Modelling Fogwater Deposition of Sulfate on Roundtop Mountain, Quebec

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SUMMARY

Fogwater deposition and its associated chemistry may have major negative impacts on high altitude forest ecosystems, especially when the fogwater is polluted by anthropogenic emissions, such as sulfate. This paper will describe a wet deposition model to assess the spatial variations of sulfate deposition from fogwater on Roundtop Mountain, in southern Quebec. Features of the fogwater deposition model include: an assumed homogeneous forest canopy, with the tree tops considered to be cones of uniform height; wind speed and wind direction spatial variations at 1.5 m above the canopy are assumed representative; liquid water content of the fog varies with height from the cloud base; the chemistry of the fogwater is assumed to be represented by measurements on Roundtop ridge (845 m MSL). An example of model results for a specific period during summer 1987 will be presented.

INTRODUCTION

The impact of fogwater acidity on forests at higher elevations, has been of concern for the past two decades. Acidity in deposition from fogwater can be several times greater than that for precipitation, and may be a factor in widespread damage to mountain forests (*e.g.*, Mohnen and Kadlecek, 1989; Muller *et al.*, 1991; Saxena and Lin, 1991). Saxena *et al.* (1989) suggested that high elevation fogs with very low pH values have the potential to create injury, and add to natural stresses caused by exposure, wind, and poor soil conditions. The major acid ions of concern include sulfate (SO_4^{2-}) and nitrate (NO_3^-), with SO_4^{2-} normally being the dominant ion (Barrie and Sirois 1986).

Ideally, a spatial assessment of ion deposition, chemistry and fluxes from fogwater, is necessary for a complete understanding of damage to forests. Logistics, however, prevent direct measurement of gross deposition in complex terrain (Mueller *et al.*, 1991). However, an understanding of the spatial patterns of deposition can be obtained with the assistance of simple models, incorporating a characterization of liquid water content, wind flow over the complex terrain, a representative deposition of acid ions to the vegetative surface, parameterisation in terms of mean or median droplet radius, and terrain position (Barrie and Schemenauer 1986; Coe *et al.* 1991).

This paper provides a methodology to estimate the spatial distribution of the wet deposition of SO_4^{2-} over Roundtop Mountain from fogwater. The MS-Micro/3 model (Walmsley *et al.*, 1989; Bridgman *et al.*, 1994) is used to estimate wind variations in the complex terrain of the mountain. Focus is at the top of the canopy with supporting data from field measurements taken during the summer of 1987. Similar work has been undertaken in Europe (Gallager *et al* 1992)

LOCATION

Roundtop Mountain (45°05'N, 72°32'W) (Figure 1) summit is 970 m MSL, and Roundtop Ridge, extending to the northwest of the summit, is at an elevation of 845 m MSL. The Roundtop complex covers an area of about 164 km² at a base elevation of 230 MSL. Roundtop is almost completely covered by 3 to 6 m tall mixed coniferous and deciduous forest. Exceptions include some scattered cleared areas along river banks and in the foothills (mainly below 70 m), the town of Sutton on the western edge and several narrow ski runs through the forest, extending down the north slope from Roundtop Ridge. Schemenauer (1986) found that Roundtop summit is in cloud about 44% of the time during the year; and Roundtop ridge about 38% of the time.

MEASUEMENTS AND METHODOLOGY

Three sites (Summit, Ridge, and Valley, 11 km west) on or near Roundtop were fully instrumented to measure meteorological parameters and collect precipitation and fogwater, as part of the Chemistry of High Elevation Fog (CHEF) project. Details of operation are included in Schemenauer *et al.* (1995). Fogwater was analyzed for inorganic ions using ion chromatography. Measurements of SO_4^{2-} form the basis for spatial distribution analysis in this paper.

The method used to evaluate wind flow over Roundtop was the MS-Micro/3 model, described in detail by Walmsley *et al.* (1986). The details of model results for Roundtop, including wind direction and speed variations, and vector winds, are presented in a separate paper (Bridgman *et al.*, 1994, hereafter BWS94). The model assumes low slope terrain (30%), an isolated feature on an otherwise flat plain, an outer inviscid flow region, an inner region where shear stresses operate, and linear perturbations (driven by pressure gradients in the inviscid layer) which are slope-dependent. Surface roughness variations can be incorporated, but because forest dominated as a surface cover on Roundtop Mountain, roughness was set at a constant value, allowing a more straightforward evaluation of the impact of the terrain on wind and ion deposition. The model adjusts the surrounding terrain to satisfy its requirements for a flat surface (Walmsley *et al.* 1990). The inner and outer layers are blended to create a more realistic overall wind picture. The upwind vertical structure is assumed to follow the universal wind profile. Wind interactions on the mountain from a separate wind reference site some distance upwind can be calculated.

The results of a number of different studies have established that fogwater is deposited at the top of the canopy from stratiform clouds by three major pathways: mixing by turbulent eddies interacting with the tree tops; sedimentation of droplets; and inertial impaction on surfaces (see Saxena *et al.*, 1989 for a review). Of these, impaction is most important, especially at the top of the canopy in a windy environment (>2 m s^{-1}). The amount of deposition is highly site-dependent, based on six factors: canopy inhomogeneity; horizontal wind speed; the collection efficiency of the tree top; the liquid water content of the fog; the change of fog frequency with altitude; and the droplet chemistry. For a size radius of about 3 to 11 μm, representative of much of the fogwater range, Coe *et al.* (1991) suggested that the impact of droplet size can be neglected.

For the Roundtop Mountain spatial analysis, the six factors are handled as follows:

(1) The forest is assumed to be homogeneous, given the horizontal scale involved and considering that the wind fields apply at a height of 3 m above the canopy. The tree tops are considered to be cones of uniform height above ground level, with the cone bases touching adjacent cone bases. The treetop cone angle is 60°, and spacing between the trees centers is 1.73 m. Trees touch 1.5 m from the top. Tree density is 3340/ha. Trees are assumed vertical; deposition is assumed to occur at the canopy top.

(2) Spatial variations in wind speed and direction caused by variations in terrain, are assumed to be adequately described by the MS-Micro/3 model, as applied in BWS94. The trajectories of the droplets are assumed to follow the airflow streamlines, an assumption similar to that used by Coe *et al.* (1991). The deposition of ions from fogwater depends on the angle of the wind to the horizontal plane and the vertical cone.

(3) The collection efficiency of the tree tops is assumed to be represented by the samples from the fogwater collector (Joslin *et al.*, 1990). The tree-top vertical cross-sectional area is assumed equal to the horizontal cross-sectional area of the conical top; *i.e.*, 1 m^2 of vertical cross-section at the canopy top deposits water on 1 m^2 of horizontal surface.

(4) The liquid water content (LWC) of the fog cannot be directly determined from collector sample amounts because of the variation in collector efficiency with wind speed and droplet size (Mueller and Imhoff, 1989). The cloud LWC at different elevations is calculated from cloud base height observations and an assumption that the LWC above cloud base is 38% of the adiabatic value. When compared with the LWC of the fog given by Saxena *et al.* (1989) good agreement is found.

(5) The change in fog frequecny with altitude is assumed to be as described by Schemenauer (1986).

(6) The chemistry of the fogwater is assumed to be represented by the measurements at Roundtop Ridge. This approach is similar to that of Coe *et al.* (1991) and Joslin *et al.* (1990), who treated the cloud as bulk water and assumed an equilibrium between all gas and aerosol species. Although fogwater may have been collected over a longer period of time than the modelling period, it is assumed that the chemistry of the collected fog is representative of that during the modelled periods.

The fogwater flux, defined as the product of liquid water content and wind speed (Joslin *et al.*, 1990), then describes the fogwater deposition at the top of the canopy, with the collection efficiency of the canopy not considered to be a major factor. The fogwater flux increases with height above the cloud base, mainly due to increases in LWC. Sensitivity tests on our combined wind-deposition model established the importance of incorporating a spatially-variable wind field and LWC that varies with height in fog, to make reliable estimates of fogwater deposition of acid ions. To obtain ion deposition estimates, the LWC is multiplied by the ion concentration and appropriate unit adjustments made to provide concentrations as μeq m^{-3} in air. This result is then multiplied by the wind speed to obtain deposition fluxes in μeq m^{-2} s^{-1} across the mountain.

RESULTS AND DISCUSSION

To evaluate the spatial distribution of acid ions on Roundtop, a representative upwind situation, September 12-13, 0900-0900, was chosen as an example. The wind data for this period is presented in Table 1. Model speeds were calibrated with measured speeds at the Valley site. Table 2 presents the input parameters used for the calculations. Parameter $P_c = a_0 + a_1 z$ (MSL) is the percentage of time in cloud at a given MSL altitude.

On 12-13 September, the cloud base was near the altitude of the ridge. A mixed fogwater/rainwater sample was collected in the fog collector on the ridge and was used in Table 2 to represent the fog chemistry for the period.

Table 1

Measured wind speeds (m s^{-1}) and wind directions (°) for the CHEF Valley and Ridge sites on Roundtop Mountain, September 12-13, 1987.

Location	Sept. 12, 1987 0900-0900
Valley	
Direction	175
Speed (3 m)	3.0
Ridge	
Direction	178 ± 10
Speed (3 m)	9.4 ± 0.5

Table 2

Model input parameters: September 12, 0900-0900

Parameter	Units	Sep 12-13
Base altitude	m	230
Valley site elevation	m, MSL	250
Ridge site elevation	m, MSL	845
Summit site elevation	m, MSL	970
Wind direction	°	175
a_0	%	-318.0
a_1	% m^{-1}	0.400
P_c at Summit	%	70
Cloud base height	m, MSL	845
LWC at cloud base	g m^{-3}	0.050
LWC rate of change[1]	g m^{-3} m^{-1}	0.00103
$SO_4^{=}$ concentration[2]	µeq L^{-1}	154

[1]Linear increase with height; 38% of calculated adiabatic rates
[2]Roundtop ridge measurement

Figure 2 shows fogwater deposition for SO_4^{2-} during the September 12 period. The maximum of 284 µeq m^{-2} h^{-1} occurs at the summit. For the period presented, the spatial distribution of SO_4^{2-} is a small proportion of the Roundtop surface area. Depositions of less than 50 µeq m^{-2} h^{-1} exis at Roundtop ridge, increasing to over 200 µeq m^{-2} h^{-1} near the summit. Concentrations measured in fog at Roundtop ridge (Table 2) are considerably higher than those in rainfall (44.7 µeq L^{-1} - Schemenauer *et al* 1995). If such high concentrations, and relatively continuous deposition, exist in persistent fog near the top of Roundtop, there is a strong possibility of acidic damage to the mountain vegetation.

CONCLUSIONS

A model of wind flow over complex terrain has been combined with in situ wind measurements and field measurements of fog chemistry. This has allowed the calculation of wet deposition patterns and amounts on a small forested mountain range in southern Quebec. The model calculates wind speed and direction over the sloping surfaces of the terrain and then calculates fog deposition by impaction at the canopy top. The deposition patterns follow the terrain contours in large part, with the highest deposition from fog in the highest elevation areas. This is primarily due to an increase in both fog liquid water content and wind speed with altitude and to higher fog frequencies at higher altitudes.

The model used here is not the only approach that could have been taken. For example, Dore *et al.* (1992) have redrawn the wet deposition (from precipitation) map for the United Kingdom to allow for the observed changes in precipitation chemistry and amount with altitude observed there. They found increases of deposition of up to 76%. Coe *et al* (1991) examined several models of cloud water deposition to complex terrain in the United Kingdom. The emphasis was on turbulent deposition of cloud water to grass surfaces. They included both cloud microphysics and chemical processes in some of the models and found that the simplest deposition models usually provided good estimated of deposition rates.

The results presented here clearly show that the wet deposition of $SO_4^{=}$ on the higher elevations of Roundtop Mountain can be modelled, showing variations by elevation and location. Concentrations are of considerable importance, and are considerably higher than measured in rainwater (Schemenauer *et al.* 1995). These results strongly indicate that, where regions contain higher elevations, the wet deposition calculations should be adjusted for elevation effects. In particular, if the hills or mountains are frequently covered in fog, the standard deposition calculations using only precipitation will seriously underestimate the true deposition.

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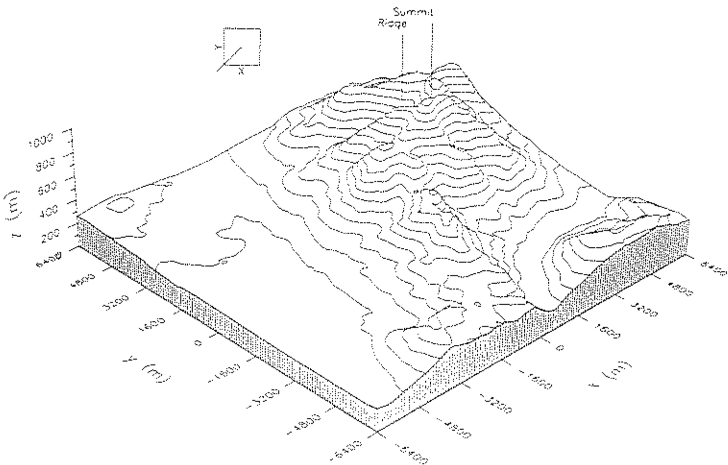

Figure 1
A three-dimensional depiction of the Roundtop Mountain complex in southern Quebec, from an azimuthal direction of 225° (see insert) and an elevation of 30°. The contour interval is 50 m, and the grid resolution is 100 m. The locations of the CHEF ridge and semmit sites are indicated.

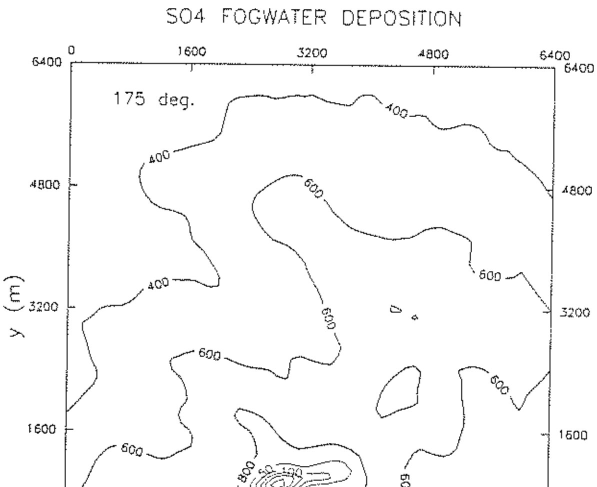

Figure 2
Sulfate fogwater deposition modelled for September 12-13, 1987, 0900-0900. Peak value is 284 μeq m^{-2} h^{-1}; isopleth interval is 50 μeq m^{-2} h^{-1} area shown is a plan view of the northeast quadrant of the area shown in Figure 1. Heavy lines are topographic contours at 200 m intervals.