Journal of Hydrology, 135 (1992) 87–101
Elsevier Science Publishers B.V., Amsterdam

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Blanket bog in Newfoundland. Part 1. The occurrence and accumulation of fog-water deposits

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(Received 26 July 1991; accepted 21 October 1991)

ABSTRACT

Price, J.S., 1992. Blanket bog in Newfoundland. Part 1. The occurrence and accumulation of fog-water deposits. J. Hydrol., 135: 87–101.

Fog deposition on to a blanket bog near Cape Race, Newfoundland, was measured with a fog collector and a lysimeter. Fog is most frequently produced by warm southwesterly airflow over cold offshore water, although cooler northeasterly air is also important. Between 21 June and 14 July 1989 fog deposition was 50% of rainfall, averaging 1.8 mm day^{-1}, with a maximum daily deposition of 10.2 mm. Evaporation was also restricted during fog and rain events; evaporation on days with fog or rain averaged < 1.1 mm, compared with 2.5 mm when it was not foggy or raining. The addition of water to the surface by fog, combined with low evaporation rates may be critical to the development of blanket bog in this area.

INTRODUCTION

Fog drip has long been recognized as an important component of the hydrological cycle in certain environments (Oberlander, 1956), which along with its enhanced geochemical composition can influence the regional vegetation diversity (Azevedo and Morgan, 1974). In Newfoundland, where fog is very common in spring and summer (Banfield, 1981), its hydrological and geochemical role has never been studied. The southern portions of the Avalon and Burin peninsulas are the foggiest locations in Canada (Hare, 1952; Joe, 1985, cited in Barrie and Schemenauer, 1986), and correspond to the only occurrence of blanket bog (a bog consisting of extensive peat deposits that occur more or les uniformly over gently sloping hills and valleys (Environment Canada, 1987)), in eastern North America (Davis, 1984).

Advection fog deposition commonly occurs when clouds intersect up-slope

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0022-1694/92/$05.00

mountain regions. For example, Californian redwood and Douglas fir forests collected up to 140 mm of fog drip per day (Azevedo and Morgan, 1974), and Andean forests over 800 mm $year^{-1}$ compared with 150 mm of rain (Cavelier and Goldstein, 1989), prompting Schemenauer et al. (1988) to explore the possibility of using collectors to harvest fog as a water resource. Advection fog is also important in some maritime areas. R.M. Cox (personal communication, 1991) estimated that fog drip represented half of the total precipitation on to a birch canopy near the Bay of Fundy, and that its acidic composition was damaging the foliage (Cox et al., 1989).

Although fog drip may be heavy from trees exposed to wind-driven fog, the huge collecting surface of trees is not present in coastal barren regions such as the southern Avalon and Burin peninsulas of Newfoundland. There, bog and heath surface cover have a surface area index close to unity, and present an essentially horizontal surface to incoming fog. The implications of this are unclear in terms of the flux to the surface. Lovett (1984) calculated that windspeeds of 2–10 m s^{-1} result in a droplet impaction velocity of 0.1–0.7 m s^{-1} on to vertical surfaces, compared with a settling velocity of 0.02–0.05 m s^{-1} on to horizontal surfaces. This suggests that a barren surface will receive less fog deposition than a forested one, other things being equal. Furthermore, the high aerodynamic resistance of such surfaces provides an additional resistance to droplet flux (Shuttleworth, 1977), although the larger droplets which characterize advection sea fog (Barrie and Schemenauer, 1986) increase the settling velocity somewhat. Barrie and Schemenauer (1986) found total flux rates reported in the literature of 0.1–4 mm h^{-1}.

The significance of fog deposition in the blanket bog zone is unknown. However, published historical records of mean annual streamflow (Environment Canada, 1990) exceed total annual precipitation (Environment Canada, 1982) by 400 mm. The imbalance between inputs and outputs is even more severe if evaporation losses are considered. The objective of this study is to assess the relationship between climate and advection fog in the blanket bog region of the southern Avalon Peninsula region, and to determine the quantity of fog deposition on to the bog surface. This information will help clarify some of the hydrological processes responsible for the development of blanket bog in the region.

STUDY AREA

The study location (Fig. 1) was at Cape Race, (46° 38′ N; 53° 06′ W), which lies within the southeast climatic zone of Newfoundland, being characterized by cool summers with persistent fog (Banfield, 1981). The average total annual precipitation registered at Cape Race is 1379 mm, 12% of which falls

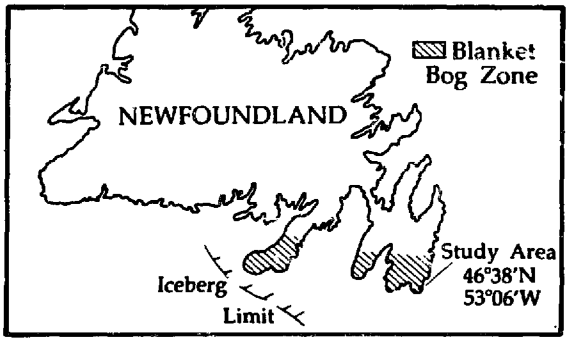

Fig. 1. The study area, indicating the blanket bog zone of the Atlantic Oceanic Wetland Region (Energy, Mines and Resources, 1986), and the general area to which the results of this study apply.

as snow (Environment Canada, 1982). Mean annual runoff from local rivers exceeds 1800 mm (Environment Canada, 1990). The climate is strongly controlled by the Labrador current, which encircles the Avalon and Burin peninsulas, bringing cold water and ice in the spring and summer (Farmer, 1981) (see Fig. 1). In summer, warm predominantly southwesterly air flows over the cold ocean, and produces advective fog (Table 1).

Coastal exposures in the study area indicate that approximately 6 m of stony glacial till overlie sandstone bedrock. The area was deglaciated approximately 10 000 years ago (MacPherson, 1981). The topography is characterized by gently rolling hills, with a relief ranging from 30–50 m at the cliff crest, to about 60 m at the study site, which lies 750 m from the coast at its nearest point. The blanket bog is extensive (Wells, 1976), and its surface is predominantly *Sphagnum fuscum*, with a variety of small ericacea such as *Empetrum* spp., and patchy cover of *Rubus* spp. and *Cladonia* spp. There is a thin but fairly even cover of *Scirpus* spp. A *Kalmia* heath cover occurs on the drier upland sites. Except for the *Scirpus* spp., which is approximately 15 cm high, the ground cover is very low, typically less than 3 cm.

TABLE 1

Average number of days at Cape Race, Newfoundland, with observations of fog (visibility reduced below 1 km) between 1951 and 1980 (Environment Canada, 1984)

	Month												Total
	J	F	M	A	M	J	J	A	S	O	N	D	
No. days	7	8	10	14	19	21	24	22	12	11	9	7	164

METHODS

The study period extends from 26 May to 16 August 1989. Rain (P) was measured with a factory-calibrated Rimco tipping bucket rain gauge. This was situated in a local depression with the orifice at the approximate level of the peat surface, to minimize wind turbulence. Evaporation (E) was determined using the Bowen ratio/energy balance method. Net radiation (Q^*) was measured with a REBS net radiometer positioned 2.5 m above the surface. This was factory calibrated prior to use, and was cross-calibrated with a new Middleton net radiometer, before and after the study period. There was no appreciable drift. Ground heat flux (Q_G) was measured with a factory-calibrated REBS soil heat flux plate, embedded 1 cm beneath the *Sphagnum* surface, which was remarkably uniform at the site. Dry bulb temperature (T_D) and wet bulb temperature (T_W) were measured at 0.5, 1.0, 1.5, and 2.0 m with potted thermocouples housed in aspirated chambers, the wet bulbs being covered with saturated wicks. Vapour pressure (e) was calculated as

$$e = e^* - \gamma(T - T_W) \tag{1}$$

where e^* is the saturation vapour pressure at T_W, and γ is the psychrometric constant. Evaporation was determined by evaluating the Bowen ratio (β)

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{\delta T_D}{\delta e} \tag{2}$$

and then

$$E = \frac{Q_E}{L_V} = \frac{Q^* - Q_G}{(1 + \beta)L_V} \tag{3}$$

The temperature profile system was within the boundary layer as the fetch in all directions was at least 200 m.

Wind speed and direction were measured at 3 m with a Wind Sentry anemometer and vane. All sensors were sampled at 20 s intervals, and the half-hour averages were calculated and stored with a Campbell Scientific 21 × Micrologger.

Fog was collected in two ways. A collector consisting of 2000 m of monofilament nylon line strung on to three concentric cylindrical aluminium frames (Goodman, 1985), was positioned over a funnel which was directed into a tipping bucket rain gauge. The depth of fog deposition on to the collector was determined as the volume of water divided by the area of the collecting funnel, which was 0.65 m diameter. If rain was registered simultaneously, fog deposition could not be distinguished, so these values were excluded from the totals. Given the relative infrequency of rain compared with fog, and the significantly smaller half-hourly totals of fog deposition, the consequent underestimation of fog by the collector method is not considered to be serious. The fog collector was not representative of the peat surface, so these unadjusted values are valid only as a record of the relative volumes and time of fog.

A lysimeter was used to determine the actual flux to the surface. The lysimeter was not deployed until 21 June, and the fog collector malfunctioned after 12 July. The lysimeter consisted of a galvanized steel box (0.3 × 0.3 × 0.3 m) open at the top, which was filled with an undisturbed peat monolith whose surface was typical of the bog, and set in the ground so its surface was flush with the surrounding vegetation. The measurement period for the lysimeter was approximately 12 h. It was weighed morning and evening to determine the mass change (dM), and the fog flux (F_{fog}) was determined as

$$F_{fog} = \frac{dM}{\rho A} - P + E \tag{4}$$

where ρ is water density, assumed to be $1000\,kg\,m^{-3}$ and A is the area of the lysimeter ($0.09\,m^2$). The resolution of the scale was such that fog accumulations of 0.1 mm could be measured under ideal conditions. However, under typically windy field conditions the resoluti n was only ± 1 mm. Daily adjustments were made to ensure that the water level in the lysimeter matched that surrounding it.

RESULTS

In the spring and summer season the study site (Fig. 1) is surrounded by cold water and icebergs brought south by the Labrador Current. Prevailing winds are onshore (Fig. 2), mostly from the southwest section (31.6%), or from the northeast (21.9%).

Advective fog is produced as moist air passes over cold water, and the condensate is blown onshore. The most frequent and highest yielding fogs are produced from the southwest sector (Fig. 3(a)), which have the warmest winds (Fig. 3(b)), and also the highest vapour pressure (Fig. 3(c)). Fog is also common from the onshore flow of southeasterly air which has a moderately high vapour pressure. A narrow band in the north-northeast sector also has a high frequency of fog. These are not directly onshore flows, but are related to cooler air conditions which produce condensation. A similar trend can be noted for rain (Fig. 3(d)).

Fog is most likely to occur at 04:30 h (Fig. 4) when the coolest diurnal temperature occurs (Fig. 5(a)) following the nightly period of radiative cooling (Fig. 5(b)) when the saturation vapour pressure is normally achieved

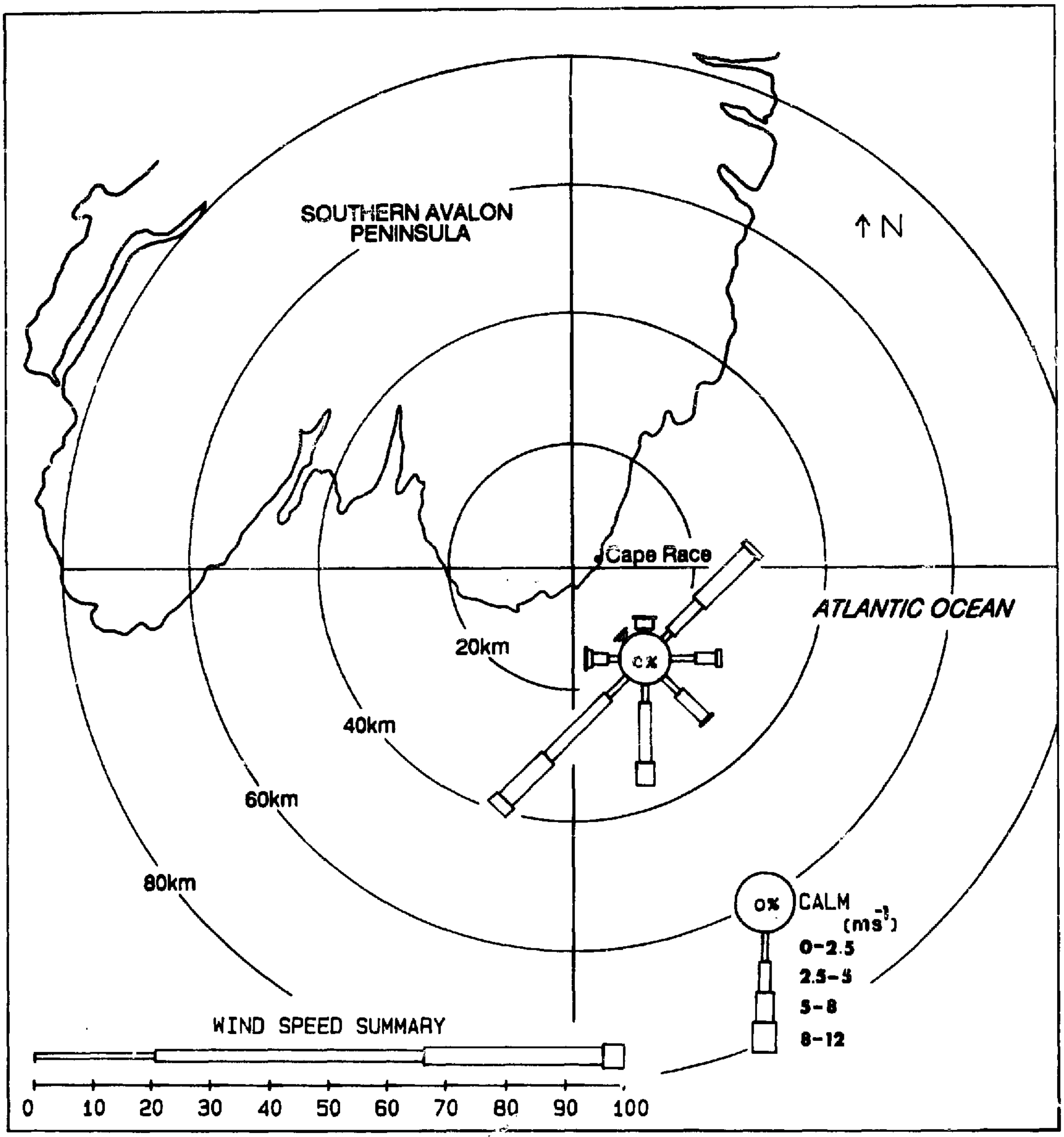

Fig. 2. Wind summary for 25 May–10 July 1989 near Cape Race, Newfoundland, based on half-hourly records, and directional compass indicating path length and direction for various trajectories of onshore and offshore air flows.

(Fig. 5(c)). The probability of fog declines from the early morning maxima (0.65), to the daily minimum at noon (0.18) when radiative heating peaks. A secondary peak occurs in the early afternoon, probably owing to the enhanced sea breeze effect. Although the fog is of advective origin, local air brought to saturation by cool nighttime temperatures cannot disperse incoming fog, and may even enhance it. The frequency of rain follows a similar trend to fog, but is much lower (Fig. 4).

Fog was experienced on 39 of the 44 days studied, compared with 28 days

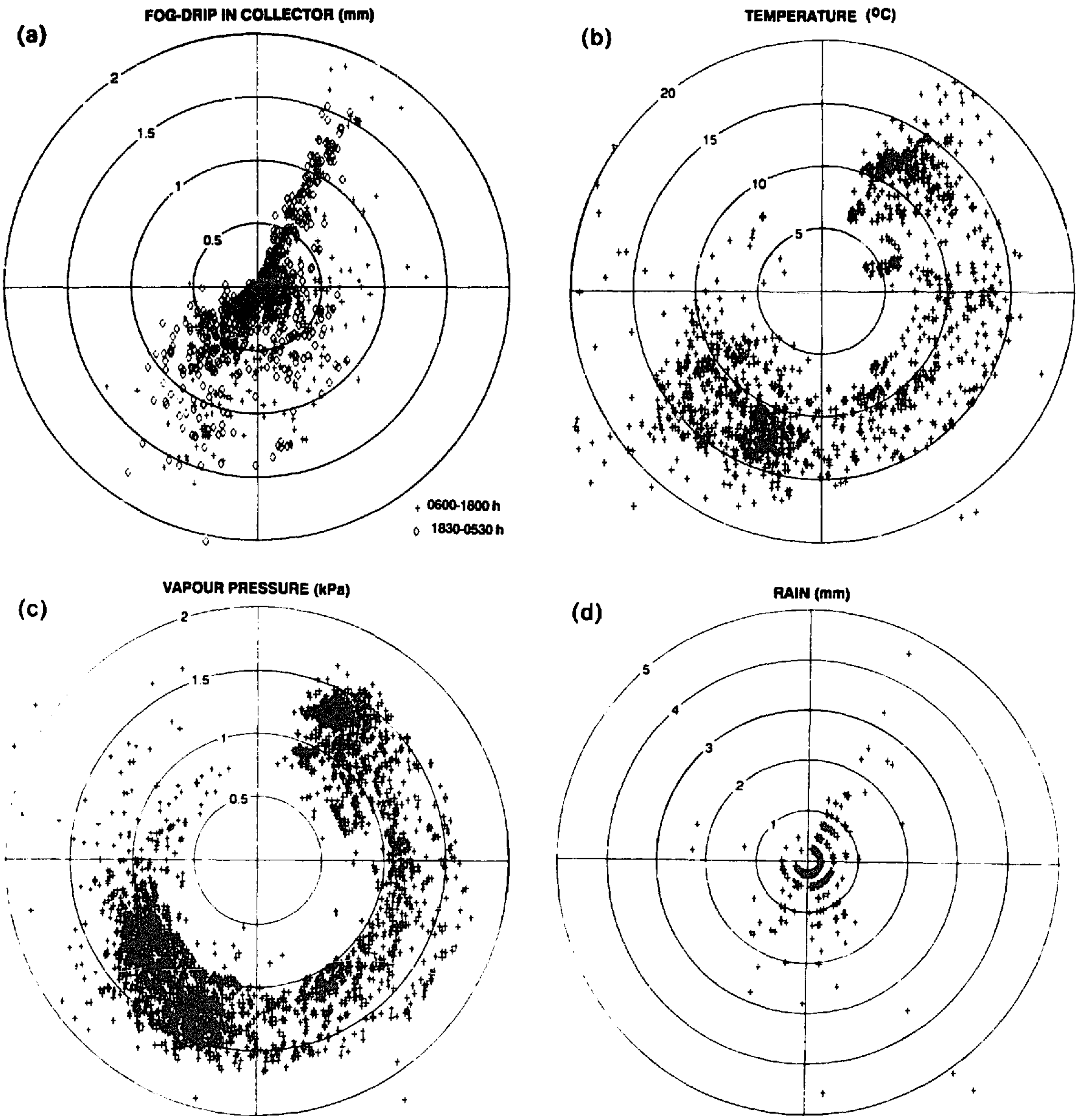

Fig. 3. (a) Half-hourly total of fog drip in the collector, indicating the average wind direction during the observation, for the period 26 May–11 July 1989. Two periods (06:00–18:00 and 18:30–05:30 h) are identified. (b) Half-hourly averages of air temperature, indicating the average wind direction during the observation, for the period 26 May–11 July 1989. (c) Half-hourly averages of vapour pressure, indicating the average wind direction during the observation, for the period 26 May–11 July 1989. (d) Half-hourly totals of rain, indicating the average wind direction during the observation, for the period 26 May–11 July 1989.

with rain (Fig. 6). Correspondence between fog and rain is poor, but fog is directly associated with warmer temperatures. The higher temperatures are associated with mesoscale atmospheric circulation patterns which bring warm southwesterly air onshore (Fig. 3(b)). The fog (and rain) produced under such conditions result in lower net radiation at the surface (Fig. 7(a)), and hence

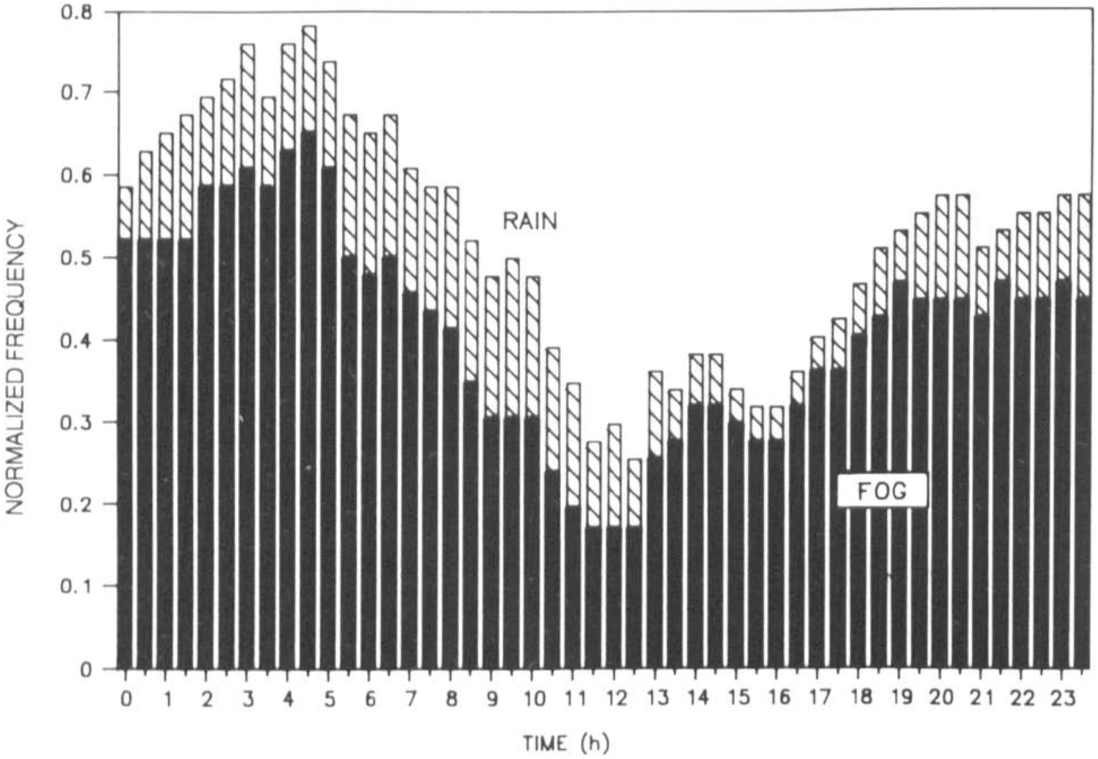

Fig. 4. Normalized frequency of fog and rain during specified half-hourly intervals between 25 May and 10 July 1989. The probability of rain is given by the length of the bar, rather than its position.

cooler surface temperature. The high vapour pressure over the weakly heated surface generates almost no vapour pressure deficit (VPD) during fog and rain (Fig. 7(b)), and consequently the rate of evaporation is low during these periods (Fig. 7(c)).

The daily flux of fog to the surface was estimated by summing the semi-daily fluxes calculated with eqn. (4) (Fig. 8). On some days negative values occurred due to measurement errors. Evaporation error analysis (Price, 1992) indicates accuracy to within $\pm 16\%$ and $\pm 20\%$ during clear and fog periods, respectively. Rain typically has a similar range of accuracy (Gray, 1970). However, measurement periods with rain exceeding 8 mm consistently overfilled the lysimeter, so were excluded from the analysis. Weighing the lysimeter under field conditions probably produced the largest source of error. Negative values between 0 and -2 mm (Fig. 8) suggest a daily error range of ± 2 mm for F_{fog}. The maximum daily deposition was 10.2 mm on 10 July. During the foggiest period (21 June–14 July) the cumulative fog deposition was 43 mm, averaging 1.8 mm day^{-1}. This represents approximately 50% of the rainfall (83 mm) during the same period. Over the entire period of lysimeter operation (21 June–16 August), fog deposition dropped to 30% of

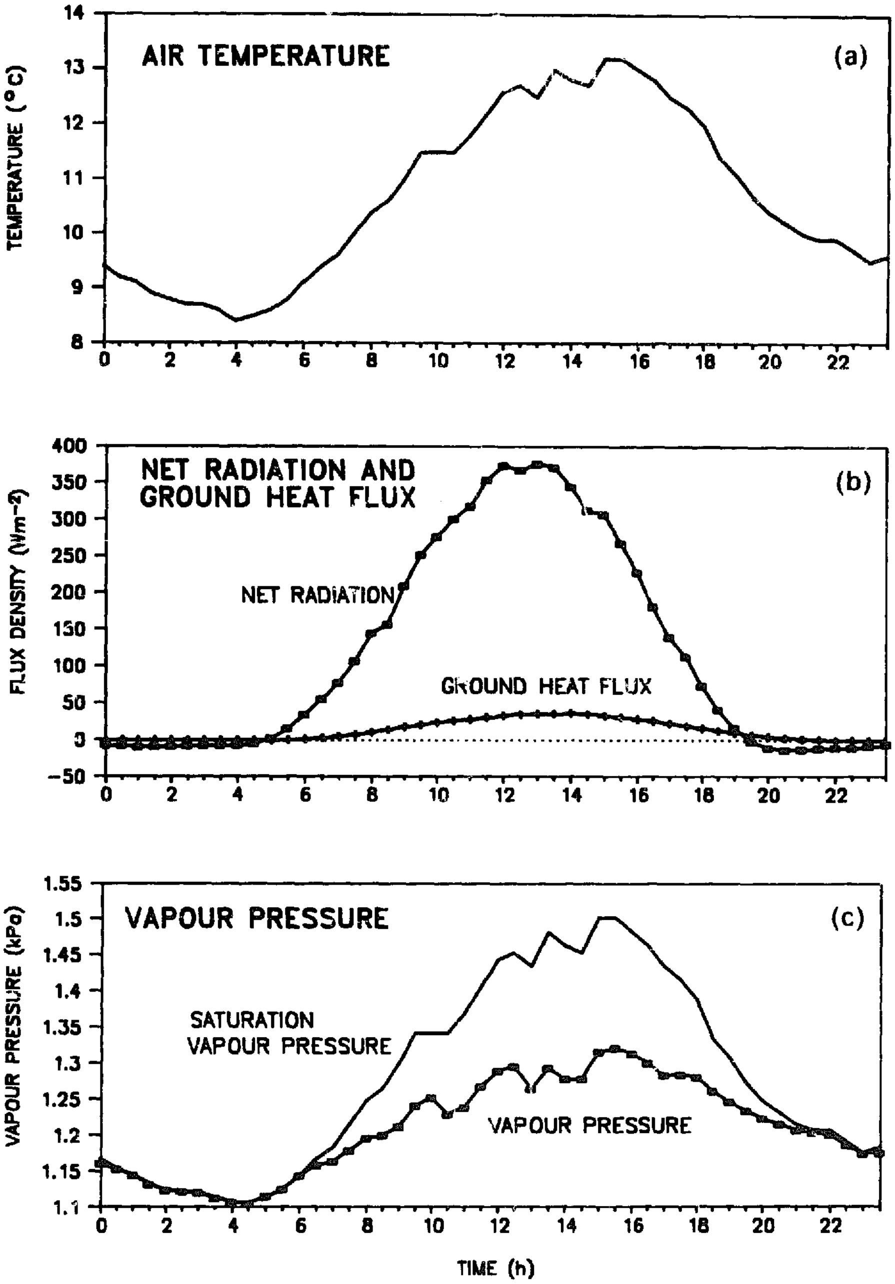

Fig. 5. Seasonal average (26 May–11 July) of half-hourly averages of: (a) air temperature at 1 m; (b) net radiation and ground heat flux; and (c) vapour pressure at 1 m.

rainfall, but since most fog occurred from mid-May to mid-July, this may underrepresent the true flux. Since fog deposition in semidaily periods when rain overfilled the lysimeter is not included in these totals, the actual value may be slightly higher.

It was hoped that the early-season accumulation of fog deposits could be estimated by calibrating the fog collector with the lysimeter. However, the

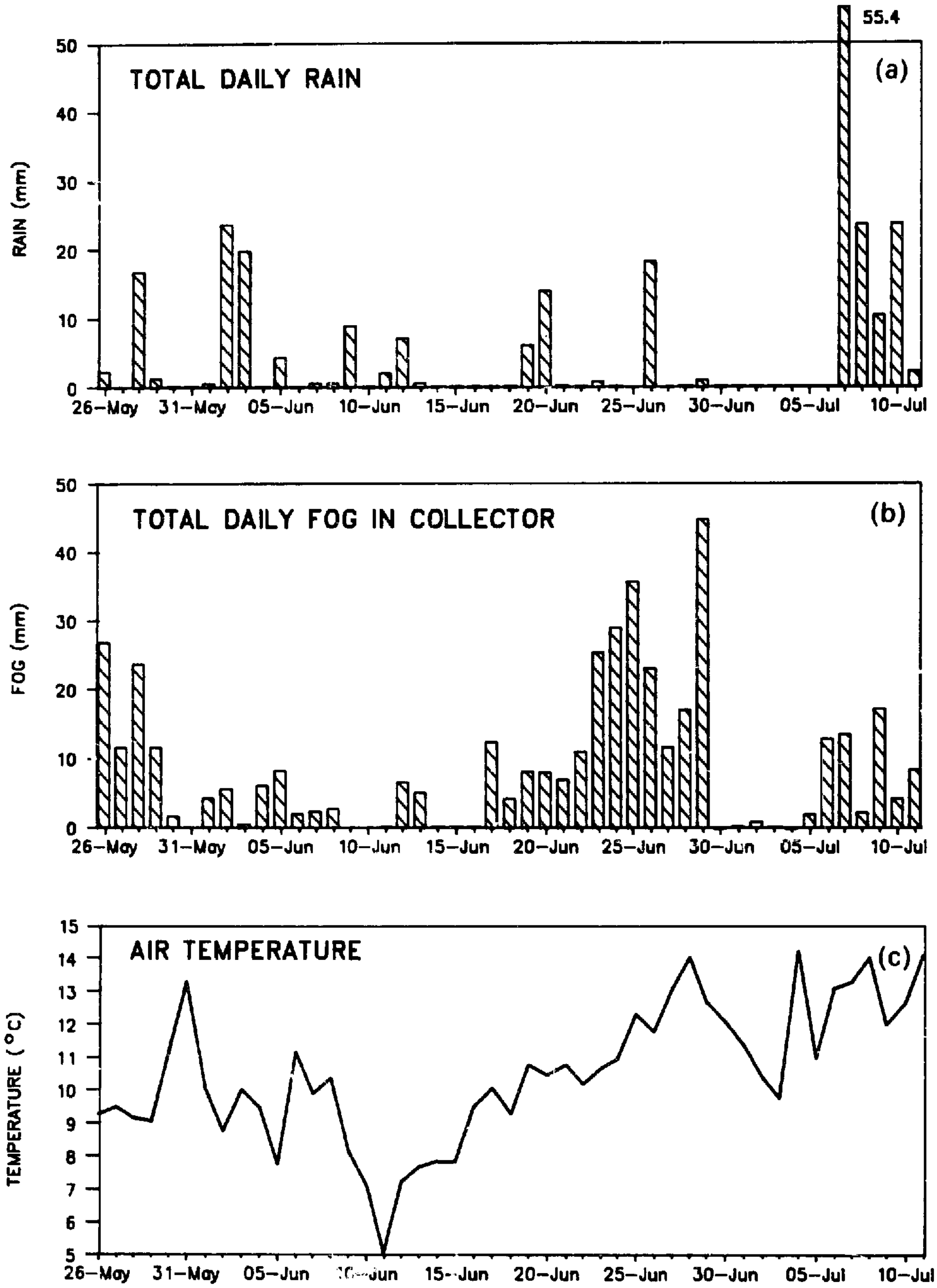

Fig. 6. (a) Total daily rainfall (upper), (b) fog deposition in the fog collector (middle), and (c) average daily air temperature (lower). Fog collector totals do not include half-hourly periods that registered rain and fog.

short period of overlap in their operation, the numerous rain events which overfilled the lysimeter, and the high variability of the catch ratios (see inset in Fig. 8) preclude a reliable calibration. The median and mean of the catch ratios are 0.12 to 0.32 (Table 2). Thus fog deposition registered in the collector between 26 May and 12 July is estimated to represent 50–137 mm at the

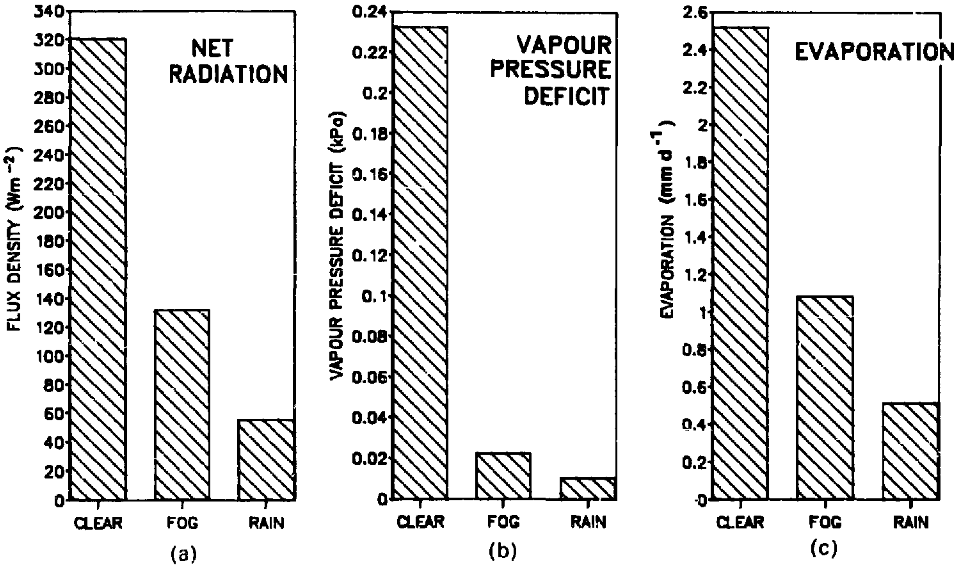

Fig. 7. Average values during the study period of: (a) net radiation (left); (b) vapour pressure (centre); (c) evaporation (right) between the hours of 06:00 and 18:00 h NST. 'Clear' refers to periods in which fog or rain were not recorded.

surface, or 20–50% of rain (251 mm) during that same period, and a maximum hourly flux between 0.8 and 1.3 mm h^{-1} (06:30–07:30 h NST on 23 June).

DISCUSSION AND CONCLUSIONS

Fog is produced under two different conditions. Most fog results from warm southwesterly sea breezes, which pass over cold upwelling water near the coast, cooling the air to below the saturation vapour pressure, and advecting the fog inland. Given the frequency of southwesterly air flow, this is the most common fog-producing condition at the Cape Race site. A secondary maximum in fog occurs when cooler northeasterly air blows onshore. As this cooler air is already near the saturation vapour pressure, it readily forms fog. The fog most frequently occurs at night (Fig. 4) when air temperatures at the site are cooler. Although the fog is advected from offshore, it may be enhanced by radiative cooling at night. This is supported by Fig. 3(a), which indicates that fog occurring between 18:30 and 05:30 h is much more common when it is from either the southwest or the north-northeast, traverses which are not direct sea breezes. Fog in the daytime (Fig. 3(a)) is more common from northeast to southeast, where the sea breeze is most direct, and there is least opportunity for radiative heating. During the daytime, radiative heating on the surface raises the saturation vapour pressure so the VPD is larger (Fig. 5(c)), and fog cannot penetrate inland as frequently,

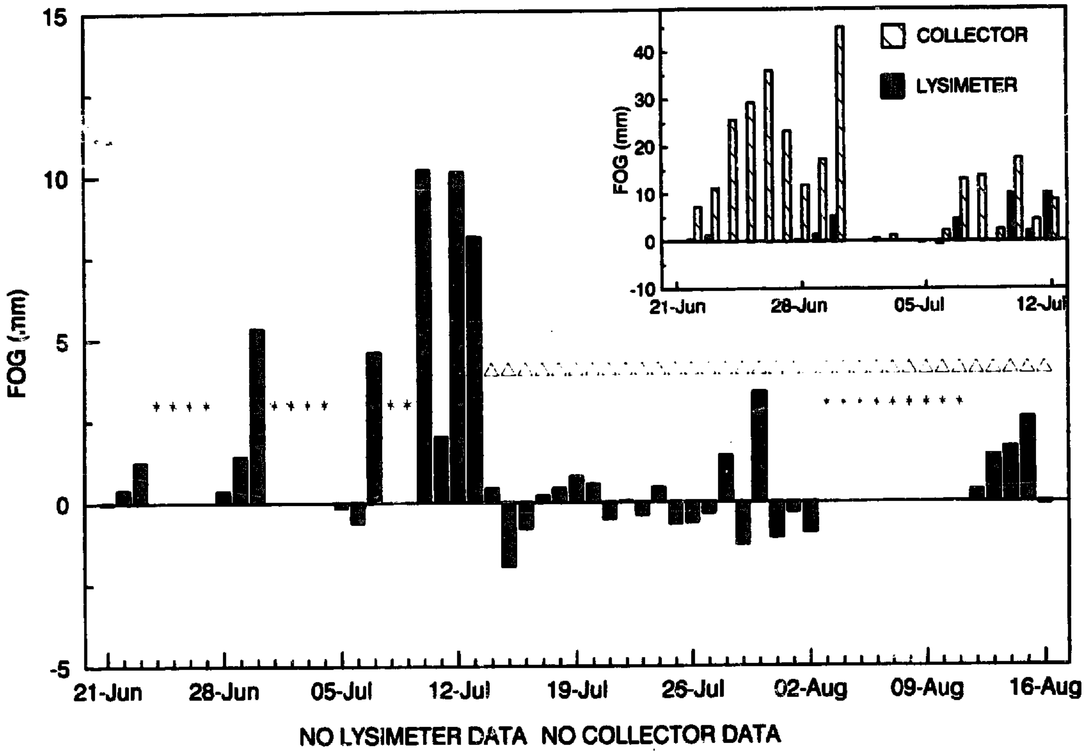

Fig. 8. Actual flux of fog to the surface determined with the lysimeter. Negative values are indicative of the daily error. Inset shows fog deposition in the collector (open bars) and lysimeter (solid bars) during the period of simultaneous operation. Missing lysimeter data between 24 June and 4 July were due to rain overfilling the lysimeter, and to unrecorded storage changes.

or as far. The areal extent of the fog is not well known, although a map of '% of hourly observations reporting fog' by Joe (1985, cited in Barrie and Schemenauer 1986) indicates a strong gradient of decreasing fog with distance inland, with the foggiest location in Canada corresponding to the blanket bog zone (Fig. 1).

TABLE 2

Mean and median ratios of fog catch in the lysimeter-to-catch in the collector

	Mean	Median	Standard deviation	No. of samples
All data included	0.32	0.12	0.37	9
Extremes excluded[a]	0.25	0.12	0.21	7

[a] Highest and lowest values excluded.

The amount of water provided by fog is significant. Between 21 June and 14 July, the amount of fog deposition was roughly half that of rainfall, or one-third of the total precipitation. R.M. Cox (personal communication, 1990) estimated fog drip in a birch forest near the Bay of Fundy using a model, and found that it was similar in magnitude to rain. Considering the small collecting surface of the bog, the high total deposition at this site reflects the high frequency of fog more than the efficiency of the surface as a collector. However, the maximum hourly rate of deposition at the surface estimated by the approximate calibration of the fog collector (0.8–1.3 $mm\,h^{-1}$) was well within the range of 0.1–4 $mm\,h^{-1}$ reported for forest canopies (Barrie and Schemenauer, 1986). Such high rates indicate that aerodynamic resistance of the relatively smooth surface is less than the 200 $s\,m^{-1}$ indicated by Shuttleworth (1977). Measured values of aerodynamic resistance here (Price, 1992) ranged from 20 $s\,m^{-1}$ with windspeeds of 10 $m\,s^{-1}$, to 60–140 $s\,m^{-1}$ with windspeeds near 2 $m\,s^{-1}$. Because of windy conditions (average 4.0 $m\,s^{-1}$ during fog and 5.0 $m\,s^{-1}$ when clear), the aerodynamic resistance is relatively low, favouring higher deposition rates. Furthermore, the larger fog droplets associated with sea fogs (Barrie and Schemenauer, 1986) enhances deposition.

Given the limitations of the data set, the total annual deposition of fog is unknown. Most fog occurs between May and August (Table 1), and most of May and August are unaccounted for in this study. Even so, it is unlikely that fog deposition can explain the excess of mean annual stream flow over mean annual precipitation (Environment Canada, 1982, 1990). Rain gauge undercatch at the Atmospheric Environment Service gauge in such an exposed windy location (Gray, 1970), probably results in a significant underestimate of local precipitation.

The southern Avalon and Burin peninsulas are dominated by blanket bog (Fig. 1) where there is a high frequency of fog. North of this area fog is diminished because of droplet interception to the surface in more coastal zones, and by radiative surface heating which disperses the fog during the daytime. Thus in the blanket bog zone, fog is an important source of water. In conjunction with reduced evaporation rates (Fig. 7(c)), fog alters the nature of the water balance, favouring higher water-table conditions. This is a requirement for blanket bog development, so fog may be a critical factor which enables the blanket bog to develop here, when it does not anywhere else in eastern North America (Davis, 1984).

ACKNOWLEDGEMENTS

I am grateful for the financial assistance of the Natural Sciences and Engineering Research Council of Canada, and the Centre for Fisheries

Innovation (through on Atlantic Canada Opportunities Agency grant), and to the Department of Fisheries and Oceans for accommodation at the site. I also appreciate the field assistance of John Crant.

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