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Detecting fog deposition to tussock by lysimetry at Swampy Summit near Dunedin, New Zealand

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Abstract

Fog deposition on narrow leaved snow tussock canopy has been suggested as an important component of the water balance and therefore as a reason for retaining this species as cover in water supply catchments in southern New Zealand. The objective of this study was to identify fog deposition periods and amounts using a large weighing lysimeter at a fog-prone tussock grassland site at 736 m elevation near the city of Dunedin on the east coast of the South Island. The lysimeter water balance was solved for the sum of the unknown fog deposition (F) and evaporation (E), using measured rainfall (P), storage change (ΔS), and drainage outflow (Q):

$$(F + E) = \Delta S - P - Q$$

Periods when the sum of these two unknowns is positive were considered as possible periods of fog deposition. There were 40 such days in 3 years of record and 70mm of apparent fog deposition. This is less than 2% of measured rainfall, and we cannot discount the possibility that the amount calculated could be the result of undercatching by the rain gauges. The weather on the 40 days is, however, indicative of cloud-ground intersection at the site. The median fog deposition rate was 0.05+/-0.03 mm hr^{-1} which is similar to measurements elsewhere over forest, pasture, and moorland.

We conclude that fog deposition is not important in terms of water supply from tussock catchments in southern New Zealand.

Introduction

Water deposited on plant canopies from fog, cloud, or mist (occult precipitation) has largely been ignored by hydrologists and rarely quantified. Gauze or net structures mounted over collectors or precipitation gauges (Twomey, 1957; Schemenauer and Joe, 1989) collect advected water from the airstream which they obstruct and so it is impossible to extrapolate such measurements directly to deposition on an extensive area of vegetation.

Nagel (1956) suggested that water droplets in fog or cloud contacting the ground may collect on vegetation surfaces and contribute to soil water and runoff. Fog deposition has been observed in coastal forests, along ridge tops in steep topography, and at the upwind edges of forests (Ekern, 1964; Azevedo and Morgan, 1974; Harr, 1982). In these circumstances fog deposition on vegetation is an advective process, dependent on windspeed, and diminishing downwind from abrupt changes in vegetation height (Oberlander, 1956). Price (1992a,b) used lysimetry, together with Bowen ratio measurements, to estimate fog water deposition onto uniform bog vegetation at a coastal site in Newfoundland, Canada. Ingraham and Matthews (1988) identify fog drip as a source of groundwater recharge in Northern Kenya. Gallagher *et al.* (1988) and Beswick *et al.* (1991) have measured vertical fluxes of fog water using gradient and eddy correlation techniques respectively and Shuttleworth (1977) provides a physically based model of the process.

In New Zealand Mark and Rowley (1976) and Holdsworth and Mark (1990) used many single-plant drainage lysimeters to compare outflow from various tussock treatments in the uplands of southeastern South Island. They hypothesised that high water yield from unmodified snow tussock was due to interception of fog water. Since the city of Dunedin obtains much of its water for supply and power generation from catchments near the sites of their measurements, Holdsworth and Mark (1990) concluded that retention of tussock cover would be valuable for sustaining the city's supply. These studies have been the basis of a continuing debate, mostly in the popular press, about the importance of fog deposition and tussock cover for water yield from upland regions of Otago.

During a study of the impact of afforestation on tussock grassland hydrology at Glendhu, near Lawrence in east-central Otago (Fahey and Watson, 1991; O'Loughlin, *et al.* 1984; Pearce *et al.* 1984), Campbell (1989) used a large weighing lysimeter to measure evaporation from tussock. The role of fog in the water balance was minor at this site (Campbell and Murray, 1990). In late 1989 the lysimeter, with its soil monolith intact, was relocated at a fog-prone tussock site on Swampy Summit near Dunedin (Fig. 1). This paper examines the lysimeter water balance for the period March 1991 to February 1994. We assessed the importance of fog by identifying likely periods of fog deposition, and by estimating amounts of water that may have been deposited on the tussocks.

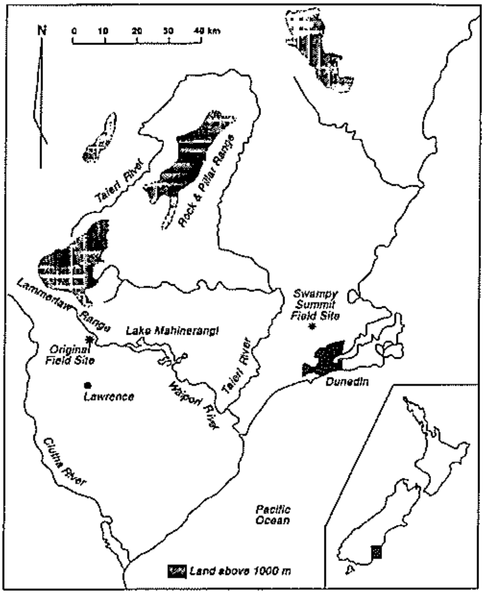

Figure 1 - Location map showing Swampy Summit field site and the site of the previous location of the lysimeter near Lawrence.

Definition of fog deposition

While there are several mechanisms of fog and cloud formation, fog is most commonly defined in terms of visibility, for example when visibility is reduced to less than 1000 m (Barry and Chorley, 1987). Drop size is also used as the basis for definition: fog occurs when a large number of water droplets, generally smaller than 20 μm diameter, are suspended in air which is close to its saturation point, with relative humidity usually in the range 97% to 100% (Cotton and Anthes, 1989). Since typical raindrops have diameters of the order of 1mm and a conventional size separation between cloud and rain droplets is 100 μm diameter (McDonald, 1958), there is a considerable size range in which fog and cloud merge into fine drizzle and rain.

Since we have drop size data for only parts of a four-month period outside the duration of this study (Cameron *et al.*, 1996) our definition of fog deposition is determined by our instrumentation: fog deposition is any liquid water which collects on the tussock canopy but is not caught in a rain gauge. This definition encompasses fog deposition by turbulent transport, but also includes the effects of rain gauge undercatching and we cannot make an explicit distinction in our data. Further, since we do not explicitly determine evaporation, our inferences refer to net fog deposition.

The definition is practical nevertheless, since management decisions will be based on precipitation measured, for the most part, with standard rain gauges. Hence our analyses and conclusions will be relevant to water balance relationships for tussock land, though our term 'fog deposition' may include rain not caught in rain gauges.

Field site

The field site is 10 km north-northwest of Dunedin (Fig. 1), on Swampy Summit, a broad (1 x 2 km) north-south oriented plateau with a maximum elevation of 739 m and underlain by basalt. Tall tussock grassland is the main vegetation, with red tussock (*Chionochloa rubra*), as well as bracken (*Pteridium esculentum*), hebe (*Hebe odora*), flax (*Phormium colensoi*), and introduced grasses (*Agrostis* sp. and *Holcus* sp.). The land surrounding the lysimeter is flat to gently convex (Fig. 2) with minor irregularities in canopy height and topography for more than 100 m in each of the two main wind directions, the northeasterly and the southwesterly quarters.

The regional climate is characterised by the passage of fronts and anticyclones in a prevailing westerly flow and local weather is quite variable. The climate on Swampy Summit is more severe than that of Dunedin where the mean annual rainfall of 800 mm is uniformly distributed through the year. Between March 1991 and February 1994 the lysimeter site received almost twice as much precipitation (4150 mm) on almost twice as many raindays (760) as the official Dunedin station at sea level. Snow is common in winter, and possible in any month. Winter snow may survive as small drifts between tussocks for several weeks. Two main weather situations lead to fog. When maritime air is forced over the 700 m mountain by onshore easterly winds, a local cap cloud of variable thickness develops with its base some distance below the summit on the windward side. Cold fronts in the westerly and southwesterly flows frequently bring low cloud and rain to Swampy Summit and the surrounding area.

Methods

The lysimeter comprises a 5.8 m^2 x 0.7 m deep, undisturbed monolith including eight mature snow tussocks (Fig. 2). It rests on an Aspendale-type beam balance (McIlroy and Sumner, 1961) on loan from CSIRO Division of Plant Industry, Canberra, Australia. Details of design and

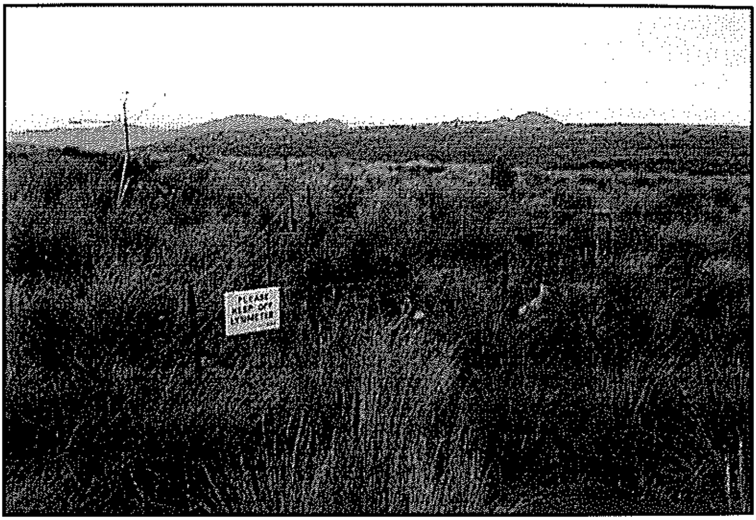

Figure 2 - Lysimeter and surroundings after tussocks had been replanted around the monolith, showing the vegetation and topography of the upwind area to the east.

construction are provided in Pearce and Newman (1987). The monolith, originally isolated at Glendhu, a few kilometres north of Lawrence (Fig. 1), was installed, with the soil and tussocks intact, in the new pit on Swampy Summit in 1990. Excess water drains from the monolith base and is measured by a tipping bucket. Lysimeter weight changes are detected as pulses from a reversible screw which drives a travelling weight along the lever arm to keep it in balance. The machinery was reconditioned before installation and recalibrated.

Ground disturbance during installation was restricted to one quadrant to the southeast of the lysimeter. Spoil not required for back-filling was removed and approximately 200 tussocks were transplanted into the disturbed area at a density similar to that occurring naturally at the site. Although the species of tussock in the lysimeter (*Chionochloa rigida*) is different from that in the surrounding area, its morphology is similar. Each plant has a dense base of vertical cylindrical tillers which splay outwards and become long narrow U-shaped leaves tapering to very fine, often dead, tips. Measurements on live and dead tussock material 50 m from the lysimeter indicate a one-sided leaf area index of 3.0. The maximum height of tillers in each tussock averages about 0.8 m both inside and outside the lysimeter. Tussock basal area is less variable inside the lysimeter than outside, where there are many small tussocks with only a few tens of tillers per plant and there are more grasses and herbs between the tussocks.

Additional measurements include precipitation from up to 8 tipping bucket gauges, wet- and dry-bulb temperature, wind speed and direction, all sampled at 30 second intervals and logged every 30 minutes.

As there are no independent measurements of fog deposition (F) and evaporation (E), the water balance of the lysimeter can only be arranged to solve for the sum of both:

$$(F + E) = \Delta S - P - Q \qquad (1)$$

in which P is precipitation, Q is drainage from the base, and ΔS is the change in water storage calculated from the weight change. Transfers of water into the lysimeter are considered positive. Thus when $(F + E) > 0$ we may suspect fog deposition because the inputs to the lysimeter exceed the measured precipitation. There are, however, other causes of positive (F + E) values. Snow caught in rain gauges will not be recorded until it melts, which may be some time after the storm has passed. In the meantime the lysimeter shows an increase in weight but no drainage, and so the right hand side of equation (1) is positive. Later, if snow melts in the rain gauges and on the lysimeter at the same time, weight loss and drainage will cancel but the precipitation is now registering, so (F + E) is correspondingly negative. On this basis we discarded those days on which positive (F + E) values appeared to be related to snowfall and melt.

The inference that fog deposition occurs when $(F + E) > 0$ must also take into account bias, and random uncertainties of measurements of DS, Q, and P. While a perfect rain gauge would collect the amount of water that reaches the vegetation canopy if the gauge is not there, a gauge which projects above the canopy alters the normal air flow and may undercatch by 10-15% (Rasmussen and Halgreen, 1978; Allerup and Madsen, 1980). The effect is greatest for snow and rain with small drop sizes (Rodda, 1967) and increases with windspeed (Dreaver and Hutchinson, 1974). Bias can be minimised by setting the gauge orifice flush with the ground surface in a non-splash surround (Green, 1970; Helvey and Patric, 1983), but in tussock with canopy at 0.8 m it is necessary to clear an area around the gauge. We installed 8 rain gauges, with a single ground level gauge and the others set approximately 0.6 m above ground among tussocks with a 1 x 1 m non-splash screens around the orifices to smooth the airflow (Campbell and Murray, 1990). The gauges were individually calibrated for low intensities, with bucket volumes in the range 0.12-0.17 mm.

Comparison of the records of all gauges shows no consistent pattern of relative over- or undercatching by any gauge in up to moderate windspeeds. For winds greater than $20\ \mathrm{m\ s^{-1}}$ the ground level gauge seems to be unduly sheltered, but all other gauges catch within 8% of the mean for most conditions. Because of instrument malfunctions, rainfall totals from all gauges operating over the entire 36 month period couldn't be compared. However, between 21 April 1991 and 29 February 1992, 5 gauges provided an uninterrupted record; the average catch was 1189 mm and the range 78 mm. For the period 1 June to 25 November 1991, all 8 gauges were operating. The mean was 763 mm and the range was 48 mm.

Since our water balance estimate of fog deposition is calculated from three small quantities with a sum close to zero, the uncertainties of measurement cannot be ignored. Following Campbell and Murray (1990) we combine estimates of random uncertainty in pulse counts, calibrations and lysimeter area measurements to estimate uncertainties in ΔS and Q. Precipitation is estimated as the mean of the tipping bucket rain gauges. The standard error of the mean includes instrument uncertainty and spatial variation. Combining uncertainties in terms on the right hand side of equation (1) gives an uncertainty term for (F + E) (Taylor, 1982).

Table 1 shows examples of daily water balance components and the error terms for P and (F + E) to illustrate the effects of rainfall variation across the site. For days without rain the standard error of estimate of (F + E) is 0.03 mm; the value varies gradually with magnitude of Q and ΔS to a maximum of 0.06 mm in all our data. On days with rain, however, the uncertainty in precipitation controls the uncertainty in (F + E). The standard error of the mean precipitation increases with precipitation. For

Table 1 - Lysimeter water balance components and error terms for selected days. Rainfall has the greatest effect on error in (F + E), and the uncertainties in measurement of drainage and storage change a smaller effect. If (F + E) is negative there is net evaporation and if it is positive there is net deposition.

Date	Rainfall mm	Drainage mm	Storage change mm	(F + E) mm	Rainfall error mm	(F + E) error mm
10/3/91	0.00	0.00	-1.36	-1.36	0.00	0.03
16/2/92	0.00	-0.42	-1.48	-1.05	0.01	0.03
24/11/91	0.98	0.00	-0.74	-1.71	0.04	0.05
18/1/92	1.79	-0.08	-0.11	-1.83	0.07	0.07
27/2/92	8.51	0.00	6.65	-1.86	0.13	0.13
20/1/92	10.42	-5.60	4.09	-0.73	0.24	0.24
9/2/92	18.11	-11.83	5.85	-0.43	0.22	0.22
18/7/91	20.45	-15.34	6.25	+1.13	0.73	0.73
28/12/91	24.38	-11.68	11.87	-0.83	0.39	0.39
23/4/91	31.03	-24.80	7.38	+1.16	0.84	0.84

rainfalls less than 1 mm the standard error is generally less than 0.05 mm, but the standard error increases for larger events to 0.84 mm, which still represents a coefficient of variation of less than 3%. Thus (F + E) is estimated poorly during periods of precipitation, but will generally be known to within 0.1 mm at 95% confidence when precipitation is less than 0.5 mm. Because of the uncertainties in measurements of P and (F + E), we discarded days with positive (F + E) < 0.2 mm, and those on which the (F + E) totals for the day were less than twice the standard error of the mean rainfall for the same period.

Results

Rain and wind

In most rain events cloud intersects the ground at the study site, so fog conditions at the lysimeter usually begin before and last after, measurable rain. A rain event is defined here as a period in which at least two gauges tip in each 30-minute logging interval, and event rainfall is the average of all gauges operating during the event. There were 1888 rain events during the 3-year period of record: 45% registered less than 0.2 mm; 41% had durations of 30 minutes with 60% lasting up to an hour; in the 3 years, 45 events were longer than 12 hours. With a rainday defined as any midnight-to-midnight period with at least one event with 0.2 mm rainfall or more, there were 667 raindays during the 3-year period, with a further 231 days with less than 0.2 mm rain. On 490 days the rainfall recorded was 1 mm or greater; on 7 days the gauges registered more than 40 mm, but 6 of these were associated with snowmelt. The exception was on 22/12/93 when there was 70 mm rainfall. Analysis of all the 30-minute logging periods reveals that for 78% of the time no rainfall is recorded, but 50% of the dry intervals are less than 2 hours in duration and the longest continuous period without rain is 6 days. Maximum rain intensity recorded is less than 20 mm hr^{-1} and in most of the larger storms, maximum 30-minute intensity is less than 10 mm hr^{-1}.

The wind regime at the site is summarised as percent frequencies in Figure 3a. The wind is from the east or the northeast 31% of the time and from the west, southwest or northwest 59% of the time. Speeds are less than 2 m s^{-1} for 8% of the time and between 2 and 15 m s^{-1} for 89% of the time. Maximum 30-minute mean windspeeds are just over 20 m s^{-1}. For wind from both the east and west, modal speeds are about 5-10 m s^{-1}, although westerly winds of 10-15 m s^{-1} are almost as frequent. Figures 3b and 3c depict rainfall depth and duration in terms of wind speed and direction: Figure 3b shows the percent frequency of total rainfall depth while Figure 3c shows the percent rainfall duration. Only 3% of rain is

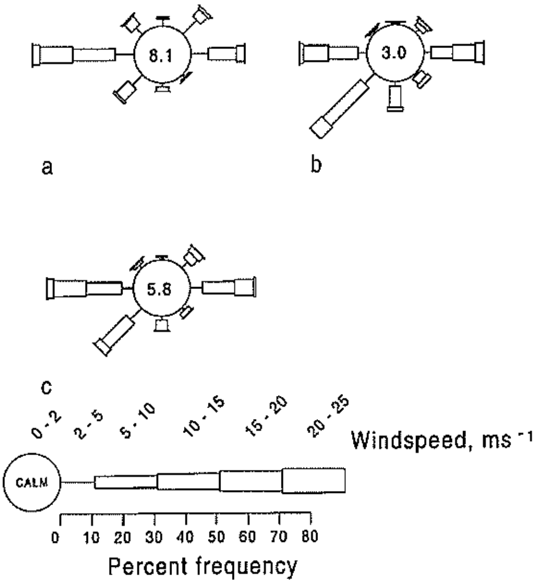

Figure 3 - Wind roses for 3 years' data. Each rose is a classification by wind speed and direction of the frequency of a chosen variable: (a) wind duration which shows the percent time the wind is in each direction and speed class; (b) rain depth showing the percent of total rainfall which has fallen in each wind speed direction class ; (c) rain duration which shows the wind direction and speed for the percent of total time it is raining. Comparison of the rain depth and duration classes permits inference of average rainfall intensity in relation to the overall mean intensity.

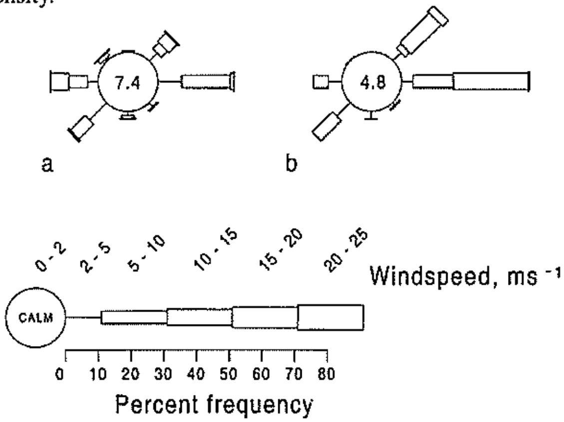

Figure 4 - Wind roses for days when (F+E) > 0.2:mm, showing percent duration of the wind by speed and direction: (a) for all 40 fog days, during which a total of 70 mm fog deposition occurred. (b) for March 22 to March 30, 1991 when 32 mm occurred.

associated with speeds < 2 m s^{-1}. Thirty-one percent of rainfall occurred at higher than average intensities during southwesterly conditions though these prevail less than 14% of the time. Rain during southerlies and southeasterlies is similar though depths are much less. In westerly, easterly and northeasterly conditions rainfall durations are longer and so intensities tend to be lower than average, but windspeeds are slightly higher.

The rainfall climate is benign: there are many periods of intermittent drizzle, and large rainfall totals are due to rain of long duration rather than high intensity. In the easterly and westerly conditions in which fog has been observed, windspeeds tend to be higher than average, which would assist fog deposition by turbulent transport to the tussock surfaces. Foggy conditions, however, are almost always accompanied by low intensity drizzle with small drop sizes, which together with high windspeed are conditions in which rain gauges will undercatch.

Fog deposition

In searching the lysimeter water balance record for periods where (F + E) > 0.2 mm we used the daily data, because in the half hour data there were many periods in which (F + E) fluctuates irregularly from positive to negative, in part due to fluctuating wind stress on the lysimeter surface which is not totally damped out. We selected days in which (F + E) > 0.2 and then eliminated any with snow, or where the confidence interval on the deposition included zero. This leaves 40 days from the 3-year record. Although there are several periods of instrument malfunction, especially in the second and third years, these 40 days seem reasonably representative of the conditions at Swampy Summit.

There was measurable rainfall on each of the 40 days totalling 330 mm, and apparent fog deposition of 70 mm, which is less than 2% of the rainfall over the 3-year record. On 18 days the deposition was more than 1 mm and on 4 days it exceeded 5 mm. On only one day did fog deposition exceed measured rainfall. Temperatures ranged between 3°C and 15°C; relative humidity was close to 100% in all cases. The wind regime for the selected days (Fig. 4a) is quite different from the average distribution: winds are from the east or northeast for 55% of the time, from the west or southwest for 34% of the time, and 28% of the time speeds are above 10 m s^{-1}. The easterly and northeasterlies have modal frequencies of 10-15 m s^{-1}.

Deposition rates were not uniform: 32 mm was recorded in one continuous period of 9 days in March 1991 when unusually high speed winds from the east and northeast prevailed for 7 days, followed by a cold front and a change to southwesterly conditions for 2 days (Fig. 4b). Over this period 93 mm of rainfall was recorded and temperatures were high for fog days, at around 11°C. There is no other comparable period of sustained high winds from the easterly direction in the 3-year record. The maximum 2-hourly deposition rate over all events was 0.6 mm hr^{-1}, but less than 6% exceeded 0.2 mm hr^{-1} and the median rate was 0.05 mm hr^{-1}.

Four of the 40 fog days have been chosen to represent the range of conditions (Table 2) and illustrate the patterns of rainfall and fog deposition over time (Fig. 5). March 27 and 29, 1991, were days with little rain and contrasting wind directions: on March 27th the wind was consistently from the east at speeds between 11 and 14 m s^{-1} until 2100 hours, with a change to the southwest after 2300 hours and speeds decreasing to 5 m s^{-1}; on March 29th the wind was from the west all day with speeds between 4 and 8 m s^{-1}. On the 27th small amounts of rain were recorded in the early morning and again with the wind change, temperature varied between 12°C and 14°C, while the radiation records suggest continuous fog cover. Fog deposition (F + E) was positive, but quite small, during the morning and again at the end of the day, but negative for 5 hours in the middle of the day. The 29th was cooler (4°C to 9°C), the radiation was almost identical, and rainfall was again intermittent early, absent in the middle of the day but more substantial from 1400 hours onwards, giving 4.1 mm for the day. Through the early morning (F + E) is positive, becomes negative until 1500 and reaches 0.6 mm at 2300 hours, coinciding with 1.2 mm rainfall.

April 25 and December 6 1991 also have contrasting wind directions but have substantial rainfall. Both days had wind speeds between 7 and 12 m s^{-1}, temperatures from 5°C to 8°C, with net radiation positive but low from 0800 to 1700 hours. Fog deposition was continuous throughout April 25 but fluctuated in phase with three pulses of rainfall. On December 6 (F + E) remained positive for most of the day but there is less correspondence with the smaller rainfall pulses.

Table 2. Wind direction, rainfall and fog deposition for four selected fog days illustrating the two main wind directions and the effects of rainfall on (F + E).

Date	Wind direction	Rainfall) mm	(F + E) mm
27/3/91	east	0.9	1.6
29/3/91	southwest	4.1	1.3
25/4/91	west	32.8	7.6
6/12/91	east	16.7	2.9

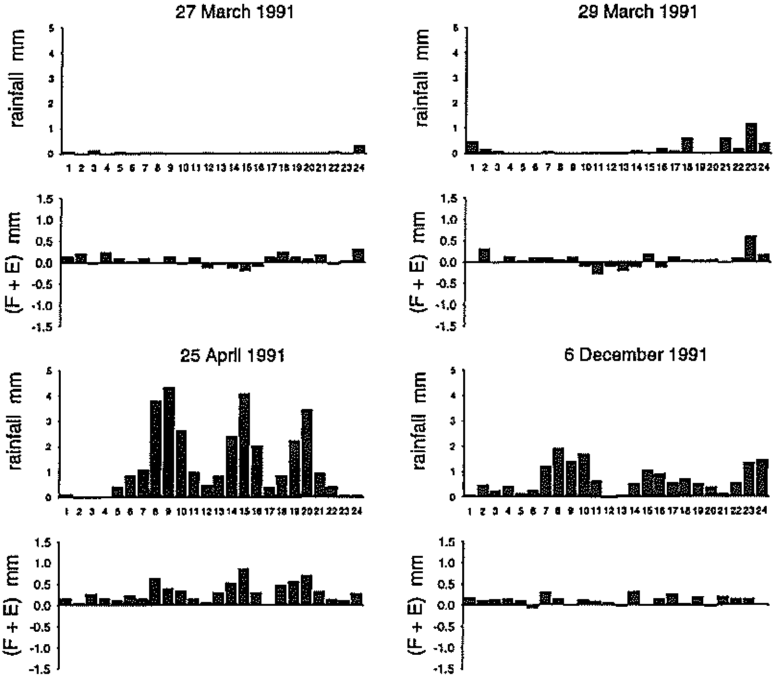

Figure 5 - Hourly rainfall and (F + E) for four selected fog days to show the patterns through time and association between the variables.

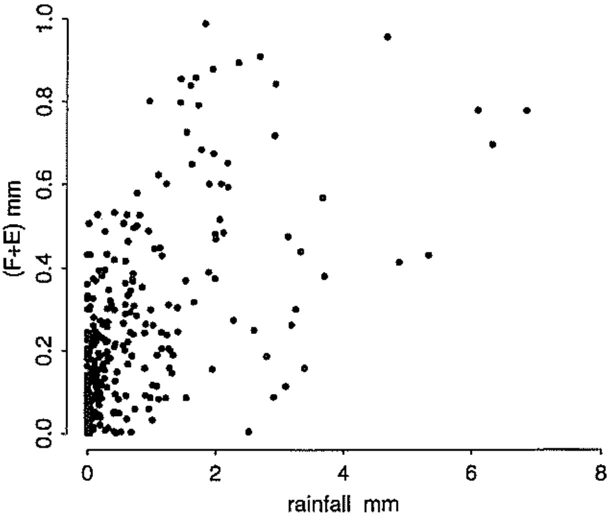

Figure 6 - Two-hourly rainfall versus (F + E) for all fog days.

These diagrams suggest some correlation of net fog deposition with recorded rainfall, lending support to our suspicion that rain gauge undercatching is responsible for the apparent fog deposition detected with the lysimeter. In Figure 6 we have plotted rainfall against positive fog deposition for all 2-hour periods from the selected fog days. Some correlation is evident. Separation of the data by windspeed classes does not increase correlation, and so, while rain gauge undercatch occurs in some events, it is not obviously the cause of all our apparent fog deposition.

Discussion

The inference that water deposited on the lysimeter, in excess of that caught in the rain gauges, is from fog is problematical. Light intermittent rain has small drop sizes, and all events with (F + E) > 0 have relatively high windspeeds. Most of our fog days have intermittent rain and intensities are invariably less than 5 mm hr^{-1}. While these are the conditions which would enhance turbulent transport of water drops to the surface, they are also conducive to undercatching by the rain gauges. At a nearby similarly exposed and elevated site, Dreaver and Hutchinson (1974) estimated catch deficiencies of 25% for windspeeds over 10 m s^{-1} for standard rain gauges. Our conditions are at least as severe, but if our (F + E) data are attributed entirely to gauge undercatch, some would be greater than 25% of measured rainfall. As always with rain gauge deficiencies this argument must remain a hypothesis.

Gallagher *et al.* (1988) measured fog deposition to grass on Great Dun Fell in the English Pennines using a gradient technique and a small weighing lysimeter. Over several runs the two methods were in reasonable agreement at 0.04 mm hr^{-1}. Harvey and McArthur (1989) calculated fog flux rates to grazed moorland pasture in the Peak District of Britain and obtained a similar average rate from 17 runs over three years. Other studies over short vegetation have provided fairly consistent average rates from 0.02 to 0.05 mm hr^{-1} (Dollard *et al.*, 1983; Fowler *et al.*, 1990). Forest has a higher aerodynamic conductance than short grass surfaces; deposition rates there have been measured at up to 0.4 mm hr^{-1} (Lovett, 1984). The rates measured at Swampy Summit appear similar to these, though our maximum is somewhat greater than the last which could indicate rain gauge undercatch is also contributing.

Unsworth and Wilshaw (1989) simplified the aerodynamic model of Shuttleworth (1977), assuming neutral conditions and similarity of eddy diffusion for momentum and water droplets, and calculated fog deposition rates as the product of fog liquid water content and aerodynamic conductance for the surface. Using Campbell's (1989) value of 0.14 m s^{-1} for tussock aerodynamic conductance and a representative liquid water content of 0.25 g m^{-3} (Rogers and Yau, 1989), fog deposition rates would be 0.13 mm hr^{-1}.

The median hourly deposition rate from our data is 0.05 mm hr^{-1}, with 78% exceeding 0.02 mm hr^{-1} and a maximum of 0.6 mm hr^{-1}. While the largest of these values is distinctly higher than values from the studies cited for short vegetation, Murray *et al.* (1991) have shown that upland tussock is more akin to forest than pasture for aerodynamic transfer. Even so, unlikely values of windspeed and liquid water content would be required for the model of the process to match our highest rates, which are higher than any measured, even for forest. The explanation for our 'fog deposition' may thus be more than just turbulent transport, and rain gauge undercatch is the most likely. Paradoxically, because (F + E) was generally small, our rain gauges with their novel shields were probably not undercatching to the extent expected for the windy and low intensity rainfall conditions common at Swampy Summit. There are occasions, however, when severe undercatching is evident.

It is difficult to compare our results with those of earlier lysimeter studies (Mark and Rowley, 1976; Holdsworth and Mark, 1990). Small lysimeters are more prone to edge effects, and this is exacerbated when plant size is similar to lysimeter diameter. A single tussock isolated in an 0.6 m diameter tank is inevitably less representative than several tussocks in a larger lysimeter, since over- or under-exposure of the individual plant cannot be compensated for within the measurement system. When non-weighing lysimeters are used, individual events cannot be examined or the effects of rainfall separated from those of fog, as the time intervals used must assume zero change in storage. The measurements of fog interception on tussocks over shorter intervals (Holdsworth and Mark, 1990) were not representative in terms of exposure and rainfall, and fog interception values were small quantities being expressed as percentages of small and inevitably biased rainfall estimates.

Conclusions

If lysimetry is to be used to solve the water balance for one component, the measurements must be accurate and complete. Our median fog deposition rate of 0.05 mm hr^{-1} has a standard error of ±0.03 mm hr^{-1} when there is no rain. Because rainfall varies across the site this uncertainty is larger when rain accompanies fog, and it increases with the amount of rain so that in many rain events we were unable to detect fog deposition. Bias in rainfall measurement is also a problem. Although we have used up to 8 rain gauges, shielded or at ground level, we cannot be confident that we are estimating mean rainfall on the lysimeter without bias in all conditions. There is, however, other evidence for fog deposition: the weather conditions in the selected periods are indicative of fog and would be conducive to turbulent transport of small water droplets from the airstream to the canopy.

The rates of fog deposition that we have detected are occasionally higher than have been measured elsewhere for short vegetation without advective edge effects. To model our measured rates would require fog with an unusually high liquid water content and longer periods of high wind speeds than those recorded. Cameron *et al.* (1996) explore this aspect of fog deposition on Swampy Summit in more detail.

In spite of these provisos, fog deposition to the tussock canopy on Swampy Summit is unlikely to be important hydrologically: although the 70 mm net deposition over 3 years, representing less than 2% of the measured precipitation, has excluded periods with snow and the very small events, it seems unlikely that much larger amounts of fog deposition are occurring. The amount is in close accord with the 1.2% of precipitation estimated for fog deposition at the earlier lysimeter site (Campbell and Murray, 1990). The process undoubtedly occurs however — in a continuous period of 9 days with rather unusual weather, 32 mm more water entered the lysimeter than was measured in the rain gauges, and some was probably from turbulent deposition of fog droplets to the canopy.

Acknowledgments

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