Cloud-water chemistry and estimated rates of occult deposition in a forested area of the Sumava Mts (south Bohemia, Czech Republic)

V. ELIAS & M. TESAR
Institute of Hydrodynamics of the Czech Academy of Sciences in Prague, Podbabska 13, 166 12 Praha 6, Czech Republic

Abstract The chemical and hydrological fluxes to the mountainous ecosystems via wind-driven, cloud-water droplets are described. The studied area is characterized by both a high fog occurrence and fog-water solution of high ionic concentrations. Fog deposition rates were estimated with the use of a mathematical micrometeorological model. These predictions show that this process can be an important pathway of water and chemicals from the air to the forest canopy. Estimated gross deposition of cloud water is about 10% of the total annual precipitation. Samples of cloud water obtained with the aid of an active collector were analysed for major ions. A wide range of concentrations were encountered. Estimated wet deposition for NH₄⁺, NO₃⁻ and SO₄²⁻ via cloud droplet impaction and sedimentation represents 1360, 264 and 2936 kg km⁻² year⁻¹, respectively (i.e. 164, 11 and 72% with respect to weighted mean precipitation). Wind-driven clouds from the north and west regions are shown to be associated with the lower concentrations, in contrast to radiation fogs coming from the east and south sectors.

INTRODUCTION

The deposition of water and chemicals to vegetation from wind-driven clouds and fogs has long been recognized as an important hydrological input in many mountainous and coastal environments (Lovett et al., 1982). Since the concentration of chemical species is several times higher in cloud water than in precipitation, the chemical deposition associated with cloud and fog droplet interception by vegetation can be significant, or even predominant, with respect to deposition due to precipitations (Fuzzi et al., 1985; Wong et al., 1991).

Despite the importance of horizontal precipitation, estimates of the amount of cloud water deposition are still crude. A demonstration of the methods for prediction of occult precipitation and a discussion of their applicability is given by Lovett (1988).

CHARACTERIZATION OF THE SUMAVA MTS

The chemical and hydrological significance of horizontal precipitation has been suggested for the higher elevation zones of the Sumava Mts. These zones, especially above an elevation of 1000 m above sea level, are characterized by high wind speeds, lengthy periods of cloud and fog immersion, and coniferous vegetation, all of which
contribute to high potential rates of cloud droplet capture. In this region fog frequency ranges from 4 to 15% (Strnad et al., 1988) depending on the intensity of fog. The climate of this zone is cold (the mean annual temperature is about 5°C), wet (the amount of annual rainfall is roughly from 650 to 1500 mm) and windy (the annual average wind speed is roughly 10 m s\(^{-1}\)), the snow cover in the highest parts is from 120 to 150 days a year, the soils are thin and rocky. The sampling site is located at an elevation of 1123 m a.m.s.l. on the Churanov hill top (13°36'56"E, 49°04'08"N).

In order to explore the natural environment, especially from the hydrological and ecological point of view, an experimental base was established in the vicinity of the above mentioned sampling site in 1975. Two experimental forested watersheds Liz (0.99 km\(^2\)) and Albrechtec (1.61 km\(^2\)) were founded. These two catchments form coupled forested drainage basins of the mountainous type. The conclusions of our studies concerning cloud-water chemistry and amount will serve as input data for these catchments.

**METHODOLOGY**

A resistance model of the deposition of cloud droplets to a spruce forest canopy (Lovett, 1984) has been tested. The model is composed of two sub-models, the first simulating a turbulent diffusion of cloud droplets into the forest and their deposition on to foliar and branch surfaces, and the second simulating the evaporation/condensation process under cloud-immersion conditions in the forest. Both the cloud deposition model and the evaporation/condensation models have been described by Lovett (1982, 1984, 1988). Although these models depend on the estimation of a number of parameters whose accurate measurement is difficult (the leaf area index, the droplet size distribution and the cloud liquid-water content), it represents a very instructive tool enabling estimation of both gross and net deposition (total cloud-water deposition minus total evaporation) and examination of their reactions to changes in meteorological and canopy structure parameters. For calculating the ion deposition via cloud-water, a direct estimate of gross water input is needed which is why we have applied the above-mentioned model. Some canopy structure parameters are described by Thorne et al. (1982) and Lovett & Reiners (1986).

In order to estimate the cloud liquid-water content (LWC) and to gain cloud-water samples, the sample taking device was constructed: an active CWP collector as described by Daube (1987). Collectors of this type have been used during relatively extensive fog research in the USA and the measured data were published (Weathers et al., 1988). The CWP active cloud-water collectors are constructed of chemically inert materials; the inlet is located on the bottom of the collector to avoid the collection of rain water.

Receptor orientated air trajectories arriving at the sampling site were used to trace the movement of the sampled air during the 72 h preceding the sampling (Ogren & Rodhe, 1986). The trajectories were constructed as isobaric and based on the 850 hPa geostrophic winds.

**RESULTS AND DISCUSSION**

The results of model predictions of gross cloud droplet deposition, net cloud droplet
deposition and simulated cloud water deposition velocity (gross flux divided by the liquid water content) are \(0.505 \times 10^{-3} \, \text{g cm}^{-2} \, \text{min}^{-1}\), \(0.175 \times 10^{-1} \, \text{cm h}^{-1}\) and \(20.9 \, \text{cm s}^{-1}\), respectively. Model predictions were made for canopy structure parameters in harmony with the literature (Lovett & Reiners, 1986) for the similar state of growth of the chosen spruce forest. Furthermore, the estimates were made for annual mean meteorological conditions during cloud and fog events according to Strnad et al. (1989), with wind speed 3.2 m s\(^{-1}\), relative humidity 96\%, cloud-water content 0.4 g m\(^{-3}\), mean droplet diameter 10 \(\mu\)m, net radiation 0.071 cal cm\(^{-2}\) min\(^{-1}\) and air temperature \(-0.2^\circ\)C. If we assume that the spruce forests in the Sumava Mts are immersed in clouds and fogs for 322 h year\(^{-1}\) on average and that, for 104 h year\(^{-1}\), rime-ice accretion reduces the deposition rate by 50\% according to Lovett et al. (1982), then the estimated annual gross deposition of cloud-water is 81 mm year\(^{-1}\), while the net deposition is 47 mm year\(^{-1}\). These estimates are admittedly crude, but they certainly are the best estimates available.

Over a time period from October 1989 to October 1992, 40 samples of fog water were collected in the Sumava Mts. Analytical results are summarized in Table 1. These concentrations have not been weighted for sample volume. Nevertheless, it is of interest to note the high concentrations of the major ions in cloud and fog water. Table 2 brings a comparison between calculated deposition due to fog and measured deposition via precipitation both on an annual basis. Higher concentrations of NH\(_4^+\) and SO\(_4^{2-}\) ions may be explained by the relatively high intensity of agricultural activities between 4 to 8 km from the Churanov station. Ammonia is formed as a result of bacteriological and fungal transformation of urea in manure and fertilizers. In this area about 3500 cows were

<p>| Table 1 Chemical analyses of fog water collected in the Sumava Mts from 30 October 1989 to 11 October 1992. |
|---------------------------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Fog</th>
<th>Rain</th>
<th>Mean*</th>
<th>Enrichment factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Range</td>
<td>Average</td>
<td>Mean*</td>
</tr>
<tr>
<td>conductivity [(\mu)S cm(^{-1})]</td>
<td>23.2-854</td>
<td>267</td>
<td>25.5</td>
</tr>
<tr>
<td>Na(^+) [mg l(^{-1})]</td>
<td>0.09-5.17</td>
<td>0.97</td>
<td>0.10</td>
</tr>
<tr>
<td>K(^+) [mg l(^{-1})]</td>
<td>0.12-7.91</td>
<td>1.09</td>
<td>0.09</td>
</tr>
<tr>
<td>NH(_4^+) [mg l(^{-1})]</td>
<td>0.1-50.8</td>
<td>16.8</td>
<td>0.67</td>
</tr>
<tr>
<td>Mg(^{2+}) [mg l(^{-1})]</td>
<td>0.06-2.86</td>
<td>0.48</td>
<td>0.05</td>
</tr>
<tr>
<td>Ca(^{2+}) [mg l(^{-1})]</td>
<td>0.66-33.4</td>
<td>5.13</td>
<td>0.34</td>
</tr>
<tr>
<td>F(^-) [mg l(^{-1})]</td>
<td>0.02-0.7</td>
<td>0.26</td>
<td>0.02</td>
</tr>
<tr>
<td>Cl(^-) [mg l(^{-1})]</td>
<td>0.65-10.3</td>
<td>3.24</td>
<td>0.27</td>
</tr>
<tr>
<td>NO(_3^-) [mg l(^{-1})]</td>
<td>0.35-134</td>
<td>36.35</td>
<td>2.03</td>
</tr>
<tr>
<td>SO(_4^{2-}) [mg l(^{-1})]</td>
<td>2.83-132</td>
<td>39.44</td>
<td>3.29</td>
</tr>
</tbody>
</table>

* Precipitation-weighted means for the central part of the Sumava Mts according to Santroch et al. (1989).
Table 2  Comparison between calculated deposition due to fog and measured mean weighted precipitation deposition on an annual basis (1986 and 1987). Total water deposition is also reported.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Weighted precipitation yearly deposition* (Py) [kg km⁻² year⁻¹]</th>
<th>Fog deposition (F) [kg km⁻² year⁻¹]</th>
<th>F/Py [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>123.8</td>
<td>44.8</td>
<td>36</td>
</tr>
<tr>
<td>K⁺</td>
<td>111.4</td>
<td>48.8</td>
<td>44</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>61.9</td>
<td>26.4</td>
<td>43</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>420.9</td>
<td>279.2</td>
<td>66</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>829.4</td>
<td>1360.0</td>
<td>164</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>334.2</td>
<td>245.6</td>
<td>73</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>2513.1</td>
<td>264.0</td>
<td>11</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>4073.0</td>
<td>2936.0</td>
<td>72</td>
</tr>
<tr>
<td>F⁻</td>
<td>24.8</td>
<td>20.8</td>
<td>84</td>
</tr>
</tbody>
</table>

Water deposition (mm) 1160.0 81.0 7

* Precipitation-weighted mean deposition according to Santroch et al., 1989.

stable and a high input of fertilizers containing urea was applied here. Ammonia is very soluble in water. Under foggy and cloudy circumstances the major amount of atmospheric NH₃ is present in the water phase, where NH₄⁺ is formed. Also airborne NH₄⁺ aerosols are absorbed by these water droplets, or form condensation nuclei to form droplets. Ammonia causes an increase of the pH of water droplets, causing a higher oxidation rate of SO₂ to SO₄²⁻ and an increased uptake of SO₂ into the alkalized drops. By these processes the wet deposition of SO₄²⁻ is enhanced by an increased NH₄⁺ concentration. Solution of NH₃ in water occurs more efficiently in clouds than in falling rain drops (Adema et al., 1988).

The above mentioned receptor-orientated trajectories were grouped into four sectors according to the direction of their arrival: west (NW, W, SW), south (S), east (SE, E, NE) and north sector (N). Examples of trajectories are given in Fig. 1. The most sampled fogs and low cloud came to the sampling site from western sector (see Fig. 2) despite the fact that most fogs occurring in this region come from an easterly direction. Lower concentrations of chemicals were encountered in the west and north sectors, in contrast to cloud water coming from the east and south sectors. This difference is attributed to the fact that the fogs and clouds coming from a south and east direction have advection and radiation origins, but the fogs from the west and north sectors are frontal often accompanied by rain, which washes out the chemical species. The above-mentioned agricultural activity also occurs in the east sector. The variability of SO₄²⁻ and NH₄⁺ according to the direction of trajectories is given in Figs 3 and 4, respectively.

Conclusions

Without wishing to generalize the above reported findings, the results clearly show that
Fig. 1 Examples of trajectories coming at the sampling site on indicated dates (these examples represent heavy polluted fogs coming from the east sector). Each arrow represents 24 h.

Fig. 2 Frequency of receptor-oriented air trajectories arriving at the sampling site on sampled days (40 samples).
in the examined area (Sumava Mts) the combined effect of high fog frequency and high ionic concentration of the solution droplets result in wet deposition rates for chemical substances which can be important to the environment. From the above results these conclusions can be drawn:

(a) The gross water input via cloud- and fog-water represents about 10% of the total...
annual vertical precipitation. This amount of water represents the direct water-input
to our two small experimental catchments.

(b) Concentrations of major ions in cloud- and fog-water are approximately 15 times
greater (so called enrichment factor reaches values from 10 to 25).

(c) Cloud-water droplet deposition can increase wet deposition of $\text{SO}_4^{2-}$, $\text{NO}_3^-$ and
$\text{NH}_4^+$ by 72, 11 and 164%, respectively. This transport represents 2936, 264 and
1360 kg km$^{-2}$ year$^{-1}$, respectively. These amounts of chemical species represent
direct mass inputs to our two small experimental watersheds.

(d) Transport of air from the north (N) and west (NW, W, SW) regions is shown to be
associated with lower concentrations, while the higher concentrations occurred in
conjunction with transport from the east (NE, E, SE) regions. The lower concentra-
tion of west fogs may be explained by the fact that fogs coming from west region are
largely the frontal ones often connected with rain events.

REFERENCES


which reduce rain contamination. *Atmos. Environ.* 4, 893-900.


and chemical inputs. *Science* 218, 1303-1304.

18(2), 361-371.

38B(5), 319-327.

Lovett, G. M. (1988) A comparison of methods for estimating cloud water deposition to a New Hampshire (USA) subalpine


25(6), 1014-1021.

1026.