3.1 Precision Calculated from Field Replicates Collected in a Single Snowpit

Replicate and triplicate samples were collected for comparisons to original environmental samples, and data collected from 1999 to 2006 were evaluated for differences in SWE and concentrations of major constituents at several sites in and near the ROMN. Samples from the same snowpits were collected as a measure of precision at the smallest scale (1 m between samples) at sites in GLAC, in northwestern Colorado, and in GRSA. Calculations of precision from field replicates incorporate all sources of uncertainty, including heterogeneity of snowpacks over short distances, potential for contamination during collection, transport, and processing of samples, and analytical precision. At the Granite Park site in GLAC, percent differences for three sample pairs ranged from 0.0 percent for sulfate to 76.5 percent for calcium (table A2). Percent differences of less than one percent were noted in triplicate SWE measurements in northwestern Colorado at Buffalo Pass in 2002 (table A3). Triplicate measurements of concentrations elsewhere in northwestern Colorado at Ned Wilson Lake in 2005 and Ripple Creek NADP in 2006 generally were within 1.1 microequivalent per liter (eq/L) or less (with the exception of calcium, 1.5 and 2.5 eq/L). Percent differences ranged from 1.0 to 50.0 percent for all concentrations in triplicates. However, most of the high percent differences were based on small concentrations, particularly for hydrogen (calculated from independent measurements of pH and Gran titration of alkalinity (for details see *http://or.water.usgs.gov/alk/methods.html*). Replicates from three sites in GRSA (table A4) also reflected high percent differences (20 to 50 percent) associated with small concentrations of hydrogen (0.5 to 0.9 eq/L), whereas calcium percent differences were as high as 31.2 percent. Percent differences for ammonium, nitrate, and sulfate were less than 7.6 percent. These comparisons generally indicate small precision errors and most ranged from 0 to 20 percent difference (tables A2–A4).

2.3.2 Precision Calculated from Field Replicates Collected in Adjacent Snowpits

To assess the precision of snowpack-chemical measurements, field replicate samples were collected from two adjacent snowpits less than 10 m apart at Rabbit Ears Pass (sites 1 and 2) in northwestern Colorado during most years of the study. The results from 13 field replicate pairs collected during 1993–2006 are presented in table A5. Percent differences ranged from 0.4 to 10.5 for SWE, and ranged from 0.0 to 70.8 percent for ammonium, calcium, hydrogen, nitrate, and sulfate. As observed in tables A2–A4, although several percent differences greater than 20 percent were noted for SWE and concentrations of major constituents (especially for calcium and hydrogen), most (87 percent) percent differences were 20 percent or less. These similar ranges of precision error among samples and replicates collected side-by-side in a single snowpit or from two snowpits located close together indicate low variability of both SWE and concentration at distances of 1 to 10 m.

2.3.3 Differences between Forest and Meadow Sites

Further examination of differences in precipitation and snowpack chemistry at sites separated by short distances was conducted by comparing data from two pairs of snowpack-sampling sites located less than 200 m apart in ROMO during 2000–2006. One pair of sites was located near Loch Vale on the east side of ROMO, and the other pair was located near Lake Irene on the west side of ROMO (fig. 2). To assess potential differences in SWE and concentrations of major constituents between forest and meadow locations, both pairs of sampling sites included one snowpit located in a treeless meadow roughly 50 to 100 m in diameter and one snowpit in a small forest clearing about 5 to 10 m in diameter. Meadow sites were sampled in an open, mostly flat area with full exposure to the sun; forest sites were sampled less than 200 m away in forest clearings, with substantial shading from the winter sun and more potential for litterfall and washout of dry deposition intercepted by the trees. Wilcoxon signed-rank tests indicated significantly higher values ($p \leq 0.05$) of SWE, ammonium, calcium, nitrate, and sulfate at the forest sites (table A6). The greatest median difference in the chemical constituents was 3.5 eq/L for calcium. Hydrogen ion concentrations showed no significant differences, probably because the balance between base cations such as calcium and acid anions such as nitrate and sulfate was not changed. These results generally indicate that more snow accumulates at the forest sites, and that the forest canopy is a more efficient scavenger of atmospheric contaminants, especially dry deposition and deposition from mists or clouds (both of which eventually are added to snowpacks). Snowpack samples from open meadows may not fully represent atmospheric deposition to the surrounding area because meadows lack the scavenging potential of forests. Further, wind scouring of meadows may result in less snow accumulation than in forests. Therefore, presented with a choice between a small forest clearing or an open meadow, the forest clearing would be the preferred snowpack-sampling site.

2.3.4 Differences along Elevational Gradients

At the 1- to 5-kilometer scale, a comparison was made between snowpack data collected at a higher-elevation site and a nearby lower-elevation site in ROMO. The Lake Irene (3,255 m) and Phantom Valley (2,752 m) sites lie about 3 km apart, differ in elevation by about 500 meters, and offer a long-term (14-year) comparison (fig. 5; table A7). The Wilcoxon rank-sum test was used to determine: (1) if SWE at Lake Irene was greater than SWE at Phantom Valley, and (2) if concentrations of selected major constituents at Lake Irene were less than concentrations at Phantom Valley. SWE was significantly greater at Lake Irene than at Phantom Valley ($p<0.0001$), while concentrations at Lake Irene were significantly less for hydrogen ($p=0.03$) and sulfate ($p=0.01$). No significant differences in ammonium, calcium, or nitrate concentrations were noted.

At a slightly larger scale, a second comparison was made using the same tests between a higher-elevation site at Buffalo Pass (3,139 m) and a somewhat more distant (about 9 km) site 579 meters lower in elevation at Dry Lake (2,560 m) in northwestern Colorado (fig. 2). Results showed significant differences for SWE ($p<0.0001$) with greater SWE at the high-elevation site. Differences in concentrations of major constituents were significant only for nitrate ($p<0.001$), with concentrations at Dry Lake exceeding those at Buffalo Pass (table A8).

2.3.5 Summary of Comparisons and Discussion

Comparisons made in this section offer insights into sample spacing, physical settings, and elevations. Comparisons of precision of SWE measurements and of concentrations of major constituents from snowpack samples spaced from distances of 1 to 10 m apart were similar with the percent difference (variation) being less than 20 percent for most (87 percent) of the comparisons. Nanus (written commun., 2008) also determined that concentrations of major constituents for some snowpack-sampling sites remain similar for much greater distances.

Comparisons of SWE and concentrations of major constituents for snowpack sites in forests and meadows indicate that snowpack samples from open meadows may not fully represent atmospheric deposition to the surrounding area. Meadow sites generally have lesser amounts of SWE than forests and are subject to wind scouring that may result in less snow accumulation than in forests. Concentrations are greater at forest sites because more scavenging of atmospheric contaminants occurs than at meadow sites. Therefore, presented with a choice between a forest site and a meadow site, the former would be the preferred snowpack-sampling site.

Comparisons of SWE and concentrations of major constituents in snowpack samples collected at different elevations (3,255 and 2,752 ; and 3,139 and 2,560 meters) indicate that the SWE was greater in the higher-elevations sites, while concentrations were greater in samples from the lower-elevation sites. Thus, precipitation and concentration may be significantly influenced by elevation differences of about 500 meters or more, and also may be affected by horizontal distances. Given that sufficient resources are available, it is preferable to sample both higher- and lower-elevation sites. When resources are limited to one site, the selection of the higher-elevation site might be preferable because of the greater amount of SWE, which often translates into greater total deposition of major constituents. When considering potential impacts of anthropogenic activities on watershed functions and health with a small number of sample sites, it may be better to overestimate than underestimate chemical deposition.

2.4 Sample Frequency

Composite snowpack samples of the entire snowpack representing the majority of annual precipitation, including wetfall and dry deposition, are collected once at all network sites during late winter or spring before snowmelt begins. The collection of just one annual sample per site provides an economical advantage so that resources may be directed to many sampling sites in a large network.

2.5 Sample Timing

It is critical that snowpack sampling occurs before snowmelt begins and before chemical solutes leave snowpacks. The snowpack-sampling season should begin in late February or early March and be completed in April or May in most cases, depending on the elevations of sites to be sampled. More information about sample timing and scheduling guidance is given in SOP 3.

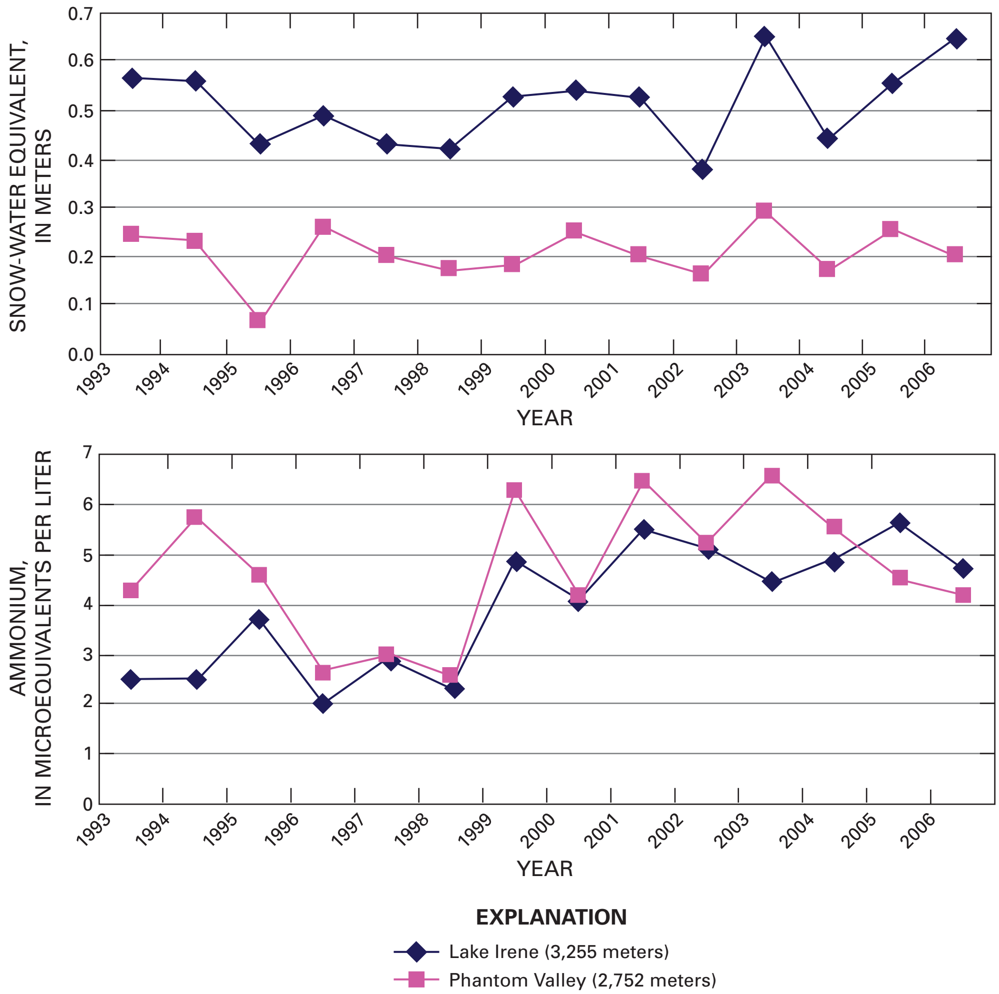

Figure 5. Time series for snow-water equivalent (SWE) and dissolved ammonium concentrations (as NH_4^+) in snowpacks at Lake Irene and Phantom Valley sites, 1993 through 2006.

3 Field Methods

3.1 Introduction and Snowpack-Sampling Methods Overview

Key elements of seasonal snowpack-sampling field methods include accessing snowpack-sampling sites with regard to resource protection, locating the established site where the sample will be collected, collecting snowpack samples, taking field notes, collecting quality-assurance field blanks and replicates, handling samples to avoid contamination, and transporting frozen samples to a freezer for preservation.

Seasonal snowpack samples collected using this method were assumed to be representative of regional atmospheric deposition for a substantial part of each year. A primary objective in collection of seasonal snowpack samples is to successfully capture composite samples including all layers of a given snowpack without contamination. Because only one sample will be collected for the year, utmost care should be taken to ensure success. If problems with field sampling methods are noted in subsequent weeks or months, it is unlikely that a second sample can be collected.

3.2 Resource-Protection Overview

Travel to backcountry snowpack-sampling locations in national parks such as GLAC, ROMO, and GRSA is restricted to non-motorized means. With few exceptions, access to sites is done on skis or snowshoes. Only under special circumstances may snowmobiles be used to accomplish sampling objectives (for example, under administrative travel on the west side of ROMO). Natural resources are not affected by snowpack sampling because nothing but the snow is collected and no constructs are required. When the sampling operation is complete, snowpits are backfilled to minimize any hazard or unnatural appearance.

3.3 Locating Established Sites

Location information for 42 snowpack-sampling sites in and near ROMN parks (including both long-term and intermittent sites) is provided in the Appendix (table A1). The table provides latitude and longitude coordinates, and elevations of snowpack-sampling sites and nearby SNOTEL sites, as well as vegetative cover type and historical sample-collection dates. Further information for seven sites selected for continued monitoring are given in table A9 including location information, Federal Information Processing Standards (FIPS) codes for surrounding states and counties, and estimated travel time over snow to sampling sites. However, conditions may be quite variable, and actual time required for a given party to access the site may differ substantially. The use of hand-held Global Positioning System (GPS) units for navigation to the sites is highly recommended, and users should be familiar with GPS navigation in advance of sampling trips.

3.4 Relocating Sites

ROMN snowpack-sampling sites under this protocol are already established (table 1 and figs. 6, 7, and 8). Established sites may need to be relocated due to restrictions to access, changes in climatology (for example, a case where seasonal snowpacks no longer persist), construction of new facilities or infrastructure, or for other reasons. If it is decided to relocate a site, it would be best to relocate to the nearest suitable site to the original site for continuance of long-term records. As discussed, if an alternate site is selected at a substantially different elevation, considerable differences in precipitation and concentrations of major constituents may distort long-term records including both the original and the relocated site. Further guidelines for relocating sampling sites are presented in SOP 10.

3.5 Site Photos

Site photos are optional, and may be taken as sampling operations proceed in the snowpit; however, noteworthy appearances in snow stratigraphy should be photographed. For example, unusually thick melt-freeze layers, ice lenses, dust layers, or any other peculiar findings are documented on the data sheet, and photo documentation is recommended. Other items of interest, such as recent avalanche activity or other obstacles, hazards, or natural phenomena influencing snowpacks or safe access, also should be photo-documented. A digital camera should be used whenever possible to speed image distribution.

3.6 Recommended Sampling Method

The seasonal snowpack-sampling method is recommended for collection of snowpack samples. A very brief summary of field methods is given in section 3.1; details are listed in SOPs 12–15.

3.7 Data Management in the Field

A single data sheet is required for notes taken during snowpack sampling. Information about sampling personnel, location, weather conditions, snowpack conditions, and time of collection, and any noteworthy or unusual conditions that might affect the sample are recorded on the data sheet (SOP 11). All information outlined on the data sheet should be completed by the end of the sampling operation. Data sheets should be returned to the office for subsequent checks for completion and data entry into a database (SOP 14).

3.8 Quality-Assurance Field Blanks and Field Replicates

Snowpack-sampling techniques are monitored for quality assurance by collecting field blanks and field replicates for detection of contamination and precision, respectively (SOP 13). Additional quality-assurance information is given in section 5, Analytical Methods.

3.9 Post-Sampling Processing of Data and Samples

Upon completion of sampling events and field activities, several important steps must be followed. Sample-collection data for each sample should be entered into a database before laboratory analyses commence (SOPs 14 and 19). Foremost, snowpack samples must be safeguarded from exposure to sources of contamination and maintained below freezing during transport to the freezer facility where the temperature is maintained well below 0°C (SOP 15). Further sample processing is detailed in SOP 16.

Figure 6. Selected snowpack-sampling sites in Glacier National Park, 2007.

Figure 7. Selected snowpack-sampling sites in Rocky Mountain National Park, 2007.

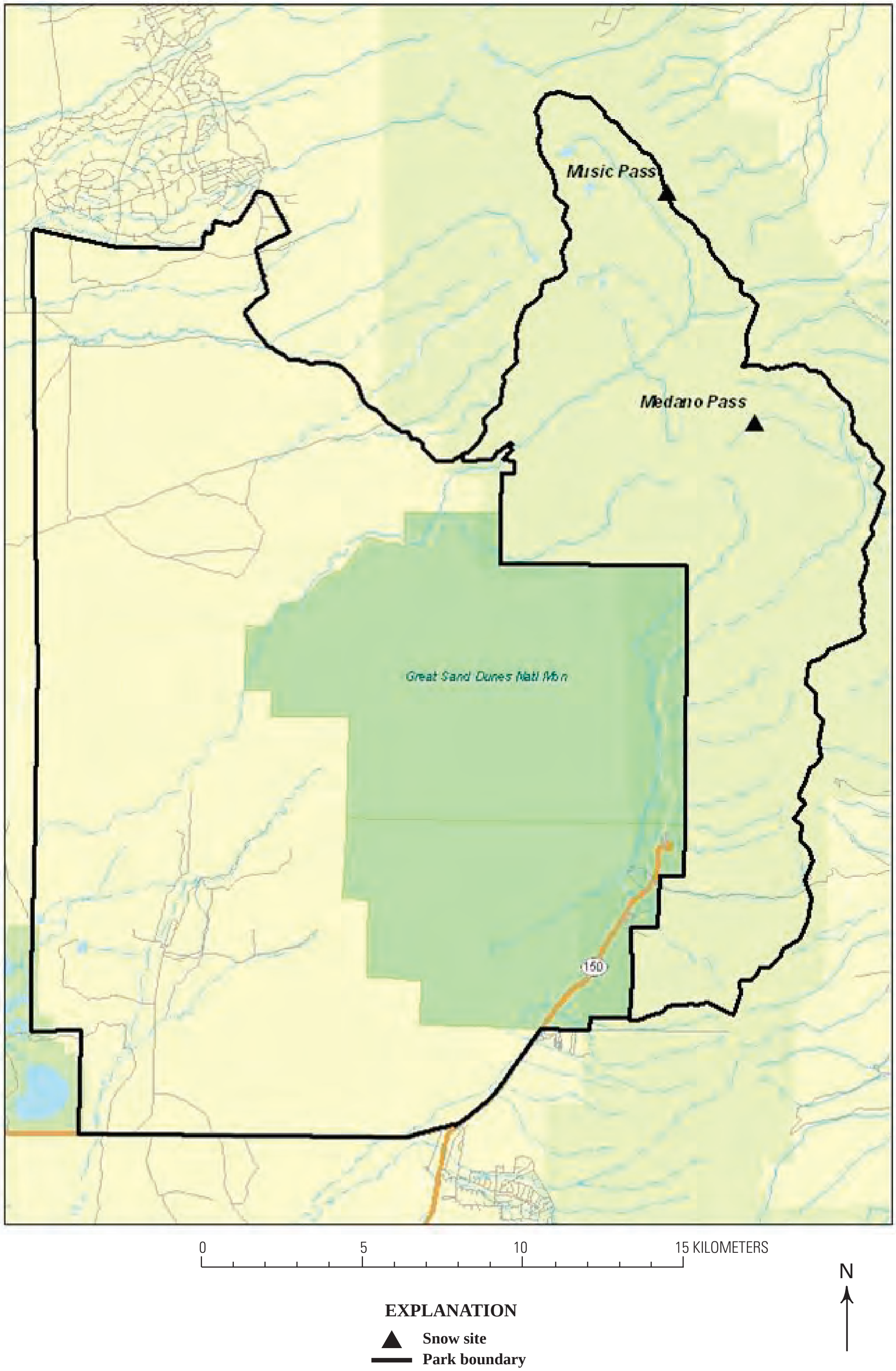

Figure 8. Selected snowpack-sampling sites in Great Sand Dunes National Park and Preserve, 2007.

4 Managing a Sampling Season

4.1 Introduction

Management of a field season includes the advance coordination of personnel, purchasing and preparation of equipment and materials, submitting collection permits, and training personnel; and for end-of-season data processing, sample analysis, and data storage. Purchasing of equipment and arrangements for personnel should be planned months in advance.

4.2 Pre-Season Preparation

Once the number of sample sites to visit has been determined and the timing of sampling has been scheduled, personnel can be organized, lodging requirements determined, and schedules for site visits can be finalized. Sufficient numbers of field personnel must be planned for each site to be sampled. A crew of at least two persons should be assigned to sample a given site under moderately demanding conditions (for example, day trips over reasonable distances to sites where the snowpack is likely to be about 2 m deep or less). For more demanding sampling trips, three or four persons should be assigned to the field crew, especially if the snowpack is deep (3 m or more) and if the remoteness of the site would make emergency rescue difficult.

Equipment and vehicles should be organized to handle the total number of sampling sites to be visited in advance of the initial sampling dates. Field sampling equipment must be organized and cleaned and packaged in advance of the sampling season to ensure successful results and minimize contamination (SOP 4). Purchasing and preparation of over-snow-travel gear, and other special field equipment necessary such as backcountry sleds, avalanche beacons, shovels, probe poles, or communications equipment should be done well in advance of the sampling season (SOP 5).

Communication with NPS staff at individual parks is integral to the sampling season. Scientific Collection Permits must be acquired before field work commences (SOP 2). Permit applications provide park managers with updated information about actual sampling operations including dates, housing needed, site locations, number of personnel involved, access routes, and completion dates. After permits are issued for snowpack sampling, coordination with park staff at about the time of site visits also is necessary. Such communication updates provide the researchers and park staff important opportunities to exchange information that may affect the sampling success and is a courtesy to hosting staff. For example, recent events or emergencies may have occurred such as avalanches, road closures, or accidents. Finally, for safety purposes, communication with park staff before and after site visits should be done whenever possible.

4.3 Training

Several types of training are needed for personnel venturing into mountainous backcountry in wintertime (SOPs 6–9). Crews should be trained in a variety of skills including first aid, backcountry route selection, communications, winter survival, and avoidance of dangerous wildlife.

4.4 End-of-Season Procedures

After all samples have been collected, field-data sheets are checked for completeness, and the accuracy of data entered into the database is verified. After all samples are entered into a database, analytical work can begin (SOP 16). In brief, samples are melted, preprocessed, and distributed for desired analyses. Tracking of samples through chemical analyses begins prior to submission of aliquots to laboratories. Analytical results are checked for quality assurance and re-analyses of samples is done as needed.

Sampling equipment, including coolers used to transport snowpack samples, are rinsed with deionized (DI) water and allowed to dry before storage. All equipment is reserved for snowpack sampling and secured in a clean environment during the off-season.

5 Analytical Methods

5.1 Introduction

Analytical methods include pre-processing snowmelt samples for analyses, laboratory methods and quality assurance, and method detection limits. Particular care should be given to avoid contamination of dilute snowmelt during all analytical steps.

5.2 Methods and Detection Limits

Pre-processing of snowmelt samples is necessary to distribute aliquots of sample to several analysts in different laboratories (SOP 16). Briefly, snow is melted in the same 8-liter (L) Teflon bag used to collect the samples and each contains a single, depth-integrated, composite sample from each snowpit. Next, aliquots are drawn from the snowmelt as either whole water (unfiltered), or subsequently filtered to 0.45 microns. This operation should be done in a clean laboratory equipped to melt and filter snowpack samples efficiently and without contamination. Once sample aliquots have been prepared, certified laboratories are used for the analyses of dilute snowmelt. Laboratories must be experienced in detection of low-level concentrations of major constituents including anions chloride, nitrate, and sulfate; and cations ammonium, calcium, magnesium, potassium, and sodium. Alkalinity, conductivity, and pH also are determined in the laboratory by qualified personnel. Analyses of trace elements such as mercury or other metals may be desired and also will require specialized methods for low-level detection.

Analytical laboratory methods and quality-assurance procedures for analyses of major-ion- and mercury concentrations in snowmelt are described by Turk and others (2001), Ingersoll and others (2002), and Mast and others (2003). Determinations of concentrations of major constituents typically are performed using the following methods: ion chromatography (anions), inductively coupled-plasma mass spectrometry (cations), Gran titration (pH and alkalinity), total-organic-carbon analyses (DOC), and cold-vapor atomic-fluorescence spectrometry (mercury). Quality-assurance blanks, replicates, and reference standards should comprise 10 to 20 percent of analytical processing. Ionic-charge balances should be computed as a measure of the quality of the chemical analyses for major ions. The analyzing laboratories should participate in round-robin analyses with other laboratories. Additional information including interlaboratory comparisons of USGS standard reference samples can be found at *http://bqs.usgs.gov/srs#contacts* (accessed 11/10/08). Further details about suggested analytical methods for snowmelt are given in SOPs 16–17.

Experience over the last 15 years indicates that acceptable method detection limits are about 1.0 μeq/L for alkalinity, 0.2 to 2.0 μeq/L for major ions (calcium, 1.2; magnesium, 0.6; sodium, 2.0; potasssium, 0.4; ammonium, 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 nanograms per liter (ng/L) for mercury.

6 Safety

6.1 Introduction

Safety of field personnel is the highest priority in backcountry research operations. Accordingly, personnel tasked with collecting snowpack samples should possess adequate physical abilities and be familiar with backcountry travel in winter. Because the wintertime environment in mountainous areas can be hazardous, sampling crews must be trained in several areas of expertise. Critical safety-related training includes the use of winter-survival equipment, weather and backcountry travel considerations, avalanche safety, first aid, radio or telephone communications, and avoidance of dangerous wildlife.

6.2 Personal Gear and Responsibilities

Snowpack-sampling crew members should be in strong physical condition, have suitable clothing for winter conditions, and be equipped to travel over snow. Conditions at high elevations in the region can be severe; therefore, high-quality, well maintained personal gear is essential for the prevention of hypothermia and cold-weather injuries. Extra personal gear such as warm garments, extra food and water, overnight gear, and basic survival equipment must be considered for backcountry site visits.

6.3 Weather Conditions, Backcountry Travel, and Avalanche Safety

Weather conditions, backcountry travel, avalanche safety, and arrangements with a contact person who will monitor the safe return of the crew are central to the safety and success of snowpack-sampling activities. Details are discussed in SOPs 6 and 9. Coordination with local authorities is recommended to obtain current information about weather and adverse conditions affecting travel in the area.

6.4 First Aid

During backcountry emergencies, injured personnel may be dependent upon the first-aid skills of one or two other members of the sampling crew for response to life-threatening injuries. Therefore, it is essential for crews to be well trained and equipped for medical emergencies (SOP 6).

6.5 Communications

To enable contacting rescuers in an emergency, or if other problems arise, communications equipment (radios, cellular telephones, or satellite telephones) must be carried by snowpack-sampling crew members (SOP 8). Such devices and their networks should be tested before going to the field. Coordination with local authorities is recommended to obtain radio support and information about authorized radio use.

6.6 Wildlife

Although interaction with dangerous wildlife in the ROMN is unlikely during the snowpack-sampling season, precautions should be taken to avoid dangerous encounters (SOP 7). Coordination with local authorities is recommended to obtain current information about dangerous wildlife.

7 Data Management

A relational database capable of managing large datasets and tracking numerous analytical operations is recommended for the management of snowpack-chemistry data. From entry of the first sample-collection data through final retrieval of results, the database should be capable of efficient and error-free management (SOP 14). Data archives should be maintained both onsite and offsite to prevent data loss (SOP 20).

8 Analysis and Reporting

Snowpack-chemistry results may be used to show spatial distributions of concentration and deposition of major constituents at selected sites in a given area. This provides a basic means of spatial analyses of chemical data at local sites as well as over a larger geographic area. More advanced analysis techniques can be applied to interpolate concentrations over a study area or region (Nanus and others, 2003) or evaluate trends over time throughout a network of sampling sites (Ingersoll and others, 2008). Techniques for analysis and a variety of reporting formats are given in SOP 21.

9 Administration of the Protocol

9.1 Introduction

This protocol should be centrally maintained to promote consistent adherence to established methods. As snowpack-sampling methods used in the RMS program evolved, protocol development was carefully evaluated. In particular, effects of various procedures on the chemistry of snowmelt in samples collected were watched closely as tests were done to ensure defensibility of existing or new procedures. For example, washing procedures that used ultra-pure DI water or liquid soap and tap water were tested analytically to determine if contamination was introduced during cleaning procedures. If changes are made to the protocol by some sampling crews and not others, data collected may not be comparable. As time goes on, a series of independent changes to the protocol may result in substantial differences in reported chemistry. As other needs for changes to the protocol arise in the future, it will be important to coordinate and effect those changes centrally and to communicate those changes to all sampling crews deployed in a sampling season.

9.2 Personnel Skills, Qualifications, and Responsibilities

Skills, qualifications, and responsibilities of personnel using this protocol are too numerous to list here. Details are discussed in sections 5–10, and SOPs 1–21, respectively.

9.3 Compliance and Permitting

Adherence to NPS regulations and policy is required when conducting field work in national parks. Communication with NPS staff at individual parks before sample-collection visits is both a courtesy and a source of valuable information. Compliance and permitting requirements are discussed in section 4.2 and SOP 2.

10 Revising the Protocol

Revisions to the protocol may be necessary as circumstances change through time, or as errors are discovered. Because of the effects changes may have on the long-term record, introduction of new procedures or deletions of old procedures should be carefully considered. To make positive improvements to the protocol and the sampling program, procedures and methods must be field tested and should be evaluated on an annual basis. An example of a reason for protocol revision is the occurrence of outliers in analytical results. As chemical data become available after each sampling season, quality-control measures will identify suspect or anomalous values. In the process of investigating such peculiarities, links back to protocol problems either in the laboratory, in the field, or elsewhere may provide justification for revision of certain SOPs.

11 Summary

Since 1993, the U.S. Geological Survey, in cooperation with the National Park Service, the USDA–Forest Service, and others, have established and maintained the long-term Rocky Mountain Snowpack (RMS) program designed to monitor and interpret atmospheric deposition chemistry in high-elevation watersheds of the Rocky Mountains. Long-term operation of the network of snowpack-sampling has resulted in the development of a robust sampling protocol to produce consistent and high-quality data. The protocol used in the RMS program to collect snowpack samples for snow-water equivalent (SWE) measurement and for chemical analyses was presented for use in National Park Service lands in the Rocky Mountain Network (ROMN), including Glacier National Park, Rocky Mountain National Park, and Great Sand Dunes National Park and Preserve. This report contains three parts: (1) a narrative of snowpack-sampling procedures, (2) a discussion about optimal sample spacing based upon snowpack samples collected in and near ROMN parks, and (3) a detailed set of 21 standard operating procedures (SOPs) for annual snowpack sampling.

The narrative sections discuss several critical elements necessary for successful snowpack sampling. The sample design for the protocol describes the location and number of sample sites, comparisons of replicate samples and neighboring sites, and the timing of collection of samples. The field methods include outlined key elements such as accessing snowpack-sampling sites with regard to resource protection, locating established sites, the recommended sampling method for collecting snowpack samples, taking field notes, collecting quality-assurance field blanks and replicates, transporting frozen samples and handling samples to avoid contamination. Managing a sampling season includes advance coordination of personnel, equipment, collection permits, and training; and end-of-season data processing, sample analysis, and data storage. Analytical methods include pre-processing snowmelt samples and submission to laboratories for analyses, laboratory methods and quality assurance, and acceptable method detection limits. Safety training includes the use of winter-survival equipment, weather and backcountry travel considerations, avalanche safety, first aid, radio or telephone communications, and avoidance of dangerous wildlife. A relational database and an archiving system are recommended. Techniques for analysis of data and examples of reporting formats are given. Last, the need for administration and possible revision of the protocol are discussed.

Second, to clarify variability inherent in the RMS sample design, statistical comparisons are made for SWE and concentrations of major constituents (ammonium, calcium, hydrogen, nitrate, and sulfate) in snowpack samples at different local scales, physical settings, and elevations. Percent differences were calculated between replicate pairs of each constituent and the Wilcoxon rank-sum and signed-rank tests were used to statistically compare SWE and concentrations for paired sites in different physical settings and at different elevations. Variations in SWE and concentrations from replicate samples (about 1 meter apart) from seven different sampling sites and from two adjacent sites (about 10 meters apart) showed only small variation in percent differences of less than 20 percent for most (87 percent) of the comparisons. Comparisons of SWE and concentrations between two pairs of forest and meadow sites showed significantly larger amounts of both SWE and concentrations at the forest sites. Based on these results, forest sites are preferred to meadow sites. Comparisons of SWE and concentrations in snowpacks for two pairs of high-elevation (3,255 and 3,139 m) and low-elevation (2,752 and 2,560 m) sampling sites showed significantly greater amounts of SWE at the higher-elevation sites and significantly greater concentrations of some major constituents at the lower-elevation sites. Thus, precipitation and concentration may be significantly influenced by elevation differences of about 500 meters or more, and also may be affected by horizontal distances. Given these differences, both higher- and lower-elevation snowpack-sampling sites are suggested. But if resources are limited to one site, the selection of the higher-elevation site is preferable because of the greater amount of SWE, which often translates into greater total deposition of major constituents.

Third, SOPs developed for essential elements of the snowpack-sampling protocol are presented in detail. Twenty-one individual SOPs describe necessary steps including advance planning, collection-permit compliance, equipment preparation, personnel training, safety considerations, sampling-site operations, quality assurance, sample handling and analyses, and data management and reporting.

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Standard Operating Procedures

1 SOP: Advance Sampling-Site Selection and Early Organization

Introduction

Planning the sampling season should commence in October or November before the season begins. A primary goal in successful seasonal-snowpack sampling is the collection of samples before snowmelt begins. Sampling sites to be visited in the ROMN should include existing long-term monitoring sites in the Rocky Mountain Snowpack network in GLAC and ROMO and sites established in 2006 in GRSA. As sampling budgets are determined at the onset of each fiscal year, sites to be sampled should be selected and plans should commence to organize personnel and equipment for site visits. Sampling operations tend to be more effective if logistics are developed several weeks in advance of the planned sampling date. SOP 3 outlines suggested sample timing.

Steps

- Determine if budgets will support snowpack sampling at the desired number of sites.
- Consider resources available to collect the desired number of samples.
- Finalize the number of sites to be sampled.
- Forecast the dates that sites are to be visited.
- Apply for scientific collection permits with the NPS (SOP 2).
- Begin scheduling personnel and equipment to be dedicated to the operation.
- Determine purchasing needs for sampling equipment, field gear, and vehicles.
- Monitor snowpack conditions as the snowfall season progresses.

Change History

Document pertinent changes in this SOP. If changes to this or other SOPs are deemed necessary, documentation should be made in this section, and the edition of the SOP(s) should be effected.

2 SOP: Using the National Park Service Permitting System

Introduction

When scientific investigations take place in National Park Service units, a scientific collection permit is required in advance of data collection. Investigators must submit an application describing objectives, methods, hypotheses, expected benefits, and deliverable products to the National Park Service through its Web site (*http://science.nature.nps.gov/research*) to apply for the permit. At the end of each year, or the end of the study, researchers are required to submit Investigators Annual Reports (also to be submitted online at the same NPS Web site), and document results and objectives that have been accomplished.

Steps

Instructions are explicitly posted on the Web pages as the information is submitted online.

Change History

Direction from the NPS Web site will be expected as changes in permitting and annual reporting protocols occur.

3 SOP: Sample Timing

Introduction

A primary goal in successful seasonal-snowpack sampling is the collection of samples before snowmelt begins. Although physical measurements of the snowpack made just before snowpack samples are collected will determine if the snowmelt has begun at a given site (SOPs 10–12), the following recommendations will help to avoid sampling the snowpack after the onset of snowmelt. The snowpack-sampling season typically begins in late February or early March and ends in April or May, depending on the elevations of sites to be sampled. Lower-elevation sampling sites below 2,400 m are likely to begin melting by early March, especially in Colorado and Wyoming. Higher-elevation sites (generally above 2,400 m) should be sampled by early April, in general. Historical information from nearby SNOTEL sites provides good estimates of when seasonal snowpacks are likely to reach their annual maximum (Western Regional Climate Center, 2008). Based on 30-year averages, selection of sampling dates 2 or 3 weeks in advance of the date of maximum SWE is recommended. If weather conditions result in warmer-than-average air temperatures, then earlier-than-average snowmelt is likely. So planning site visits early will increase the probability of obtaining samples before substantial melt ensues, and before chemical solutes melt through snowpacks. Additional information on the condition of local snowpacks may be found by contacting the local snow survey office of the National Resources Conservation Service (National Resources Conservation Service, 2008).

Steps

- List selected sites by elevation and latitude and longitude (table A1).
- Determine which sites are most vulnerable to early snowmelt giving priority to lower elevation (<2,400 m) sites.
- Monitor nearby SNOTEL sites weekly at a minimum. More frequent monitoring is necessary if unusually warm temperatures and below-average snowpacks are present during late February and March.
- Consider other sources of information pertinent to snowpack accumulation (recent regional storms, snow-depth reports, early melting, avalanches, or extreme weather).
- Plan to visit sites in March or early April (earlier in unusually dry or warm conditions).

Change History

Document pertinent changes in this SOP. After each season, update the dates and years sites were sampled in table A1.

4 SOP: Preparation of Sampling Equipment

Introduction

Field sampling equipment must be organized in advance of the sampling season to ensure successful results and minimize contamination. As mentioned in section 4.2, sampling equipment and materials require careful cleaning, calibration, and packaging before the sampling kits are deployed to the field. Tools needed to prepare the snowpit, make physical measurements, and collect the snowpack samples must be cleaned, and thermometers must be calibrated before assembling in sampling kits. Cleaning of sampling scoops and shovels and Teflon bags for receiving the snowpack samples requires time in a clean laboratory environment where ultra-pure (18 megohm resistance) de-ionized (DI) water is available. The source of running water (both tap water and de-ionized water) must have the capacity to provide several gallons per hour. Copious amounts of rinse waters are required for the cleaning operation. Adequate time should be allotted for this preparation in advance of the sampling season.

Steps

1. Clean sampling tools and Teflon sample bags.
    - Thoroughly wash and scrub polycarbonate sample-shovel blades and polycarbonate scoops used to collect samples in a solution of tap water and laboratory-grade soap.
    - Soak shovel blades and scoops in a 5-gallon bucket filled with clean tap water for one minute then rinse all surfaces under running tap water a minimum of three times.
    - Soak shovel blades and scoops in a second 5-gallon bucket filled with DI water for 5 minutes.
    - Remove shovel blades and scoops from DI water bucket and rinse with DI water. Rinse all surfaces under running DI water a minimum of three times.
    - Place shovel and scoop in a clean 6-mil polyethylene bag and seal securely.

- Label outside of bag “cleaned with soap wash, tap rinse, and DI rinse, by [user’s name] on [date]” and pack in a sample kit box.
  - Triple rinse all Teflon sample bags using ultra-pure DI water with at least 1 liter per rinse, and place inside doubled, clean Ziploc plastic bags. Next, place each double-bagged set inside a 61 by 91 cm (24 by 36 inch), 6-mil polyethylene bag, fold, and secure with tape. Store in a clean freezer to prohibit contamination until they are to be deployed to the field.
  - If bags are being pre-cleaned for analysis of organic carbon compounds (pesticides, for example), extra rinsing with tap water and laboratory-grade soap, and final rinsing with DI water is recommended.

2. Calibrate bimetal thermometers (pack a minimum of three per sampling kit with temperature ranges covering at least –20°C to 20°C). Digital thermometers are not recommended because they are subject to battery failure and to malfunction from high humidity and freezing conditions. Bimetal thermometers certified directly traceable to National Institute of Standards and Testing (NIST) are recommended because they are not affected by these problems. To calibrate
   - Prepare an ice bath in a 4-L bucket filled with densely packed ice and water.
   - Immerse thermometers and allow to equilibrate.
   - Adjust thermometers to read exactly 0.0°C with minimal parallax error.
   - Store three thermometers in a box that will cushion them (in foam for example), label the lid with the calibration date, and pack it in the sample kit box.
3. Organize and pack the remaining equipment in a sample kit box (all items are reusable except the Teflon and polyethylene bags, labels, duct tape, and cable ties).
   - Test 2-kg-capacity analytical balance, insert new batteries, and add extra batteries to the sample kit.
   - Pack snow cutter, lid, and spatula, and store in a box or sack.
   - Pack at least five 8-inch cable ties per sample bag.
   - Pack 4 × 4 inch labels in small Ziploc bags with preprinted “site name, date, and time.” Pack one label per sample plus an extra.
   - Pack extra pencils and marking pens.
   - Pack snow-crystal lens and card (with millimeter grid and snow-crystal identification information printed on it).
   - Pack roll of duct tape for sealing samples in 6-mil polyethylene bag.
4. Clean and dry 70- or 100-quart capacity coolers to be used to transport samples, and store “blue ice” blocks in freezer.
5. Pack sealed Teflon bag in kit boxes just prior to departure to site(s).

Change History

Document pertinent changes in this SOP.

5 SOP: Preseason Preparation of Backcountry Gear for Site Access

Introduction

Backcountry equipment should be organized to handle the total number of sampling sites to be visited in advance of the initial sampling dates. Purchasing and preparation of skis, snowshoes, or other over-snow-travel gear, and other special field equipment necessary, such as backcountry sleds, avalanche beacons, shovels, probe poles, and communications equipment, should be accomplished well in advance of the sampling season.

Steps

- Determine the number of samples to be collected and transported.
- Determine the number of personnel needed for the site visit(s).
- Determine whether site visits will require day trips or overnight trips in the backcountry.
  - Backcountry overnight trips will require extra gear including sleeping and cooking accommodations. At a minimum, crews should have a winter-weight sleeping bag, tent or bivouac bag, thermally protective sleeping mat, and provisions for food and drink for the required number of days (plus extra, in case of delays).
  - Determine the type of equipment needed for travel and transportation of equipment and samples to be collected (for example, will skis or snowshoes be used; and will backpacks be sufficient to haul loads, or will a backcountry sled be necessary?).
  - Pack personal clothing sufficient to maintain body temperature in colder conditions than expected to be prepared for potentially changing winter weather. A good-quality parka and bibs or wind pants are a must during snowfall events. Extra warm hats, gloves, sunglasses, socks, and thermal layers may become very useful, especially if snowfall persists and garments get ice-covered or wet.Pack two or three pairs of gloves to complete the snowpit preparation and allow for a dry pair to be on hand for the return trip.
  - Personal gear also should include a headlamp and extra batteries and bulb, extra food and drink, lighter or matches, signal mirror, whistle, and a thermal pad. A bivouac bag and extra down or fleece coat should be considered on long day trips.
  - Ensure all equipment is tested, maintained, and readied for variable conditions; include repair kits and spare parts for skis (or snowshoes), bindings, poles.
  - Ensure all crew members have complete, serviceable, avalanche safety gear including beacons, shovels, and probe poles.
  - Test beacons to verify that all units transmit and receive, and pack extra batteries.
  - Test communications and GPS gear, test networks to be used if possible, and pack extra batteries. Carry an extra cellular or satellite telephone depending on network access.
  - Ensure first aid equipment or other personal medical items (such as medications for asthma or other condition) are included.
  - Carry bear spray as a precaution, especially in Glacier National Park.

Change History

Document pertinent changes in this SOP.

6 SOP: Personnel Training, First Aid, Avalanche Safety, Winter Survival, and GPS Navigation

Introduction

Crews should be trained in advanced first aid techniques and equipped with appropriate field kits for medical emergencies. Periodic refresher training of first aid skills should be a priority in years subsequent to initial training. First aid training is available locally at beginning and advanced levels that require from 4 hours to 3 days of instruction.

Training in safe mountain travel, route selection, and avalanche safety is recommended for all personnel involved in snowpack-sampling in the ROMN. Specialized training for these skills is available regionally from several vendors. Level I and Level II avalanche awareness courses teach beginning and more advanced skills, respectively, and usually require 1 to 3 days. Additionally, the National Resources Conservation Service (NRCS) operates a week-long Snow Survey School each year (for details see: *http://www.nedc.nrcs.usda.gov/catalog/westsnowsurvey.html*). After initial or refresher training, avalanche safety equipment should be tested and rescue techniques should be practiced before traveling into hazardous terrain.

Training in winter survival skills also is critical because of the potential for travel delays or emergencies to occur in the backcountry during the snowfall season. The NRCS Snow Survey School also offers instruction in this topic as part of other important training discussed above in this SOP.

Familiarization with GPS equipment, its capabilities for navigation, and its limitations is necessary to ensure effective operation. Personnel should be competent in navigation to a given set of coordinates to increase the speed and accuracy of snowpack-sampling-site location. In an emergency, precise GPS coordinates can be vital to rescue operations. Lastly, it is highly recommended that field crews have a detailed topographic map of the area, a compass, and familiarity with their use as a backup to the GPS system.

Steps

- Ensure all personnel have initial training in first aid, avalanche safety, and winter survival.
- Practice first aid techniques and avalanche rescue techniques each season.
- Monitor needs for annual or biannual refresher training, and ensure personnel training is kept current.
- Familiarize all personnel with GPS equipment and effective navigation to a given set of coordinates.
- Ensure a compass and detailed topographic map of the area are included.

Change History

Document pertinent changes in this SOP.

7 SOP: Grizzly Bears and Other Dangerous Wildlife

Introduction

Interaction with dangerous wildlife in the ROMN typically is unlikely during the snowpack-sampling season; however, occasional encounters with bears and other large mammals during the transition between winter and spring have occurred. Although the likelihood of such encounters between humans and dangerous wildlife generally is small in winter in this region, researchers should be aware of the possibility and take precautions.

Steps

- Ensure all personnel are aware of the potential for encounters with dangerous wildlife for particular sampling areas.
- In areas where the likelihood of such encounters is considerable, ensure personnel attend appropriate training as needed.
- As a precaution in all ROMN parks, bear spray should be available.
- Consult local authorities for advice and updated information.
- Avoid interaction with wildlife, and minimize any activity that could result in stressful circumstances for wildlife.

Change History

Document pertinent changes in this SOP.

8 SOP: Field Communications

Introduction

Communications equipment (radios, cellular telephones, or satellite telephones) must be taken on snowpack-sampling trips in case problems arise. The use of communications equipment and their networks must be studied by all members of the crew before departure to remote areas. Such familiarization will enhance proficiency in the field and alert personnel to important advantages and limitations. Radio use in national parks should be in compliance with standard radio discipline and local protocols. Coordination with local authorities on radio use (including authorized frequencies, personnel call numbers, and repeater locations) should be done before sampling trips. Equipment selected should be thoroughly tested, and extra batteries should be on hand. As an added safety measure, pack an extra radio or telephone. Possession of such communication devices, and knowledge of their operational capabilities, is extremely valuable for contacting rescuers in case of emergency.

Steps

- Determine what communications equipment will be operational in the area where field work is to be performed.
- Familiarize all personnel with communications equipment (radios, cellular telephones, or satellite telephones) that will be required.
- Pack extra batteries, charging devices, and extra radios or telephones as needed.
- Test equipment at trailhead to ensure frequencies, telephone numbers, and other information are correct and operational.
- Test equipment to verify service in extended backcountry areas enroute to sampling sites.
- Use existing radio networks to check in with local dispatchers as needed.

Change History

Document pertinent changes in this SOP.

9 SOP: Field Sampling: Safety, Weather

Introduction

Although snowpack-sampling site visits usually are accomplished within one day, considerations should be made for travel to remote areas, extreme weather conditions, and potential emergencies. Field crews should be trained and equipped to avoid cold injuries such as frostbite and hypothermia. Weather conditions and forecasts for the sampling areas must be reviewed in advance of departure to sampling sites. Very cold air temperatures (minus 25°F (~minus 4°C) or colder) should discourage any travel into the backcountry and snowpack-sampling activities. To the extent possible, if sampling activities must be performed on very cold days, plan to accomplish sample collection during the warmest part of the day. Personnel always should have extra layers of clothing and extra food and water for added warmth during field sampling operations. The use of extra-large laboratory gloves to allow insulative glove liners to be worn under them will help prevent cold injuries to the hands. In colder weather, mittens are advised before and after sample collection to maintain warmth in hands. Proper winter headwear, footwear, and preservation of the body core temperature will prevent cold injuries to the feet.

If winter storms are predicted, or heavy snowfall and strong wind events have recently occurred, backcountry travel may be particularly hazardous. Many areas of the Rocky Mountains may be difficult to reach safely for several days during and after snow storms. Potential avalanche danger and snow conditions should be carefully considered when selecting safe routes in steep terrain. Careful consideration should be given to the route selection, current weather and snow conditions, and the fitness of the sampling crew. If there is any doubt about safe access, sampling trips should be postponed until conditions improve. A communication plan must be implemented that includes a reliable contact person who is notified of sampling trip itineraries, including departure and return times, and who will notify authorities if the crew is overdue. Arrangements should be made for that contact person to notify authorities if the sampling party does not communicate their safe return by a certain time.

Steps

- Acquire full sets of proper winter garments for all personnel involved in winter backcountry travel. Plan to dress in multiple layers for control of body heat. Include the following items: wool or fleece hat, wool or fleece balaclava, sunglasses or goggles, water-resistant parka (with hood) and pants (or bibs), water-resistant and insulated gloves or mittens, wool or synthetic undergarments and socks, backcountry ski boots or heavy-duty insulated boots for winter wear. Last, extra layers such as vests, jackets, or pants made of fleece or other synthetic materials provide adjustable layering of garments underneath the outer layer.
- Ensure all personnel are in good physical condition to engage in strenuous travel and sampling activities.
- Ensure adequate food and drinking water are available for all personnel.
- Check weather conditions and determine if the crew is able to safely undertake the site visit.
- Avoid cold injuries and monitor other crew members for signs of frostbite or hypothermia.

- If weather conditions are severe due to storm activity or extreme cold, postpone site visits until conditions improve.
- Safety must be the highest priority when planning travel into the backcountry during wintertime.
- Ensure a travel plan has been implemented with a reliable contact person who will notify authorities if the sampling party does not return by a certain time.

Change History

Document any changes in protocol procedures.

10 SOP: Relocating Sites

Introduction

There may be several reasons to consider moving a site either temporarily or permanently. Weather conditions including extreme snowfall events and avalanche danger are prime examples of justifiable reasons to collect a sample away from the intended site location. For example if a site was originally selected in an avalanche-free zone, but avalanches occur at the site in subsequent years, movement is mandatory. Drought or unusual warming also may necessitate the selection of alternate locations. In another example, if the snowpack has begun to melt at a traditional site, chemical solute likely has been lost to runoff, and the sample will not be representative of the seasonal snowpack before melt commenced. So, a cold sample collected at a nearby site where the snowpack had not yet begun to melt would be a clear preference. If it is decided not to sample the original site, and no satisfactory choices for selecting an alternate sample site are available, it would be preferable to collect the best available sample than no sample at all. In such a case, detailed notes need to be included on the field-data sheet. Another reason for such a move would be the appearance of a new local disturbance such as a cabin with a wood-burning stove, or a staging area for snowmobiles.

Steps

- Determine what the obstacle is necessitating the move, and how it can be avoided.
- Carefully evaluate if the new site is free of local emissions or other disturbances.
- Make at least 12 depth measurements to develop an estimate of typical depths over a 100-m course at the snowpit site (this will provide a transect of depths from which a general average or typical depth can be determined).
- Choose a uniform snowpack that is not scoured or drifted in an area of typical depth.
- Make detailed notes on the field-data sheet as to where and why the site was moved.
- Obtain GPS coordinates.

Change History

Document any changes in site locations that may affect long-term consistency of data interpretation.

11 SOP: Completion of Field Data Sheet

Introduction

Because field notes contain most of the sampling information, it is important that field (snowpack-sampling) data sheets be completed accurately. Data entered on data sheets must be directly entered in a computer database for permanent storage, so it is important that errors be minimized and writing is legible. Although plastic-laminated paper is preferred for all-weather use, attempts should be made to protect the data sheet from soaking by precipitation and subsequent damage. If data required are unknown or unusual, annotate as such. Crews should be trained in the identification of physical characteristics of snowpacks; annual refresher training is recommended. Notes, and photos if applicable, should be taken about unusual circumstances or sampling conditions as they may provide important clues for later interpretation of results. One common example of an unusual and noteworthy finding is the presence of distinct dust layers in snowpacks (typically visible as grey, red, or brown, in contrast with white snow).

Steps

- The completion steps listed in this SOP should be accomplished in conjunction with steps listed in SOP 12.
- On the snowpack-sampling data sheet fill in correct site name, sample date, and names of all observers.
- Start up GPS unit, and after good coverage has been acquired, record latitude, longitude, and elevation in the blanks indicated. If estimated precision error is known, record in left margin.
- Note snowpit location. Describe location of site so it could be located without a GPS unit.
- Note weather conditions.
- Measure and record slope, aspect, and air temperature.
- Note size and tare weight of density cutter.
- Record thermometer precision.
- Lay out dimensions of the scale needed to define depth intervals for snowpack stratigraphy and physical data. Scale and label snowpack to be sampled by 10-cm increments in “Depth interval” column on data sheet (fig. 9). Clearly mark top of snowpack near ***top*** of data sheet with exact depth in cm; note snow-soil boundary and clearly mark near ***bottom*** of data sheet. For snow depths greater than 2 m, use 20-cm intervals to scale the data sheet.
- Record soil conditions under snowpack.
- Record total snow depth at snowpit sample face once snowpit is prepared (see report cover image).
- As distinct snowpack layers are defined, sketch their boundaries in the “Sketch layers…” column.
- Record all temperatures, grain types, sizes, and hardnesses by layers defined in sketch.
- Define snowpack layers as one of the following four general grain types:
  1. Temperature gradient (TG)—angular grains with a difference in snow temperature of 1.0ºC or more per 10 cm of snow depth.
  2. Equitemperature (ET)—rounded grains with a difference of <1.0ºC per 10 cm of snow depth.
  3. Melt-freeze (MF)—melted and refrozen snow grains.
  4. New snow (new)—soft, uncompacted snow from recent snowfall events.
- Define snowpack hardness with one of the following five general categories. Apply a moderate force with one arm extending one of the five objects below, and moving perpendicularly to a point on the snowpit face. From the five choices listed, choose the largest object that penetrates the snowpack. For example, if 4 fingers will not penetrate with a moderate force, but 1 finger will penetrate, then the hardness is 1F.
  1. knife (K)
  2. pencil (P)
  3. 1 finger (1F)
  4. 4 fingers (4F)
  5. fist (fist)
- Add any pertinent comment about individual layers in adjacent comment column.
- Record all SWE values by depth interval. Techniques for the measurement of snow densities and SWE can be found at these two websites: *http:www.wcc.nrcs.usda.gov/factpub/ah169/ah169p05.htm.*, or *http:www.snowmetrics.com.*
- Note sampling time just before sampling is to commence.
- Use different times for subsequent replicates and blanks collected.
- Be thorough yet keep remarks concise and accurate; do not include extraneous comments.
- Have all observers sign data sheet.

Change History

Document any changes in protocol procedures.

2008 Snowpack-Sampling Data Sheet	**Sample type**	**Collect time**	**Sample ID**
	Std Rocky Mt. Snowpack, 3-kilo Teflon bag,		
	3-kilo Teflon bag, replicate		
	3-kilo Teflon bag, field blank,		

Site name:	**Sample Date:**	**Total snow depth (cm):**	
Lat:	Long:	Elev:	Check isotope samples collected:, ___^{34}S
Observers:		Aspect:	Slope:
Air temp (^{o}C):	Weather:		

Thermometer precision: record range of values in same snowpack layer before sampling _____°C, and after _____°C
Soil condition under snowpack? moist? muddy? Frozen? dry?
Pit location description:

Depth interval (cm)	Temp (°C)	Sketch layers by grain type (TG, ET, MF, new)	Grain size (mm)	hardness (K, P, 1F, 4F, or fist)	SWE (g)	comments
						more cells on reverse

Signatures of Observers:________________________ ____________________ ___________________

Figure 9. Snowpack-sampling data sheet.

Continue from front page if necessary:

Depth interval (cm)	Temp (°C)	Sketch layers by grain type (TG, ET, MF, new)	Grain size (mm)	hardness (K, P, 1F, 4F, or fist)	SWE (g)	comments

Figure 9—Continued. Snowpack-sampling data sheet.

12 SOP: Snowpit-Site Selection, Thermal Verification, Snowpit Preparation, Sample Collection, and Contamination Avoidance

Introduction

Snowpits should be prepared in areas where local disturbances have not affected seasonal chemical deposition. Once the sampling crew has traveled to the general area of the snowpack-sampling site, a specific point must be chosen for the snowpit. A uniform snowpack free of drifting or scouring effects and representative of all seasonal snowfall events should be selected. Excessive tree litter should be avoided, and sites should be selected in clearings in the forest (estimated at the canopy) no smaller than 10 m in diameter. The exact position of the site selected should be documented on the data sheet. If there is any doubt about the snowpack warming, verification that the snowpack has not yet become isothermal is required. Thermal verification is done briefly by digging a quick 1-m test-pit about 0.5 m in diameter to allow placement of thermometers at a few intervals along the uppermost meter of the snowpack. This quick observation should yield a difference in temperatures with depth, (henceforth referred to as “a temperature gradient”) of about minus 1ºC or more over the distance between the upper and lower thermometers. If such a gradient does not appear, and the thermometers consistently read at or near 0.0°C, then the snowpack may be melting. In that case, move to a new location nearby and repeat the test-pit. Choosing a more northerly aspect and a gentle to moderate slope may result in the snowpack being colder and not isothermal near 0ºC.

Figure 10. Workers prepare a snowpit before collecting a sample near Buffalo Pass, Colorado, 2006.

Once thermal verification indicates a suitable temperature gradient, prepare the snowpit (fig. 10) and begin recording information on the data sheet. Collect physical data first before collecting the snow sample to ensure the snowpack is acceptable and that minimal melting has occurred. A thorough examination of the snowpack will verify this. Upon completion of physical measurements, clear a clean area of untracked snow adjacent to the snowpit and prepare to collect the sample. At this point, contamination should be carefully avoided and crew members should not engage in any eating, drinking, smoking, or other activities that may contaminate the clean tools, equipment, and sample. After the sample is collected and sealed for transport, the snowpit should be backfilled, and all equipment, trash, or other items should be removed from the area.

Steps

- The steps listed in this SOP should be accomplished in conjunction with steps listed in SOP 11.
- Once a location is selected for digging the pit, scribe a line perpendicular to the direction of the sun to delineate the face of the pit wall.
- Keep foot traffic clear of this area so the snowpack to be sampled will not be disturbed.

- Prevent eating, drinking, smoking, or other activities that may contaminate the clean tools, equipment, and sample. Keep dogs or other animals away from the operation.
- Dig the pit so the wall faces away from the sun.
- Avoid walking on or shoveling snow on the snow surface for at least 2 m on the other side of the line (where the pit wall will be sampled).
- Metal shovels can be used to dig the snowpit. Dig a smooth vertical wall from the snowpack down to ground level at least 1 m wide.
- Once you are at the ground surface, clear an area of at least 1/2 m^2.
- Check the soil conditions to see if the soil is moist, frozen, muddy, etc., and annotate as stated in SOP 11.
- Once pit is prepared, bisect pit wall to be sampled with a 2-m fiberglass rule vertically with 0 cm at the soil-snow interface.
- Plan to collect sample(s) on one side of the snowpit face; make physical measurements (SOP 11) on the other side to avoid contamination of sample-face.
- The final vertical surface (at least 50 cm wide) of the snowpit face to be sampled should be cut back into the face with the clean, snow-scrubbed carbonate shovel for an additional 10–20 cm at least. This removes any paint, metals, soils, or dirty snow spread around while digging the pit.
- Before samples are collected, clean tools again by plunging polycarbonate scoop and polycarbonate sampling shovel blade into clean snow at least 12 times to remove soiled snow and scrub off any remaining snow or water from a previous sample. Do this tool cleaning at an undisturbed corner of the snowpit reserved for tool-scrubbing, and adjacent to the sampling face, while avoiding excavated snow, access steps, equipment, personal gear, skis, and any disturbed snow.
- Clear a flat area of about 1/2 m^2 in clean, undisturbed snow next to the snowpit for placement of sampling equipment.
- Ensure that the snowpack-sampling shovel, scoop, Teflon bag, two cable ties, and sample label are readily accessible on the adjacent area of clean snow.
- Avoid contamination of the very dilute snow samples with soil, forest litter, sweat, etc. Keep your head back away from sample tools and bags.
- Discard the top 5 cm of snowpack at snow-air interface to avoid inclusion of contamination from preparation of the snowpit.
- Instruct assistant to remove the Teflon sample bag from the clean storage bags and prepare to receive the sample.
- Lay the clean polyethylene bag on the clean snow surface alongside the snowpit for later receipt of the sample. Do not touch the inside of the polyethylene bag.
- Do not touch the inside of the Teflon bag with anything but the clean snowpack-sampling shovel and scoop.
- All workers collecting samples should wear latex or vinyl gloves. One person holds the Teflon bag open, being careful not to touch inside of bag and not to tear it at the seam, while another person scoops out a vertically representative column of snow using the polycarbonate snow shovel and the polycarbonate scoop provided.
- This process can be tedious in a deep or very consolidated snowpack. Starting at the top and working downward, a column of snow is cut out with the scoop and shovel. With the shovel cutting horizontally into the column to be removed, vertically scoop out sample down to the shovel with the polycarbonate scoop provided, and dump this increment into the Teflon bag. Repeat at 10- to 15-cm intervals downward until within about 5 cm of soil. In snowpit is less than 2 m deep, cut into the snowpack face with the scoop about 2 cm horizontally, then cut downward by 10- to 15-cm increments allowing snow to fall into shovel blade. For snowpacks with depths greater than 2 m, cut only about 1 cm into the snowpack face when collecting the column.
- Stop short of sampling the soil and repeat collection of integrated columns of snow (if necessary to fill the bag 2/3 to 3/4 full) with thin columns by scraping lightly up the face collecting roughly equal amounts of sample from all layers. If soil gets on the blade or scoop, plunge into snow away from sample-face 12 times to clean. Fill the bag to no more than 3/4 full to allow for closure of the bag.

- Close the bag and twist the opening to allow securing bag with at least two cable ties immediately. Pull cable ties tight and add extras if in doubt. Occasionally cable ties fail, so fasten extra ties to be sure. Be careful not to overfill sample-bag or put undue pressure on it because seams may fail.
- Place the sample-filled bag and annotated label inside a clean polyethylene bag in a position with the label visible. Fold opening of the polyethylene bag to seal and secure against contamination. Minimize contact with the inside of the polyethylene bag. Do not write on Teflon bag. Secure with at least two complete wraps of duct tape so that the label is visible for later accounting.
- Stow sample in snowpack to keep it cold until it is time for transport. Place the sample in a pack or other container for transport and protect from puncture.
- Transport to cooler and maintain below freezing as soon as possible.

Change History

Document any changes in this sampling protocol that may affect long-term consistency of sample collection.

13 SOP: Quality Assurance Field Blanks and Field Replicates

Introduction

Snowpack-sampling techniques should be monitored for quality assurance by collecting field blanks and field replicates for detection of contamination and precision, respectively. Field blanks reflect the cleanliness of sample-collection tools and the careful handling of samples by the sampling crew. Replicate samples collected from the same clean snowpit face as original, environmental samples reflect, in addition to analytical precision, the precision of snowpack-sample collection in a given snowpit by a given crew. Selection of sites where field blanks and replicates will be collected should be distributed sufficiently to include all sampling crews for verification of contamination-free- and repeatable techniques. The combined number of field blanks and field replicates should compose 10 to 20 percent of the total number of environmental samples collected.

Steps, Field Blanks

- Use ultra-pure DI water for all blanks. A periodic analysis of DI water used for blanks is important to rule out the possibility of contaminants being present before deploying DI water for field blanks. Transport 2 L of blank water to the field in clean Teflon bottles that are securely contained in two clean, plastic bags (one inside the other) and stored inside a cooler to prevent freezing.
- Before collection of snow samples begins at the snowpit, collect the field blank to allow detection of potential contamination on the snowpack-sampling shovel and polycarbonate scoop.
- Ensure no local sources of contamination are occurring nearby that might affect the quality of the field blank. For example, avoid smoking, operating vehicles, shoveling snow, or other disturbances. If a local source of wood smoke or unexpected vehicle traffic occurs, suspend field blank collection, and note accordingly.
- Clear a flat area of about 1/2 m^2 in clean, undisturbed snow next to the snowpit.
- Ensure two members of the sampling crew are wearing clean lab gloves (latex or vinyl) for the duration of the field blank handling.
- Ensure that the snowpack-sampling shovel, scoop, field-blank Teflon bag, two cable ties, sample label, and 2 L of DI water for the blank are readily accessible on the adjacent area of clean snow.
- Remove a clean Teflon snowpack-sample bag from the clean plastic bags used for transport.

- Instruct one crew member to carefully open and hold upright the Teflon snowpack-sample bag over a clean snow platform adjacent to the snowpit. The bag should be held without touching the inside, in a position to receive the blank water, and in a position to support the added mass of 2 L. If the bag is dropped during the process, the field blank should be discarded and a new field blank collected in a new, clean bag.
- Both crew members collecting the field blank should keep their bodies back from the opening of the Teflon bag to avoid contamination from perspiration, clothing, hair, etc.
  - Carefully rinse about 1 L of DI water across the shovel blade and into the field-blank Teflon bag. Rinse the second liter of DI water across the scoop and into the field-blank Teflon bag.
  - Without touching the inside, carefully twist the Teflon bag opening until it is gathered tightly enough to be closed by cable ties.
  - Secure at least two cable ties to close the Teflon bag.
  - Place the Teflon bag inside a clean polyethylene bag with the label and secure as in SOP 12.
  - Safeguard field blanks from contamination by placing inside coolers.
  - Safeguard coolers from handling by unauthorized personnel.

Steps, Field Replicates

- Collect replicate samples from the same snowpit face as the original sample according to steps in SOP 12.
- To replicate the original sampling, choose an undisturbed, smooth area of the snowpit face directly adjacent to where the original sample was collected. Collect an integrated sample representing the same snowpack layers as the original sample.
- Place replicate sample in the cooler used for original snow samples as soon as possible to avoid melting.

Change History

Document any changes in this sampling protocol that may affect long-term consistency of sample collection.

14 SOP: Sample Entry Into Database, Data Management, and Tracking Analytical Status

Introduction

Upon returning from the field, data sheets for each sample should be checked for completeness, and data entered into a relational database. Sample-collection data for each sample (including blanks and replicates, if applicable) should be entered and a unique identification number assigned (Sample ID in fig. 9). Information including site name, collection time and date, snow depth, and SWE must be entered into the database before laboratory analyses commence. A method for entering samples into an analytical tracking system should be adopted so that specified analyses may be selected and managed, and results may be maintained consistently. Accuracy of data entered into the database must be verified against field-data sheets.

Steps

- Verify that all field sheets are accounted for and have been completed.
- Enter into database the site description (name, latitude, longitude, elevation, county, state).
- Enter site name, collection time and date, snow depth, SWE, and any other pertinent information about the sample.
- Select analyses to be performed on the samples (for example, anions, cations, pH, conductivity, dissolved organic carbon, mercury, or other constituents).
- With appropriate software, track the progress of analytical work done on each sample for all analyses.

Change History

Document any changes in database or software use that may affect long-term consistency of data management.

15 SOP: Snowpack-Sample Handling and Storage

Introduction

Snow samples must be protected against contamination, melting, or puncture during transport from the sampling site to the storage freezer. Heavy (6-mil) polyethylene bags are used to provide the first layer of protection around Teflon bags during transport. Samples should then be placed inside durable containers such as backpacks or coolers for transport to vehicles. Sealed "blue ice" blocks or dry ice should be on hand in coolers to preserve samples below freezing while in route to freezer facilities. Samples and equipment should be safeguarded against exposure to vehicle emissions or any other sources of contamination. Sampling equipment also must be kept in clean, secure containers to minimize contamination during transport between sampling sites. Potential for theft or accidental handling of samples and equipment by others should be avoided (in a public parking lot, for example). Once samples are transported to a permanent storage facility, they should be maintained at a temperature well below 0°C (minus10°C or colder is recommended).

Steps

- Protect snow samples from contamination, melting, or puncture during transport from sampling site to vehicle.
- Pre-position a cooler and refrigerant in vehicle to receive snow samples as soon as possible to avoid melting samples.
- Safeguard samples from contamination by vehicles by enclosing inside coolers.
- Safeguard samples from accidental handling of samples and equipment by unauthorized personnel.

Change History

Document any changes in protocol procedures.

16 SOP: Sample Pre-Processing: Preparing Aliquots for Analyses

Introduction

Pre-processing of snowmelt samples is necessary to distribute aliquots of sample to analysts in several different laboratories. This operation is done in a clean laboratory equipped to melt and filter snow samples efficiently and without contamination. Snow samples require about 48 to 72 hours at 20°C to completely melt. Once melted, samples should be processed within 12 hours. Use refrigeration to control melt as needed so that samples can be processed as soon after they melt as possible (for example, it is best to avoid having more samples fully melted than can be processed the same day). Specialized sample processing containers, flasks, and tubing must be thoroughly rinsed in ultra-pure DI water and reserved for snowmelt processing. Triple rinsing with 100 to 500 milliliters (mL) of DI water (for each rinse) is recommended. When in doubt, rinse apparatus with more DI water. The following items are needed to pre-process snowmelt into aliquots: a peristaltic pump (with Teflon tubing pre-cleaned and reserved for dilute water chemistry); six pre-cleaned 1-L Teflon bottles; a 0.45-micron, 300-mL filter flask and vacuum pump; and pre-cleaned, 1-L glass receiving flasks. Unused polyethylene bottles are recommended and should first be DI-water rinsed, then allowed to soak full of DI water, before aliquot bottling. Oven-baked, amber, glass bottles should be used for dissolved organic carbon aliquots; acid-soaked (10% HCl) and DI-rinsed, clear, glass bottles are recommended for mercury aliquots.

Steps

- Establish a clean, dust-free, water-chemistry laboratory that can be dedicated to processing snow samples.
- Clean polyethylene aliquot bottles (125-mL size for major constituents including pH, alkalinity, cations, and anions) by DI-water rinsing and DI-water soaking.
- Obtain factory cleaned, oven-baked 125-mL amber, glass bottles for DOC; do not rinse.
- Obtain factory cleaned, 125-mL clear, glass bottles for mercury; acid-soak, DI-water rinse, and DI-water soak.
- Remove from the freezer the number of snow samples that can be processed in one day and transport to pre-processing laboratory.
- Melt snow in the same 8-L Teflon bag in which the sample was collected while being isolated from contamination in clean coolers.

- Record laboratory procedures followed, sample ID number, site name, and processing sequence number in a bound notebook.
  - Thoroughly rinse all containers used in the aliquot distribution three times in ultra-pure DI water before and after each use.
  - Flush pump tubing with at least 500 mL of ultra-pure DI water before and after each sample is filtered.
  - Place sample bag containing snowmelt water in 3-gal plastic bucket fitted to an orbital shaker and circulate sample at 200 revolutions per minute for 2 minutes.
  - Pump snowmelt out of the Teflon bag into pre-cleaned 1-L Teflon bottles for distribution to aliquot bottles.
  - Pump the whole-water sample aliquot for mercury analyses from the sample bag into a pre-cleaned 125-mL glass bottle.
  - Whole-water aliquots for analyses of alkalinity, specific conductivity, and pH are poured from 1-L Teflon distribution bottles.
  - Filter aliquots for analyses of anions, cations, dissolved organic carbon, and for a sample archive, by pouring from the 1-L Teflon distribution bottles into 0.45-micron filtration flasks.
  - Secure the remainder of the unfiltered snowmelt sample in Teflon bag and freeze as an archive (SOP 18).
  - Verify accounting of all sample aliquots intended for analyses at individual laboratories.
  - Deliver aliquots to analytical laboratories with appropriate chain of custody.

Change History

Document any changes in protocol procedures.

17 SOP: Chemical Analyses: Constituents Analyzed, Detection Limits, and Laboratories Used

Constituents Analyzed and Detection Limits

Snowpack samples are analyzed to determine concentrations of selected constituents including alkalinity, pH, anions (chloride, nitrate, and sulfate); cations (ammonium, calcium, magnesium, potassium, and sodium); and mercury. Suggested guidelines for detection limits in this report were developed as part of the Rocky Mountain Snowpack program to enable low-level detection of concentrations of major constituents in dilute snowmelt. Similar to those endorsed by a well-established national program also analyzing dilute precipitation chemistry (National Atmospheric Deposition Program, 2005), acceptable method detection limits are about 1.0 μeq/L for alkalinity, 0.2 to 2.0 μeq/L for major ions (calcium, 1.2; magnesium, 0.6; sodium, 2.0; potasssium, 0.4; ammonium, 0.5; chloride, 0.5; sulfate, 0.3; nitrate, 0.2), 0.15 mg/L for dissolved organic carbon, and 0.4 ng/L for mercury. Examples of analytical laboratory methods and quality-assurance procedures for analyses of major-ion and mercury concentrations are described in Turk and others (2001), Ingersoll and others (2002), and Mast and others (2003).

Laboratories Used

Laboratories selected for the analyses of dilute snowmelt should be experienced in detection of low-level concentrations of major constituents, including ammonium, calcium, chloride, magnesium, nitrate, potassium, sodium, and sulfate. Alkalinity, specific conductivity, and pH also should be determined in the laboratory by qualified personnel. Analyses of mercury or other metals may be desired and also will require specialized methods for low-level detection. U.S. Geological Survey laboratories in Lakewood, Colorado; Boulder, Colorado; and Middleton, Wisconsin, have developed analytical methods for all analyses of dilute snowmelt mentioned above. The analyzing laboratories should participate in round-robin analyses with other laboratories. Additional information including interlaboratory comparisons of USGS standard reference samples can be found at *http://bqs.usgs.gov/srs#contacts* (accessed November 2008).

Change History

Document any changes in protocol procedures.

18 SOP: Archiving Samples

Introduction

To the extent possible, aliquots of snowmelt should be preserved frozen as archives. This is especially important for subsequent quality assurance and re-runs of analytical methods. Recommended archive bottles should be amber in color and volumes should be at least 125 mL. As a further precaution, a second 125-mL amber bottle should be archived if sample volume permits. If sample volume remains in the Teflon sample bags, preserve the remainder in the bag as an additional archive.

Steps

- When filtered sample aliquots are being distributed (SOP 16) fill 125-mL, amber, ethylene bottle to 90 percent volume to allow for ice expansion.
- Secure remaining unfiltered snowmelt sample as mentioned in SOP 16 and freeze for archiving.
- Transport all archive samples to a freezer for permanent storage the same day that the snow sample was melted and pre-processed.
- Enter information for each sample into the database to reflect whether an archive was preserved or not.

Change History

Document any changes in protocol procedures.

19 SOP: Quality Assurance of Data

Introduction

Preliminary results of SWE and concentrations of major constituents should be checked for anomalous values or outliers against long-term, typical values before acceptance as final results. After analytical processing is complete, results should be plotted and reviewed for deviations from the range of expected values based upon previous observations. Comparisons should be made between environmental samples and replicates, and field and laboratory blanks should be checked for concentrations at or near detection limits. Samples should be considered for reanalysis if results differ greatly from historical values for that site. SWE calculations should be checked against field data sheets, and snow densities should be calculated to verify that SWE values fall within an acceptable range based on long-term observations. Snow density is the percentage of water per unit volume of snow, and is expressed as the quotient of SWE divided by snow depth.

Steps

- Check SWE and concentration data for anomalous values or outliers against long-term, typical values, if possible.
- Compare SWE and concentrations in quality-control replicates to original samples.
- Check concentration data for quality-control blanks.
- Consider additional analytical processing for suspect values for selected constituents.
- Track further analytical processing and determine whether additional analytical results support original results or suggest replacement with second set.
- Update the database to include the quality-assured data.

Change History

Document any changes in laboratories used, analytical methods, or in protocol procedures.

20 SOP: Archiving Data

Introduction

Data archives should be established on separate file servers, external hard drives, compact discs, or other media both onsite and offsite to prevent loss.

Steps

- Determine size of storage needed for the archiving database(s) and other files containing snowpack-chemistry results.
- Perform regular backups to archives with database(s) and other supportive files; a daily or weekly basis should be considered.
- Store archives both onsite and offsite to prevent loss.

Change History

Document any changes in protocol procedures.

21 SOP: Data Analysis and Reporting

Introduction

To analyze chemical patterns in snowpack chemistry from areas of interest, concentrations of major constituents should be plotted to geographically represent sampling locations. As successive years of data are collected, differences between sites and temporal trends at sites (or groups of sites) should be computed. Precipitation data commonly exhibit non-normal distributions, so non-parametric statistical methods are recommended for data analyses. Effective statistical techniques include using Wilcoxon rank-sum and signed-rank tests to compare sample sites with multiple years of data (Wilcoxon, 1945) and calculating percent differences to test precision of samples and replicates. Example applications of these techniques are discussed in section 2, Sample Design. Further analysis of regional trends can be done by applying Regional Kendall tests for combined spatial and temporal trends (Helsel and others, 2006; Ingersoll and others, 2008).

It is important to report snowpack-chemistry results to both the scientific community and the general public in the appropriate format. In addition to concentrations of major constituents, depositional amounts may be of interest depending on the context of the report. Quality-assurance data also are useful to report so that the reader can understand variation and error in results. Reporting formats may vary, ranging from brief progress reports to more interpretive journal articles (Heuer and others, 2000; Clow and others, 2002). Reports documenting annual operations and results from work performed in National Parks should be submitted as Investigators Annual Reports. Other official reports should be considered to provide results to the general public. Two examples include a U.S. Geological Survey Open-File Report format for a basic data report (Ingersoll and others, 2005), or an interpretive report such as a U.S. Geological Survey Scientific Investigations Report (Mast and others, 2005).

Steps

The following steps may be necessary to publish a typical report or journal article once analytical work and quality assurance are complete:

- Compile data in final form.
- Plot and analyze spatial patterns (and temporal patterns if applicable).
- Consult other research and compare relevant or similar research findings.
- Do statistical tests, as appropriate, and make interpretations.
- Write draft of methods, results, and conclusions with emphasis on important findings.
- Submit for colleague and editorial reviews.
- Revise and resubmit for agency approval.
- Submit Investigators Annual Reports to the National Park Service (*http://science.nature.nps.gov/research/ac/ResearchIndex*).
- Submit to journal if that option is chosen.

Supplemental Data

Table A1. Location information for snowpack-sampling sites and SNOTEL sites, vegetative cover type, and dates of snowpack-sampling events (1993–2008) at selected sites in the Rocky Mountain Network.

[Lat, latitude; Long, longitude; Elev, elevation above the North American Vertical Datum of 1988; dd, decimal degrees; m, meters; SNOTEL, snow-telemetry; dm, degrees and minutes]

Snowpack-sampling site name	Lat (dd)	Long (dd)	Elev. (m)	Vegetative cover type[1]	Years sampled	Range of dates sampled	Average date sampled[2]	Nearby SNOTEL site name	SNOTEL[3] Lat (dm)	SNOTEL Long (dm)	SNOTEL Elev (m)
Glacier National Park, Montana											
Apgar Lookout	48.51806	114.02000	1,579	forest	1996–2004, 2006–2008	Mar. 4–Apr. 4	Mar. 14	Flattop Mountain	48°48'	113°51'	1,920
Bowman 1	48.86750	114.18667	1,541	forest	2001	Mar. 8	Mar. 8	Flattop Mountain	48°48'	113°51'	1,920
Bowman 2	48.88333	114.18000	2,071	forest	2001	Mar. 8	Mar. 8	Flattop Mountain	48°48'	113°51'	1,920
E1	48.69806	113.52167	1,393	forest	1999	Mar. 24	Mar. 24	Many Glacier	48°47'	113°40'	1,494
E2	48.68028	113.58944	1,471	forest	1999, 2000	Mar. 20–Apr. 1	Mar. 26	Many Glacier	48°47'	113°40'	1,494
E3	48.67694	113.64389	1,581	forest	1999, 2000, 2002	Mar. 12–28	Mar. 20	Many Glacier	48°47'	113°40'	1,494
E4	48.68722	113.66528	1,688	forest	1999, 2000	Mar. 21–29	Mar. 25	Many Glacier	48°47'	113°40'	1,494
E5	48.71111	113.65111	2,163	forest	1999, 2000, 2002, 2003	Mar. 13–30	Mar. 22	Many Glacier	48°47'	113°40'	1,494
E6	48.69139	113.65778	1,937	forest	1999, 2000, 2002	Mar. 13–31	Mar. 21	Many Glacier	48°47'	113°40'	1,494
E7	48.68889	113.66083	1,860	forest	1999, 2000	Mar. 22–31	Mar. 26	Many Glacier	48°47'	113°40'	1,494
Granite Park	48.77111	113.77028	2,006	meadow	1999–2003	Mar. 10–Apr. 8	Mar. 23	Flattop Mountain	48°48'	113°51'	1,920
Oldman Lake	48.45833	113.37806	1,922	forest	2003, 2004	Mar. 11–17	Mar. 14	Many Glacier	48°47'	113°40'	1,494
Snyder Lake	48.62500	113.80444	1,600	meadow	2003, 2004	Mar. 8–31	Mar. 19	Flattop Mountain	48°48'	113°51'	1,920
Swiftcurrent 1	48.79472	113.68556	1,542	meadow	2001, 2002	Mar. 13–19	Mar. 16	Many Glacier	48°47'	113°40'	1,494
Swiftcurrent 2	48.79417	113.67778	1,530	meadow	2001	Mar. 13	Mar. 13	Many Glacier	48°47'	113°40'	1,494
W1	48.67778	113.81750	1,117	forest	1999	Mar. 22	Mar. 22	Flattop Mountain	48°48'	113°51'	1,920
W2	48.72667	113.76417	1,083	forest	1999, 2001	Mar. 8–28	Mar. 18	Flattop Mountain	48°48'	113°51'	1,920
W3	48.76583	113.81194	1,702	forest	1999	Apr. 1	Apr. 1	Flattop Mountain	48°48'	113°51'	1,920
W5	48.74528	113.77889	1,112	forest	2000, 2001	Mar. 9–21	Mar. 15	Flattop Mountain	48°48'	113°51'	1,920
W6	48.77583	113.76667	2,181	meadow	2000, 2001	Mar. 10–22	Mar. 16	Flattop Mountain	48°48'	113°51'	1,920
W7	48.77889	113.76361	2,192	meadow	2000, 2001	Mar. 10–22	Mar. 16	Flattop Mountain	48°48'	113°51'	1,920
W8	48.76583	113.78333	1,883	forest	2000, 2001	Mar. 10–22	Mar. 16	Flattop Mountain	48°48'	113°51'	1,920
W9	48.76583	113.79528	1,703	meadow	2000, 2001	Mar. 9–23	Mar. 16	Flattop Mountain	48°48'	113°51'	1,920
W10	48.76472	113.80583	1,467	forest	2000–2002	Mar. 9–23	Mar. 14	Flattop Mountain	48°48'	113°51'	1,920
Rocky Mountain National Park, Colorado											
Andrews Buttress	40.28889	105.67611	3,402	meadow	2002	Apr. 1	Apr. 1	Lake Irene	40°25'	105°49'	3,262
Bear Lake	40.31667	105.65000	2,896	forest	1999–2003	Apr. 3–14	Apr. 9	Bear Lake	40°18'	105°38'	2,896
Forest Canyon Pass	40.42500	105.80528	3,414	forest	2002	Mar. 29	Mar. 29	Lake Irene	40°25'	105°49'	3,262
Lake Irene	40.41508	105.81925	3,255	meadow	1993–2008	Mar. 24–Apr. 11	Apr. 1	Lake Irene	40°25'	105°49'	3,262
Lake Irene Forest	40.41278	105.81972	3,243	forest	2002–2005	Mar. 29–Apr. 5	Mar. 31	Lake Irene	40°25'	105°49'	3,262
Lake Irene Meadow	40.41194	105.82167	3,237	meadow	2002–2005	Mar. 29–Apr. 5	Mar. 31	Lake Irene	40°25'	105°49'	3,262
Loch Vale Forest	40.28944	105.66750	3,216	forest	1994, 1995, 1997–2008	Apr. 1–15	Apr. 7	Bear Lake	40°18'	105°38'	2,896
Loch Vale Meadow	40.29028	105.66667	3,215	meadow	1993, 1996, 1999–2008	Apr. 1–14	Apr. 7	Bear Lake	40°18'	105°38'	2,896
Lone Pine	40.23056	105.73611	2,975	forest	2003, 2007	Mar. 29–Apr. 2	Mar. 31	Lake Irene	40°25'	105°49'	3,262
Mills Lake	40.28972	105.64306	3,056	forest	2003–2005	Mar. 24–Apr. 8	Apr. 2	Bear Lake	40°18'	105°38'	2,896
N. Inlet Grand Lake	40.28639	105.75222	2,896	forest	2001	Apr. 4	Apr. 4	Phantom Valley	40°24'	105°51'	2,752
Phantom Valley	40.39804	105.84576	2,752	forest	1993–2007	Mar. 6–Apr. 10	Mar. 21	Phantom Valley	40°24'	105°51'	2,752
Upper Andrews Creek	40.28944	105.67000	3,246	meadow	2001	Apr. 10	Apr. 10	Bear Lake	40°18'	105°38'	2,896
Wescott Falls	40.23000	105.75778	2,804	forest	2000	Mar. 28	Mar. 28	Phantom Valley	40°24'	105°51'	2,752
Wild Basin	40.19861	105.61111	2,987	forest	2007	Apr. 2	Apr. 2	Bear Lake	40°18'	105°38'	2,896
Great Sand Dunes National Park and Preserve, Colorado											
Medano Pass	37.86389	105.47361	3,339	forest	2006, 2007	Mar. 21–22	Mar. 21	Medano Pass	37°51'	105°26'	2,941
Mosca Pass	37.71333	105.47028	3,380	meadow	2006	Mar. 23	Mar. 23	Medano Pass	37°51'	105°26'	2,941
Music Pass	37.92833	105.50500	3,484	forest	2006–2008	Mar. 20–21	Mar. 20	South Colony	37°58'	105°32'	3,292

[1] Snowpack-sampling sites generally were divided into two basic vegetative-cover types: either predominantly wooded (forest) or open (meadow).

[2] Average date sampled is mean of all dates sampled.

[3] For more precise latitude and longitude coordinates, contact the local Snow Survey Office of the National Resources Conservation Service at *http://www.wcc.nrcs.usda.gov/partnerships/links_wsfs.html*.

Table A2. Comparison of dissolved concentrations of selected major constituents in environmental snowpack samples and replicate samples at one site in Glacier National Park, Montana, 1999–2001.

[µeq/L, microequivalents per liter; Difference, replicate – sample; %Difference, ((replicate – sample)/sample) × 100]

Collect date	Constituent	Sample (µeq/L)	Replicate (µeq/L)	Difference (µeq/L)	%Difference
		Granite Park			
3/31/1999	ammonium as NH_4^+	4.1	3.5	–0.6	–14.6
	calcium as Ca^{2+}	2.0	1.5	–0.5	–25.0
	hydrogen as H^+	6.3	7.6	1.3	20.6
	nitrate as NO_3^-	4.9	4.7	–0.2	–4.1
	sulfate as SO_4^{2-}	3.9	4.3	0.4	10.3
3/22/2000	ammonium as NH_4^+	4.1	3.9	–0.2	–4.9
	calcium as Ca^{2+}	1.0	0.5	–0.5	–50.0
	hydrogen as H^+	9.3	10.5	1.2	12.9
	nitrate as NO_3^-	4.9	5.3	0.4	8.2
	sulfate as SO_4^{2-}	4.6	4.6	0.0	0.0
3/10/2001	ammonium as NH_4^+	4.0	3.5	–0.5	–12.5
	calcium as Ca^{2+}	1.7	3.0	1.3	76.5
	hydrogen as H^+	8.7	8.1	–0.6	–6.9
	nitrate as NO_3^-	7.7	7.3	–0.4	–5.2
	sulfate as SO_4^{2-}	10.5	5.2	–5.3	–50.5

Table A3. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples and pairs of replicate samples at three sites in northwestern Colorado, 2002–2006.

[Difference, replicate – sample; %Difference, ((replicate – sample)/sample) × 100; SWE, snow-water equivalent; m, meters; µeq/L, microequivalents per liter]

Year	Constituent[1]	Sample	Replicate 1	Difference	%Difference	Replicate 2	Difference	%Difference
				Buffalo Pass				
2002	SWE (m)	0.790	0.785	–0.005	–0.6	0.787	–0.003	–0.4
				Ned Wilson Lake				
2005	ammonium as NH_4^+	3.7	3.3	–0.4	–10.8	3.1	–0.6	–16.2
	calcium as Ca^{2+}	7.0	8.5	1.5	21.4	6.5	–0.5	–7.1
	hydrogen as H^+	3.4	2.3	–1.1	–32.4	2.3	–1.1	–32.4
	nitrate as NO_3^-	7.0	7.8	0.8	11.4	6.3	–0.7	–10.0
	sulfate as SO_4^{2-}	4.5	4.9	0.4	8.9	4.6	0.1	2.2
				Ripple Creek NADP				
2006	ammonium as NH_4^+	4.2	4.5	0.3	7.1	4.1	–0.1	–2.4
	calcium as Ca^{2+}	12.5	15.0	2.5	20.0	13.0	0.5	4.0
	hydrogen as H^+	1.2	0.6	–0.6	–50.0	1.3	0.1	8.3
	nitrate as NO_3^-	10.1	10.2	0.1	1.0	10.9	0.8	7.9
	sulfate as SO_4^{2-}	4.7	4.8	0.1	2.1	4.5	–0.2	–4.3

[1]Concentrations of major constituents are given as microequivalents per liter.

Table A3. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples and pairs of replicate samples at three sites in northwestern Colorado, 2002–2006.

[Difference, replicate – sample; %Difference, ((replicate – sample)/sample) × 100; SWE, snow-water equivalent; m, meters; µeq/L, microequivalents per liter]

Year	Constituent[1]	Sample	Replicate 1	Difference	%Difference	Replicate 2	Difference	%Difference
				Buffalo Pass				
2002	SWE (m)	0.790	0.785	–0.005	–0.6	0.787	–0.003	–0.4
				Ned Wilson Lake				
2005	ammonium as NH_4^+	3.7	3.3	–0.4	–10.8	3.1	–0.6	–16.2
	calcium as Ca^{2+}	7.0	8.5	1.5	21.4	6.5	–0.5	–7.1
	hydrogen as H^+	3.4	2.3	–1.1	–32.4	2.3	–1.1	–32.4
	nitrate as NO_3^-	7.0	7.8	0.8	11.4	6.3	–0.7	–10.0
	sulfate as SO_4^{2-}	4.5	4.9	0.4	8.9	4.6	0.1	2.2
				Ripple Creek NADP				
2006	ammonium as NH_4^+	4.2	4.5	0.3	7.1	4.1	–0.1	–2.4
	calcium as Ca^{2+}	12.5	15.0	2.5	20.0	13.0	0.5	4.0
	hydrogen as H^+	1.2	0.6	–0.6	–50.0	1.3	0.1	8.3
	nitrate as NO_3^-	10.1	10.2	0.1	1.0	10.9	0.8	7.9
	sulfate as SO_4^{2-}	4.7	4.8	0.1	2.1	4.5	–0.2	–4.3

[1]Concentrations of major constituents are given as microequivalents per liter.

Table A4. Comparison of dissolved concentrations of selected major constituents in environmental snowpack samples and replicate samples at three sites in Great Sand Dunes National Park and Preserve, Colorado, 2006.

[meq/L, microequivalents per liter; Difference, replicate – sample; %difference, ((replicate – sample)/sample) × 100]

Collect date	Constituent	Sample (µeq/L)	Replicate (µeq/L)	Difference (µeq/L)	%Difference
			Medano Pass		
3/22/2006	ammonium as NH_4^+	12.0	12.2	0.2	1.7
	calcium as Ca^{2+}	49.4	46.9	–2.5	–5.1
	hydrogen as H^+	0.9	0.5	–0.4	–44.4
	nitrate as NO_3^-	16.6	17.3	0.7	4.2
	sulfate as SO_4^{2-}	15.9	17.1	1.2	7.5
			Mosca Pass		
3/23/2006	ammonium as NH_4^+	9.8	10.1	0.3	3.1
	calcium as Ca^{2+}	36.9	48.4	11.5	31.2
	hydrogen as H^+	0.6	0.3	–0.3	–50.0
	nitrate as NO_3^-	18.0	17.9	–0.1	–0.6
	sulfate as SO_4^{2-}	13.8	14.7	0.9	6.5
			Music Pass		
3/21/2006	ammonium as NH_4^+	9.9	9.8	–0.1	–1.0
	calcium as Ca^{2+}	40.4	34.9	–5.5	–13.6
	hydrogen as H^+	0.5	0.4	–0.1	–20.0
	nitrate as NO_3^-	13.4	13.9	0.5	3.7
	sulfate as SO_4^{2-}	13.4	13.0	–0.4	–3.0

Table A5. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples and replicate samples for two adjacent sites at Rabbit Ears Pass, Colorado, 1993–2006.

[SWE, snow-water equivalent; m, meter; µeq/L, microequivalents per liter; Difference, replicate – sample; %difference, ((replicate – sample)/sample) × 100]

Year	Site	SWE (m)	Ammonium as NH_4^+ (µeq/L)	Calcium as Ca^{2+} (µeq/L)	Hydrogen as H^+ (µeq/L)	Nitrate as NO_3^- (µeq/L)	Sulfate as SO_4^{2-} (µeq/L)
			Rabbit Ears Pass				
1993	1	1.005	4.6	1.9	16.2	10.5	11.3
1993	2	0.944	5.0	2.5	12.0	10.3	10.2
Difference		–0.061	0.4	0.6	–4.2	–0.2	–1.1
%Difference		–6.1	8.7	31.6	–25.9	–1.9	–9.7
1994	1	0.766	6.2	9.7	12.8	14.2	12.3
1994	2	0.733	6.2	9.3	11.7	14.0	11.6
Difference		–0.033	0.0	–0.4	–1.1	–0.2	–0.7
%Difference		–4.3	0.0	–4.1	–8.6	–1.4	–5.7
1995	1	0.655	5.9	5.0	13.9	10.0	12.2
1995	2	0.667	6.4	5.4	13.5	11.8	12.5
Difference		0.012	0.5	0.4	–0.4	1.8	0.3
%Difference		1.8	8.5	8.0	–2.9	18.0	2.5
1996	1	0.956	3.0	5.0	9.8	8.0	7.9
1996	2	0.950	3.1	5.0	7.9	8.8	8.3
Difference		–0.006	0.1	0.0	–1.9	0.8	0.4
%Difference		–0.6	3.3	0.0	–19.4	10.0	5.1
1997	1	0.852	3.1	4.8	11.2	9.3	8.9
1997	2	0.833	2.9	1.4	13.5	7.1	9.6
Difference		–0.019	–0.2	–3.4	2.3	–2.2	0.7
%Difference		–2.2	–6.5	–70.8	20.5	–23.7	7.9
1998	1	0.740	5.1	3.5	19.5	11.9	9.6
1998	2	0.793	4.5	2.0	20.4	11.7	10.0
Difference		0.053	–0.6	–1.5	0.9	–0.2	0.4
%Difference		7.1	–11.8	–42.9	4.6	–1.7	4.2
1999	1	0.619	7.1	7.0	10.5	11.0	9.7
1999	2	0.650	6.2	8.0	9.5	12.4	10.1
Difference		0.031	–0.9	1.0	–1.0	1.4	0.4
%Difference		5.0	–12.7	14.3	–9.5	12.7	4.1
2000	1	0.845	5.4	6.0	10.2	10.4	8.5
2000	2	0.926	5.6	6.0	13.2	11.4	9.4
Difference		0.081	0.2	0.0	3.0	1.0	0.9
%Difference		9.6	3.7	0.0	29.4	9.6	10.6
2001	1	0.737	6.2	7.0	6.9	13.7	10.2
2001	2	0.717	5.3	6.5	9.5	13.9	9.5
Difference		–0.020	–0.9	–0.5	2.6	0.2	–0.7
%Difference		–2.7	–14.5	–7.1	37.7	1.5	–6.9
2002	1	0.570	4.9	8.0	9.8	14.8	8.5
2002	2	0.630	5.3	7.0	9.5	13.8	7.8
Difference		0.060	0.4	–1.0	–0.3	–1.0	–0.7
%Difference		10.5	8.2	–12.5	–3.1	–6.8	–8.2
2003	1	0.673	8.2	8.0	7.9	12.3	8.6
2003	2	0.650	6.4	7.5	10.7	12.0	8.1
Difference		–0.023	–1.8	–0.5	2.8	–0.3	–0.5
%Difference		–3.4	–22.0	–6.3	35.4	–2.4	–5.8
2004	1	0.765	4.9	4.2	12.6	13.0	7.9
[1]2004	2	-	-	-	-	-	-
Difference		-	-	-	-	-	-
%Difference		-	-	-	-	-	-
2005	1	0.684	4.7	4.5	6.6	8.7	7.2
2005	2	0.657	4.2	4.0	7.6	8.9	7.2
Difference		–0.027	–0.5	–0.5	1.0	0.2	0.0
%Difference		–3.9	–10.6	–11.1	15.2	2.3	0.0
2006	1	1.065	5.1	7.5	5.0	11.0	7.2
2006	2	1.061	5.3	9.0	4.6	12.1	7.8
Difference		–0.004	0.2	1.5	–0.4	1.1	0.6
%Difference		–0.4	3.9	20.0	–8.0	10.0	8.3

[1]No sample collected at this site in 2004.

Table A6. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples from four sites located in either forests or meadows in two areas of Rocky Mountain National Park, Colorado, 2000–2006.

[SWE, snow-water equivalent; m, meter; µeq/L, microequivalents per liter; difference, forest sample – meadow sample; median difference, median of all differences in this table for each constituent]

Site name	Year	Collect date	SWE (m)	Ammonium as NH_4^+ (µeq/L)	Calcium as Ca^{2+} (µeq/L)	Hydrogen as H^+ (µeq/L)	Nitrate as NO_3^- (µeq/L)	Sulfate as SO_4^{2-} (µeq/L)
Loch Vale								
Forest	2000	4/11/2000	0.920	6.7	8.0	9.3	10.9	8.1
Meadow	2000	4/11/2000	0.708	4.6	5.0	10.2	6.4	6.9
difference	2000	4/11/2000	0.212	2.1	3.0	–0.9	4.5	1.2
Forest	2001	4/10/2001	0.710	6.0	11.0	6.8	14.6	10.0
Meadow	2001	4/10/2001	0.512	7.3	8.5	6.6	13.4	9.3
difference	2001	4/10/2001	0.198	–1.3	2.5	0.2	1.2	0.7
Forest	2002	4/1/2002	0.507	5.7	13.5	6.2	19.3	7.8
Meadow	2002	4/1/2002	0.374	3.1	2.5	6.0	8.2	1.6
difference	2002	4/1/2002	0.133	2.6	11.0	0.2	11.1	6.2
Forest	2003	4/8/2003	1.122	6.9	12.5	6.2	10.4	8.5
Meadow	2003	4/9/2003	0.816	6.1	14.5	1.5	9.5	5.9
difference	2003	4/9/2003	0.306	0.8	–2.0	4.7	0.9	2.6
Forest	2005	4/7/2005	0.806	6.3	5.5	5.6	10.9	6.8
Meadow	2005	4/7/2005	0.555	4.3	3.5	5.5	8.3	4.7
difference	2005	4/7/2005	0.251	2.0	2.0	0.1	2.6	2.1
Forest	2006	4/3/2006	0.895	4.8	14.5	1.0	10.8	6.8
Meadow	2006	4/3/2006	0.643	3.8	20.5	0.5	10.0	5.9
difference	2006	4/3/2006	0.252	1.0	–6.0	0.5	0.8	0.9
Lake Irene								
Forest	2002	3/29/2002	0.354	4.7	15.0	3.8	14.3	7.0
Meadow	2002	3/29/2002	0.432	3.5	10.5	7.2	14.7	5.8
difference	2002	3/29/2002	–0.078	1.2	4.5	–3.4	–0.4	1.2
Forest	2003	4/1/2003	0.654	4.6	9.0	5.9	10.2	6.9
Meadow	2003	4/1/2003	0.757	4.9	4.0	8.5	9.8	5.5
difference	2003	4/1/2003	–0.103	–0.3	5.0	–2.6	0.4	1.4
Forest[1]	2003	4/1/2003	0.654	4.3	7.5	8.9	9.6	6.1
Meadow	2003	4/1/2003	0.757	4.0	4.0	8.1	8.7	4.7
difference	2003	4/1/2003	–0.103	0.3	3.5	0.8	0.9	1.4
Forest	2004	3/30/2004	0.443	4.8	9.1	7.0	12.6	7.2
Meadow	2004	3/30/2004	0.351	3.5	2.6	5.9	8.2	2.6
difference	2004	3/30/2004	0.092	1.3	6.5	1.1	4.4	4.6
Forest	2005	4/5/2005	0.557	5.7	6.5	4.8	9.4	5.7
Meadow	2005	4/5/2005	0.432	4.6	3.0	5.6	8.6	4.3
difference	2005	4/5/2005	0.125	1.1	3.5	–0.8	0.8	1.4
p-value[2] (unitless)			**0.02**	**0.02**	**0.03**	0.45	**0.003**	**0.002**
Median difference (meq/L)			0.1	1.1	3.5	0.1	1.0	1.4

[1]A replicate sample is included for both Lake Irene Forest and Lake Irene Meadow for 2003.

[2]p-values for alternate hypotheses of Forest > Meadow (H_a: x>y) are results of 1-tailed Wilcoxon signed-rank tests. Bold values indicate a significant difference (p≤0.05).

Table A7. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples from two sites located in high- or low-elevation areas in Rocky Mountain National Park, Colorado, 1993–2006.

[SWE, snow-water equivalent; m, meter; eq/L, microequivalents per liter; H_a, alternative hypothesis]

Year	SWE (m)	Ammonium as NH_4^+ (µeq/L)	Calcium as Ca^{2+} (µeq/L)	Hydrogen as H^+ (µeq/L)	Nitrate as NO_3^- (µeq/L)	Sulfate as SO_4^{2-} (µeq/L)
			Lake Irene 3,255 meters elevation			
1993	0.566	2.5	1.9	10.2	5.3	6.5
1994	0.563	2.5	6.5	9.5	10.4	6.9
1995	0.433	3.7	3.1	10.7	9.6	7.1
1996	0.491	2.0	3.1	7.1	5.4	5.8
1997	0.430	2.9	3.2	3.7	8.6	5.0
1998	0.422	2.3	2.0	16.2	10.7	6.5
1999	0.528	4.9	13.0	3.3	9.5	6.4
2000	0.543	4.1	4.5	9.8	8.6	5.5
2001	0.528	5.5	6.5	8.3	13.0	8.4
2002	0.378	5.2	17.0	2.7	14.6	7.3
2003	0.654	4.5	8.2	7.4	9.9	6.5
2004	0.443	4.8	9.1	7.0	12.6	7.2
2005	0.557	5.7	6.5	4.8	9.4	5.7
2006	0.646	4.7	9.5	2.5	10.8	6.1
			Phantom Valley 2,752 meters elevation			
1993	0.243	4.3	2.0	12.3	9.0	9.4
1994	0.232	5.7	7.9	13.8	13.1	9.6
1995	0.065	4.6	3.8	12.9	11.4	8.3
1996	0.258	2.6	5.0	7.1	7.4	6.7
1997	0.203	3.0	4.1	7.6	9.3	5.2
1998	0.171	2.6	2.0	20.9	11.9	6.9
1999	0.181	6.3	19.5	3.9	12.0	12.6
2000	0.249	4.2	5.5	10.0	9.7	6.3
2001	0.200	6.4	8.7	13.0	18.9	11.3
2002	0.162	5.2	7.5	12.6	19.0	7.4
2003	0.291	6.6	8.5	7.9	12.8	7.5
2004	0.173	5.5	7.7	11.0	16.3	8.7
2005	0.256	4.5	4.5	5.9	8.0	4.5
2006	0.202	4.2	7.5	5.8	12.5	7.3
H_a	x>y	x<y	x<y	x<y	x<y	x<y
p-value[1] (unitless)	**<0.0001**	0.07	0.45	**0.03**	0.07	**0.01**

[1]p -values for alternate hypothesis of Lake Irene > Phantom Valley (H_a: x>y), or alternate hypotheses of Lake Irene < Phantom Valley (H_a: x<y) are results of 1-tailed Wilcoxon rank-sum tests. Bold values indicate a significant difference (p≤0.05).

Table A8. Comparison of snow-water equivalent and dissolved concentrations of selected major constituents in environmental snowpack samples from two sites located in high- or low-elevation areas in northwestern, Colorado, 1993–2006.

[SWE, snow-water equivalent; m, meter; eq/L, microequivalents per liter;]

Year	SWE (m)	Ammonium as NH_4^+ (μeq/L)	Calcium as Ca^{2+} (μeq/L)	Hydrogen as H^+ (μeq/L)	Nitrate as NO_3^- (μeq/L)	Sulfate as SO_4^{2-} (μeq/L)
			Buffalo Pass 3,139 meters elevation			
1993	1.219	3.9	1.9	15.8	8.4	11.5
1994	0.905	10.9	9.8	17.6	17.3	19.8
1995	0.950	7.6	8.5	12.9	12.3	15.2
1996	1.044	3.6	5.8	10.0	10.3	9.0
1997	1.503	2.6	4.7	1.4	10.8	9.7
1998	1.190	4.7	3.5	19.1	11.0	11.0
1999	1.183	5.5	13.0	6.2	12.8	12.1
2000	1.180	4.8	6.8	10.9	11.1	7.4
2001	1.075	6.5	7.0	10.5	13.1	11.1
2002	0.807	5.8	11.5	6.8	15.2	9.3
2003	1.272	7.5	19.5	1.5	13.1	11.0
2004	1.025	6.6	6.2	17.6	12.3	9.6
2005	1.098	4.8	4.5	7.4	7.9	7.1
2006	1.220	5.0	5.0	8.1	11.5	7.7
			Dry Lake 2,560 meters elevation			
1993	0.508	5.0	5.6	15.5	13.8	12.3
1994	0.349	6.0	7.4	18.4	18.0	14.3
1995	0.410	7.0	6.1	20.7	18.8	13.1
1996	0.571	3.0	7.0	10.0	12.2	7.9
1997	0.672	3.1	6.1	14.8	12.9	9.4
1998	0.464	6.6	4.0	22.4	15.8	12.9
1999	0.427	6.3	13.0	10.2	16.7	13.2
2000	0.538	5.7	5.3	13.8	12.6	10.3
2001	0.460	6.6	7.5	16.6	20.7	10.3
2002	0.430	6.4	9.0	14.1	21.5	8.8
2003	0.507	6.8	11.0	8.7	16.9	10.0
2004	0.467	3.4	6.7	10.7	17.0	6.9
2005	0.448	5.0	8.0	6.2	11.4	8.1
2006	0.583	4.2	7.5	7.4	16.2	6.6
H_a	x>y	x<y	x<y	x<y	x<y	x<y
p-value[1]	**<0.0001**	0.51	0.31	0.10	**0.0007**	0.56

[1]p-values for alternate hypothesis of Buffalo Pass > Dry Lake (H_a: x>y), or alternate hypotheses of Buffalo Pass < Dry Lake (H_a: x<y) are results of 1-tailed Wilcoxon rank-sum tests. Bold values indicate a significant difference ($p \leq 0.05$).

Table A9. Location information and estimated travel times from automobile parking areas to selected snowpack-sampling sites in Rocky Mountain Network parks.

[dd, decimal degrees; m, meter; FIPS, Federal Information Processing Standard]

Site name	Latitude (dd)	Longitude (dd)	Elevation (m)	FIPS State Code	FIPS County Code	Approximate one-way ski or snowshoe travel time (hours)
			Glacier National Park, Montana			
Apgar Lookout	48.51806	114.02000	1579	30	29	2
			Rocky Mountain National Park, Colorado			
Lake Irene	40.41508	105.81925	3255	8	49	4
Loch Vale Forest Snow	40.28944	105.66750	3216	8	69	2
Loch Vale Meadow Snow	40.29028	105.66667	3215	8	69	2
Phantom Valley	40.39804	105.84576	2752	8	49	0.2
			Great Sand Dunes National Park and Preserve, Colorado			
Medano Pass	37.86389	105.47361	3339	8	109	4
Music Pass	37.92833	105.50500	3484	8	27	5

Ingersoll and others—**Snowpack Chemistry Monitoring Protocol for the Rocky Mountain Network**—Administrative Report