ROCKY MOUNTAIN SNOWPACK CHEMISTRY RELATIVE TO EL NIÑO EFFECTS OF WATER YEARS 1993–97

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ABSTRACT

Snowmelt-dominated runoff is correlated with El Niño-related Southern Oscillation Index events in the Rocky Mountain region. Generally, during El Niño winters, the Rocky Mountains are drier in the north and wetter in the south.

Annual snow sampling by the U.S. Geological Survey during water years 1993–97 at 52 sites throughout the Rocky Mountain region near a variety of regional anthropogenic emissions sources revealed strong inverse relations between snow depth and chemical concentrations in the snowpack. The Southern Oscillation Index (SOI) indicates that 1995 was the strongest El Niño year affecting the Rocky Mountains during water years 1993–97. However, neither greater snowfall amounts nor correspondingly lower snowpack concentrations of ammonium, nitrate, or sulfate occurred that year. During water year 1997, the year with the least negative SOI and the weakest El Niño effect, the greatest variance in snow depths among the study sites was observed ($p<0.005$) relative to the other 4 years. Snow depths as a group in water year 1997 were significantly greater ($p<0.06$) than any other year (1993–96) with numerous record depths. Variance in snowpack chemistry among sampling years relative to water year 1995 correlates poorly to expected effects of El Niño. Differences in snow depths or snowpack chemistry have not occurred contemporaneously with El Niño events, indicating that recent El Niño years may have little effect on snowpack chemistry in the Rocky Mountains.

INTRODUCTION

Annual snowpacks are the major source of water in the Rocky Mountain region, and thus, predictions of annual snowmelt runoff volumes are important. Although the relations between snowcover and subsequent runoff are well documented in the Western U.S.A. (USDA, National Resources Conservation Service, 1997a), uncertainty remains about how large-scale climatic events such as the El Niño/ Southern Oscillation (ENSO) may affect the continental snowpacks of the Rocky Mountain region. As ENSO events are occurring with greater frequency during the last 20 years (Redmond, 1998), when compared to records as far back as 1860, concerns for the causes and effects of this phenomenon are high. This El Niño water year (WY98) is one of the strongest on record (National Weather Service, Denver, 1998) and affords an opportunity to see the effect a substantial ENSO event has on annual snowfall accumulation in the Rocky Mountain region. Although above-average snowfall (100 to 150% of all other water years) in the region has been observed in some areas of the Rocky Mountains in El Niño years during 1951–97 (Midwestern Climate Center, 1998), expansive mountainous areas of Colorado, Idaho, Montana, and Wyoming concurrently received below-average snowpacks.

Because this global-scale weather phenomenon heavily influences precipitation amounts in the region, atmospheric deposition of pollutants associated with acidic precipitation (e.g., ammonium, nitrate, and sulfate) also may be affected. Chemical concentrations of annual snowpacks are directly related to the volume of precipitation (Schlesinger, 1997), and ENSO events may alter trends in atmospheric deposition. Although numerous papers in the literature discuss physical and meteorological effects from strong El Niño years, little is known about what effects ENSO events may have on seasonal precipitation chemistry. Other work examining relations between climate change and ecological effects (Hauer, et. al., 1997) has cited the possible influence of ENSO events causing substantial variations in regional meteorology from year to year. In the Rocky Mountains, where the majority of annual precipitation is from snowfall, seasonal snowpacks act as a collector of meteoric deposition and offer a composite sample indicative of the ambient air quality during a large part of each year. With increasing human population in the region, identification of processes either increasing or decreasing pollutant deposition is of increased importance to the monitoring and regulation of air-pollution sources. In this paper, a method is presented to demonstrate relations between atmospheric deposition to snowpacks and large-scale climatic events that substantially alter annual precipitation.

STUDY AREA

The study area includes 52 snow-sampling sites where snowpacks persist throughout the snowfall season at selected high-elevation locations in the Rocky Mountain ranges of Montana, Wyoming, Colorado, and New Mexico (fig. 1). The network of alpine and subalpine sites in the four-State area represents snowpacks located in protected National Forest or National Park lands near the Continental Divide. Sampling sites were selected in this setting of limited local anthropogenic activity to be suitable for long-term monitoring of regional snowpack-chemistry trends that are less likely influenced by local human activity and more indicative of regional influence. Sites were established at distances from plowed roadways ranging from about 50 m to several kilometers to minimize contamination from vehicular traffic.

Seasonal snowfall events from about early October to late March represent about 65 to 70% (USDA, National Resources Conservation Service, 1997b) of yearly precipitation in alpine and subalpine catchments in the region. Snowcover remains into May and June at many sites in the study area where the fraction of annual precipitation as snow is 75 to 80%. Water contents contained in the annual snowpacks in the study area may range from about 0.2 m in the drier Southern Rocky Mountains to about 1.7 m in the Central and Northern Rocky Mountains. Elevations of sampling sites range from 1,850 m at Noisy Basin in Montana to 3,630 m near Loveland Basin in Colorado. At these elevations, the seasonal snowpack is maintained throughout the winter, and substantial melt usually does not occur until spring runoff in March, April, or May. As latitude increases along the Continental Divide, the elevation at which seasonal snowpacks persist generally decreases. Most Colorado and New Mexico sites are at elevations ranging from 2,700 to 3,400 m; Wyoming and Montana sites are typically lower at about 2,000 to 2,700 m.

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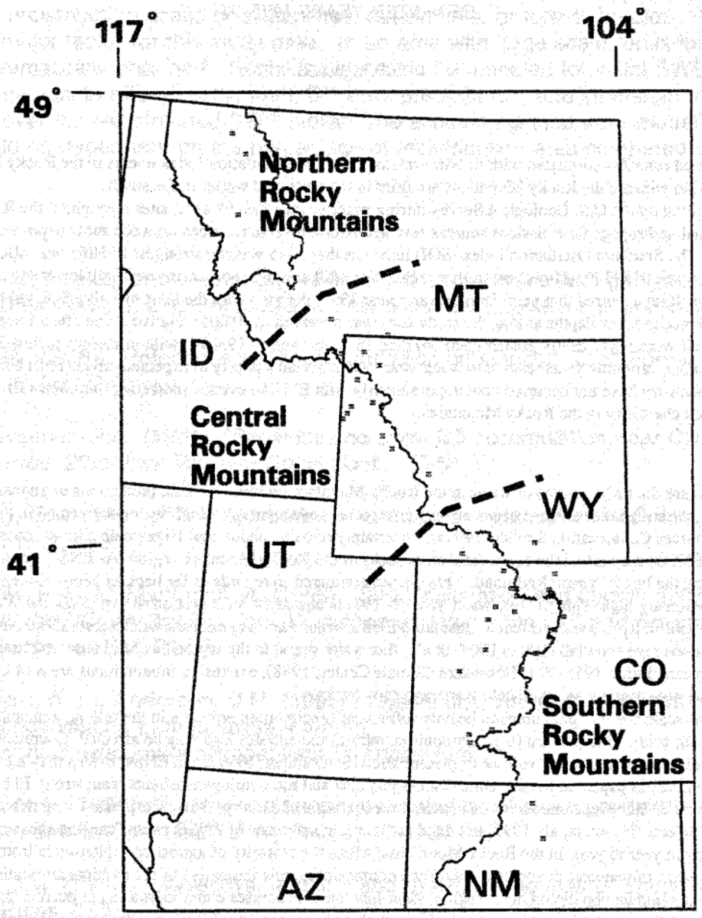

Figure 1. Snowpack chemistry sampling sites (shaded boxes) during 1993–97 near the Continental Divide (gray broken line) in the Rocky Mountain region of the U.S.A. Dashed lines delineate subregions within the study area.

METHODS

During water years 1993–97, the U.S. Geological Survey (USGS) collected snowpack samples from a network designed to provide long-term information about atmospheric deposition and physical snowpack characteristics in seasonal snowpacks at 52 sites in the Rocky Mountain regional area (including Montana, Wyoming, Colorado, and New Mexico). Each year, the full snowpack depth was sampled for chemical concentrations of ammonium, nitrate, and sulfate (NH_4^+, NO_3^-, and SO_4^{2-}) at about the time of maximum annual accumulation. Because significant midseason melt rarely occurs at these selected sites, snowcover measurements and chemical sampling performed near maximum seasonal accumulations are representative of most of the snowfall season.

Snowmelt chemistry for all sites for individual years was regressed against snow depth to establish a general relation for the region as a whole. To view the same relation between chemical levels and volume of precipitation at single sampling points, concentrations of the three compounds for all 5 years of the study were plotted against snow depths measured at sampling times. Individual concentrations of ammonium, nitrate, and sulfate from snowmelt samples at each of a subset of 15 sites geographically representing the region also were evaluated for effects of increased precipitation on concentration. To further examine this relation and observe the precision of 2 separate chemical measurements, concentrations of the same 3 compounds from wetfall precipitation collectors operated by the National Atmospheric Deposition Program (NADP, 1997) were retrieved for 10 NADP sites representative of the extent of the USGS snowpack sampling network. When possible, the USGS snow-sampling sites were collocated with NADP sites for this comparison.

Chemical concentrations of the variety of snowpacks throughout the region also were analyzed to examine if statistically significant differences were present between the snowmelt chemistry at northern versus southern sites. This division of the Rocky Mountain region into two basic subregions for analysis roughly coincides with the geographic distribution of drier and wetter precipitation zones noted in the Western U.S.A. during ENSO events. Redmond and Koch (1991) present a very detailed work concerning the occurrence of such a division of the Western U.S.A. into distinct precipitation regimes ranging from wetter-than-average to drier-than-average coincident with El Niño or La Niña years. Hypothesis tests with the F-statistic and Wilcoxon Rank-sum tests were used to examine differences between concentrations of ammonium, nitrate, and sulfate among the two subregions by individual years to illuminate any notable effects during ENSO years.

The Southern Oscillation Index (SOI) has been established as a measure of the potential strength of an ENSO event. Sea surface temperatures in the equatorial Pacific during the summer and fall months preceding an El Niño winter set the stage for the development of numerous storm systems that are pushed toward the Americas by jetstream winds. A standardized value of the difference between ocean temperatures at Darwin, Australia, in the Western Pacific, and Tahiti to the east has been computed (National Oceanic and Atmospheric Administration, 1998a). These SOI data were used to determine and compare intensities of El Niño and La Niña events during the study period to identify variability in chemical concentrations occurring during individual years that might be driven by large-scale atmospheric circulation anomalies.

Detailed descriptions of El Niño, La Niña, and SOI events can be found at the following web sites: http://www.wrcc.sage.edu, and http://nic.fb4.noaa.gov/data/cddb/cddb/soi. Another source of other related ENSO information, data, and links to other sources can be found at the web site http://www.wrcc.sage.dri.edu/enso/enso.html.

RESULTS AND DISCUSSION

Chemistry of the snowmelt throughout the region during the 5-year study was inversely proportional to the snow depths. Generally, snowmelt samples showed a decreasing chemical concentration with increasing snow depth. At both USGS snow-sampling sites and NADP wetfall collection sites, an inverse relation between chemical levels and volume of precipitation was observed. At a subset of 15 USGS snow-sampling sites and at 10 NADP precipitation sites, a consistently negative correlation between chemical concentrations of the 3 compounds (NH_4^+, NO_3^-, and SO_4^{2-}) and snowmelt volume was noted for most cases. Thus, a key variable driving the levels of concentrations in snowpacks is the amount of precipitation. What effect, then, would be expected from ENSO events—greater precipitation and, hence, lower chemical concentrations?

Annual snowfall amounts in the Rocky Mountain region during water years 1993–97 were substantial for most of those five winters. However, only two moderate El Niño events (WY1993 and 1995) and one moderate La Niña (WY1996) event occurred during that time (National Weather Service, Denver, 1998). The greatest variance in snow depths among sites for a single water year ($p<0.005$), and significantly deeper ($p<0.06$) snowpacks as compared to the other study years, was observed in water year 1997, a non-El Niño year. SOI data are plotted for July through November in figure 2 for comparisons between a recent (1982–83), strong El Niño year and the years of the study period. Note that the deepest snowpacks observed in the study (during WY1997) coincided with the weakest SOI effect of the study period. During this 5-year study, heavy accumulations of Rocky Mountain snowfall were not related to ENSO events.

During this warmer phase of the Southern Oscillation, the Northern Rockies typically have received less snowfall than the Southern Rockies based on records from 1895–1997, analyzed by Livezey, et. al. (1998), in the Climate Prediction Center (National Oceanic and Atmospheric Administration, 1998c). Average wintertime precipitation rankings for El Niño years (from very dry to very wet), based on their work with long-term historical data, clearly show the Northern Rockies experienced dry winters while the Southern Rockies were near-normal or wetter-than-normal. However, snowpack depths at sites in both the Northern and Southern Rocky Mountains showed roughly similar depths for both El Niño years 1993 and 1995. Similarly equivalent relations between northern and southern subregional snowpacks also were observed for the non-El Niño years.

During the study, only one La Niña year (WY1996) was noted. The La Niña effect, sometimes overlooked as the other half of the ENSO phenomenon, occurs when temperatures are cooler than normal in the Eastern Pacific—just the opposite of the El Niño effect—so ocean temperatures are cooler nearer to the Americas. These conditions typically translate to drier winters in the Southern Rockies and correspondingly wetter winters in the Northern Rockies. Only a slight adherence to a pattern of a wetter-than-normal winter in the Northern Rockies coincident with a somewhat drier winter in the Southern Rockies during the La Niña winter of 1996 can be seen when snow depths are compared between subregions for the individual years of study (fig. 3).

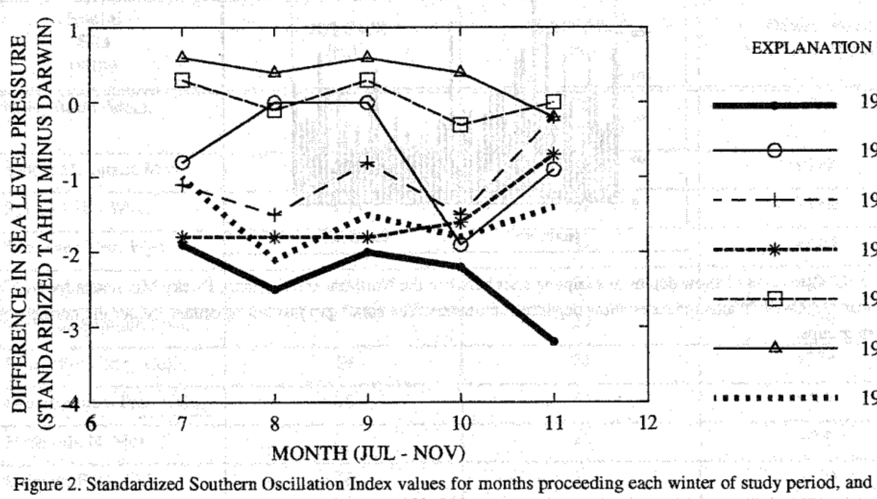

Figure 2. Standardized Southern Oscillation Index values for months proceeding each winter of study period, and including the most recent strong El Niño event of 1982–83.

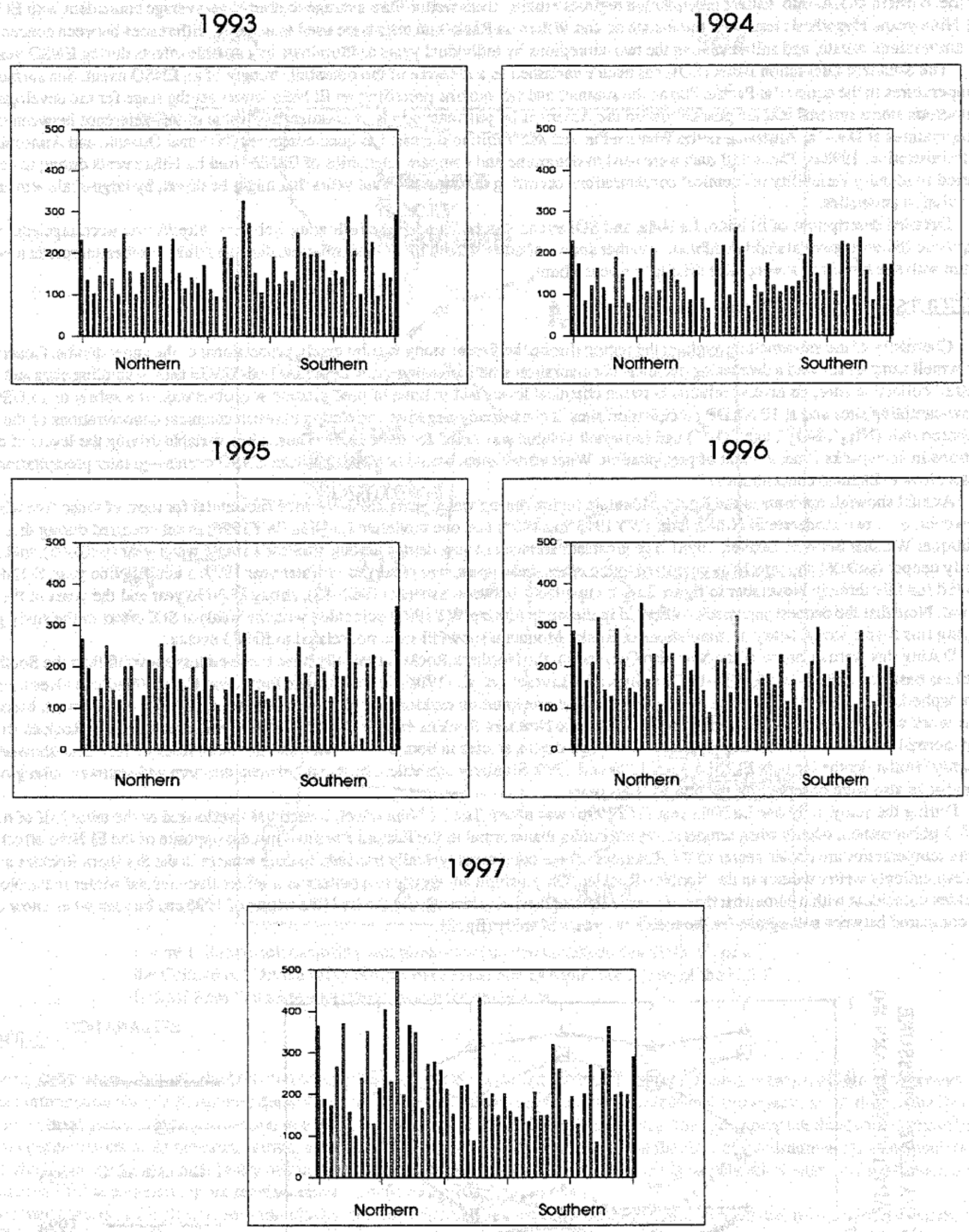

Figure 3. Comparisons of snow depths at sampling sites between the Northern and Southern Rocky Mountains for each of water years 1993–97. Y axis indicates snow depth in centimeters. The small gap just left of center divides the northern and southern groups.

Statistical analyses comparing the chemistries of ammonium, nitrate, and sulfate among the northern and southern subregions by individual years showed weak associations between the occurrence of greater or lesser concentrations and the coincident El Niño events. No meaningful significance ($p \leq 0.05$) was noted when using either F-tests or Wilcoxon Rank-sum tests for nitrate or sulfate concentrations between sites in the Northern Rockies ($n=23$) and Southern Rockies ($n=29$). However, the same tests yielded significant differences ($p<0.001$) in ammonium concentrations between the two subregions for water years 1993 and 1994. In both cases, the northern snowpacks had more concentrated ammonium than was found at the southern sites. Corresponding snow depths between the two subregions for both the moderate El Niño year (1993) and non-El Niño year (1994) were similar. Because no pattern of greater or lesser snow depths was noted for the northern subregion, it is unlikely that higher concentrations are due to lesser amounts of precipitation. Further, the highest levels of ammonium regardless of snow depths or year were detected at the northern snow-sampling sites, so the cause of elevated concentrations is not likely due to precipitation amounts.

Although La Niña or El Niño effects have not caused any significant differences in snowfall accumulation as shown by the comparisons between moderate and non-El Niño years during water years 1993–97, what about stronger El Niño events that occurred in the region before the study period? The relations between the SOI and precipitation demonstrated by Redmond and Koch (1991) for 1933–94 show doubtful significance ($p>0.05$) of a correlation in much of the Rocky Mountain region, especially in Colorado and Wyoming. A few sections of the southernmost Rocky Mountains in New Mexico and ranges in northwestern Wyoming and western Montana are more strongly correlated with precipitation, but roughly half of the Rocky Mountain region is not. Areas in the Western U.S.A. where correlations are the strongest include the southwestern deserts, the Pacific Northwest, and northwestern Montana. Similarly, snowpacks measured at 10 Snotel (snow telemetry) sites near the annual maximum during the last major El Niño event of WY1983 showed a trend toward a drier winter in the north, while the southernmost site at Gallegos Peak, New Mexico, recorded a much wetter winter as compared to snowpacks observed at the same time during the non-El Niño year, 1997 (table 1, USDA, National Resources Conservation Service, 1997b). Although this comparison agrees somewhat with correlations mentioned above, it is pointed out here to demonstrate how much of the region, especially Colorado, does not seem to be affected by El Niño, considering the numerous above-average snowfall seasons observed in the region in the 1990's. Other factors seem to be controlling the unusually heavy winter-precipitation patterns observed in the Rocky Mountain region both before and during the study period.

As for the water year 1998 snowpack, during possibly the strongest El Niño events on record, snow-water accumulations in basins in Montana, Wyoming, Colorado, and New Mexico at the time of this writing (April 1998) generally are below 30-year averages and well below several recent years when greater-than-normal snowfall was observed in the Rocky Mountain region. Although past moderate El Niño events discussed in this paper have not noticeably perturbed Rocky Mountain snowpacks during water years 1993–97, stronger events, such as the current El Niño of water year 1998, may have a clearer effect on annual precipitation amounts and on snowpack chemistry. So far this winter, below-average to average snowfall accumulations in most of the region, and the occurrence of successive above-average annual snowpacks independent of El Niño events during the last 5 years, especially 1997 (USDA, National Resource Conservation Service, 1997a), suggests that the Southern Oscillation between El Niño and La Niña may not be the source of the heavy winter precipitation observed during the mid-1990's.

Table 1. Comparison of snowpack water equivalent (SWE) at Snotel sites near the annual maximum accumulation (mid- to late April) for El Niño year 1983 versus non-El Niño year 1997 (USDA, National Resources Conservation Service, 1997b)

Snotel Site name	1983 SWE (in.)	1997 SWE (in.)	Difference of 1997 versus 1983
Noisy Basin, Mont.	50	75 (estimated)	+50%
Saddle Mountain, Mont.	27	42	+55%
Sylvan Lake, Wyo.	23	32	+39%
Togwotee Pass, Wyo.	27·	37	+37%
Tower, Colo.	52	58	+12%
Berthoud Summit, Colo.	26	29	+12%
University Camp, Colo.	19	26	+37%
Red Mountain Pass, Colo.	36	33	–8%
Hopewell, N. Mex.	27	25	–7%
Gallegos Peak, Colo.	18	12	–33%

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