AIR TEMPERATURE, WIND, PRECIPITATION AND ATMOSPHERIC HUMIDITY IN THE McMURDO REGION, ANTARCTICA.

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ABSTRACT

The mean annual air temperature near sea level in the McMurdo region is close to $-20^{\circ}C$. This temperature decreases inland. The annual mean amplitude of air temperature is $20^{\circ}C$ at Vanda Station and $13^{\circ}C$ at Scott Base. Stations in the area have recorded air temperatures as warm as $+15^{\circ}C$ and as cold as $-57^{\circ}C$. The yearly warm peak tends to occur early in January at Vanda Station. The cold peak may occur in any month from June through September but has occurred in July in each of the three winters that measurements have been made. Mean daily air temperatures in winter at Vanda Station do not closely correlate with those at Scott Base. The topographic lapse rate in the region is $4.0 \pm 0.5^{\circ}C$ per 1000m. This is at least two orders of magnitude larger than horizontal temperature gradients.

The wind regime in McMurdo oasis is dominated by easterly and westerly winds. The former are more common near the coast whereas the latter predominate in the west. Winds from the southwesterly quarter predominate along the fringe of the continental ice sheet. At Scott Base and for most of Ross Island, winds from the easterly quarter are more common but winds from the southerly quarter are stronger. The predominant winds in the summit area of Mt Erebus are west-southwesterlies.

Precipitation is low in the region and most occurs as snowfall or wind blown snow. Sea spray is not uncommon around the coast when open sea water is present. Mean annual precipitation is probably less than 10mm water equivalent at Vanda but is higher near the coast and at higher elevations. Rain is not unknown but is uncommon.

Atmospheric relative humidities are variable, varying from less than 10 percent to greater than 100 percent (with respect to ice). On the average, relative humidities are less in McMurdo oasis than in McMurdo Sound. Topographic gradients of relative humidity are variable; on the average positive gradients probably exist from low elevations in the central parts of McMurdo oasis towards higher elevations and towards both the west and east. Absolute humidities are around 10^{-3} kg.m^{-3}.

1. INTRODUCTION

1.1 Outline

The McMurdo region, comprising Ross Island, McMurdo Sound and McMurdo oasis (Figure 1) is one of the most intensely studied areas in the whole of Antarctica. In particular the oasis, consisting of 3000 - 4000 km^2 of mainly snow-and ice-free ground centred around Taylor, Wright and Victoria Valleys in southern Victoria Land, has been the focus of much earth science research. The climate of the area is fundamental to many studies.

Published data and information on the climate of McMurdo region in general and McMurdo oasis in particular is scattered and incomplete. This publication summarises much of what is known of specific aspects of the climate of the McMurdo region with the emphasis on the oasis. Present patterns of surface weather are detailed, including aspects of air temperature, air temperature gradients, wind, precipitation and atmospheric humidity. Temperature and humidity gradients and circulation in the lower atmosphere are also discussed. New data are presented in some sections.

This review is part of a PhD study of salt distribution and origin in the McMurdo region, and the Taylor Glacier saline discharge phenomena (Keys 1979). The contents of the present review are hence directed particularly towards the requirements of that study, but for completeness other information is presented also.

1.2 The antarctic situation and the surface inversion

Antarctica is cold and arid. The low temperatures are primarily caused by the large angle that the earth's rotation axis makes with the plane of the orbit around the sun. The average angle of incidence of solar radiation is low at high latitudes; at the Antarctic Circle it is $23\frac{2}{3}$ degrees, while at South Pole it is 0 degrees. Thus, unit horizontal areas of the earth's surface receive an annual amount of solar energy that decreases with increasing latitude to reach a minimum at the geographic poles. This effect is accentuated by the properties of the predominant surface cover in these regions. Snow reflects most of the incident (solar, shortwave) radiation and also radiates more energy than it absorbs (as terrestrial, long wave radiation). Descriptions of the heat flux and radiation balance in the region are outside the scope of this paper, and interested readers should refer to Rusin (1964), Solopov (1967), Schwerdtfeger (1970) and Thompson *et al.*, (1961, 1971a). The high mean elevation of Antarctica causes additional cooling. Because of the low temperatures, antarctic air can hold little moisture and the water substance is predominantly in the solid form. Therefore the continent is arid.

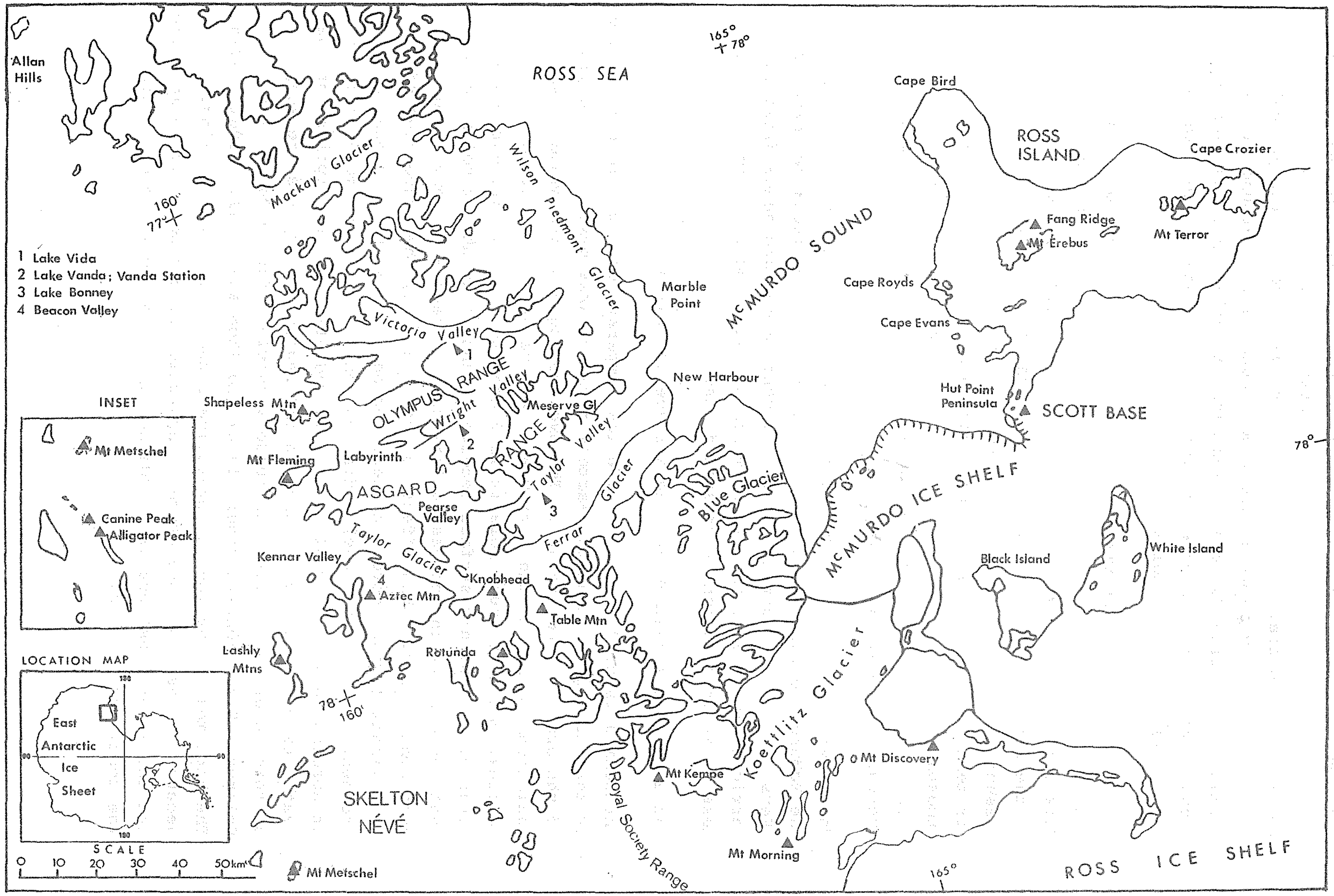


FIGURE 1 The McMurdo region

It is necessary to briefly discuss the phenomenon of the surface inversion, or the temperature increase with height in the lower to 1 to 1.5 km of the troposphere. Inversions are frequent over the McMurdo region, including the oasis, except during summer (Simpson 1919; Thompson and MacDonald 1961; Schwerdtfeger 1970). They are formed in relatively calm conditions when the surface air is cooled by nett radiation loss from the underlying snow surface. Inversion strengths exceeding 30^{o}C in the lower kilometre of the troposphere have been measured in the interior of Antarctica (Weyant 1967; Schwerdtfeger 1970). Air temperatures near the surface are colder during an inversion, but rise when the inversion is destroyed by wind or cloud. Information on the surface inversion phenomena is contained in many articles, including those by Simpson (1919), Thompson and MacDonald (1961), Rusin (1964), Solopov (1967) and Schwerdtfeger (1970).

1.3 Seasons and time

The seasons in Antarctica occur primarily as a result of variations in insolation over the yearly period. Changes between air masses also effect seasonal changes (Hidore 1972). In this publication the seasons are defined as in Table 1, following Rusin (1964).

TABLE 1 Duration of the four seasons in Antarctica (after Rusin 1964) and temperate regions

Season	Duration		
	Antarctica	Temperate (southern hemisphere)	Temperate (northern hemisphere)
Summer	December, January	December-February	June - August
Autumn	February, March	March - May	September - November
Winter	April - September	June - August	December - February
Spring	October , November	September - November	March - May

Tables 2 and 3 show that these seasons have characteristic mean air temperatures. Summer is characterised by relatively warm and stable temperatures, while winter is distinguished by the coldest temperatures and relatively little month to month variation. The three sunless months May, June and July are occasionally referred to as the three mid-winter months. As will be seen, however (Fig. 2), the extreme cold temperatures do not always occur in this mid-winter period. In the transitional seasons the temperatures rise rapidly (spring) and fall rapidly (autumn). In the interior of the continent there is some justification for considering winter as the period March through October (Rusin 1964), but this is not done here.

TABLE 2 Mean monthly air temperatures and mean daily range °C, at Vanda Station, calculated from New Zealand Meteorological Service data. Also included are standard deviations of mean monthly temperatures, monthly temperature extremes and year in which these extremes occurred.

	JAN.	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT	OCT.	NOV.	DEC.
No. of years of records	6	3	3	3	3	3	3	3	3	3	10	11
Mean monthly air temperature (MMAT)	+1.4	-5.9	-20.4	-29.7	-29.2	-30.2	-38.0	-32.3	-31.2	-15.8	-6.7	+0.2
Standard deviation	1.1	0.8	2.4	2.6	4.7	5.3	1.0	7.3	3.1	2.8	1.2	1.0
Mean daily range	6.7	7.6	9.5	9.6	11.3	10.0	9.2	11.6	11.0	11.5	9.2	6.6
Extreme maximum air temperature	+15.0	+4.4	-0.1	-6.0	-1.2	-0.9	-7.6	-3.2	+2.6	+0.7	+9.5	+14.3
Year of occurrence	1974	1970	1970	1974	1974	1970	1970	1970	1970	1969	1971	1978
Extreme minimum air temperature	-11.4	-21.8	-41.4	-46.7	-48.8	-49.4	-56.9	-55.2	-50.7	-36.7	-24.0	-9.5
Year of occurrence	1972	1969	1974	1969	1969	1969	1969	1970	1970	1974	1976	1968

TABLE 3 Mean monthly air temperatures and mean daily range °C, and extremes (with years of occurrence) at Scott Base, calculated from New Zealand Meteorological Service records from March 1957 to December 1977. Also included are the MMATs at McMurdo Station after Schwerdtfeger (1970) for the period March 1956 to February 1968.

	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
Scott Base: Mean monthly air temperature (MMAT)	-4.8	-10.8	-20.5	-24.4	-27.4	-26.3	-29.2	-30.3	-28.1	-22.6	-11.9	-5.4
Mean daily range	6.9	7.4	9.1	10.5	12.6	12.2	12.5	13.2	12.3	11.4	8.7	6.9
Extreme maximum air temperature	+6.8	+5.0	-2.0	-4.6	+0.2	-4.8	-4.2	-2.7	-3.3	-0.2	+1.3	+5.0
Year of occurrence	1970	1958	1970	1968	1971	1972	1959	1972	1960	1977	1961	1957
Scott Base: Extreme minimum air temperature	-19.7	-30.2	-44.6	-50.4	-53.2	-52.2	-54.2	-56.1	-57.0	-52.0	-37.2	-22.8
Year of occurrence	1960	1962	1965	1960	1965	1976	1961	1975	1968	1976	1966	1961
McMurdo Station: mean monthly air temperature	-3.4	-8.3	-18.9	-21.2	-23.9	-23.4	-25.5	-27.8	-24.1	-19.9	-8.8	-3.8

The time standard used in the McMurdo region and referred to in this study is New Zealand Standard Time (NZST) and the 24-hour clock is used. Occasionally, literature pertaining to the McMurdo region uses Greenwich Mean Time, 12 hours behind NZST. The local noon in the McMurdo region occurs at about 1300 hours NZST. Where more precision is required the relation

$$\frac{180 - \text{longitude}}{15}$$

gives the time, in hours, that local noon occurs after 1200 NZST.

2. AIR TEMPERATURE

2.1 Mean annual temperatures

The mean annual air temperature (MAAT) at sea level in the McMurdo region is close to -20°C. In South Victoria Land, MAAT decrease inland towards the west as the elevation of the surface increases. Quantitative data for most areas of the oasis are limited: some are derived in this publication in section 3 based on the summary of this present section. Published MAAT at the three stations in the area are: Vanda Station, -20.0°C (for 1969, 1970; Thompson *et al.*, 1971a); Scott Base -20.0°C (Thompson and MacDonald 1961; Thompson 1969); McMurdo Station -17.7°C (1957 - 1963, Nichols and Ball 1964; Anon 1969) and -17.4°C (1956 - 1968, Schwerdtfeger 1970). Some first estimates of the MAAT in McMurdo oasis appear slightly warm (e.g. -18°C, Ragotzkie and Likens 1964; -16°C, Bull and Carnein 1968).

There is a significant difference between the MAAT at Scott and McMurdo, only 2.5 km apart. It is believed that this difference is due to Hut Point Peninsula acting as a dividing ridge, thereby directing air from generally warmer sources onto McMurdo (Thompson and MacDonald 1961). The surface inversion (1.2) may also contribute to the difference, since the recording thermometers at the two stations are located at different heights above the ground (M. Sinclair, NZ Meteorological Service, personal communication) and because McMurdo has a significantly higher mean wind speed than Scott (section 4.5).

In order to update the value of the MAAT at Vanda, data recorded in 1974 by New Zealand Meteorological Service (NZ Met. S.) personnel were added to those of 1969 and 1970. Mean air temperatures for a particular year are obtained by averaging the twelve individual months' mean air temperatures which are in fact the mean daily air temperatures during each one of those twelve months. Mean daily air temperatures for a particular month are determined by averaging that month's mean maximum and mean minimum air temperatures, which themselves are the averaged daily maximum and minimum air temperatures over that month. Mean air temperatures obtained in this way do not differ significantly from those calculated on a day-to-day basis

(Bromley, NZ Met. S., personal communication). The updated MAAT at Vanda was calculated to be -19.6°C. This does not differ significantly from the MAAT at Scott since the average of the mean temperatures for the same three years (1969, 1970, 1974 data from NZ Met. S. records) there, is -19.5°C.

Short time series such as these cannot give accurate representations of MAAT; the standard deviation of the updated MAAT at Vanda is 1.9. A better indication of MAAT at Scott is obtained by averaging the individual yearly mean temperatures from 1958 to 1977 (NZ Met. S. records): the value obtained is -20.2°C with standard deviation of 1.1. Since this cannot be done for Vanda, the individual monthly mean temperatures available (from December 1968 to December 1978, NZ Met. S. records) have been averaged. The resulting mean monthly air temperatures (MMAT) are included in Table 2, along with standard deviations of individual monthly mean temperatures from these MMAT. Table 2 also includes the mean daily temperature range over each month (M. Sinclair, pers. comm.), and monthly temperature extremes, with the year in which the extreme occurred. The MMAT plus mean daily range and extreme maximum and minimum data at Scott (calculated from NZ Met. S. records) and MMAT at McMurdo (Schwerdtfeger 1970) are given in Table 3. From these tables best estimates of MAAT have been calculated for Vanda and Scott and are given in Table 4, along with standard deviations and maximum recorded deviations, plus similar data for January, the warmest month of the year.

<u>TABLE 4</u> Best estimates of mean annual air temperatures and mean January temperature (warmest month) at Vanda Station and Scott Base.

Parameter	Vanda Station	Scott Base
<u>MAAT (°C)</u>	-19.8	-20.2
standard deviation	1.9	1.1
maximum deviation	-2.0	-2.2
<u>mean January air temperature</u>	+1.4	-4.8
standard deviation	1.1	1.7
maximum deviation	-1.4	-4.0

These best estimates may change by a few tenths of a degree when extra years data are added, because of the short observation series involved.

The difference between the MAAT at Vanda and Scott is not significant even though these sites are some 140 km apart and have significant meteorological differences. However, the MMAT at the two sites are significantly different.

2.2 Mean monthly temperatures, annual amplitudes and annual peaks of air temperatures

The differences between summer and winter MMAT at Vanda and Scott have been discussed previously (Thompson *et al* 1971a; Riordin 1973). It can be seen from Tables 2 and 3 that MMAT at Vanda are about 6 degrees warmer in summer and up to 9 degrees cooler in winter than those at Scott. This reflects the more continental climate of Vanda. The warmer summer temperatures at Vanda are due to higher absorption of solar radiation by the ice-free surface, while the cooler winter temperatures there are caused by increased upward radiation from the surface together with relatively infrequent advection of warmer air into Wright Valley in winter (Thompson *et al* 1971a).

The annual mean amplitudes of the air temperature (half the difference between the warmest MMAT and the coldest MMAT) are 19.7 degrees at Vanda, 12.8 degrees at Scott and 12.2 degrees at McMurdo. These amplitudes may be compared with those calculated from data for twenty-five antarctic stations (including Antarctic Peninsula, South Shetland and South Orkney Island stations), listed in Schwerdtfeger (1970). It may be stated that the annual mean amplitude at Vanda is one of the largest, if not the largest of all antarctic stations. The absolute validity of such comparisons is not certain because of the differing lengths of observation series at some of these stations (Schwerdtfeger 1970).

The extreme range of temperatures is 71.9 degrees at Vanda and 63.8 degrees at Scott. Here too, Vanda's range is greater than that of all twenty-five stations in Schwerdtfeger (1970).

It is unfortunate that extreme minimum temperatures at Vanda have not been obtained for most winters since 1970. Measurement of these has been prevented due to shaking down of the pins in the minimum thermometers, caused by wind-induced vibration of the meteorological screens (Bromley NZ Met. S., personal communication). Other than those in 1969, 1970 and 1974 only two winter extreme temperatures are known for McMurdo oasis. These are -62°C in 1960 at Lake Vida (350m elevation) (Bull 1966) and -47.5°C in 1973 at Screen A (95m elevation) Vanda Station (NZ Met. S. Records).

The extreme maximum temperature measured at Vanda + 15.0°C (January 1974) is warmer than that at any of the twenty-five stations listed by Schwerdtfeger (1970). Extreme maximums of this magnitude have occurred twice in the last decade (NZ Met. S. records) and caused much more melting than occurs in "average" years. (Hoehn *et al*; 1974; Anderton and Fenwick 1976; Chinn 1979). Angino *et al* (1962) measured a maximum air temperature of +23.9°C at Lake Bonney in December 1961, but this was not under standard conditions.

The antarctic "coreless" winter typically lacks a well-defined trough; any of the months from June to September can be the coldest of the year (Rusin 1964). Figure 2 presents daily mean air temperatures averaged over the particular months (i.e. mean daily air temperatures MDAT) at Vanda and Scott, over a number of years since March 1967. Of the eleven winters at Scott recorded in this Figure, the mean cold peak occurs in June once, July three times, August three times and September four times. However, all three winters at Vanda had coldest MDAT in July.

Despite the absence of a well-defined winter cold peak, the McMurdo region does experience a defined summer warm peak. January has the warmest MMAT at both Vanda and Scott. However the mean daily warm peak does not always occur in January (Figure 2). Table 5 presents some data for Vanda indicating this variability.

TABLE 5 Occurrence of extreme maximum summer air temperature and approximate timing of peak on smoothed temperature curve for Vanda Station. Data from sources indicated (nd = not determined)

Summer	Month or date of extreme maximum summer air temperature	Approximate timing of peak on smoothed temperature curve	Reference
1968/69	December	nd	NZ Met.S. records
1969/70	January	early in second week of January	NZ Met.S. records
1970/71	January 3	first week of January	Yoshida *et al* (1971)
1971/72	November 24	last week of December	Torii *et al* (1972)
1972/73	December	nd	NZ Met.S. records
1973/74	January	first week of January	NZ Met.S. records
1974/75	December?	nd	NZ Met.S. records
1975/76	January	nd	NZ Met.S. records
1976/77	January 21	second week of January	NZ Met.S. records
1978/79	December 29	last week of December	NZ Met.S. records

A generalised air temperature curve at Vanda would tend to peak in the first week of January.

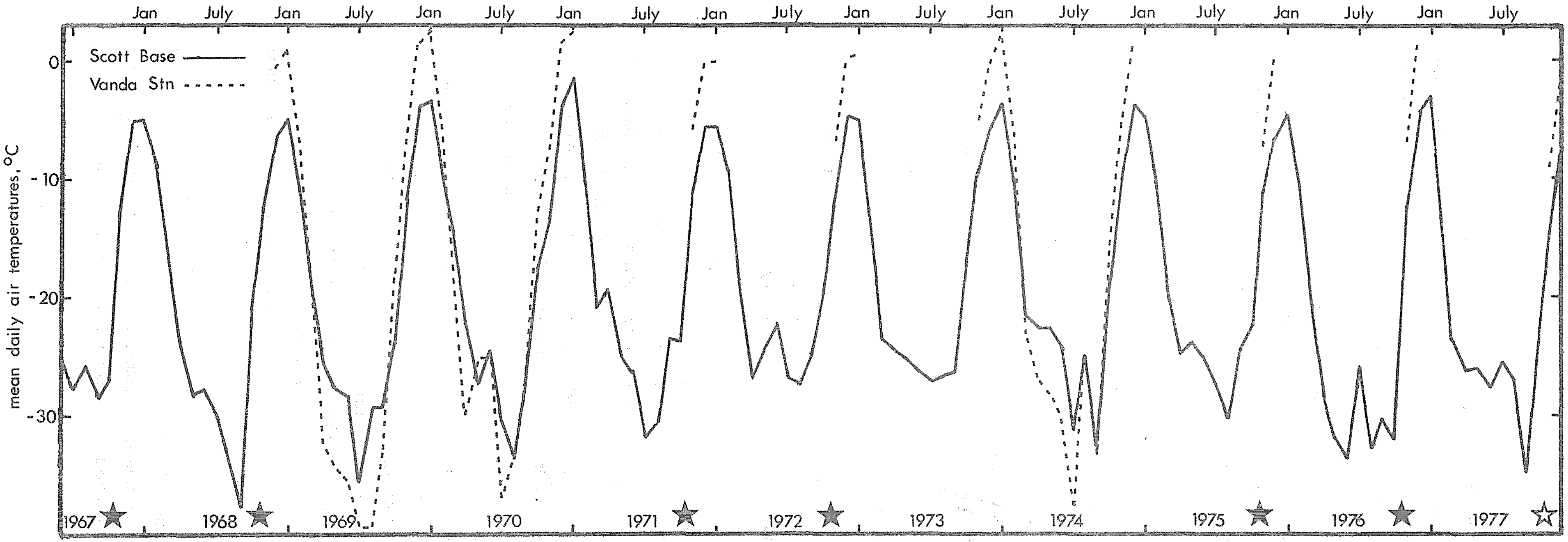


FIGURE 2 Mean daily air temperatures at Vanda Station (dashed line) and Scott Base (solid line) for the months June 1967 to December 1977 inclusive (data from NZ Met. Service records). Stars show years in which saline discharges occurred at Taylor Glacier (Keys 1979).

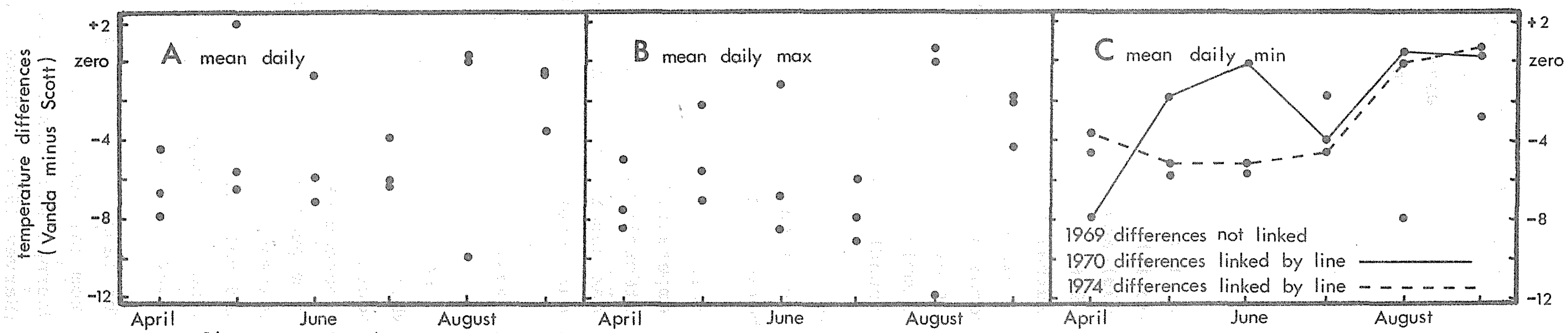


FIGURE 3 Scatter diagrams showing the differences between the air temperatures at Vanda Station and those at Scott Base during the six winter months; A, mean daily temperature differences; B, mean daily maximum temperature differences; C, mean daily minimum temperature difference (differences for individual years are indicated).

2.3 Mean daily air temperatures and phase lags of temperature peaks

The year-to-year variations in MDAT at Vanda and Scott are illustrated in Figure 2. The Figure shows that irregular differences exist between MDAT of corresponding winter months at each site. A close correlation of MDAT does not exist (correlation coefficient for linear regression line is 0.34, see scatter diagram Fig. 3a). Thus winter MDAT for a particular year at Scott should not be used to estimate MDAT values for Vanda. Similarly, little correlation exists between mean daily maximums or minimums over the same period at these two sites (Figures 3 b,c). The differences between the two sets of records are due mainly to the different geographic environments at Vanda and Scott.

Specific examples of the diurnal temperature variation have been published for Vanda (Yoshida *et al* 1971; Torii *et al*, 1972; Riordin 1973) and Scott (Thompson and MacDonald 1961). In addition, Bull (1966) contains similar data for various places in McMurdo oasis. The diurnal range in midsummer seldom exceeds 10 degrees at Vanda, whereas in winter the range may exceed 35 degrees (Riordin 1973; NZ Met. S. records). Large temperature changes may be almost instantaneous in winter (Thompson and MacDonald 1961). Riordin (1973) illustrates an example of a change of greater than 25 degrees (at 0.15m above the ground) in about 6 hours at Vanda in late July 1969.

The mean diurnal temperature ranges for each month at Vanda and Scott are given in Tables 2 and 3. The mean diurnal range is the difference between the mean monthly maximum and the mean monthly minimum.

There is little published data on the phase lag and peaks of the diurnal temperature cycle. Investigation of NZ Met. S. and personal meteorological records indicates that in summer in the oasis, the warm peak generally occurs between about 1300 and 1630 hours, while the cold peak occurs at about 0200 to 0500 hours. This is consistent with the limited data of Thompson *et al* (1971 b) and Colacino and Stocchino (1975) for the oasis, and of Thompson and MacDonald (1961) for Scott Base. In places where extensive shading occurs, these peaks may be offset from these times. At the saline discharge site (Keys 1979) which tends to be shaded around midday by Asgard Range, the warm peak occurs later, generally between 1400 and 1800 hours. Bull (1966) produced data from the 1958/59 summer at Vanda showing that the diurnal warm peak occurred at about 1330 hours when easterly winds were blowing, whereas with westerlies it was about 1630 hours. In winter the warm and cold diurnal peaks are not regular (Thompson *et al*, 1961, 1971 b) since air temperatures then are controlled by meteorological rather than solar influences.

The lags of the diurnal and annual warm peaks from the local noon and from the summer solstice (December 21 - 22) in summer, are due to diurnal and seasonal imbalances between incoming and outgoing radiation (Harvey 1976). These imbalances lead to storing of heat at the surface and in the atmosphere on a diurnal and seasonal basis. Antarctic air possesses a significant heat storage capacity, although it is relatively dry (section 6.1). The annual lag is up to about 15 to 20 days (Table 5), while the diurnal lag is about 1 to 3 hours.

2.4 Air temperature and wind

Air temperature varies markedly with wind as well as with solar radiation (Bull 1966; Thompson *et al* 1971 a; Thompson 1972; Yoshida and Moriwaki 1972; Riordin 1973; Colacino and Stocchino 1975). The wind regime in the McMurdo region is discussed in section 4 below, but some comments are pertinent here.

The relationship between temperature and wind at Vanda is well portrayed by Yoshida and Moriwaki (1972) in their figure 8. Westerly winds in Wright and Taylor Valleys are generally warmer than the easterlies. Westerly winds are generally foehn winds (4.8) where the air is adiabatically warmed as it descends into the valleys: furthermore these winds tend to break up or at least penetrate the surface inversion in the valleys during winter (Thompson 1972; Riordin 1973).

In other areas in the region, temperature and wind are also linked. At McMurdo Station, southerly winds tend to produce warmer temperatures whereas northerlies and easterlies produce cooler temperatures (Weyant 1967).

2.5 Variations over the last 20 to 80 years

Short term temperature changes in the McMurdo region and in Antarctica in general have important consequences for many studies. Nichols and Ball (1964), found that the mean annual sea level air temperature in the McMurdo Sound area has been close to $-20^{\circ}C$ for some time. This conclusion was drawn from drill hole data and from comparison of air temperatures recorded on the Scott and Shackleton expeditions ($-17.4^{\circ}C$) with those recorded more recently at McMurdo Station ($-17.7^{\circ}C$). Schwerdtfeger (1970) points out that Wexler's (1959) "warming trend at Little America" can be explained by the latitude difference between the stations (Framheim, 78° 38'S; Little America V, 78° 11' S) involved. Schwerdtfeger also concludes that the only station in southern regions (Orcadas, 60° 44' S, 44° 44' W) with an adequate observational record (1904 - 1967) does not give convincing evidence of "a warming trend in the first half of the century nor of a reversal in the more recent years".

Nevertheless, it is instructive to analyse the Scott Base record of twenty years (Figure 4, Table 5).

Mean air temperatures at Scott Base for the years 1958 through 1977 are shown on Figure 4. Linear regression analysis has been applied to data for selected periods. The single gradient curve for 1958-1977 shows a

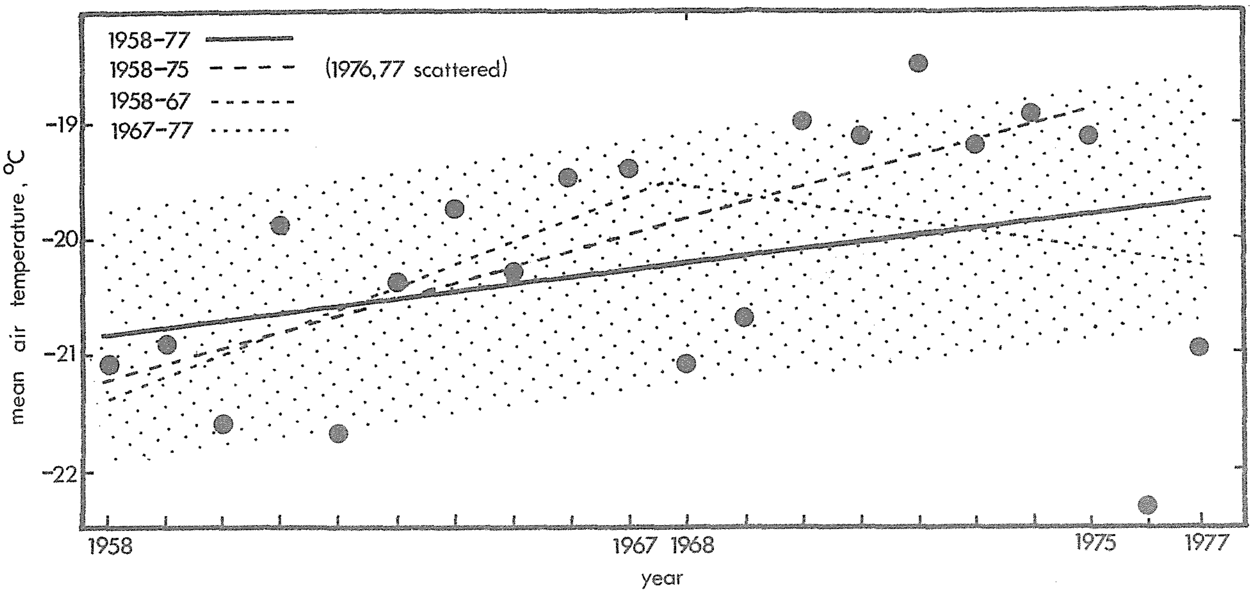


FIGURE 4 Mean air temperature at Scott Base for the years 1958 to 1977 inclusive (data from NZ Met. Service records) with linear regression curves constructed for selected periods. Shading indicates the area lying within one standard error of the 1958-1977 curve.

positive correlation but the curve does not fit the data well (correlation coefficient r=0.32). An improvement in the fit is obtained when the 20 year period is split into two decades, with the period 1958 - 1967 showing a close fit warming trend (r=0.73). However, the 1968-1977 decade cooling trend is poorly fitted (r=0.14). For temperatures up to 1975, a best fit warming trend is again evident (r=0.74). Data are scattered after 1975. The gradients of the regression curves tend to be positive and up to 0.2°C per year indicating up to this amount of warming tendency. The t statistic for a small number of data (Freund *et al* 1960) for the 1958-1977 period is 1.44 (Table 6), whereas the numerical value $t_{c/2}$ of 'students' t distribution for 20 minus 2 degrees of freedom at significance level c, is 1.73 at the 90% confidence level. Since

$$-t_{c/2} \leq t \leq t_{c/2} \quad \text{(Freund } et\ al \text{ 1960)}$$

the warming trend during 1958 to 1977 is not significant at the 90% confidence level. However the trend for the 1958-1975 period (t=4.37) is significant at the 99% confidence level ($t_{c/2}$ = 2.92 for 16 degrees of freedom) indicating a definite warming between 1958 and 1975. The actual amount of warming is small because of the short time period. Table 6 gives the averages of the multi-annual mean air temperature over the two successive decades, and the t statistic (Freund *et al* 1960) for the difference between the averages. This difference is not statistically significant because t is small.

TABLE 6 Trends of mean air temperature (°C) at Scott Base from 1958 to 1977 from linear regression

Period	Average temperature	Temperature trend (i.e. slope of regression line ($^{o}C.a^{-1}$)	Correlation coefficient	Standard deviation (and standard error)	t statistic (see text)
1958-1977	-20.2	0.06	0.32	1.1 (1.0)	1.44
1958-1975(1)	-20.0	0.14	0.74	1.0	4.37
1958-1967	-20.4	0.22	0.73	0.9	0.21
1968-1977	-19.9	-0.06	0.14	1.3	

(1) 1976, 1977 data are scattered well below the regression line by more than one standard error

3. AIR TEMPERATURE GRADIENTS

3.1 Introduction

It has been seen (2.1) that there is a significant difference between the MAAT at Scott Base and McMurdo Station, only 2.5 km apart. Therefore, Vanda's MAAT may not be representative of other places in McMurdo oasis and of Lake Bonney in particular. It is necessary to obtain estimates for horizontal and vertical* temperature gradients, so that the known MAAT may be extrapolated to find those in other areas. Such gradients vary in space and time depending on several inter-related variables including; locality, topography, elevation, season, natures of the ground surface and atmospheric boundary layer and strength of the surface inversion. However a detailed examination of the variation of lapse rates with the nature of the boundary layer and surface inversion is beyond the scope of this work. General atmospheric lapse rates are not of prime concern here since the object of this section is to provide a basis for extrapolating mean screen (i.e. near surface) temperatures.

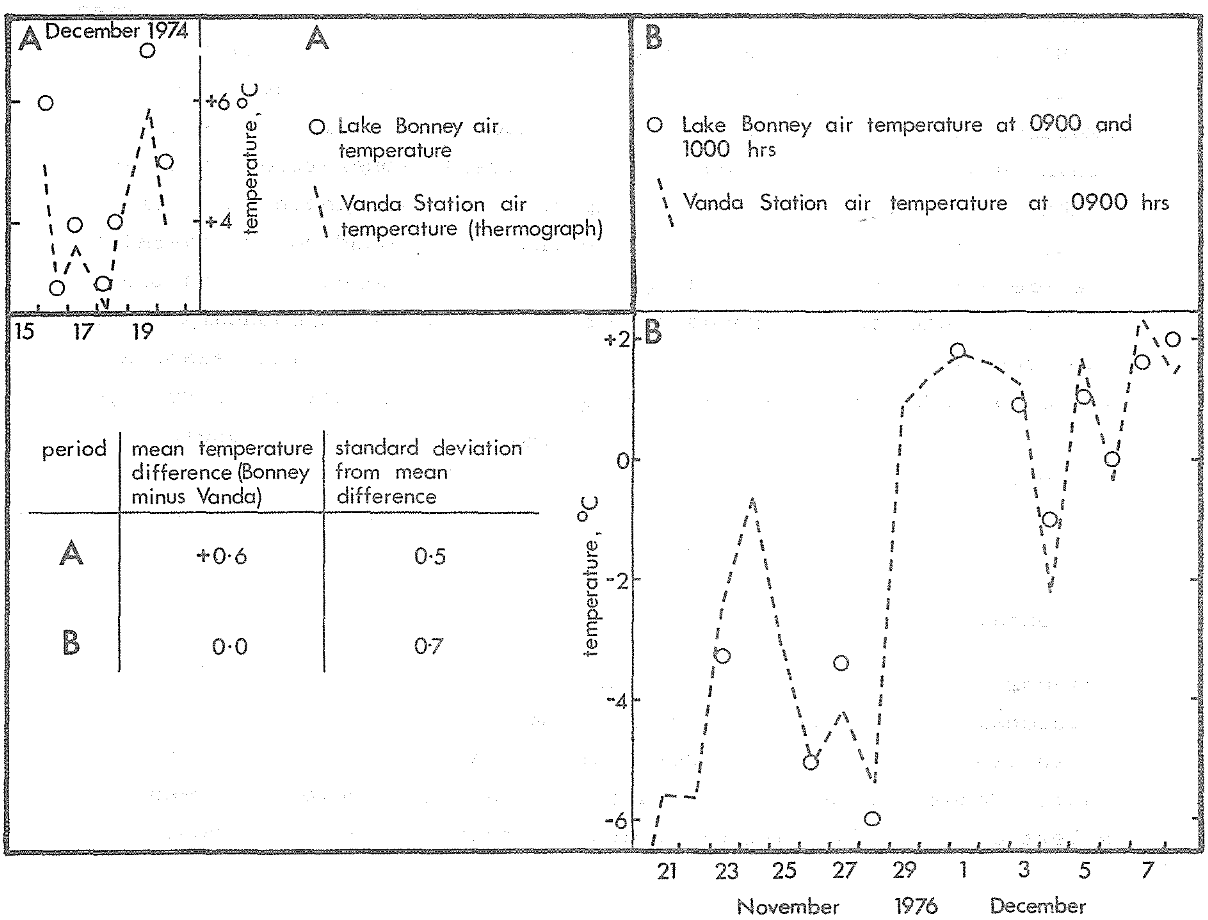
3.2 Horizontal gradients

Horizontal temperature gradients are usually small. The mean meridional temperature gradient in summer for all antarctic stations at sea level is 0 to 0.3 degrees celsius per degree of latitude (Rusin 1964). Schwerdtfeger (1970) indicates that the gradient between Hallett and McMurdo Stations (average longitude 168°E) is about 0.2 to

*the vertical temperature gradient is the lapse rate, which is the decrease of temperature with height. Here it is expressed in °C per 1000m. The meridional gradient is the north-south horizontal gradient.

0.4 degrees celsius per degree of latitude. Therefore the summer temperature difference due to the latitude difference between Vanda Station and the Lake Bonney area should be less than 0.1°C, topography and surface factors being very similar.

The MAAT at Lake Bonney is probably very similar to that of Vanda Station. Figure 5 compares air temperatures measured in Screen A, Vanda Station (77° 31.6'S, 161° 40.1'E, 95m elevation; data from NZ Met.S. records) with some measured at the same or nearly the same time at the western end of Lake Bonney (77° 43.6'S, 162° 17.1'E, 57m elevation). The latter measurements were made using standard whirling psychrometers where the temperature is read off the dry bulb. The temperatures at these two sites are compared in two different ways. In Figure 5a, temperatures measured at various times at Bonney are compared with those at Vanda, using data taken from the thermograph record for the same times. In Figure 5b, the 0900 hours dry bulb temperatures at Vanda are compared with those taken between 0900 and 1000 hours at Bonney. Since there are two distinct sets of data, the temperature difference of each set are treated separately. The differences between the Bonney and Vanda temperatures are very small, (Figure 5) and are not significant considering the magnitude of error associated with the MAAT value at Vanda.



period	mean temperature difference (Bonney minus Vanda)	standard deviation from mean difference
A	+0·6	0·5
B	0·0	0·7

FIGURE 5 Comparison between air temperatures at Lake Bonney and Vanda Station during two short summer periods (data from VUW Antarctic Expeditions and NZ Meteorological Service Records).

Similar temperatures were expected since the terrain at each site is similar and both sites are located in east-west trending valleys. Any small temperature differences due to the lower elevation of Bonney are probably offset by the greater amount of shading due to the Asgard Range and the proximity of Taylor and Rhone Glaciers which are cooling influences. In any case, such differences tend to be evened out by turbulent mixing of air moving through the valleys.

The general climate of these adjacent valleys and at these two sites only 27 km apart, is probably very similar. Therefore the difference between the MAAT at Vanda and Bonney must be small. Hence, -20°C can be considered to be the MAAT at Lake Bonney. Some unsubstantiated previous estimates (e.g. -17°C, Shpaiker 1973) differ from this slightly.

Bull (1966) showed the existence of east-west (zonal) temperature gradients in the valleys of McMurdo oasis, at least in summer. He states (p.182) that "in (the) 1958-1959 (summer) the western end of Wright Valley was 2°C warmer than Marble Point". Although such differences are probably smaller than the variations in mean temperatures from year to year at these sites, it is necessary to examine the east-west gradient.

The summer temperature difference noted by Bull (1966) is due probably to a stronger marine (cooling) influence and decreased solar heating at the coastal site. As will be seen in section 4 below, the occurrence of cooler easterly winds decreases inland to the west throughout the whole year. In winter however, strong radiational cooling at inland sites lowers the temperature well below that of coastal sites. Over the whole year average temperatures at Marble Point and New Harbour will be closer to those at McMurdo Station and Capes Evans and Royds, than to the MAAT at Vanda. The MAAT is probably within a degree of -18°C for the Marble Point - New Harbour area.

The east - west temperature gradient, averaging up to -0.06°C per km in Taylor Valley, would probably not be noticed when windy conditions prevail throughout the entire valley. Under such strong mixing conditions, Colacino and Stocchino (1975) found that air temperature was constant throughout Taylor Valley from New Harbour to Lake Bonney.

3.3 Lapse rates

Elevation is the most important factor controlling MAAT in Antarctica, especially on the continent (Weyant 1967). In antarctic literature it has occasionally (but erroneously) been assumed that average environmental and topographic lapse rates* are equal and have a value

*the environmental lapse rate (ELR) is the rate of decrease of air temperature with height in free air, whereas the topographic lapse rate (TLR) is the decrease in temperature with elevation up a slope on the earth's surface (Harvey 1976).

equivalent to the dry adiabatic lapse rate of 9.8°C per 1000m (Hughes 1971; Drewry 1977). This assumption is made because the rate of condensation of water vapour is very slow at low temperatures, and hence little latent heat of vaporisation is liberated upon raising (cooling) a parcel of antarctic air. However, because of radiation (surface inversion) and turbulence effects (Simpson 1919) it appears that these average lapse rates are generally even less than the saturated adiabatic lapse rate which is 8.6°C per 1000m at -20°C and 1000 mb (Harvey 1976).

Some environmental and topographic lapse rates for the McMurdo region are given in Table 7. These have been calculated using published data (Weyant 1966a; Ugolini 1967; Schwerdtfeger 1970; Hughes 1971; Holdsworth 1974), and unpublished data. The latter includes air temperatures measured using whirling psychrometer dry bulb thermometers (VUWAE meteorological observations) which were compared with measurements made at the same time by thermograph and/or dry bulb at Screen A, Vanda Station, and at Scott Base (NZ Met. S. records). Lapse rates obtained from balloon ascents in the lower troposphere are environmental lapse rates (ELRs). The englacial temperatures correspond to mean annual surface temperatures (MAST) not MAAT; hence lapse rates obtained using them are topographic lapse rates (TLRs) as are those obtained by surface air temperature comparisons. The lapse rates obtained using unpublished data include the horizontal temperature gradients; the correction for these is neglected here since it amounts to probably no more than 0.2°C.

There is a strong seasonal effect on environmental lapse rates (Table 7). These are lowest in winter when temperature inversions in the boundary layer are strongest and most frequent. Generally the lapse rates are closest to the saturated adiabatic lapse rate in summer, when significant inversions are very infrequent and weak. The range of ELRs indicated is 2 to 7°C per 1000m. Since the lower rates prevail for most of the year, the mean annual ELR in the lower troposphere is about 4 to 5°C per 1000m. This is very similar to the mean ELR above the temperature inversion obtained by Simpson (1919). However, Simpson's data were obtained in relatively low wind conditions such that little vertical mixing of air would have been occurring in the boundary layer. Thus it is possible that the value given above for the mean annual ELR is also biased towards calmer conditions. According to Simpson (1919) and Harvey (1976), the average ELR in the troposphere is about 6.5°C per 1000m, but it is not known by the writer whether this value is applicable to antarctic conditions.

Topographic lapse rates in summer may be slightly greater than the summer ELRs (Table 7). However the validity of the comparison is questionable considering the magnitude of the errors involved in the TLRs. Furthermore, Table 7 contains inhomogenous data on which it is difficult to obtain average values.

TABLE 7 Environmental and topographic lapse rates in McMurdo region for selected months, calculated from published and unpublished data. References; (1) Weyant 1966a, 1967; (2) Ugolini 1967; (3) Schwerdtfeger 1970. (kilometres and geopotential kilometres are assumed to be equal).

Month	Lapse rate (°C per 1000m) † uncorrected for horizontal temperature gradients	Method of data collection (Altitudes in km or geopotential km*)	Source of original temperature and altitude data
January (1958-62)	5.6	MMAT at McMurdo (Table 2.2) and weather balloon (0-1)	2, 3
(1958-62)	6.2	Weather balloon (1-5)	2
February (1959-62)	5.5	MMAT at McMurdo and weather balloon (0-1)	2,3
(1959-62)	4.9	Weather balloon (1-5	2
(1962)	8.0	Air temperature measurements during ascent of Erebus	2
March (1958-62)	3.5	MMAT at McMurdo and weather balloon (0-1)	2,3
(1958-62)	4.2	Weather balloon (1-5)	2
(1956-65)	2.7	Weather balloon (0-2.6*)	1,3
(1908)	mean 4.0†	Air temperature measurements during ascent of Erebus	2 quoting David in Shackleton (1909)
June (1956-65)	2.7	Weather balloon (0-2.6*)	1,3
	5.2	Weather balloon (2.6*-4.9*)	1,3
September (1956-1965)	2.4	Weather balloon (0-2.5*)	1,3
	5.0	Weather balloon (2.5*-4.9*)	1,3
November (1958-61)	6.9	MMAT at McMurdo and weather balloon (0-1)	2,3
(1958-61)	5.8	Weather balloon (1-5)	2
November 18-25, 1974	8.6 ±2.7†	Air temperature measurements made at Table Mtn and compared with Vanda thermograph	Keys; NZ Met.S records; USGS 1:250,000 map.
November 26 - December 4,1974	7.8 ± 2.0†	Air temperature measurements made at Knobhead and compared with Vanda thermograph	Keys; NZ Met.S records; USGS 1:250,000 map
December (1959-61)	8.0	MMAT at McMurdo and weather balloon (0-1)	2,3
(1959-61)	6.3	Weather balloon (1-5)	2
(1956-65)	6.7	(0-2.7*)	1,3
December 5-15,1974	8.3 ±3.0†	Air temperature measurements made at New Mt and compared with Vanda thermographs	Plume; NZ Met. S records; USGS 1:250,000 map
December (1972-1979)	mean 5.2† std.dev 1.4	Air temperature measurements made at Erebus summit camp and compared with Scott Base drybulb measurements (29 comparisons)	Keys; NZ Met S. records
All year	4 to 8	Englacial temperature profiles, Meserve Glacier	Hughes 1971; Holdsworth 1974

A better comparison involves the TLR obtained from englacial temperature profiles in Taylor Glacier. Such profiles enable mean annual surface temperatures (MAST) to be measured. This is normally considered to be the temperature measured at the depth of penetration of seasonal changes of air temperature. For snow substrates the depth taken is 10 metres but this cannot be applied to ice because it has different thermal properties (Müller 1976). A depth of 17 metres was used for the ablation zone of Taylor Glacier. This depth was found by measurement (Robinson 1979), and by calculation using a Fourier equation solution that describes periodic heat flow in one direction through a semi-infinite homogenous solid (for example see Cameron and Bull 1962). In the ablation zone of glaciers at least, MAST are usually a few degrees warmer than MAAT and certainly the two are not equal (Müller 1976). However, MAST differences can be used to obtain TLR's which are assumed herein to be applicable to ice-free areas also.

Englacial temperatures were measured (1976-1977; 1977-1978) by Robinson (1979) using thermistor probes in drill holes and crevasses up to 20m deep. Table 8 shows the derivation of the TLR.

<u>TABLE 8</u> Topographic lapse rate from mean annual surface temperatures, Taylor Glacier. Elevations (m) from (a) USGS Reconnaissance series maps (b) Stern's (1978) relative altitudes and (c) a combination of (a) and (b).

	<u>Line C</u> (MAST[1] -17.0 ±0.2 °C)	to	<u>Line F</u> (MAST[2] -20.1± 0.1°C)	
	Elevation Line C	Elevation Line F	Elevation difference	Lapse rate °C per 1000m
(a)	180	950	770	4.0
(b)	140[3]	930[4]	790	3.9
(c)	180[3]	990[4]	810	3.8
	<u>Line F</u> (MAST[2] -20.1 ± 0.1 °C)	to	<u>Line G</u> (MAST[2] -21.5 ±0.1°C)	
	Elevation Line F	Elevation Line G	Elevation difference	Lapse rate °C per 1000m
(a)	950	1250	300	4.7
(b)	930[4]	1330[5]	400	3.5
(c)	990[4]	1330[5]	340	4.1
	Central value of lapse rate 4.0 ±0.5 °C per 1000m			

1 From crevasse temperatures near terminus measured by P.H. Robinson
2 From englacial temperatures measured by P.H. Robinson
3 Based on elevation at pole C6
4 Based on elevation at pole F6
5 Based on elevation at pole G5

The value, 4.0°C per 1000m is not affected by seasonal changes or wind conditions and is the value used in this study. It appears that the average TLR and average ELR are similar in the McMurdo region. However, they are slightly lower than the TLR in the eastern European Alps (5.3°C per 1000m calculated from the data of Geiger 1965).

Estimates of MAAT at various localities in the McMurdo region can now be made (Table 9). The MAAT at Scott (-20.2 ± 1.1°C) was used for the MAAT determination at Mounts Erebus, Morning and Discovery. Vanda's MAAT (-19.8 ± 1.9°C) was used for the other localities in Table 9.

TABLE 9 Mean annual air temperature estimated at selected localities in the McMurdo region, using a mean lapse rate of 4.0 ± 0.5°C per km and MAAT at Vanda of -19.8 ± 1.9°C and at Scott of -20.2 ± 1.1°C. (Elevation of Vanda, 95m; Scott 16m)

Locality	Elevation (m) (from USGS 1:250,000 map)	Estimated MAAT (°C)	Maximum Error Limits (± °C)
Mt Erebus	3794	-35.3	3.0
Mt Morning	2723	-31.0	2.5
Mt Discovery	2681	-30.9	2.4
main valley at Table Mountain	1600	-25.8	2.7
valley between Knobhead and Mt Handsley	1500	-25.4	2.7
Beacon Valley	1400	-25.0	2.6
Kennar Valley	1600	-25.8	2.7
west end of Labyrinth	900	-23.0	2.4
Lake Vida	350	-20.8	2.1

4. WIND AND CIRCULATION

4.1 Introduction

Distribution of salts is intimately involved with both wind and circulation. In this section the wind regime at Vanda, then the rest of McMurdo oasis, is discussed before the regime at Scott, McMurdo and Ross Island. Finally air circulation over the rest of East Antarctica is discussed.

4.2 Vanda Station

The wind direction at Vanda and in the oasis generally is almost completely controlled by valley orientation. The topography channels the wind into east and west directions (Bull 1966; Nichols 1966; Thompson 1972; Yoshida and Moriwaki 1972). Complete sets of wind roses and histograms for Vanda data from the years 1969 and 1970 have been published by Yoshida *et al* (1972) using NZ Met. S. records. The following wind characteristics at Vanda have been taken from Thompson *et al* (1971a), Thompson (1972), Yoshida and Moriwaki (1972) and Riordin (1973).

Easterly winds are most frequent, especially in summer. The prevailing direction on a yearly basis is around 090° True, while the second most pronounced direction is around 260° True. The easterly winds are relatively light: wind velocities greater than 17-18 $m.s^{-1}$ are restricted to those from the west and southwest. In both 1969 and 1970 the maximum gusts (40, 41 $m.s^{-1}$ or ca. 80 kts) were both from the west and both occurred in August. Winter winds are more intense but less frequent than during the summer. This is shown by Tables 10 and 11. Table 10 gives the mean monthly wind speeds at Vanda averaged from data for 1969, 1970 and 1974 and maximum gusts during 1969. Maximum gusts are defined in different ways, based on different time periods; for this reason they are approximate only. Table 11 gives the wind rose data for Vanda Station for the period January 1972 to January 1978. The data in Table 11 have been normalised so that frequencies per thousand observations are tabulated: the table is based on 176 observations in 'spring', 291 in 'summer', 92 in 'autumn' and 92 in 'winter' where these seasons are defined as in temperate regions (Table 1). Thus, the summer wind regime is better represented although the Table is not weighted towards the summer months.

The well-known diurnal-based wind regime which operates in the valleys of the oasis during the sunlit months is well developed at Vanda. Steady easterlies of 8-10 $m.s^{-1}$ blow during the afternoon and evening when ground temperatures are warmest. Calm periods or westerlies of 0-10 $m.s^{-1}$ develop during the early morning, when the influx of solar radiation is at a minimum (Thompson *et al* 1971a; Thompson 1972, Yoshida and Moriwaki 1972; Riordin 1973). Thompson (1972) has this sequence well illustrated for November 1971. These winds are of limited thickness reaching up the valley sides no further than about 800 to 1200m (Bull 1966; Thompson 1972).

TABLE 10 Mean monthly wind speeds and maximum gusts at Vanda and McMurdo Stations. Vanda mean speed data calculated from New Zealand Meteorological Service records for the years 1969, 1970, 1974; gust data from Riordin (1973) for 1969 only. McMurdo data after Schwerdtfeger (1970). Units are metres sec^{-1} (ng not given)

		JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
VANDA	Mean wind speed	6.6	5.6	3.6	2.2	4.3	3.0	2.8	4.9	4.5	7.2	6.6	7.0	4.9
	Standard devia-tion	0.2	1.0	0.3	1.1	2.8	1.8	1.6	2.6	1.1	2.1	0.6	0.4	0.6
	Maximum gust 1969	ng	25	28	37	27	26	37	40	34	32	30	ng	41 (1970)
MCMURDO														
	Mean wind speed	5.3	7.0	7.3	6.1	6.9	7.2	6.5	6.4	6.9	6.2	5.4	6.5	6.5
	Maximum gust	24	29	27	28	43	43	36	38	41	37	35	24	43

TABLE 11 Wind rose data for Vanda Station and Scott Base based on daily observations at 0900 NZST. Frequencies are given per thousand observations. 0 indicates occurrences less than 0.5; a blank indicates no occurrences. (After NZ Met.S. computerised records). Conversion from Beaufort Force to wind speeds in $m.s^{-1}$ after Amiran and Schick (1961).

VANDA STATION Total observations used: 651

Beaufort Force:	1	2-3	4	5	6	7+	Total
Direction/ Speed at 2m ($m.s^{-1}$)	0-1.6	1.6-4.8	4.8-8.0	8.0-10.8	10.8-13.8	13.8+	
N	8	1					9
NE	25	22	13	0	1	0	61
E	40	101	82	24	10	1	258
SE	3	2	3	1			9
S	5	3	1	1	2	1	13
SW	2	8	6	17	19	28	80
W	18	21	22	23	24	46	154
NW	9	2	0	1			12
						Calm	402

SCOTT BASE Total observations used: 2221

Beaufort Force	1	2-3	4	5	6	7+	Total
Direction/ Speed ($m.s^{-1}$)	0-1.6	1.6-4.8	4.8-8.0	8.0-10.8	10.8-13.8	13.8+	
N	24	99	81	34	16	1	255
NE	21	151	155	62	16	1	406
E	4	24	16	7	1		52
SE	2	15	12	12	7	3	51
S	5	6	8	7	9	12	47
SW	5	8	3	1	1	3	21
W	6	8	3	0	1		18
NW	3	11	15	13	11	2	55
						Calm	93

4.3 Elsewhere in McMurdo oasis

Elsewhere in Wright Valley the wind regime is slightly different from that at Vanda. In the eastern half of the valley, westerly winds are less common (Bull 1966) especially in the spring and summer. At the hut adjacent to Meserve Glacier, maximum and mean wind speeds are less than at the valley floor (Everett 1971) in the summer at least. During summer in the Wright Upper Glacier area the influence of the easterly winds is reduced from that at Vanda whereas the westerly influence is increased.

Personal meteorological recordings during five periods totalling eight weeks show that the wind patterns are similar in Taylor Valley. Up valley easterly winds are most common in the east and their influence decreases westward towards the ice sheet*. At Lake Bonney a diurnal wind regime, similar to that at Vanda, operates during the spring, summer and probably autumn months. Easterly winds are relatively uncommon as far west as Kennar Valley. Nevertheless, easterly conditions do occasionally occur even further west in Skelton Neve and plateau areas. Strong southwesterly and southerly winds are common along the western fringe of the oasis and in areas within the oasis exposed to the south. These winds are associated with the general surface wind regime of the East Antarctic Ice Sheet and cyclonic storms, and are further discussed in sections 4.8 and 4.9 below. During the winter strong west to south-west winds are important in Taylor Valley, even at the coastal end. This can be seen from geomorphic evidence including wind blown sand and gravel on the sea ice up to 10 km east of Cape Bernacchi. Presumably the wind regime in winter is similar to that in Wright Valley.

Similar wind patterns are followed in the Victoria Valley system. East of Lake Vida, easterly winds are the most predominant, strongest and most constant, at least in the sunlit months; in November 1961 to January 1962 Calkin (1964) found that the wind blew almost constantly from the east, averaging some 4 $m.s^{-1}$. However, northerlies and south-westerlies are known in this area (Bull 1966); gusty, southwesterly winds of at least 23 $m.s^{-1}$ have been recorded (Calkin 1964). Further west, winds off the ice sheet, blowing from the west to southwest are common and are stronger than the easterlies (Calkin 1964; Bull 1966). It is evident from studies of the field of transverse sand dunes in Lower Victoria Valley, that the wind direction there is dominantly from the west in winter, while in the summer, easterlies dominate (Morris *et al* 1972; Selby *et al* 1974). From a study of ventifact distribution in eastern Victoria Valley, Selby *et al* (1973) concluded that the wind regime that exists there at present has probably been similar for much of the Quaternary.

The wind regime at Marble Point is significantly different to that of the valleys of the oasis. South and southeasterly winds predominate, although northerlies, easterlies and local westerlies also occur (Bull

*the polar plateau

1966; Nichols 1966). A diurnal cycle of north to east winds alternating with westerlies in the summer months appears to be less developed than at Vanda (Bull 1966).

4.4 Winds with vertical development

There are many examples of wind with vertical development. Dust devils and snow and dust whirls occur frequently in Wright Valley (Bromley, N.Z. Met S. personal communication; Riordin 1973) and have been observed in other places as well (personal observations; Mawson 1915; Rusin 1964). Most of the thermally induced dust devils have vortices up to 20m high with diameters up to 5m wide, although vortices up to 400m high and diameters as wide as 100m have been known (NZ Met. S unpublished manuscript'a'). Snow and dust whirls up to 200m high and occasionally tornadoes up to 1000m high occur in the winter during severe westerly gales (Bromley NZ Met. S, personal communication). Velocities in these vortices are sufficient to move and carry large objects such as packing cases, and to damage buildings and stores at Vanda Station (NZ Met. S, unpublished manuscript 'a'). Rusin (1964) noted very sudden velocity increases from zero up to $35 m.s^{-1}$ followed by rapid velocity drop-offs during the passage of such vortices at Mirny Station.

Other examples of vertical winds or updrafts also exist in the McMurdo region. Cumulus clouds indicating upward convection are not uncommon in summer over ice-free areas. Orographic effects and clouds have been noted on Mounts Erebus and Discovery. Much of the kinetic energy of the surface winds, particularly the westerlies, is converted to turbulent energy during their passage over the uneven topography of the oasis (Solopov 1967).

Warmer air from dry valley regions overriding maritime air has also been noted in the region and elsewhere (Mawson 1915; Thompson and MacDonald 1961; Bull 1966). Synoptic scale effects such as convergent wind systems (cyclones) are discussed below in sections 4.8 and 4.9.

4.5 Scott Base and McMurdo Station

The wind regime on Ross Island is significantly different from that in McMurdo oasis. Histograms and wind roses for Scott Base and McMurdo Station have been published in Thompson and MacDonald (1961) and Weyant (1967). The following discussion is based on these works and also on Table 11, which includes wind rose data from Scott Base for the period January 1972 to January 1978 (from NZ Met. S. records). At McMurdo, easterly winds are most frequent during all seasons, although northeasterlies, southeasterlies and southerlies are also common. Southerlies have the highest wind speeds. Northeasterlies are relatively more frequent in the autumn and early winter months, while southeasterlies and southerlies are relatively more common in the winter and spring. Winds from the north to southwest also occur. The pattern is similar at Scott, with northeasterlies predominating, and with southerlies being the strongest. In summer, half the observations record north-easterly winds. Table 10 gives the mean windspeed and maximum gust data at McMurdo (Schwerdtfeger 1970). The mean windspeed at McMurdo is significantly stronger than at both Vanda and Scott which have similar mean speeds. As in the oasis, the strongest winds occur in the winter; however the mean windspeed tends to be highest during the winter at the Ross Island stations, which is not the case at Vanda.

4.6 Ross Island, excluding the summit area of Mt Erebus

Elsewhere on the coast of Ross Island, the annual wind regime is affected by topography. Mt Erebus causes considerable deflection of surface flow. Snow drifts, windscoops and lee effects (e.g. removal of snow cover from the sea ice to the northwest of and north of Dellbridge Islands) indicate that winds from the southeasterly quarter have the dominant effect along the western coast of Ross Island. Also meteorological observations there show that easterly to southeasterly winds predominate, although winds from the north and north-northwest are also common; winds from the western quarter are less common (David and Adams in Shackleton 1909; Simpson 1919). There is apparently some tendency for the wind conditions to become calmer in this area, once the sound has become firmly frozen over (David and Adams in Shackleton 1909). At Cape Crozier the dominant flow is southwesterly (Simpson 1919).

4.7 Summit region of Mt Erebus

The summit of Mt Erebus (3794m) experiences a different wind regime from that at sea level nearby. Observations of the plume of Mt Erebus led to the first statistical study of the prevailing wind direction in the middle troposphere (Schwerdtfeger 1970, quoting Meinardus 1938). This prevailing wind direction is west-southwest (Weyant 1966a; Logvinov 1968; Schwerdtfeger 1970).

However, winds from the west and southwest do not feature strongly on Table 12. This Table summarises wind observations made at the summit Observatory and camp site mainly during summer over a total of 64 days in October to January 1972 to 1979. At this site the topography may put an easterly bias on winds from the south. Wind speeds were measured with hand held anemometers two metres above the ground. The anemometers most commonly used (Sims, Model k/k) gave low readings in temperatures below about -20^{o}C; temperatures are usually colder than this (as cold as -35^{o}C, even in January). Therefore wind speeds were often estimated using the Table in Met 812 (1974), and maximum gusts given in Table 12 are approximations. The Table indicates that southeasterly and southerly winds predominate during the summer months at least - the time people are usually at the summit. Winds from the southwest and west total only about eleven percent of 95 observations. However, when observations made at the acclimatisation camps at Fang Glacier (77° 30'S, 167° 14'E, 2800m elevation) are included, west to southwest winds add up to fifteen percent of the observations.

TABLE 12 Summary of wind observations made at Mt Erebus summit camp/ Observatory site (77° 32'S, 167° 08'E, 3600m asl) over 64 days in October, November, December, January 1972-1979.

Direction	N	NE	E	SE	S	SW	W	NW	Calm
Frequency of occurrence (percent)	4	2	2	35	21	7	4	10	15
Approximate maximum gust at 2m ($m.s^{-1}$)	5	5	20	33	25	5	10	10	-

On the summit plateau and near the Observatory, the sastrugi patterns are dominated by winds from the southerly quarter. Along the northern border of the collapsing snow basin adjacent to the Observatory, the tallest (ca. 0.5m) sastrugi are dominated by south-easterly to southerly winds indicating that these winds are strongest on an annual basis. On the first ascent of the volcano in March 1908 David (in Shackleton 1909) found that the sastrugi were aligned SW-NE on the summit plateau northwest of what is now called Nausea Knob. These sastrugi had "a sharp edge directed towards the west".

According to the studies on sastrugi by Lister (1959) at South Ice, some of the tallest (oldest) sastrugi are aligned parallel to the direction of the strongest winds; the angle at the head of these sastrugi is more acute, they generally have the hardest surfaces and are more undercut. However, the more closely set sastrugi are aligned with the most frequent wind direction, where this is of generally lower velocity (Lister 1959). This is consistent with the sastrugi pattern on Erebus. The more frequent westsouthwest winds tend to steepen the western sides of the more southerly oriented sastrugi. Very occasionally heavy snowfalls (e.g. from the north) could obliterate the existing sastrugi pattern and subsequent winds re-establish a differently oriented pattern. However the dominant wind regime would eventually reassert itself on the modified snow cover. It is of interest here that a snow condition known as windslab, which typically occurs on lee slopes, has been noted (December 1972) on the east-facing inner slope of Side Crater.

A comprehensive set of upper air data from McMurdo Station was not obtained for this study. However rocket soundings from McMurdo (Logvinov 1968) have shown that near the elevation of the summit there is a marked seasonal trend in both wind direction and altitudes where various winds are predominant. Westerly winds dominate the easterlies in the zonal component except in spring and summer while southerlies dominate the meridional component and are strongest in the spring, at an altitude of 4000m. At about 5-6000m however, northerlies dominate the latter component except in the spring. Presumably then, westerlies are more common in winter at the summit of Erebus, although southerlies are stronger.

Evidently wind directions in the troposphere are complex. David and Priestley(in Shackleton 1909) noted this by observing the motions of an eruption cloud from Erebus in June 1908 and other clouds. Up to an altitude of about 2000m asl the wind was northerly; above this a southerly was blowing up to an altitude of about 4600m. From this level to at least 7000m the wind was again northerly. Table 13 illustrates the effect of altitude on wind direction from 10 November to 20 December 1966. The raw wind data was obtained (Bromley, NZ Met.S. personal communication) from upper air maps for midday (NZST) at McMurdo. The altitudes of the 500 mb and 700 mb surfaces are the December values given by Weyant (1966a). A data summary for the Erebus summit campsite gives a comparison; this summary does not include data from observations made in October and January. Although the two observation series are of different lengths and over different years, the following conclusions can be made.

TABLE 13 Frequency (%) of wind directions at various altitudes above McMurdo Station (10 November 1966 to 20 December 1966) and at the summit campsite, Mt Erebus (November, December 1972 - 1979, broken observation series).

	Altitude and Elevation (m)			
Wind Direction (quadrant)	1000 mb (surface)	700 mb (2700)	Erebus Camp (3600)	500 mb (5100)
North	26	27	7	41
East	27	11	32	4
South	31	35	50	15
West	16	27	11	40

A topographic bias apparently increases the frequency of south to south-east winds at the summit camp over what would be expected at a free atmospheric position of the same altitude. At the campsite, the prevailing winds are probably aligned parallel to the average slope contours, which are approximately north - south. The cold antarctic air tends to flow around topographic obstacles rather than rising over them (M. Sinclair, N.Z. Met. S. personal communication). The prevailing surface flow in the summit area is probably west-southwest, that being the prevailing wind direction in the middle troposphere (Schwerdtfeger 1970). However the strongest winds near the summit cone are south-easterlies to southerlies.

4.8 The cause of winds in the McMurdo region

A detailed account of the relationship between atmospheric pressure and synoptic situations with the surface wind regime is not necessary here. However, some comment on this relationship is desirable.

The local regime at Vanda is a complex interaction between the prevailing synoptic situation and topographical and local circulation effects. The diurnal regime of the sunlit months is due to local insolation and drainage effects along the mountain and valley sides and floor (NZ Met. S., unpublished manuscript 'b'; Thompson *et al* 1971a; Riordin 1973).

The larger scale flow patterns due to synoptic scale systems also affect wind regime in the oasis. Such flow occurs throughout the year when winds from synoptic disturbances aloft are channelled into the valleys becoming easterlies, westerlies (Thompson 1972; Yoshida and Moriwaki 1972; Riordin 1973), and/or northerlies or southerlies in exposed places. The westerly winds are of the foehn type (warmer than the air they displace), rather than true katabatics (gravity flow of cold air, colder than the air they displace), (Schwerdtfeger 1970; Thompson 1972; Yoshida and Moriwaki 1972). Nevertheless, Thompson (1972) acknowledges that gravity may play an important secondary role. In fact the prevailing anticyclonic flow aloft over the oasis, which is southerly (Mather and Miller 1967), has a westerly component along the edge of the plateau adjacent to the oasis. In this region the plateau rises to the west. Apparently then the prevailing flow, often influenced by synoptic disturbances, is deflected down towards the east into the valleys, becoming adiabatically heated during the descent. In the valleys these westerly winds are usually associated with low barometric pressure (Riordin 1973) or large pressure drops (Yoshida and Moriwaki 1972).

Near Scott and McMurdo the prevailing anticyclonic flow is given an easterly component by the bulk of Mt Erebus (Simpson 1919; Mather and Miller 1967). This deflection westwards by Mt Erebus and eastwards by Mt Terror, gives rise to an area of flow divergence with generally lighter winds in the area known as Windless Bight.

Cyclonic storms in the region give rise to strong winds from the south-east and south in the McMurdo Sound area, and also in areas of the oasis exposed to the south. According to Rusin (1964) cyclonic activity has marked seasonal trends; cyclonic winds prevail around the coast in summer but are less common in winter. Although cyclones are common in coastal areas (Rusin 1964), their influence is markedly reduced inland since they only occasionally penetrate deeply into the interior (Lamb and Britton 1955; Astapenko 1964; Rusin 1964; Weyant 1967). Further than about 100 km from the coast of South Victoria Land, frontal passage and cyclone activity are infrequent.

4.9 Surface winds in East Antarctica and general atmospheric circulation

In East Antarctica the predominant surface flow is broadly outwards towards the coast (Mather and Miller 1967). On the plateau surface the prevailing direction is at a constant angle (about 45^{o}) to the true left of the fall line. With increasing height through the lowest few hundred metres of the atmosphere, this prevailing "inversion" wind tends to turn to blow parallel to the contours (Schwerdtfeger 1970). At South Pole the mean annual wind speed is $4.8 m.s^{-1}$ while at Vostok it is $5.1 m.s^{-1}$ (Schwerdtfeger 1970).

Such winds are different from those produced by gravitational attraction for cooled air of greater density lying above steeply inclined snow and ice surfaces. The latter type of wind is a true katabatic (Schwerdtfeger 1970) and is common around the coast of East Antarctica in places where the continental ice sheet drops sharply towards the sea (Cape Denison, Mawson and Mirny Stations). However, winds from the easterly quarter generally prevail in the coastal zone of East Antarctica, outside the regions where katabatic flow occurs (Rusin 1964; Mather and Miller 1967; Weyant 1967; Schwerdtfeger 1970).

Both the inversion and katabatic winds are affected by synoptic disturbances (Rusin 1964; Mather and Miller 1966; Schwerdtfeger 1970), such as cyclones. A simplified current view of the antarctic circulation pattern in the troposphere depicts what is effectively a recurring blocking anticyclone centred over central East Antarctica, surrounded by low pressure areas centred north of the continent (Astapenko 1964; Solopov 1967; Schwerdtfeger 1970, quoting Taljaard 1969). Effectively, the anticyclone allows the prevailing outward surface flow with cyclones orbiting this high, and occasionally penetrating inland.

Astapenko (1964) distinguishes two types of cyclones: relatively shallow cyclones which are formed mainly on Antarctic and intra-Antarctic fronts and move latitudinally from west to east around the continent; and deep, high cyclones which are formed mainly on Polar fronts and move with a meridional component (Solopov 1967). The Antarctic fronts occur at about 60 - 70^{o} S, whereas the Polar fronts occur at about 45 - 50^{o}S (Lamb 1970). Weyant (1967) illustrates the tracks of cyclones with a series of maps depicting mean monthly conditions. These show that some storms completely cross West Antarctica from Ross to Weddell Seas and some cross (eastern) Wilkes Land and northern Victoria Land. Penetration into the East Antarctic interior is infrequent; when this occurs it is usually south from Ross Sea or Marie Byrd Land and only occasionally from the South Atlantic and Indian Oceans. Pressure gradients developed during the passage of these cyclones may strongly affect surface winds (Mather and Miller

1966). The normal surface flow may be intensified or reduced to the extent where winds may become contrary to the prevailing direction.

For example, one low pressure disturbance was observed during its passage into the interior, at Alligator Peak (78° 27'S, 158° 45'E, 1550m elevation) in December 1973. This site is some 75 km from Hillary Coast and 150 km inland from McMurdo Sound. High cloud began arriving at 1400 hours on the 15th and the prevailing strong southwest wind dropped soon after. At 1700 hours on the 16th, a northeast wind of 4.6 $m.s^{-1}$ was blowing. At 2130 hours on the 17th, snow was falling lightly and intermittently, and the wind was again calm. Atmospheric pressure was rising at this time. By 0830 hours on the 18th a light southwest wind was blowing and snow was still falling very intermittently. The prevailing strong southwesterly was blowing by 1330 hours on the 19th.

Upon reaching the high elevation surface of the East Antarctic Ice Sheet, the lower portion of cyclones are deformed and slowed down: hence it is mainly the upper sections which penetrate the interior in the form of currents of relatively warm and humid sea air (Rusin 1964). It is this meridional inflow of tropospheric air that mainly replenishes the heat lost by radiation from Antarctica (Weyant 1966b) and leads to the nourishment (5.1) of the continental ice sheet. The inflow involves mainly Marine Antarctic and Marine Temperate Air masses, but occasionally Marine Tropical Air (Solopov 1967). There are preferred areas of inflow (and outflow) in the atmosphere above Antarctica, although "large deviations of the meridional wind components from their average values exist in space or time" (Lettau 1969 p.332). Modelling the distribution of the nett annual mass flux around the periphery of the continent from the surface up to 50 mb, Lettau (1969) suggested that maximum values of mass inflow occurred at Byrd, Davis and Mirny Stations, while maximum outflow occurred at Hallett, Dumont d'Urville and Ellsworth Stations. Weyant (1966b) suggested that two-thirds of the inflow into the East Antarctic interior occurs in the 140° sector between longitudes 80°E and 140°W. Ohtake (1976) using air trajectory analysis, showed that air arriving at Pole Station normally enters the continent in the 80° sector between 90° W and 170°W.

Meridional circulation also occurs in the antarctic stratosphere (Logvinov 1968; Lettau 1969; Lamb 1970). Logvinov (1968) illustrates the meridional component of wind velocity in the atmosphere, particularly the stratosphere above McMurdo. Southerly flow dominates the meridional component from the surface to about 5 km, while northerly winds (up to about 25 $m.s^{-1}$) dominate this component in the rest of the troposphere and in the entire stratosphere (see also Table 13).

Generally then, the 'average' meridional circulation pattern in the troposphere and stratosphere above East Antarctica, is one of radial inflow followed by subsidence (Logvinov 1968; Lamb 1970; Schwerdtfeger

1970; Lysakov 1978) and outward surface flow. This pattern is superimposed on the dominant strong westerly circulation (the circumpolar vortex) in the upper troposphere and lower stratosphere (Weyant 1966a; Solopov 1967; Logvinov 1968; Schwerdtfeger 1970).

5. PRECIPITATION

5.1 General

Precipitation is an important hydrometeorological element in Antarctica, playing fundamental roles in the water and heat budgets of the continent. The discussion here is mainly based on forms of water, both in the atmosphere and on the ground, as they apply to vertical and horizontal transport of saline material. Some general aspects of precipitation are outlined first, followed by discussions on the precipitation regime in McMurdo oasis and on the various types of precipitation.

The original source of nearly all the atmospheric water vapour precipitated over Antarctica is the open water of the southern hemisphere oceans (Weyant 1966b). This moisture is transported mainly in the troposphere in the regions of preferred inflow as outlined in section 4.9. Most of the moisture is carried by the warmest air (Lettau 1969). However the saturation vapour pressure of water (see section 6.1) is very low at the mean temperatures (see Figure 6) of the antarctic troposphere. Hence there is very little 'precipitable water' in antarctic air and Antarctica experiences an arid or semi arid environment. However there is a large amount of moisture not readily available in the continental ice sheet, glaciers and frozen ground.

In Antarctica, precipitation is almost always in the solid form. Consequently its direct measurement is difficult, mainly due to the influence of wind which under different conditions may cause snow to be blown from, or deposited in snow gauges (Bull 1971). Instead, nett precipitation or accumulation which includes a large contribution from blowing and drifting snow, is often measured. Ablation of surface snow is very small on the plateau west of McMurdo oasis (section 6.2). Therefore there, accumulation is a good measure of total precipitation (including blown snow). The mean annual accumulation over the antarctic continent and ice shelves is around 150 $kg.m^{-2}$ (Bull 1971). This is equivalent to 430mm of snow of density 350 $kg.m^{-3}$ (Bull 1971) or 150mm of water.

In specific localities the accumulation may vary by a large amount from the average of 150 $kg.m^{-2}$ (Table 14). At a snow pit site in the McMurdo Ice Shelf 5 km east of Scott Base, the average accumulation was 176 $mm.a^{-1}$ water equivalent (density 390 $kg.m^{-3}$) for the period 1914 - 1958 (Stuart and Bull 1963). A reliable estimate of precipitation at Scott Base itself is not known, but snow falls there on about 90 days in a year (Thompson 1972). Each typical snowfall amounts to a few millimetres only, but occasionally a fall of a few centimetres occurs. Further north on the coast of McMurdo Sound, snow falls on more days (Rusin 1964). Early expeditions obtained estimates of precipitation of around 200mm water equivalent at Cape Royds (David and Priestley in Shackleton 1909) and 500mm water equivalent at Cape Adare (Wright and Priestly 1922). Annual precipitation is much less at Vanda Station.

TABLE 14 Annual snow accumulation and precipitation in Ross Dependency (Standard deviations in parentheses)

Locality	Accumulation (water equivalent	Precipitation in millimetres)	Reference or source of data
Vanda Station	nil	5 (6)	Thompson *et al* (1971a); NZ Met. S. unpublished manuscript 'c' Section 5.2
whole of McMurdo oasis	0 - 100	100	
Ross Ice Shelf drainage system	100±20	-	Giovinetto (1964)
Skelton Neve (Station 72)	130	-	Crary (1966)
whole of Antarctica (including ice shelves)	150	-	Bull (1971)
5 km east of Scott Base	180 (50)	-	Stuart and Bull (1963).
Cape Royds	Nil	200	David and Priestley in Shackleton (1909)
Cape Adare	Nil	500	Wright and Priestley (1922)

Reasonable estimates of the snowfall at Vanda are 82mm (1969), 7mm (1970) and 115 mm (1974) (Thompson *et al* 1971a; NZ Met. S. unpublished manuscript 'c'); the mean is 68mm.a^{-1} with a standard deviation of 78mm.a^{-1}. Bromley (NZ Met. S. personal communication) determined the snow density of two typical falls to be close to 80 Kg.m^{-3}. This low value is close to that of snow composed of delicate stellar crystals and deposited in little wind (60 Kg.m^{-3}) (La Chapelle 1969). Thus the mean annual precipitation at Vanda is equivalent to around 5 mm of water (standard deviation, 6mm); however the three year observation series is too short for this figure to be reliable. For comparison, at Station 72 on the plateau west of Skelton Neve, the mean annual accumulation is equivalent to about 360 mm of snow (Crary 1966) or about

130mm of water. For the whole Ross Ice Shelf drainage system Giovinetto (1964) calculated that the mean annual accumulation was equivalent to about 300 ± 60mm of snow or about 100 ± 20mm of water. Most of the original precipitation contributing to this accumulation is snow that falls during the passage of cyclones (Rusin 1964).

The general pattern in Antarctica is one of relatively high precipitation on the coast. Precipitation tends to decrease inland away from the sea. The contribution of blowing snow may affect these generalisations. Generally, precipitation is erratic in arid areas; relatively large amounts of precipitation can be expected on a long return basis.

5.2 Snow and precipitation in McMurdo oasis

The precipitation regime at Vanda Station has been discussed by NZ Met. S., unpublished manuscript 'C' entitled "Precipitation in the dry valleys of southern Victoria Land". Some of the following discussion is based on parts of this manuscript.

Snow falls account for virtually all the precipitation in the oasis. Other forms of precipitation occurring in the McMurdo region are discussed below in sections 5.4 and 5.5 The snowfalls at Vanda are very variable; falling snow at the station itself, was reported on 59 days in 1969; but only on 11 days in 1970 (Thompson 1972). In the general vicinity of the station however, snowfalls are not infrequent, occurring on an average of about 100 days per year (standard deviation ca. 60 days, calculated from NZ Met. S., unpublished manuscript 'C'). Although snow may fall at any time during the year, snow falls on more days during the sunlit months. There is no marked increase in precipitation at Vanda during the summer, although there appears to be some tendency for greater amounts of snowfall in the autumn or early winter: in 1970 the heaviest single fall of the year (5mm) occurred in April, while March 1974 had the largest monthly total (89mm) since records began in 1969 (NZ Met. S., unpublished manuscript 'C'). Significantly, March has the most days with snowfall at Hallett Station (Schwerdtfeger 1970) on the coast of northern Victoria Land. February and March also feature in such records at Scott Base (Thompson and MacDonald 1961). This correlates with the greater amount of cloud during autumn at Scott, McMurdo and Hallett (Thompson and MacDonald 1961; Schwerdtfeger 1970) and during December - February at Vanda (Thompson *et al* 1971a).

Snowfalls occur commonly as showers from convective clouds in McMurdo oasis during the sunlight months, although the winter pattern is also followed: in winter lengthier falls occur from low status and strato-cumulus clouds drifting into the valleys from the east and west (Riordin 1973; NZ Met. S., unpublished manuscript 'C'). On these occasions, the snowfalls are associated with major depressions passing over or north of the area. Such depressions give rise to moist east or northeast air streams which have travelled across open sea before passing over the region (NZ Met. S. unpublished manuscript 'C').

There are marked precipitation gradients in the valleys of the oasis. More snow falls in the eastern and far western ends of Wright Valley than at Vanda; generally the eastern parts of the valleys receive the most snowfall (Calkin 1964 ; Bull 1966; Everett 1971; Riordin 1973; NZ Met S., unpublished manuscript 'C'). The snowline is lowest in the east and rises towards the west (Bull 1966; Wilson 1967). Snow drifts left from winter are common in spring along the coastal areas bordering McMurdo Sound, but become less common inland in central parts of the oasis.

Precipitation is higher in Taylor Valley than in Wright Valley. The former is open to the east, whereas Wright Lower and Wilson Piedmont Glaciers form a barrier 300 - 400 metres high, against westward - moving clouds and moist air. Wright Valley is significantly drier than Taylor Valley as indicated by the more common presence of suprapermafrost groundwater in Taylor Valley (Cartwright *et al* 1975), and a greater abundance of small lakes. Snowfall is more prevalent and heavier at higher elevations than on the valley floor. Falls exceeding 100mm may occur above 600m (Riordin 1973 ; NZ Met. S. unpublished manuscript 'C'). Anderton and Fenwick (1976) suggest (in a preliminary report) that in the hanging valleys of Asgard, Olympus and St Johns Ranges (i.e. above about 1000m elevation) the bulk of the annual precipitation usually occurs in summer. On five glaciers in the oasis (Sykes, Alberich, Heimdall, Meserve and Packard) stake networks have shown that the nett annual accumulation is less than 100mm water equivalent at most locations (Anderton and Fenwick 1976). Maximum recorded annual ablation above 1000m elevation on these glaciers is about 100mm water equivalent (Chinn unpublished). Therefore, 200mm water equivalent is probably a rough estimate of maximum annual precipitation above 1000m elevation in McMurdo oasis. Both accumulation and ablation on these glaciers are affected by topography (Chinn unpublished), and therefore the estimate is probably high.

100mm water equivalent (100 $kg.m^{-2}$ or 1000mm of snow of density 100 $kg.m^{-3}$) is probably a reasonable estimate of average annual precipitation in McMurdo oasis.

The fallen snow does not lie for long periods on the valley floors and lower portions of the valley sides. In winter the snowfall will lie until the arrival of strong to gale foehn westerly winds. These winds which are associated with low relative humidities (6.1) quickly clear most of the snowfall in winter, but often isolated snow drifts are left in sheltered places (Riordin 1973; NZ Met. S., unpublished manuscript 'C'). In summer the foehn winds, high solar radiation and relatively warm ground surfaces quickly clear any snowfall. It is well known that most snow is cleared by sublimation and that little melting occurs on a regional basis. Locally however, melting may occur in summer, especially on sunny days, around the fringes of snowdrifts, snow patches and dark rocks in sub-zero air temperatures. This occurs from sea level to at least 3800m elevation, (personal observations in December 1974 of the surface of permafrosted ground on Mt Erebus), especially on north-facing slopes. When air temperatures are above zero, melting may be intense.

5.3 Structure and growth of the snow crystals

The typical snow particles falling in McMurdo oasis and near the coast around McMurdo Sound are stellar crystals (dendrites), usually about 1-3mm in diameter (Mawson in Shackleton 1909; NZ Met. S. unpublished manuscript 'C'; personal observations). Individual stellar crystals larger than 5mm have been seen throughout the region in summer, as have large snow flakes (assemblages of individual crystals). Such crystals are probably formed in the saturated environment of stratiform clouds when there is little wind to break up the delicate structures. Such wind conditions during snowfalls are typical of the oasis, especially in winter (NZ Met. S., unpublished manuscript 'C'). Low, detached nimbostratus clouds and probably low level convective clouds, also produce such frail tabular crystalline snow forms and some plates (Wright and Priestley 1922; and quoting Bentley 1901; Shumskii 1964). These crystals may become broken in the slightly stronger winds and turbulence associated with such clouds. The crystals will be broken into many fragments by the strong winds which are typical in blizzards.

Fine granular snow, usually less than 1mm in diameter is also common at Vanda (NZ Met. S., unpublished manuscript 'C'). This snow may be a small form of 'graupel', consisting of fragments of snow crystals completely enveloped in rime due to passage through a supercooled cloud (La Chapelle 1969). Fine granular snow, often less than 0.5mm in diameter and consisting of minute columns and plates, is also typical of snow falling in polar regions (La Chapelle 1969).

More solid crystals are produced in clouds at higher levels. Intermediate-level clouds (altostratus and altocumulus) deposit crystals which have solid hexagonal centres with some dendritic extensions (Wright and Priestley 1922; and quoting Bentley 1901; Shumskii 1964) in relatively warm conditions. Combined ice crystals, up to 1mm diameter, in the form of sideplanes (sectors), bullets and columns are created in such clouds in colder conditions as at South Pole in summer (Ohtake 1978). Cirrus and cirrostratus clouds form compact columnar type crystal assemblages, 1mm or larger, composed of combinations of bullets and some small plates (Shumskii 1964; Ohtake 1978). In general cyclonic disturbances contain different types of clouds at different levels. Large scale vertical mixing of air in these storms will lead to a variety of crystal shapes, many of which will be fragmented.

Evidently then, in Antarctica the growth of snow crystals is predominantly by diffusion controlled processes. In cold, dry air growth of a newly nucleated ice particle is slow and tends to be parallel to the crystallographic c-axis of the ice crystal. The precipitated crystals are small, compact and columnar forms are apparent. Where relatively large amounts of water vapour are present, growth is relatively fast and parallel to the a-axis. Thus the precipitated crystals are larger, and stellar and plate forms are evident. In warm and saturated or supersaturated environments ice and snow crystals may grow by riming as water droplets collide with and freeze to the crystals. This accretional growth occurs in cloud droplet regions when temperatures are between 0 and $-15^{o}C$ (Magono and Lee 1966). At antarctic stations near the coast a significantly high proportion of precipitated crystals have been found to have grown by accretion (Warburton and Linkletter 1978).

5.4 Blowing snow

When wind blows over a snow surface, horizontal stresses are developed in that surface. At a certain wind speed these stresses are strong enough to shear snow particles loose from the surface. These particles are raised to a height determined by the wind speed and turbulence, and travel with the flow of air. Although the technical details of wind transported snow are not discussed here, certain aspects of blowing snow are necessary to the discussion of salt transport.

Under normal antarctic conditions, horizontal snow transport commences near the surface when the wind speed at 5m reaches about 6.5 to 10 $m.s^{-1}$ (Rusin 1964; Oura and Kobayashi 1968) or at 10m exceeds 8 $m.s^{-1}$ (Schwerdtfeger 1970; Maki 1971). The exact speed is dependent on the state and temperature of the snow surface. With higher wind speeds the snow is carried higher into the air. At 18 $m.s^{-1}$ the snow reaches higher than 3m, while in the most violent winds snow may be carried by turbulent suspension to heights of hundreds of metres. Most snow however is transported within about half a metre of the surface, and mainly by saltation processes.

Blowing* and drifting* snow are important sources of snow accumulation in Antarctica. However, in McMurdo oasis their influence is small except in local areas near alpine glacier neves and exposed eastern but more especially western ends of the major valleys. Occasionally vast clouds of blowing snow are swept off the plateau by violent westerly gales. These clouds extend up to 3000m in height and completely fill Wright Valley to the west; however only a little snow settles behind the larger boulders (NZ Met. S., unpublished manuscript 'C').

*Blowing snow consists of snow (and ice) particles raised by the wind to more than a metre above the ground; whereas with drifting snow, the particles are raised to heights of a metre or so, so that visibility at eye level is not noticeably diminished (Armstrong *et al* 1973).

Blowing snow is common in the McMurdo Sound area. Table 11 indicates that winds from all eight major directions are sometimes strong enough to blow snow at localities along the coast. Sticky snow impregnated with salt that is common on the surface of the sea ice of McMurdo Sound (Wellman and Wilson 1963), will be blown free from the surface but at higher velocities than normal macroscopically salt-free snow. Along the coastal areas, blowing snow is responsible for large drifts and permanent ice accumulations. Strong winds from the south and southeast create large drifts in areas where the wind speed locally decreases, such as in the lee of hills and smaller obstacles on the land surface at Cape Evans, Barne and Royds. David and Adams (in Shackleton 1909) noticed that during the earlier part of blizzards, snowdrifts were formed mainly of old snow. Towards the end of the blizzard however, fresh snow would be deposited, probably produced from moisture carried by the upper air currents in the storm.

Blowing snow is of major importance in areas along the western side of McMurdo oasis such as Kennar Valley, Shapeless Mountain (etc) that border the plateau . Snow blowing off the plateau may settle as a thin veneer, or in drifts and may create permanent ice accumulations. Favoured areas for these types of snow accumulations are those where the wind speed locally decreases such as gullies, depressions and north through eastern sides of boulders, hills, bluffs and ridges. From observations in those western ice-free areas such as Kennar Valley it appears that they more commonly experience precipitation from blowing snow than do adjacent areas to the east such as Beacon Valley.

Obviously such accumulation is not restricted to areas west of McMurdo Sound. Blowing snow affects ice-free areas and nunataks along the entire Transantarctic Mountains. At Roberts Massif at the head of Shackleton Glacier, Claridge and Campbell (1968) noted that much of the snow was derived from snow blown off the plateau. They also suspected that most of such snow was removed by sublimation rather than melting.

On the plateau itself, blowing and drifting snow are responsible for transporting vast amounts of snow. This transport is generally outwards from the interior in the direction towards which the prevailing surface wind is blowing (see 4.9). It has been estimated that a flux of around 3×10^6 Kg and 6×10^7 Kg respectively of snow is transported per metre of surface each year at Byrd Station and Cape Denison (Schwerdtfeger 1970). Transport at Pole Station is similar to that at Byrd. The number of days with blowing snow at various antarctic stations is listed in Weyant (1967) and Schwerdtfeger (1970). Byrd, Ellsworth, Little America V, McMurdo, Pole and Wilkes Station areas experience some winter months with 10 to 15 days or more of blowing snow. At most antarctic stations the frequency of blowing snow is less in November through February, mainly because of lower mean wind speeds in those months, but also because of warmer surface conditions.

5.5 Other forms of precipitation

Although snowfall and blowing snow account for most precipitation and accumulation in Antarctica, other forms of precipitation do occur. These other types of precipitation may have some relevance to the question of salt origin.

One of the biggest fallacies popularly held about the antarctic climate is that rain is unknown. Rain, an efficient remover of soluble material from the atmosphere (Gorham 1961) is very uncommon, but does occur occasionally in the coastal regions of Antarctica. Known occurrences of rain or near-rain in and near Ross Dependency are listed in Table 15; each produced very small amounts of precipitation.

TABLE 15 Known occurrences of rain and near-rain in or near Ross Dependency

Precipitation form	Locality	Date	Reference
Drizzle and rain	Ross Sea	February 1842	Ross (1847)
Rainbow	Cape Royds	22.12.08	Murray in Shackleton (1909)
Rain	Ross Sea	1910 - 13 expedition	Wright and Priestley (1922)
Rain	Cape Adare	1910 - 13 expedition	Wright and Priestley (1922)
Rainbow	NNE Cape Evans	14.2.11	Simpson (1919)
Drizzle	Little America V Station	10.5.57	Vickers (1966)
Slushy snow	Little America V Station	11.5.57	Vickers (1966)
Sleet	Little America V Station	31 March and 1 April 1958	Vickers (1966)
Rain	McMurdo Sound	30.11.58	Quartermain (1958)
Rain	Lake Vanda	January 1959	Bull (personal comm.)
Rain and slushy snow	Little Rockford Station 79°S 151°W	early February 1961	Quartermain (1961)
Light drizzle	Hallett Station	18.1.62	Anon (1962)
Light rain shower	Vanda Station and west end of Lake	late December 1968	Bromley, NZ Met.S. personal communication
Rain	Vanda Station	January 1970	NZ Met.S. 'C'
Rain showers	Vanda Station	19.5.74	Bromley NZ Met. S. written communication
Wet snow falls	McMurdo oasis and coast of McMurdo Sound	occasional	Bromley NZ Met.S. personal communication; Keys, personal observations.

Clouds containing super-cooled water droplets are a normal occurrence in Antarctica, especially in summer. Such clouds exist up to at least 3000m. Pilots reported freezing rain on some occasions when flying missions over Antarctica in early Operation Deepfreeze years (Dufek 1957). Fogs, mist, frost smoke+, hoarfrost, ice flowers* and rime accumulations are not uncommon in the McMurdo Sound area. A special case of rime accumulation occurs around the summits of Mounts Discovery and Morning. Snow and ice features up to 20m high are largely covered with the characteristic (La Chapelle 1969) rough, channelled and feathered deposit of rime and rime-cemented snow. Orographic type clouds involving rapid lifting of air in strong winds from the south have been seen (December 1974) blanketing the upper part of Mt Discovery. Such conditions probably lead to the formation of these rime accumulations which indicate the presence of super-cooled water droplets at temperatures as cold as about -20°C. Fogs containing such droplets have been observed at temperatures as low as -34°C in the vicinity of Little America Station (Rusin 1964). In the interior of the continent fogs consist of ice crystals in winter but probably mixtures of ice crystals and super-cooled droplets in summer (Rusin 1964) if the ambient air temperature is warmer than about -40°C.

At Vanda Station a wet formation with "the appearance of a quite heavy dew" is not uncommon: this "dew" forms on rocks, particularly the darker ones around the station (e.g. 11, 12 February 1970; Bromley NZ Met.S., personal communication). Frosts have also been noted (NZ Met. S. records).

Ice crystals falling from a clear sky ('no cloud precipitation') is a common form of precipitation in the interior and also in the McMurdo region (Rusin 1964; Schwerdtfeger 1970; Riordin 1973; Ohtake 1978). At South Pole in summer, this form of precipitation is created in the lowest 1000m above the surface and consists of thin hexagonal plates and columns smaller than 0.2mm (Ohtake 1978). The thin plate crystals are formed at temperatures colder than -22°C (Ohtake 1978) whereas their generally accepted range of formation temperatures is between -10 and -18°C (Magono and Lee 1966). To explain their formation in humidities less than the water or ice saturation values, Ohtake (1978) proposes a mechanism of "deposition nucleation" - water deposition directly onto nuclei under sub-water or ice saturation conditions.

+ frost smoke is thin fog-like cloud formed by contact of cold air with relatively warm water.

* Ice flowers are fern-like ice formations up to ca.30mm long formed by freezing of frost smoke, fog or water vapour under some conditions: the term, as used here, includes "fog crystals" and some types of "frost crystals" (Wright and Priestley 1922) but not Tyndall figures (forms caused by internal melting of ice (Shumskii 1964, quoting Tyndall 1858). Ice flowers have been seen by the present author on the sea ice of McMurdo Sound and the lake ice of Lake Bonney.

Spray blown from the sea is a major form of precipitation within 200-300m of the coast of McMurdo Sound (Wright and Priestley 1922). For this form of precipitation to be important, there must be open water relatively close to the windward side of land and the wind must be strong enough to blow the tops off waves. Spray is blown from the sea when the wind is stronger than about 10 $m.s^{-1}$; spindrift occurs when the windspeed is 14-17 $m.s^{-1}$ or stronger (Harvey 1976). Winds of this strength are common from the southerly quarter in the coastal areas of the Sound (4.5, 4.7, Table 11). Winds from the northerly quarter are also strong enough on occasions. Open water may exist in late summer, autumn and early winter to the north and south of Cape Armitage, Hut Point, Capes Evans, Barne, Royds, Cape Bird ice-free area and Cape Bernacchi-Marble Point area. In the autumn sea spray may form the well-known 'storm ice foot' along the coast line itself (Wright and Priestley 1922). Early expeditions report instances of heavy deposition of frozen sea spray and the formation of 'spray ridges'. Spray was blown ca.400m inland at Cape Royds during a five-day southeasterly blizzard in February 1908 when Backdoor Bay was only partly clear of ice; accumulations of frozen spray up to ca.2m thick were formed (Shackleton 1909). Clearly, over many years, wind-blown sea spray is an important form of precipitation in coastal areas of McMurdo Sound, despite the presence of sea ice for twelve months of a particular year at some localities.

5.6 Variations in precipitation over the last 80 years

At stations in the McMurdo region the observation series are too short to show any significant recent changes in the precipitation regime. Precipitation parameters from Orcadas Station suggest a slight decline in precipitation activity since 1935; this may be interpreted as a slight lessening in intensity of cyclonic activity in the area (Schwerdtfeger 1970). Some studies have pointed to an increase in snow accumulation in the interior and there is evidence for a decrease of ice in some coastal areas near the Antarctic Circle (Schwerdtfeger 1970). No significant trends are evident in the snow pit data of Stuart and Bull (1963) for 45 years of accumulation between 1913 and 1958 revealed at a site on McMurdo Ice Shelf 5 km east of Scott Base.

6. ATMOSPHERIC HUMIDITY

6.1 General

Humidity affects the hydration state of some salts in the region. Also Wilson (1979) proposed that migration and separation of salts occurs down slopes under the influence of fluctuating humidities and humidity gradients in the McMurdo region. For the separation process to be viable in the field, positive humidity gradients must at times exist up slopes. In this section, atmospheric humidities and humidity gradients are discussed.

Several quantities and characteristics of atmospheric humidity or moisture content may be defined and measured. Here the emphasis is placed on relative humidity, but absolute humidity, water vapour pressure, saturation vapour pressure, dew point and mixing ratio are also mentioned. These terms are defined in Table 16.

TABLE 16 Definitions, symbols and units of terms relating to humidity used in this study (definitions after Wexler 1970; and Weast 1975).

Term or Quantity	Symbol	Unit	Definition and Characteristics
Water vapour pressure	e	millibars*	partial pressure exerted by the water vapour present in the atmosphere.
saturation vapour pressure	E_w E_i	mb	the pressure of water vapour (unmixed with a foreign gas) in equilibrium with a plane surface of pure, liquid, water (Ew), or pure, solid, ice (E_i). Decreases with decreasing temperature (Figure 6).
'saturated'	-	-	a moist gas is said to be saturated with respect to liquid water or solid ice when it can co-exist with pure liquid water or pure solid ice at a given temperature and pressure.
absolute humidity	a	$Kg.m^{-3}$ or mb	mass of water vapour present in a unit volume of the atmosphere. It may also be defined in terms of the water vapour pressure, e
relative humidity	f	percent	the ratio of the quantity (or pressure) of water vapour present in the atmosphere to the quantity which would saturate (or the saturation vapour pressure) at the existing temperature. When the temperature is less than $0^{o}C$ at NZ stations in Antarctica, the saturation is defined with respect to ice (Tomlinson, NZ Met.S. personal communication).
dew point (frost point)	T_d T_i	^{o}C	the temperature at which condensation of atmospheric water vapour takes place: the temperature at which the air is saturated with respect to water (T_d) or ice (T_i).
mixing ratio	r	$g.kg^{-1}$	the mass of water vapour associated with a unit mass of dry air.

*the millibar is not an SI unit: however its use is retained here to be consistent with units of atmospheric pressure previously mentioned and also with NZ Met.S. usage. Note that 1 mb = 100 pascals ($N.m^{-2}$).

The problems of measuring humidity at low temperatures are well known (Thompson and MacDonald 1961; Rusin 1964; Schwerdtfeger 1970; Wexler 1970). These problems are due to the difficulty of measuring the small amounts of water vapour present; the concentration may be less than 0.75 ppm (Wexler 1970). Even some modern hygrometers have reduced sensitivity and accuracy at low temperatures (Wexler 1970). Computational methods based on the temperature-saturation vapour pressure relationship and ambient temperature may be more reliable in such conditions (Schwerdtfeger 1970; Artem'ev 1973). For these reasons many values of humidity given in the antarctic literature must be treated with reserve. Strictly speaking, 'mean relative humidity' or 'mean dew point' cannot be used to deduce the mean moisture content at a locality because of the non-linear relationship between temperature and saturation vapour pressure (Figure 6) (Schwerdtfeger 1970). Often qualitative estimates may be useful.

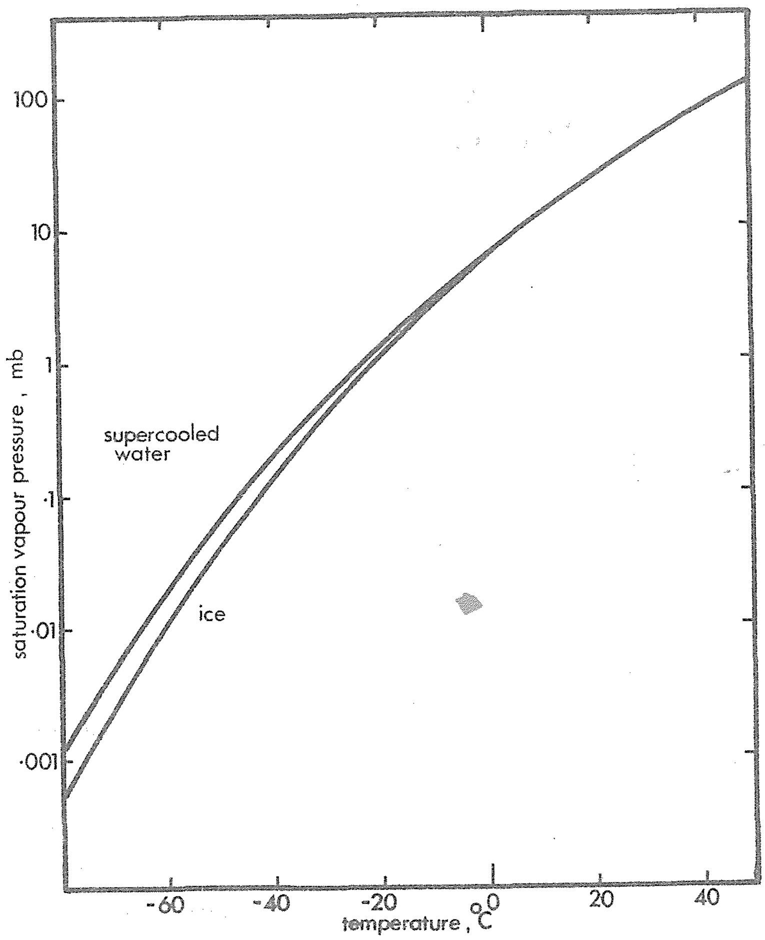


FIGURE 6 Relationship between the saturation vapour pressure and temperature of the pure water substance (after Wexler 1970).

The published monthly averages of relative humidity values at Vanda (Thompson *et al.*, 1971a; Thompson 1972) show consistently lower values in summer. The relative humidities average 30 - 50 percent in summer (minimum less than 10) and probably 50 - 80 percent in winter; during 1969 and 1970 the average RH was 54 percent (Thompson 1972; NZ Met.S. records). At Scott Base, average monthly relative humidities are seldom less than 60 percent and range to more than 80 percent with relatively little difference between winter and summer; during 1958 the average RH was 71 percent (Thompson and MacDonald 1961; NZ Met.S. records). It has been estimated (Schwerdtfeger 1970) and calculated (Artem'ev 1973) that considerable supersaturation with respect to ice may occur in the air at interior stations, especially in winter. It is suggested that this supersaturation, of up to 20 percent probably occurs on occasion in the McMurdo region also, as evidenced by fog, rime and ice crystals (5.5).

The relative humidities at Vanda (and elsewhere) may be converted to absolute humidities using Figure 6 and Equation 3 below. The mean summer temperature at Vanda is about +0.8°C and the mean winter temperature is about -32°C (Table 2); saturation vapour pressures at these temperatures are 6.473 and 0.309 mb respectively (Weast 1975). The absolute humidity a, in $kg.m^{-3}$ is related to the water vapour pressure e, in millibars and to absolute temperature T, by the following approximate formula (Petterssen 1941):

$$a = \frac{0.217e}{T} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; 1$$

For meteorological purposes moist air can be assumed to be an ideal gas; relative humidity f, then is given by:

$$f = \frac{e}{E} \times 100 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; 2$$

where E is the saturation vapour pressure at the ambient temperature, T. By substitution we have:

$$a = \frac{f.E}{T} \times 2.17 \times 10^{-3} \quad . \; . \; . \; . \; . \; . \; . \; . \; 3$$

Using Equation 3 and the mean values of T and E given above, the average values of absolute humidities at Vanda were calculated to be about $(1.5 \text{ to } 2.6) \times 10^{-3}$ $kg.m^{-3}$ in summer, and about $(0.14 \text{ to } 0.22) \times 10^{-3}$ $kg.m^{-3}$ in winter. On a purely scientific basis these results are slightly high due to the non-ideality of moist air; however in practical meteorological terms such precision is not necessary.

The central regions of East Antarctica contain the "Pole of lowest absolute humidity" (Rusin 1964). Generally, it can be stated that the air moving down off the polar plateau has low absolute humidity; that maritime air is relatively moist; and that the relative humidity of both these types of air "masses" will increase when they move over cold water, pack ice, shelf ice or snow-covered ground (Schwerdtfeger 1970).

The relationship between wind and humidity in McMurdo oasis is well known. Westerly winds are adiabatically heated upon entering the oasis (4.8) although the absolute humidity does not usually rise appreciably (Bull 1966). Thus relative humidities and dew points are very low during westerly winds (Bull 1966; Thompson *et al* 1971a; Yoshida and Moriwaki 1972) The minimum humidities are about five percent

(Bull 1966; NZ Met.S. records) indicating a high potential for evaporation in summer. Easterly winds however, have higher humidities and dew points (Bull 1966; Yoshida and Moriwaki 1972) and saturated air is common in the east, especially at higher altitudes.

6.2 Horizontal gradients

It has already been intimated that horizontal gradients of atmospheric humidity may exist in McMurdo oasis. The predominance of cool, moist easterly winds (2.4, 4.3) and higher precipitation (5.2, 5.5) in the east of the dry valleys, result in higher average absolute and relative humidities near the coast than in the central parts of the oasis. On the average, a negative gradient of absolute humidity probably exists inland towards the west.

Relative humidity gradients are more complex. Saturated air is common in the east despite the slightly warmer mean annual air temperatures there (3.2). Apparently saturated air is also common in the west on the plateau and along its fringe, despite the low absolute humidities. At Shapeless Mountain an igloo and tracks from four stroke tobaggans made by VUWAE members in November 1971 (Barrett pers.comm. VUW) were virtually unchanged in November 1973. This indicates that ablation was minimal during this two year period, due to the ambient vapour pressure being close to saturation in the cold air temperatures. Furthermore Annexstad (1980) found that ablation is only 0.05 $m.a^{-1}$ on blue-ice at 2000m elevation west of Allan Hills. Snow in the area is likely to ablate even slower than that because of the higher albedo of snow than ice. This is consistent with high average atmospheric humidities (greater than 70 percent) at stations in the interior of East Antarctica (Rusin 1964). Thus on the average, negative gradients of relative humidity probably exist from the western and eastern margins in towards the central parts of the oasis.

6.3 Vertical gradients

Two vertical gradients of atmospheric humidity may be defined, analogous to vertical gradients of air temperature (3.3). The environmental gradient describes the gradient in free air, while the topographic gradient describes the case up an incline on the earth's surface.

Environmental humidity gradients are determined from humidity or dew point measurements during balloon ascents. Reservations may be held about the absolute quantitative worth of the antarctic data for the reasons outlined earlier. Solopov (1967) has studied the environmental gradients above oases and snow and ice covered surfaces along the coast of East Antarctica. He found that the nett environmental relative humidity gradient was predominantly negative upwards over the snow-covered surfaces all year round and over the oases in winter. Over the oases in summer the nett gradient is predominantly positive upwards due to upward transfer of water vapour by turbulent moisture exchange from the ground into the atmosphere. However in summer these gradients are often very small. Average relative humidity gradients in the troposphere are usually negative above most antarctic stations (Weyant 1966a) A negative gradient of mean mixing ratio exists above McMurdo Station in January (Schwerdtfeger 1970).

Although the nett environmental gradients are mostly negative, considerable variation may occur on any particular balloon sounding, due to the presence of cloud and humid layers. Figure 7 illustrates the variation of relative humidity with pressure altitude on three typical soundings in January 1975 from McMurdo Station. The relative humidities in this Figure were obtained (U.S. Naval Support Force, Antarctica) from measurements of dew point by a modern type of dew point hygrometer, and temperature measurements; these relative humidities are probably accurate to within a few percent. The levels of cloud and humid layers are evident on Figure 7.

The presence of cloud against hill and valley sides in the region will create locally positive topographic gradients of relative humidity. The mean cloud cover is significantly greater in summer than in winter at Vanda (Thompson *et al* 1971a) and McMurdo oasis, but only slightly

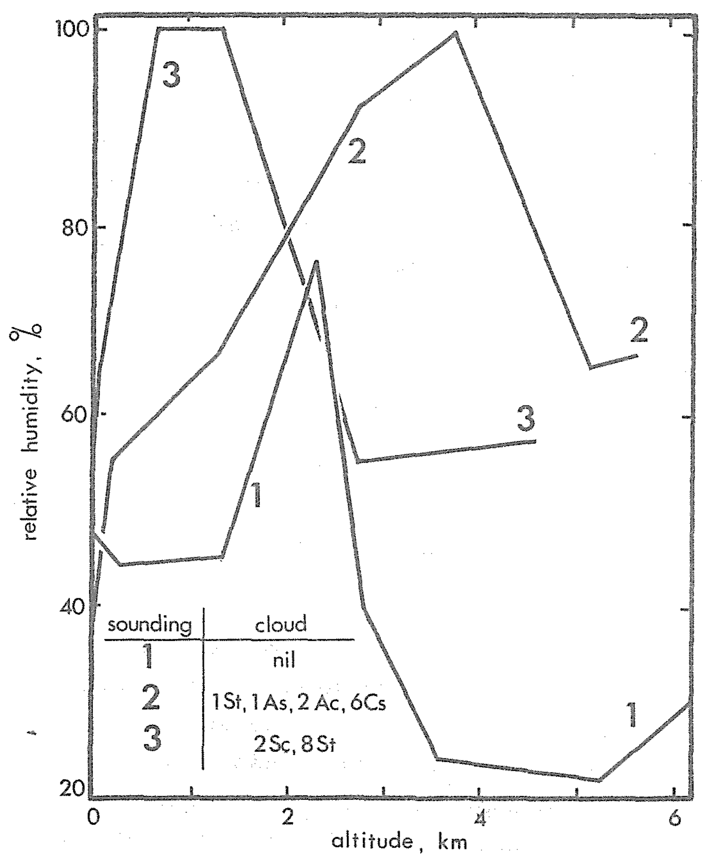


FIGURE 7 Three balloon soundings showing environmental relative humidity gradients above McMurdo Station in January 1975 on the 16th, 20th and 23rd respectively: balloon release time 1130 hours. Independent parameter, altitude, is plotted on the horizontal axis (data from Meteorology Section, Mac Centre, NSFA, McMurdo).

greater in summer at Scott and McMurdo (Thompson and MacDonald 1961; Schwerdtfeger 1970). Furthermore, precipitation increases with elevation in the oasis, especially in summer (5.2). Thus, topographic relative humidity gradients are probably often positive upwards in McMurdo oasis. However Schofield's (1971) observations of lichen growth above 600m only, in Miers Valley, do not provide irrefutable evidence for permanently positive gradients. Moisture is available from other sources such as blown snow and snowfall beside atmospheric water vapour, and the latter moisture supply may be intermittent.

Topographic gradients of humidity were measured at one locality in the region (Figure 8). Relative humidities were measured (13 November 1974) up and down the northern side of Mt Kempe (Royal Society Range), using a Vaisala HM11 Humicap humidity meter and probe; the probe has a film capacitive sensor. The meter had been calibrated with phosphorus pentoxide (zero percent) and saturated water vapour (100 percent) in New Zealand and this calibration was rechecked at Scott Base. The atmospheric relative humidity was measured at 0.3 to 0.5m above the ground surface; the humidity data are probably accurate to within a few percent. The elevations were measured by an altimeter calibrated against the USGS 1:250,000 map, while the air temperatures were measured using a whirling psychrometer. Weather conditions at the time were clear skies with a southwest wind of 0-3.6 $m.s^{-1}$.

In Figure 8 each plot shows a range of relative humidities due to fluctuations of this parameter at each station. The Figure illustrates that topographic relative humidity gradients may be positive or negative. Figure 9 examines the variation of relative humidity with temperatures to determine whether the relative humidity changes in Figure 8 were due to changes in the water vapour content of the air or to temperature changes. If the latter were the case, relative humidity would decrease with increasing temperature. Figure 9 shows that the relative humidities are not inversely dependent on temperature. In fact there is a very weak trend (correlation coefficient +0.43) for relative humidity to increase with temperature. Thus the changes in relative humidity reflect temporal and spatial changes in the water vapour content of the air. Using Equation 3, it can be shown that the air involved here has absolute humidities ranging from 0.14×10^{-3} to 0.29×10^{-3} $kg.m^{-3}$.

Obviously there are a great range of topographic relative humidity gradients that are possible. These reflect fluctuations in atmospheric humidities near the ground. Such humidities vary between 100 percent and less than 10 percent and tend to be higher in winter (Thompson 1972). Fluctuations of at least 10 percent RH may occur within minutes (Figure 8) and of at least 50 percent RH within hours (Yoshida and Moriwaki 1972).

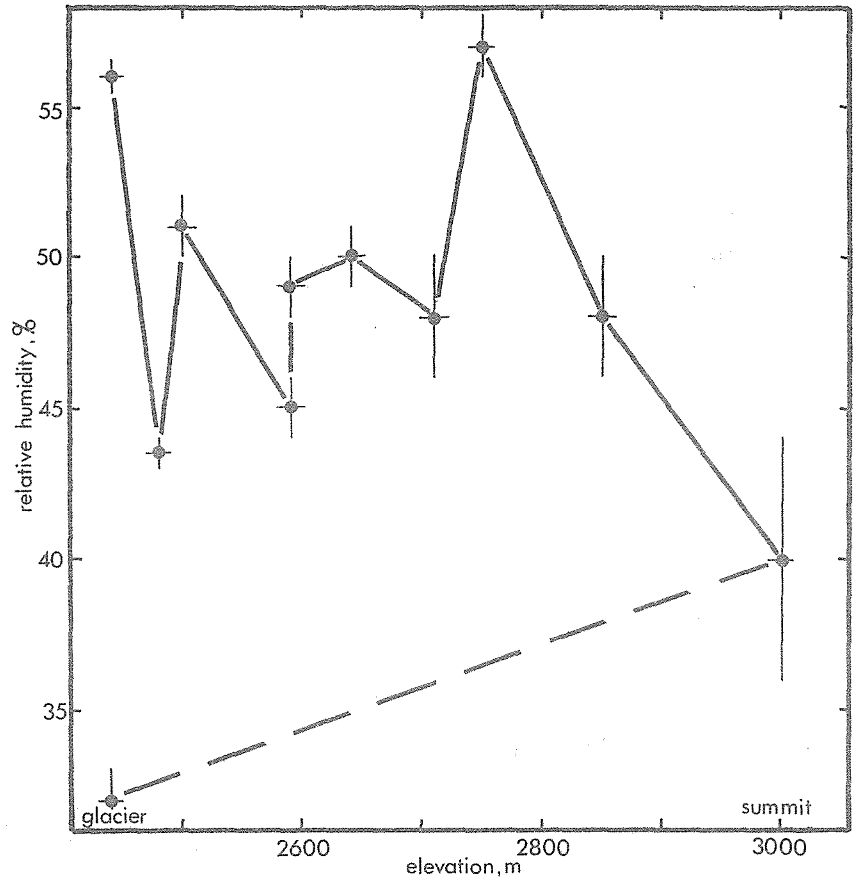


FIGURE 8 Topographic relative humidity gradients between Kempe Glacier and the summit of Mt Kempe (independent parameter, elevation, plotted on the horizontal axis).

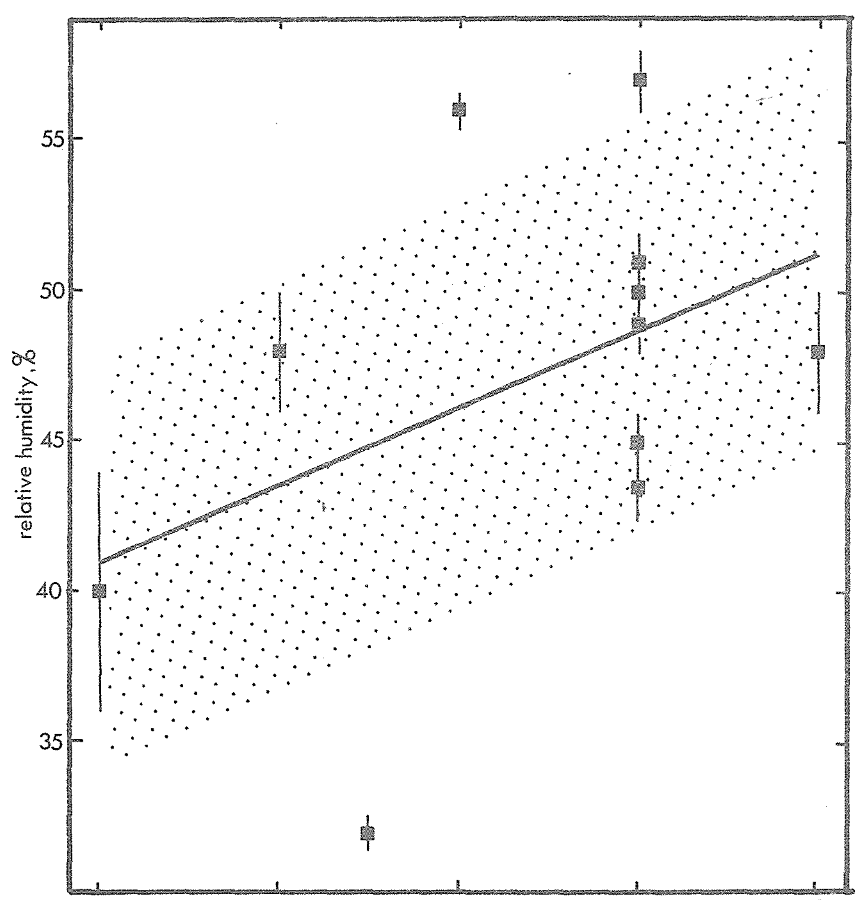


FIGURE 9 Relative humidity versus air temperature on Mt Kempe. Shading indicates the area lying within one standard error of the

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