Reports

Cloud Droplet Deposition in Subalpine Balsam Fir Forests: Hydrological and Chemical Inputs

Abstract. *Subalpine forests of the northern Appalachians are subject to significant deposition of water and chemicals via cloud droplet impaction. This deposition has been estimated by a method linking micrometeorological measures of turbulent transfer, a detailed representation of canopy structure, and experimentally derived capture efficiencies. Water inputs from clouds are about 46 percent, and chemical inputs range from 150 to 430 percent of the bulk precipitation.*

The deposition of water to vegetation from wind-driven clouds has long been recognized as an important hydrological input in many mountainous and coastal environments (*1*). The chemical and hydrological significance of this phenomenon has been suggested for the higher elevational zones of the northern Appalachian Mountains (*2, 3*). Orographic enhancement of precipitation alone would cause greater deposition of water and scavenged chemicals to these ecosystems than to surrounding lowlands (*3*). In addition, the subalpine zones, especially above an elevation of ~ 1200 m, are characterized by high wind speeds, lengthy periods of cloud immersion, and coniferous vegetation (*4*), all of which contribute to high potential rates of cloud droplet capture. Air masses passing over this region contain high concentrations of mineral acids, trace metals, and NH_4^+ (*5*). Thus, precipitation combined with cloud capture can lead to exceptionally high rates of deposition of potentially harmful and beneficial substances in these high-elevation ecosystems (*6*).

Earlier investigators of cloud droplet deposition (*1, 2*) have measured the rates of cloud water collection with artificial collectors. Because of the complexity of the forest canopy structure, these results cannot readily be extrapolated to cloud water capture by an actual canopy.

A more direct procedure is to determine the rate of water deposition to the forest floor as throughfall (TF) and stemflow (SF) during cloud immersion. We are currently making such measurements in the subalpine balsam fir [*Abies balsamea* L. (Mill)] forests in the mountains of New Hampshire. Our results typically show SF + TF rates of several tenths of a millimeter per hour. Even direct measurements of SF and TF are hard to extrapolate, however, for several reasons: (i) a large number of biological and meteorological factors influence cloud water deposition, making it extremely variable in space and time; (ii) since some of the deposited cloud water evaporates from the canopy (*7*), measurement of SF and TF gives an estimate of net, rather than gross, cloud water deposition; and (iii) chemical alteration of the deposited solution by the canopy prohibits its estimation of ion deposition from an analysis of SF and TF. To calculate ion deposition via cloud water, a direct estimate of gross water input is needed. Consequently, we have developed models of deposition and evaporation which allow us to estimate both gross and net deposition and to examine how they respond to changes in meteorological and canopy structure parameters.

We visualize the exchange of cloud droplets and water vapor between the canopy and the atmosphere as encompassing two aerodynamic regimes. Within these regimes, fluxes are calculated as the ratio of potential (concentration) gradients and resistances. The appropriate gradients are the cloud liquid water content for cloud water deposition and the vapor pressure deficit for evaporation. The leaf surfaces are assumed to be saturated and perfect sinks for cloud droplets.

The first regime is the crown space of the canopy, where air is mixed by turbulent eddies. We partitioned this space into layers 1 m high and calculated the transfer resistances between the layers from the aerodynamic roughness of the canopy and the canopy-top wind speed (*8*).

The second aerodynamic regime encompasses the boundary layers surrounding the individual canopy surfaces. Here water vapor moves primarily by molecular diffusion, whereas cloud droplets penetrate by inertial impaction (*9*). Resistances to vapor transfer through this regime have been determined for conifer shoots (*10*). We have measured the boundary layer resistances to droplet impaction for six canopy components (*11*) on the basis of wind-tunnel experiments (*12*). At each height level, the boundary layer resistances for all canopy components are summed in parallel. To convert these resistances to a ground-area basis, we divide by the appropriate ratio of component surface area to ground area. These ratios were determined by sampling in subalpine forests (*13*).

Similar models have been developed for evaporation (*14*) and for the deposition of other atmospheric substances (*15*). They consist of systems of simultaneous linear equations relating fluxes to the ratio of concentration gradients and resistances for each stratum in the canopy; the equations are easily solved by matrix algebra in a computer. The solution requires knowledge of several canopy-top meteorological parameters (*16*). In the results presented here, we use canopy structure data from a typical, monospecific stand of balsam fir 10.3 m tall. Model predictions, based on the use of measured meteorological parameters, are within 7 percent of the observed net deposition rates as measured by SF-TF collections during four cloud events in a real 10.3-m stand.

Table 1. Model predictions of gross cloud droplet deposition (100 percent relative humidity) and net cloud droplet deposition rates (in millimeters per hour) at various values of wind speed (u) and relative humidity (R.H.). Wind speeds are for the canopy top, not free-stream values; cloud liquid water content = 0.4 g m^{-3}; mean droplet diameter = 10 μm; net radiation = 0; temperature = 1°C.

R.H. (%)	u (m sec^{-1})		
	2	4	6
100	0.12	0.32	0.54
99	0.11	0.30	0.51
97	0.08	0.26	0.46
95	0.05	0.22	0.40

Predictions of gross and net (that is, gross minus evaporation) droplet deposition fluxes for a realistic range of wind speeds and relative humidities are shown in Table 1. Gross deposition is sensitive to wind speed, and net deposition is sensitive to both wind speed and relative humidity. The simulated cloud water deposition velocity (gross flux divided by the liquid water content) for this

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Table 2. Annual ion deposition by cloud droplet capture and bulk precipitation at an elevation of 1220 m in a 10.3-m balsam fir stand on Mount Moosilauke, New Hampshire. (See text for sources of cloud deposition.) Bulk precipitation values are based on Dingman's (*3*) estimate of incident precipitation and Cronan's (*23*) estimate of ionic concentrations in the bulk precipitation.

Ion	Cloud deposition (kg ha^{-1} year^{-1})	Bulk precipitation (kg ha^{-1} year^{-1})	Percentage of sum contributed by clouds
H^+	2.4	1.5	62
NH_4^+	16.3	4.2	80
Na^+	5.8	1.7	77
K^+	3.3	2.1	61
SO_4^{2-}	275.8	64.8	81
NO_3^-	101.5	23.4	81

stand, for a wind speed of 4 m sec^{-1} and a cloud with a modal droplet size of 10 μm, is 23 cm sec^{-1}.

If we assume (i) annual mean meteorological conditions as listed in Table 1 (*17*), with a wind of 4 m sec^{-1} and a relative humidity of 97 percent (typical conditions measured during cloud events at our subalpine field site), (ii) that these forests are immersed in clouds 40 percent of the time (*4*), and (iii) that rime ice accretion reduces the deposition rate by 50 percent for 6 months of the year (*18*), then our estimated annual gross deposition of cloud water is 84 cm and the net deposition is 68 cm. These estimates are admittedly crude, but they are probably conservative and are certainly the best estimates available. Our estimate of annual gross flux is almost half the estimated annual precipitation of 180 cm (*3*).

The concentrations of dissolved substances are usually higher in cloud water than in rain or snow (*19, 20*). We have analyzed the concentrations of six chemical species from ten cloud events including two in autumn 1980, two in winter 1981, and six in summer 1981 (*21*). Cloud droplet chemistry is highly variable within and between cloud events, and so there is no precise concentration value for any substance. Means with standard deviations (in microequivalents per liter) are as follows: H^+, 288 (193); NH_4^+, 108 (89); Na^+, 30 (29); SO_4^{2-}, 342 (234); NO_3^-, 195 (175); and K^+, 10 (4). These values are within the range of analogous values measured in 1979 at the summit of Whiteface Mountain, 180 km west of our site (*19*). By multiplying these concentrations by our estimate of gross deposition (84 cm year^{-1}), we have estimated the annual deposition of these ions via cloud water (Table 2). Also shown in Table 2 are estimates of the deposition by bulk precipitation and the percentage contribution of cloud droplet deposition to the sum of both sources. Ignoring cloud deposition would lead to a serious underestimate of the total influx. These data suggest extremely high rates of total atmospheric deposition of both beneficial substances, such as inorganic nitrogen, and potentially detrimental ones, such as mineral acids and trace metals. As a result, subalpine ecosystems may show the most exaggerated accumulations and effects of these substances in the northeastern United States (*2, 6, 22*).

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References and Notes

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7. The evaporation is driven by high winds and the small saturation deficit that normally exists in orographic clouds and fogs [H. R. Pruppacher and J. D. Klett, *Microphysics of Clouds and Precipitation* (Reidel, Dordrecht, Netherlands, 1978)].
8. Following A. S. Thom [in *Vegetation and the Atmosphere*. vol. 1, *Principles*, J. L. Monteith, Ed. (Academic Press, London, 1975), p. 57], we calculated canopy-top turbulent diffusivity (K_m) from specified canopy-top wind speeds and knowledge of the canopy zero-plane displacement (d) and roughness length (z_0) (820 and 105 cm, respectively). We assumed that K_m would decrease exponentially within the canopy as a negative function of cumulative canopy surface area index. We calculated the resistances by integrating $1/K_m$ between height layers.
9. In windy environments such as these, sedimentation accounts for < 5 percent of the total amount of cloud water delivered.
10. J. J. Landsberg and A. S. Thom, *Q. J. R. Meteorol. Soc.* **97**, 565 (1971).
11. These components include needle-bearing twigs (i) ≤ 2 years old, (ii) > 2 years old and retaining < 75 percent of their needles, and (iii) > 2 years old and retaining < 75 percent of their needles, plus bare twigs 0 to 1 cm, 1 to 2 cm, and 2 to 3 cm in diameter.
12. Representative samples were exposed to monodisperse droplets at controlled wind speeds in a low-speed wind tunnel. Capture efficiencies for each component type were expressed as a function of Stokes number (a nondimensional inertial parameter) [see S. Twomey, *Atmospheric Aerosols* (Elsevier, Amsterdam, 1977), pp. 56–60]. The boundary layer resistance of each canopy type was computed as the inverse of the product of capture efficiency and wind speed.
13. G. M. Lovett, thesis, Dartmouth College (1981). Individual trees were sampled by a stratified clip method, and component densities were regressed against tree height, measurement height, and stand density. Coefficients of determination ranged from, 0.50 to 0.80 for the different component types.
14. P. E. Waggoner, G. M. Furnival, W. E. Reifsnyder, *For. Sci.* **15**, 37 (1969). Our model differed from this in that we assumed a wet canopy and therefore ignored stomatal resistance. Because the forest floor is nearly always wet in the subalpine zone, we assumed that the net radiation reaching the forest floor was balanced by evaporation and we ignored heat storage in the soil.
15. P. E. Waggoner, in *Vegetation and the Atmosphere*, vol. 1, *Principles*, J. L. Monteith, Ed. (Academic Press, London, 1975), p. 205; *BioScience* **21**, 455 (1971). Our model differs from the latter in ignoring stomatal resistance (not relevant to the deposition of droplets), in not predicting concentrations in the air above the canopy, and in adding more detail to the within-canopy processes.
16. These include wind speed, net radiation, temperature, relative humidity, and the cloud parameters of liquid water content and modal droplet size. We assumed that wind speed and net radiation decrease exponentially within the canopy on the basis of extinction coefficients that we measured in the field. Using the method of A. C. Best [*Q. J. R. Meteorol. Soc.* **77**, 418 (1951)], we partitioned the liquid water content of the cloud into three drop size classes (0 to 10, 10 to 20, and 20 to 30 μm).
17. The temperature data are from (*4*), and the use of the zero net radiation value assumes that clouds occur with equal frequency during day and night. The cloud data are typical values from our own measurements and those published by the Mount Washington Observatory, N.H. (Quarterly Progress Reports for January, April, and July 1951), which constitute the most complete synopsis of New England orographic cloud characteristics available.
18. This reduction is based on a simulation of the effects of rime accumulation on the capture efficiency of a shoot during the course of a cloud event.
19. P. D. Falconer and J. A. Kadlecek, *Cloud Chemistry and Meteorological Research at Whiteface Mountain: Summer 1979* (Publication 748, Atmospheric Science Research Center, Albany, N.Y., 1980), pp. 1–42.
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21. The H^+ was measured with dual electrodes and a *p*H-meter; NH_4^+, SO_4^{2-}, and NO_3^-, with standard Technicon Autoanalyzer techniques; and Na^+ and K^+ with a flame photometer attached to the Autoanalyzer.
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