

SNOWPACK DRY DEPOSITION OF SULFUR: A FOUR-DAY CHRONICLE

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ABSTRACT

A four-day sequence of dry deposition measurements based upon a snowpack mass balance indicated large sulfur dry deposition on the first day under blowing snow conditions followed by three consecutive days of essentially zero snowpack sulfur exchange under stable conditions. Snowpack mass balance data were adjusted for the effects of blowing snow to calculate sulfur dry deposition rates of $4.13 \text{ mg m}^{-2}\text{d}^{-1}$ and a deposition velocity for total atmospheric sulfur of 0.4 cm s^{-1} on the first day.

INTRODUCTION

Several studies in Scandinavia and North America have shown that snowpack accumulations of chemical elements over time can be used to estimate dry deposition rates (Barrie and Walmsley, 1978; Forland and Gjessing, 1975; Dovland and Eliassen, 1977). This paper reports on evaluation of snowpack dry deposition rates of sulfur using a mass balance approach during four consecutive 24-hr periods in January, 1984. The results chronicle days with both gains and zero sulfur exchange, the impact of blowing snow on evaluation of dry deposition, and the spatial variation in snowpack dry deposition among ten adjacent sampling sites. Dry deposition of sulfate in Pennsylvania is of particular interest, since the wet deposition of sulfur in the state is the highest in North America.

SITE CONDITIONS

Measurements were conducted from January 19 through January 23, 1984 at the Rock Springs Experimental Farm south of Pine Grove Mills along Pa. Rte. 45 in Centre County, Pennsylvania (lat. $40^{\circ}47'$ and long. $77^{\circ}37'$). Snowpack measurements were conducted in a narrow grassed strip of land between two large, flat plowed fields. The plowed fields exhibited soil clods up to 10 cm height, but no major wind obstacles existed for more than 100 m upwind. The area was a site of other measurements of dry deposition rates conducted by the Meteorology Department, The Pennsylvania State University.

Measurements were initiated on the morning of January 19, 1984 following several days of light snowfall. Snowfall was recorded at State College, Pa. 16 km to the north of the study site on January 17, 18 and 19 (Table 1). Light snowfall prior to 19 January was removed from the measurement sites. During the first two measurement days (January 19-20 and 20-21) weather was dominated by low pressure centers in northern New England and the northern Great Lakes, respectively. Winds were brisk and from the NW to WSW. Air temperatures were extremely low with maximums of $\leq 5^{\circ}\text{C}$ during these first two days. During the latter two measurement days (January 21-22 and 22-23) weather was dominated by high pressure centers over the Ohio River Valley, Washington, DC, and along the New England coast on consecutive days. Winds were calm and air temperatures were even lower, ranging from a low of -25°C to a high of -4°C during the latter two days.

Snowpack surface conditions varied during the four-day measurement period. Drifting snow was observed during the visits to the site on the morning of January 19 and 20, but drifting had essentially ceased by the morning of January 21 and was not observed on the mornings of January 22 and 23. Thus for the entire first 24-hr period and the early morning of the second period drifting snow could have influenced the measurements. Drifting snow created a surface composed of broken ice crystals averaging about 1 mm in width with a slight wind crust. The mean snowpack water equivalent measured at the site was 11.5 mm for the 4-day period, which was considerably above the snowfall of 4.6 mm recorded at State College due to drifting at the experimental site (Table 1). Snowpack water equivalent averaged about 5 mm on the first measurement day, which is believed to be a good estimate of the initial snowfall.

TABLE 1
Weather Conditions for State College, Pa. During Snowpack Dry
Deposition Measurements

Date 1984	Precipitation (mm) preceding 24-hr	Wind at 0700 EST		Air Temperature ($^{\circ}\text{C}$)	
		Direction	Speed (m/s)	0700 EST	max/min
1/17	1.8	SW	calm	-8	-5/-15
1/18	T	E	3.6	-9	-1/-10
1/19	4.6	NW	3.6	-13	-5/-13
1/20	-	WSW	2.2	-20	-8/-20
1/21	T	SW	1.8	-24	-10/-24
1/22	T	SSE	0.9	-25	-12/-25
1/23	-	-	calm	-15	-4/-25

METHODS

Sampling was conducted from approximately 9:30 to 10:30 am on five consecutive days from Thursday, January 19 through Monday, January 23, 1984. Data collected allowed computation of dry deposition rates for four consecutive 24-hr periods. Calculation of the daily dry deposition rate on the snowpack was accomplished using the mass balance expression:

$$\text{DDR} = (L_{t2} - L_{t1}) / (t_2 - t_1)$$

where

DDR is the dry deposition rate ($\text{mg m}^{-2}\text{d}^{-1}$), L_{t2} is the mass (mg m^{-2}) stored in the snowpack at the end of the period (t_2) and L_{t1} is the mass stored at the beginning of the period or t_1 . Mass added by precipitation or lost via melting were negligible during the experiment and thus could be ignored. The load stored in the snowpack (L) at a given time was computed as $C_s W_s$; where C_s is the concentration of the constituent in the snowpack and W_s is the water equivalent of the snowpack sampled.

Snowpack cores were obtained from the top of plastic-covered, 1.22 x 2.44 m, plywood sheets with a 14.6-cm diameter plexiglass cylinder. Ten cores were collected from each plywood sheet each day and composited to obtain enough water for chemical analysis. Snow on ten adjacent plywood sheets aligned in a lengthwise row, which was roughly

perpendicular to prevailing winds, was sampled each day. Sampling from the plywood sheets proceeded from the downwind position to the upwind position to avoid disturbing upwind snow over the five-day period.

Because blowing snow occurred during the experiments, adjustments for changing snowpack load due to scour and deposition by the wind were needed. This adjustment was made by assuming that any change in snowpack water equivalent (W_s) from the mean of 5 mm measured on 19 January was due to blowing snow with the mean concentration of 1.77 mg/L of sulfate measured on the first day. Thus the load of sulfate in the snowpack after 19 January was adjusted to reflect snowpack load without blowing snow effects; a correction reducing snowpack load by an average of 46% on subsequent days.

Chemical analysis of snowpack sulfate concentrations was conducted at the Institute for Research on Land and Water Resources, The Pennsylvania State University. Analysis was completed within recommended holding times for sulfate using the turbidimetric method (EPA, 1983).

RESULTS AND DISCUSSION

Computed dry deposition rates with and without a correction for blowing snow indicated the snowpack gained sulfate during the first 24-hour period (Table 2). During the first 24-hr period (19 to 20 January) the snowpack in the vicinity of the measurement boards gained considerable water equivalent due to drifting snow; going from an average of 5.0 to 14.5 mm (Table 2). Snowpack sulfate concentration also markedly increased due to dry deposition from 1.77 to 2.62 mg L⁻¹. The snowpack sulfate content increased from 8.95 mg m⁻² on the morning of 19 January to 38.20 mg m⁻² on 20 January, but obviously a large part of the increase was due to increased accumulation caused by drifting. The correction for blowing snow reduced the snowpack sulfate on 20 January by 16.87 mg m⁻², which was calculated from the increase in water equivalent from 5.0 mm to 14.5 mm at an assumed sulfate concentration of 1.77 mg L⁻¹ for the blowing snow. The actual sulfate concentration of blowing snow was not measured. Since snowfall had occurred the day before measurements began in this study, the snowpack was considered reasonably homogeneous. Wind scour of old snowpack surfaces, which had accumulated considerable dry deposition, could produce blowing snow with very high sulfate concentrations. With the correction for blowing snow, the indicated dry deposition rate for sulfate for the first 24-hr period is 12.4 mg m⁻²d⁻¹; 58% less than the rate computed without this correction. Based upon variations among the ten sampling sites, this mean dry deposition rate is significantly different from zero at the 0.001 error level.

The estimate of dry deposition of sulfate for the first measurement period of 12.38 mg m⁻²d⁻¹ is higher than deposition found in past snowpack dry deposition studies. Barrie and Walmsley (1978) reported snowpack dry deposition of sulfate of 4.66 mg m⁻²d⁻¹ during one pollution episode in Canada, Dovland and Eliassen (1977) give a mean value of 5.3 mg m⁻²d⁻¹, and Forland and Gjessing (1975) report values ranging from 0.4 to 2.7 mg m⁻²d⁻¹. It is possible that the blowing ice particles near the snowpack surface in our study enhanced sulfur deposition by exposing a greater surface area to the air than a static snowpack surface. In addition, since Pennsylvania exhibits the highest wet deposition of sulfate in North America, the high value may reflect high atmospheric sulfate contents.

The dry deposition rate measured for the first 24-hr period can be used with atmospheric sulfur concentration data to compute a deposition velocity. Available data indicate for the period that gaseous S equaled 0.0107 mg S m⁻³ and particulate S 0.0016 mg S m⁻³. The deposition rate of 12.38 mg SO₄²⁻ m⁻²d⁻¹ is equal to 4.13 mg S m⁻²d⁻¹ and the indicated deposition velocity is about 0.4 cm s⁻¹. Deposition velocities for SO₂ on snow of about 0.1-0.2 cm s⁻¹ have been previously reported (Hicks, 1984). The higher rate of 0.4 cm s⁻¹ found for the first 24-hr period in this study may reflect the enhanced trapping efficiency of blowing snow particles.

Small negative snowpack sulfate deposition rates were computed for the latter three 24-hr periods (see Table 2, 20 to 23 January). Variations in rates among the ten sampling sites were relatively large on these days and the computed rates for the second and third periods (20 to 21 January and 21 to 22 January, respectively) were not significantly different from zero at the 0.05 error level. However, the negative dry deposition rate

for the final period (22 to 23 January) was significantly different from zero at the 0.001 error level.

Negative dry deposition rates computed for the last three days are probably caused by the uncertainty in the concentration of sulfate used in the correction for blowing snow. It was assumed that all blowing snow had a concentration of 1.77 mg/L sulfate. If the actual concentration of blowing snow had been greater, the correction for blowing snow could have produced zero or positive computed dry deposition rates. For example, sulfate concentrations in blowing snow of 11.8, 3.1 and 5.8 mg/L would have produced zero computed dry deposition rates for the second, third and fourth 24-hr periods, respectively.

Sampling variations among the ten sites indicate a large number of composite samples would be needed to accurately estimate dry deposition rates for the conditions of this experiment. For an estimate accurate within 10% of the mean dry deposition rate at a 0.05 error level; 66, 2500, 1829 and 235 composite samples were needed for the first through fourth 24-hr periods, respectively. As previously indicated, ten composite samples daily were sufficient to give computed dry deposition rates significantly different from zero at the 0.001 error level for two of the four 24-hr periods.

CONCLUSIONS

Snowpack dry deposition can vary drastically with atmospheric and snow surface conditions. Under blowing snow conditions the snowpack experiences large gains of sulfur which may be enhanced by increased contact between the air and ice particles transported by the wind. Zero sulfur exchange can also occur under calm, stable conditions.

Dry deposition rates for snowpacks determined from a snowpack mass balance should be adjusted for changes in snowpack water equivalent and chemical concentration due to blowing snow. It is recommended that the chemical concentrations in blowing snow be measured for the most accurate adjustment in future assessments.

Spatial variations in snowpack sulfur dry deposition rates were quite large in this experiment, necessitating sampling at multiple adjacent locations to obtain representative spatial means.

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TABLE 2
Mean (Standard Deviation) Snowpack Conditions and Computed Dry Deposition Rates for Sulfate With and Without
Correction for Blowing Snow

Date	n	Snowpack Water Equivalent (mm)	[SO ₄ ²⁻] (mg L ⁻¹)	Snowpack SO ₄ ²⁻ (mg m ⁻²)		SO ₄ ²⁻ Dry Deposition Rate (mg m ⁻² d ⁻¹)	
				uncorrected	corrected ¹	uncorrected	corrected ²
1/19/84	10	5.0(0.07)	1.77(0.03)	8.95(2.02)	8.95(2.02)	29.25(13.06)	12.38 ² (5.02)
1/20/84	10	14.5(4.89)	2.62(0.25)	38.20(13.79)	21.33(5.79)	-3.54(16.46)	-2.88(7.21)
1/21/84	10	14.2(2.86)	2.43(0.16)	34.66(8.65)	18.45(3.82)	-5.90(8.95)	-2.60(5.56)
1/22/84	10	12.3(2.68)	2.34(0.25)	28.76(7.10)	15.85(3.68)	-4.07(2.69)	-2.78 ² (2.13)
1/23/84	10	11.6(3.13)	2.14(0.23)	24.69(7.15)	13.08(2.66)		

¹ Corrected for effects of blowing snow.

² Mean rates significantly different from zero at the 0.001 error level.

