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Measurements of cloud water deposition on vegetation using a lysimeter and a flux gradient technique

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ABSTRACT

The deposition of cloud droplets onto moorland vegetation has been measured using two independent methods. Vertical gradients in wind velocity and liquid water content (LWC) provided cloud deposition fluxes of typically 10 mg m^{-2} s^{-1} and deposition velocities (v_g) in the range 21 to 39 mm s^{-1} for droplets with a number mean radius in the range 6 to 7 μm. In these conditions, the aerodynamic resistance provided the major limitation to deposition rates contributing 60% of the overall transfer resistance. Simultaneous measurements of net water exchange between the atmosphere and the ground using a lysimeter showed that the bulk of the water (typically 80%) was deposited as a vapour flux onto frozen soil within the lysimeter. The vapour deposition continued to dominate the water flux measurements until the frozen soil thawed. The measurements show that cloud water deposition at Great Dun Fell (altitude 847 m asl) may increase annual wet deposited SO_4^{2-}, NO_3^-, H^+ and NH_4^+ by 12%, but if such high altitude sites were afforested, the increase would be 44%.

1. Introduction

The interception of cloud water droplets by vegetation has been widely observed (Hori, 1953; Rutter, 1975), but for most sites, it is generally a minor component of the hydrological budget. The process of fog or cloud water deposition at the ground has therefore been largely ignored by hydrologists. Trees growing in coastal regions that are frequently exposed to wind-driven fog represent a special case, and such sites (e.g., on the North Californian and Oregon coast) may receive a large additional annual input of water through this mechanism. Tall vegetation has even been considered as a means of reducing the effects of sea fogs in coastal areas (Hori, 1953).

More recently, interest in the fate and effects of industrial sulphur and nitrogen oxide emissions has stimulated studies of cloud chemistry and deposition (Lovett, 1984). The stratus clouds which frequently envelop the land above 500 m asl in Britain contain large concentrations of the major ions SO_4^{2-}, NO_3^-, NH_4^+ and H^+ in the range 50 to 2000 μeq l^{-1} (Dollard et al., 1983; Fowler et al., 1988). Similarly, large concentrations have been observed at mountain sites in West Germany and in the Adirondak Mountains in NE America (Schmitt, 1988; Weathers et al., 1988). These large concentrations have attracted the interest of physiologists and ecologists in their search for the causes of recent declines in the health of spruce and fir in Europe and North America (Krause et al., 1986).

Rates of deposition of cloud water on to forests have been measured indirectly by collecting the yield of "intercepted water" in throughfall and stemflow below the tree canopy (Lovett, 1986; Hori, 1953). For shorter vegetation Dollard et al. (1983) measured cloud water deposition using a micrometeorological technique. Large rates of deposition were demonstrated and the rates of deposition appeared to be limited only by rates of turbulent diffusion towards the intercepting surfaces. Theoretical aspects of the interception of cloud droplets by vegetation have been considered by Shuttleworth (1977), and evaporation

of water from vegetation while cloud water droplets are being deposited has been discussed by Unsworth (1984) and by Milne et al. (1988). No direct measurements of cloud water deposition have been reported.

The study reported here was designed to obtain measurements of the rates of cloud water deposition onto moorland vegetation at Great Dun Fell simultaneously by two independent methods: (i) a direct measurement of the cloud water flux to the ground using a very sensitive lysimeter and (ii) a micrometeorological, flux/gradient technique. The combination of these two very different techniques, would, it was hoped, also provide a test of micrometeorological methods at a non-ideal site.

2. Methods

2.1. *Micrometeorological method*

In its simplest form, the one-dimensional vertical flux of cloud droplets (F_p) is obtained as the product of the eddy diffusivity (K_p) for the droplets and the vertical gradient in liquid water content ($\partial x/\partial z$)

$$F_p = K_p \partial x/\partial z. \quad (1)$$

The eddy diffusivity for cloudwater (K_p), which is assumed in neutral atmospheric conditions to be identical to that for momentum, is obtained from measurements of the wind velocity (u) profile with height (z) which, over extensive, uniformly rough terrain has a logarithmic form and is discussed by Thom (1975) among others:

$$U_z = \frac{U_*}{k} \ln\left(\frac{z-d}{z_0}\right), \quad (2)$$

where U_* is the friction velocity, k is von Karmans' constant, from which

$$K_p \; (\simeq K_m) = kU_*(z-d). \quad (3)$$

In planning experiments, it was considered that at the site chosen, at an altitude of about 600 m asl with 10 m windspeeds generally in excess of 10 m s^{-1} and measurements made in cloud, the lowest few metres at the atmosphere would be thermally neutral. It was therefore assumed that there would be no requirement for air temperature profile measurements to correct for stability or instability effects. In practice, the vapour flux onto the moorland surface resulted in a large latent heat release at the surface, the effects of which are considered in Section 4.

2.2. *The site*

The site, 620 m asl on the west facing slopes of Great Dun Fell (Fig. 1) is covered by moorland vegetation comprising *Eriophorum* and *Juncus* with a "canopy" height of about 15 cm. The slope of the ground in the upwind sectors from SSW through W to NNW is less than 5% within 70 m of the mast, but the land is not perfectly flat. Undulations of ± 0.5 m are common along the moorland surface and individual tussocks of the dominant vegetation (*Eriophorum*) which are typically 0.4 cm in height and 0.25 cm across, present further irregularities in the fetch. Despite these irregularities, the wind profiles showed a remarkably uniform log/linear form (Fig. 2) for the wind directions noted above. The roughness length (Z_0) and zero plane displacement were consistently 1.0 cm and 5.0 cm, respectively, throughout the fetch sectors.

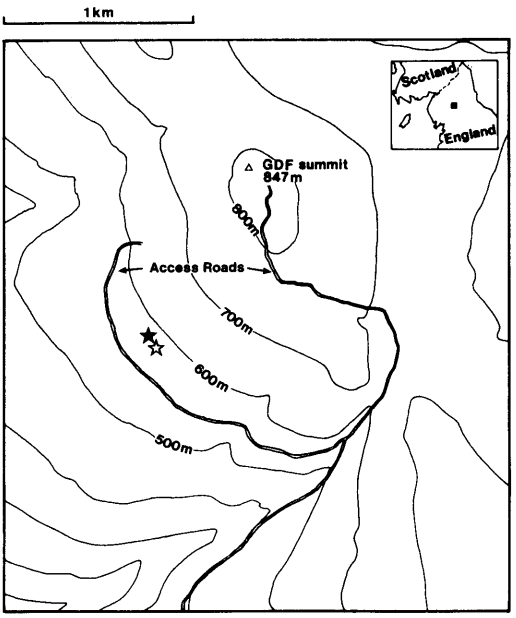


Fig. 1. The location of Great Dun Fell and the topography surrounding the site of cloud deposition measurements.

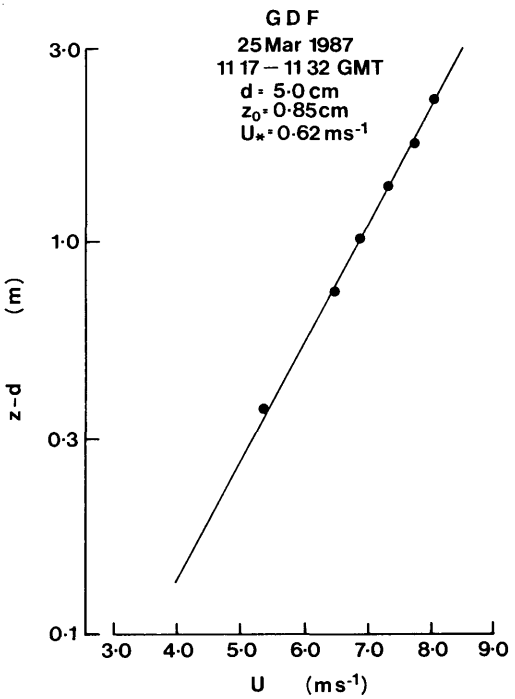


Fig. 2. A typical wind velocity profile from the measurements on 25 March 1987 (wind direction 248°).

2.3. *Wind speed and cloud liquid water measurements*

The wind speed measurements were made using 6 sensitive cup anemometers (Vector instruments) arranged at 0.4, 0.8, 1.0, 1.5, 1.8, 2.2 m above the ground. All anemometers were calibrated prior to the field measurements against a Pitot static velocity probe in a wind tunnel with a cross section of 2 m.

Additional wind velocity and direction measurements were made at 10 m on a separate mast. Air temperature at 2 m was also monitored.

Cloud liquid water content measurements were made using Knollenberg forward scattering spectrometer probes (FSSP-100) at two heights (0.5 and 1.5 m) above the vegetation. These instruments were calibrated prior to the field measurements using methods described by Choularton et al. (1986) and compared in the field by sampling at the same height above the vegetation to eliminate systematic differences, relative differences between the instruments being more important for these measurements than absolute accuracy.

Data from the FSS probes was recorded at 1 Hz to provide 1-min averages of the size distribution of cloud water droplets and the cloud liquid water content (LWC). These were later averaged over 15 min to provide the LWC's at two heights, which in combination with wind velocity measurements yielded the average fluxes for comparison with the lysimeter measurements.

The FSS probes were intercompared to determine channel-by-channel normalization factors with the intention of determining the deposition velocity as a function of droplet size. However, these intercomparisons, while providing agreement on total liquid water content (LWC) measurement to better than 5% (which is adequate for detection of the expected vertical gradients which provides typically 15% differences between heights), did not provide statistically reliable normalization factors for the smallest and largest channels. A later investigation of the droplet size dependence of deposition velocity at this site following a more extensive intercomparison has been reported by Gallagher et al. (1989).

2.4. *Lysimeter method*

The second method to measure cloud droplet deposition used a sensitive weighting lysimeter and consisted of a section of the hillside vegetation and soil supported by an electronic balance (Fig. 3).

The electronic balance which was enclosed in a weatherproof housing had a sensitivity of ± 0.1 g, an accuracy of ± 0.5 g and weight capacity up to 30 kg.

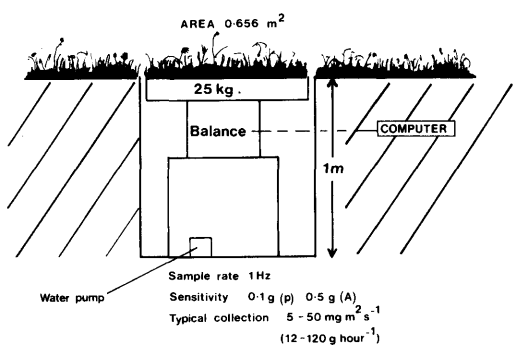


Fig. 3. The weighing lysimeter used for cloud water deposition measurements.

The lysimeter pan which is placed on the weighing pad of the balance had an area of 0.656 m^2 and a depth of 5 cm. This pan was watertight so that when the ice melted, no drainage occurred.

A section of the vegetation from the site was placed in the lysimeter pan, the thickness of the turf being about 5 cm (Fig. 3). At the time of the measurements, the hillside was frozen to a depth of about 10 cm measured during cutting of the turf section. The balance with the vegetation and soil were placed in a hole cut into the hillside and drained using a submersible pump. The turf on the polypropylene tray fitted the surface of the hole so as to restore the original profile of the site. In cloud, the lysimeter collection rate varied between 5 and 50 mg m^{-2} s^{-1} (12–120 g h^{-1} for the lysimeter pan).

Data from the balance were sampled at a rate of 1 Hz and 1-min averages computed. These 1-min average values smoothed most of the wind noise from the signal, but the remaining effects of turbulence which were still apparent are further smoothed when the mean rate of weight change is computed for the 15-min periods to match the micrometeorological sampling periods.

3. Results

3.1. Lysimeter measurements

The measurements were made over 2 days: 24–25 March 1987. On 24 March when measurements began (1730 GMT), cloud base was approximately 500 m asl and liquid water content of the cloud at the experimental site was in the range 0.20 to 0.30 g m^{-3}. Wind speed at 2 m was between 10 and 12 m s^{-1} and wind direction provided a uniform fetch of between 100 and 200 m. Air temperature 2 m above ground was approximately 2.5°C and total solar radiation was less than 10 W m^{-2} (it was almost dark). The surfaces of the vegetation were wet, but the underlying peat and soil was frozen to a depth of approximately 10 cm from the preceding month of cold weather.

Following installation of the lysimeter earlier in the day, and calibration checks with standard weights, the weight gain with time of the lysimeter was monitored throughout the period 1700–2214 GMT. The site was in cloud throughout the measurement period and Fig. 4a shows the weight gain with time plotted from the 1-min averages.

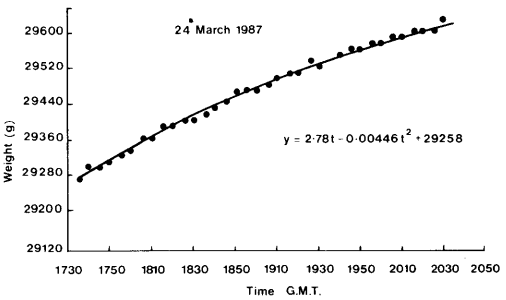


Fig. 4. The weight gain of the lysimeter with time on 24 March 1987 in the presence of wind driven cloud (no precipitation). The fitted line is that of a quadratic, providing the best fit ($r^2 = 0.99$).

The flux of water to the lysimeter throughout the first 100 min was almost constant at about 2.7 g/min, equivalent to about 70 mg m^{-2} s^{-1}. The deviations about the line were caused by turbulence, but over the 15-min sampling periods for comparisons with the flux gradient studies, these deviations have only a minor effect on the slope of the line (Fig. 4). As there was no precipitation throughout the measurement period, the weight gain by the lysimeter was due entirely to cloud water deposition and any vapour exchange between the lysimeter and the atmosphere.

The fitted line in Fig. 4 is a quadratic and shows the very slow decrease in the weight gain with time, the flux during the last 90 min averaging 45 mg m^{-2} s^{-1}. This much smaller flux was in the presence of the same mean windspeed and cloud liquid water content as the earlier period. Air temperature 2 m above the ground was also similar at 2.5°C.

During the morning of 25 March, atmospheric conditions were similar to those of the evening of 24 March. Wind speed at 2 m was 11 m s^{-1}, air temperature at 2 m was 1.5°C and total shortwave solar radiation 50 W m^{-2} at 1030 GMT. The cloud liquid water content was approximately 0.2 g m^{-3} and the wind (270°) provided between 100 and 200 m of uninterrupted fetch.

The rate of weight gain of the lysimeter during the morning was much smaller than on the previous evening until mid-day when it began to

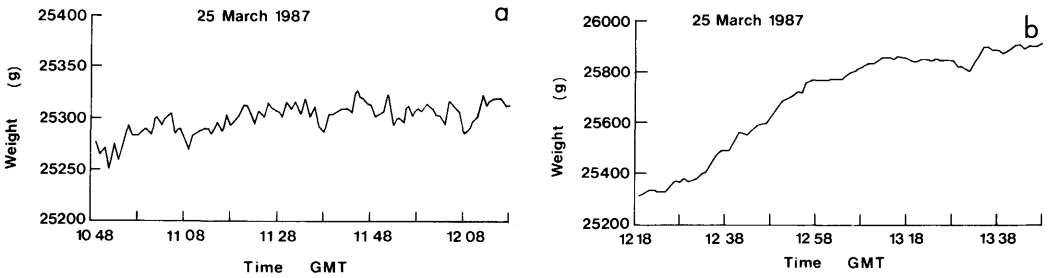


Fig. 5. (a) The weight changes with time of the lysimeter on 25 March 1987 in the presence of thin variable cloud (no precipitation, the decreases representing evaporation). (b) The weight changes with time of the lysimeter on 25 March 1987 during a light snow shower.

Table 1. *Cloudwater deposition measurements 24 March 1987 by flux-gradient methods*

Surface: moorland, short vegetation; 0.1 m (soil frozen);
air temperature 2.5°C;
wind speed (at 2 m) 9 m s^{-1},
aerodynamic roughness (Z_0) 1 cm

Run no.	GMT + duration	$\bar{r}$ (μm)	LWC (g m^{-3})	U_* (m s^{-1})	Flux (mg m^{-2} s^{-1})	V_g(l) (mm s^{-1})	V_m (mm s^{-1})
1	1734 (15)	5.6	0.34	0.58	10.1	29.5	45.7
2	1749 (15)	5.7	0.38	0.59	12.4	32.6	45.8
3	1806 (15)	5.9	0.40	0.65	13.7	34.3	55.2
4	1823 (15)	6.3	0.33	0.64	11.2	33.7	51.2
5	1840 (15)	6.6	0.30	0.61	6.4	21.4	49.3
6	1857 (15)	6.6	0.26	0.64	8.9	34.6	51.5
7	1914 (15)	7.0	0.24	0.66	9.2	38.7	57.5

snow and no further measurements of cloud water fluxes were possible. The results (Fig. 5a) show the broad trend in the data, prior to the snow, while Fig. 5b shows the data for the period during which snowfall dominated the weight changes with time. There were short periods between 1130 and 1230 GMT when the measurement site was out of cloud, when weight decreased showing evidence of evaporation from the lysimeter.

3.2. *Flux/gradient measurements*

On the evening of 24 March, the wind velocity measurements provided precisely log-linear profiles for the 7 runs and fairly constant wind velocities, friction velocities (U_*) and the deposition velocity V_m for momentum transfer between the atmosphere (at $z - d = 1.0$ m) and the ground (Table 1). The deposition velocity for momentum (V_m) provides an approximation to the upper limits for mass transfer by turbulent deposition and was in the range 40 to 50 mm s^{-1} for the measurement period. The aerodynamic roughness of the surface, as characterized by the roughness length (z_0) averaged 5 mm for these measurements, varied little and showed no dependence on wind direction or speed.

The cloud liquid water content varied from 0.24 to 0.34 g m^{-3} over the 5 h and was characterized by drops with a number mean radius of about 6 μm while the bulk of the liquid water mass was present in the size range 7 to 10 μm. A typical droplet size spectrum during these measurements is shown in Fig. 6. The differences in liquid water content between 1.5 m and 0.5 m above the surface were typically 0.05 g m^{-3}, representing 15% of the LWC at 1.5 m. The calculated fluxes to the ground were fairly constant at 10.3 mg m^{-2} s^{-1} ($\pm$1.7 mg m^{-2} s^{-1}). The deposition velocities (V_g) were typically 3 cm s^{-1},

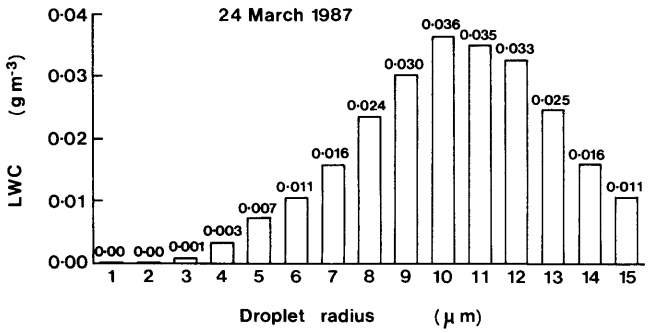


Fig. 6. Liquid water content of the cloud as a function of droplet size during cloud water deposition measurements on 24 March 1987.

and approximately 60% of V_m. The results are summarized in Table 1.

The flux/gradient measurements for 25 March were limited to a short period from 1050 until 1130 GMT, after which cloud liquid water contents were too small (<0.1 g m^{-3}) to obtain measurable differences in LWC between the two probes. For this short period, the windspeeds were approximately 11 m s^{-1} at 2.2 m and friction velocity 0.5 m s^{-1}, i.e., similar to the previous evening, but LWC decreased from 0.20 to 0.132 between 1050 and 1130 GMT. The flux of cloud water decreased during this period from 15 to 6 mg m^{-2} s^{-1}, and deposition velocity decreased from 11.4 to 9.7 mm s^{-1}. The corresponding lysimeter fluxes decreased from 23 mg m^{-2} to almost zero as the cloud base lifted above the site of measurement.

4. Discussion

The measurements of cloud water deposition using micrometeorological methods show that the measured deposition velocities were about 60% of the deposition velocity for momentum (Table 1). These values show that the transport process was limited mainly by turbulent transport to the ground and that surface resistance to the deposition process was small. The results are consistent with those of Dollard et al. (1983) using similar methods. The drop sizes containing the bulk of the liquid water mass are those for which wind tunnel studies (Chamberlain, 1975) have shown close agreement for momentum and particle deposition. For much smaller droplets, transport through the viscous sub-layer restricts transport to the surface.

The data set presented here is not adequate to study the particle size dependence of deposition velocity for the reasons discussed in Sections 2 and 3, which is the subject of a related paper from later measurements at the same site (Gallagher et al., 1989).

The lysimeter measures the net exchange of water, through turbulent deposition and sedimentation of cloud droplets and the net water vapour exchange. In contrast, the flux gradient system only measures the turbulent deposition of cloud droplets. The comparison of cloud water deposition fluxes from the aerodynamic method, with the fluxes deduced from lysimeter measurements, reveals a major discrepancy (Table 2). The comparison shows for the measurements between 1730 and 1930 GMT on 24 March that the fluxes measured by the lysimeter exceeded those from the flux/gradient method by a factor of 5. The discrepancy was reasonably consistent for the first five, 15-min sampling periods. The last measurement shows a much smaller discrepancy.

The site conditions at the start of measurements (1739 GMT) provided air temperature of 2.5°C at 2 m while the soil/peat in the lysimeter was frozen. The water deposited onto the soil surface was maintained at a temperature very close to 0°C because of the frozen soil, so that with the air between the cloud droplets at saturation, a water vapour pressure gradient towards the surface was present. If these temperature measurements were used to estimate the gradient in absolute humidity, the micrometeorological measurements may be used to deduce the

Table 2. *A comparison of cloudwater deposition measurements 24 March 1987 by lysimeter and gradient methods*

Surface: moorland (soil frozen) vegetation height 0.1 m;
air temperature 2.5°C;
windspeed (at 2 m) 9 m s^{-1};
roughness length (Z_0) 5 mm

GMT + duration	Weighting lysimeter total water flux (mg m^{-2} s^{-1})	Flux/gradient cloudwater flux (mg m^{-2} s^{-1})	Sedimentation flux (mg m^{-2} s^{-1})	Vapour flux (mg m^{-2} s^{-1}) (% total)	Latent heat flux (W m^{-2})
1751 (15)	78.2	12.4	1.0	64.4 (82)	164
1807 (15)	66.5	13.7	1.5	51.3 (77)	132
1823 (15)	65.3	11.2	1.6	52.5 (80)	135
1840 (15)	69.6	6.4	1.3	61.9 (89)	158
1857 (15)	65.6	8.9	1.2	55.4 (85)	147
1914 (15)	25.6	9.2	1.0	15.4 (60)	41

corresponding flux of water vapour to the cold surface.

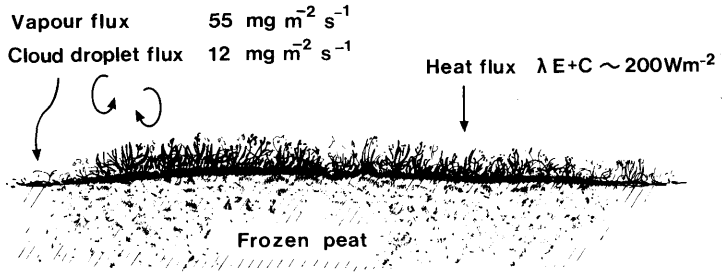
The flux of water vapour to the cold surface F_w may be approximated by

$$F_w = X_s(Z_2) - X_s(Z_1)/r_a,$$

where $X_s(Z_2)$ is the absolute humidity at height 1 m above the surface where air is assumed to be saturated at the measured air temperature (2.5°C), $X_s(Z_1)$ is the absolute humidity at the surface where temperature is assumed to be 0°C as the underlying surface was frozen, and r_a is the atmospheric resistance to vapour transport between Z_2 and Z_1. Substituting the estimated values for these conditions gives an approximate water vapour flux of 45 mg m^{-2} s^{-1}, which is close to the measured differences (50 to 60 mg m^{-2} s^{-1}) between the fluxes from the lysimeter and those from the gradient method (+ sedimentation) for the first 4 runs (Table 2). The fluxes of cloud water and latent and sensible heat are summarized in Fig. 7.

As the vapour flux accounts reasonably well for the discrepancy between the two methods, the column in Table 2 for vapour flux assumes that the differences observed between the two methods are entirely due to the vapour flux. The possibility of substantial vapour fluxes was identified by Shuttleworth (1977) and may be an important feature determining the water exchange between the atmosphere and the ground in wind-driven cloud conditions.

The substantial latent heat flux which results from the condensation of water vapour at the ground is of course accompanied by a sensible heat flux as the ground is cooler than the air. Using similar arguments to those above, this can be shown to be of the order 50 to 100 W m^{-2} during the first 4 runs on 24 March. These latent and sensible heat fluxes would lead to rapid melting of the frozen peat. The melting ice may be assumed to maintain a "ground" temperature of approximatley 0°C despite the large heat input. The temperature difference between the ground and the air at 2 m induces thermal stratification of the air close to the surface, and curvature in the wind profile (Thom, 1975). The absence of a multi-point temperature profile system prevents the correction for the stability effects but such effects are a much stronger function of windspeed than temperature gradients, and with the large windspeeds at this site, the curvature in the wind profiles is not detectable. The later measurements on the evening of the 24 March show a decline in the proportion of water flux accounted for by vapour deposition from between 80% and 90% of the total to about 65%. By the following morning, although there are very few measurements, the flux/gradient method gave similar values to those using the lysimeter. By this time, the ice in the lysimeter had largely melted, and the temperature differences between air at 2 m and the lysimeter were small.



How important is cloudwater deposition ?

Consider G D F 250 d yr^{-1} under cloud, 8h per day (2000 h yr^{-1})
LWC 0·3 g m^{-3}

	z_0 m	Vg cm s^{-1}	mm yr^{-1}	% ppt	% annual wet dep $[SO_4^{2-}, NO_3^-, H^+, NH_4^+]$
1. Moorland	0·01	5	116	6	12
2. Forest	1·00	20	432	22	44

Fig. 7. Summary of the cloud and vapour fluxes above frozen moorland (see text for further details) and the magnitude of cloud water deposition for annual precipitation (ppt) and for wet deposition of the major ions in precipitation. λ_E, latent heat flux; C, sensible heat flux; Z_0, roughness length; V_g, deposition velocity.

Later in the morning of 25 March, the cloud base lifted above the site of measurements and it began to snow, shown in the very rapid weight gain with time in Fig. 5b.

The deposition of cloud droplets onto the moorland vegetation has been shown to be an efficient process with deposition velocities in the range 2–4 cm s^{-1}. These rates of deposition yield significant fluxes of the major ions present in the cloud water. The concentrations of SO_4^{2-}, NO_3^-, NH_4^+ and H^+ from an extensive sampling of cloud water on Great Dun Fell are larger than their concentrations in rainwater by about a factor of 2 (Fowler et al., 1988). With the frequency of cloud on the hill summit which occurs on 250 days each year (Choularton et al., 1986) and is assumed to be present for 8 h each day, with mean annual windspeed of 10 m s^{-1} and a roughness length of 5 mm, an estimate may be made of the contribution of cloud water deposition to the input of major ions to the hill surface. This is shown diagrammatically in Fig. 7 along with a summary of the vapour and droplet fluxes to the frozen hillside. These calculations indicate a modest increase in the total input of all these ions of 15 to 20%. The upland areas of western and northern Britain have been subject to a widespread afforestation programme during the last 25 years. Such sites as the Pennine Hills on which Great Dun Fell lies are potential sites for these land use changes. If the aerodynamic roughness of the surface at Great Dun Fell were to be increased by afforestation ($Z_0 \sim 2$ m), then assuming that the deposition velocities of cloud water are similar to those for momentum, the cloud water flux to the surface may increase the wet deposition inputs of major ions by 50% (Fig. 7).

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