SNOW CHEMISTRY AND PHYSICS OF THE MOGOLLON RIM IN ARIZONA

by
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ABSTRACT

Snowpack samples from the central mountain region of Arizona were analyzed for eleven major ions and thirty trace elements. The results indicate a relatively pristine snowpack that is weakly influenced by anthropogenic activity in most samples. Trace metals associated with human activity (Ag, As, Co, Cr, Hg, Se, Zn) were below detection limits. A pH range between 4.9 and 5.7 was measured with a mean value of 5.4, and these findings exhibit some temporal and spatial tendencies. A majority of samples had extremely low ionic strengths. The results suggest a combination of ammonium and calcium salts, sea salt, and inorganic and organic acids in the snowpack. The free proton (H^+) accounted for a significant portion (32%) of the total cation availability. Meteorological influences were investigated by separating the observations by winter storm event. Samples collected on 2/4/93 exhibited a significantly greater ionic strength due to a different weather pattern during this storm. Spatial variations due to local effects were also evident in the snowpack.

INTRODUCTION

During the past three winter seasons (2/92-2/94), we have collected and chemically analyzed snowpack samples from the rugged, mountainous region of central Arizona known as the Mogollon Rim. This work is part of the Arizona Program, a scientific effort intended to improve our understanding of winter storms in the Southwest. The observations we report here appear to represent the first survey of snowpack chemistry in Arizona. In this paper, we provide some historical background and motivation for the snow chemistry research; report the results of our analyses; and identify some temporal and spatial tendencies in the snowpack.

Topography of the Mogollon Rim

The Mogollon Rim is part of a great geologic fault that diagonally bisects central Arizona over a distance of 500 km (Figure 1). The ancient escarpment has been segmented, and in some places lifted, by later faulting, erosion and volcanism. The highest point on the central portion of the Rim is Baker Butte at 2460 m above sea level. Observed from the south, the central Rim is a steep, rugged escarpment, towering 600 m above the low-lying Verde Valley in some places. This south-facing escarpment marks the high edge of the Colorado Plateau which rises southward. North of the Rim, high-elevation forests occupy the southern Colorado Plateau and White Mountains to the east.

The Mogollon Rim is the drainage divide and physical impediment that stimulates precipitation by forcing the prevailing southwesterly flow of warm, moist air to higher, cooler elevations.

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Much of the precipitation from winter storms falls within this drainage area, where the rugged topography and forest vegetation provide important watersheds for the Little Colorado River system to the north, and the Verde, Salt and Gila River systems to the south.

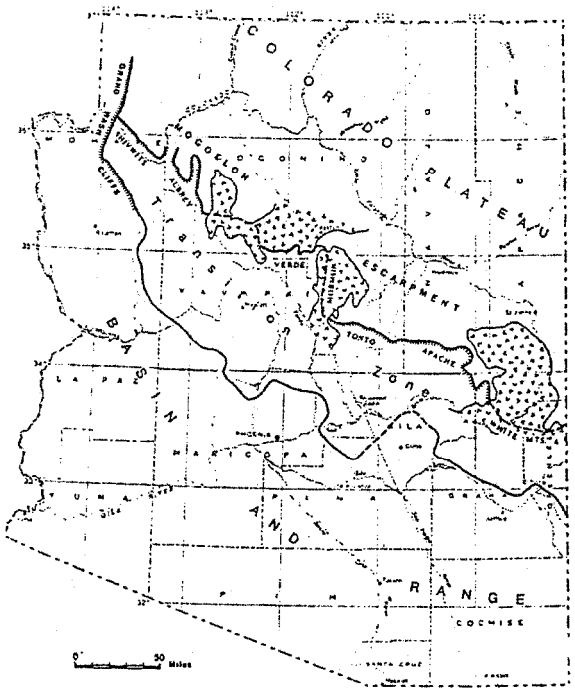

Figure 1. Physiographic map of Arizona showing the three main regions and the Mogollon Rim (source: Arizona Bureau of Mineral Technology).

Winter Storms

Most of Arizona's winter precipitation is associated with mid-latitude cyclones imbedded in the prevailing westerlies (Figure 2). Under certain conditions, the state can receive abundant precipitation during the winter. These conditions depend upon a westward displacement of the Pacific high pressure ridge and the formation of a semi-permanent, low pressure trough over the Pacific Ocean. When this occurs, rather than passing through Washington and Oregon, storms follow the prevailing flow and move southward along the west coast, often proceeding as far south as southern California before coming ashore [Sellers and Hill, 1974].

Winter storms typically produce two days of widespread precipitation before passing off toward the northeast under the influence of strong southwesterlies on the east side of the upper level trough. However, once this pattern is established, it tends to persist, with several storms in succession passing over the state at intervals of about one week. Both stratiform and imbedded cumulonimbus clouds occur in these systems. When the Pacific high pressure ridge is especially well-developed, low pressure systems stagnate and intensify off the California coast for several days before moving inland. By the time these storms reach Arizona, they are fully developed and sometimes bring heavy snowfall to the higher elevations. Snow accumulation may reach depths of 2.5 m or more during the winter. The gradual melting of this snow during the spring maintains a water supply in the main rivers and reservoirs of the state. This slow run-off usually lasts until the summer rains begin in July.

Previous Winter Studies on the Mogollon Rim

The first documented winter field studies were those of the Bureau of Reclamation who conducted two-month observational programs in 1987 and 1988. Their studies included a ground-based microwave radiometer, tracer releases and airborne measurements. They documented the characteristics of winter clouds and precipitation, with an emphasis on the availability and transport of cloud liquid water (CLW) over the central (1987) and eastern (1988) Mogollon Rim [Super et al, 1989]. Most of the observed CLW was concentrated in a few widespread storms that lasted from one to three days. These storms produced significant snowfall but were inefficient in producing snow during portions of their lifetimes. Periods of abundant CLW over the central Rim typically had moderate to strong southwesterlies and shallow clouds with warm tops (-12°C) and little or no ice [Super et al, 1989]. Aircraft observations demonstrated the crucial role that topography and wind-flow patterns play in cloud development

and precipitation over the complex terrain of the Mogollon Rim.

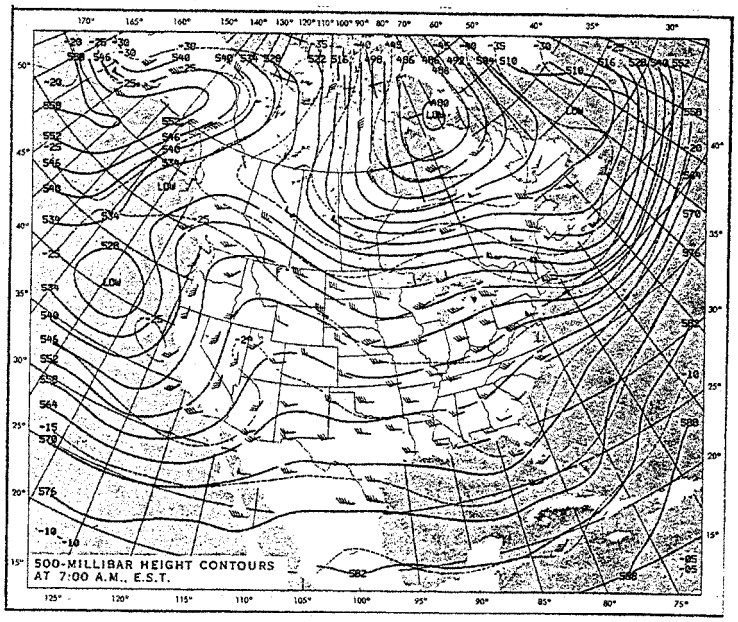

Figure 2. 500 mb height contours at 7 a.m. eastern standard time, 2/10/92, showing a typical snow-producing winter storm (source: NOAA Daily Weather Maps).

In 1990, the University of Arizona (UA) and the National Center for Atmospheric Research (NCAR) began to extend the Bureau of Reclamation work by developing a computer model to simulate terrain, wind flow, cloud development and precipitation over a 150 km length of the central Mogollon Rim that lies downwind of the Verde Valley and approximately perpendicular to the prevailing southwesterlies. Over the past three years, several cases have been selected from the Bureau of Reclamation data set to compare with model simulations. The results have been described in detail [Bruintjes et al, 1994a]; [Bruintjes et al, 1994b].

Local storm dynamics and cloud microphysics were found to be strongly coupled in the modelled wind flow patterns [Bruintjes, 1994a]. The simulations show that the interaction of wind flow with the Black Hills and Mingus Mountain gives rise to a stationary gravity wave that largely determines the location and amount of CLW. The enhancing effect of the wave on precipitation downwind of the Verde Valley (the central Rim) is reflected in the climatological record. Unfortunately, no microphysical measurements are available to verify the modelled characteristics of the wave clouds or their effect on the development of precipitation.

In 1992, we conducted a small scale field program using a light aircraft, wind profiler and rawinsondes to verify the existence of the gravity wave. We ran the Clark model [1977] in real time to simulate the gravity wave, and the results were found to be extremely helpful in predicting important physical features of the wind flow.

We began snow sampling during the 1992 field program. We observed the ice crystal habits of falling snow. We collected and analyzed falling snow samples for stable isotopic composition (^{2}H, ^{18}O) which is sensitive to the temperature of ice crystal formation. Our preliminary observations were consistent with the warm-cloud temperatures observed in the 1987 study. A detailed description of the snow physics will be published elsewhere. We also collected our first eight snowpack samples from National Forest locations on the central Mogollon Rim and on Mingus Mountain in 1992.

EXPERIMENTAL

Snowpack Sampling

A total of thirty snowpack samples were collected from thirteen sites in the Apache/Sitgreaves, Coconino, Kaibab and Prescott National Forests on the Mogollon Rim and on Mingus Mountain (Figure 3) following five major winter storms over a three year period (2/92-2/94). Sampling sites were chosen to reflect homogeneous topography and limited land use patterns, with the exception of Munds Park, downwind (< 1 km northeast) of Arizona Highway 17. All sites were within an elevation range of 2000-2250 m except Hannagan Meadow (2550 m) on the east Rim.

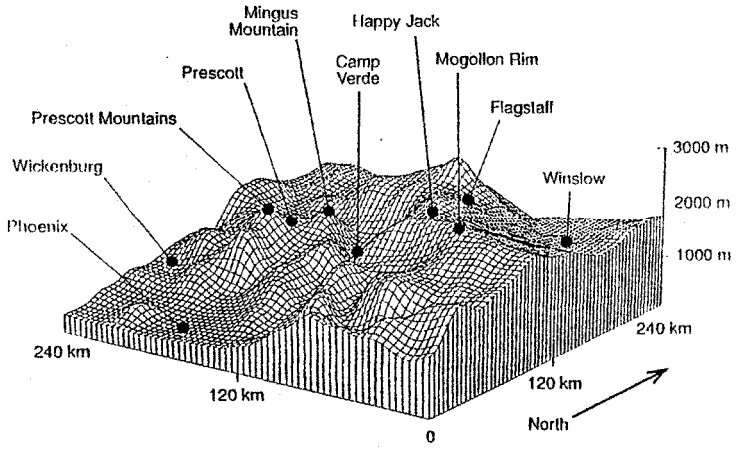

Figure 3. Clark's three-dimensional image of the central Mogollon Rim, Verde Valley (Camp Verde), the Black Hills (Mingus Mountain) and the topographic features of the region [Bruintjes et al, 1994a].

Snowpack sampling equipment consisted of Nalgene low-density polyethylene (LDPE) scoop and 500 ml, wide-mouth bottles, pre-cleaned and sealed in ziplock bags in the laboratory. A thermometer, camera and log book were carried to the sampling sites to document the location and site conditions after samples were collected and sealed. Field blanks (sample bottles half-filled with deionized water) were carried to a sampling site on several occasions. A laboratory disposable apron with sleeves and polyethylene gloves, also sealed in ziplock bags, were worn. At each site, a fresh apron and set of gloves were used.

Samples were collected after hiking (into the wind) to the center of a clearing or pasture in forested areas. Facing the wind, the scoop was rinsed with snow, then several more steps were taken into the wind before samples were collected. The bottles were filled with snow from within 30 cm of the snowpack surface without making contact with the ground surface below. The filled bottles and scoop were returned to their respective bags and resealed. The samples were packed in dry ice and preserved in the frozen state in a portable electric cooler until returning to the lab, where they were stored in a deep-freezer at -10°C.

Chemical Analysis

The snow samples were analyzed by ion chromatography using a Dionex Ion Chromatograph DX-100 system (Ionpac AG4A guard column, AS4A analytical column, ASRS-1 self-regenerating anion suppressor for anions; Ionpac CG12 guard column, CS12 analytical column, CSRS-1 self-regenerating cation suppressor for cations). The eluents used were 1.7 mM sodium bicarbonate ($NaHCO_3$)/1.8 mM sodium carbonate (Na_2CO_3) for inorganic anions; 10 mM sodium borate ($Na_2B_4O_7$) for organic anions; 25 mM methanesulfonic acid (MSA) for cations. Sample injections were made through pre-rinsed Gelman 0.45 um PTFE membrane filters. Standards were prepared using standard dilution techniques and research grade chemicals.

Measurements of pH were made with a Fisher Accumet model 95 pH/ion meter and Ross model 8102BN combination pH electrode. The pH meter was calibrated with pH 4.01 and 7.00

buffers (Radiometer Copenhagen, +/- 0.010 at 25°C). We added standard 1 mM additions of calcium chloride to 10 mL sample aliquots and rechecked the pH to ensure that the ionic strength of the sample was sufficient to provide an accurate measurement.

A purified starch solution was prepared by mixing 16 g of soluble starch (Aldrich) with 400 mL of nearly boiling deionized water in a pre-cleaned Nalgene LDPE beaker. Thirty mL of ion exchange resin beads (Rexyn Research Grade I-300 H-OH) were added to the starch solution after cooling. The mixture was stirred slowly overnight and then centrifuged at 7500 rpm for two minutes to separate the desired starch solution from the undissolved starch and ion exchange resin. Roughly 200 mL of the soluble starch solution was decanted. The starch mass ratio (1.43% w/w) was determined gravimetrically by evaporating aliquots of the solution in the laminar flow hood.

Twenty mL of the purified starch solution was mixed with 100 mL of sample snowmelt which was then refrozen and freeze-dried similarly to the methods described by Heaton et al [1990]. The purpose of this procedure is to to concentrate trace impurities onto the high-surface area starch. The resulting starch, weighing roughly 0.2 g and resembling cotton candy, was transferred to pre-treated Nalgene LDPE 18 mL vials and sealed in pre-cleaned ziplock bags for shipment. A set of eight snow samples (collected during 2/92) were analyzed for trace elements by instrumental neutron activation. Samples were irradiated in the 2-MW research reactor of the Rhode Island Nuclear Science Center. The advantage of this method is the simultaneous determination of multi-element concentrations. Elemental masses were quantified by comparing gamma-ray spectra from samples and co-irradiated Standard Reference Materials. A detailed description of the analytical method is described by Heaton et al [1990] and Hamilton and Chatt [1982].

Data Quality, Precision, Accuracy, Detection Limits

Precautions were taken to preserve the quality of the snow samples. We strictly adhered to ultraclean lab and field procedures throughout the life cycle of the samples. They were kept deep-frozen until thawed at 4°C; aliquots were brought up to 25°C during analyses; and the remaining sample was maintained at 4°C. A plexiglas laminar flow hood fitted with an Emerson Model 1479 electronic clean air system provided clean room conditions for sample transfers and clean storage. Lab and field sampling plasticware was pre-cleaned with distilled, deionized Milli-Q water (18 Mohm-cm) and checked by ion chromatography. Plasticware designated for elemental analysis was pre-treated with 10% research grade hydrochloric acid (one week); 10% research grade nitric acid, (one week); soaked overnight in 10% trace metal grade nitric acid; and subsequently rinsed thoroughly with deionized water. Ultrapure chemicals (Fluka Chemika microselect, puriss p.a. grades) and degassed, deionized Milli-Q water were used in the preparation of eluents, lab standards and analytical solutions. Duplicate samples were taken at each site and analyzed to verify the major ion concentrations reported here. Lab and field blanks were checked for contamination by ion chromatography. Experiments with blanks early on helped us to develop consistently contaminant-free results.

Precision and accuracy of the ion measurements were determined from the standard deviation and mean of repeated analyses of the same standard. We define the ion detection limit as the signal equivalent to three times the standard deviation of a 1 uM lab standard. Over 90% of the standard reference evaluations were within 10% of the standard values. Precision for the major ions was typically less than 10%, with Na^+ and Cl^- exhibiting the largest variability (3-17%).

Eight samples and three blanks were submitted for trace elemental analysis by neutron activation. Large uncertainties (on the order of 50-100%) were exhibited for Cu, Mg and Mn

in the majority of samples caused by overlapping spectral emissions of two or more elements in the sample. Elements observed at values below the minimum, or practical, detection limit are detectable, but not quantifiable, and are not represented in the statistical data. We define the elemental detection limit as the concentration equivalent to three times the standard deviation of the blanks. Elemental mass concentrations were adjusted by subtracting the average blank values. Freeze-drying losses were accounted for by calculating the initial mass of the starch in solution and comparing this to the mass of the final product. Mass concentrations were adjusted to reflect freeze-drying losses (2-9%), assuming the same weight loss for each element detected in the sample.

RESULTS AND DISCUSSION

Trace Elements

A summary of statistical data for the snowpack samples is presented in Table (1). Fourteen of the thirty trace elements were detected in one or more samples. A majority of metals associated with anthropogenic activities (Ag, As, Co, Cr, Hg, Se, Zn) were below detection limits. The detection limits were acceptably low for our purposes in that they represent concentrations below or comparable to those found in snowpack samples from remote locations worldwide [Galloway et al, 1982]. Four elements (Ca, Cl, Mg, Na) were analyzed by neutron activation and by ion chromatography, and some differences were indicated between the two methods. The differences were probably due to the insoluble fraction in the snowpack. Only the soluble fraction is measured by ion chromatography. Ca and Na agreed closely with their ion counterparts Ca^{+} and Na^{+} in the same sample. Total chlorine exceeded Cl^{-} in most samples, and we attribute this to small amounts of plant matter in the unfiltered trace element samples. Insoluble Mg accounted for thirty percent of the total Mg in the snowpack. Cu was present in six of eight samples.

The elements Ca, Fe, Mg, Mn, Sc and V observed in the snowpack appear to be primarily terrestrial in origin. A convenient way to compare the snowpack chemistry to that of the soil is to scale the elemental concentrations to Al, a major component of soil (Figure 4). This scaling method has been used in regional pollution aerosol studies performed by Rahn [1981] and in the atmospheric deposition assessment by Galloway [1982]. The global average abundance of the elements in crustal rocks was used [Mason, 1966]. Snowpack elements falling on the line of unit slope contain relative abundances similar to those in the crustal average; elements falling above the line are enriched in the snowpack beyond the crustal average. Considering the fetch of the air mass over the Pacific Ocean, it is possible that Na, Cl, and Br are enriched due to the presence of sea salt. Although a large degree of uncertainty (100%) was associated with the Cu measurements by neutron activation, it is

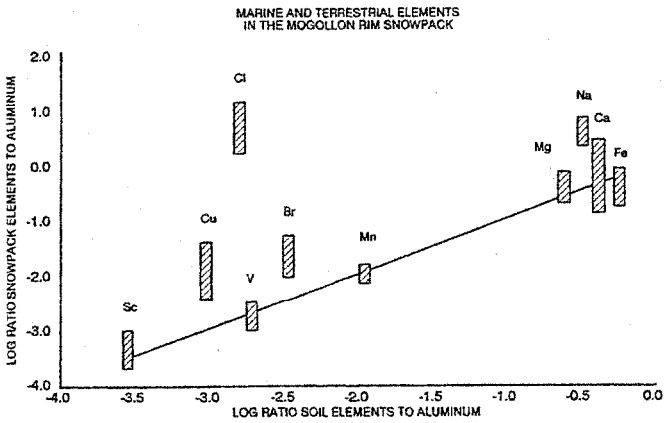

Figure 4. Relative abundances of trace elements in Mogollon Rim snowpack. Elements falling above the line of unit slope are enhanced beyond the global crustal average [Mason, 1966].

Table I. Statistical Data on Mogollon Rim Snowpack Samples

Constituent	MDL*	# Obs > MDL	Min	Mean	Max
Major Ions** in order of their relative abundance					
NO3-	0.19	30	0.67	3.63	12.6
SO4- -	0.30	30	0.69	2.97	19.0
Cl-	0.36	30	0.56	2.49	7.92
HCOO-	0.42	8	0.45	0.63	0.98
CH3COO-	0.28	9	0.28	0.51	1.56
pH		30	4.92	5.42	5.66
H+		30	2.19	3.80	12.0
NH4+	0.28	30	0.55	2.88	21.2
Ca++	0.48	23	0.55	1.85	6.27
Na+	0.50	24	0.57	1.71	4.61
K+	0.34	7	0.42	0.84	1.77
Mg++	0.26	16	0.26	0.79	1.58
Trace Elements*** in alphabetical order					
Ag	0.01	0			
Al	0.8	8	7.6	22.1	41.8
As	0.003	0			
Ba	2.7	1	4.2	4.2	4.2
Br	1.0	3	1.1	1.7	2.1
Ca	2.9	8	14.0	37.4	96.3
Ce	0.002	0			
Cl	1.1	8	36.5	126	296
Co	0.003	0			
Cr	0.02	0			
Cs	0.002	0			
Cu	0.21	6	0.28	0.44	0.77
Eu	0.002	0			
Fe	2.1	6	2.1	7.4	18.1
Hf	0.007	0			
Hg	0.001	0			
I	0.22	5	0.23	0.54	0.80
Mg	1.2	8	3.2	13.3	28.0
Mn	0.1	2	0.22	0.43	0.65
Na	15.5	6	60.0	74.6	95.2
Ni	1.1	0			
Rb	0.2	0			
Sc	0.0002	8	0.0003	0.0004	0.0005
Se	0.01	0			
Ta	0.005	0			
Tb	0.005	0			
Th	0.002	1	0.005	0.005	0.005
V	0.003	8	0.009	0.057	0.125
Yb	0.001	0			
Zn	0.1	0			

* Minimum Detection Limit
** In microequivalents per liter of sample (ueq/L)
*** In micrograms per liter of sample (ug/L)

apparently enriched in our samples. This could be due to regional mining activities and/or to the relatively high abundance of Cu in Arizona soils.

Major Ions

Thirty snow samples were analyzed for eleven major ions, and the results are summarized in Table (1). Many samples exhibited extremely low ionic strengths. A pH range between 4.9 and 5.7 was measured with a mean value of 5.4. The pH of our snow samples was similar to the findings of Gunz and Hoffmann [1990a], who reported an average value of 5.4 for the mountain regions of southern and central California, and Berg et al [1991], who reported 5.3 for the Sierra Nevada Mountains in central California.

Table (2) provides a comparison of our results to those observed in other Western U.S. mountain regions. Gunz and Hoffmann [1990a, 1990b] reported the highest relative ionic strengths, probably due to a strong marine influence and proximity to the Southern California Air Basin. The Sierra Nevada and Cascade Mountains were influenced by a combination of terrestrial, marine and anthropogenic sources. These mountain ranges appear to be influenced most significantly by meteorological conditions and proximity to anthropogenic sources. Agricultural and feedlot operations appear to weakly influence the central Sierra Nevada snowpack; the Cascades snowpack was slightly affected by steel-making facilities in Portland and Seattle and the Tacoma Copper Smelter [Laird et al, 1986]. Laird reported, however, that the snowpack in the higher Cascades and Sierra Nevada was not strongly influenced by anthropogenic activities.

Constituent	Mogollon Rim Central Arizona	Sierra Nevada Central California [Berg et al, 1991]	Mountain Regions Southern California [Gunz/Hoffman, 1990]	Sierra Nevada (Carson Range) [Mitchell/Lamb, 1989]	Cascade-Sierra Nevada (Wash, Ore, Calif) [Laird et al, 1986]
NO3-	0.7 - 12.6 (3.6)	0.5 - 29.5 (5.3)	1.5 - 15.8 (4.3)	0.1 - 19.5 (5.0)	0.1 - 8.6 (1.8)
SO4- -	0.7 - 19.0 (3.0)	0.0 - 19.3 (3.4)	BDL - 17.2 (4.5)	0.1 - 12.1 (2.4)	0.8 - 6.7 (2.9)
Cl-	0.6 - 7.9 (2.5)	0.0 - 58.3 (5.6)	BDL - 128.2 (13.6)	0.2 - 30.5 (4.1)	0.3 - 28.2 (6.2)
CH3COO-	BDL - 1.6 (0.5)	NR	BDL - 13.4 (4.1)	BDL - 32.3 (9.9)*	NR
HCOO-	BDL - 1.0 (0.6)	NR	0.5 - 4.9 (2.1)	NR	NR
pH	4.9 - 5.7 (5.4)	4.7 - 5.6 (5.3)	4.5 - 6.2 (5.4)	5.0 - 6.5 (5.4)	5.1 - 5.9 (5.6)
H+	2.2 - 12.0 (3.8)	0.3 - 20.0 (5.0)	0.7 - 31.6 (5.5)	0.3 - 10.5 (4.3)	0.5 - 8.0 (3.0)
NH4+	0.6 - 21.2 (2.9)	NR	BDL - 8.1 (5.6)	0.1 - 16.9 (7.8)	0.1 - 12.9 (5.7)
Ca++	BDL - 6.3 (1.9)	0.0 - 9.8 (1.1)	BDL - 4.4 (3.2)	NR	0.3 - 8.0 (2.1)
Na+	BDL - 4.6 (1.7)	0.0 - 33.4 (4.7)	BDL - 115.7 (8.4)	0.2 - 42.7 (5.7)	0.4 - 11.3 (3.0)
K+	BDL - 1.8 (0.8)	0.0 - 3.8 (0.5)	BDL - 8.8 (2.5)	BDL - 0.4 (0.2)	0.3 - 7.7 (0.5)
Mg++	BDL - 1.6 (0.8)	0.0 - 6.9 (0.7)	BDL - 9.9 (1.3)	NR	0.2 - 4.2 (0.8)

Table 2. A comparison of major ions (ueq/L) in snowpack from Western U.S. mountain regions. Ranges and means (bracketed) are listed for ion species. (*) denotes rime ice measurement; (NR) not reported; (BDL) below detection limit.

In general, our results indicate a relatively pristine snowpack on the Mogollon Rim. A simple linear regression was performed; the major constituents (those ions with mean values greater than

1 ueq/L) most strongly correlated were: ammonium and sulfate (r = 0.96); sodium and chloride (r = 0.84); ammonium and nitrate (r = 0.79); calcium and sulfate (r = 0.72). The free proton (H^+) significantly correlated with the sum of organic ions (acetate and formate), nitrate and sulfate (r = 0.85). H^+ accounted for a significant portion (32%) of the total cation availability. The ion balance R (the ratio of total anion concentration over total cation concentration) showed an anion deficit, and this was reflected in the majority of samples. The mean ratio (R = 0.86) is reasonable and is often found in the measurement of low ionic strength snowpack [Berg et al, 1989; Gunz and Hoffmann, 1990a; Berg et al, 1991].

The organic ions acetate (CH_3COO^-) and formate ($HCOO^-$) were present in half of the samples at concentrations much lower than those observed by Gunz and Hoffmann [1990b]. This may indicate secondary anthropogenic sources for these acids, such as photochemical smog. The highest organic ion concentrations observed in Mogollon Rim snowpack were found in the samples collected near the highway (Munds Park).

The samples collected at Mingus Mountain showed high ionic strengths, including elevated levels of Ca and Mg, perhaps due to the presence of a cement plant in the Verde Valley. Samples collected from the East Rim, downwind of the Phoenix metropolitan area, were generally low in ionic strength and did not appear to exhibit an urban influence.

Meteorological influences were investigated by separating the observations by winter storm event. Samples were collected after five winter storms and the results of the ion analyses are shown in Figure (5). The lowest values of pH (4.9/5.2 mean) were observed in the 2/1/93 storm. The highest values of ionic strength (79.2 ueq/L); acetate (1.6 ueq/L); magnesium (1.6 ueq/L); free proton (12.0 ueq/L); nitrate (12.6 ueq/L); sulfate (19.0 ueq/L); ammonium (21.2 ueq/L) all occurred in the 2/1/93 storm. Sodium and chloride account for only eight percent of the total ionic budget on 2/1/93; typically, these species account for twenty percent of the total budget of our snowpack samples.

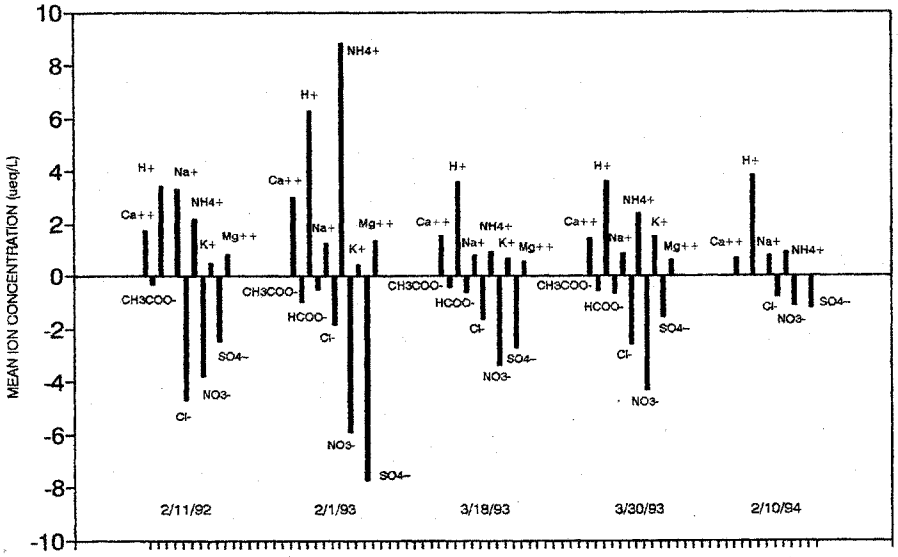

Figure 5. Mean ion concentrations of Mogollon Rim snowpack after five winter storms over a three-year period. The East Rim is represented on 3/18/93.

A different weather pattern was observed during the 2/1/93 storm (Figure 6). The majority of snowfall occurred while the center of a low pressure system was located over southern Utah on 1/31 and 2/1. Surface winds were northwesterly during this event and provided a more continental air fetch for the storm system over the Mogollon Rim. The remaining four winter storms (2/11/92; 3/18/93; 3/30/93; 2/10/94) occurred during more typical conditions (Figure 2)

with a long marine fetch. During these events, the center of the low was generally further west and south and provided more of a marine influence from the southwest.

Spatial variations due to local effects were evident in the snowpack. Samples from Munds Park (the highway site) consistently showed low pH values and high ionic strengths; the Happy Jack and Clints Well samples had consistently moderate pH values and low ionic strengths. Samples from these two locations exhibited little temporal variability and were least affected by local activity. Snowpack samples from Happy Jack and Clints Well appear to represent the regional background conditions on the Mogollon Rim.

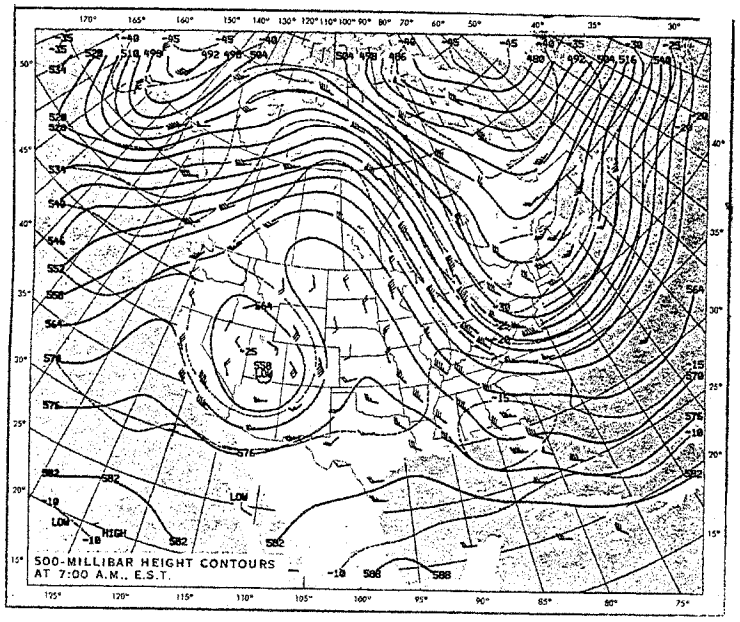

Figure 6. 500 mb height contours at 7:00 a.m. eastern standard time, 2/1/93. The closed low pressure system centered over southern Utah was also observed at the surface (source: NOAA Daily Weather Maps).

CONCLUSIONS

The prevailing south-westerly winds coupled with weak local emissions provide a relatively clean snowpack to key watersheds along the Mogollon Rim. Our results suggest a combination of ammonium and calcium salts, sea salt, and inorganic and organic acids in the snowpack. The snowpack does not appear to be significantly influenced by emissions in the Phoenix urban area. It is likely that the relatively high concentrations observed after the winter storm on 2/1/93 were influenced by regional anthropogenic and terrestrial sources that regularly influence the Sierra Nevada mountain range to the northwest.

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