THE OCCURRENCE AND UTILIZATION OF FOG.

by

DEREK WILLIAM HAYES
B.Sc., University of Hull, 1969.

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

in the Department
of
Geography.

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
May, 1970

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Department of GEOGRAPHY

The University of British Columbia
Vancouver 8, Canada

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ABSTRACT.

The thesis is proposed that, under certain favourable conditions, water may be deposited from fogs on to plants, and utilized by them. Where other sources of water are scarce, this addition may be critical for their survival.

The physical characteristics, and the spatial and temporal occurrence of fogs are discussed. An attempt is made to define some of the associated meteorological conditions, and some of the causal mechanisms, of certain common fog types, by a detailed analysis of the temporal coincidence of fog and certain meteorological parameters at Vancouver International Airport. This information is then used to construct a conditional probability model for the prediction of fog occurrence.

The techniques of mechanically measuring interception of water from fogs are next considered. Experiments with screened raingauges, in England, and a gauze - cylinder type recording fog gauge, at Vancouver International Airport, are described, and the significance of the results assessed.

It is hypothesized that there are two main pathways of fog water utilization by vegetation; the evidence for each is assessed. These are direct absorption of deposited water, which usually occurs under moisture stressed conditions, and drip to the ground, with replenishment of soil water, and subsequent normal root absorption.

It is considered that certain plant morphologies, at various scales, influence the amount of water that may be intercepted from fog. These are discussed, and attempts are made at experimentation, using laboratory fog

simulation. The difficulties of accurately measuring fog drip amounts from complex vegetation types are evaluated, and some simple models of fog drip assessed.

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ACKNOWLEDGEMENTS.

I should especially like to thank Dr. J.E. Hay, my advisor, for his encouragement, help, and advice at all stages.

Thanks are also due to other members of the Department of Geography, U.B.C., particularly Dr. G.R. Gates, for encouragement, and financial help with instrumentation; Prof. K.G. Denike, for considerable help with statistical problems; Dr. H.O. Slaymaker, for reading the final draft and giving advice, and Prof. M. North, for reading and helpful criticism. Dr. A. Black, of the Department of Soil Science, U.B.C., read and offered advice on chapter five. Dr. J.D. Chapman and the U.B.C. Geography Department are thanked for financial assistance with instrumentation, and the U.B.C. Geology Department is thanked for the long loan of a microscope.

The Department of Transport, particularly Mr. W.Mackie, Mr. N. Penny, and Mr. H. Christiansen, is thanked for allowing me to site my fog gauge at Vancouver International Airport.

Finally, I should like to thank Dr. R. Ward, of the Department of Geography, University of Hull, England, who initially fostered my interest in the possibilities of fog precipitation.

CHAPTER ONE.

INTRODUCTION.

Internationally defined, fog is a disperse system of water droplets suspended in the air such that the visibility is reduced to 1000 metres or less. It is usually thought of, because of this reduction in visibility, to be detrimental, and to be dispersed if possible.

The main object of this thesis is to show that fog can also be beneficial; whilst hindering economic activity in one area, it may make it possible in another.

It is considered that fog is underestimated as a source of water available for the growth of plants in many areas where fogs are prevalent. This is particularly the case where the normal precipitation is low. Research into this largely untapped water resource is at the present time minimal, and more is needed.

Plant growth in many semi - arid coastal areas is thought to be possible only due to the occurrence of fog. Water supplies may be augmented and utilized for irrigation. Wire nets strung across the mouths of some Chilean coastal desert valleys bear witness to this utilization. Forest fires may be minimized in other areas.

Chapters two and three consider how and where, and with what frequency, fog is formed, for little is known about the spatial and temporal distributions of fog. The spatial and temporal discontinuities in fog occurrence mean that it is very difficult to accurately define, and its distribution difficult to depict.

Chapter four considers the possible techniques

for measuring water contributed from fogs, as an essential preliminary to any quantitative assessment.

The subsequent chapters are concerned with the alternative ways in which vegetation may utilize water obtained from fog. It is hypothesized that there are two pathways of water use. The first is a comparatively minor one in terms of the absolute quantities of water involved, and requires water stressed conditions. This is the direct absorption of water into the plant through the aerial organs, and is discussed in chapter five. This may, however, be of great significance where other supplies of water are limited. The second pathway is when vegetation intercepts fog water droplets which subsequently drip to the ground. This augments the soil moisture, and may then be absorbed normally through the plant roots. In chapter six, this process is considered, especially in relation to forests, since here the vegetal surface exposed to the fog, and potentially able to intercept water from it, is at a maximum.

In chapter seven it is hypothesized that there are certain plant and tree morphologies which are most efficient in intercepting water from fog. An attempt is made to demonstrate the effect of leaf area and shape by laboratory experimentation.

It is concluded (Ch. 8) that, under certain conditions and in certain locations, fog is of great potential beneficial use, and it is at present under - utilized as a water resource.

CHAPTER TWO

PHYSICAL ASPECTS OF FOG.

Fog is the result of the condensation of water vapour in the air, forming minute water droplets. The rate of vapour condensation, and thus the rate of fog droplet growth, are a function of many interrelated factors, some of which are still being identified by cloud physicists. It may be stated:

$$\frac{dq}{dt} = f(\ T,\ p,\ w,\ \ldots\ )\ +\ f(\ n,\ d,\ \ldots\ )$$

where dq/dt is the rate of droplet growth, and the first expression involves meteorologic variables:

T = temperature

p = vapour pressure

w = a measure of turbulence;

and the second expression is to include environmental variables, such as

n = concentration of suitable condensation nuclei

d = diameters of droplets already formed.

It will be convenient to discuss the effect of these two sets of variables separately, although it will be readily appreciated that in reality the two cannot be separated, and the formation of fog will rely largely on their spatial and temporal coincidence.

TYPES OF FOG.

Fogs may be classified on the basis of their method of formation. There are very many ways in which fog may be formed, but there are two major ones; by

cooling of the air such that the dewpoint is reached, and by the evaporation of water into the air with no necessary change in the ambient air temperature. Although most fog classifications to date have been presented on a genetic basis (Byers, 1965b; Willett, 1944), this distinction has not been emphasized. A fog classification has been derived (Fig. 1, overleaf) which, within this basic subdivision, takes account of the method of cooling of the air, or of evaporation into it.

All known naturally occurring fog types are covered in this classification. However, three types of fog are most frequently encountered, and these will be considered further.

(i) Radiation Fog.

Radiation fogs are caused by cooling of the air in contact with a comparatively cold ground surface by radiative flux divergence. The air is thus cooled, and if the temperature approaches the dewpoint temperature, radiation fog may form. The cooling of the layer of air in contact with the ground produces an inversion of temperature which tends to stabilize any thin layer of fog as it forms. Deepening will only occur if there is some wind, to create enough turbulence to thicken the fog layer.

Radiation fog is normally "young" (it has not existed for more than a few hours); consequently the modal droplet size is normally small, in the range 2 - 20 μ. This means that it has a tendency not to impact on to vegetation, but to flow around it (see Ch. 7). Also, windspeeds are usually light, and there is not the necessary movement to allow "combing" of the

A. CAUSED BY COOLING OF AIR AND CONSEQUENT SATURATION.

1. Advective cooling.

i. Sea fog .....warm air cooled over cold water
ii. Land & sea breeze fog.warm air blowing to colder land or sea surface.
iii.Tropical air fog.....large scale tropical air movement to higher latitudes, thus cooling
iv. Monsoon fog.....large scale movement of tropical air in summer over cold water

2. Adiabatic cooling.

i. Hill fog..... upslope motion causing cooling; includes cloud on ground.
ii. Isobaric fog.....flux of air mass across isobars to lower pressure area
iii.Isallobaric fog.....cooling due to fall of pressure

3. Radiative cooling.

i. Ground radiation fog..radiation flux divergence in fairly still air
ii. High inversion fog....continental scale radiation of heat,cooling of air, creation of high level inversion.(100 - 600m)
iii. Radiation-advection fog .....night radiational cooling of air advected inland in day

4. Mixative cooling.

i. Horizontal mixing fog. horiz. mixing of air, cooling
ii. Front passage fog.....cooling at a front due to mixing of air masses

B. CAUSED BY SATURATION DUE TO EVAPORATION. (No necessary temperature change)

1. Downward vapour flux (frontal)

i. Pre warm front fog....
ii. Post warm front fog...
evaporation from warmer rain falling through colder air below

2. Upward vapour flux (steam)

i. Arctic sea smoke..... warm water evaporation into very cold air
ii.Habitation fog.....local saturation by animal herds & settlement in very cold air

Fig. 1. A genetic fog classification system.

water from them by vegetation.

(ii) Advection Fog.

Advection fogs are formed by the cooling of the air to its dewpoint by transportation over a colder surface. Advection fog is typically formed by warm air moving offshore from a warm land mass, to be cooled by a colder current. The cause of fog along the coast of western North America, South America, and South West Africa, where there are "foggy deserts" (see Ch. 5.) is advection of air from warm water to cold water in an onshore direction. The cold water along the coasts of the west coast deserts is the result of the characteristic cold currents of those regions.

The theory of Sverdrup (1942), as to the cause of the fog on the British Columbia coast is that during part of the year north-westerly winds in addition to the Coriolis force cause a south-westerly movement of water away from the coast. This is replaced by cold water upwelling to the surface, and provides the necessary cooling medium for onshore winds. (Pincock and Turner, 1956)

(iii) Hill Fog.

Hill fog, also termed mountain or upslope fog, is formed when air is forced to rise, and as a consequence is cooled adiabatically to its dewpoint. True hill fog is probably quite rare, (George, 1951), but in the present study any cloud type <u>touching the surface</u> in an upland region will be considered as hill fog. In the mountain water catchment areas

considered later (Ch. 6) this is probably the main fog type.

CONDENSATION AND NUCLEI.

Whilst the preceding fog classification (Fig. 1, p.5) indicates that meteorologic factors play a dominant role in determining fog formation, physical environmental factors, such as the availability of nuclei for the condensation process, also play an important, though less well-defined, role. Some of the non - meteorologic factors will now be considered.

In air artificially freed from aerosols and free ions, condensation cannot occur until about an eightfold supersaturation has been reached. (Relative humidity = 800 per cent.) Condensation at this supersaturation has been termed spontaneous condensation by Landsberg (1938). In air pure except for free ions, condensation may occur when a fourfold supersaturation has been reached. (Relative humidity = 400 per cent.) However, the air is in reality never totally free from aerosols, and it is generally considered that the formation of fog and cloud droplets occurs around the millions of hygroscopic nuclei normally found in the air. Condensation occurs because of the zone of lower saturation vapour pressure found around the hygroscopic nucleus.

The discovery of this fact was due to the classic experiments of Aitken (1888 - 1892) and Wilson (1897). Growth of droplets occurs because of the effect of surface tension. Small droplets in cloud and fog have slightly higher vapour pressures than the larger droplets. The smaller droplets thus evaporate to give vapour which condenses again on the larger ones.

(Langmuir, 1948). This pressure difference is very small, but is very important in the growth of fog and cloud droplets up to 20 - 30 μ diameter. Whilst other processes have to be considered in droplet growth above this diameter, (Mason, 1957), this process probably accounts for the growth of most types of fog, where the modal droplet diameter is 20 - 30 μ . Okita (1962) concluded from a study in Hokkaido, Japan, that ordinary fog droplets grow mainly by condensation.

There are many types of condensation nuclei. Atmospheric condensation nuclei are believed to originate in three main ways: by condensation and sublimation of vapours during smoke formation, and in gaseous reactions; by the mechanical disruption and dispersal of matter, such as the formation of dust and spray; and by the coagulation of nuclei, which may yield mixed particles as well as simply larger ones. (Mason, 1957). Since condensation nuclei play an important role in the condensation process, it will be of value to briefly discuss the different types of nuclei, and consider where they might occur.

Hygroscopic nuclei.

Several investigations have shown that sea salts, including NaCl, $MgCl_2$, $MgSO_4$, and $CaSO_4$, are the most frequent types of condensation. (Simpson, 1941) Results of chemical composition analyses carried out by Gindel (1966), at Rehovot, Israel, suggested that at least in a semi - arid environment, chlorides and sulphates formed the most abundant nuclei types. Soil particles and cosmic dust have also been found as hygroscopic nuclei in fogs. (Myers, 1968).

Simpson (1941) calculated that if sea salts

were entirely responsible for condensation, nuclei would have to be produced from the ocean surface at the unlikely rate of 50,000 cm^{-2} sec^{-1}. Mason (1957) pointed out that although Simpson probably overestimated, it is likely that other sources of hygroscopic condensation nuclei are important. Ogiwara and Okita (1952) concluded, from a study at Sendai, Japan, that combustion products were the main source of hygroscopic condensation nuclei in their samples. They considered that sea salts played only a minor role, despite the fact that Sendai, where the samples were taken, is only 12 km. from the sea.

Combustion products, from factories, automobiles, and the like, produce billions of hygroscopic nuclei, particularly sulphur trioxide, that rapidly disperse and become a significant fog - aiding factor in many areas. Locally, man's activities strongly augment the number of available condensation nuclei. (Byers, 1965a)

The famous study of Hrudicka (1938) is of relevance here. Hrudicka analysed historical records, and produced figures for 20 year intervals of the average number of foggy days in Prague, Czechoslovakia:

Date	1801-1820	1821-1840	1841-1860	1861-1880	1881-1900	1901-1920
Av.No. foggy days/year.	83	80	87	79	158	217

The increasing number of foggy days was attributed by Hrudicka to the effect of increasing industrialization after about 1880, and the consequent provision of condensation nuclei resulting from the burning of coal. Beyond 1920, there was apparently no further increase, due

to, according to Geiger (1965), "improvements in the construction of fireplaces," and "replacement of steam locomotives by electric ones." (Geiger, 1965, p. 492.)

In many industrialized parts of the world, fog frequency has now decreased with the availability of more sophisticated technology to remove pollutants, increased public awareness, and legislation, such as the Clean Air Act (1956) passed for London, England, as a result of public outcry against the 1952 smog. Household chimneys in that city now produce only 13 per cent of the smoke that they produced in 1952. (Province, Vancouver, B.C. newspaper, 1. 12. 69., p. 2.)

The absorptive properties of hygroscopic nuclei allow condensation to begin at comparatively low relative humidities, down to about 65 per cent, although normally condensation will not occur until the relative humidity is over 90 per cent.

Non - hygroscopic nuclei.

One author, Kuroiwa (1953) found that condensation could occur on non - hygroscopic nuclei. These were derived from combustion products such as carbon - black and tars, but the physics of this condensation process is uncertain. Kuroiwa also found fog droplets apparently without a nucleus at all. These he explained by hypothesizing that larger drops accumulating around non - hygroscopic nuclei may split into two pieces, making one a no - nucleus droplet. It is possible, Kuroiwa states, that when a cloud is formed in violent air streams, such as that in cap clouds over the summit of a mountain, or in the clouds produced in steeply rising air currents, larger water droplets may occasionally be broken up by purely mechanical

causes.

Table 1 , below, from Kuroiwa (1953) and Nakaya (1957), gives an indication of the relative frequencies of different nucleus types.

Type of Fog.	Combustion product	Soil material	Sea salt	No nucleus	Sample total.
A.Sea fog	49.12	14.03	28.07	8.77	57
B.Mt. fog	51.28	28.20	12.82	7.69	39
C. Both	50.00	19.79	21.87	8.33	96
D.Sea fog	50.00	10.00	40.00	not given	255

Table. 1 . Percentage frequency of fog droplet nuclei.[1]

1 Includes hygroscopic and non - hygroscopic nuclei. A,B, and C are calculated from figures given by Kuroiwa, (1953), p. 372; D is from Nakaya (1957).

SPATIAL DISTRIBUTION OF CONDENSATION NUCLEI.

Little work has been carried out on analysing the spatial distribution of condensation nuclei; from what has been said previously, this is of significance to the present study. One study that has been made is that of Landsberg (1938). He analysed the nucleus contents of the atmosphere in different localities, and found that the average concentration is smallest over the oceans and in the upper air, and is greater in air subject to industrial pollution. Landsberg's results are shown in Table 2 , overleaf.

Interpretation of these nucleus concentration figures is very difficult, as there are so many variables

Locality	No. of places	No. of observations	Average nucleus concentration. (cm^3)
City	28	2,500	147,000
Town	15	4,700	34,300
Country, inland	25	3,500	9,500
Country, shore	21	2,700	9,500
Mt., 500-1000m.	13	870	6,000
Mt.,1000-2000m.	16	1,000	2,130
Mt., 2000m. +	25	190	950
Islands	7	480	9,200
Ocean	21	600	940

Table. 2 . Spatial distribution of condensation nuclei. (Adapted from Landsberg, 1938)

that need to be considered. Landsberg attempted some correlations with climatic parameters, including fog frequency, without success, and he concluded that the nucleus count at a given station is controlled too much by local influences to permit general inferences.

In West Pakistan, and also in Mexico, measurements of condensation nucleus concentrations by Fournier D'Albe (1957) showed that in these locations the main nuclei source was the sea and coastal zones. The main agent of nucleus removal from the air was found to be precipitation, but Fournier D'Albe found that if the nuclei escaped precipitation near the coasts they could easily penetrate far inland.

It is clear that it is not at present possible to draw any firm conclusions as to the relationship of fog to condensation nucleus distributions; nuclei are

normally unlikely to be the limiting factor on fog or cloud formation, however. (Mason, 1957)

FOG DROPLET SIZES.

Before considering fog distribution, and the meteorologic factors associated with this distribution, (Ch. 3), it will be of value here to consider briefly the droplet size characteristics and liquid water contents of fogs, since this is of obvious significance in any consideration of fog water use by plants. The larger the water droplet, the greater the momentum it may possess to impact on to vegetal surfaces.

Nucleus sizes do not affect the size distribution of the fog droplets themselves. (Kuroiwa, 1953) Woodcock (1950), however, found that large nuclei (diameter $> 1 \mu$) induced more rapid growth of a fog droplet than smaller nuclei.

Natural fogs are rarely monodisperse, that is, with droplets of equal sizes, but have a range of diameters varying from 2 - 3 μ up to 60 - 80 μ . Natural fogs may thus correctly be termed polydisperse. The normal droplet size distribution of fog can be approximated by a normal curve, with a modal frequency around 20 - 30 μ . The range of droplet sizes is due to the fact that the factors causing droplet growth are almost never exactly spatially equal; slight variations in vapour pressure yield a polydisperse fog. (Coalescence of fog droplets is not normally by collision; see p. 8)

Modal droplet size appears to increase with time, that is, with the "age", or persistence of the fog. Malrous (1954), in a study of fogs off the English east coast, found that the only factor increasing the mean

droplet diameter in sea fog was the length of persistence. Thus it may be concluded that where fog persists, the probability of the growth of larger droplets is increased; this in turn will increase the chance of impaction on to vegetation, due to increase of momentum with mass.

LIQUID WATER CONTENT.

The problems associated with the measurement of fog liquid water content are considerable, (Mason, 1957), mainly relating to sampling procedures. From the evidence that exists, liquid water content of fog appears to increase with temperature, since the air is capable of holding more water at higher temperatures. (Zaitsev, 1950.)

This assumption is important since it means that in hot arid or semi-arid areas, fogs will contain more water for the same volume of air at a given relative humidity. Possible drip of fog water from leaves of plants, or absorption into the leaves (see CH. 5 and 6) will also increase due to the decrease in water viscosity with temperature increase.

The relationship of liquid water content to droplet size distribution in the fog is unclear. Increase of momentum with mass (see above) is important for vegetal impaction. Grunow (1959), substituting a wire mesh for vegetation, studied the amounts of water collected in relation to the fog droplet spectrum. (Since Grunow measured this on Mt. Hohenpeissenberg, in Bavaria, he was dealing with cloud touching the surface, which is included here under the term 'fog'; see p. 6) He found that the efficiency of cold polar air for depositing water was very poor. This was characterized

by small diameter droplets, ranging from 2 to 15 μ . Increasing water catch was found to result from maritime air masses, both temperate and subtropical in origin, when the cloud droplet spectrum was characterized by a wider range of droplet diameters, from 4 to 25 μ , with a modal frequency of 8 - 14 μ . Deposits were found to be heaviest from air masses that had degenerated due to continental influence. In this case, the droplet spectrum was found to range from 5 to 60 μ, with a modal frequency of 12 to 18 μ diameter. Thus it seems that the effective liquid water content, from the point of view of impaction on to vegetation, increases with age, increase of temperature, and is also a function of air mass origin.

In the next chapter, the spatial occurrence of fog, and the meteorological factors associated with its occurrence, will be considered.

CHAPTER THREE

FOG OCCURRENCE AND FREQUENCY.

No significant amounts of water are likely to be gained from fogs if the phenomenon occurs only rarely. It is therefore of value to consider where, and with what frequency, fog may form.

FOG OCCURRENCE.

i. The Data.

For the present purpose, that of considering the contribution to the water economy that may be gained from fogs, most of the existing maps of fog frequency are inadequate, in that they do not give fog duration. Fog duration represents the time during which fog is available for possible utilization by the vegetation.

There have been comparatively few maps of fog frequency, but those that do exist record "fog - days" as the unit of frequency, whereas this study requires the use of a much smaller time interval. Hourly data is probably much more justifiable here.

In North America, the first map of "fog - day" frequency appears to have been that of Stone (1936). Five years later, in 1941, a map of the "Average Annual Number of Days with Dense Fog" in the United States was published (U.S.D.A., 1941). Both of these maps, however, failed to take account of the changing definitions of the terms " fog " and " dense fog " that had occurred in the

period from which they derived their mean values.

In 1966, in an attempt to overcome difficulties of definitions, a map was produced by Court and Gerston (1966) of fog frequency in the United States, which rigorously defined the terms used in visibility definitions to make up a composite map for 60 year means of "fog - days."

However, from the present point of view, this map was still of limited validity because it again failed to delimit any temporal minima to the occurrence of fog within a particular day.

A map of fog frequency by hours is required to give a more realistic picture of fog duration. A comparatively small number of meteorological stations record hourly weather, when compared to the total number recording weather daily. This applies to North America and elsewhere. In Canada, hourly data are available (Hourly Data Summaries, for individual stations), but the hours of "fog" recorded include all visibilities, ice fog included, of less than six miles. This definition does not agree with the international definition of visibility in fog. (see p. 1) For the purpose here, the assessment of potential availabilities of fog for plant use, this data source is not very helpful without modification.

ii. Spatial and altitudinal variation of fog in British Columbia.

In any attempt to construct a map of fog frequency, some knowledge of the factors influencing the distribution of fog would be useful.

Correlation analyses were carried out on the "fog - day" data, available in the form of mean values,

for 36 stations in British Columbia. No significant correlation (at the 0.5 per cent level) was found between fog - day frequency and either altitude or distance from the sea. Even if only non - coastal stations are considered, to eliminate the eleven stations recording 'distance from sea' as zero, still no significant correlation is found. The results are shown in Table 3, below.

	CORRELATION COEFFICIENTS OF FOG-DAY FREQ.	
	with dist. from sea.	with altitude.
All stations (36)	+ 0.080*	- 0.061*
Non - coastal stations (25)	- 0.030*	- 0.219*

* = not significant at the 0.5 per cent level.

Table 3. Correlation of fog - day frequency, distance from sea, and altitude in British Columbia.

In an attempt to see if this insignificant correlation was true even with more defensible data, means of the number of hours of fog with visibility of 5/8ths mile or less (as internationally defined), and also with visibility of ¼ mile or less, were compiled for 13 stations in southern British Columbia. The period used was the five years 1957 - 1961 inclusive, since this was the last complete five year period for which the data were available in published form. The "General Summaries of Hourly Weather Observations in Canada" (D.O.T., annually), from which the data were extracted, ceased publication in 1961.

One of the station records used was that for

Old Glory Mountain, near Rossland, B.C., at an altitude of 7700 feet, several thousand feet above the next highest station in B.C. Since this station is somewhat exceptionally high, correlation analyses were carried out both including it and excluding it, against altitude. Results are shown in Table 4, below.

1. HOURLY DATA:	Correlation coefficient:	
	Fog[1]/ Altitude	Thick fog[2]/ Altitude
With Old Glory Mt.	+ 0.8177	+ 0.8064
Without Old Glory Mt.	+ 0.3899*	+ 0.3450*

2. FOG - DAY DATA, FOR COMPARISON:	Correlation coefficient:	
	Fog[1]/ Altitude	Thick fog[2]/ Altitude
With Old Glory Mt.	- 0.0624*	Data not available.
Without Old Glory Mt.	+ 0.1538*	

* = not significant at the 0.5 per cent level.

1 = visibility recorded as 5/8ths mile or less.
2 = visibility recorded as $\frac{1}{4}$ mile or less.

Table 4. Correlation of fog and altitude for 13 B.C. stations.

The scatter diagram for hours of fog against elevation is shown in Fig. 2, overleaf.

It can be seen that the hourly data produce higher correlations than the fog - day data. The production of a significant correlation coefficient by the inclusion of an extra station, Old Glory Mountain, is slightly dubious intuitively, but is statistically

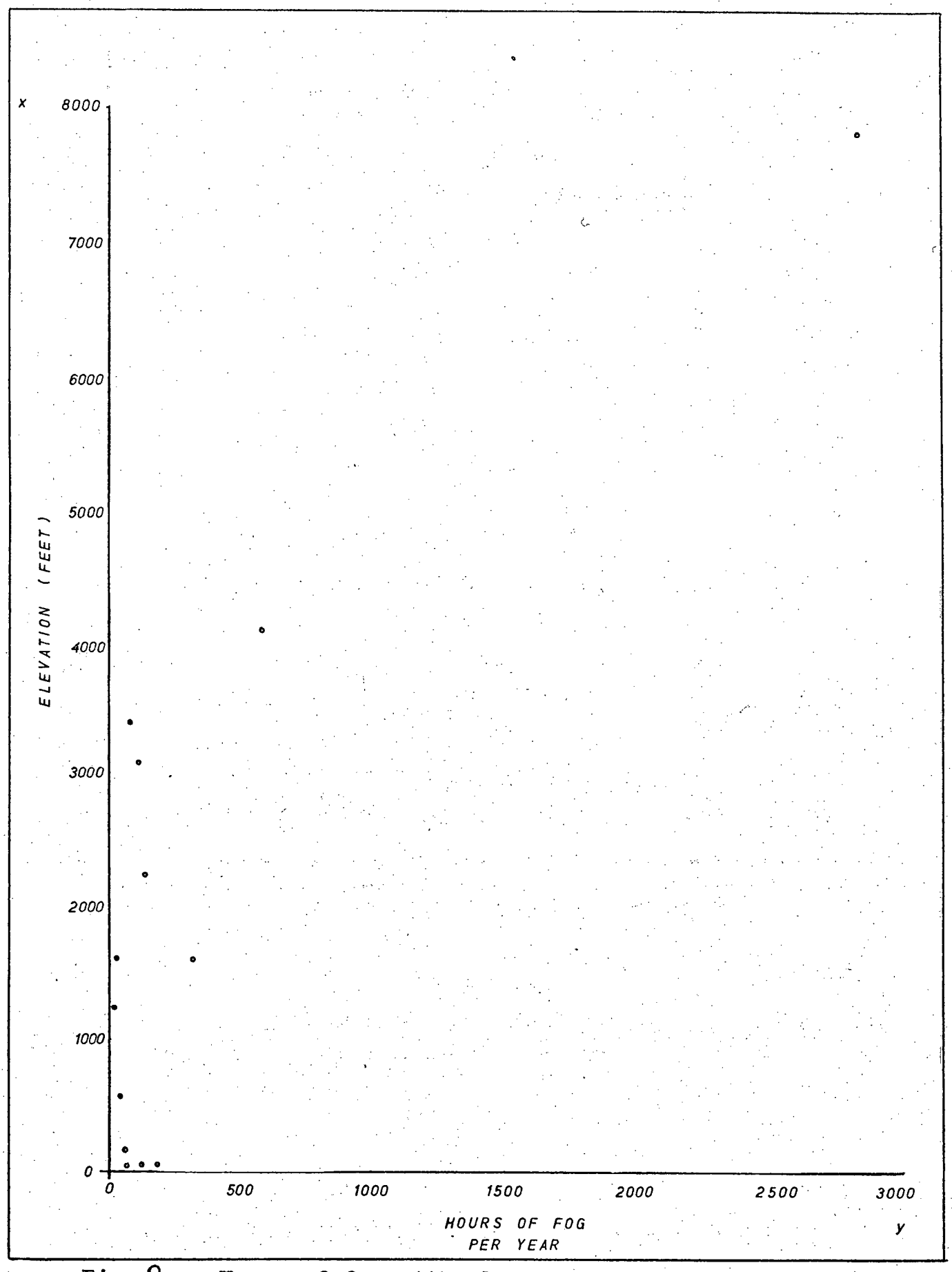


Fig. 2 . Hours of fog with elevation, southern B. C.

permissable; the trend in the scatter of fog/altitude plots at low frequencies and altitudes is resolved by the inclusion of this both high frequency and high altitude station. It may thus be tentatively stated that fog duration, as measured by hourly frequency, increases with height in southern British Columbia.

Without Old Glory Mountain, however, the poor correlation of hourly fog frequency with height means that more data would be required before techniques of spatial interpolation could be correctly applied to construct a fog frequency map.

THE METEOROLOGICAL FACTORS ASSOCIATED WITH FOG.

It is impractical in the present context to carry out a comprehensive analysis of the meteorological parameters associated with the occurrence of fog on any widespread scale. It is considered, however, that it would be useful to analyse in detail the factors promoting the formation of fog, and those hindering its formation, for a single station. Although this station may not be completely typical, if such a station exists at all, this should provide general insights into the factors affecting the frequency with which fog forms.

It is also useful to analyse the meteorological factors which accompany fog before attempting to reverse the analysis, with the selected "best" variables, to predict the occurrence or non - occurrence of fog.

Analysis of fog at Vancouver International Airport.

Mainly because of ease of availability of data, and also because the fog gauge described in Ch. 4 could be located there, Vancouver International Airport was chosen for the detailed fog analysis. Monthly climatological summary sheets, issued for this station by the Canada Department of Transport, were utilized for this study (D.O.T., monthly). The use of summary data makes analysis of a long period more feasible than it would be if the daily surface records had to be used. By reference to a subjective one - sentence desdription of an individual day's weather, the occurrence or non - occurrence of fog, and its approximate duration, could be found.

If a long period of data was analysed, such as that for which climatic normals are derived (30 years),

the problem of non - stationarity of the data would probably become acute, since much recent evidence has been found for the alteration of climatic parameters with the advance of urbanization, and the development of the Greater Vancouver area has been considerable in the last 30 years. Thus it was felt advisable to reduce the period considered to 5 years, and since concern is here with what is happening at the present time, the last period of 5 consecutive years (1965 - 1969 inclusive) was used. For the purpose of the present part of the study, considering the association of meteorological parameters with fog, without attempting to predict, a five year period is considered adequate.

Fog was analysed at Vancouver International Airport on the basis of three categories: "all day fogs", "morning fogs", (A.M. fog) and "evening fogs", (P.M. fog). The Department of Transport defines A.M. fog as any fog which occurred during the period 0000 hours to 1200 hours, but not elsewhere; P.M. fog means any fog that occurred between the hours 1200 and 2400, but not elsewhere; all day fog refers to fog that occurred during a minimum of all the daylight hours. The errors that have been introduced by the use of these durational divisions are not considered likely to be of significance for the present purpose, though the limitations imposed by the data must be borne in mind . The use of easily available data outweighs any minor disadvantages.

In the five year period, 120 A.M. fogs were reported, 16 all day fogs, and 11 P.M. fogs.

Time of year.

It is useful to look first at the time of year in which fogs have been reported, since the periods of

maximum frequencies presumably represent those times when the causal factors most frequently intersect, or the dissipation factors are infrequent.

All but four of the 120 days on which morning fog was reported fell within the period August to March inclusive. These eight months have thus been given the most attention. The frequency of days with morning fog, by months, is shown in Fig. 3, p. 25.

Days recorded as having fog all day are concentrated into the months of November and October. (Fig. 4, p. 26.) If it is hypothesized that the majority of morning fogs are likely to be radiation fogs, whereas the majority of fogs persisting all day are advection fogs, it is interesting to compare the data for Victoria International Airport with the Vancouver data. During the same period of five years, Victoria recorded a similar number of all day fogs (21), but considerably fewer morning fogs. (70) Evidence will be presented later (p. 38) showing that wind speeds of less than about 5 mph are required for the formation of radiation fog. Thus it may be concluded that, provided other factors remain relatively unchanged, the lesser number of morning fogs recorded at Victoria is due to the higher wind speeds normally recorded there. (see p. 44)

Fog and temperature.

The volume of water required to saturate or nearly saturate the air increases as the temperature is increased. If other conditions remained equal, fog frequency would thus be expected to decrease with increase in temperature, but in fact higher temperatures are indicative of higher levels of available energy, and

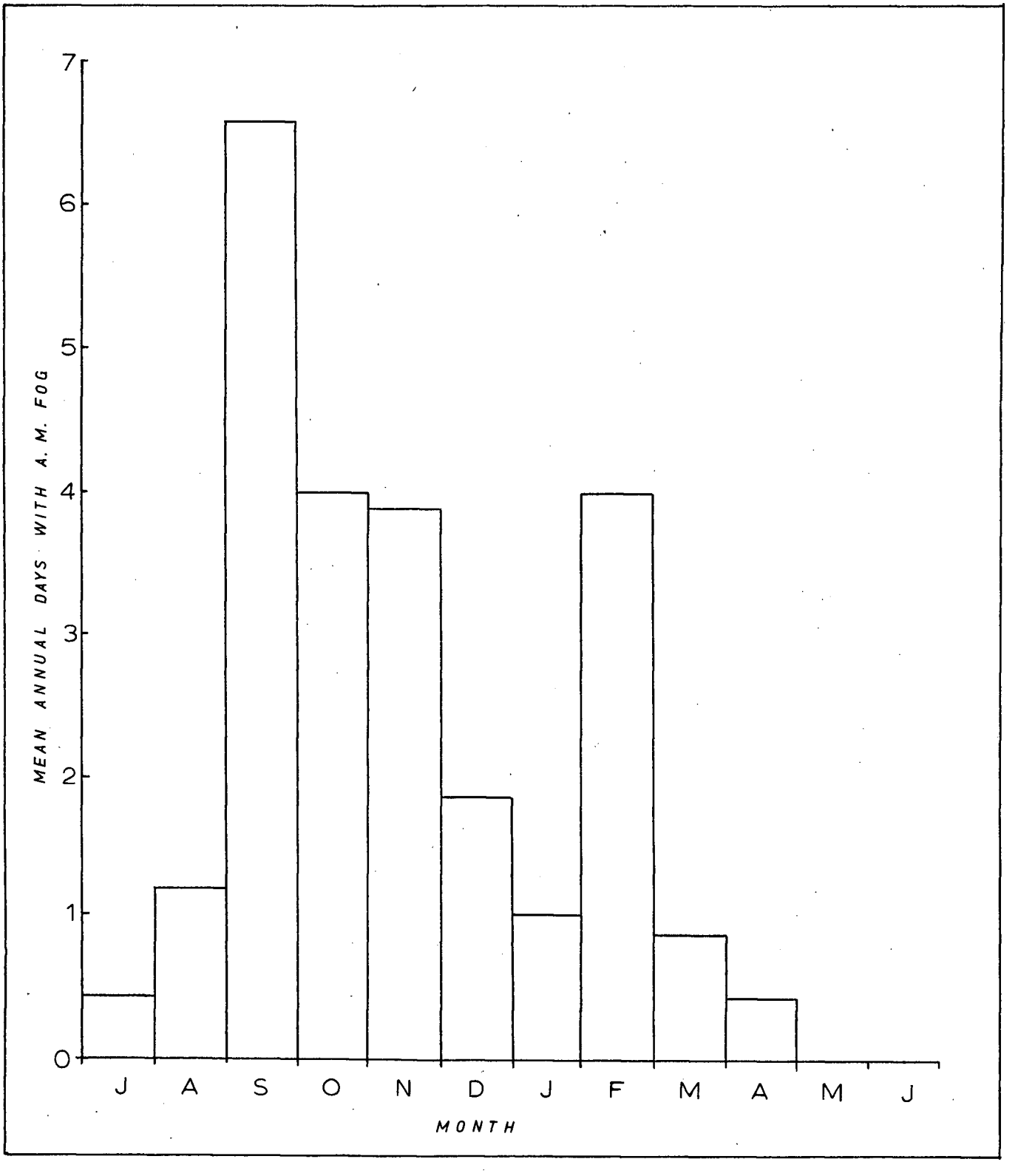


Fig. 3 . Mean annual frequency of A.M. fog. Vancouver International Airport, 1965 - 1969.

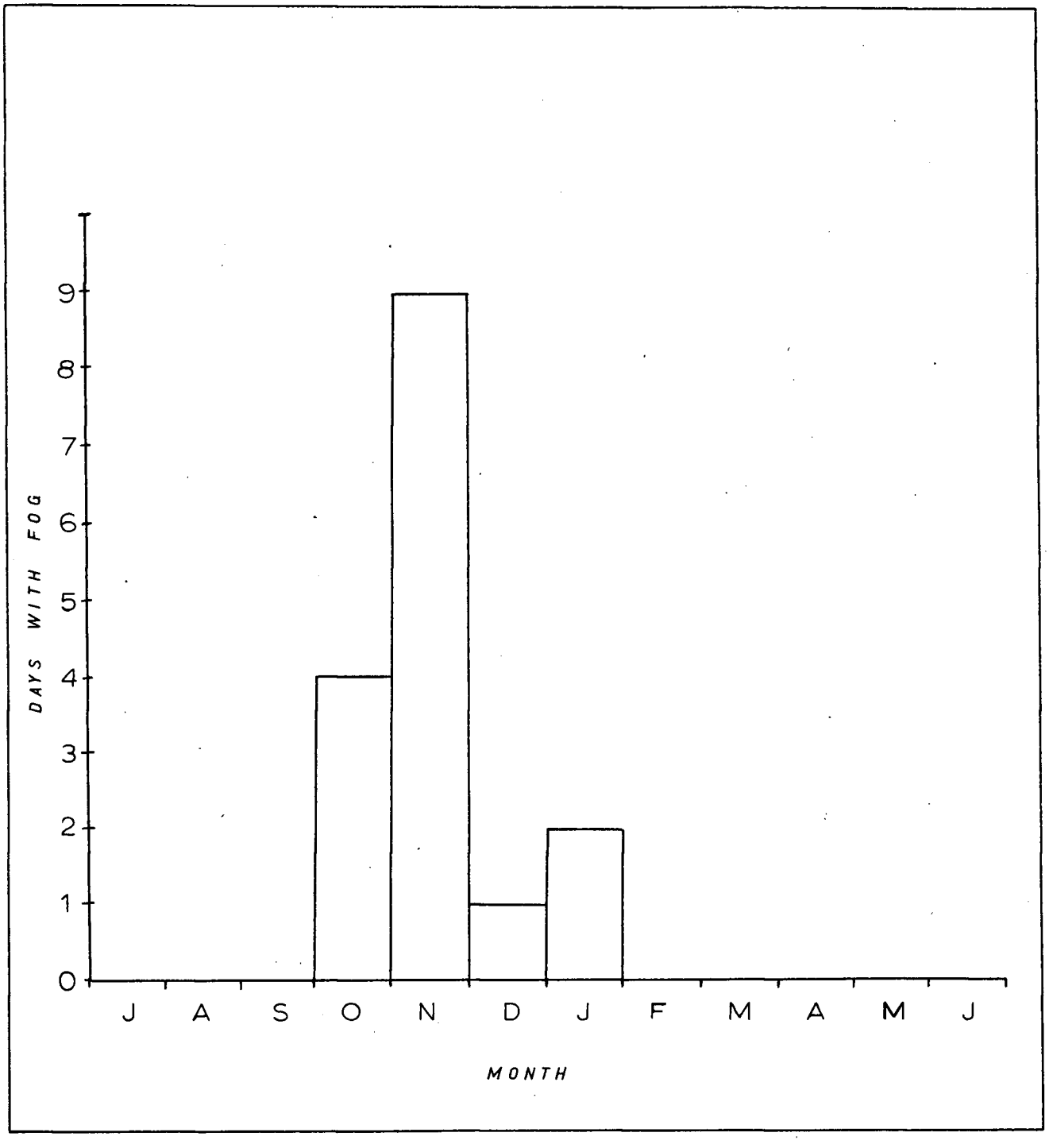


Fig. 4 . Total days with all day fog*, by month. Vancouver International Airport, 1965 - 1969.

*as defined; see p. 23.

consequently greater evaporation may also occur.

It should be mentioned that it is normal for a vertical inversion of the temperature lapse rate to be associated with fog. This is always true with radiation fogs, but "the same is true, in most cases, for advection fogs."(Pettersen, 1939, p. 18). In hill fog, as defined here (see p. 6), this does not have to be the case, as the fog top is at the point where stability is reached.

The temperatures at which fogs characteristically form will of course vary with the location of individual stations. However, where fogs form at temperatures below about - 30°C., they are composed principally of ice crystals, and as such they are probably unusable by vegetation. Fogs at temperatures above about - 30°C.,remain as liquid droplets because of their minute individual droplet sizes. These fogs, which form 95 per cent of the world's fogs (Myers, 1968), are termed "warm" fogs if it is required to distinguish them from ice fogs.

Mean temperatures during fogs are reduced, since the total solar radiation input is reduced. For instance. at Vancouver International Airport, the mean temperature on days recording all day fog in November was 41.1 °F. as compared with 45.3 ° F. on days without fog. (From a sample of 5 per month per year for the 5 years; differences significant at the 0.05 per cent level.) It should be noted that the minimum temperatures are not necessarily lower when the mean temperature is lower, for the temperature variation is within a smaller range (see Fig. 5, p. 29). When the fog formed <u>in the morning</u> only, the minimum temperature <u>for the day as a whole</u> may be decreased. This is due to the loss of heat by the

ground surface, cooling the air beneath its dewpoint, and the lesser advection of warm air to the site due to the lower windspeeds recorded during fog. (see p.43) The reduction of minimum temperatures for the day when morning fog was recorded is shown in Table 4, below.

Month	Temperature min. (F) Days recording A.M. fog.	Temperature min, (F) Days not recording fog.
August	53.17	54.56 *
Sept.	46.88	49.92
Oct.	39.90	44.96
Nov.	33.53	40.08
Dec.	29.44	35.04
Jan.	30.08	30.20 *
Feb.	28.60	33.60
Mean	38.16	40.83

* = not significant at 0.05 per cent level.
For test of significance, see Appendix I.

Table 4. Minimum temperatures: days with morning fog and days without fog, Vancouver International Airport, 1965 - 1969.

Daily temperature range in fogs that exist all day is reduced, compared with the temperature range on non - foggy days. This is accounted for by the fact that the top of a cover of fog reflects a high percentage of the incoming solar radiation, and at the same time the fog droplets absorb and re-transmit much of the long - wave radiation from the ground. Means of temperature ranges for fog and non - fog conditions are shown in Fig. 5, p.29.

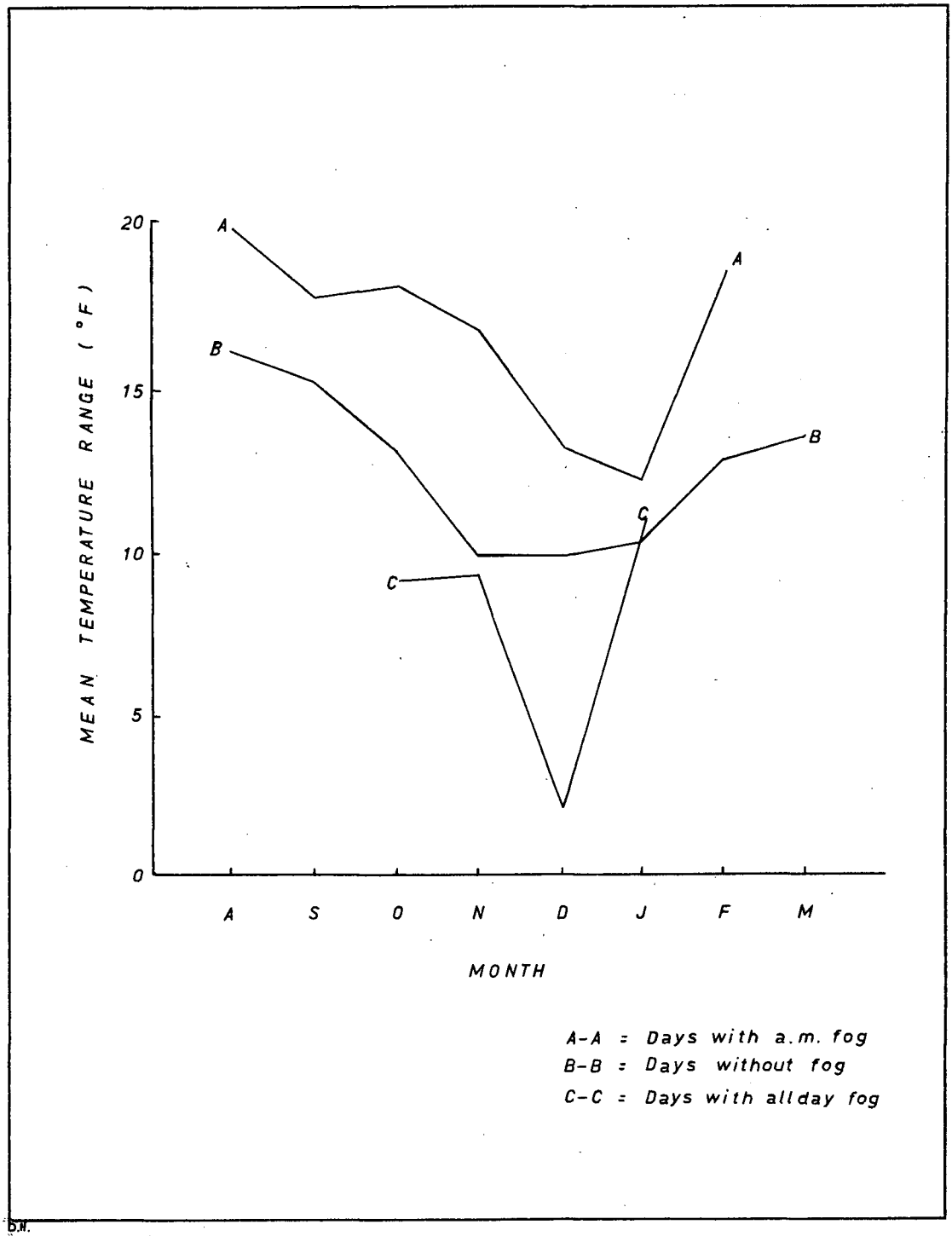


Fig. 5 . Mean daily temperature ranges. *
Vancouver International Airport, 1965 - 1969.

* "mean temperature range" as used here is the difference between mean maximum and mean minimum temperature for the month concerned.

It can be seen that the mean daily temperature is lowest during days when fog was recorded all day.

The mean daily temperature range is highest at Vancouver International Airport on days when morning fog was recorded. This is due to the reduction of temperature by radiational cooling, with subsequent formation of fog in the early morning, and also the clearness of the skies (allowing uninterrupted inputs of solar radiation), which, after "burning off" the fog, increases the air temperature.

An interesting comparison with the Vancouver data may be made with the following table (Table 5), taken from data collected by Grubb and Whitmore (1966), in the tropical montane forest of Ecuador.

Temperatures in °C.		Fog - bound days (= 7)	Fog - free days (= 14)
1 metre above ground in clearing	Temp. max.	19.4	25.6
	Temp. min.	13.0	11.5
	Temp. mean	16.2	18.6
	Daily range	6.4	14.1
1 metre above ground in forest undergrowth	Temp. max.	16.3	19.3
	Temp. min.	13.0	12.1
	Temp. mean	14.7	15.7
	Daily range	3.3	7.2

Table 5. Temperature characteristics on fog days and non - fog days in the montane forest of Ecuador.

(From Grubb and Whitmore, 1966)

It can be seen that the daily temperature range is halved when fog occurred. Minimum temperatures were

not reduced, but the mean temperature was reduced. The fact that a reduction in the minimum temperature does not necessarily accompany reduction in mean temperatures, since the temperature range is also reduced, has been previously noted. (p. 27)

Fog and relative humidity.

Relative humidity approaches 100 per cent as the dewpoint temperature is approached, and fog forms. Although normally relative humidity will be 100 per cent when the fog forms, earlier condensation induced by a surplus of condensation nuclei may allow it to be lower. (see p. 7)

At Vancouver International Airport, the relative humidity is given in the summary sheets four times a day, at 0600, 1200, 1800 and 2400 G.M.T. (2200, 0400, 1000, and 1600 P.S.T.)

Table 6, below, shows relative humidities on days with fog all day, as compared with days without fog.

P.S.T.	0400		1000		1600		2200	
	fog	no fog	fog	no fog	fog	no fog	fog	no fog
Oct.	95.50	89.44	96.00	81.72	92.25	75.52	95.25	91.76
Nov.	98.44	85.92	98.11	83.52	97.44	80.44	98.11	87.60
Dec.	100.00	90.40	100.00	85.96	100.00	83.80	100.00	84.76
Jan.	98.00	82.10	99.00	83.35	93.50	83.55	97.50	83.75
All obs.	97.75	87.22	97.81	83.65	95.81	80.68	97.44	87.14

All differences significant to the 0.05 per cent level. (see Appendix I.)

Table 6. Relative humidity (per cent) with and without fog all day, Vancouver International Airport, 1965 - 69.

It is clear that the relative humidity stays closer to saturation all the time during fog, as might be expected. Decrease of relative humidity during daylight hours is characteristic of most days, with or without fog, due to the increase in temperature, and the consequent increase in the water holding capacity of the air. This decrease is apparent from Table 6. (p. 31).

Similar differences may be noted in the relative humidities recorded on days with morning fog (Table 8, overleaf.) From the readings at 1000 hours, PST, onward, however, the differences between foggy and non - foggy days becomes less as most of the morning fogs are at least in the process of being dissipated by the sun by that hour.

The increase of relative humidity with fog is to be expected anywhere, since it is always necessary for the dewpoint temperature to be approached or reached to give fog. This increase has been shown by Grubb and Whitmore (1966) for a tropical montane rain forest in Ecuador. The relative humidity of this environment is normally high, but is even higher in fog. They showed an increase in the duration of periods with a relative humidity of greater than 95 per cent. (Table 7, below.)

Site	Means for fog - bound days (= 7)	Means for fog - free days (= 14)
1 metre above ground in clearing	19.5 hours	13.5 hours
1 metre above ground in forest undergrowth.	23.0 hours	16.0 hours

Table 7. Durations of high relative humidities with and without fog, in montane forest in Ecuador.
(Adapted from Grubb and Whitmore, 1966, pp. 311 & 312)

P.S.T.	AUG.		SEPT.		OCT.		NOV.		DEC.		JAN.		FEB.		MAR.		ALL OBSERVATIONS	
	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog	With Fog	No Fog
1600	71.0	63.6	75.8	70.8	83.4	75.5	83.9	80.4*	89.7	83.8	86.6	83.5*	82.2	78.6*	78.0	66.9	81.1	75.2
2200	88.3	85.2	91.5	85.6	91.9	91.6*	92.7	87.6	96.3	84.8	94.8	83.7	92.3	88.4	93.7	82.7	92.4	86.3
0400	95.2	90.2	97.6	91.0	96.1	89.4	98.0	85.9	96.9	90.4	94.6	82.1	96.0	89.6	95.2	87.7	96.8	88.4
1000	80.0	74.8	84.7	79.2	85.0	81.7*	91.2	83.5	95.8	85.9	96.2	83.3	89.3	82.9	83.2	74.5	87.8	80.7
1600	67.7	63.6*	74.9	70.8*	80.6	75.5	85.9	80.4	88.2	83.8	90.0	83.5	79.4	78.7*	75.0	66.8	79.6	75.2
2200	81.5	85.2	89.1	85.6	91.7	91.7*	91.0	87.6	94.1	84.7	95.8	83.7	91.3	88.4	92.0	82.7	90.4	86.3

* = difference not significant at 0.05 per cent level.

Table 8. Relative humidity (per cent) before, during, and after the occurrence of A.M., with comparison of non - fog days, by months, 1965 - 1969, Vancouver International Airport.

Hours of sunshine.

Bright sunshine is notably reduced when fog occurs at Vancouver International Airport. (Table 9, below.)

	Oct.	Nov.	Dec.	Jan.	All obs.
Days with fog all day	2.20	0.28	0.0	0.1	0.72
Days without fog.	4.24	1.68	1.64	1.38	2.28

All differences significant at the 0.05 per cent level. (see Appendix. I)

Table 9. Mean number of hours of bright sunshine with and without fog, Vancouver International Airport, 1965 - 1969.

The study of Grubb and Whitmore (1966), previously noted, found a similar result from the tropical montane forest of Ecuador. Mean sunshine duration in a clearing was 0.7 hours on foggy days, but 5.5 hours on fog free days. This is significant in that the probable energy availability for evapotranspiration is reduced on foggy days, a factor increasing the possibility of water economy by the vegetation, aside from any considerations of actual water gain from fog. (see Ch. 5)

Net radiation is a function of sunshine. A considerable reduction of the net radiation in fog has been observed by Yevfimov (1951), Krasikov (1948), and Shifrin and Bogdanova (1955)

Shifrin (1951) computed an equation for this reduction in net radiation, of the form:

$$F_0 = F_0 \left(1 - e^{-(a + r)} \right)$$

where: F_0 = the net radiation of a clear sky.
and $a + r$ = coefficients of absorption and reflectivity calculated for the whole fog thickness.

The effect of sunshine as a fog control is of relevance. As will be shown later, the maximum probability of fog is just before sunrise, when the sun has had no chance to dissipate ("burn off") the fog by evaporation from the top surface of the fog and to create turbulence that might dissipate it.

This was also found by Buma (1960), in an analysis of fog at Leeuwarden, in the Netherlands. In London, England, Davis (1951) found that the maximum frequency of fog was two to three hours after sunrise, a delay attributed to pollution effects arising from smoke fires.

It has already been hypothesized that most of the fog recorded at Vancouver International Airport is radiation fog.. If this is so, then the hours of sunshine recorded on that day might be expected to be increased from that on days without fog, since clear skies during the night of radiation fog formation are necessary to allow enough radiational cooling to occur. An examination of Table 10, overleaf, shows that this is indeed the case, and it might reasonably be concluded that the hypothesis presented above is correct.

Most authors concur with the above result, but George (1951) states as well that one of the main conditions for the formation of radiation fog is that "the air has been under a cloud cover ... during the day previous to its formation." (George, 1951, p. 1184) He is alone in this conclusion, however. (Myers, 1968)

Month	Day preceding A.M. fog. 1	Day with A.M. fog. 2	Day without, and not preceding A.M. fog. 3
Aug.	8.150*	9.030	7.724
Sept.	6.829	6.910	6.756
Oct.	5.005*	6.080	4.240
Nov.	4.772	4.080	1.684
Dec.	1.750*	2.380	1.644
Jan.	1.140*	1.940	1.375
Feb.	5.286	7.060	2.536
Mar.	6.975	7.070	4.740
Apr.	1.750	10.000	5.420

* = not a significant difference at the 0.05 per cent level. (Col. 1 and 2 compared to Col. 3.)

Table 10. Hours of sunshine associated with morning fog occurrence, Vancouver International Airport, 1965 - 1969. (See text for explanation.)

George's statement is not supported by the data of hours of sunshine (indicating little cloud cover) on days previous to morning fog formation at Vancouver. (see col. 1 in Table 10, p. 36) In fact, the amount of sunshine is higher (but insignificantly so in four months), and thus cloud cover may be taken as less, on days preceding morning fog, as compared to the days not preceding fog formation.

Fog and wind.

The intensity of turbulence generally increases with the wind speed. Thus it might be expected that moderate wind speeds would create enough turbulence to enable the fog to thicken above its site of formation and attain a height in the order of several hundred feet. Fogs that exist when there are strong winds are usually very deep, because they fill the entire layer below an inversion, which is itself normally raised by turbulent mixing.

Lack of any mixing due to turbulence on calm days will not allow the formation of any great thickness of radiation fog, and may prevent active inland movement of advection fogs. On the other hand, once the wind speed increases too much, the absolute value of this speed being dependent on the stability of the air, the fog may be dissipated, or be raised to a layer of stratus cloud.

Strong winds are in many situations likely to be one of the more significant controls on fog formation, and prediction of the wind speed will often allow prediction of a situation where it is possible for fog to form if the required increase in relative humidity to nearly 100 per cent also occurs.

Fog will tend to be dispersed by wind unless there

is a constant supply of further fog. For the reason that stratus cloud at higher levels tends to be more stable than fog on the ground beneath an inversion (which is easily disturbed by wind unless it is very marked), the strongest wind recorded during fog is often on high ground. This is within hill fog, as defined here. (see p. 6.) For instance, Nagel (1956) found an average wind speed of 13 m. sec^{-1}. during the times that the "Table Cloth" covered Table Mountain, South Africa. During an experiment by the writer, (see p. 66) visibility at 500 feet altitude on Beachy Head, a coastal headland in Sussex, England, remained at about 30 yards with a WSW wind greater than 11 m. sec^{-1}.

With fogs formed at lower levels, wind is usually an important control. It is clear that the in situ conditions of the formation of radiation fog make it more sensitive to wind; stability, through turbulence, may easily be disturbed.

However, the upper limit of windspeed at which fog can exist is greater over the sea than over land. This is partly due to the increased friction over land, which causes increased vertical mixing. (Taylor, 1917) Nevertheless, advection fog appears to have a modal occurrence coinciding with comparatively low windspeeds. Fig. 6, p. 39, shows a graph constructed from data given by Taylor (1917) of the frequency of certain windspeeds in advection fog over the sea off Newfoundland.

Considerable reductions in both the average hourly wind run and the maximum (one minute) windspeed during all day fogs were found at Vancouver International Airport.(Tables 11 and 12, p. 40.)

The average wind run and the average maximum windspeed for all observations of all day fog at Victoria International Airport, (21 obs.) during the same five year

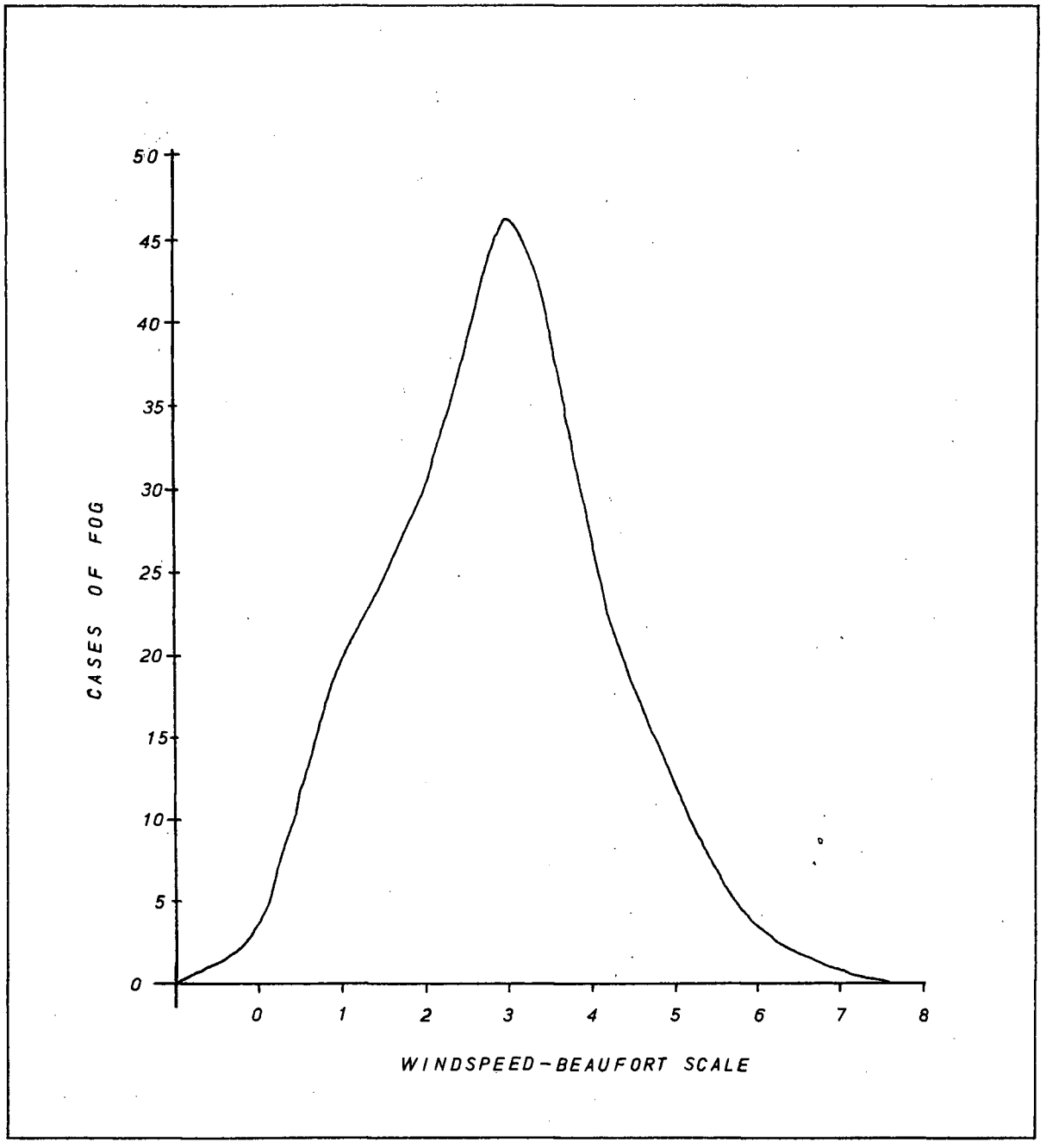


Fig. 6 . Frequency of fog at different windspeeds, over sea off Newfoundland. (after Taylor, 1917.)

Beaufort Scale 0 = Less than 1 mph.

Beaufort Scale 7 = More than 32; less than 38 mph.

	Fog days	fog free days
October	4.82 MPH	7.33 MPH
November	3.06	6.29
December	6.50	8.85
January	4.65	8,37
All obs. (Oct - Jan only)	3.91	7.68

All differences significant at the 0.05 per cent level.

Table. 11. Average Hourly Wind Run at Vancouver International Airport, 1965 - 1969.

	Fog days	fog free days
October	9.00 MPH	13.92 MPH
November	7.00	11.72
December	7.00	15.88
January	9.00	16.40
All obs. (Oct - Jan only)	7.75	14.38

All differences significant at the 0.05 per cent level.

Table 12. Mean maximum (one minute) windspeeds at Vancouver International Airport, 1965 - 1969.

period 1965 - 1969 were slightly higher than those at Vancouver, being 5.99 MPH and 11.90 MPH respectively. This suggests that a larger proportion of the fogs are advection fogs, which may exist at these windspeeds.

For the formation of radiation fog, it has already been noted (p. 38) that wind speeds have to be relatively low, to avoid too much turbulence, which would tend to dissipate the fog. It has also been noted that complete calm is not suitable for fog formation, since a certain amount of turbulence is required to transport fog formed at the ground surface upwards, and replace the ground layer with more air for cooling. A study of the characteristic windspeeds associated with the formation of morning fog (the majority assumed to be radiation fogs; see p. 35), at Vancouver International Airport showed a very significant difference in the windspeeds on days preceding the formation of fog as compared with the days not preceding fog formation. Figs. 7 and 8, on the next two pages, show the mean windspeeds in both cases from 1800 PST on the day previous to 1200 PST the next day. The great difference in wind speeds, and the apparent early start to the trend to lower wind speeds when fog forms the next morning, is taken advantage of later (p. 47) to predict the occurrence of morning fog.

In a negative sense, Taylor (1917) showed how windspeeds the evening before could be used to predict the "non - occurrence" of fog. His table, given in Table 13, p. 44, was used for this "negative forecasting." A fog - free morning was predicted at Kew, England, from where the results are derived, on every occasion when the windspeed at 2000 GMT was greater than 5.5 MPH, and only two incorrect predictions were made in the five year period.

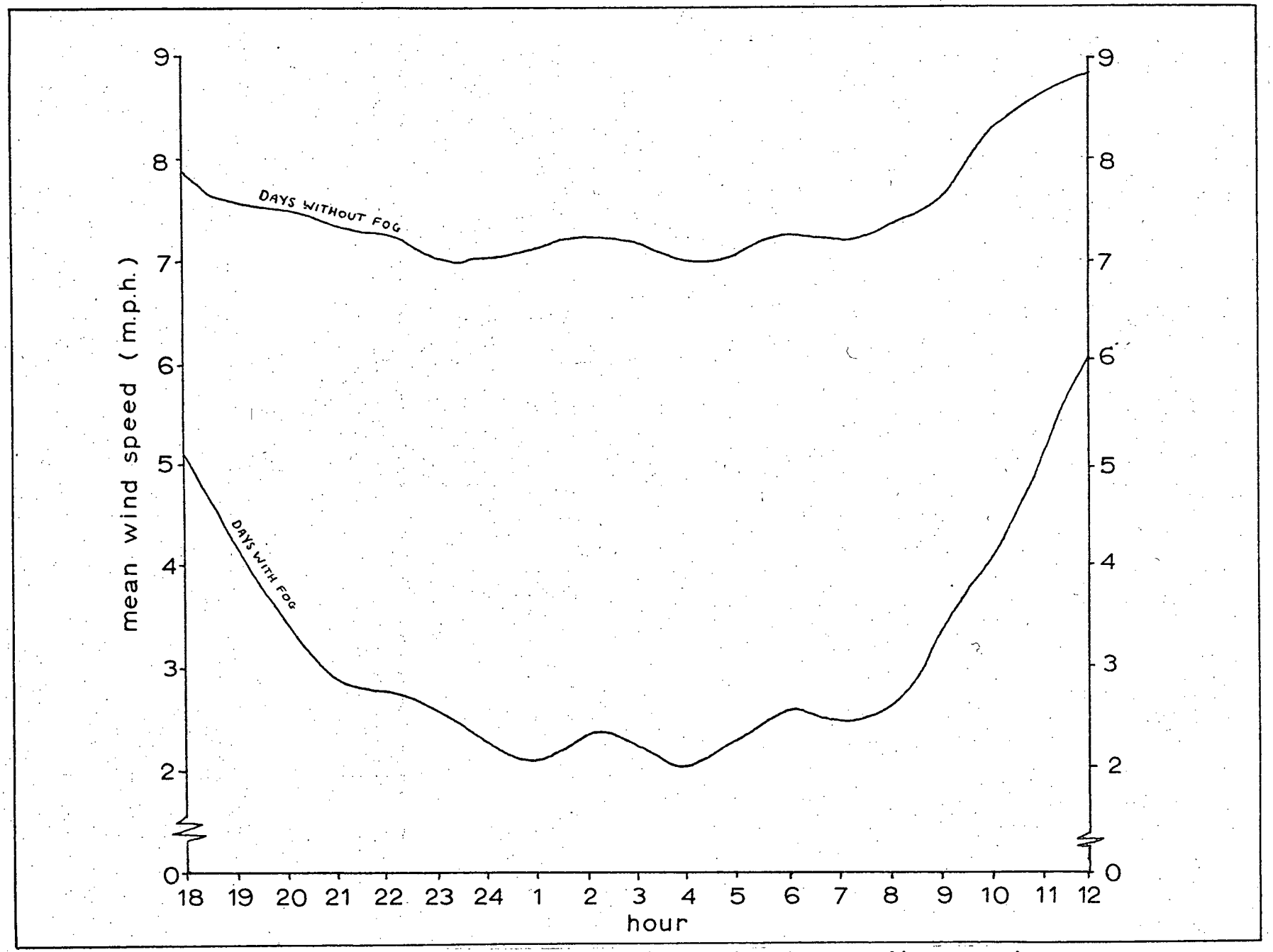


Fig. 7 . Mean wind speeds preceding and not preceding morning fog, Vancouver International Airport, 1965 - 1969.

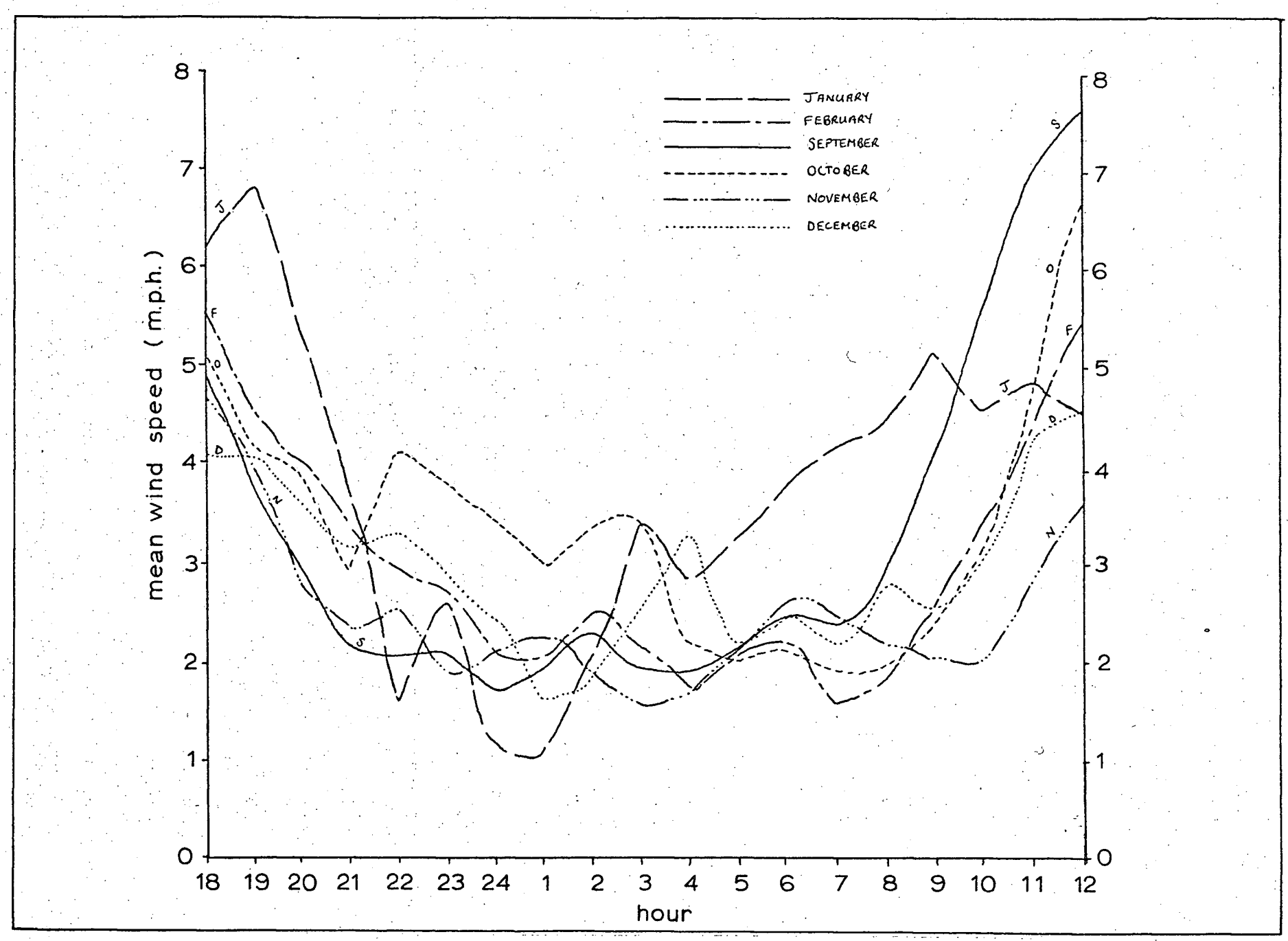


Fig. 8. Mean wind speeds preceding and during morning fogs, by months, Vancouver International Airport, 1965 - 1969.

Wind velocity MPH *	1600	1800	2000	2200	2400 GMT
0 - 3.3	24	35	50	58	62
3.3 - 5.5	23	20	18	10	5
5.5 - 9.2	16	13	1	2	3
9.2 -13.6	7	2	1	1	1

Total number of cases = 70 * These class intervals coincide with the Beaufort scale units.

Table 13. Frequencies of windspeeds preceding formation of night fogs at Kew, England, 1900 - 1905. (After Taylor, 1917.)

At Victoria International Airport, many of the fogs recorded as morning fogs are probably advection fogs, since thin advection fogs are known to be frequent at this station. (Pincock and Turner, 1956) Some of the fogs recorded only during the A.M. hours are radiational in origin, but the record of morning fog essentially contains both types. Thus in the graph of hourly windspeeds for Victoria , shown overleaf, (Fig. 9.), although windspeeds are less during and preceding fog, as compared with periods not preceding fog, they vary about a higher mean value.

Wind direction.

Brief mention should be made of wind directions during fog. Like temperatures, there will be no characteristic direction for all stations; the prevailing

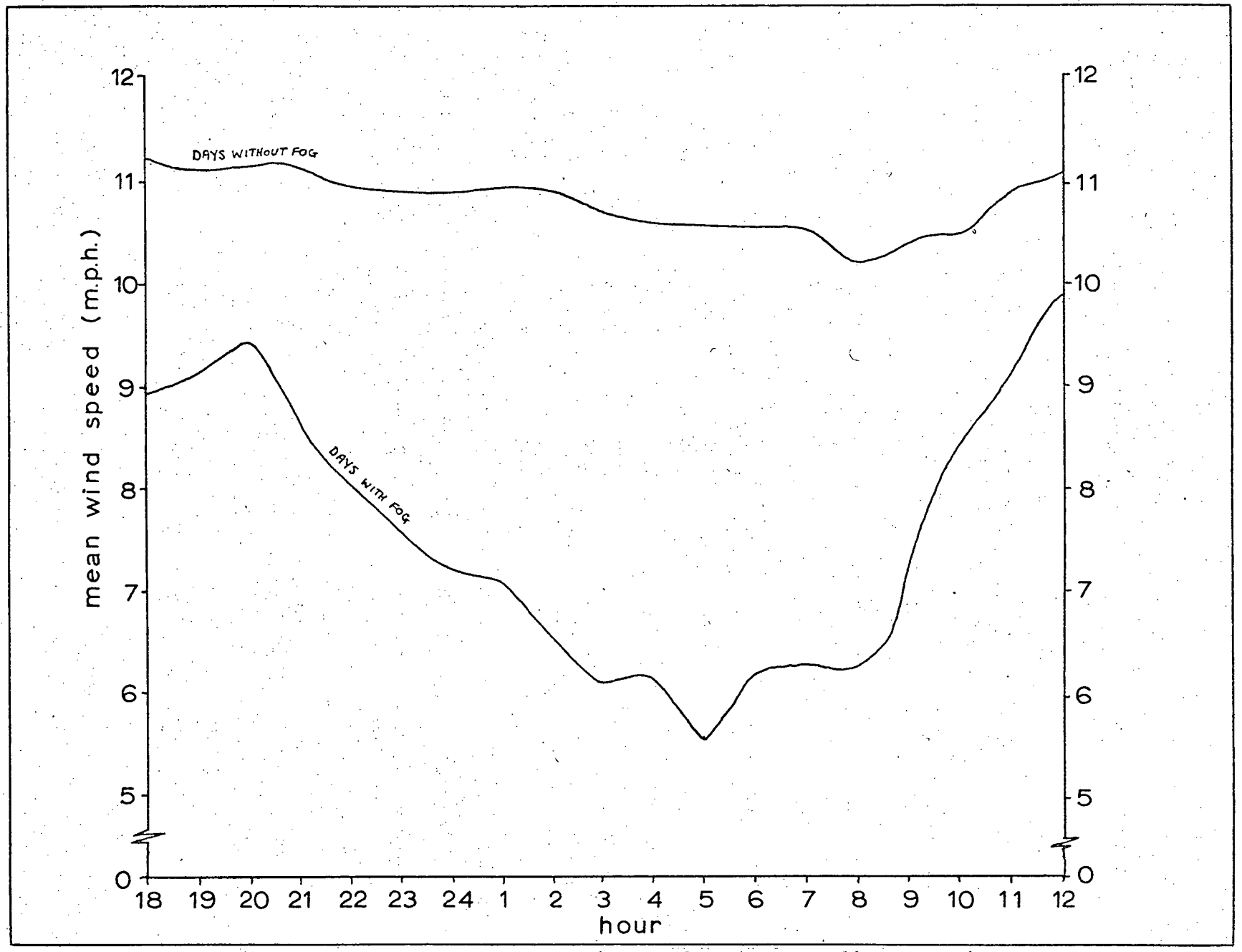


Fig. 9. Mean wind speeds preceding and not preceding morning fog, Victoria International Airport, 1965 - 1969.

wind direction depending solely on local conditions. The prevailing wind direction at Vancouver is east, and this also applies during fog. (56.25 per cent of the total observations.)

Whilst characteristic wind directions during fog may be of value at some stations, especially where a causal relationship is expected, the lack of generality of application limits their use. (Woodward, 1941; Pincock and Turner, 1956.)

FOG PREDICTION : A MODEL.

It is of value to attempt to predict the occurrence of fog, since successful prediction may allow extrapolation of fog frequency data beyond that actually available.

It is evident that for fog to occur and persist, certain combinations of climatic factors must occur. Some of these factors have previously been mentioned; it is, however, important to distinguish between cause and effect. Fogs can be formed in several different ways, and an ideal model would include all the possible approaches to fog formation, but such a model would be very complex.

A fog prediction model is presented here which applies to Vancouver International Airport, and is derived from 12 years of data, from 1958 to 1969 inclusive, initially using only the last 5 of those years. This 12 year data period is the maximum available, in accessible form, since the times of the relative humidity and temperature readings on which the model depends were altered on 1st June, 1957. This period is only 3 years short of the 15 year period recommended by Panofsky and Brier (1968) for this type of usage.

The probability of fog by hours has been calculated from a 20 year summary published by the Department of Transport. (D.O.T., 1970) Although this data includes cloud ceilings of lower than 200 feet in addition to fogs with visibility of 0.5 mile or less, it allows the deduction of certain conclusions. (see Fig. 10, overleaf) Two periods of maximal fog probability are evident, and if the hypothesis that the majority of fog at Vancouver International Airport is radiation fog is accepted (p. 24 and 35), the analysis may be based on the expectation of radiation fog. It may thus be hypothesized

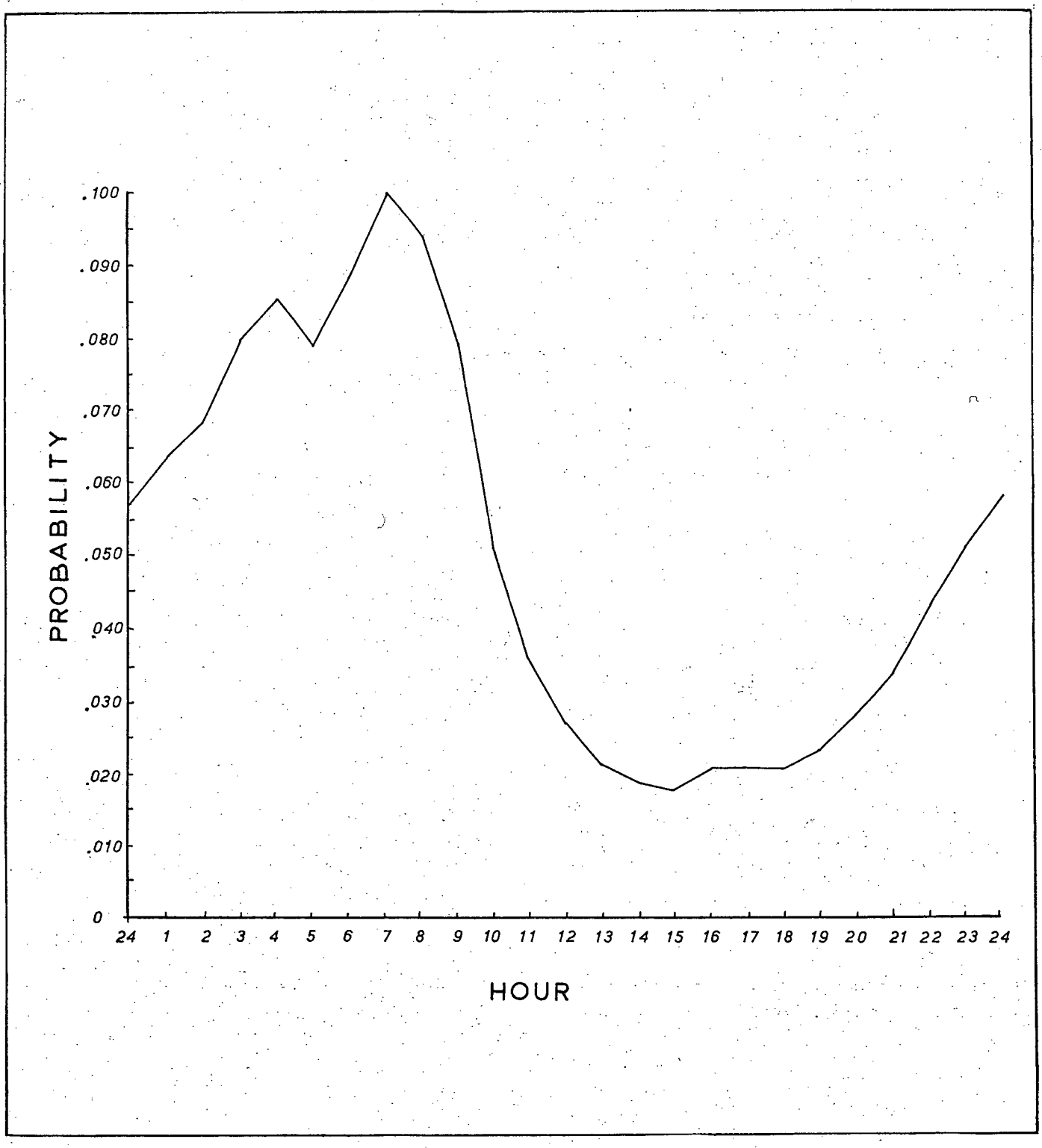


Fig. 10. Empirical probability of fog with visibility less than 0.5 mile or ceiling of less than 200 feet, by hours, Vancouver International Airport. 20 year record 1950 - 1969. This graph refers to the period Sept. - Jan. only.
Source: V.I.A. records, Dept. of Transport, 1970.

that the two periods of maximal fog probability, from 0300 to 0500 and from 0600 to 0830 PST, are the results respectively of the first falling of the temperature to near the dewpoint temperature, and to the period just after sunrise when the sun (unhindered normally by cloud; see p. 35) heats the ground surface enough to cause turbulent mixing, so that a thin layer of ground fog not necessarily recorded (observations are taken at eye level) thickens and deepens.

It is evident that the degree of saturation of the air, and the windspeed, will be the major climatological factors characteristically associated, at a certain value, with fog formation. Diagrammatically, these ideas may be shown:

Present Temperature	$\xrightarrow{\text{cooling}}$	Dewpoint $T_E = T_d$ fog starts to form.	$\xrightarrow[\text{cooling}]{\text{further}}$ mist phase	Sunrise: uneven heating; turbulemce; thickening.	$\rightarrow$	FOG

Thus it may be stated that fog (F) is a function of several variables:

$$F = f\left\{\left(\left[T_d(RH_i, T_i) - T_E\right] \geqslant n_{crit}\right) , w\right\}$$

where:

T_d = the dewpoint temperature, itself a function of
RH_i = initial relative humidity, and
T_i = initial temperature.
T_E = air temperature
n_{crit} = critical value of the difference between the dewpoint and the actual air temperature.
w = windspeed.

The critical value of n, or at least an acceptable estimate, will have to be found by an examination of the data.

It is hoped that the main causal factors of morning fog formation at Vancouver International Airport have now been identified, and so they will now be used in an attempt to predict the occurrence of fog.

The model constructed here utilizes the recorded parameters of temperature, relative humidity, and windspeed. The first two are used to calculate the dewpoint temperature at the time concerned ($T_d(RH_i, T_i)$) ; windspeed is added as an important control factor. (see p. 37)

In the five year period of data initially considered, 1965 - 1969, there were 120 days with morning fog recorded during the eight month period considered, August to March inclusive. Also, a stratified random sample 200 days without fog was used (5 per month per year) to calculate "non - fog" probabilities; the days preceding these were of course used. Relative humidity and temperature were noted for 1600 and 2200 PST, and windspeed at 2200 PST.

To find the association of relative humidity and temperature to dewpoint temperature, a multiple regression equation was set up, from values extracted from a chart given by Pettersen (1939). The equation took the form:

$$y = 0.1997x_1 + 0.9750x_2 - 19.2786 \qquad \ldots\ldots (1)$$

where:

y = dewpoint temperature (°C)
x_1 = relative humidity (per cent)
x_2 = temperature (°C)

which had a multiple correlation coefficient of $r^2 = 0.966$, significant at the 0.001 per cent level. The standard error of estimate was 0.4995 °C.

Thus, for each day before morning fog and each sample day not before morning fog in the first five year sample, the dewpoint was calculated from observed values of relative humidity and temperature, at 1600 and 2200 PST. Since temperatures were recorded in degrees Fahrenheit at Vancouver, a conversion of the temperature to this scale (°C) was carried out prior to using the above formula. The calculated values of the dewpoint were then converted back to Fahrenheit for comparison with the recorded actual air temperature. The frequency, in class intervals of one degree Fahrenheit, of the difference between the actual temperature and the dewpoint temperature, was plotted in four tables, for cases with fog the next day, and those without, for 1600 and 2200 PST. (see Tables 14 and 15, p. 52 and 53.)

Another frequency table, again for both fog and non - fog cases, was drawn up for windspeeds, taken at 2200 PST. (see Table 16, p. 54.) From observation of these six tables, it was subjectively decided to define the following three parameters for use in the predictive model, the first two being the decided values for the critical value of n. (p. 49 - 50)

v = At 1600 PST, the difference between the actual air temperature and the dewpoint LESS THAN 5 °F.

y = At 2200 PST, the difference between the actual air temperature and the dewpoint LESS THAN 5 °F.

z = At 2200 PST, the windspeed LESS THAN OR EQUAL TO 5 MPH.

a) Preceding Fog.

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12+
Aug	-	-	-	1	-	-	-	-	1	-	-	3	1
Sep	-	2	-	1	-	4	2	4	5	3	7	2	2
Oct	2	-	1	3	4	2	2	3	2	-	-	-	1
Nov	1	2	4	4	1	1	2	2	2	-	-	-	-
Dec	1	2	1	4	1	-	-	-	-	-	-	-	-
Jan	-	1	-	2	-	-	2	-	-	-	-	-	-
Feb	-	-	2	1	8	4	2	1	1	1	-	-	-
Mar	-	-	-	1	-	-	1	1	-	-	1	-	-
Total	4	7	8	17	14	11	11	11	11	4	8	5	4

b) Not preceding fog.

Aug	-	-	2	-	-	1	-	-	3	1	-	4	14
Sep	-	2	-	-	1	1	-	2	3	2	6	1	7
Oct	-	2	-	2	1	-	4	5	3	1	3	-	4
Nov	1	1	3	4	1	4	2	3	1	1	1	2	1
Dec	5	2	1	2	4	3	1	1	2	2	1	1	-
Jan	4	2	1	2	1	3	2	3	-	-	1	-	1
Feb	-	2	3	1	3	1	3	3	1	4	1	1	2
Mar	2	-	1	-	1	-	1	3	1	1	3	1	11
Total	12	11	11	11	12	13	13	20	14	12	16	10	40

Table 14. Frequencies, by months, of days when the difference between the actual temperature and the dewpoint was of the magnitude indicated, 1600 PST. Vancouver International Airport, 1965 - 1969.

a) Preceding Fog

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12+
Aug	-	1	2	1	1	-	1	-	-	-	-	-	-
Sep	10	9	4	4	2	2	1	1	-	-	-	-	-
Oct	6	3	7	1	1	-	1	1	-	-	-	-	-
Nov	11	2	3	1	-	1	-	1	-	-	-	-	-
Dec	8	1	-	-	-	-	-	-	-	-	-	-	-
Jan	2	3	-	-	-	-	-	-	-	-	-	-	-
Feb	8	6	3	1	-	-	2	-	-	-	-	-	-
Mar	1	3	-	-	-	-	-	-	-	-	-	-	-
Total	46	28	19	8	4	3	5	3	-	-	-	-	-

b) Not preceding fog. (sample size = 200)

Aug	2	2	2	4	3	5	4	-	2	-	-	1	-
Sep	3	1	1	4	6	4	1	2	1	1	-	-	-
Oct	5	5	10	3	1	1	-	-	-	-	-	-	-
Nov	5	5	2	5	2	2	1	-	2	-	1	-	-
Dec	5	2	5	2	1	2	1	3	1	2	-	-	1
Jan	2	1	2	1	5	1	2	2	-	1	1	-	-
Feb	7	3	4	2	3	2	2	2	-	-	-	-	-
Mar	2	3	1	4	2	3	6	4	-	-	-	-	3
Total	31	22	27	25	23	20	17	13	6	4	2	2	4

Table 15. Frequencies, by months, of days when the difference between the actual temperature and the dewpoint was of the magnitude indicated, 2200 PST., Vancouver International Airport, 1965 - 1969.

a) Preceding fog.

MPH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Aug	4	2	-	1	-	1	-	-	-	-	-	-	-	-	-
Sep	13	4	5	6	1	1	-	1	1	-	1	-	-	-	-
Oct	4	-	3	2	4	2	1	1	2	-	-	-	-	-	1
Nov	6	3	-	3	3	2	1	-	-	1	-	-	-	-	-
Dec	-	2	3	-	2	1	-	-	-	1	-	-	-	-	-
Jan	2	-	1	2	-	-	-	-	-	-	-	-	-	-	-
Feb	3	2	6	2	4	2	1	-	-	1	-	-	-	-	-
Mar	1	-	-	-	-	1	1	-	-	-	1	-	-	-	-
Total	33	13	18	16	14	10	4	2	3	3	2	-	-	-	1

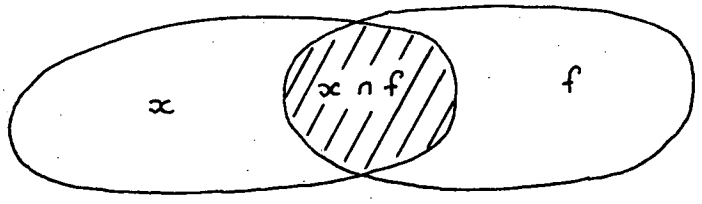
b) Not preceding fog. (sample size = 200)

Aug	3	1	1	1	6	2	2	5	-	1	2	1	-	-	-
Sep	1	2	3	3	1	7	1	1	3	-	-	2	-	-	1
Oct	2	1	2	3	1	3	3	3	-	1	1	1	1	-	3
Nov	4	-	-	3	1	2	3	2	1	1	-	1	3	-	4
Dec	2	3	1	1	1	-	1	3	2	1	-	-	5	1	4
Jan	1	1	-	-	-	2	1	2	4	2	1	-	2	1	3
Feb	3	2	3	2	3	2	-	3	1	2	1	1	-	-	2
Mar	3	-	2	3	5	1	2	2	-	1	-	-	1	1	3
Total	19	10	12	16	18	19	13	22	11	9	5	6	12	3	20

Table 16. Frequencies, by months, of days when the wind speed was of the magnitude indicated, 2200 PST. Vancouver International Airport, 1965 - 1969.

These parameters, v, y, and z, will be used in the following discussion.

The probability of fog the next morning may be calculated from any ONE of these parameters in the following manner: Consider two sets, one the occurrence of fog, the other the occurrence of a certain parameter, x. There will be an intersection of the two sets, which will have a certain probability, $p\ (x \cap f)$



The probability of association of a certain parameter, x, given that fog (f) exists, is thus

$$p(x/f) = \frac{p(x \cap f)}{p(f)} \qquad \ldots\ldots(2)$$

where:

$p(f)$ = the probability of fog independent of x;

and $p(x)$ = the probability of x independent of fog.

It is then possible to reverse the analysis, according to the law of conditional probability. (see Mosteller, et al., 1961, p. 85.)

Then

$$p(x\ \ f) = p(x/f).p(f)$$

and $$p(x/f).p(f) = p(f/x).p(x)$$

Thus $$p(f/x) = \frac{p(x/f).p(f)}{p(x)} \qquad \ldots\ldots(3)$$

or
$$\frac{n(f \cap x).n(f)}{n(x)^2} \qquad .....(4)$$

where n is the number of occurrences of the parameters. The probability of fog remains a constant throughout this analysis of the five year period of data:

$$p(f) = \frac{n(f)}{n(f+nf)} \qquad .....(5)$$

where:

n(f) is the total number of foggy days, and
n(n+nf) is the sample space, the total number of days between August and March in five years, allowing for the addition of February 29th in 1968.

Thus:
$$p(f) = \frac{120}{1216} = 0.0994$$

The probability of fog given a parameter within a specified range was calculated from equation (3), and the results are shown in Table 17, below.

Dewpoint difference at 1600 PST		Dewpoint difference at 2200 PST		Windspeed at 2200 PST	
Range	p(f)	Range	p(f)	Range	p(f)
0 - 0.99	0.0341	0 - 0.99	0.0669	0 mph	0.0711
1 - 1.99	0.0493	1 - 1.99	0.0650	1 mph	0.0655
2 - 2.99	0.0525	2 - 2.99	0.0517	2 mph	0.0683
3 - 3.99	0.0324	3 - 3.99	0.0333	3 mph	0.0598
4 - 4.99	0.0632	4 - 4.99	0.0224	4 mph	0.0541
				5 mph	0.0448
TOTALS	v =0.2315		y = 0.2393		z = 0.3636

Table 17. Fog probabilities in specified parameter ranges.

These probabilities were also calculated for this period with another seven years added. (1958 - 1964, incl.) totalling twelve years in all. The final single parameter conditional probabilities, then, were:

$$p(f/v) = 0.4336$$
$$p(f/y) = 0.2552$$
$$p(f/z) = 0.4595$$

with standard errors of estimate for the conditional fog probabilities, calculated by considering individual years of 0.068, 0.007, and 0.039, respectively.

These probabilities are themselves interesting and are in some part useful. However, the predictive power of the model may be increased by combining the parameters.

The probability of fog given the intersection of all three parameters, $p(f/v \cap y \cap z)$, is not equal to the sum of the probabilities of fog occurring when one is present, since some of the set overlaps would be double counted. Reference should be made here to Fig. 11, overleaf, which shows a set theoretical model illustrating fog and "non - fog" intersections with the defined parameters v, y, and z.

It may be stated that

$$p(f/v \cap y \cap z) = \frac{p(f \cap v \cap y \cap z)}{p(v \cap y \cap z)} \qquad .....(6)$$

Now,

$$p(f \cap v \cap y \cap z) = \frac{n(f \cap v \cap y \cap z)}{n(f+nf)} \qquad .....(7)$$

where:

$n(f \cap v \cap y \cap z)$ is the number of cases of intersection

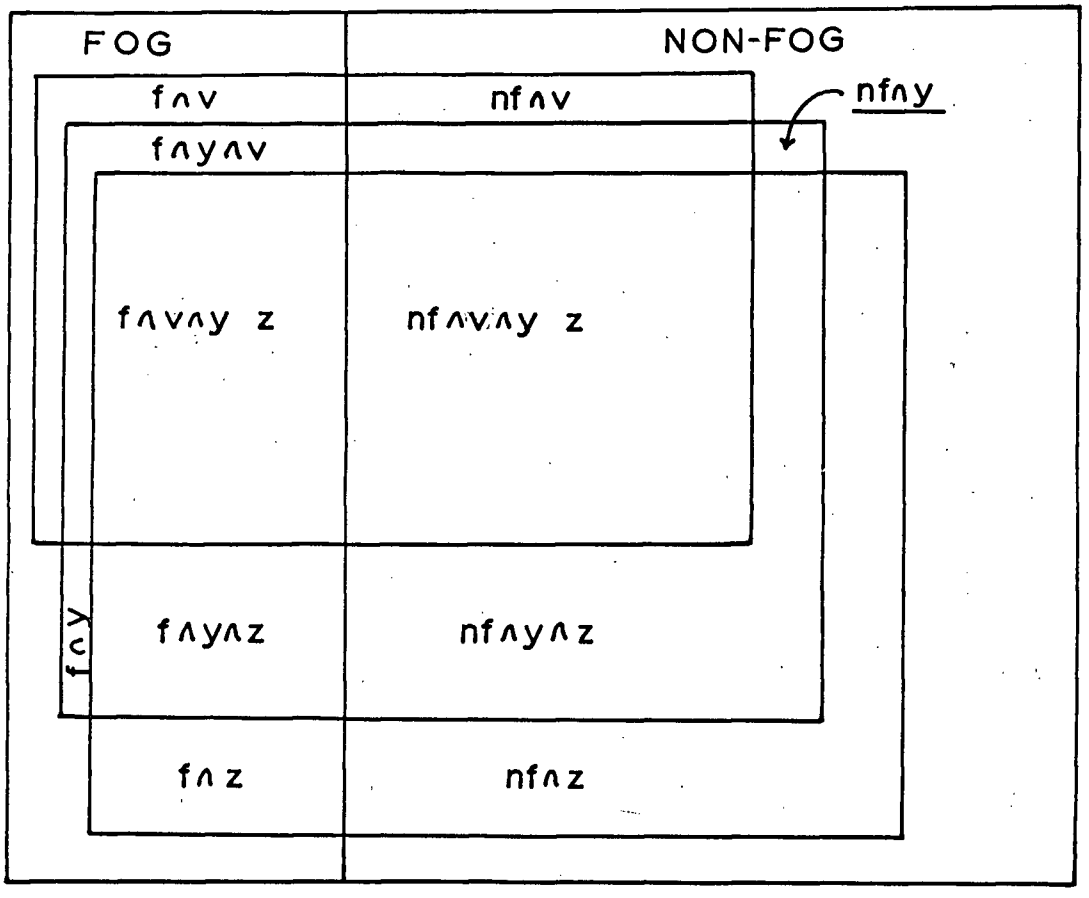


Fig. 11 . Set Model of fog and non-fog intersections with the parameters v, y, and z. (see text for explanation.)

Total sample space = 2919 days; fog = 314 days; p(f) = 0.1076.

of fog with v, y, and z;

and $n(f+nf)$ is the sample space, as in equation (5).

Also $$p(v \cap y \cap z) = \frac{n(v \cap y \cap z)}{n(f+nf)} \qquad .....(8)$$

so that, substituting in equation (6), and cancelling,

$$p(f/v \cap y \cap z) = \frac{n(f \cap v \cap y \cap z)}{n(v \cap y \cap z)} \qquad .....(9)$$

(It should be noted that the set $(v \cap y \cap z)$ includes the set $(f \cap v \cap y \cap z)$ as a nesting subset. See Fig. 11, p. 58.)

Analysis of the five year data period 1965 - 1969 for Vancouver, for August to March inclusive, yields

$$p(f/v \cap y \cap z) = \frac{45}{64} = 0.703$$

giving a conditional fog prediction to a 70.3 per cent probability level. For the months of October to January inclusive, only, the probability $p(f/v \cap y \cap z)$ increases to 0.778.

The stability of these probabilities for any individual year may be tested by adding a further period of data to the analysis, and testing for any trends. The seven year period 1958 - 1964 will be used for this.

The total number of occurrences of morning fog in the months of August to March inclusive in this seven year period was 194 days, out of a maximum possible of 1703. (Allowing for two leap years in this period.) The probability of fog for the 7 year period, then, was 0.1139. The probability of fog for the total 12 years was thus 0.1076, representing 314 days out of a maximum

possible of 2919. Dealing now with a 12 year period of data, the probabilities of fog given the defined parameters v, y, and z, may be computed, using equation (9) . The average probabilities, for a cumulative number of years, from the expression $p(f/v \cap y \cap z)$ are given in Table 18, p. 61. The standard error of estimate of the final probability, 0.7485, calculated from individual probabilities for single years, is 0.08266.

The possibility that a trend exists in the probability of fog for individual years may be tested using the Mann Test. (Mann, 1945; Tintner, 1952, p. 214 - 15.) This is a non - parametric test for trend. The technique is described fully in Appendix II, p. 156 . Applied to the present data, for the 12 years 1958 - 1969, the test yielded a rank correlation coefficient of $\tau = + 0.9394$, which, according to a formula given by Kendall (1955), means that there is less than a 0.0001 per cent probability that there is <u>no</u> trend. (See Appendix II) The magnitude of this trend is not investigated further here, as a very long time series of probabilities would be required for this. Predictions of fog probabilities far in advance of the final year (1969) considered here, however, would first have to assess the magnitude of this trend, or compute the fog probabilities for the intervening period. The probabilities computed here appear likely to apply at least for several years.

Despite the good predictive power of the combined parameter $(v \cap y \cap z)$, it only accounts for some 42.8 per cent of all the fog cases, and it would be more acceptable if this amount were increased. It has been found that this may be done by using the parameter $(y \cap z)$, that is, both the 2200 PST parameters. In this way, 84.3 per cent of the fog may be accounted for whilst maintaining a good level of predictability. As may be seen from Table 19,

	1	2	3
Year added	$n(f \cap v \cap y \cap z)$	$n(v \cap y \cap z)$	$\frac{\text{col 1}}{\text{col 2}} = p(f/v \cap y \cap z)$ added and averaged.
1969	8	12	0.6667
1968	10	14	0.6923
1967	7	11	0.6760
1966	8	12	0.6735
1965	12	15	0.7003
1964	9	10	0.7297
1963	10	14	0.7272
1962	15	17	0.7523
1961	11	15	0.7500
1960	17	23	0.7482
1959	7	10	0.7450
1958	14	18	0.7485

Table 18. Average probability of morning fog: three variables. Vancouver International Airport, 1958 - 1969. (see text for explanation.)

p. 63, the probability of fog given $(y \cap z)$, is 0.6695 averaged over the 12 year period; that is, as equation (9):

$$p(f/y \cap z) = \frac{n(f \cap y \cap z)}{n(y \cap z)} = \frac{227}{339} = 0.6695$$

The trend in the probabilities of fog for individual years for this model were also investigated using the Mann Test (op. cit.; see Appendix II) The rank correlation coefficient was here $\tau = +0.8788$, so that here the probability of no trend (Kendall, 1955) was also extremely small. (Again less than 0.0001 per cent.)

The high precentage of fog cases accounted for by this model suggests that the slight loss of predictive power is worthwhile; it also suggests that the degree to which the dewpoint is approached and the controlling influence of windspeed are very real factors in fog formation at Vancouver International Airport. The remainder of cases (15.7 per cent) are likely to be caused by other mechanisms; one of these may be advection.

At least then, in the case of radiation fog, if the major causal and controlling factors have been found, it may prove possible to extend this model to cover stations at which fog has not long been recorded, but only the climatic parameters of temperature, relative humidity, and windspeed. A predictive model, for fog prediction in areas where climatological data are sparse, may be invaluable in estimating the fog frequency, and thus the potential possibilities of water addition to vegetation.

	1	2	3
Year added	$n(f \cap y \cap z)$	$n(y \cap z)$	$\frac{\text{col } 1}{\text{col } 2} = p(f/y \cap z)$ added and averaged.
1969	9	13	0.6923
1968	25	35	0.7084
1967	17	26	0.6885
1966	18	17	0.6819
1965	19	24	0.7053
1964	17	26	0.6956
1963	23	35	0.6879
1962	26	30	0.6649
1961	20	28	0.6700
1960	34	46	0.6823
1959	19	26	0.6557
1958	29	36	0.6695

Table 19. Average probability of morning fog; two variables. Vancouver International Airport, 1958 - 1969. (see text for explanation.)

CHAPTER FOUR

FOG INTERCEPTION INSTRUMENTATION.

The difficulty of directly measuring fog interception by vegetation (see Ch. 7) has led several workers to devise mechanical instrumentation. The idea of these instruments, which substitute an artificial intercepting surface in place of the vegetal surface, is to give some idea of the relative potentials of various sites to gain water from fog. All the instruments devised suffer from the disability that they cannot be directly calibrated with a specific vegetation type, since their intercepting surfaces do not, and are frequently not intended to, reproduce the morphology of vegetation.

As early as 1900, Marloth, in South Africa, was measuring water contribution on Table Mountain by placing reeds in bundles over raingauges and comparing the amounts caught with uncovered gauges (Marloth, 1904, 1907).

Fog interception by screens.

For a number of years the Atomic Energy Commission on Mt. Washington Observatory has maintained a screen device principally for studies of riming, but which also intercepts fog in the liquid state. Twenty rigid 3mm thick bars in a frame about two feet by one foot have been known to collect about a quart of water in two hours.

The first use of a vertical wire mesh in specific fog and cloud water interception studies was by Twomey (1956, 1957) in Tasmania, Australia. On

Mt. Wellington, Tasmania, a 4,160 ft. peak, Twomey set up a "cloud collecting screen" which he constructed using wire mesh attached to an angle frame. An 8 inch raingauge was placed under the mesh, and a control gauge was located in the open a few yards away. The gauges were read at intervals over a 10 day period, during which the mountain summit was covered almost continuously with stratocumulus clouds. Over the 10 day period the screened gauge collected 43.99 inches, whilst the open gauge recorded only 4.075 inches. Thus the overall ratio of the volumes of water collected by the screened and unscreened gauges respectively was 10.4; the ratios of individual readings ranged from 2.6 to above 200. Twomey states that "it is significant that low values of this ratio were associated with higher rainfall rates." (Twomey, 1956, p. 121)

Twomey calculated that, on the basis of estimated wind velocities, the maximum value of the ratio as a result of raindrop collection by the mesh would be about 4.0, which is less than the overall ratio and far less than the maximum ratio values obtained, viz. 100, in $1\frac{1}{4}$ hours in a 5 $m.sec^{-1}$. estimated wind; 114, in the same time and windspeed, and 224, in 4 hours with a 5 $m.sec^{-1}$. wind. Twomey thus concludes:

"it seems certain, therefore, that the major part of the water received by the screened gauge originated as cloud water which was intercepted by the wire mesh." (Twomey, 1956, p. 122)

A similar apparatus was utilized in Hawaii, by Carlson (1961), and Ekern (1964), but here the screen was pivoted and kept orientated into the wind by a vane. Thus this is not strictly comparable with Twomey's apparatus.

A comparable experiment was carried out in December, 1967, and January, 1968, by the writer, on Beachy Head, near Eastbourne, Sussex, England. The experiment was designed to test the likelihood of fog water precipitation at lower levels, (site was at 400 ft. altitude,) and in England, where it had apparently never before been attempted.

Two steel wire screens were constructed, each 3 ft. square, and supported on thin painted hardwood frames above two standard British 5 inch raingauges; the bottom of the mesh was not attached to the frame but kept taut by supports on the ground, so as to facilitate the runoff of water. The screened gauges were placed about 10 feet apart with an unscreened control gauge approximately halfway between the two. One screen was orientated north - south, and the other east - west. The gauges were read at intervals depending on the conditions between December 17th, 1967 and January 6th, 1968. An abstract of the results is given on p. 67 , overleaf. In a 6 hour period from 1500 to 2100 on December 22nd, 1967, gauge (1) yielded 259.5 times that of the open gauge, and gauge (3) yielded 337.6 times that of the open gauge. Gale force winds and light drizzle could have given a similar result, but as it was known that actual conditions were heavy fog, with a maximum estimated wind speed of 10 $m.sec^{-1}$., it is considered that this was not likely to be the case in this instance. Not so spectacular, but perhaps the most significant result of all, was the ratio 7.8 times, given at 2200 hours on December 19th, 1967, when fog covered parts of Beachy Head, and there was little wind to influence the results. Over the entire period the screened fog gauges each caught about four times that recorded by the open gauge. This compares with about

PERIOD (HRS) SINCE PREVIOUS READING	AMOUNT CAUGHT IN SCREENED GAUGE #1 (in 0.01 inch)	AMOUNT CAUGHT IN SCREENED GAUGE #3 (in 0.01 inch)	AMOUNT CAUGHT IN OPEN GAUGE #2 (in 0.01 inch)	RATIOS		EST. WINDSPEED ($m.sec^{-1}$)	WIND DIRECTION
				1/2	3/2		
13	23.5	23.5	3.0	7.834	7.834	calm	-
6	173.0	140.0	3.3	52.420	42.420	5 - 6	WSW
6	98.0	101.3	0.3	259.500	337.600	8 -10	WSW
24	61.0	84.0	9.0	6.700	9.300	5 - 6	WSW
17	40.0	53.0	12.0	3.300	4.400	2	N
23	50.0	45.0	19.0	2.600	2.300	2	N
31	8.0	8.0	1.5	5.300	5.300	2	W
16.5	84.0	76.0	16.0	5.250	4.750	3	W
8	89.0	71.0	10.0	8.900	7.100	10 -11	W
TOTALS	1024.0	1009.8	260.5	3.930	3.880		

Table. 20. Abstract of results of screened gauge exposures on Beachy Head, England, Dec. 1967 - Jan. 1968.

10 times the open gauge in Twomey's (1956, 1957) results; it must be remembered that he was dealing with conditions of continuous cloud cover, whereas many days during the three weeks of this experiment were totally clear.

Although indicating that considerable amounts of water may be added to the ground through fog and low cloud, no attempt was made to measure the amounts of water caught by the downland chalk scrub of the area. However, the importance of this probable addition of water is suggested by the fact that the Penman and Thornthwaite evapotranspiration formulae (see Penman, 1963) when calculated for this area show a theoretical need for irrigation in nine years out of every ten. That irrigation is not practiced even in those types of agricultural enterprizes where it is known to be profitable, strongly suggests an additional water source not accounted for by the equations, which utilize the precipitation data from normal raingauges.

Local knowledge of the Sussex downland situation tends to support the idea of additional water from fogs. The filling of the so-called "dew - ponds" has never been satisfactorily explained, and these have been observed to have taller vegetation growing round them. The combining of cereal crops in the summer is often impeded until 10.00 or 11.00 in the morning due to wettness of the crop. This is sometimes the result of heavy dew, but is more often the result of night-time fogs which dissipate rapidly when warmed by the sun. The addition of a small amount of water may be critical in the water economy of crops here; if nothing else, excessive evapotranspiration may be delayed until the late morning. Thus the screen fog water interception technique is here justifiable

in that it indicates an unaccounted water input. The actual importance of this water is perhaps better assessed by the use of a balance type of instrument.

Balance instruments.

Many of the dew gauges now on the market utilize a balance mechanism to continually weigh any water added to a flat surface by dew. An adaptation of this idea follows the technique devised by Hirst (1954) in continually weighing an actual plant shoot. An initially turgid shoot is kept constantly supplied with water from the mid-point of the balance beam; this makes up transpiration loss. Growth is too slow to affect daily records, and daily changes from photosynthesis or reapiration are too slight for the beam sensitivity. The balance is placed in the required position, which may be in the centre of a growing crop of the same plant.

The main problem with this type of instrument is that wind may totally upset the records if the windspeed is too high, despite the damping of the oscillation with a vane immersed in oil. However, wind speeds tend to be low during the occurrence of fog (see Ch. 3) so that the critical periods of water addition may be properly recorded.

A modification of this type of instrument replaces the plant with a cylindrical screen for horizontal fog interception; nevertheless this still suffers from the drawback of wind effects. The same applies if the apparatus is placed on an electronic transducer, which converts downward pressure to an electrical current; several measuring devices of this type have been designed, but the probable disturbing

effects of wind meant that they were unlikely to operate successfully, and so they were not built.

Fog interception by cylindrical - mesh modified raingauges.

The most widely used type of gauge for the measurement of fog interception is the raingauge modified by the placing of a cylindrical wire gauze directly above the gauge orifice. The principle is that water runs from the gauze and drips into the gauge, where it is recorded. Since the intercepting device is a cylinder, catch is independent of wind direction.

The first use of a gauge of this type appears to be by De Forest (1923), in interception studies in Maryland, U.S.A. He used a narrow collar of wire netting on top of a non - recording raingauge. Dieckmann (1931), in Germany, used a 35 cm. high gauze cylinder inserted into a raingauge. Grunow (1952) followed Dieckmann's work but made the height of the gauze cylinder equal to twice its diameter, on the principle that the effective intercepting area, taken as height x diameter, was equal to the catching area of the raingauge. This enabled him to compare the results more closely with the amounts recorded in a normal open raingauge.

Since Grunow's work, a number of workers have utilized the cylindrical gauze technique in various studies. Nagel (1956, 1962) used a similar gauge to measure water gained from Table Mountain's "Table Cloth," in South Africa, and from South-West Africa's coastal fogs. Baumgartner (1957) utilized it in a study of the vertical variations of fog precipitation in Bavaria; Kirigin (1959) used it for a study of the effects of continentality and slope on the amounts of

fog precipitation in Yugoslavia; Bauer (1963) for investigations of vertical fog precipitation variations in the Hunsruck and Eifel Mountains of Germany.

Kummerow (1962a, 1962b), working with a Grunow type fog interceptor on the north Chilean coast, recorded in one year an extra 1700 mm of water reaching the ground as fog precipitation. Comparisons with amounts recorded in gauges under trees showed that the gauges caught an average amount similar to that dripping from the trees.

Vogelmann et al. (1968), used a double coil of aluminum wire screen for their study in the Green Mountains of Vermont, U.S.A., and found that catch increased significantly with elevation, even compared to open raingauge catches. Most recently, the University of Thessalonika, Greece, has initiated a project to discover how water may be drained from fog and cloud on Mt. Olympus; similar mesh cylinders are being used for this (Kyriazopoulos, 1968).

The writer investigated the use of cylindrical gauze screened gauges in a preliminary experiment, again on the South Downs of Sussex, England, during July, 1969, when five non-recording gauges, screened as shown in Plate 1, p. 72, were exposed for 14 days. It was here that the problem of water retention on the mesh was first noticed by the present author. Although water collected in the screened gauges whilst none collected in the open gauges, it was evident that not as much was collected as could have been if all the water intercepted by the gauze flowed from it.

Since it was known that the collection efficiency of a solid cylinder can be calculated with some accuracy (Langmuir, 1961), the idea of using a cylinder composed of vertical wires only seemed to have merit. Knowing

Plate 1. Gauge fitted with mesh modifier, Beachy Head, England, July, 1969.

individual wire diameters and length, their theoretical collection efficiencies could be summed.

Albrecht (1931) showed that impaction occurs on to cylindrical wires when a certain critical value of the expression

$$\frac{rv}{c}$$

is reached. Here r = radius of droplets
v = wind velocity
and c = cylinder radius.

With this in mind, a gauge modifier was constructed from a series of vertical wires, each of diameter 0.008 inch, with 16 wires, 14 inches high, per 1 inch of cylinder circumference. (Plate 2 , p.74) In this manner, it would have been possible to fairly accurately calculate the collection efficiency of the apparatus under varying conditions. Once built, however, preliminary tests showed that although this type of gauge modification captured fog particles, it did not do so very rapidly. In a fog at the University of British Columbia, the gauge was exposed from 1000 hours on 31st October, 1969 to 1000 hours on 1st November, 1969. During this time, approximately 0.06 inches of water was collected; during the same period a normal raingauge, at U.B.C. Climate station, collected only 0.01 inch.

However, the collection of an additional 0.05 inches of water in a 24 hour period of thick fog was not considered a fast enough response rate in view of the fact that the water was to be measured in a tipping bucket recording raingauge where one tip of the bucket represented 0.01 inch of water.

Thus the advantages of this type of gauge, the relatively small interruption of the airflow, the possibility of calculating an accurate theoretical

Plate 2. Vertical wire gauge modifier as originally constructed.

collection efficiency, and the lesser water retention on the mesh part of the gauge, were disregarded in favour of a net - mesh type collector, as used in other studies. This type modifies the airflow to a larger extent than the more open prototype, but is far more efficient as a collector, in terms of the absolute amount of water collected.

Construction and exposure of a fog gauge at Vancouver International Airport.

The mesh type fog catcher actually constructed and used is shown in position on a 0.01 inch tipping bucket recording 8 inch raingauge in Plates 3 and 4 , (p. 76 and 77). This gauge was exposed for a trial period in the meteorological enclosure at Vancouver International Airport from 26th November, 1969, to 1st March, 1970.

The frame of the fog intercepting device was constructed of aluminum strip and covered with aluminum mesh, with wires of 0.153 inch diameter, with 18 meshes to the inch. The height of the device was 14 inches, and the diameter 7.5 inches, so that it fitted just inside of an 8 inch gauge orifice. This gave an effective vertical intercepting area of 102.5 square inches. This compares with an area of 50.3 square inches which the gauge would have presented horizontally if unmodified. Thus the collecting area was effectively doubled. The horizontal and vertical water collecting surfaces are quite comparable in fog, due to the horizontal nature of the fog precipitation. (see p. 80) Records from the normal recording raingauge, installed about 6 feet from the fog gauge, were used as a control. This was a 10 inch diameter

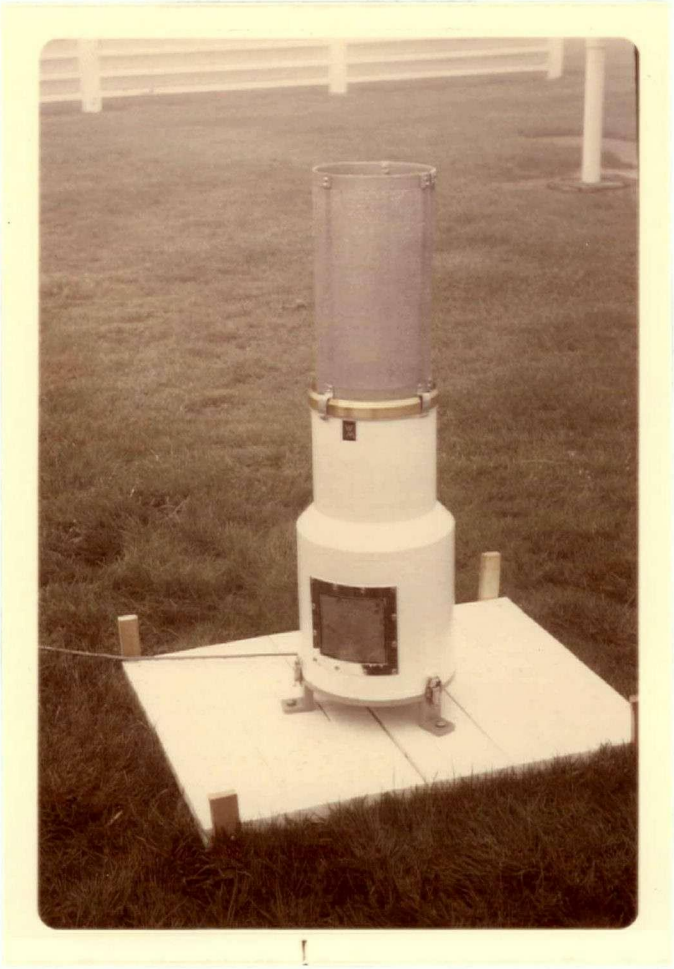


Plate 3. Fog gauge, Vancouver International Airport, winter 1969 - 1970.

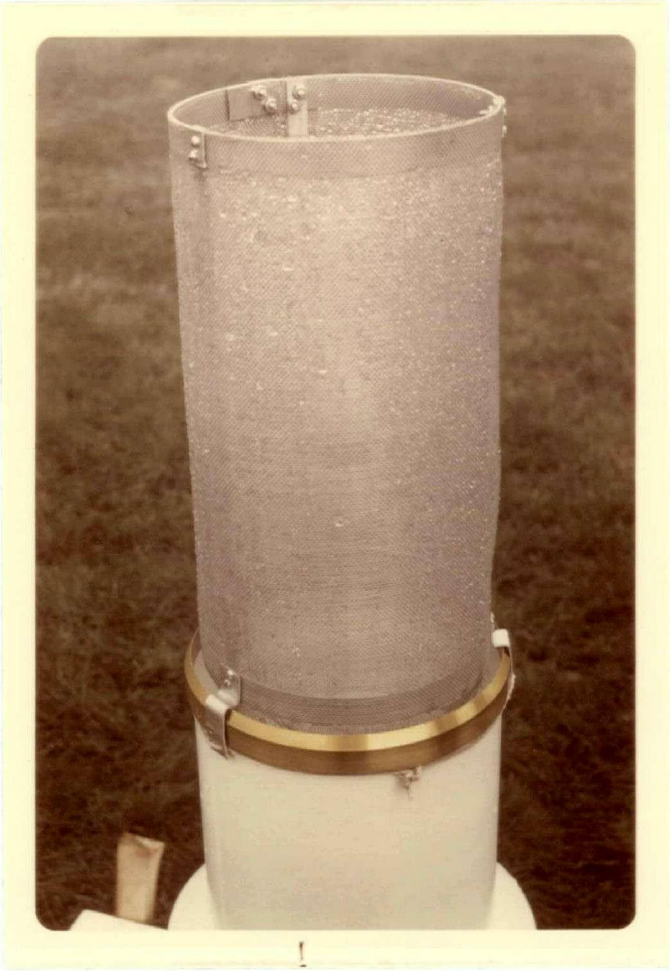


Plate 4. Detail of fog catching device, fog gauge, Vancouver International Airport, winter 1969 - 1970.

orifice gauge, giving a horizontal collecting area of 78.5 square inches.

During rain, the fog catcher also collects water from the rain, and since the total rainfall catching area of a fog gauge is that of the raingauge orifice and the gauze cylinder together, the fog gauge will collect more water from rain than an open gauge, except during very light winds. Nagel (1962) has shown that the wind has to be strong enough to angle the falling rain to 8° from the vertical to catch rainwater. He noticed that the ratio of catch of rain by the gauze to that of the open gauge did not increase greatly after a windspeed of about 14.25 $m.sec^{-1}$. (approx. 25 mph); some calculations with the present gauge indicated a similar asymptote to this ratio at about 8.6 $m.sec^{-1}$. (approx. 15 mph) It is evident that most of the rain that can be angled into the gauge is being so by the time this windspeed is reached.

The problems associated with the measurement of fog precipitation during rain are considerable. During the 3 month period that the fog gauge was exposed, no rain was ever observed to fall during fog. In fact, this is normally the case at low level stations, and it is only in higher hill and mountaintop situations that the problem of rain catch simultaneously with fog catch becomes a real one. (A. Bleasdale, 1968, personal communication.) At all other times it has been the usual practice to deduct the amount caught in a normal open gauge from the total caught in the screened gauge. (Nagel, 1956) There are errors in this practice, however, since during rain the vertical area of the fog catching device is not strictly comparable with the horizontal area of the raingauge orifice.

Thus, during the period of gauge exposure here,

only those situations where fog existed without rain at the same time have had to be considered. Nagel (1956) has shown how easily fog droplets can be induced to to flow horizontally. (Fig. 12 , p. 80) It is evident that beyond a windspeed of about 2 $m.sec^{-1}$., little fog will enter a horizontal orifice, but will all be intercepted by the vertical gauze. Since windspeeds of greater than 1 m. sec^{-1}. (2 mph) have been shown (p. 37) usually to be necessary during fog, in order to prevent the fog droplets from falling out of the air, little fog is precipitated into the open control gauge; that a very small amount is recorded is accounted for by the downward turbulent catch from eddies over the raingauge itself, in a similar manner to the small amounts delivered directly to the ground surface by turbulent impaction. (Kuroiwa and Kinosita, 1953)

The amount captured by a cylindrical gauze may be calculated approximately from an equation, modified from Albrecht (1931) and Matsumura (1953). Let E denote the "capturing coefficient" of the fog catching cylinder, A the effective sectional area of the wire screen, in this case 102.5 square inches, v the wind velocity, and w the fog water contents. Then the amount of fog water F deposited in time t is represented by the equation

$$F = EwvAt$$

In the present case there is a measured amount of fog water falling into the gauge (D); this amount will equal (F - R) , where R is the water retained on the meshes. Thus the amount recorded in the gauge may be represented by

$$D = (EwvAt) - R$$

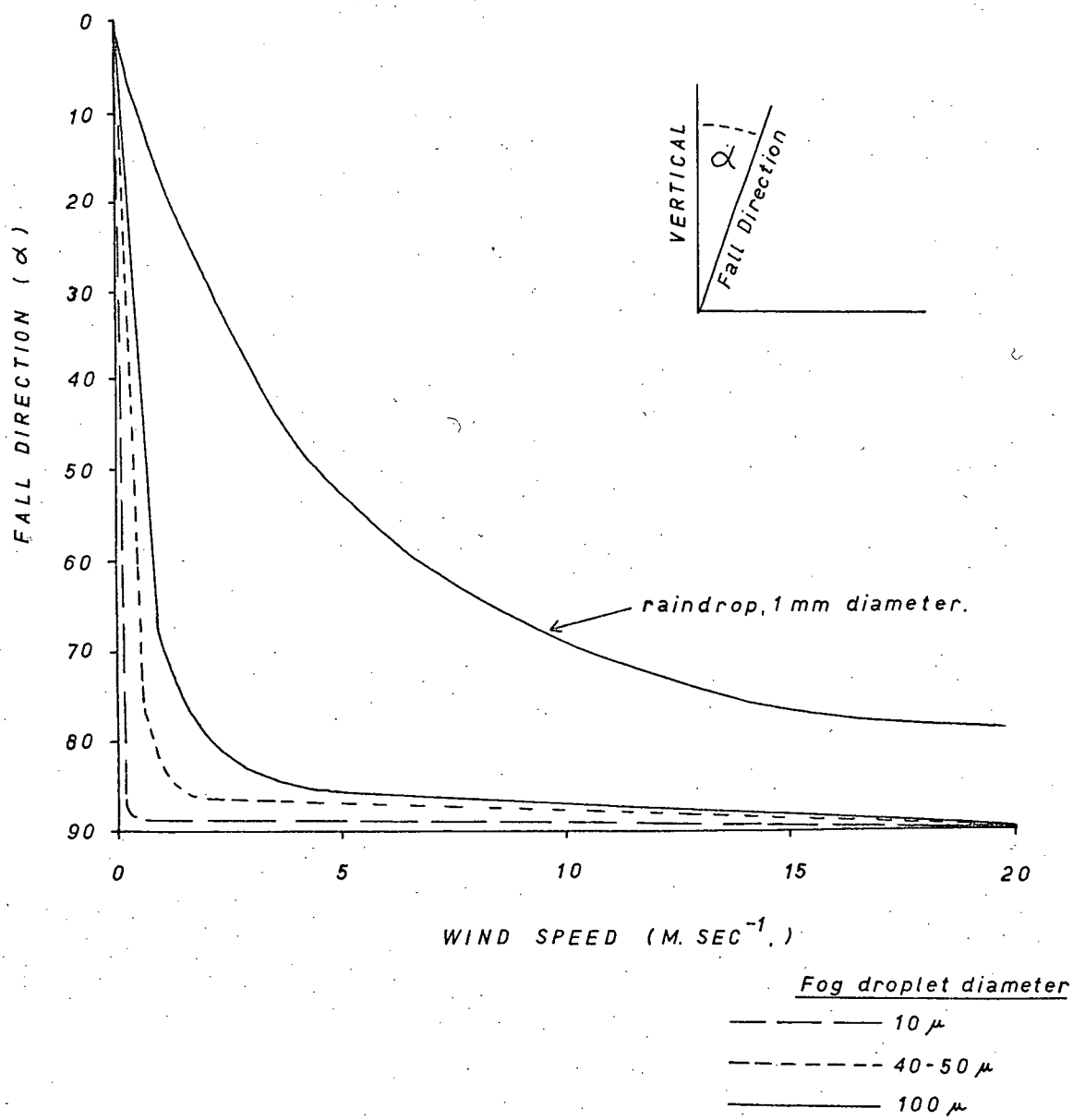


Fig. 12. Angle of fall of fog and raindrops in varying windspeeds. (Adapted from Nagel, 1956, p. 456.)

and the fog water content by

$$w = \frac{(D+R)}{EvAt}$$

It has already been mentioned (p. 14) that increasing amounts of fog precipitation are dependent on the weather situation; not only does the velocity of the depositing air current influence intercepted water amount, but also the origin of the air mass affecting the area. The heaviest deposits are likely to occur where maritime warm air masses from temperate or subtropical zones are predominant. The deposits are small if the air masses originate in polar or arctic zones. (Grunow, 1959) This variable affects the value of E in the previous formulae, in that it affects the drop size distribution of the fog, the modal drop diameters being smaller in the air masses of polar and arctic origin.

Some results from a fog gauge installed at Vancouver International Airport.

It became obvious after a short period that the fog gauge installed at Vancouver International Airport (Plates 3 and 4 , p. 76 and 77) would only be effective in recording additional water interception during long period fogs, when a threshold amount of water was reached, allowing water to flow from the gauze into the gauge orifice. This threshold may be as much as 0.1 inch of water, and is accounted for by water caught on the gauze but retained on it due to surface tension. This is the main problem with any sort of device that requires the water to flow

from a gauze before it is measured, despite the fact that water that was deposited on foliage of plants may be of use to those plants even if it is not a sufficient quantity to drip. (see Ch. 6) Thus amounts smaller than approximately the 0.1 inch threshold value escape the record, and the water evaporates. The amount of water held on the gauge can be seen from Plate 4 , p. 77. The effect on the recorded precipitation even during fogs that exceed the threshold value is that there is a time lag between deposition and recording. It was also found that droplets deposited on the gauge gauze froze when the temperature dropped to 32° F., and took some time to melt again when the temperature rose, since the energy required for the latent heat of melting must first be satisfied. The effect of these two lags was to make the data very hard to analyse.

Regression techniques could not properly deal with the differential time lags; also, the water deposited was recorded in 0.01 inch amounts (that required to tip the gauge bucket). Consequently, the fog record, at the time scale considered, was discrete; that is, an event was either recorded or it was not. This added to the difficulties of any statistical analysis. Nevertheless, certain inferences may be drawn by reference to some of the graphs. (Figs. 13 and 14, p. 85 and 86)

Firstly, it is evident that the temperature within the fog must be higher than 32° F.; otherwise any water deposited on the gauze will freeze and escape being recorded. Sometimes this water is recorded many hours later, perhaps after the fog itself has been dissipated by the sun or wind. For instance, the fog that covered much of the lower part of the Fraser Delta on the night of 31st December, 1969 - 1st January, 1970

(see p. 143), under freezing conditions, deposited some water on the gauze of the gauge. This was not recorded at all until 1000 hours on the morning of 1st January, 1970; by which time the visibility had risen to 3 miles. Between 0900 and 1000, the temperature rose from 31° to 35° F.

It also appears that little deposition of water occurs unless the air has been fully saturated for at least 5 hours; visibility also has to have been zero for this time. This is the time lag of the instrument. Visibility is partly a function of the liquid water content of the fog. Visibility is recorded as zero if visibility is less than 220 feet. (70 metres) Thus, according to Trabert's Law (Trabert, 1901), which states the relationship between visibility and liquid water content of fogs,

$$w = \frac{2rc}{v}$$

where:

w = liquid water content (gm. m^{-3}.)

r = mean drop radius

c = a constant, approximately 3.0

v = visibility

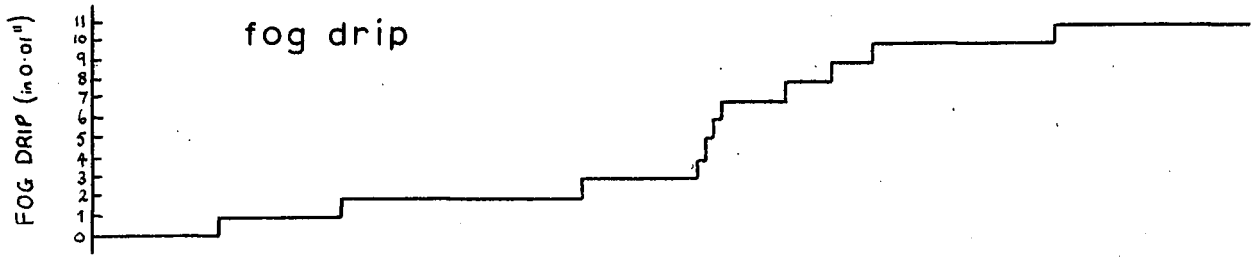
the liquid water content of fog will have to be greater than 1.29 gm. m^{-3}. before any water will be deposited in the gauge. This calculation is based on a mean droplet diameter of 30 μ , which microscopic studies have shown to be a good estimate.

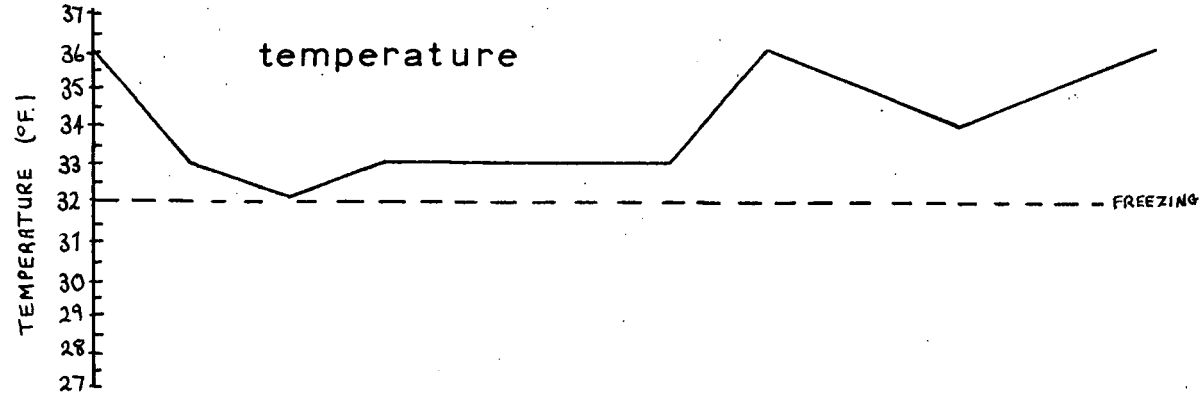
Wind speed and run also appear to have to be above about 2 mph (1 m.sec^{-1}.) for water to be deposited in the gauge. The association of the higher maximums of wind speed (> 5 mph) with larger amounts of water falling into the gauge is probably due to the dislodging of droplets deposited on the gauze, allowing

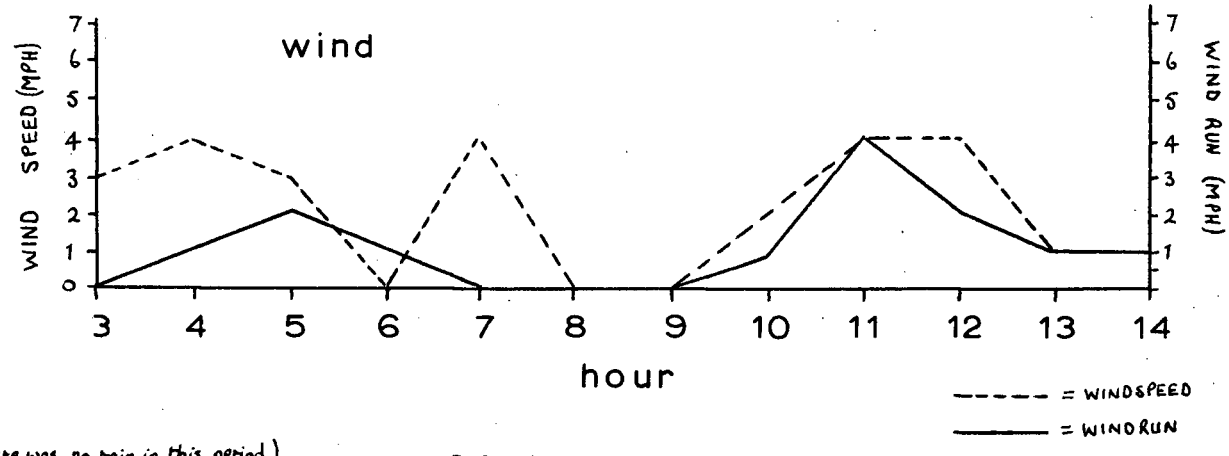
them to drop directly into the gauge orifice. It is possible that some water could be lost to the ground outside the gauge in this manner, but is much more likely to occur on the leeward piece of gauze.

It is evident that in a lowland temperate situation, fog gauges of the cylindrical gauze type are likely to be less efficient than balance type gauges. Although the latter are far more expensive to construct, and still suffer from certain disadvantages (see p. 69), they would probably yield results amenable to analysis by normal statistical procedures, and thus of greater interpretive value.

DEWPOINT TEMPERATURE (°F)	36	33	32	33	33	32	33	36	35	34	35	36
RELATIVE HUMIDITY (per cent)	100	100	94	100	100	100	100	100	100	100	100	100
VISIBILITY (miles)	0	0	0	0	0	0	0	0	0	0	0	0





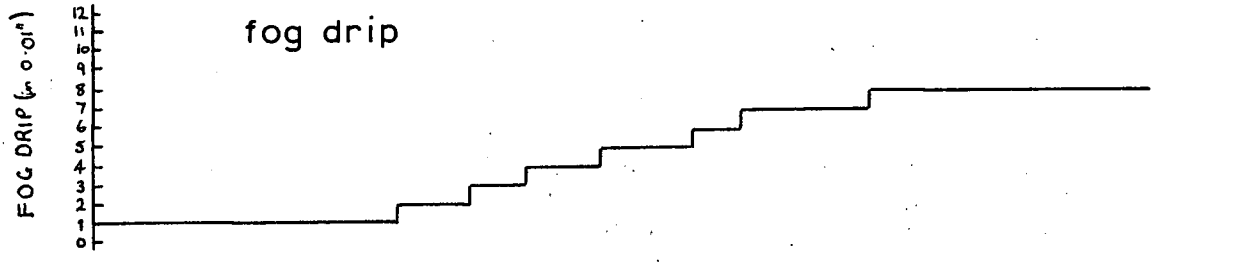


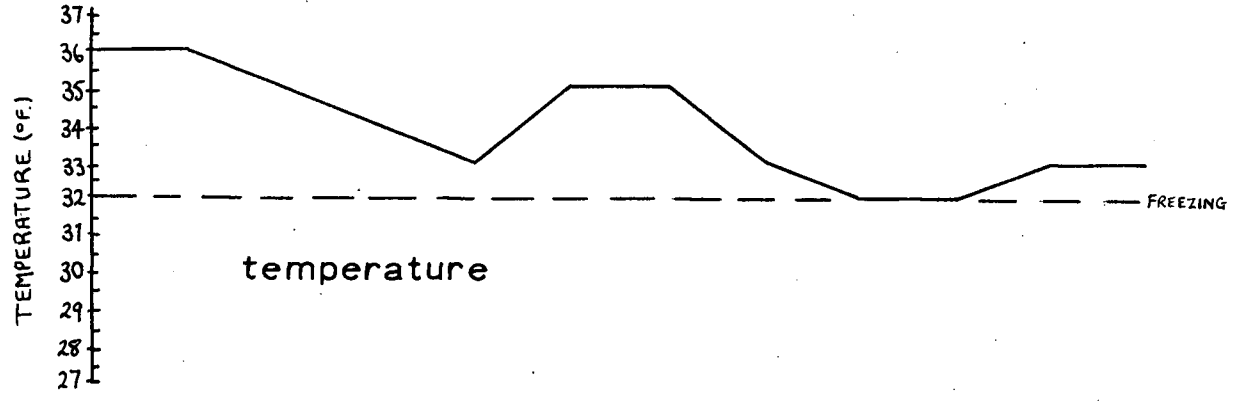
(There was no rain in this period)

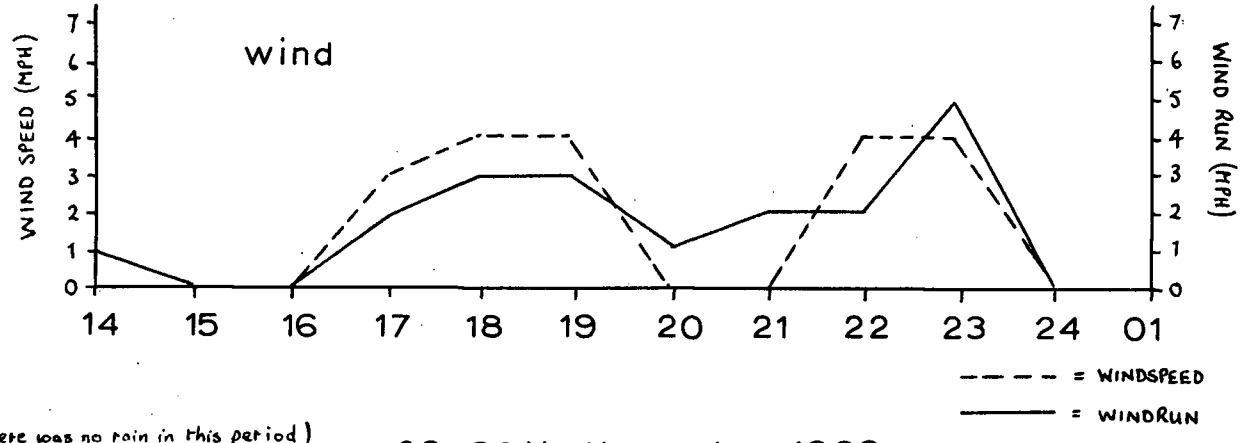
29 th November 1969.

Fig. 13. Climatic parameters and fog drip. (I)
Vancouver International Airport.

DEWPOINT TEMPERATURE (°F)	36	36	35	34	33	35	35	33	32	31	33	31
RELATIVE HUMIDITY (per cent)	100	100	100	100	100	100	100	100	100	97	100	91
VISIBILITY (miles)	0	0	0	0	0	0	0	0	0	0	0	0







(There was no rain in this period)

29-30th November 1969.

Fig. 14. Climatic parameters and fog drip. (II)
Vancouver International Airport.

CHAPTER FIVE.

DIRECT ABSORPTION OF FOG WATER BY THE AERIAL PARTS OF PLANTS.

The aerial parts of some plants are capable of directly absorbing, and utilizing, water deposited from fogged air. However, the conditions under which this "negative transpiration" may occur, and its importance, are not fully understood, and some of the experimental evidence is contradictory.

The factors affecting the entry of atmospheric water into, and its passage through a plant are the surface characteristics of the leaves, the resistance to movement within the plant, and the gradient of water potential across the soil - plant - atmosphere system.

Numerous studies have shown that the rate of water uptake will depend primarily on the potential gradient developed, and also the resistance to flow. (Bonner, 1959; Edlefsen, 1941; Philip, 1958; van den Honert, 1948.) In this, it is no different from normal (root) absorption of water.

THEORETICAL CONSIDERATIONS.

In theory, water may be absorbed by any part of the plant that is at least slightly permeable if sufficient diffusion pressure deficit[1] (Meyer, 1945) is allowed to develop, or, in more modern terms, the chemical potential

---

1. Diffusion pressure deficit DPD = OP - TP ,
   where OP is osmotic potential,
   and TP is turgor pressure. This equation equals (2) overleaf.

is high enough.[2]

The water potential of the plant cell vacuolar sap (ψ_v) under isothermal conditions is determined by the concentration of solutes in the vacuole; that is, its osmotic potential, matric potential,[3] and the pressure exerted by the cell wall. Thus the equation may be written

$$\psi_v = \psi_s + \psi_m + \psi_t \qquad (1)$$

where ψ_s, ψ_m, and ψ_t represent the contributions made by solutes, the matrix, and turgor pressure respectively. ψ_s and ψ_m are negative amounts, while ψ_t is generally positive. ψ_m is conventionally assumed to be negligible, so that the equation reduces to

$$\psi_v = \psi_s + \psi_t \qquad (2)$$

Water will be taken up by a cell as long as ψ_v is more negative, that is, lower, than the potential of the water on the outside of the cell (ψ_e). Uptake of water will dilute the vacuolar sap, and ψ_v will become more positive, that is, it will increase. However, since the cell wall is swollen outwards by the increase in content of the cell, ψ_t will also increase. Water uptake will stop when $\psi_v = \psi_e$. If for the moment it can be assumed that the water on the outside of the cell is pure (pH = 7) so that its potential will be zero ($\psi_e = 0$), then at the point of equilibrium $\psi_v = 0$; the cell is termed

---

2. Chemical potential expresses the same property of a system as DPD, and the two are numerically equal, but opposite in sign: ψ = -DPD.
3. The attraction between water molecules and the matrix with which they are in contact.

fully turgid.

Under such conditions, osmotic potential will equal turgor pressure, or

$$\psi_s = -\psi_t \qquad (3)$$

If the external water contains solutes, so that , then equilibrium will be established at below the maximum volume of the cell, when it is not fully turgid. Here

$$\psi_s - \psi_e = -\psi_t \qquad (4)$$

However, in a plant under water stress in, for instance, a coastal desert area, where the atmosphere is at or approaching saturation due to impinging advection fog, the total plant system will be in a situation with two external water solutions in contact with the outermost cell walls. One of these is in the soil, and the other in the atmosphere. Evaporation for a long period from the surface layers of the soil, before the onset of a foggy period, will be partly responsible for the water deficit in the soil and will have increased the concentration of salts in the remaining soil water available to the plant. Thus the water potential in contact with the root system will be 'more negative' than the potential of the water vapour in contact with the aerial part of the plant, and that already caught or condensed out on vegetal surfaces. Thus

$$\psi_{soil} < \psi_{aw} \qquad (5)$$

where ψ_{soil} is the potential of the soil water in contact with the root system;

and ψ_{aw} is the potential of the aerial water. (water on the vegetal surfaces, and water vapour in the zone immediately above the leaves.)

But where

$$\psi_{soil} < 0 \qquad (6)$$

and

$$\psi_{aw} \leqslant 0 \qquad (7)$$

water absorbed by the total plant system will tend to be from the source with the least diffusion transfer resistance, that is, from the fogged or saturated air.

Several German workers have mentioned the fact that leaf surface water (they were concerned with dew) is relatively free of salts, unlike water taken up by the roots, and they considered that much of the importance of this water source was in that it provided a supply of pure water otherwise unobtainable. (Arens, 1934; Hiltner, 1930, 1932; Lausberg, 1935; Zattler, 1932.)

Although many coastal fogs have been found to contain sea salts, derived from condensation nuclei, the salt concentration of deposited fog water is nevertheless far less than that to be found in the soil, particularly in arid areas.

It should be noted that water actually deposited from fogged air is probably more likely to be absorbed than water vapour, since no phase change need occur. This has been confirmed experimentally by Jensen et al. (1961), who observed that resistance to water flow through leaf tissue was less when a direct water - leaf interface was substituted for an atmosphere interface, even when the relative humidity of the impinging air approached 100 per cent. This was also found by Hohn (1951), and Janes, (1954). (see p.108)

Whatever the main route of water entry into leaves, it may always be expected that the initial rate of uptake will be inversely related to leaf water content

and the water potential of the leaf. (Slatyer, 1967) This was found true experimentally by Krause (1935), and by Slatyer's experiments with Pinus echinata. (Slatyer, 1956.)

PHYSIOLOGICAL CONSIDERATIONS: PATHWAYS OF WATER ENTRY INTO AERIAL PLANT ORGANS.

1. THE STOMATA.

Since most of the water derived from transpiration passes through the stomata, it may be expected that any water vapour re-absorbed from fogged air under conditions of moisture stress would also utilize this pathway. However, the fact is often overlooked that most stomates on the majority of plant species are on the lower surface of the leaf. Thus the net amount of intake from water (seen from the above to be the most efficient absorption form) is likely to be small owing to the dislodging of incipient water droplets by gravity, aided by movement of the plant by shaking.

Nevertheless, it seems that water vapour can be absorbed into the leaf via the stomata, and there are often just a few stomates on the upper leaf surface, in any case.

Normally, the stomata would be closed during the night, since at least one of the functions of the stomata is to allow the absorption of carbon dioxide for photosynthesis, which cannot take place without light energy. The fact that the requisite vapour pressure gradient would usually only develop during the night, when the stomata are closed, is often considered evidence that if water is absorbed, the amounts would be very small.

However, it is known that some plants, under

very unfavourable water conditions, such that the leaves start to lose their turgor, are able to close their stomata partially, or even completely, for a time in the middle of the day. This may be because photosynthesis is reduced and the concentration of carbon dioxide in the intercellular spaces rises; the cause is uncertain, but the phenomenon has been observed. (Sutcliffe, 1968) The likely corollary of this is the important one from the present point of view. This is transitory opening during the night, which may be adding to the economization of water by the plant if it allows absorption of water from fogged air, or from dew.

The patterns of stomatal opening and closure vary considerably from species to species. Most cereals hardly ever open their stomata at night, and many of them can remain closed during most of the day. (Sutcliffe, 1968) In contrast, there are some plants, such as potato and onion, in which the stomata are continually open under normal moisture conditions, except for a few hours immediately after sunset. Midday closure does not take place in these plants until they are badly wilted, and even under conditions of extreme water stress opening may occur during the normal closure period.

The pattern of stomatal behaviour is quite different in many succulents and other xerophytes; here the stomata commonly open at night and close by day, perhaps because the need to conserve water in order to survive is stronger than the need to photosynthesize rapidly in order to grow.

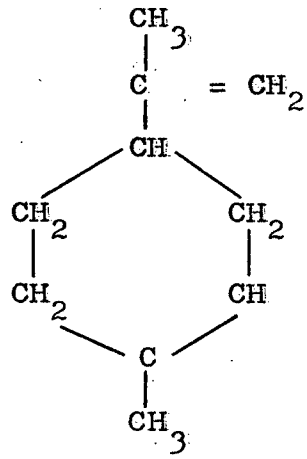
Some studies have indicated that the vapour pressure at the surfaces of the internal mesophyll cells under the stomata is likely to be greater than 0.95 (100 to 95 per cent external to internal relative humidities) in most non - transpiring plants, even when wilted, which

would mean that the gradient and hence the amount of reverse diffusion of water would be small. The vapour pressure has been observed occasionally to be less than 0.80, but only in the laboratory, under carefully controlled conditions (Stone et al., 1950; Whiteman and Koller, 1964).

Turrell (1947) argued that Citrus stomata are not penetrated by liquid water at all, although some water vapour may penetrate, as may some oils. He studied freshly killed stomates of several varieties of orange and lemon, and suggested that the resinous stomatal plugs and cutinized stomatal chambers effectively prevented the stomates from filling with water. An explanation may be provided from the work of Ebeling (1939). The contact angle (see p. 103) between distilled water and waxed capillary glass tubes was found to be large, and the height of the water rise in the tubes, zero; whereas in clean, unwaxed glass tubes, the contact angle was found to be small, and the rise of water, more than 2 cm. This showed that where contact angles are large, surfaces are small. The citrus stomatal plug consists of resin, thought to be formed by polymerization and low order oxidation of ethereal oils produced by the plant. In this, the citrus resin is similar to most plant resins. The ethereal oil limonene is found in citrus, and Turrell reasonably concluded that the citrus resin is a polymer of this substance. The structural formula shows that this substance is relatively non - polar, and thus the contact angle of water with it would be large (see structural formula overleaf). Turrell in this way concluded that no liquid water would penetrate citrus stomata.

However, the argument seems to be based on circumstantial evidence, which rather points to the likely slow rate of water absorption rather than total

exclusion. Much more significant as far as the adherence of water droplets is concerned is the fact, already mentioned, that in commom with many other plants citrus leaves have their stomata on the lower leaf surface, and thus gravity is working to dislodge the droplets of water.



Structural formula of Limonene. (After Turrell, 1947.)

The significance of contact angles of water droplets adhering to leaf surfaces will be further discussed. (see p. 103)

Rhythmic variations of tissue tensions within leaves under normal conditions have been observed by some workers, and Fogg (1947) provides indirect evidence for this. Such variations may well have important influences on stomatal movement, especially since it has been observed that the stomata of wilting leaves open first more widely, and later close. (Sutcliffe, 1968)

The experiments of Laidlaw and Knight (1916) illustrated this, with *Phaseolus vulgaris*, *Eupatorium adenophorum*, and *Maranta coccinea, var. floribunda*. Stomata on leaves detached and allowed to wilt opened temporarily before closing. Since a control detached under water, and kept supplied with water, did not alter

its stomata, Laidlaw and Knight attributed stomatal opening on the wilted leaf to water stress. They considered that this was probably due to the guard cells retaining their turgor longer than the other epidermal cells. This stomatal opening on wilted leaves was also shown, earlier still, by Darwin and Pertz. (1911)

To explain the phenomenon, Fogg (1947) put forward the hypothesis, following Martens (1934), of differential rates of contraction of superficial and underlying tissues. The differential rates were noticed in trying to explain variation in water droplet contact angles on rapidly wilting leaves. This behaviour of the stomata may be attributed to preliminary stretching of the whole epidermis, followed by release of the tension.

If guard cells of the stomata are able to retain their turgor longer than the cells underneath, whatever the reason, the replenishment of water by reversed diffusion through the stomata from fogged air or water droplets caught from fogged air, may mean that the leaf mesophyll cells may be able to partially regain their turgor before the stomata reclose.

Despite the obscurity of the relative importance of the stomata as the point of initial water absorption, it is clear (Slatyer, 1960) that the absorption of nutrients and insecticides frequently occurs in this manner. (Cook and Boynton, 1952) The latter found that the uptake of urea nutrient by McIntosh apples was through the stomata, and this has been observed with insecticidal oils, on various plants. (Ginsburg, 1930; Kelley, 1930; Knight et al., 1929; Rohrbaugh, 1934.)

2. THE CUTICLE AND THE EPIDERMIS.

The properties of the cuticle also profoundly influence transpiration, so that they would also be expected to influence any reverse flow. The influence of the cuticle is particularly noticeable when the stomata are closed. In shade plants, such as ferns, where the cuticle is thin, as much as 30 per cent of the total transpired water loss is thought to take place as cuticular transpiration. (Sutcliffe, 1968)

In desert succulents, by way of contrast, loss through the cuticle is probably negligible; this presumably means that absorption of water through the cuticle will also be small, unless the plant is specially adapted. Slatyer (1967), however, following Gessner, (1956), and referring to dew deposit on leaves, pointed out that since dew is primarily of nocturnal occurrence, and since the stomata of most species normally appear to be closed for most of the night, it seems probable that water uptake occurs primarily through the cuticle. The effect of moisture stress on the behaviour of the stomata is apparently overlooked.

The relative significance of water absorption through the stomata will in any case tend to be reduced in certain plant species with relatively high permeability to liquid flow. Vaadia and Waisel (1963) showed that the entry of tritriated water (HTO - labelled) was faster into the leaves of sunflower plants (*Helianthus annuus var. advance*), than into Aleppo Pine (*Pinus halepensis Mill.*), under the same conditions. They attributed this to the thicker cuticle of the latter.

In Australia, Wood (1925) compared water absorption by branches cut from *Eucalyptus corynocalyx*, *Sterculia diversifolia*, *Acacia decussata*, and *Atriplex vesicarium*.

To avoid the possibility that sprayed moisture might be retained in the capillary spaces between the vesicles or hairs which cover the epidermis and thus cause an apparent absorption on weighing, he placed the branches in a nearly saturated atmosphere. His results showed negligible absorption by the leaves of Eucalyptus cornocalyx, Sterculia diversifolia, and Acacia decussata, but there was significant absorption by Atriplex vesicarium. This was attributed to the fact that the three former species have cutinized leaves, whereas the leaves of the latter are uncutinized. This suggests that leaf cuticle is normally impervious to water.

Eisenzopf (1952), in experiments to induce negative water transport with several coniferous species, observed a peak rate of absorption after 90 minutes immersion in water, after which the rate of absorption decreased rapidly. He suggested that the increased rate for the first 90 minutes was the result of an increase in the permeability of the cuticle, itself caused by increased cuticle hydration, although he admitted that a similar result could have been obtained if the stomata had opened. Slatyer (1967), however, considers that "a more probable explanation" was the simple one that the gradient of water potential had been progressively reduced. This does not account for the observed distinct break in the absorption curve after 90 minutes.

The comparatively slow rates of cuticular and epidermal absorption are suggested by the experiments of Slatyer (1956), with Pinus echinata. His results indicated that the steepest part of the gradient of increasing water potential was at the leaf surface, whether under conditions favouring negative or positive water transport. Since the steepest part of the gradient might be expected to be at the root surface

during negative transport, the fact this is not so shows that, with Pinus echinata at least, the cutinized epidermis of a leaf is much less permeable to water than the suberized epidermis of a root.

Slatyer (1960) concluded that " in general, and with the present state of knowledge, it appears that most of the water absorbed by leaves is through the cuticle." (p. 369) He notes, however, that if this is so, a marked increase in cuticle permeability must occur on wetting, in order to explain the paradox of high cuticular resistance to water transport during transpiration. Slatyer regarded the evidence as "inconclusive."

Absorption through the cuticle almost certainly does occur, in some species, and in some situations, but in general it seems that cuticlar resistance is so high that the total amount absorbed in a short period is usually insufficient to do more than partially allow the leaf tissue to regain turgidity. Nevertheless, this could be important where the plant is in badly stressed conditions and is struggling to survive.

3. SPECIALIZED CELLS FOR WATER INTAKE.

Some less well known modes of water intake via the leaves of plants utilize specialized cell structures. How generally these specialized cells occur is still unknown.

Specialized cells for water intake have been observed by Zamfirescu (1931), and Meidner (1954). Field observations by the latter, in Natal, suggested that several species that were adapted to withstand severe soil moisture deficits were able to absorb water from dew deposited on their leaves. It was noted that

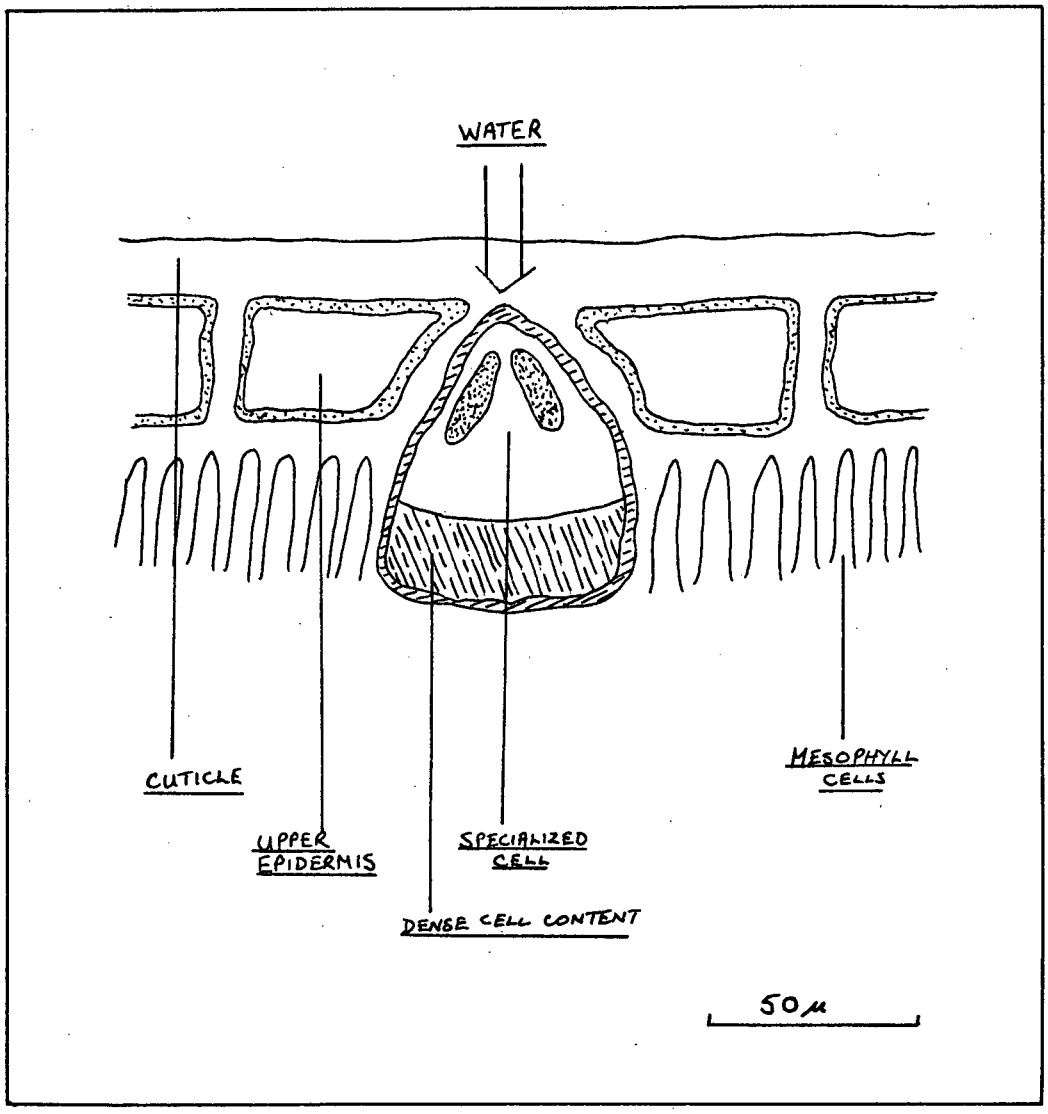


Fig. 15. Longitudinal section of a specialized epidermal cell of a leaf of Chaetacme aristata. (After Meidner, 1954, p. 424.)

water disappeared most rapidly from the leaves of Chaetacme aristata. Microscopic examination revealed, and subsequent experimentation confirmed, the presence of specialized epidermal cells with denser contents than normal (see Fig. 15, p.99). Meidner found 34 specialized cells per square millimetre in the upper epidermis, and 12 per square millimetre in the lower epidermis. Since absorption was found to be significantly greater on the upper epidermis than through the lower epidermis, it was concluded that absorption was at least aided by these specialized cells. This conclusion was confirmed by evidence from selective vital staining techniques. Meidner also noted that water was only absorbed in the liquid state, not from water vapour. Thus this process may be significant with some species in absorbing water from fog that has coalesced on the leaves; its possible application would at first be restricted to a search for species that possess these specialized cells. The development of these species might be worthwhile, but, of course, all the other factors, such as leaf configuration, surface features, and economic use, would also have to be considered concurrently.

One species with an obvious commercial value that is known to possess an apparently specialized leaf structure is the apple, Malus pumila. Roberts et al. (1948) found that the cutin of the epidermis of apple leaves was in discontinuous lamellae parallel to the outer epidermal wall. Pectinaceous substances, known to have great powers of water absorption, were found to occur in intermittent layers in the outer epidermal walls, interspersed with these cutin lamellae. These substances apparently formed a continuous pathway from the layers in the cuticle through the anticlinal walls of the epidermal cells to the cell walls of the vein extensions and

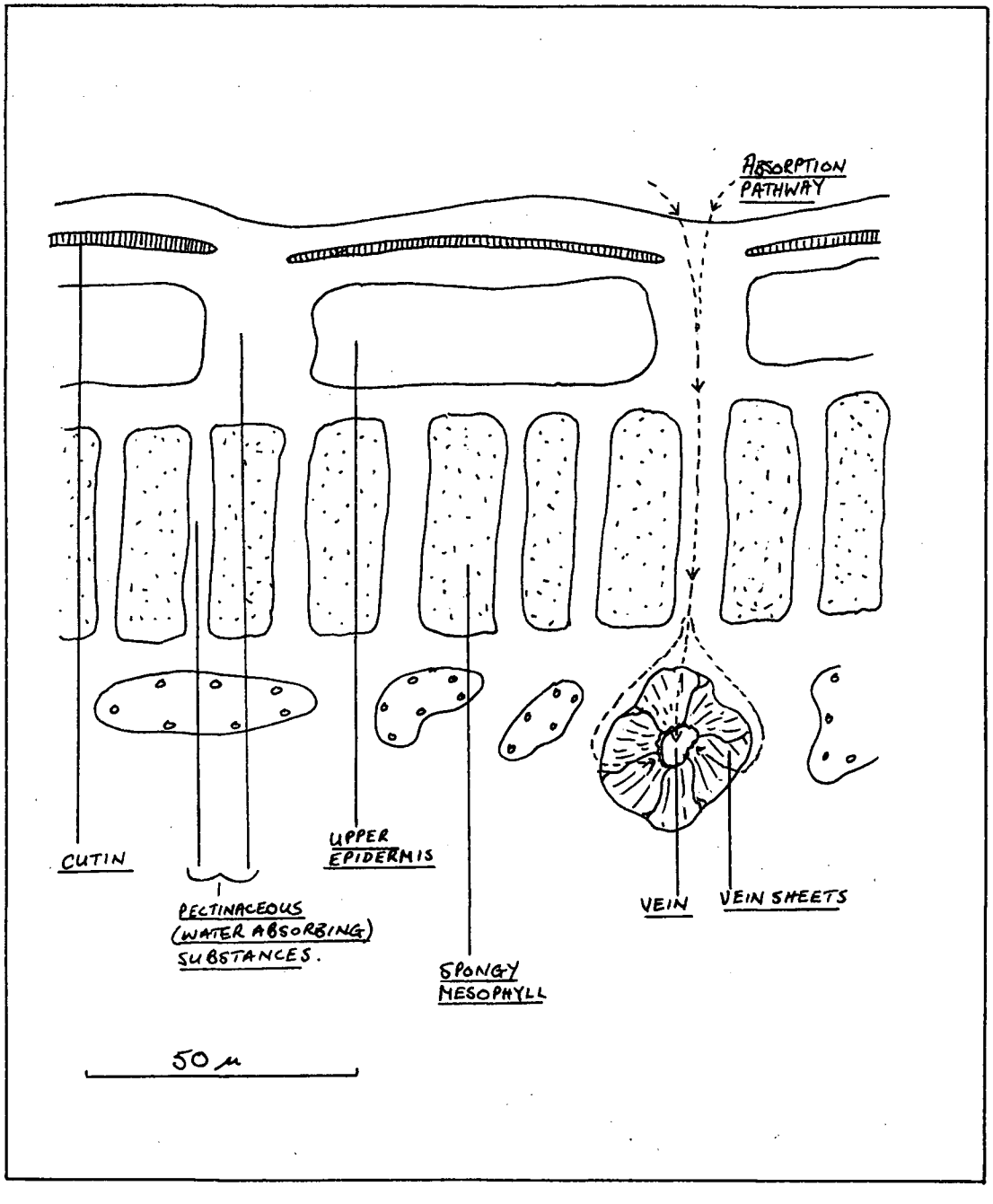


Fig. 16. Upper leaf surface structure of McIntosh Apple.(Adapted from microphotographs given by Roberts et al., 1948.)

bundle sheaths surrounding the larger veins of the leaves. This was considered to provide a possible pathway for water intake through the cuticle to the living cells surrounding the vascular tissues. (see Fig. 16 , p. 101)

A slightly earlier study by the same authors (Palmiter et al., 1946) showed that solutes did move along this pathway; similarly Steubing (1949) observed this movement of water using fluorescent dyes.

PHYSICAL CONSIDERATIONS.

1. THE EFFECT OF TEMPERATURE.

Temperature can have an effect on the rate of water absorption in the normal (positive) way, through its effect on transpiration rates. First recognized by Delf (1916), the slowing of water uptake with decrease in temperature was later confirmed by Clements and Martin (1934), with sunflower, and by Arnt (1937) with cotton plants.

Reduction of water intake is less in species native to cool environments than in species which normally grow in warm ones (Kramer, 1942). This has been attributed to the combined effects of decreased permeability of the root membranes and the increased viscosity of the water with temperature reduction. Kramer (1940) observed that water flow through root systems increased as temperature increased to 35°C., the highest temperature studied.

Experiments carried out by Jensen and Taylor (1961), on sunflower (*Helianthus annuus*) and tomato (*Lycopersicon esculentum Mill.*) indicate that the slowing of absorption with decreased temperature also applies to reversed water intake through the leaves under conditions of moisture

stress. It may be considered, however, that water stress is more likely to develop naturally under hot conditions than under cold, and thus to replenish the deficit by absorption will also be slightly easier.

2. THE WETTABILITY OF THE CUTICLE.

If the main source of water absorbed is from water actually held as droplets on the leaf surface, as is normally the case from fog precipitation (and as it would be with dew), an important point that may be overlooked is the wettability of the cuticle. The ability of a liquid to wet a surface is a function of its contact angle on the surface; this in turn depends on the surface tension of the liquid and the type of surface. Surface forces are known to be the result, in part at least, of the structures of the molecules making up the surface (Wheland, 1944).

Fogg (1947) pointed out that the area of contact between a leaf surface and the water or solution deposited on it is an important factor determining the amount of dissolved substances entering, or leaving, the leaf. Advancing contact angle was used as a measure of the extent to which wetting takes place on the leaves of Sinapis arvensis, Triticum vulgare, and some other plants (Fogg, 1944, 1947). Results showed that the contact angle increased, and thus the droplets became easier to dislodge, as the age of the leaf increased, and also as the water content of the leaf decreased. This may be significant in influencing the amount of water that a wilting and thus stressed plant is able to absorb from fog droplets deposited and coalesced on its leaves.

Water absorption may allow the leaves of some species to remain turgid enough to halt the increase in

water droplet contact angle. However, the steady rise in the value of the contact angle of water on wilting leaves may itself be due to increased wrinkling of the leaf surface as the tissues contract on losing water. This wrinkling probably involves the epidermis as a whole. (Fogg, 1947) The cuticle may pucker independently of the underlying cell walls, as Martens (1934) has shown with Tradescantia virginica. In this case the scale of wrinkling is less but the effect on the contact angle will be similar. Fogg (1947) overlooks the fact that the wrinkling of the leaf surface itself, although it increases the contact angle of the water droplets, may not increase the likelihood that they will be dislodged, since the wrinkles themselves will tend to retain water.

Contact angle is known to be reduced by the addition of wetting agents (Ebeling, 1939). Thus it may be expected that the addition of such materials would significantly improve absorption potential, at least on some types of leaves (Slatyer, 1967).

The addition of detergents to foliar sprays has been found to increase nutrient uptake, (Guest and Chapman, 1949; Cook and Boynton, 1952), and although no studies dealing directly with water absorption have apparently been carried out, a similar result may logically be expected. However, the work of Boynton (1954), on the foliar application of nutrients for plant use, has indicated that nutrient uptake can occur even when the leaf is apparently dry, so it is evident that there must be other absorptive mechanisms that are operative besides those involving the intake of water. Even so, some of this work is of value in aiding the understanding of the behaviour of water in contact with a leaf surface.

ABSORPTION AND TRANSLOCATION : EXPERIMENTAL EVIDENCE.

Many experiments have demonstrated that water impinging on the leaf surfaces of plants is absorbed, whatever the process; less evidence is available to show that the absorbed water is transported away from the leaves.

One of the earliest scientific experiments was that of Lloyd (1905), carried out in the Arizona Desert on the octillo, Fouqueria splendens. In the summer, this shrub usually loses its leaves but is able to form new ones in a matter of days when water is available. Lloyd wetted the upper part of the stem of one of these shrubs by wrapping it in cotton gauze, dipping the end into a water reservoir. New leaves were then found to develop on that portion of the stem, showing that the water was absorbed.

Marloth (1908), in South Africa, conducted a detailed physiological study of the apical hairs of succulent leaves and stems of Mesembrianthemum densum and M. barbatum, and stated that these hairs were "admirably suited" to water absorption, but he did not state how. Although Marloth did not demonstrate absorption with these species, he later studied several species of Lilaceae and Amaryllidaceae, and after also reporting their apical hairs suitable for water absorption, did demonstrate some absorption of water. (Marloth, 1926)

Lack of available water because that in the soil was frozen has not generally been considered as a condition causing moisture stress. It was, however, mentioned in research by Gates (1914). He carried out a series of water balance measurements with several evergreen shrubs and trees in Michigan. During the winter, he found that a cut branch took up moisture on a frosty

night equal to three or four times that lost by transpiration from the same branch on a cold winter day. The actual cause of the moisture here is unimportant, whether it was fog or dew, for both would wet the branch and thus be potentially absorbable.

Absorption has been demonstrated more recently by the used of dyes or labelled water. Vaadia and Waisel (1963) used tritriated water (HTO labelled) to trace water absorption and transport in Helianthus annuus and Pinus halepensis Mill. They found that transport away from the leaf was usually slow, and in some cases did not occur at all. Gindel (1966) used various dyes, such as fuchsin, and reported that 'reverse transpiration' was actually seen to take place, by the gradual colouring of the leaf, and the stem, of Zea mays and P. halepensis Mill. They had been exposed in a state of water stress in the field at Rehovot, Israel. Gindel was mainly concerned with dew absorption; nevertheless, the technique has merit for use in studies of fog water absorption.

During the 1950's a series of experiments on aerial water absorption were carried out, which are generally considered to be the "classics" in the field. As such, they are worth further consideration.

Probably the most well - known experiments are those of Breazeale, McGeorge and Breazeale (1950, 1951), and Breazeale and McGeorge. (1953a, 1953b) These experiments demonstrated, remarkably well, both absorption and negative transport through the whole atmosphere - plant - soil - system. With tomato and corn plants, they demonstrated that water could be absorbed from an artificially fogged atmosphere and exuded from the roots, whether the plants were in soil or not. The conclusions arrived at by Breazeale et al. (1950) were startling; they found that

" A tomato plant can absorb water from a saturated atmosphere, transport it to the roots, and build up the soil moisture to or above field capacity." (p. 419.)

which would appear contrary to the theoretical evidence presented previously. (p. 87) They also observed:

" Tomato plants will grow to maturity, flower, and set fruit with no other source of water than that absorbed through the leaves from a fog or an atmosphere of 100 per cent relative humidity." (p. 419.)

which would obviously be of great significance in arid areas with frequent fogs. However, under natural conditions, the atmosphere is unlikely to stay constantly fogged, so that total growth may require some additional water source. Nevertheless, this might be minimal.

Haines (1952, 1953) enlarged upon the empty flask experiment of Breazeale et al., and obtained a similar accumulation of water in the flask with either a tomato plant or a cotton wick. The latter fact, absorption through a cotton wick, "appeared finally to dispense with the necessity of invoking active secretion by the roots into saturated or partially saturated air," Haines, 1952, p. 97.) to explain the results obtained by Breazeale and Haines himself under controlled conditions of temperature and thus relative humidity. This also applied with sealed flasks allowing fluctuations of pressure relative to that of the surrounding atmosphere. In fact, if the temperature of the flasks into which the roots were sealed was kept constant, in wet shingle, no water accumulated. Haines later concluded:

" Although the leaves (of tomato plants) are undoubtedly able to absorb water for their own turgor from

fogged air ... they do not by active secretion or any other process, force water into the stem." (Haines, 1953, p. 107).

A reverse movement of water was obtained in seedlings of Pinus ponderosa by Stone et al. (1956) again only when the temperature was allowed to fluctuate and there was a resultant drop in the relative humidity of the air surrounding the roots in the flask.

These experiments suggest that other factors, not understood at present, may be at work. It might be pointed out, however, that under natural conditions the soil of arid areas in particular may fluctuate considerably from night to day; thus factors allowing absorption of water with temperature fluctuation will be favoured. Due to the difficulty of measuring small increments of soil moisture in the field, none have apparently yet been made. There seems to be a need for the use of small lysimeters for field measurement in the investigation of this problem. Species other than tomato or corn must also be investigated; they may yield totally different results.

Hohn (1951) and Janes (1954) found that plants absorbed more liquid water than water vapour, near the immediate leaf surface. While demonstrating absorption, they both found that evaporation occurred at the same time into an atmosphere already saturated.

Stone and Fowells (1955) reported that seedlings of Pinus ponderosa could reduce the soil below the permanent wilting point for the sunflower (Helianthus annuus). At this high moisture stress, artificial dew produced from a spray prolonged the life of the seedlings used for up to one month. The utilization of fogged air for prolonged survival under water stress may be important in terms of ability of some

species to tolerate a dry season, such as that of southern California. There may be some unrealized significance inherent in the practice of planting coastal sandy areas with conifers if this characteristic of the genus as a whole. It might be noted that P. ponderosa is one species able to tolerate a comparatively dry climate, and over its entire distribution in western North America, is subject to long periods of drought. Stone (1957) has suggested that its distribution may be related to frequent dewfall, and the subsequent ability to utilize it.

Survival, however, is a different matter from growth, and the production of utilizable biomass. Janes (1954) , in an attempt (which failed) to repeat the experiments of Breazeale et al., (1950, 1951) found that growth of tomato plants sealed in dry soil and exposed to fogged air, was slower than similar plants grown in moist soil, despite the fact that both appeared equally turgid. A possible explanation advanced by Janes, was that the slight moisture stress in the plants growing in dry soil prevented cell division or enlargement. Also, the uptake of nutrients from the soil was prevented in the plant exposed to fog, since any water transport was in the reverse direction. All the tomato plants in Janes' experiment, which lasted 18 days, wilted immediately they were removed from the fog.

Several authors have noted that growth is slowed or stopped by moisture stress. (Wadleigh and Ayers, 1945; Wadleigh et al., 1946; Wadleigh and Gauch, 1948.)

Thut and Loomis (1944) found in citrus trees that as moisture stress increases, a turgor deficit arises within the tree before the first visible sign of wilting appears; growth was checked by water deficits within the plant, induced by increasing moisture stress.

Absorption of fog water in sufficient quantities to permit the plant to regain its turgidity, as appears to be accepted by most authors even if the main pathway is disputed, may well be significant in helping to minimize the reduction in plant growth that would otherwise occur during a dry period.

A number of these experiments have demonstrated simple absorption without proving translocation from the leaves to other parts of the plant, although transport is often implied. For instance, Brierley (1934) did not observe any increase in soil moisture when wilted raspberry plants were exposed to a water spray, but he found that if one of a pair of joined raspberry canes was sprayed, the leaves of both canes became turgid again. This was taken , reasonably enough, to mean that the water applied to the wilted leaves on one cane must have moved down that cane and then up the other (Brierley, 1936).

AERIAL ABSORPTION IN DOUGLAS FIR.

Plants possessing a thick cuticle are likely to be the most resistant to water absorption through their aerial parts. (see p. 96) One species with a thick cuticle is Douglas Fir (*Pseudotsuga meniesii (Mirb.) Franco*.). If absorption could be demonstrated in this species, the results may well be applicable to other species with thinner cuticles. Accordingly, four Douglas Fir seedlings were collected from a forest edge, potted in natural forest soil, and kept under controlled conditions for eight weeks. Temperatures during this period ranged from extremes of 50° F to 80°F , but were mainly in the range 70°F - 80°F.

At first, the seedlings were kept well watered,

then, after about three weeks, the plants were visibly beginning to wilt. For 24 hours previous to the start of the experiment, all of the plants were kept continuously at 85° F (± 3°F) to encourage a diffusion deficit in the aerial parts of the plant. One plant died in this process and was discarded.

Two plants were selected for the first experiment. One was about 10½ inches high, and the other about 6 inches, and will be referred to as specimens A and B respectively. This height refers to the aerial part of the plant. (see Plate 5 , p.113) The soil around the roots of these two plants was not disturbed except for the taking of a sample to determine the moisture content.

The soil moisture content of specimen A was found to be high, despite the apparent dryness of the soil. Moisture content was 22.91 per cent. The soil of specimen B was much drier, being 9.09 per cent.

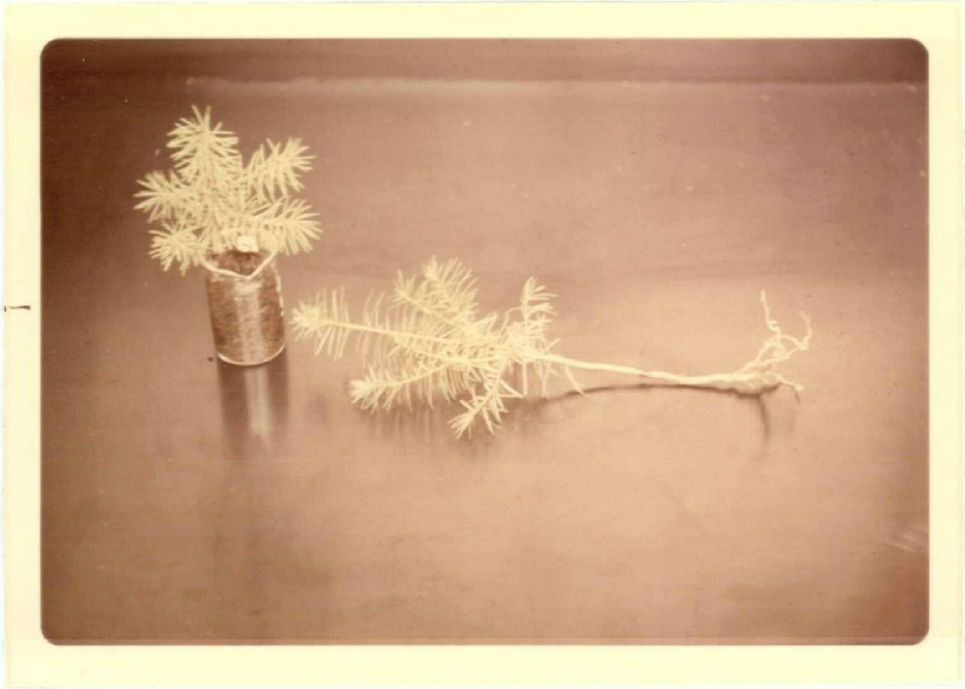
The plants were sealed into watertight containers with plastic cement, polythene, and fine wire. They were then exposed to the fine spray of the fog simulator, described in detail on p. 131. The temperature for the whole period of these experiments was 65° F. (± 1°F) inside the simulator, and the relative humidity was not allowed to fall below 98 per cent. After 24 hours, the specimens were removed, dried, and their weights checked. The smaller plant (B) showed an unexpectedly rapid weight increase, so the experiment was terminated on this plant. (It should be mentioned at this stage that a rigorous inspection was carried out for leaks; none were found.) The soil moisture content of B was again determined, and was found to be 16.93 per cent, an apparent increase of 7.84 per cent. The larger plant (A) had not at this point increased in weight, so it was replaced

into the fog spray for a further 72 hours, making a total exposure time of 96 hours. At the end of this time, the experiment was terminated, the plant and container inspected for leaks (none were found), and the soil moisture content determined. This was 20.8 per cent, a decrease of 2.1 per cent.

It appears from these two experiments that Douglas Fir is capable of absorbing water aerially and transferring it to the soil only if the moisture stress is high. The reasons for the loss of weight from specimen A are probably attributable to the lack of soil moisture stress at the start of the experiment.

A third plant, specimen C, shown in Plate 6, overleaf, was exposed with its roots in an Erlenmeyer flask without soil for 60 hours. The impracticability of weighing the plant by itself after exposure to the spray, due to the adherence of some of the plastic cement to the stem, meant that the entire flask and plant were weighed. However, no water deposit was visible inside the flask after exposure, so it may be assumed that any weight increase was due to water retained in the plant itself. This assumption was considered valid, since the weight of the flask and sealing material remained constant. Thus it was possible to calculate the net increase of weight in the plant. This yielded a weight increase of 40.1 per cent. It is likely (see p. 107) that the seedling acted as a wick, but the fact that the water was apparently able to pass through the thick cuticle possessed by Douglas Fir is of interest, and suggests that a thick cuticle, by itself, does not prevent aerial absorption of water.

(These experiments arose out of curiousity arising from the writing of the present chapter, and the results are included only from the point of view of



Plates 5 and 6. Douglas Fir seedlings used for aerial absorption experiments.

interest and relevance to the present theme; they are not intended to be definitive. It is fully appreciated that statistical significance requires experimental repetition.)

INTRA - PLANT WATER FLOW.

Some studies have specifically considered the movement of water in a negative direction within plant systems themselves. The term 'intra -' as used here refers to transfer of water within plant systems, as opposed to into plants from the atmosphere.

Bormann (1957) found that moisture was transferred between tomato plants whose roots were associated in sand or loam, or through the roots of an intervening plant which itself had access only to transferred water. This water moved in quantities sufficient to delay the onset of wilting in relatively large plants. Bormann suggested that transfer occurs only after a critical value of soil moisture tension is achieved. An interesting point is raised by Bormann's work. If water can be absorbed by the aerial parts of one species of plant, growing in association with another species not capable of absorption (perhaps in a semi - arid environment, or one with a dry season), it is speculatively possible for the non - absorbing species to survive by transfer of water across the root systems.

The pressures set up by root systems that would encourage the absorption and negative transport of water, have been considered by several authors. Hagan (1949) investigated this problem and found that there were rhythmic variations in the absorption of water into detopped root systems. He used the term "negative exudation" to describe the phenomenon of water absorption into the roots from the stem. Sunflower was

placed in soil which was reduced to the permanent wilting point. The plant was then detopped under water, and connected to a measurable water supply. Water intake by the cut stumps, or negative exudation, proceeded initially at a high rate, and approached zero after approximately one week. This negative exudation was found to be distinctly periodic. Since the experiments were carried out under controlled isothermal and isotropic conditions, the periodic fluctuations must be considered autonomic, but the reasons for the phenomenon are not clear.

Grossenbacher (1939), referring to positive exudation, suggested that autonomic cycles of root growth may be responsible for the cyclic regulation of the rate of water absorption from the soil. Skoog et al., (1938) considered that periodicity may result from changes in root permeability, but found that the maxima for cycles of positive and negative exudation were twelve hours out of phase. From this they concluded that diurnal cycles in root permeability could not be responsible for the observed cycles unless unidirectional permeability was involved. The maxima of negative exudation occur at night. This suggests that the likelihood of absorption of fog water or dew is enhanced at night, and this increased potential for absorption may coincide with transitory opening of stomata at night in a severely water stressed plant. (Sutcliffe, 1968; see p. 92).

CONCLUSION.

On balance, the evidence is that fog water deposited on aerial parts of plants, especially the leaves, can be utilized. Some sort of turgor loss, or water stress, appears to be necessary for absorption. Turgor

may be restored in plants not under soil moisture stress if they have been exposed to wind or other dessicating force for a period long enough to cause a minor deficit of water in the aerial portion of a plant.

Usually, however, a soil moisture deficit seems necessary to induce absorption, and certainly any negative transport of the absorbed water. It has been suggested that surface water may be harmful (Philip, 1932; Stockers, 1933), but in an actively growing healthy plant, especially in dry areas or in dry seasons, this is probably not as important as the beneficial effects. It is true that diseases of crops are sometimes correlated with the incidence of leaf surface water, but, again, this is more likely to be the case in consistently humid areas.

Beneficial effects are, of course, the restoration of turgor, survival, and possibly allowance of continued growth in dry periods. Also, there are two less frequently mentioned beneficial effects. The first has been briefly mentioned (p.90). This is that the water absorbed through the leaves may provide an important source of relatively salt - free water, which would be unobtainable from any other source. The second beneficial effect is the reduction of transpiration by water remaining on the leaf surface after sunrise (Jones, 1957). Since initial energy will have to be utilized to evaporate this, photosynthesis may be carried on with less water loss, and the water stress partly alleviated. Also, the evaporation of the surface water will perform one of the necessary normal functions of transpiration, that of cooling of the leaf.

It may be argued that in order to make a real contribution to the water economy of a plant, fog water deposited on leaf surfaces must permit greater growth

or production of biomass, than would otherwise be the case. Direct evidence for this is lacking, although the results of Dudevani (quoted by Gindel, 1966), showing increased growth and production with leaf surface dew almost certainly reflect some direct evidence of absorbed water.

The question will probably never be solved in the laboratory, as the environmental system can never be exactly replicated, and in the field the effects of many other factors have also to be considered. Nevertheless, there seems, with the ever more pressing requirement of increasingly efficient food production, a real need for much more experimental field evidence in coastal arid areas, with a view to the utilization of this undoubtedly significant potential water source, water deposited directly from fogs.

CHAPTER SIX

FOG DRIP AND FORESTS.

The contribution to the water economy of vegetation by interception of fog water droplets, drip to the soil, and subsequent normal root absorption, will now be considered, The contribution of drip from trees is considered since these present the largest potential intercepting surface to the fog, and thus the amount of water caught would be expected to be the largest of all types of vegetation, (see Ch. 7).

Probably due to the comparatively small amounts involved, fog drip from other types of vegetation have apparently never been considered. Due to the decreased frequency of water stressed conditions in humid environments, it is probable that fog drip from the leaves into the soil is greater than any direct absorption into the leaves, (see Ch. 5), although no direct evidence is available.

Significant wetting of surfaces below trees under foggy conditions has been noticed from the time of Gilbert White, in 1789, who wrote that "an amazing amount of water may be distilled by one tree in a night's time, by condensing the vapour which trickles down the twigs and boughs so as to make the ground below quite in a float," (White, 1789). A century later, the Australian naturalist Cox noted similar effects of trees in elevated locations in New South Wales, Australia, (Cox, 1888).

The additional precipitation of water to the ground by vegetal surfaces has been termed "occult precipitation" by Descombes (1922/23), and Aubreville (1949), although certain writers (such as Kerfoot, 1968)

have restricted the term just to dew or rime. Suring (1915) termed the phenomenon "horizontal precipitation", and Rubner (1932) called it simply "fog precipitation". The term now used most generally is that suggested by Kittredge (1948): "negative interception", since the water is precipitated in the same location(under vegetation) where "positive interception" would normally reduce the water contributed. Here, the term "negative interception" will be used for the catching of water from the fog, and "fog drip" for the dripping of the water to the soil after interception.

Techniques and results.

The most commonly used technique to measure fog drip is simply the placing of some form of rain gauge under the plant or tree and the comparison of the amount it collects with the amounts collected by similar gauges in the open.

Oberlander (1956) was impressed by the apparently large amount of negative interception of water from summer sea fogs by trees on the San Francisco Peninsula of California. In an attempt to measure this water source, Oberlander used five totalizer gauges (storage gauges) of five gallon capacity, and placed them under various tree types along a three mile stretch of the Cahill Ridge. The gauges were left in position for 39 days in the summer of 1951. The results are shown in tabular form overleaf (Table 21). Considerable variation was found in the amounts of water caught. These results suggest that fog precipitation is a variable phenomenon, increasing with the exposure of the tree, but still varying considerably as a result of the

Species	height	exposure	inches in gauge
Sequoia sempervirens	200'	in forest	1.8
Lithocarpus densiflorus	20'	direct	58.8
Pseudotsuga taxifolia	125'	partly prot. by mt.	7.2
Pseudotsuga taxifolia	125'	direct	8.9
Pseudotsuga taxifolia	125'	direct	17.1

Table 21. Fog drip measurements on the San Francisco Peninsula, five week period. (After Oberlander 1956.)

spatial non - contiguity of the fog. The small amount of fog precipitation recorded within the forest (Sequoia sempervirens) is a result directly contrary to the Japanese work on fog precipitation in the forest. (Hori, 1953; see p.126) The result from the gauge under the tan oak Lithocarpus densiflorus strongly suggests some sort of sampling error arising from the positioning of the gauge under the canopy; the 58.8 inch accumulation would represent a higher precipitation for a month than found in the open for the entire region. Oberlander unfortunately omitted to measure the rainfall in the open during the same period (although this was probably zero), and this itself detracts from the validity of his results.

The foggy San Francisco Bay area also stimulated the biogeographer James J. Parsons to experiment with the

fog drip phenomenon. (Parsons, 1960) He placed a standard 8 inch raingauge under and slightly to the lee of a 100 ft. high Monterey Pine, (Pinus radiata), a dense - foliaged, conical shaped tree, from which the lowest branches had been pruned. (This was presumably in an attempt to minimize any sampling errors such as may have been committed by Oberlander.(1956, op. cit.) During the whole summer of 1955, a total of 9.84 inches of fog drip was recorded, although no rain fell in the open. From "extrapolation of incomplete data," for 1954, 1957, and 1958, Parsons judged that the average annual fog drip in the summers of these four years was approximately 10.00 inches. Since this figure is the equivalent of nearly half the average annual precipitation for the Bay area, the importance of fog drip for tree growth in this area may well be considerable.

Another approach to the measurement of fog drip has been tried several times. This consists of building a watershed and collector around the base of a tree in order to collect all water dripping from it, and thus minimize sampling errors..

Costin and Wimbush (1961) used this procedure in conjunction with normal gauges in an investigation of rain and fog interception in the Australian Alps. Utilizing this technique, they produced evidence of increasing drip with elevation. (see p. 122) In Hawaii, Ekern (1964) used a galvanized roofing watershed 20 x 36 ft. under Araucaria excelsa Lamb. R. Br. at 2750' on Lanaihale, on Lanai, Hawaii. Collection of water by the shed was "in reasonable accord" with that by gauges under other trees. For summer periods in 1956 and 1957, the gauges measured 16.19 inches, the watershed recorded 15.52 inches, but the rainfall in

these same periods was only 1.16 inches. Average amounts of water collected in gauges beneath a tree were 391 inches per year, when 149 inches was recorded in the open. The area of the horizontal projection of the tree was almost identical with the 300 square feet area of the vertical projection of the tree crown. If it is assumed that the tree also collected all the water that would normally have collected in the rain shadow created in the lee of the tree, some 50 inches of the annual gain of 80 inches can be assigned as extra rainfall. A net increase of 30 inches is thus suggested as the average annual gain of water by negative interception on the tree. (Ekern, 1964; Carlson, 1961)

The effect of elevation above sea level.

Windspeeds tend to increase with elevation due to the lesser frictional drag. Several experimenters have confirmed that as a result, fog drip may also increase in amount. Siccama (1968) found that at higher elevations in the Green Mountains of Vermont, U.S.A., gauges under a forest canopy of Picea rubens, Abies balsamea and Betula cordifolia collected more water than at lower levels. Windspeed also increased with height, leading Siccama to attribute the water increase to increased volume of water being blown through the canopy and precipitated as fog drip.

The study by Costin and Wimbush (1961), mentioned previously, showed that, in the Australian Alps, water added by fog drip increased with elevation. In catchments between 4,000 and 5,000 feet in elevation, timbered areas were found to collect at least 1 - 2 inches of water in addition to the rainfall per year, and 2 - 5 inches above 5,000 feet.

Isaac (1946) used 27 rain gauges in the Cascade Head Experimental Forest of Oregon to catch fog drip, in coniferous forest. Gauges were placed in pairs, in the open and under the forest canopy. Comparisons of the different locations showed that the water reaching the ground under the trees increased with elevation, and also with decreasing distance from the sea. His data for annual precipitation, which, of course, includes rain as well as negative interception from fog, are shown in Table. 22 , below.

Distance from sea.	Height	
	Ridge top	Valley
5 miles	82.3"(in open) 73.8"(under tree)	77.6"(in open) 53.0"(under tree)
Less than 2 miles.	78.6"(in open) 99.1"(under tree)	65.9"(in open) 53.1"(under tree)

Table. 22 . Annual rainfall and negative interception at selected locations in the Cascade Head Experimental Forest, Oregon. (After Isaac, 1946.)

Parsons (1960), working in the Berkeley Hills of the San Francisco Bay area, reached the conclusion that fog drip was "peculiarly a hill crest phenomenon." He considered that the amount of the water contribution to the ground is a function of the size, shape, and nature of the trees as well as the wind velocity. From

experiments in the summer foggy season, he found that the fog drip under pine trees (Pinus radiata) was typically 0.02 to 0.05 inches when the air was calm. When there was a westerly wind of 10 - 15 mph, however, he found that the drip was much greater, with 0.20 to 0.30 inches often being recorded. He noted that the maximum amounts of drip were associated with the highest wind speeds. The trees on the Berkeley Hills of the San Francisco Bay area, where these measurements were taken, are all the result of afforestation within the present century. There was probably little condensation of fog water on the low perennial grasses that existed before the tree planting, but once trees have been artificially established, the fog drip they produce might well help to perpetuate them.

The apparent relationships between fog occurrence and wind speeds have already been noted, in a slightly different context. (Ch. 3, p. 37) It perhaps should be mentioned here that although fog water catch may be increased with windspeed, this assumes that the forest or other plant surfaces are dense enough and continuous enough to prevent the fog droplets diverting around the vegetal surfaces and not impacting on to them. (see Ch. 7)

Costin and Wimbush (1961) found that the strongest winds were not always the most effective in causing fog drip. They measured drip from the Snow Gum, and since this species has a fairly open foliage, Costin and Wimbush considered that a large proportion of the fog and cloud droplets were blown horizontally through, or around, the crowns. Experimental work on this factor will be referred to later. (Ch. 7.)

Effect of elevation of vegetation.

Wind speed is known also to increase with height above the ground surface, as distinct from height above sea level. This is to be expected, since friction with the land surface decreases with height. In addition, turbulence created by a rough or uneven ground surface may locally cause eddies of wind speeds equalling those at greater heights. However, if this is a factor, most experimental evidence appears not to have shown it, possibly due to the localized nature of such experiments.

Work in Hokkaido, Japan, by Kuroiwa and Kinosita (1953) has shown that the actual liquid water content of fog decreases near the ground, which they ascribed to turbulent impaction of fog droplets on to the ground (see Ch. 4.). Many experiments, for instance the one described on p. 81, have, however, found that the amounts of water precipitated from fog directly into normal raingauges placed on the ground are quite small, rarely exceeding 0.01 inch in 6 hours. Thus it seems that the volume of fog water precipitated in this way may be small. There are undoubtedly some unidentified factors at work here.

Within the forest Yosida (1953) carried out a theoretical study of the distribution of fog density. On the assumption that the vertical motion of a fog particle caused by turbulence of air in the forest is the same as a one dimensional "random walk", fog density was found to decrease exponentially downwards towards the ground. The basis of the "random walk" assumption is not stated, however, despite the fact that the entire validity of the result depends on its acceptance.

In a 'real world' forest, some of the unidentified factors affecting fog density with height have been

illustrated by the work of Ekern (1964), in Hawaii. Ekern used various types of fog collectors to measure negative interception within a stand of Araucaria excelsa Lamb. R.Br. at 2750 feet on Lanaihale Mountain. He found that there was an increase in negative interception with elevation greater than that accounted for by increase of wind with height. For a period of 35 days in June and July 1958, the catch at the 30 ft. level was 17.55 inches, as compared with 4.88 inches at the 6 ft. level.

These differences could reflect differences in collection efficiencies of gauges at various heights, but Ekern gives no indication of this possibility. Rainfall during the same period was 1.88 inches. Windspeed at a height of 30 ft. was approximately double that at 6 ft. This experiment suggests that cloud was still impacted on tree tops even when water failed to reach the ground surface. Turbulent impaction on to the ground surface was apparently absent.

Depth of penetration of fog into a forest.

It has been observed that the fog drip from both forests (Oura, 1953) and isolated trees (Kittredge, 1948; Ekern, 1964) is greater on the windward side than on the leeward. It has been claimed that fog drip is essentially an edge effect, and does not penetrate into most forests (Kittredge, 1948).

Geiger (1950) called fog drip "a true transition phenomenon which occurs only on the borders of a stand;" he later conceded that the effect was not only confined to the forest edge (Geiger, 1965), on the basis of Japanese work (Hori, 1953.).

There seems little doubt that fog drip is most important on forest edges, but capture of fog particles

does occur in the interior of forests. Linke (1921), working in the Taunus Mountains of Germany, where there are about 200 foggy days per year, found an average increase in gauge catch near the forest edge of 157 per cent of that of gauges in the open; this was still at 123 per cent in the forest interior, however. Maximum increases, (which may be subject to sampling errors,) were 300 and 260 per cent, respectively.

The Japanese work referred to earlier (p.120), particularly the work of Oura (1953), showed that whilst the front surface of a forest of Picea glehni was about three times as effective in inducing fog drip than the top surface, the tree crowns created enough downward turbulent motion to allow penetration of fog into the interior of the forest. In the forest interior, 0.5 mm of fog drip per hour was measured, when the windspeed was 4 m. sec^{-1}., and the water content of the fog 800 $mg.m^{-3}$. This was between six and ten times as much as that deposited on to grass surfaces under the same conditions.

Further Japanese work (Huzioka et al., 1953) showed that the mean fog water content in the forest crowns could be as much as 80 per cent of that above the forest, which was itself equal to the fog water content outside the forest. Turbulence at the crown - atmosphere interface was considered responsible for this result. Both of these Japanese results indicate that, at least in some situations, although fog precipitation is greater at the forest edge than in the forest interior, in the latter it is still by no means insignificant.

It is clear that in assessing the effects on the water balance of afforestation, at least some account should be taken of the role of negative interception and

fog drip. There is a need too, for further research on the importance of fog drip on vegetation other than trees, whose vegetal surfaces presented to the fog are comparatively small. In the next chapter, some efforts at micro - experimentation will be made.

CHAPTER SEVEN

FORM, WATER CATCH, AND FOG DRIP.

Scales of consideration.

The morphology of vegetation is important at three scales in influencing the amount of water which may be caught and directed to the ground.

The first of these scales is that of the community: the nature of the edge and top of the group of plants, such as a forest stand, and the density of the penetrative barrier exposed to the fog laden air. Thus for trees at a forest edge, for instance, there may be an optimum spacing depending on the maturity and type of tree.

At this scale, the reflectivity of the vegetation may have some influence; forests usually have a lower albedo than short vegetation and may create convective updrafts which prevent fog from penetrating into the canopy. At the same time enough heat will normally be retained within the stand to prevent cooling of the air below its dewpoint, with the formation of radiation fog. The roughness of the crowns of trees in a forest allows enough turbulence to be set up to allow penetration and impaction of fog droplets on the tree foliage even within the forest (see p. 127).

The second scale of investigation of the fog drip problem as related to vegetal morphology is that of the individual plant. Important here, of course, is the actual area of a plant presented to the fog, since this is by far the most significant influence on the water extraction amount (see p. 141). The surface at 90°

to the wind direction may be expected to show a relationship to the quantity of water extracted. This may be measured by the area of the horizontal projection. The fact that deciduous trees shed their leaves in winter means that for a large portion of the year a less effective collecting area of foliage is presented to any fog. On these grounds alone conifers may be considered to be more efficient in delivering extra water to the ground, at least on an annual basis. Another factor which has to be considered is the rigidity of the species involved , since decrease in rigidity will be expected to increase shaking with a given wind speed or gusting factor, and may increase drip to the ground.

Also worth consideration is what is here termed the "multiple interception ". Water caught by the tree crowns, which are in the position to catch most water from the fog, since the liquid water content of fog increases with height, (see p. 125) has a greater probability of reaching the ground without being re - intercepted and evaporated, the fewer the intervening branches between crowns and ground. This potential "multiple interception" surface could be measured by vertical projection of the branches and leaves to the ground from a specified height. The importance of this factor has been shown experimentally by Oura,(1953) (see below).

At the third scale of investigation, the effect of leaf shape, orientation, and surface characteristics, must be considered. At this scale the factors encouraging drip are those not favouring retention for possible absorption. The effect of hairs on leaves in retaining water droplets, and the effect of the nature of the cuticle, have already been discussed (Ch. 5). Needlelike leaves may be an adaptation to "condense water from fog" in some arid and semi - arid areas (Went, 1955).

Adaptation or not, needlelike leaves have been observed to be associated with greater drip than broad leaved species (Went, 1955; Carlson, 1961.).

Oura (1953) found that the most effective type of forest for "capturing" fog particles was one grown comparatively sparsely (spacing factor, scale one), with needlelike leaves (leaf shape factor, scale three), and with no lower branches ("multiple interception" factor, scale two).

THE FOG SIMULATOR.

It is difficult to study all scales of the factors contributing to fog drip from vegetation simultaneously. Accordingly, one of the little studied factors was selected for more intensive study. This was leaf shape. In an attempt to discover what leaf shape was the most efficient in catching water and directing it to the ground, a "fog simulator" was built in which leaves of controlled area and shape could be exposed (see Plate 7, overleaf). The construction and operation of this apparatus will now be considered.

Intended to be a prototype, the apparatus was constructed to produce a horizontal flow of tiny droplets of water, of a diameter (20 - 30 μ) comparable to those of natural fogs (see Ch. 2). Some diversion will be made to consider the techniques of producing fog - like diameter water droplets. Commercial fogging nozzles are available, and have been used by Stone (1957) and Breazeale et al. (1950, 1951), in their experiments on absorption (see Ch. 5). In these studies the diameter of the water droplets was unimportant, so that no reference to droplet size was made. Janes (1954) used a spray nozzle fixed so that it was slightly submerged under water. This

Plate 7. The fog simulator.

was tried in the present study, but did not produce a satisfactory result for the present purpose. The main problem was to produce a spray from which droplets with a diameter greater than 50 μ had been eliminated. This was eventually achieved, after some experimentation. Firstly, the hole in the spray nozzle, fitted on to the normal piped water supply, was made extremely small, and thus had to be checked frequently to ensure that it had not been enlarged by the water forcing through it. Although the hole in the nozzle was made in aluminum sheet, no problem of hole enlargement was encountered. Secondly, any large droplets were dealt with by making the distance from where the spray was produced to where the leaves were exposed (see Plates 8 and 9, p. 135) long enough (5' 6" approx.) to ensure that all the larger droplets initially produced fell out under the influence of gravity.

A fan was placed behind the spray nozzle to blow the water droplets forward. A resistance was placed in the electricity supply to slow it down to the point where the droplets larger than about 50 μ diameter could not be carried by the air current produced (see Fig. 12, p. 80). "Wind" speed was approximately 0.5 m. sec^{-1}. (1 mph) at the leaf. The size of the droplets passing or impacting on to the exposed leaves was checked by sampling with microscope slides coated with a Vaseline and oil mixture, and viewed with a calibrated eyepiece; samples taken from several natural fogs were compared with the droplets produced by the fog simulator. This sampling technique was that followed and recommended by Fuchs and Petrjanoff (1937); any sampling bias is towards the larger droplets. The droplets striking the position in which the leaves were exposed were in no case observed to be greater than 50 μ in diameter and appeared, after

experimentation, to have the correct modal frequency of about 25 - 30 μ.

Thus it is considered that the spray actually reaching the 'leaf' surfaces may be equated with natural fog droplets, since natural fogs have an approximately similar droplet size distribution (see Ch. 2).

A return air duct was included in the apparatus, so that the air, at or almost at, 100 per cent relative humidity, was recycled under the influence of the fan. This was necessary to maintain the relative humidity near 100 per cent, since the relative humidity in the laboratory where the apparatus was situated was normally between 40 and 50 per cent. Relative humidity could not be prevented from fluctuating slightly, but was always in excess of 95 per cent; thus evaporation from the "leaf" surfaces was assumed to be zero. Since the temperature varied only between 61° F and 71°F, changes in viscosity could be considered insignificant in the present study.

Flow from the spray nozzle varied from 38.0 ml. $min.^{-1}$ to 42.5 ml. $min.^{-1}$, unavoidable due to variations in tap water supply. It is stressed that little of this amount actually flowed past the leaf exposure position, but flowed back to an outlet under the fan; the floor of the apparatus was sloped for this purpose.

Experiments.

Despite the crudity of the apparatus, it is considered that the following results do have at least some general validity. Aluminum shapes, representing leaves (but all having the same surface characteristics so far as the retention of water was concerned) were exposed, all for three hours each, in the fog simulator over one of the three collection beakers inset into the floor. (see plates 8

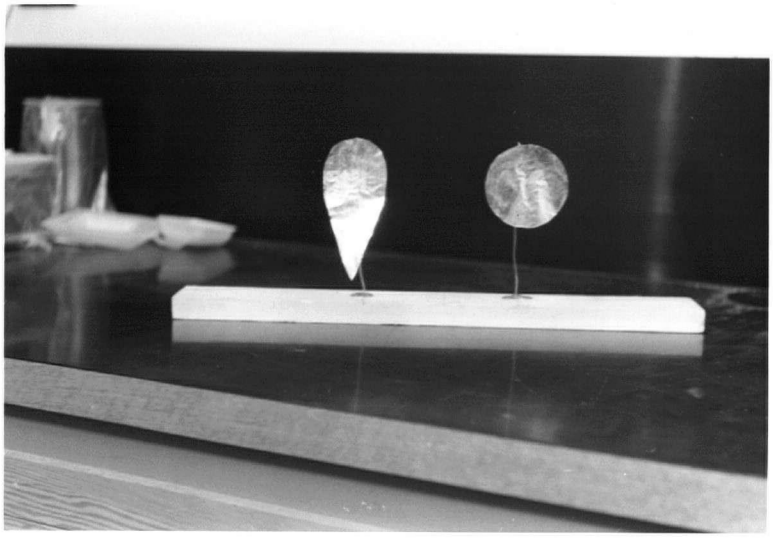


Plate 8. Two artificial leaves ready to be exposed.

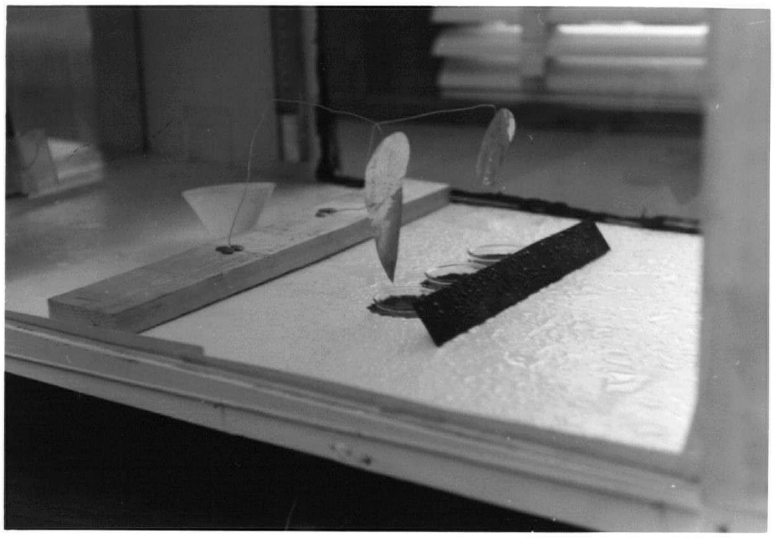


Plate 9. Technique of artificial leaf exposure.

and 9, p. 135). The shapes were suspended on thin wire so as not to present any obstruction to air and droplet flow other than that of the shape itself. The baffle placed in front of the collection beakers was to ensure that the water droplets did not flow directly into them (see Plate 9, p. 135). Any "lee wave" capturing effect would be equal for all beakers. Droplet flow over the leaves was observed in front of a black surface, and found to be giving a fairly even impaction of droplets areally over them.

The shapes of the aluminum leaves exposed are shown in Fig. 17, (p. 137). Circles were also made with identical areas to the shapes, with the idea of providing a form of "control shape". The results of the exposure of the circles will be considered first. The water intercepted in three hours is plotted against circle areas on a graph in Fig. 18, p. 138, together with a least squares regression line. From this graph it is apparent that the water intercepted increases in amount as the area of the catching surface also increases. The relative variability of each set of experiments with an individual experiment seems to increase with area up to the largest area considered, 38.2 sq. cms. (Larger sizes were not exposed since evenness of exposure to the fog spray could not be assured). In fact, the variability of the amounts caught by the circle of 38.2 sq. cms. (6.39 - 7.70 grams) may be due to increasing spatial differences in the flow of water droplets within the simulator. The correlation of water intercepted with the circle areas was $r = + 0.9306$ (significant at the 0.1 per cent level).

If the amount of water intercepted is calculated on a "per square centimetre" basis, less order is evident (see Table 23, p.139). The correlation of area with the amount of water intercepted per square centimetre was

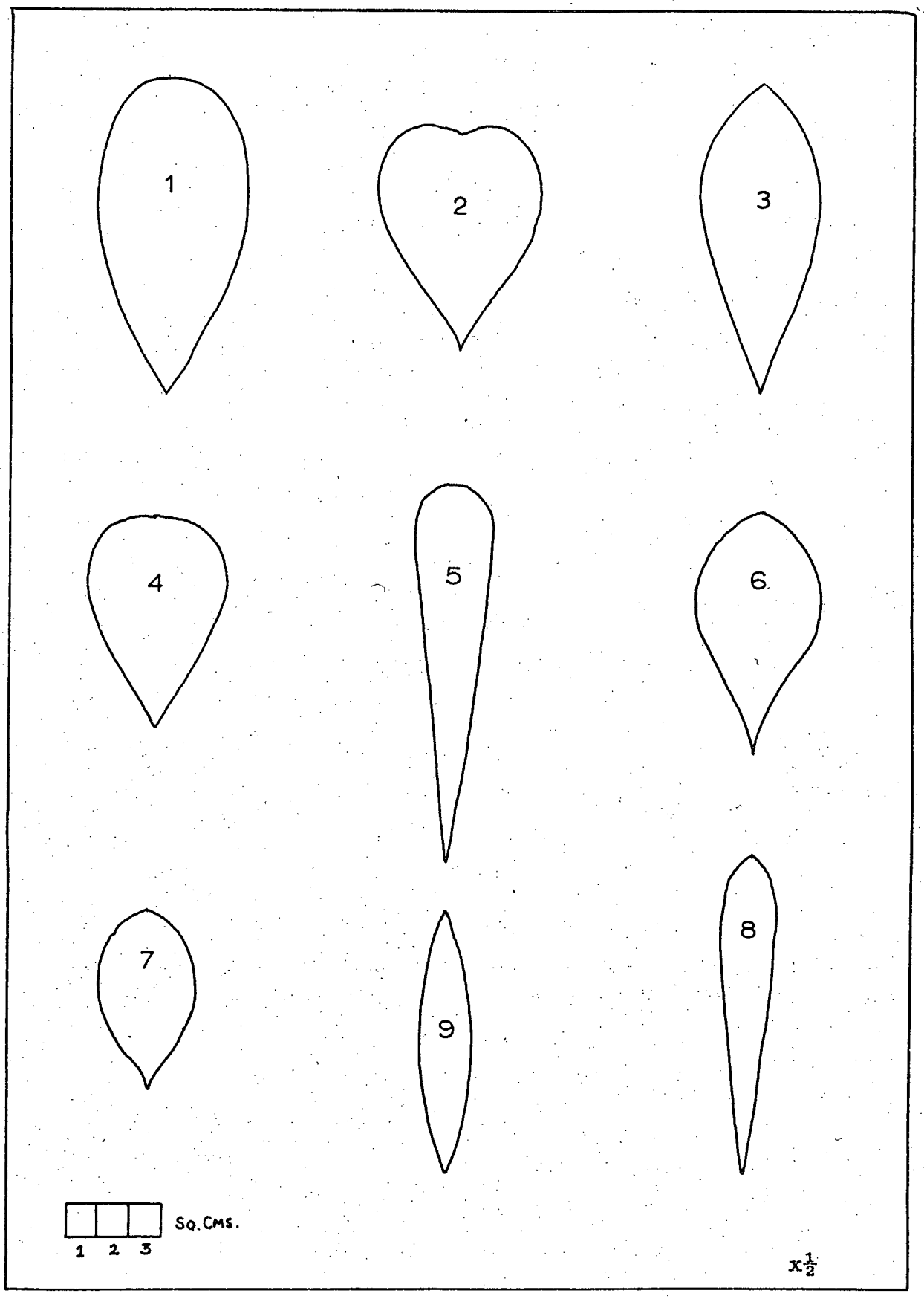


Fig. 17. Shapes of aluminum 'leaves' used in experiments. (see text for explanation.)

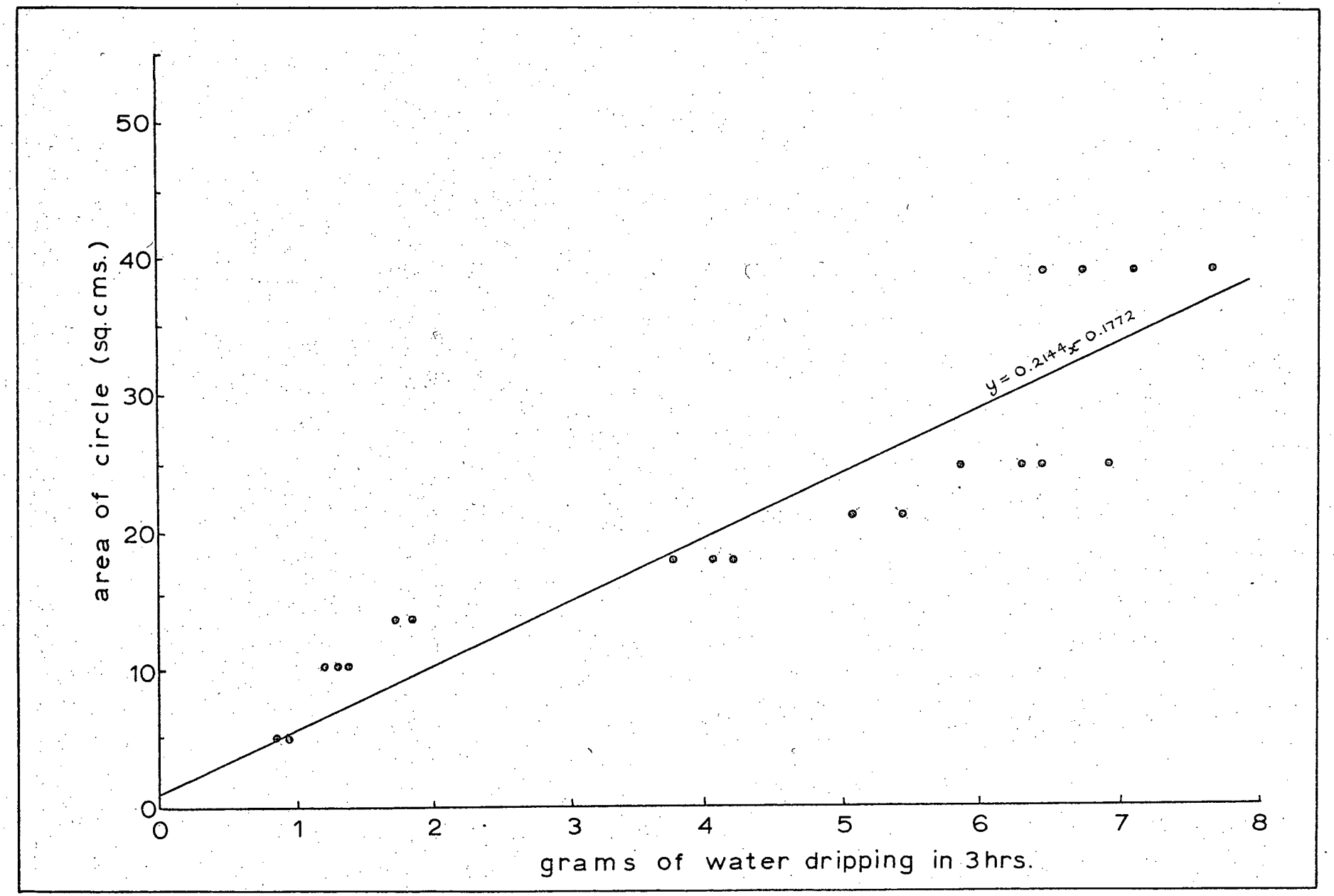


Fig. 18 . Area and drip from aluminum circles. (see text for explanation.)

r = + 0.3994 (not significant at the 0.5 per cent level). It may thus tentatively be stated that the maximal efficiency is reached within the range 15 to 25 sq. cms.; it may with more confidence be stated that as area increases, so does the total amount of water intercepted.

Area of circle (sq. cms)	38.2	24.5	21.0	17.9	13.2	10.0	5.0
Water extracted per sq. cm.	0.18	0.26	0.25	0.23	0.14	0.13	0.18

Table 23. Mean amounts of water (grams) extracted by circles.

The set of nine different shapes was also exposed in the fog simulator for three hour periods. The mean amount of drip in that time (means are derived from 3 to 4 experiments per shape) is shown in Fig. 19, p. 140. It is immediately evident that the shapes have in all cases extracted more than the circles of corresponding area. Correlation of area with amount caught was r = 0.9181 (significant at the 0.01 per cent level).

In terms of the amount of water intercepted per square centimetre, the shapes 5 and 6 (see Table 24, p. 141, and Fig. 17, p. 137) were the most efficient, extracting 0.371 and 0.364 grams per square centimetre, respectively. This may be due to the "drip tip" possessed by these leaves, facilitating the runoff of the water once intercepted from the fog. Mean amounts of water extracted per square centimetre (means of a minimum of 3 experiments per leaf) are shown in Table. 24, p. 141.

The main conclusions that may be drawn from these experiments are that, at the windspeed considered,

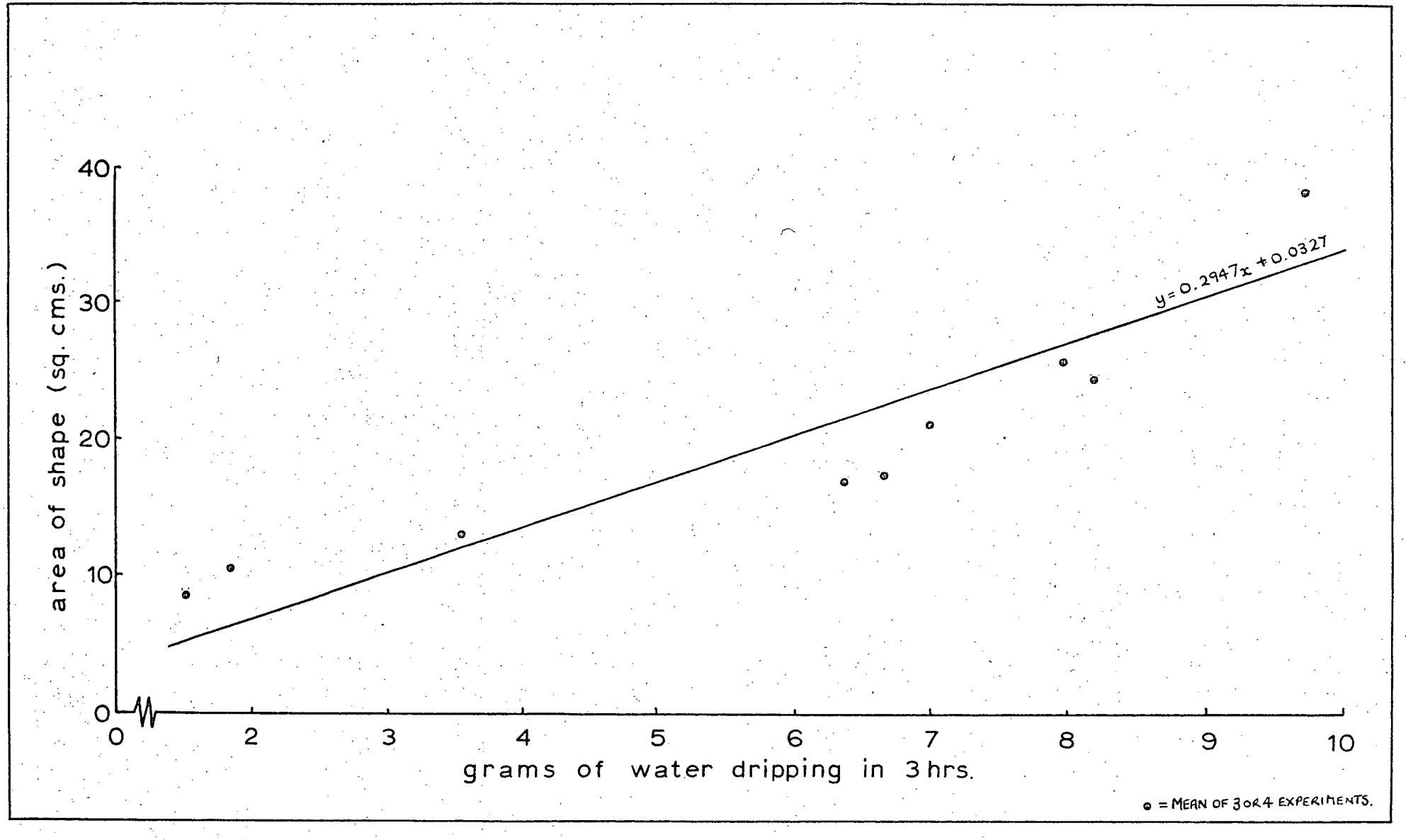


Fig. 19 . Area and drip from aluminum leaf shapes. (see text for explanation.)

(0.5 m. sec^{-1}.) :

1. Area has an overriding influence on the total amount of water caught.
2. There is a decline in the per area extraction amounts, with single leaves, above about 25 sq. cms.
3. With single leaves, the most efficient shape and size combination is a fairly elongated type of leaf, or one with a drip tip, of about 20 to 24 sq. cms. in area.

Shape number	1	2	3	4	5	6	7	8	9
Amount caught	0.25	0.31	0.33	0.33	0.37	0.36	0.27	0.17	0.17

Table 24. Mean amounts of water (grams) extracted by shapes.

These experiments show some interesting, but as yet inexplicable trends, which require further investigation. However, the comparatively crude nature of the fog simulator described here, which was in any case only intended to be a prototype, suggests that a more sophisticated simulator will be required, so that more control may be exercised over the conditions in which the leaf may be exposed. It is not known whether the comparatively small size of this simulator influenced the results; although this seems unlikely, any repetition of this simulator should be large, to eliminate any possible edge effects. Exposure to a range of wind speeds may throw more light on the problem. The use of differential windspeeds would require a source of correct size water droplets not dependent on the wind speed; here the wind speed had to be kept constant to ensure that only the

correct size droplets reached the leaf surfaces. However, although a large simulator would undoubtedly be expensive, it may prove worthwhile in pointing to the best types of plant morphologies able to exploit foggy but otherwise arid zones, such as the coastal fog deserts of South America.

INTERCEPTION FROM NATURAL FOGS.

It is not difficult to demonstrate that water is caught by real vegetation from fog, but there seems to be little relationship of amount of water caught to weight of plant, the most easily measurable parameters.

On the night of 31. 12. 69. - 1. 1. 70., a thick advection fog covered the southern half of Sea Island, and much of Lulu Island and the mouth of the main arm of the Fraser River, in Richmond, B.C., extending for an unknown distance out into the Georgia Strait. Vancouver International Airport, on the edge of this lobe of fog, recorded fog conditions from 2000 PST on 31. 12. 69. to 1100 PST on 1. 1. 70., with visibility still at $\frac{1}{4}$ mile as late as 0800 PST on 1. 1. 70.

Samples of Western Red Cedar (Thuja plicata Donn.), chosen simply because of availability, were cut and immediately sealed with Vaseline to prevent any moisture escape from the cut stems. These specimens were then taken to a point near the probable surface centre of the fog, at Steveston Highway Interchange with the Deas Island Freeway (B.C. 499), approximately $\frac{3}{4}$ mile north of the north bank of the main channel of the Fraser River. The specimens were exposed in various positions (see Table 25, overleaf) for one hour, and then sealed into small metal cannisters for weighing, about $\frac{1}{2}$ hour later. This technique is an adaptation of the one used by Costin and Wimbush (1961) to discover amounts of rime accumulating on trees. They cut small branches and sealed them into plastic bags, which were later weighed.

All the specimens used here appeared to have increased in weight slightly after exposure. This is considered significant in view of the short exposure time (see Table 25, overleaf).

Mode of exposure	height of exposure	plant weight before (grams)	plant weight after (grams)	percentage increase
1 Tied to top of pole	6'	3.93	4.16	5.852
2 Tied on to bush	4'	4.52	4.62	2.655
3 Tied on to sign	2'	2.07	2.14	3.381
4 Tied on to bush	5'	3.33	3.43	3.000

Estimated windspeed at site 1.5 mph. Mean temp. 32°F.
Relative humidity: more than 95 per cent.

Table 25. Relationships of fog water catch in one hour to weight in samples of Thuja plicata Donn.

In an attempt to ensure that this increase was not due to water from dew, a metal plate was exposed on the ground surface, and inspected after one hour. Any dew deposition would be expected to cover the plate uniformly; however, there were only several scattered tiny droplets on the plate; these were almost certainly, for the reasons just stated, fog droplets.

At Vancouver International Airport on the night of this experiment, the conditions were similar to those at the Steveston Highway Interchange; visibility ranged from 1/8 to 1½ miles, the temperature was also 32°F, and the relative humidity 100 per cent. There was a 2 mph wind. The fog extraction device installed at the airport (see p. 75) caught water from the fog, but this was not recorded until the next morning, when the temperature rose above freezing, and 0.03 inches was recorded (see Ch. 4).

The comparatively large amounts of water that may

be intercepted from fog but then held by the vegetation was shown by an experiment carried out in fog at the University of British Columbia, in January, 1970. Small branches of several species were carefully cut and sealed into plastic bags. (This was the technique, previously mentioned, used by Costin and Wimbush (1961) to measure rime accumulation). These were then weighed, the vegetal surfaces completely dried, and re - weighed, subtracting the weight of the bag. The difference was the net water catch, which may be expressed as a percentage of the surface dried sample weight. The results are shown in Table 26, below.

		1	2	3
Species	Height at which cut	surface dried specimen wt. (grams)	Net water catch (grams)	$\frac{2}{1}$ as per cent
Sequoidendron gianteum	5'	36.16	22.00	60.84
Cunninghamia lanceolata	5'	12.23	21.76	77.92
Pinus silvestris var. pumila	5'	20.33	15.33	75.40
Pinus rigida	5'	18.11	9.47	52.29
Pseudotsuga menzeii	6'	21.64	10.73	49.58
Ilex opaca	5'	5.54	9.27	167.32

Table 26. Amounts of water caught from a natural fog, U.B.C., January, 1970.

The length of time of exposure to the fog in this experiment is not known, so that only limited conclusions may be drawn from these results. It is clear, however,

that considerable amounts of water may be held by tree foliage. Ilex opaca is the only broadleaf here (all other species are conifers), and it seems likely that this species normally holds the maximum amount of water for an equal weight of foliage. The leaf surface of this species is not covered by any water retaining media, such as tiny hairs, but is shiny, with a thick cuticle. The fact that such a large percentage of water is held is indicative of the comparatively large area exposed to the fog, catching the most water (see p. 141), but also of the efficiency of retention, which is especially the case if the leaf is not held vertically.

It is apparent that the difficulties of measuring fog water additions to varied vegetal surfaces are great, and this study concurs with Yosida and Kuroiwa (1953), when they state:

" the direct measurement of the quantity of fog water captured (by the forest) is hpoelessly difficult, though it is extremely desirable to know it as accurately as possible." (Yosida and Kuroiwa, 1953, p. 261).

PRELIMINARY MODELS OF FOG DRIP.

The factors at all scales influencing the amounts of fog drip from any vegetation are complex, often interrelated, and very difficult to measure. As a result, unless the problem is considerably simplified, it is extremely difficult to construct a model of fog drip. At this stage, however, a general statement may be made, recognizing the complexity of the influencing factors, at the scale of the individual.

Amount of drip at this scale is at first a function of water intercepted, minus the amount of water retained, re - evaporated, or absorbed. Thus it may be stated:

$$D = f(A_1, A_t, s_1, c, v, d_m,; w_g, r, i_m, e, /t)$$

where:

the first 6 expressions are interception factors:

A_1 = Area of leaf surfaces exposed to the fog at 90° to the wind direction.

A_t = Area of stems, trunks.

s_1 = A shape index, increasing with elongation, and presence of drip tips.

c = A 'combing' factor, dependent on the spacings of leaves.

v = Wind velocity.

d_m = modal droplet diameter of the fog.

the second 4 expressions are essentially drip factors:

w_g = a measure of wind gusting, and thus shaking, to dislodge droplets.

r = a retention factor, dependent on leaf surface characteristics.

i_m = multiple interception. (see p. 130)

e = evaporation (normally $\simeq 0$ in fog).

t = time.

Attempts to construct quantitative models of fog drip must take into account as many of these factors as is feasible, commensurate with the accuracy required. Only one known attempt has ever been made to actually provide an equation to calculate fog drip amounts. This was carried out by Yosida and Kuroiwa (1953), as part of the Japanese studies on "fog - preventing forest" (see Hori, Ed., 1953). The equation constructed by theoretical physical techniques by Yosida and Kuroiwa assumes that a conifer tree (the only type considered) is made up of a number of short cylinders. The most difficult problem was the measurement of the effective front area of the tree. If it is assumed that an anemometer placed in front of the tree measures the wind velocity, (technically a vector quantity), then, if air density is included, the components of an equation given by Yosida and Kuroiwa for wind force on a conifer tree are obtained:

$$f = \frac{1}{2} (p \cdot A_t \cdot C \cdot v^2)$$

where:

A_t = the effective front area of the tree (m^2)

v = wind velocity

p = air density

C = a drag coefficient, which will vary slightly with the tree size, but for pine needles closely approximates the form

$$C = 0.0920 + 0.2330v \quad ,$$

a calculated least squares regression equation from a graph given by Yosida and Kuroiwa (p. 268).

The same authors have derived the equation for the amount of fog drip from a conifer, as follows:

$$q = 0.35 \cdot \sqrt{0.22} \cdot 2^{\frac{3}{4}} \cdot \sqrt{\frac{\sigma}{\eta}} \cdot (pC)^{-\frac{3}{4}} \cdot \frac{a}{\sqrt{r}} \cdot \varphi \cdot A_t^{\frac{1}{4}} \cdot f^{\frac{3}{4}}$$

which simplifies to

$$q = 3.12 \cdot 10^3 \cdot \frac{a}{\sqrt{r}} \cdot \varphi \cdot A_t^{\frac{1}{4}} \cdot f^{\frac{3}{4}} \quad \text{grams sec}^{-1}.$$

where:

p = density of air
σ = density of water
η = viscosity of air
r = radius of leaf
φ = fog water content per unit volume of air
C = drag coefficient of circular cylinder of radius r
A_t = total effective front area of all the leaves
a = mean radius of fog droplets
v = wind velocity

This appears to agree quite well with empirical results derived from a cut specimen of Picea glehni.

It can be seen from this equation that as area presented to the fog increases, so does interception; as the fog droplet diameter increases, so does interception (due to increased momentum); and as leaf radius (n.b. assumed to be cylindrical) increases, the amount intercepted decreases, ceteris paribus, since there is a greater tendency to flow round the leaf than to impact on to it.

It is clear that the factors influencing fog impaction and drip from plants need to be measured very accurately, and until this is done it will not be possible to derive accurate estimates of total water contribution. Further research may be upon these lines. However, it

must suffice here to diagrammatically summarize the ways in which fog water may come to be utilized by plants. (Fig. 20, p. 151) Laboratory and field research is needed on nearly all the potential pathways of water use.

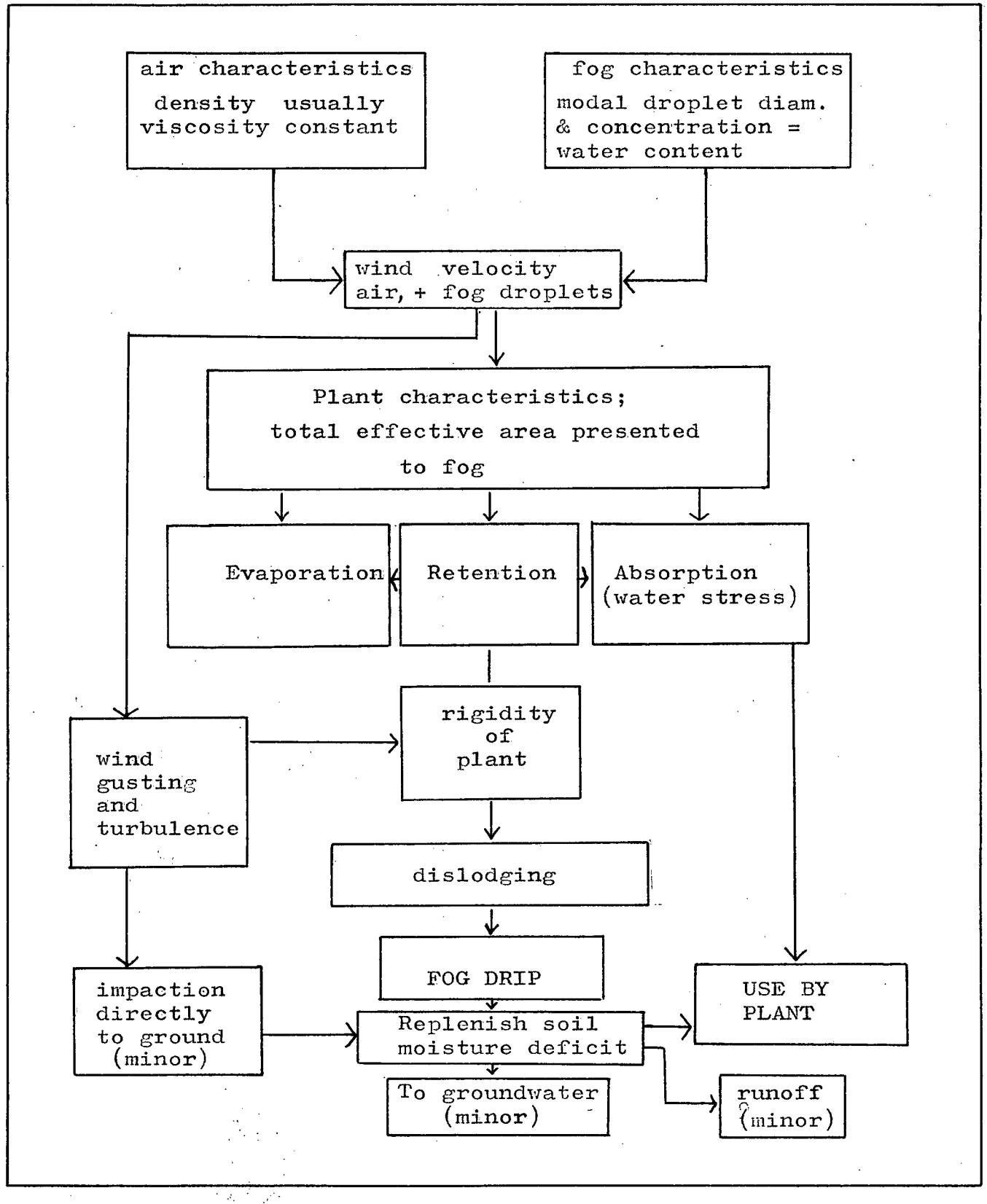


Fig. 20. Pathways of fog water use by plants.

CHAPTER EIGHT

CONCLUSION.

Fog is one of the most variable of meteorological phenomena, whether considered spatially or temporally. Since fog is more static and less damaging than some other meteorological events, such as hurricanes, it has not attracted, at least until fairly recently, as much research as might be expected; that research that has been carried out has tended to concentrate on techniques of dissipating fog, rather than utilizing it more efficiently.

Fog in a city rush hour is a different thing from fog in the desert, and it is clear that fog may only be considered a hazard relative to when and where it occurs, and whom it affects. Control in the city may mean dissipation, but control in the desert may mean the funnelling of fog to areas where it can be of use. Even in temperate climates the use of vegetation to control fog has been extended to influencing air drainage, and thereby controlling the drift of shallow radiation fogs, as in central Pennsylvania (Myers, 1967) The lessons learnt can be applied in arid areas.

Craig (1968) observed that the "garua" (advection fog) of the Peruvian coast wets the surface to the extent of creating runoff, whilst raingauges record no precipitation at all. Heavy nylon and wire nets are used in some areas to precipitate water from fogs, as they are on parts of the Chilean coast. There seems little doubt, however, that the full potentials of water availability from fog are not at present utilized, and there is scope for considerably more work on the types of vegetation most able to use it. Economic and cultural implications

also need to be considered.

The relationship between the physical requirements for the formation of fog and its actual geographical occurrence has been shown to be complex.; it is difficult to make generalizations as to its spatial occurrence. It has been shown, however, that at present, for the purposes of assessing the possible additions of water from fog, many errors can be made by taking the spatial distribution of "fog - days" as equal to the distribution of equal fog durations.

The difficulties of measuring additions of water by "occult precipitation" has been referred to several times, both in the construction of specialized instrumentation, and in calculating or measuring catch or drip from actual vegetation. The unfortunately inconclusive results from the attempts at laboratory simulation of fog emphasize this difficulty.

Despite the many experiments which have shown that water can be absorbed through the aerial parts of plants, and the coincidence of some large areas of the world where moisture stressed conditions and fog often occur together, this use of fog water is often disregarded as insignificant.

It has been shown that fog is an under - estimated factor in the evaluation of the water economy of many parts of the world. This is particularly the case in fog - prevalent forested upland areas and in foggy coastal deserts.

In the present undernourished state of much of the world, it is clear that any possible opportunity to increase food production, through opening up of water sources not at present utilized, must be seized. It is contended that in certain parts of the world fog can provide this water source. Research on the ways

in which this latent source can be tapped should be given high priority.

Appendix I. Significance Test.

The significance of the differences of the means of measured parameters as between foggy and non - foggy days in all cases in this thesis were assessed using the following test statistic. This has been modified to allow for the fact that the means of the foggy day parameters are from the entire population and those in the non - foggy days are samples.
The test statistic used was

$$Z = \frac{\overline{x_1} - \overline{x_2}}{\left(\frac{\sigma}{n - 1}\right)\left(\frac{N-n}{n-1}\right)}$$

where:

$\overline{x_1}$ = mean of sample (non - fog)
$\overline{x_2}$ = mean of population (fog)
σ = standard deviation of sample
n = Number of sample per month
N = Population of sample

The significance level of the calculated Z value may be derived from the standardized normal distribution tables.

Appendix II. Non - parametric test for trend.

The non - parametric test for trend used on p. 60 and p. 62 was derived in the following way (Mann, 1945; Tintner, 1952; K. Denike, 1970, personal communication): The probabilities for the 12 years considered were ranked p_1 , p_2 , ... p_n , where $n \leqslant 12$ if there are years with equal ranking, and 12 if not. The number of ranks of elements larger than p_1 ... p_n , in turn, were then summed over the entire range of n, to give the sum of the positive scores, P. Thus

$$P = \sum_{j=1}^{12} n_j$$

Then the total score, S, was derived from

$$S = \frac{2P - N(N-1)}{2}$$

where:

P is the sum of the positive scores, and
N is the number of observation (years).

The calculation of the rank correlation coefficient follows:

$$\tau = \frac{2S}{N(N-1)}$$

The probability of a trend NOT existing may then be derived from tables given by Kendall (1955, p. 171) if N is between 4 and 10.

But in the problem on p. 60 and p. 62, N = 12;

for larger N, it is known (Kendall, 1955) that the distribution of S converges rapidly to normality. Thus for N larger than 10 the quantity S is distributed approximately normally with zero mean and variance:

$$\frac{N(N-1)(2N + 5)}{18}$$

But the total score S is discontinuous. Thus a correction for continuity may be made (Tintner, 1952) by subtracting 1 for positive S and adding 1 for negative S. This then allows use of the continuous normal distribution tables for the derivation of the probability of NO trend existing.

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