The climate of Lake Vanda, Antarctica

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with introduction by
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Abstract

Lake Vanda lies near 77°S 162°E and is in the centre of the dry valley region of southern Victoria Land where the valley floors are ice-free. Summers there are characterised by large diurnal changes of radiation, temperature and wind. Winters are an alternation of long calm periods and strong westerly winds which arrive rapidly with a large temperature rise and a large fall in humidity. It is these westerly winds which are responsible for keeping the ground ice-free.

Contents

1 Introduction

North of the Taylor and Ferrar Glaciers of Victoria Land and west across McMurdo Sound from Scott Base lies an area of some 2500 km^2 of relatively ice-free land. Figure 1 shows the general location of this McMurdo "Oasis", which lies between latitudes 77°S and 78°S and between longitudes 160°E and 163°E. Figure 2 is a more detailed map and shows that there are three major valleys, once glacier-filled, from which the ice has retreated, leaving a barren and rocky or sandy valley floor. Figure 3 shows the horizon profile and sun heights at selected times as viewed from Lake Vanda.

The upper part of the most southerly valley, the Taylor, was discovered by Scott in December 1903; explored, the lower part of it, by Armitage, Priestly and Brocklehurst in December 1908 and January 1909; and almost the whole valley by Taylor, Debenham, Wright and Petty Officer Evans in February 1911. But what lay to the north, between the Wilson Piedmont Glacier skirting the west coast of McMurdo Sound, and the ice plateau to the west, was still unknown.

An inkling of what was there was given in some aerial photographs of "Operation Highjump" in 1947 which were published in a US Airforce manual in 1953. These showed "ground moraines" left in place as a glacier melted, and a "dry valley". Further photographs taken in 1956–57 by American and New Zealand airmen showed a more extensive "dry" area.

Two young geology students from Victoria University of Wellington, New Zealand were the first to see the general lay-out of the Dry Valley system from ground level: in early January 1958 they set up camp at Lake Vida in what is now known as the Victoria Valley. The most notable feature was a large dry valley some 55 km in length, once clearly the course of a great glacier, still extending for some way east from the ice-cap, and recognisable at the lower end of the valley as a vast mass of ice coalescing with the Wilson Piedmont Glacier at 77°25′S 163°E. This proved to be the un-named inlet on the maps of Scott's first expedition, and which is shown on the maps of Scott's 1910–13 expedition as Wright Glacier. The following summer Victoria University sent another team to the region to spend a busy 7 weeks doing geology, glaciology and surveying. And so the first detailed map of the region was made. The name Wright (after the physicist with Scott's expedition) was retained for the truncated glacier and applied also to the dry

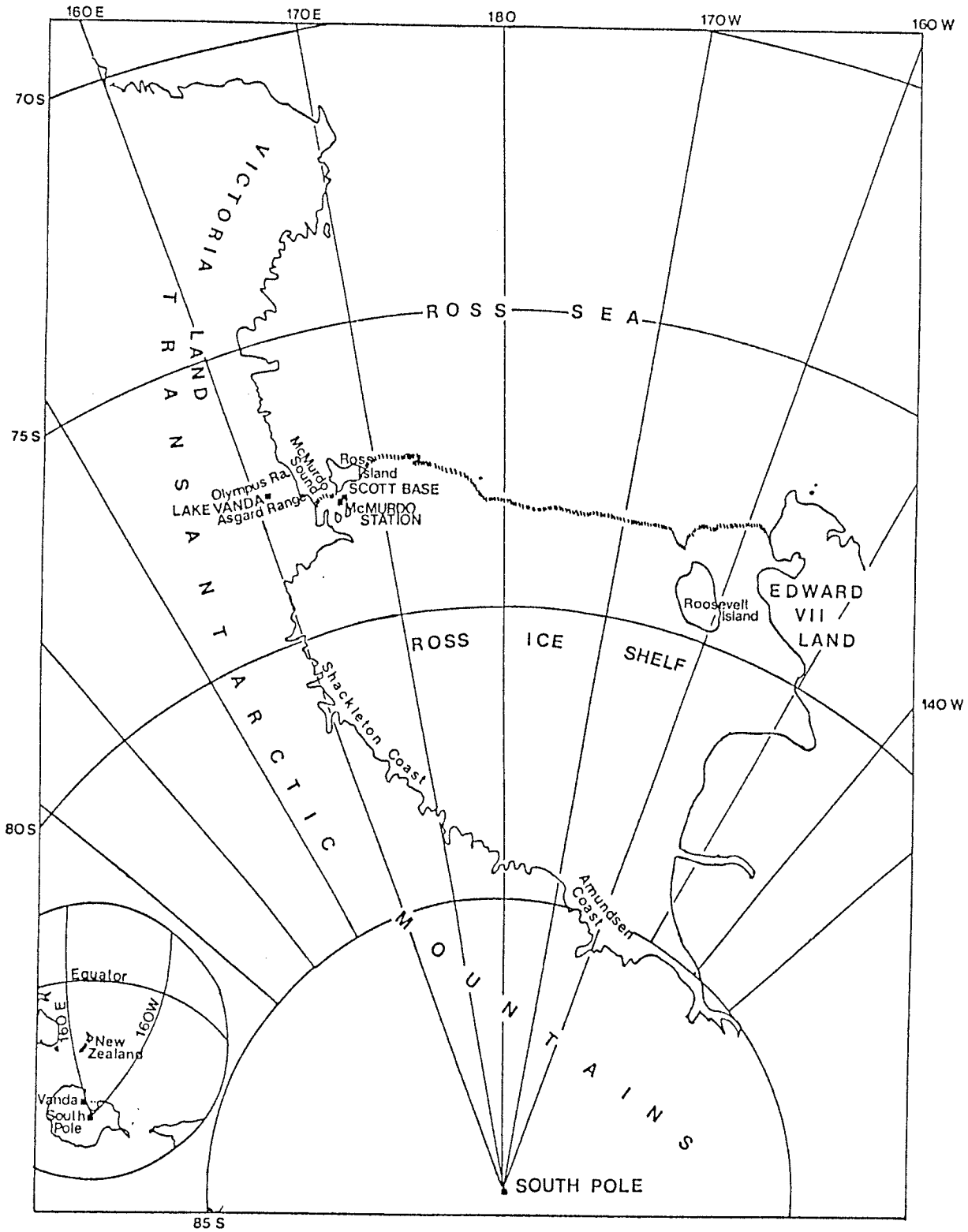

Figure 1: Map showing location of Lake Vanda in Antarctica

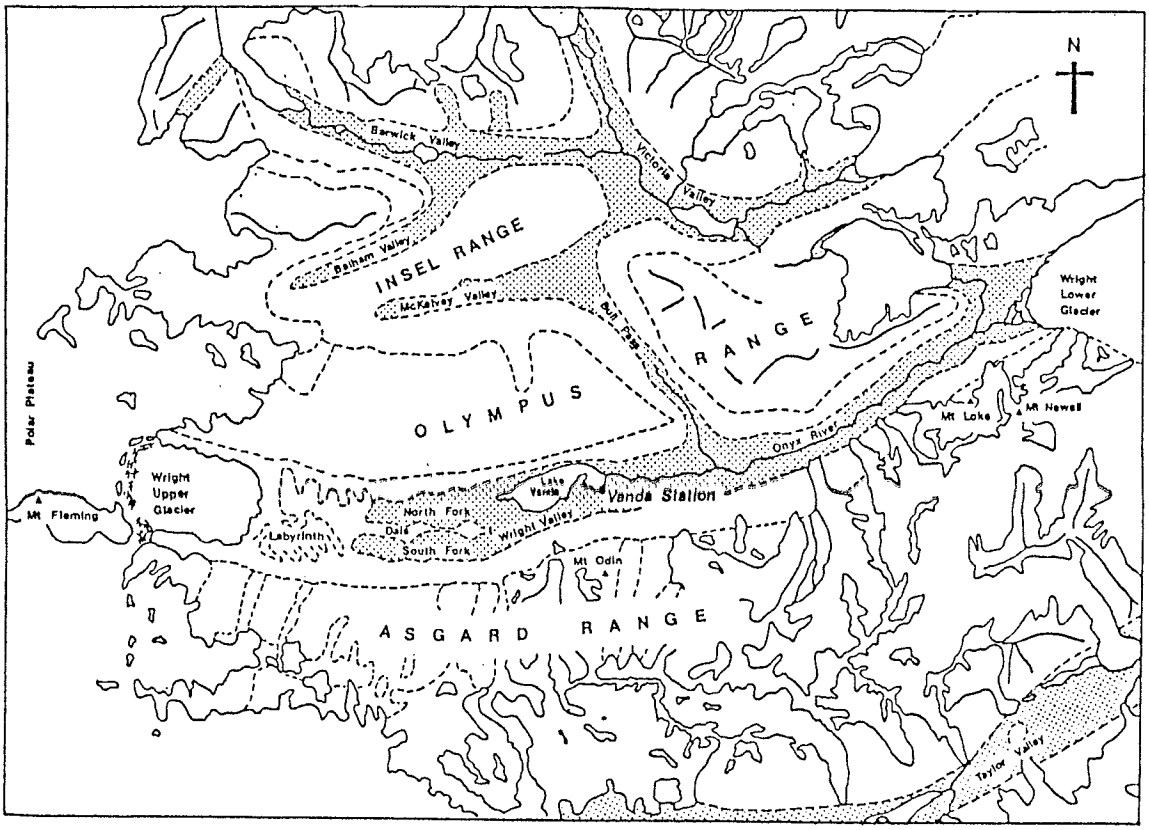

Figure 2: Map of Lake Vanda area

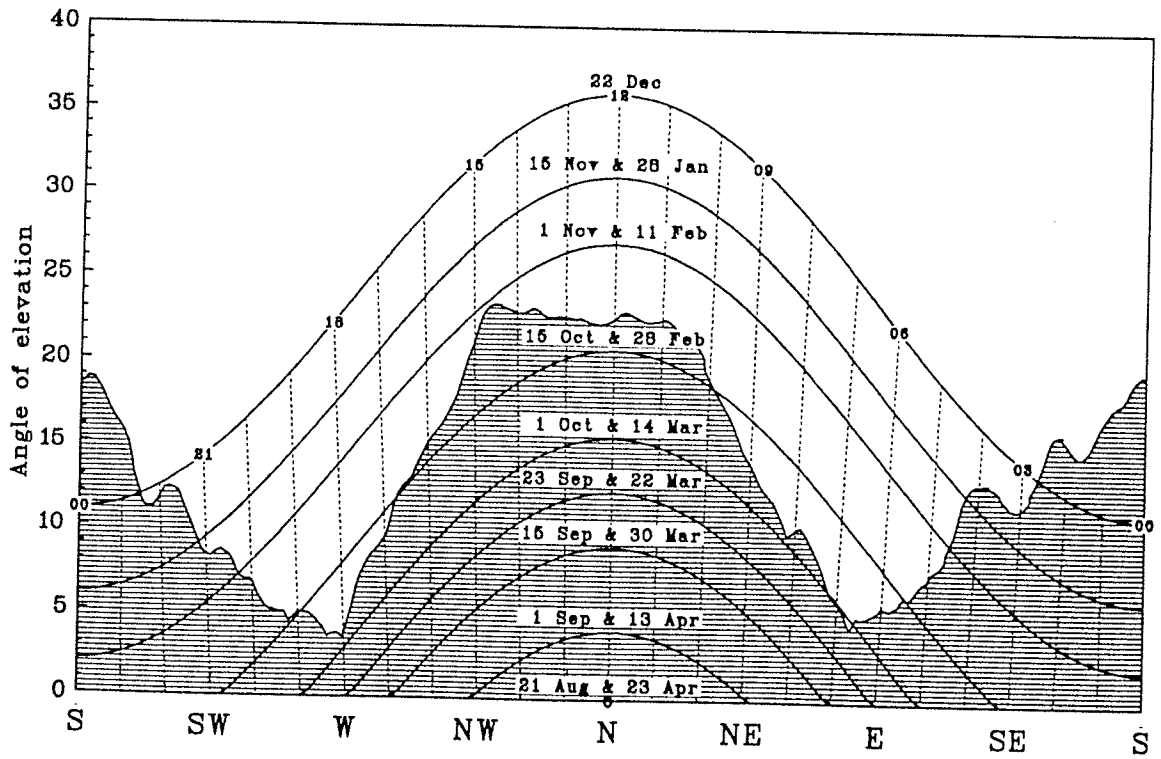

Figure 3: Horizon profile and sun heights at selected times as viewed from Lake Vanda

valley in which the upper part ends.

Vanda is an ice-covered lake in the Wright Valley at 77°32'S 161°30'E, which thaws only in mid-summer and then only on the beach-line. In summer also melt streams enter the lake from nearby glaciers and the Onyx River flows from the eastern end of the valley westwards to the lake. The name Vanda was given to the lake by Colin Bull, leader of the 1958–59 Victoria University expedition, in memory of a dog named Vanda he had when working in northern Greenland some years before.

Vanda Station was established by the New Zealand Antarctic Division on the south-east shore of Lake Vanda in late 1967 and a full meteorological observing programme has been taken at the site for the 3 full years 1969, 1970 and 1974 and all the summer seasons (i.e. late October to late January) for the other years since 1968. Measurements included three-hourly synoptic observations, continuous recordings of solar radiation, nett flux and soil flux, ground temperatures to a depth of 3 metres, wind and temperature profiling to 4 metres above ground and some other special measurements. A network of meteorological stations scattered through the valley gathered temperature data remote from the main Vanda base station.

The data is held in the New Zealand Meteorological Service archives at Wellington, New Zealand and this publication attempts to give a basic over-view of that data. Unfortunately, some of this data is only held on paper and not in computer readable form; this applies especially to the profile data and out-station temperature data and so their analysis has not been attempted.

2 Humidity and precipitation

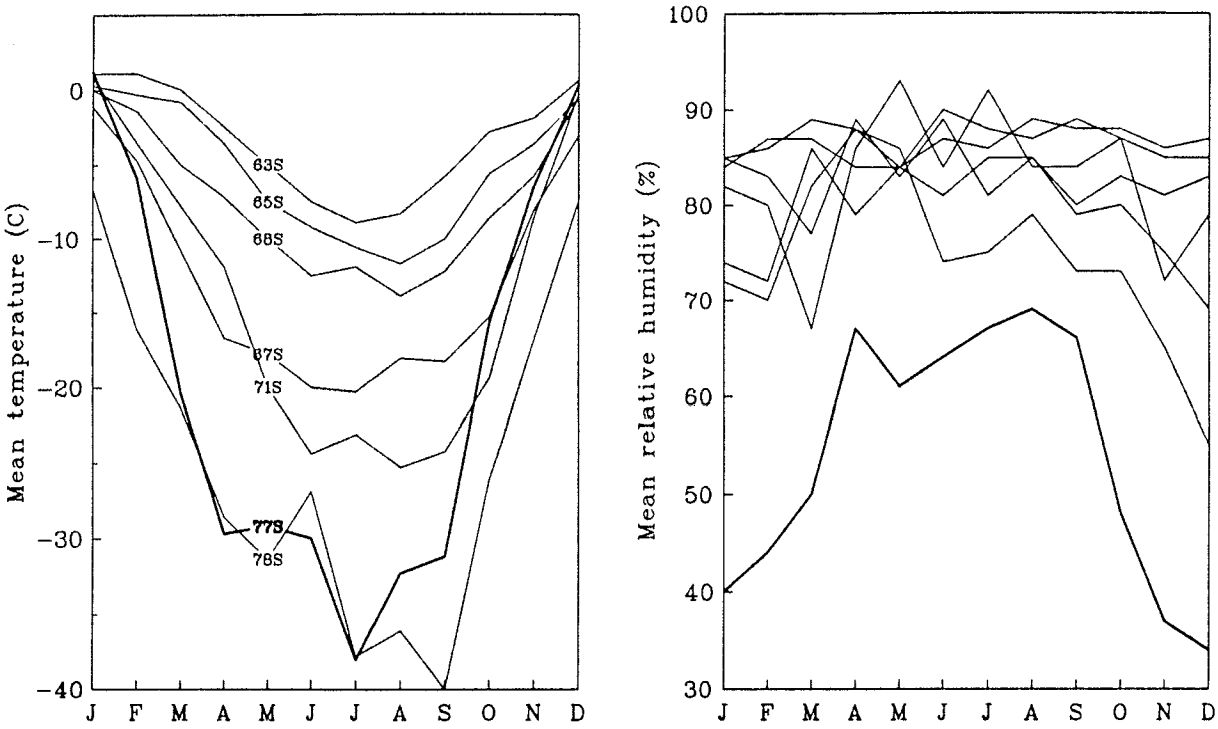

Figure 4: Mean monthly temperatures and mean monthly relative humidities for specific locations in Antarctica. Lake Vanda is shown with a heavier line

In a continent which, although largely snow or ice-covered, is a desert in terms of annual precipitation, the valleys of southern Victoria Land appear to be particulary dry as they are largely ice free. To what degree then does Lake Vanda in the Wright valley have less precipitation, and drier air than other places in Antarctica?

It would appear from Figure 4 that at any time of the year and especially from October to March inclusive, the relative humidity at Lake Vanda is much less than elsewhere. These other locations are :

Deception Island	63°S 60$\frac{1}{2}$°W
Argentine Island	65°S 64°W
Cape Denison	67°S 143°E
Stonington Island	68°S 67°W
Cape Adare	71°S 170°E
Lake Vanda	77$\frac{1}{2}$°S 161°E
Little America	78$\frac{1}{2}$°S 164°W

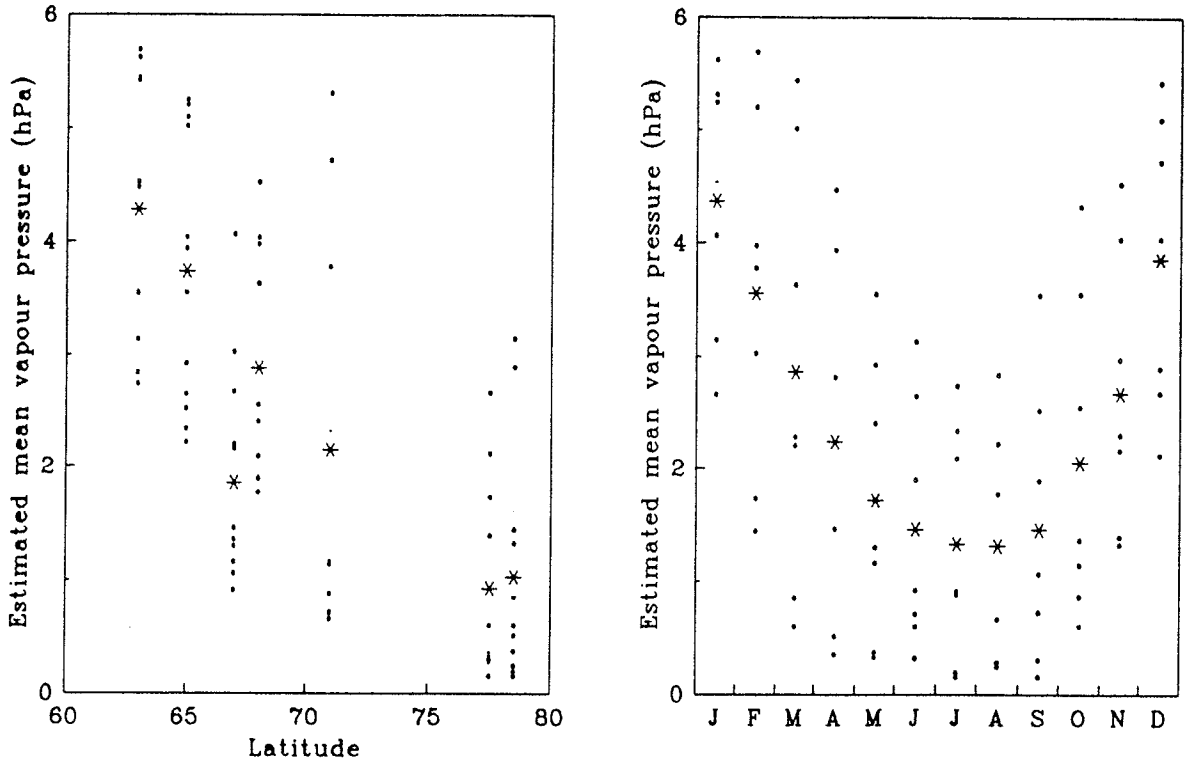

Figure 5: Estimated mean vapour pressures for the same locations as shown in Figure 4

The locations have not been indicated in the relative humidity part of Figure 4, as the differences between the stations, other than Lake Vanda, appear to be un-systematic. However, where mean temperature is concerned a systematic trend does appear with generally decreasing temperature as latitude becomes more southerly. The exception to this trend is Lake Vanda, since its summer time temperatures are as warm as those at Deception Island which is nearly 15° further north. Also, relative humidity is strongly dependent on temperature, thus Lake Vanda's humidity behaviour may be a reflection of its temperature behaviour.

Relative humidity is defined as the ratio of the vapour pressure of the actual water vapour present to the saturated vapour pressure. For a given temperature, the atmosphere can hold only a certain amount of water as vapour, (any excess water condenses out as water droplets) and the vapour pressure of this maximum amount is the saturated vapour pressure. Therefore, to remove any effect due to temperature from humidity behaviour, vapour pressures should be examined in preference to relative humidity. However, vapour pressure data is not directly available, and only approximate values for the monthly mean vapour pressures can be estimated from the monthly mean temperatures and monthly mean relative humidities. Magnus's formula was used to estimate the saturated vapour

pressure E_s from the temperature T i.e. :

$$E_s = 6.107 \exp\left[\frac{17.38T}{239+T}\right]$$

In Figure 5 the estimated monthly mean vapour pressures are plotted against latitude and against the month. Also plotted, using asterisks, are the means over all months for a given latitude, and the means over all latitudes for a given month. Apart from Cape Denison, the former appear linear with latitude and the latter parabolic with month number (i.e. January is 1 ,..., December is 12). Thus a multiple regression was made of the estimated vapour pressure against latitude, month number and the square of the month number. The coefficient of determinantion of this regression was 0.84, and this improved to 0.92 when Cape Denison was omitted, because its consistently low residuals suggested different behaviour to the other locations. If E is the mean vapour pressure, L the latitude and M the month number, the regression gave the following equation :

$$E = 20.9 - 0.213L - 1.28M + .093M^2$$

where all the coefficients are highly significant.

This analysis is probably more valid for summer than for winter, since vapour pressures are higher then, and their measurement more accurate. However, with respect to atmospheric humidity, whatever the month, Lake Vanda appears to have what might be expected for its latitude; the low relative humidities are just an expression of its unusual temperature variation through the year. Temperature largely results from the balance of incoming and outgoing radiation, which will be examined in the next section.

The accuracy of the estimated vapour pressures used in the above analysis were checked for one year at Lake Vanda. Hourly vapour pressures were calculated, using Magnus's formula, from hourly temperatures and relative humidities, then the monthly mean of these compared with a value calculated from the monthly mean temperature and monthly mean relative humidity. The mean absolute difference between the actual monthly mean vapour pressure and the estimated value was only 0.02 hPa, which in summer represents a percentage difference of about 1%, but in winter this rises to over 10%.

The calculated hourly vapour pressure were used to obtain Figure 6 which shows the diurnal variations of vapour pressure as departures from the daily mean level. The

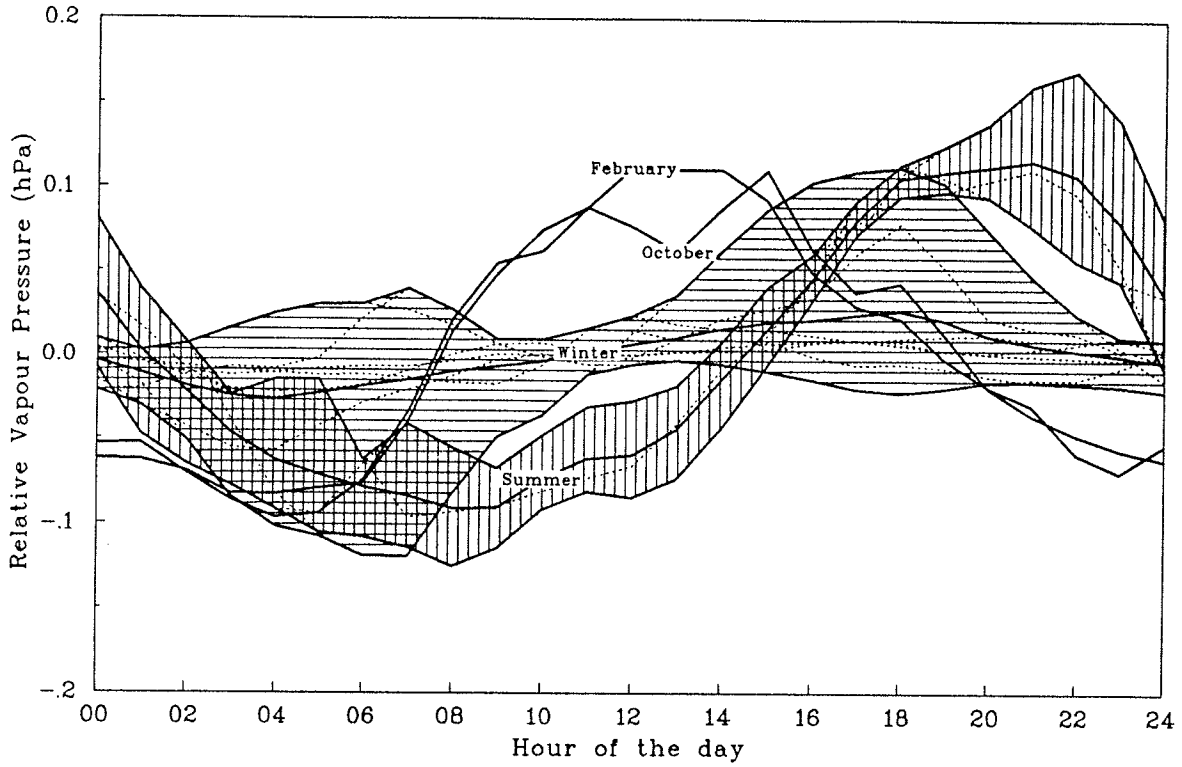

Figure 6: Diurnal variation of vapour pressure at Lake Vanda

variation for each month was plotted separately with a dotted line and 3 groups can be distinguished :

November, December and January which is labelled 'Summer' in the figure

March to September inclusive labelled 'Winter'

October and February

The range of the summer group is indicated by the horizontally hatched area and the mean by the heavy line through this area. The winter group is shown in a similar style, the range is now vertically hatched and the mean is as before. There appears to be a daily cycle in the summer, with an amplitude of about 0.2 hPa, which is approximately 10% of the mean level for these months; the cycle's minimum occurs about 8 a.m. and its maximum about 8 p.m. The February and October cycles are similar, but have a minimum near 4 a.m. and a maximum about midday. These cycles have appreciable amplitude in comparison to their mean level and so, despite being based on only one year's data, they are probably real. In contrast for the winter months, no systematic pattern is evident.

If the cycles of Figure 6 are significant, then a physical reason must exist for the phase

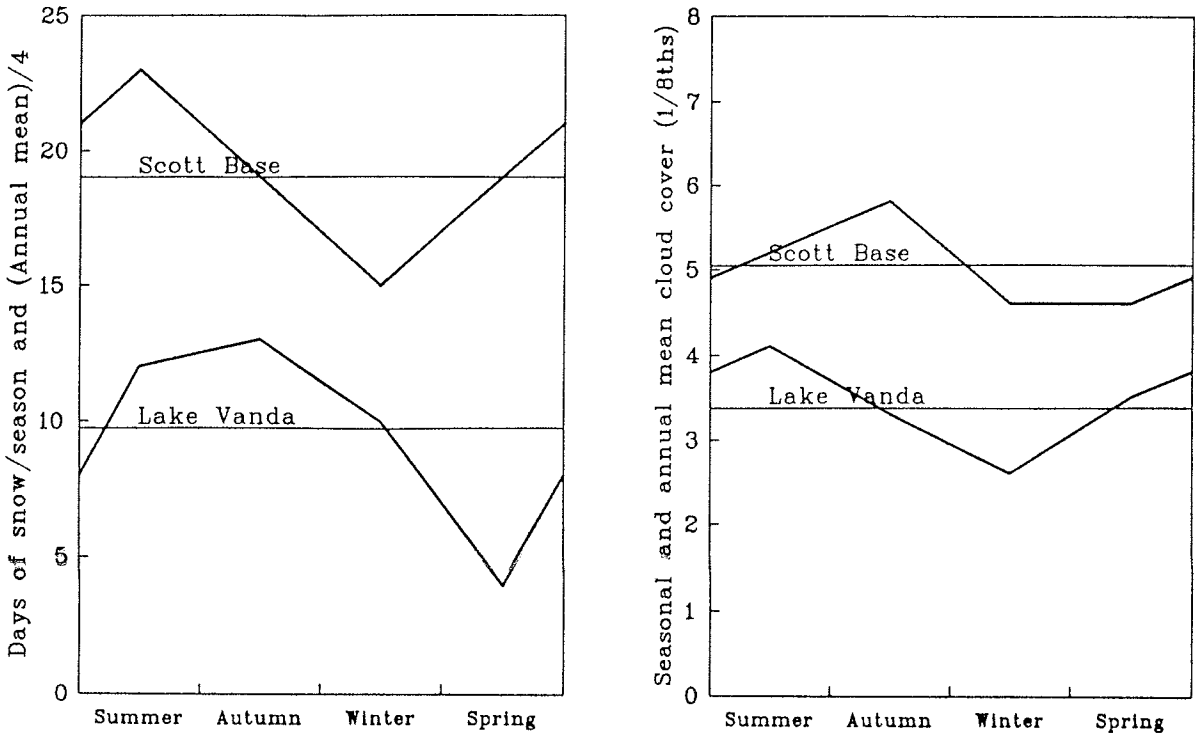

Figure 7: a) Days of snow at Scott Base and Lake Vanda. b) Cloud cover at Scott Base and Lake Vanda

difference between the summer cycle and that of the adjacent months; this reason is not at all clear. Since vapour pressure measures the absolute amount of moisture in the air, both rising temperatures and higher wind speeds will lead to higher vapour pressures as they both increase evaporation from Lake Vanda and the glaciers around the Wright Valley. As will be illustrated later (Figures 14 and 22), the 'summer' seasons for temperature and wind are different, and it may be that the vapour pressure cycle starts with the temperature cycle, but when the wind cycle starts, a delay is introduced into the vapour pressure cycle.

In the remainder of this section, precipitation and cloud cover will be examined and, when possible, compared to Scott Base. Indeed, for the remainder of this report, whenever comparisons are made they will be made with respect to Scott Base which is the nearest permanently manned station, where the usual Antarctic condition of ice covered ground exists. Such comparisons will normally be made for common periods, for example, the autumn and winter values of both parts of Figure 7 for both stations are based on 1969, 1970 and 1974, as full year data from Lake Vanda are only available for these years.

Figure 7a) shows that, on average, over the whole year Scott Base has about twice

the number of days of snow that Lake Vanda has. Also, the seasonal variations at both places are not large, and can be shown to be statistically not significant although, the spring minimum at Lake Vanda may be real and not just a random fluctuation. Similarly Figure 7b) shows that, on average, for the whole year, Scott Base is about 50% cloudier than Lake Vanda. Once again, the seasonal variations at both places are not large and unlikely to be statistically significant. However, taken together these figures do suggest a tendency for the summer and autumn to be 'wetter' than the winter and spring at both stations.

Thus, although the amount of moisture held in the air at Lake Vanda is much as expected for its latitude, the amount precipitated out, as either snow or cloud droplets, is considerably less than at Scott Base. Considering that atmospheric moisture was measured at ground level, whereas snow falls and cloud amounts must be associated with higher levels of the atmosphere, the apparent conflict between humidity and precipitation (if Scott Base is taken as a standard) is not surprising. However, Scott Base is only 130 km from Lake Vanda and the difference between the stations could be explained by considering their different exposures to the large scale air-flows which bring snow or cloud. The usual precursor for a period of snow fall in this area is the spreading and thickening of upper and middle cloud from the north or north-east i.e. from the Ross Sea area rather than the Antarctic Plateau. Thus, Scott Bases's exposure to such flows must be high, as it is a coastal station and Lake Vanda's low as it lies in a deep valley approximately 50 km from the coast.

Whenever falling snow has been observed at Lake Vanda (except for a few summer time convective showers), an east to north-east airstream was flowing over the area, associated with a major depression moving eastwards in the 65–75°S latitude band. After the middle cloud mentioned above becomes established, it lowers further, with low stratocumulus or stratus gradually filling the whole valley. All snow occurred in calm or light wind conditions and lay as a uniform layer with little drifting. In winter, at times, it lay for several days, whereas in summer, falls were dispersed almost immediately. At all times of the year, lying snow is primarily cleared mechanically by the wind which is regularly strong enough in summer, when the air is also normally dry. In winter, calm conditions can be persistent but strong, relatively warm and very dry westerlies occur, and soon

Table 1: Monthly snowfall totals (mm) at Lake Vanda (Tce is Trace)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1969	Tce	Tce	13	5	16	16	Tce	16	0	3	Tce	13	82
1970	Tce	2	0	5	0	0	0	0	0	0	0	Tce	7
1974	1	5	89	Tce	Tce	5	10	1	4	0	Tce	Tce	115

clear any lying snow (these winds will be discussed fully in the section on wind).

The depth of any particular fall of snow was usually too small to measure or was at most about 1 mm, but on rare occasions 10 mm or more has fallen. The variability in depths is illustrated by Table 1 which shows monthly totals, the maximum in March 1974 is almost all attributable to the 48 hours prior to the 13th. The usual composition of the snow was small flakes, about 2–3 mm in diameter, sometimes mixed with tiny snowgrains less than 1 mm in diameter. Snow density was only measured twice and it was found that 12–13 mm of snow were required to produce 1 mm of water.

Other forms of precipitation which have been observed are :

1. Rain was observed on 2 occasions, amounts were barely enough to dampen the ground, but, it is likely that light, isolated showers of rain occur somewhere within the dry valleys region every summer.

2. Blowing snow occurred in large quantities several times during the winters of 1969, 1970 and 1974 but very little of the snow settled on the ground.

3. Hoar frost and rime occasionally build up a layer 1–2 mm thick on the ground but these accretions clear quickly when the wind becomes moderate or more.

4. Fog in large banks often occurs in the autumn and spring.

The only evaporation measurements made at Lake Vanda have been readings from ablation pegs set in the surface of the lake ice through the winter of 1974. The total ablation from 1st April to 15th October was 63 mm, and it was found that during times of calm or light winds only 0.1 mm per day was lost, whereas during strong westerly conditions about 0.8 mm per day was ablated.

3 Radiation

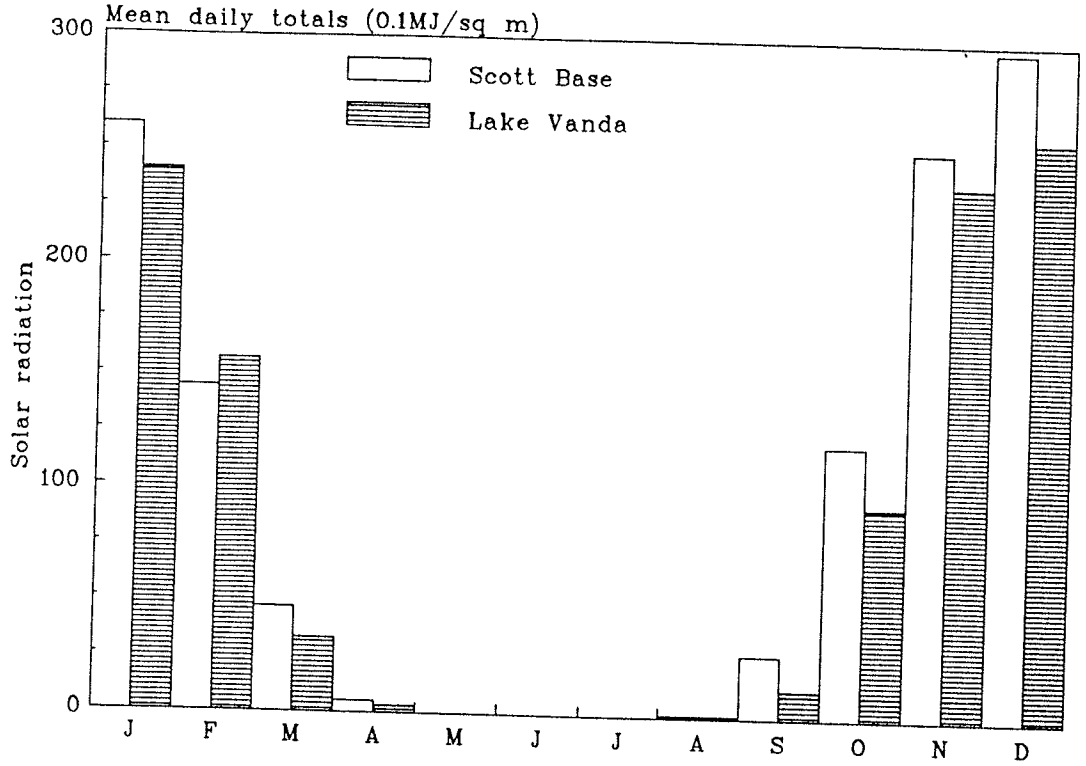

Figure 8: Solar radiation at Scott Base and Lake Vanda

In the previous section, it was shown that the low relative humidities at Lake Vanda are more a reflection of the temperature than a real measure of the atmospheric moisture at that latitude. The temperature at a particular locality, depends on both the balance of heat input to output (i.e. incoming solar radiation to outgoing radiation), and the mechanical mixing and translation of air by winds and convection currents. Radiation will be examined in this section and temperature in the next.

Figure 8 compares the mean daily solar radiation totals from Scott Base and Lake Vanda, for each month of the year. Since the sun is below the horizon from late April to late August (see Figure 3), the totals for May, June and July are zero. For the rest of the year, the stations have similar totals, but for 7 of these 9 months Scott Base is higher than Lake Vanda. The significance of this can be judged by supposing that there is really no preference for either Scott Base or Lake Vanda to be higher than the other, in which case, there would be only a 2% chance that 7 out of 9 are higher. This is a small probability and suggests that despite Scott Base being cloudier than Lake Vanda it receives more solar radiation. As can be seen from Figure 3, the mountains surrounding Lake Vanda block the sun, even in mid-summer, whereas at Scott Base the horizon profile

is much lower.

To compare Lake Vanda and Scott Base further, actual monthly totals of solar radiation and actual monthly means of cloud cover were correlated. To remove the annual cycle, the totals and means were first standardised so that the correlations are between the scaled departures from the particular month's mean. The correlation coefficients are :

	Scott Base Radiation	Lake Vanda Cloud	Scott Base Cloud
Lake Vanda Radiation	0.04	−0.05	0.07
Scott Base Radiation		−0.09	**−0.42**
Lake Vanda Cloud			0.19

These coefficients are derived from only 25 months of data, and so for a value to be significant at the 5% level, it would need to be larger than 0.4 or smaller than −0.4. Therefore, it appears that the only significant correlation is that between the solar radiation at Scott Base and the cloud amount there. This coefficient is negative so that, as expected, the tendency is for radiation to decrease as cloudiness increases. The lack of correlation between Lake Vanda's radiation and cloudiness, probably indicates that the exposure due to the horizon profile is more important than the cloudiness, which is generally less than at Scott Base.

The monthly mean daily totals for solar radiation at Lake Vanda are repeated as the 'Incoming' bars in the upper part of Figure 9. Also shown , are the monthly mean daily totals of 'Outgoing' radiation, which from March to October inclusive, exceed the incoming radiation. Apart from October, where the the excess is marginal, there is a nearly constant total output of about 4 MJ/sq m over the autumn and winter months. Also, from November to February inclusive, the output is nearly constant at about 14 MJ/sq m each month. To a lesser extent, a similar pattern appears in the lower part of Figure 9 which shows the mean daily totals of the heat flux through the soil at a depth of 8 cm. Thus, from March to September, this heat flux is about 0.6 MJ/sq m from the ground into the air and about the same from the air into the ground for the rest of the year.

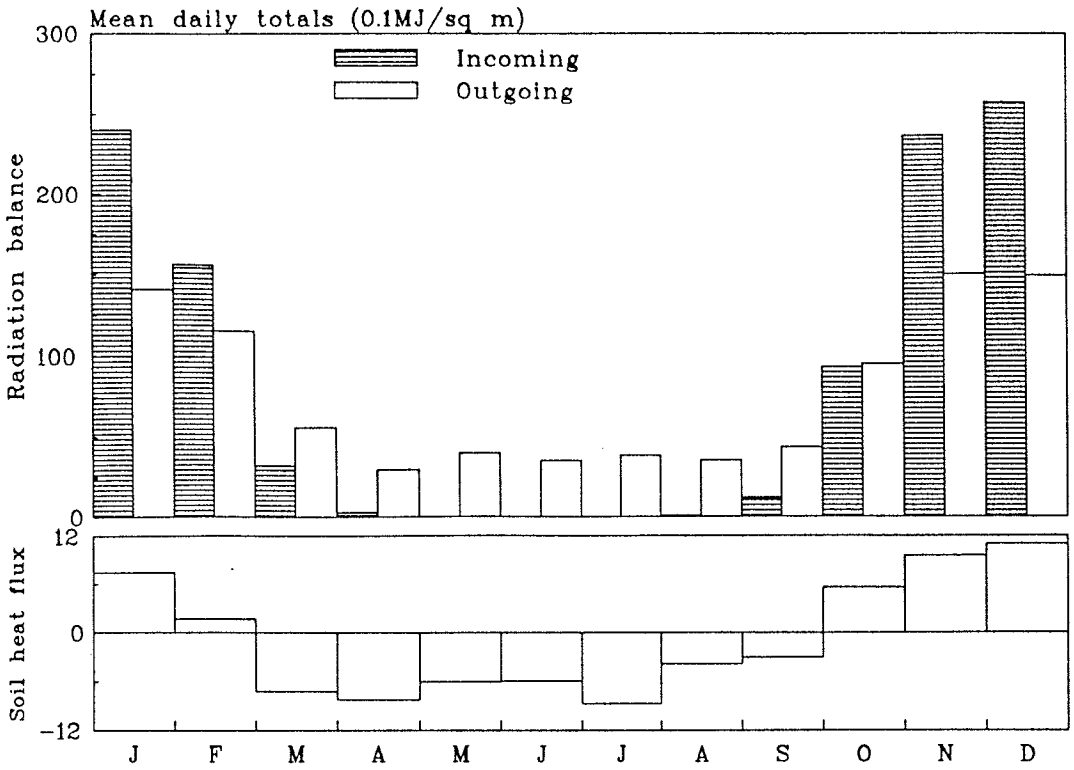

Figure 9: Radiation and soil heat flux at Lake Vanda

'Incoming' radiation is the solar radiation whilst 'Outgoing' was derived by taking the difference between the solar and the net radiations. As it is the solar and net radiations that are directly measured, the net radiation rather than outgoing radiation, will be considered in future. In these high southern latitudes, the total net radiation for a year is usually negative i.e. rather than some energy being available for heating, energy from lower latitudes must be brought south to compensate for the deficit. However, at Lake Vanda for 1970, the only complete year available, there was a net gain of 390 MJ/sq m. The reason for this is the low surface albedo of the ice and snow free ground in the dry valleys. From a large number of measurements taken over various types of surface, a value of 0.2 is estimated for the albedo.

Figure 10 shows the diurnal variations of the solar and net radiations and of the soil heat flux as departures from the daily mean level. The variation for each month is plotted separately with a dotted line, but they fall into 3 groups :

November, December and January which is labelled 'Summer' in the figure

March to September inclusive labelled 'Winter'

October and February.

The range of the summer group is indicated by the horizontally hatched area and the mean by the heavy line through this area. Similarly for the winter group, with the range

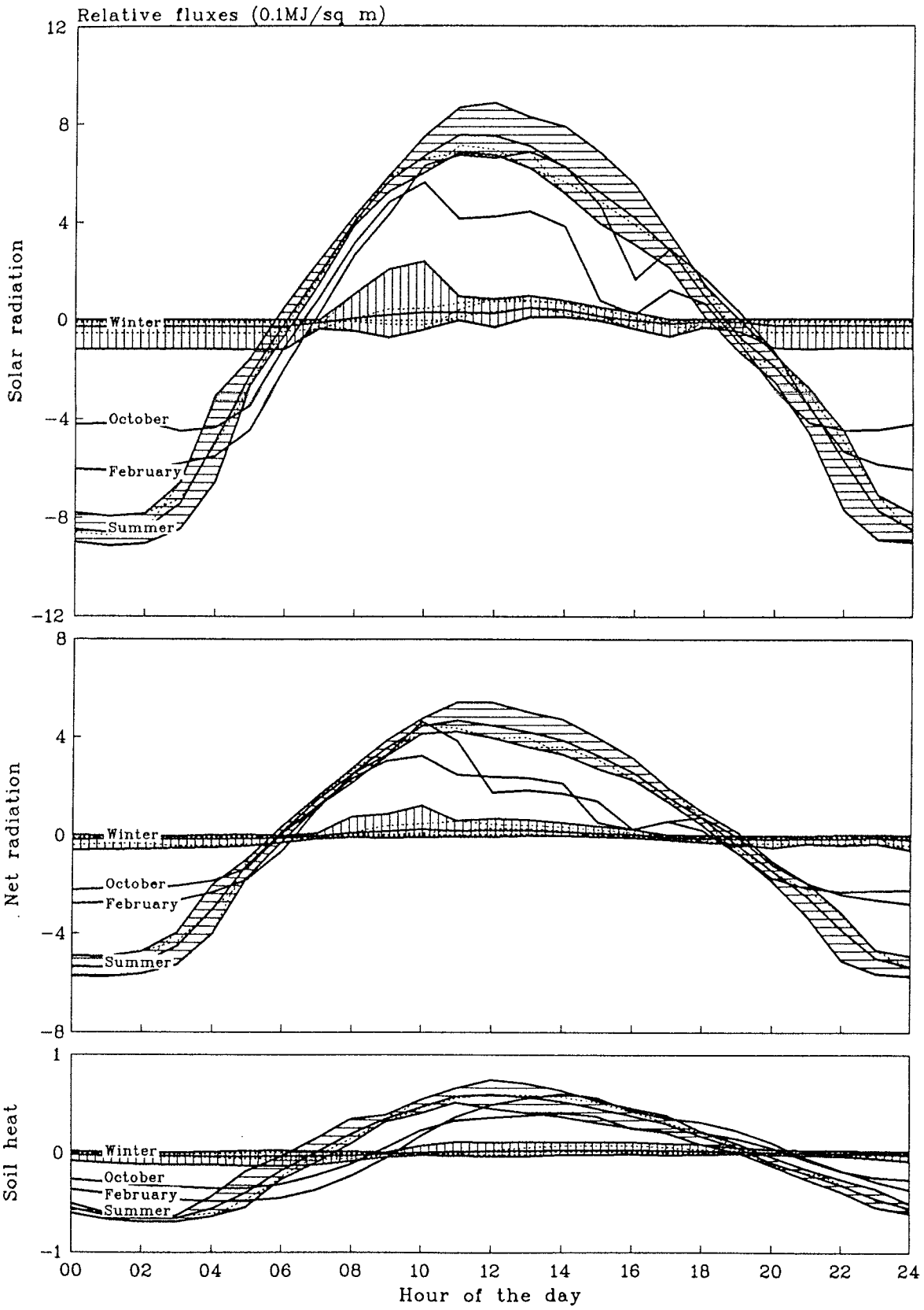

Figure 10: Diurnal variation of solar and net radiations and of soil heat flux at Lake Vanda

now vertically hatched and the mean as before. The transitional months of October and February are more like summer than winter, but have a lower amplitude cycle which is not as smooth as the summer cycle; probably the end of October and beginning of February would fit the summer pattern. This fit is spoilt by the other parts of these months when the sun starts to set for a time at midday (see Figure 3), and the midday maximum is reduced; also a real night time exists and the overnight minimum becomes much flatter.

The amplitude of the summer time diurnal cycle is 1.6 MJ/sq m for the solar radiation and 1.0 MJ/sq m for the net radiation. The scale of the soil heat flux portion of Figure 10 is 4 times that of the other 2 parts of the figure where the scale is constant. Even with the enlarged scale, the soil heat flux's summer time amplitude still appears small compared to the others, it is about 0.1 MJ/sq m. Despite the different amplitudes, all 3 cycles have their maximum at midday and their minimum at 1 or 2 a.m. This displacement from midnight is probably due to the asymmetry of the mountains to the south, so that the sun tends to set a shorter time before midnight than it rises afterwards.

Figures 9 and 10 give only an impression of the relative sizes of the solar and net radiations and the soil heat flux, whereas Figure 11 is more detailed. In the upper half of Figure 11, the seasonal variation of a comparison between contemporary hourly values of the solar and net radiations is shown as the distribution of their ratio. The contours are lines of equal percentage frequency of exceeding the ratio of net to solar radiation as indicated on the vertical axis. For example, in January about 20% of the values of the ratio of net to solar radiation lie between 0.5 and 1.0 the following clarifies this :

$$
\begin{array}{lrcl}
 & \text{Net Radiation} & = & \text{Solar Radiation} - \text{Outgoing Radiation} \\
\text{Thus} & \text{Ratio of Net to Solar} & = & 1 - \text{Ratio of Outgoing to Solar} \\
\text{Also} & \text{Outgoing} \geq 0 & \& & \text{Solar} \geq 0 \\
\text{And so} & \text{Ratio of Outgoing to Solar} \geq 0 & \Rightarrow & \text{Ratio Net to Solar} \leq 1 \\
\text{Thus} & \text{Outgoing} < \text{Solar} & \Rightarrow & 1 > \text{Ratio Net to Solar} > 0 \\
 & \text{Outgoing} = \text{Solar} & \Rightarrow & \text{Ratio Net to Solar} = 0 \\
 & \text{Outgoing} > \text{Solar} & \Rightarrow & \text{Ratio Net to Solar} < 0
\end{array}
$$

Therefore in January at Lake Vanda for 20% of the time, up to half the incoming solar radiation is re-emitted as outgoing radiation.

Only data from hours which had some solar radiation were included in the upper

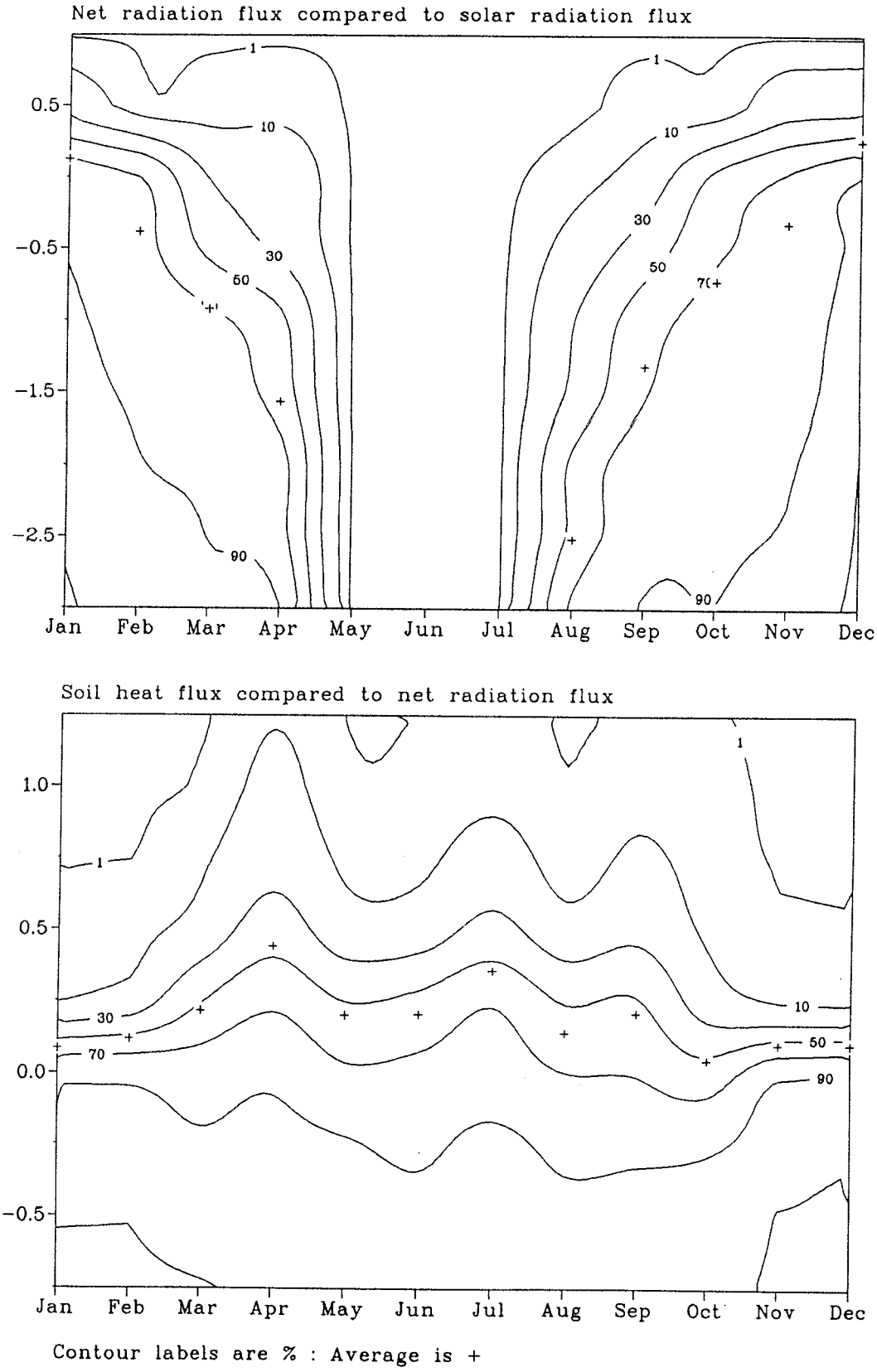

Figure 11: Seasonal variation in the relative sizes of solar and net radiations and the soil heat flux

part of Figure 11. There is no solar radiation at all during May, June and July, thus no ratio values could be calculated for these months. Also, most of August is without solar radiation, but for September through to April, there is adequate data. For these months the figure shows that the net radiation is a loss of over twice the solar radiation for only 10–20% of the time. The amount of time that there is a net gain (i.e. the ratio is positive) rises from 20% in September to about 90% in December and falls back to 20% by April.

In trying to assess how much larger the solar radiation is compared to the net radiation it might seem natural to take the average value of their ratio. The averages for each month (+) appear to run along the 60–70% contour so that the average ratio is exceeded 60–70% of the time. Therefore, a better comparison is the median (i.e. the 50% contour), where half the ratios exceed its value and half do not. The median and average are not coincident here, because some very large negative values occur and only a few such values can greatly influence the value of the average. Figure 11 shows the median to be about -0.8 in September rising to about 0.1 for October to February inclusive, thus, half the time at least 10% of the solar radiation is not re-emitted. The median falls back to about -0.8 by April.

In the lower half of Figure 11, the seasonal variation of a comparison between contemporary hourly values of the net radiation and the soil heat flux is shown as the distribution of their ratio. The contours are lines of equal percentage frequency of exceeding the ratio as indicated on the vertical axis. For example, in January 10% of the values of the ratio of the soil heat flux to the net radiation exceed 0.25.

The directions of heat flow are opposite only 20% of the time. For these ratios, the average values lie close to the 50% contour, as the distribution of the ratios are symmetrical with no bias towards either positive or negative extreme values. The 50% contour is at a value of about 0.3 from March to September falling to about 0.1 for the rest of the year. Thus, during the months when the ground loses heat (see Figure 9), half the time these ground losses account for 0.3 of the net radiation, which at that time of year is basically the outgoing radiation. However, when the ground is gaining heat during the summer, half the time the gain is no more than 0.1 of the net radiation (i.e. the available heat), thus most of the net radiation is used in heating the air and raising its temperature.

4 Temperature

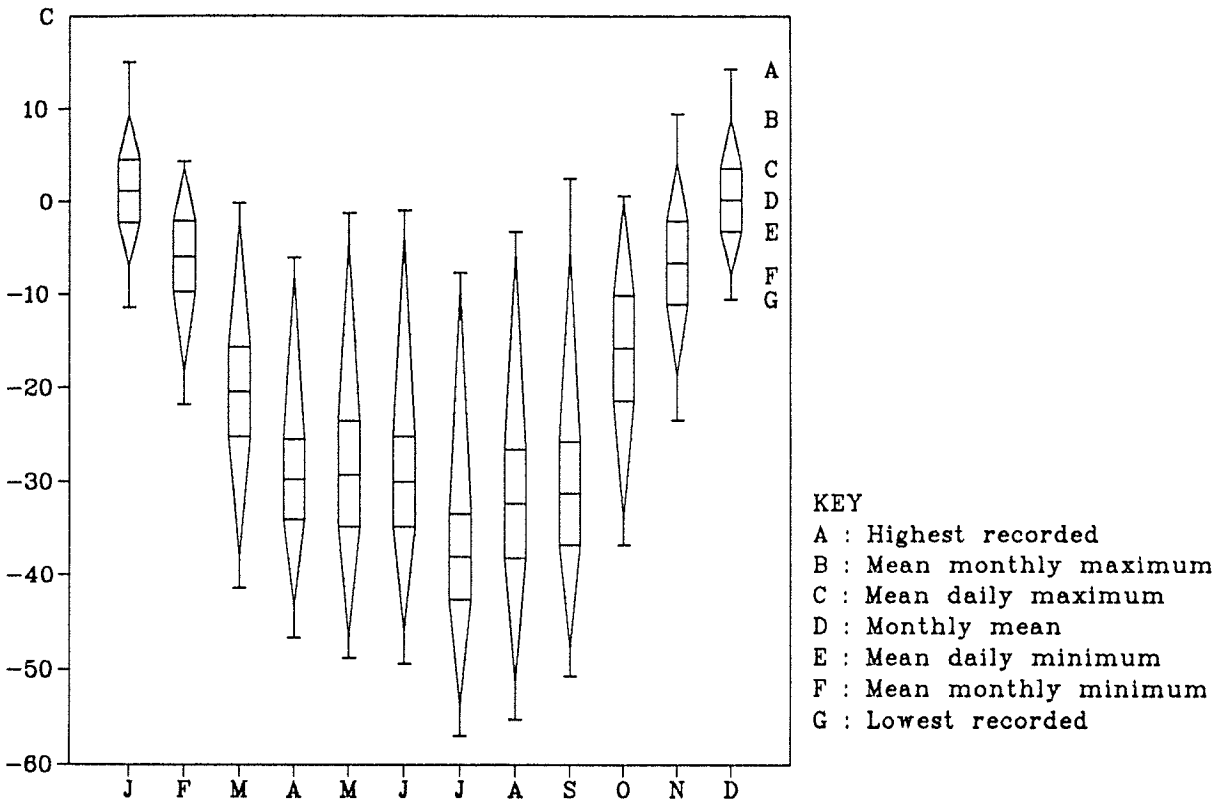

Figure 12: Seasonal variation of temperature at Lake Vanda

One source of temperature change has been examined in the previous section, and another source, that due to the wind, will be examined in the next section. In this section, the general behaviour of air temperatures, and then ground temperatures will be outlined.

Figure 12 shows that in December and January at Lake Vanda, mean temperatures are just above freezing, but every day a maximum of about 4°C, on average, is reached and once a month a maximum of about 9°C is probable. The highest recorded temperatures are 14.3 and 15.0°C, for December and January respectively. February/March and October/November appear to be transitional to and from the winter period of April to September inclusive. In this winter period, mean temperatures are about −30°C, with an average daily range of about 10°C and an overall range of −5°C to −50°C. The lowest recorded temperatures are −56.9 and −55.2 °C for July and August respectively.

Data is only available for 3 winters, thus the statistics of Figure 12 may not be representative of the real temperature behaviour at Lake Vanda. In order to assess the validity

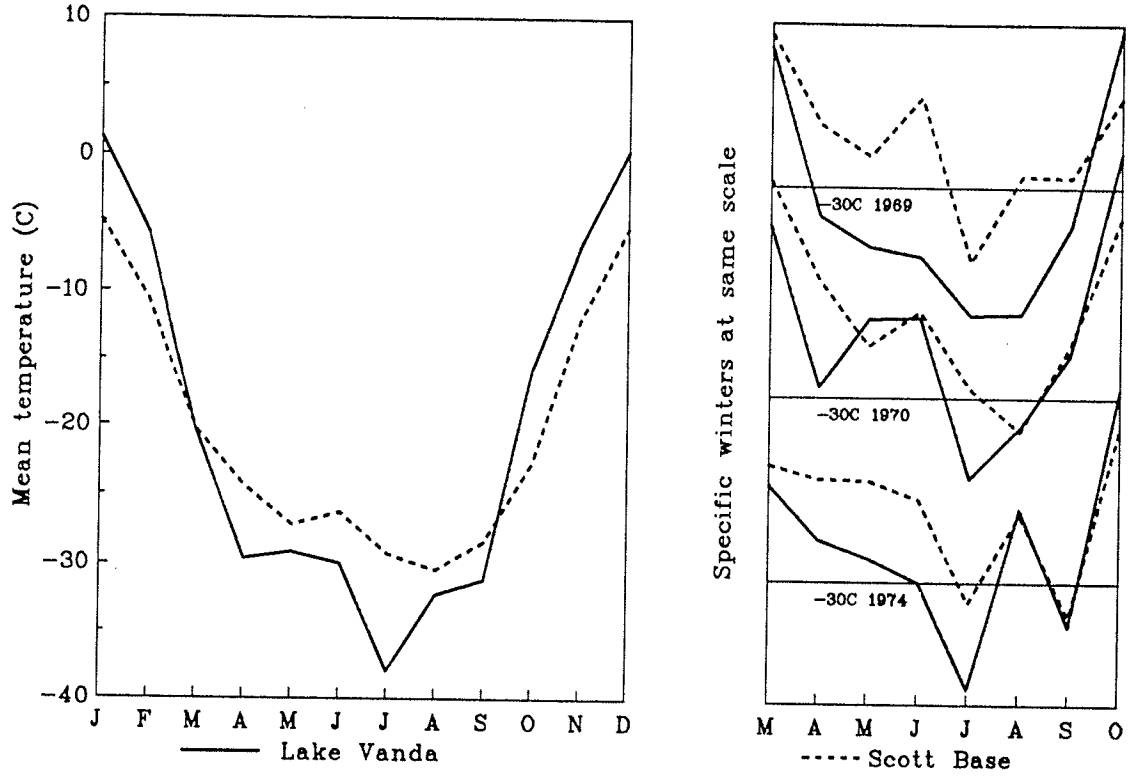

Figure 13: Seasonal variations of mean temperatures at Lake Vanda and Scott Base and a comparison of actual winters.

of the winter statistics, a comparison with Scott Base, where 30 years of data has been collected, is made in Figure 13. It can be seen that the summers are 5–7°C warmer at Lake Vanda but the winters 4–5°C colder. The actual monthly means for March to October of the years for which data are available from Lake Vanda are plotted on the right hand side of Figure 13 together with the equivalent values from Scott Base. The scales in the 2 halves of the figure are the same and it appears that during April to July, Lake Vanda is 4–5°C colder than Scott Base, however, for August and September temperatures are similar to Scott Base.

A major feature of the annual temperature cycle at Scott Base (and many other Antarctic stations) is the 'coreless' winter pattern, where the downward trend of monthly mean temperature through the autumn is halted or reversed in May or June, further falls of mean temperature to the overall annual minimum in July or August then occur (see Scott Base plot on left hand side of Figure 13). This behaviour has been attributed to the difference in cooling rates between mid-latitudes and Antarctic latitudes, so that an

enhanced temperature gradient exists for a time in May or June, which causes a greater frequency of cyclonic activity. The northerly airstreams on the eastern side of these cyclones move warm air towards the south. In the individual years, on the right hand side of Figure 13, the 'coreless' halts or reversals can be seen for both Scott Base and Lake Vanda.

A further comparison of these winter mean temperatures can be made by regressing those at Lake Vanda on those at Scott Base. The coefficient of determination for such a regression was about 70% thus the correlation between the stations is high. When the residuals were examined, it was found that positive residuals were associated with months of higher than average mean wind speed and negative ones with lower speeds; the reason for this will become clear later. In the multiple regression of Lake Vanda temperature (T_V) on its mean wind speed (W_V) and Scott Base's temperature (T_S) the coefficient of determination was 93% and the following relationship, in which all the coefficients are statistically significant, resulted :

$$T_V = -7.88 + 1.07T_S + 0.85W_V$$

If the monthly mean temperatures from Lake Vanda and Scott Base for the whole year are compared, by regressing them, a highly significant relationship is found because both stations have a similar annual cycle. The annual cycle is most simply removed by mean correcting the data for each month by the overall mean for the month concerned; monthly anomalies result. For example, the January anomalies are found by subtracting the January mean from each individual January. The regression of these anomalies from Lake Vanda, on those of Scott Base had a coefficient of determination of about 45%. However, all the largest residuals were associated with winter months and a subsequent regression excluding March to September inclusive had a coefficient of determination of 85%, and the following relationship (where the variables now refer to anomalies) resulted :

$$T_V = 0.76T_S$$

Thus, monthly mean temperatures at Lake Vanda are closely related to those at Scott Base provided an allowance is made for the mean wind speed during the winter months.

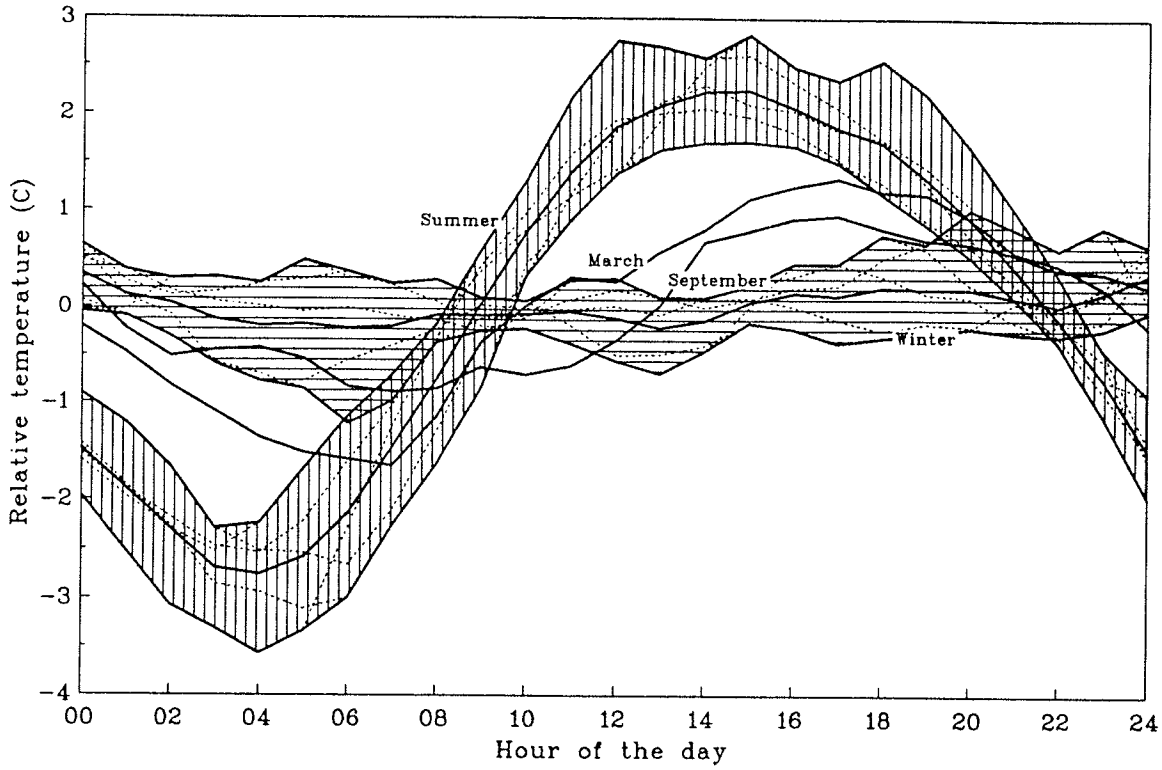

Figure 14: Diurnal variation of temperature at Lake Vanda

Figure 14 shows the diurnal variations of the temperature as departures from the daily mean level. The variation for each month is plotted separately with a dotted line but they fall into 3 groups :

October to February inclusive which is labelled 'Summer' in the figure

April to August inclusive labelled 'Winter'

March and September

The range of the summer group is indicated by the horizontally hatched area, and the mean by the heavy line through this area. Similarly for the winter group, with the range now vertically hatched and the mean as before. The transitional months of March and September are more like summer than winter but have a much lower amplitude cycle, which is not as smooth as the summer cycle; probably the end of September and beginning of March would fit the summer pattern.

The amplitude of the summer daily cycle is on average 5°C from a minimum at 4 a.m. to a maximum at 3 p.m. The transitional months have an amplitude of only 2°C, resulting

from about 5°C at the summer end of the month and near zero at the winter end of the month; their minimum and maximum were both 3–4 hours later than the summer ones. In winter no diurnal cycle is evident.

Figure 14 has 2 similarities to Figure 10, the distinct summer and winter seasons with transitional months in between and the near sinusoid cycle of the temperature or radiation through the day. However, some differences are evident : for any hour of the day the range within either summer or winter is smaller when compared to the summer cycle's amplitude for radiation. Secondly, the maximum and minimum of the summer temperature cycle are 3 hours later than those of radiation. Lastly, the transitional months are not the same but are such that radiation's summer starts a month later and finishes a month earlier. All these observations support the intuitive feeling that there is a causal relationship between radiation and temperature.

So far in this section, changes on monthly and daily time scales have been examined, but changes also take place on yearly or more and hourly or less time scales. The investigation of yearly scales involves questions of temperature trends, which require data over 20–30 years for answers to be attempted, and since this is not available such questions will not be addressed. However, changes of temperature from one hour to the next were examined.

The mean change from one hour to the next approximated zero with a standard deviation of 1.25°C, this implies that if the difference from hour to hour is normally distributed then, only 1% of the differences should lie outside of −3.2°C to +3.2°C. However, over 2% lay outside these limits with positive values (i.e. rises) reaching 20°C which as a random event, has a probability approaching zero. The negative differences (i.e. falls) were no less than −14°C, but again these values have near zero probability, and most of the largest falls were preceded by a large rise during the previous 24 hours. Therefore, a deterministic agent must be causing these large changes and in particular the rises as these precede the falls.

For the years 1969 and 1970 the 40 largest rises in temperature from one hour to the next were examined. There were 20 from each year and apart from one event on the 30th

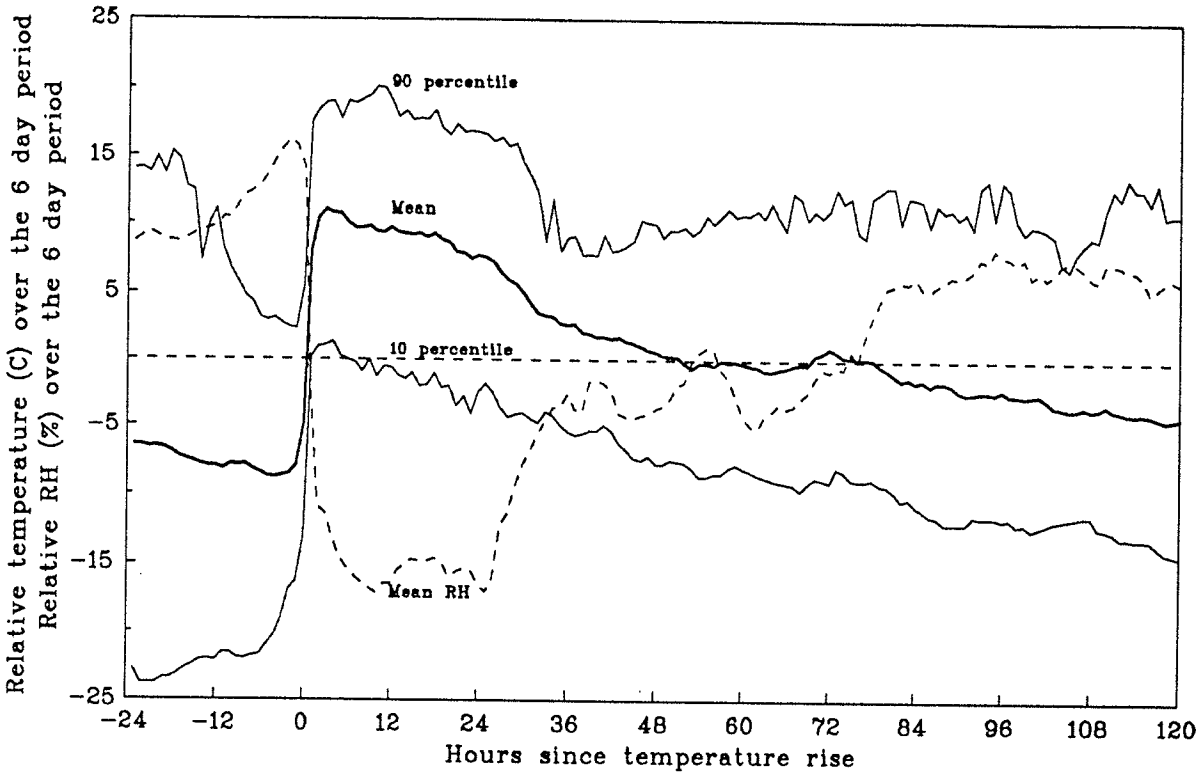

Figure 15: Mean air temperature and relative humidity response to arrival of winter westerly wind

March 1969, all rises occurred in April to September inclusive. No hour of the day seemed favoured, as might be expected for a winter time phenomenon, and in every case a change occurred in the wind from calm or light winds to a strong westerly. The mean wind after the temperature rise was found to be from 250° with a speed of 22 kt. It has also been noted that as the westerly wind arrives, not only does the temperature rise considerably, but the relative humidity drops to very low values. These characteristics are those of a föhn wind and will be discussed in the next section. Returning to the question of why the mean wind speed helps in the prediction of mean temperature in the winter, with the comparatively warm winter westerlies being generally strong to gale force, higher mean wind speed implies more frequent westerlies, and so higher mean temperature.

Figure 15 is based on the 40 largest one hour temperature rises from 1969 and 1970, although humidity data is only available for 1970. For each event, the time origin was the hour of the large rise and the temperatures and relative humidities from 1 day prior to 5 days after were corrected for their means over the 6 day period. After aligning all

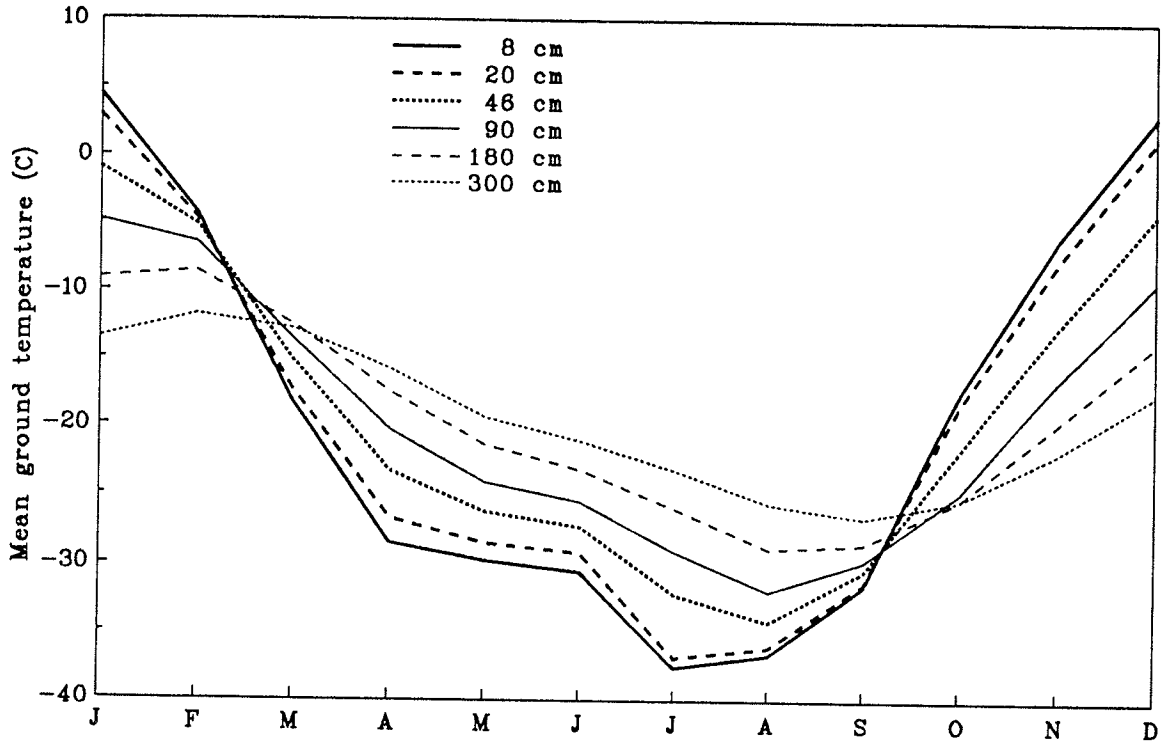

Figure 16: Seasonal variation of mean ground temperatures at Lake Vanda

the events with this origin a mean was taken across the events, the 10 and 90 percentile envelopes for the temperature were also found. The mean largest one hour temperature rise is 12.9°C but the mean rise from 3 hours before, to 3 hours after, is 19.7°C. The mean cooling trend before the event, may reflect radiation cooling in the calm and clear conditions usually prevalent at that time. The mean largest one hour relative humidity fall is 17% but the mean overall fall from 2 hours before, to 10 hours after, is 33%. The cooling trend after the event reflects the random length of these periods of strong warm westerlies. The slightly greater drop in temperature and comparatively large rise in relative humidity 24–36 hours after the event, may indicate a tendency for the warm, dry westerlies to last that long.

The winter westerlies will be discussed further in the next section while in the remainder of this section ground temperatures at Lake Vanda will be examined. These were measured at 3 hour intervals at the depths indicated in Figure 16 for the years 1969 and 1970. The variation in temperature at 8 cm corresponds to that of the air (see Figure 13),

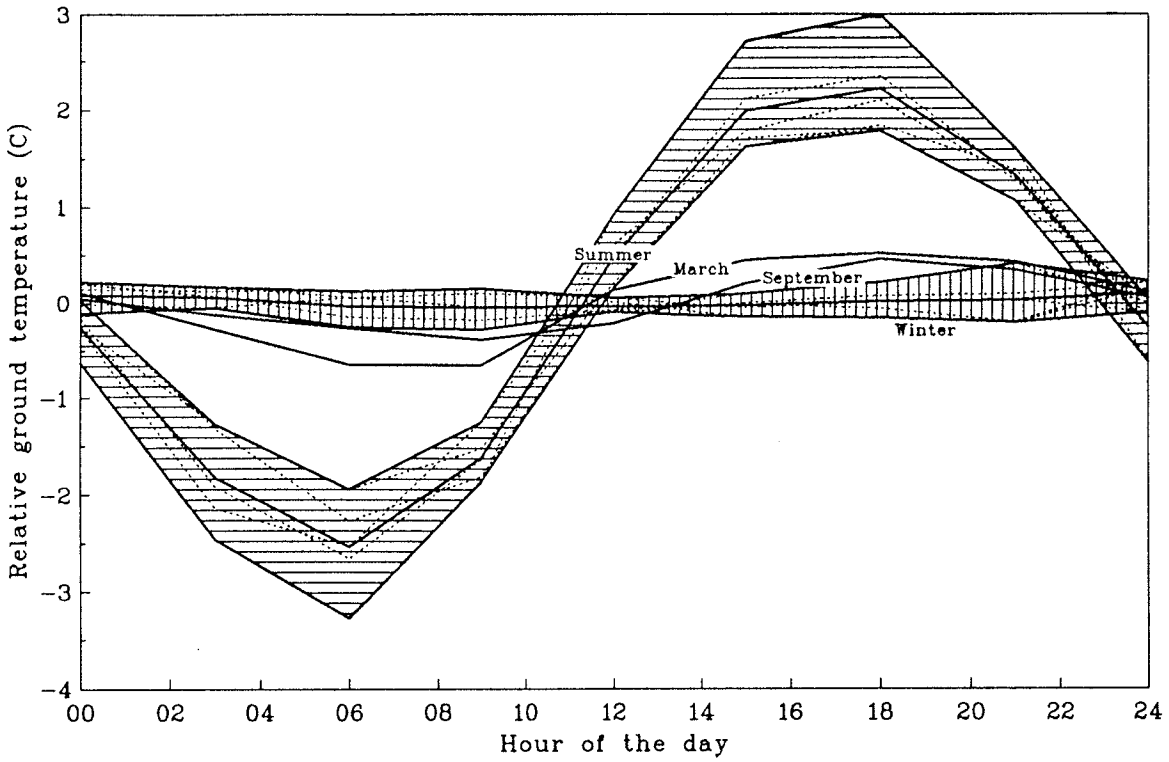

Figure 17: Diurnal variation of ground temperature at Lake Vanda

the overall range is similar and shows the 'coreless' pattern which is also easily seen at 20 and 46 cm and can just be seen at 90 cm. The presence of the 'coreless' pattern reflects the appreciable day-to-day variation in temperatures above 46 cm due to daily changes in the weather. The level of permanent freezing is estimated to occur at about 40 cm.

The general trend with depth is to a smaller range of temperature over the year, with temperatures cooling with depth from October to February, and warming from March to September. The months of maximum and minimum also vary with depth, since at greater depths there is a larger lag with the forcing agent (i.e. air temperature or radiation) such that, at the 180 and 300 cm depths the maximum occurs in February, while other depths have their maxima in January. The 8 and 20 cm have minima in July whereas the 46, 90 and 180 cm all have theirs in August, and the 300 cm minimum occurs in September. This type of ground temperature variation is usual in both the Antarctic and at latitudes further north and so the remainder of this report will refer only to the 8 cm ground temperatures.

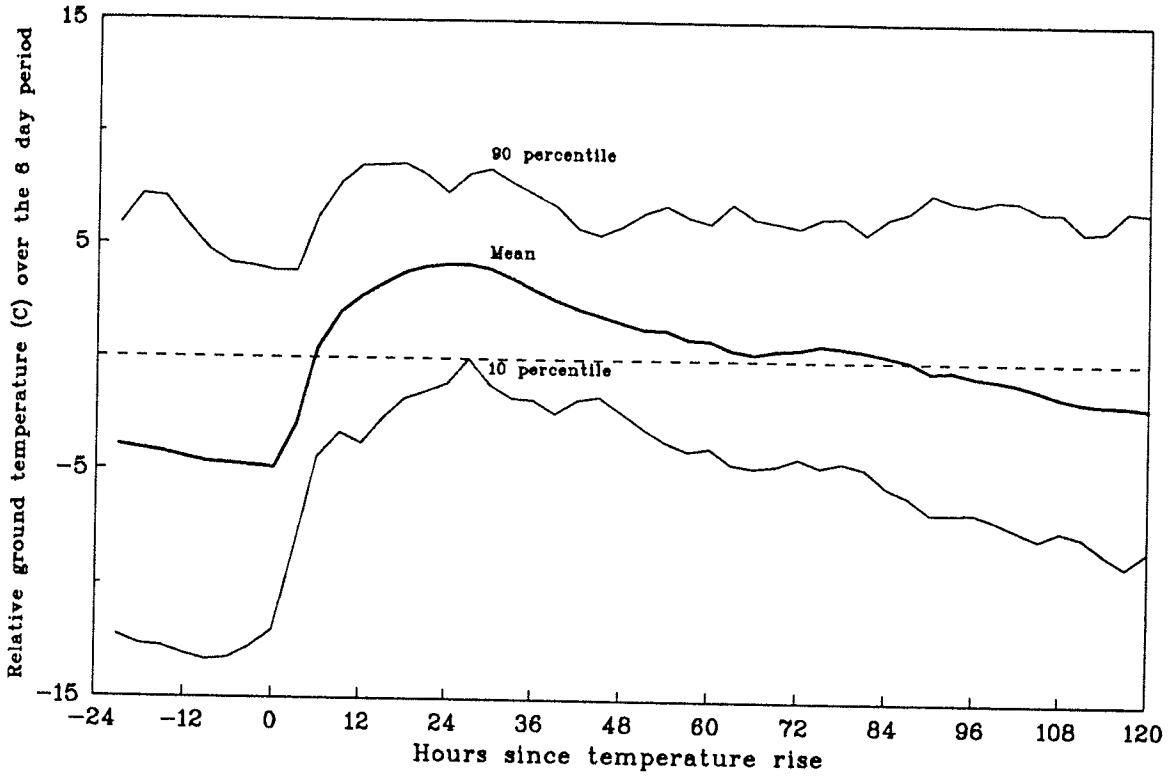

Figure 18: Mean ground temperature response to arrival of winter westerly wind

If Figure 17 and Figure 14 are compared the same general pattern emerges of identical seasons and transitional months with very similar amplitudes of the summer time daily cycle. However, there are some differences; the ground temperature's transitional months are more like its winter; the winter has less range than for air temperature; the timing of the maximum and minimum is delayed by possibly 3 hours, the exact delay cannot be obtained, since the ground temperatures were taken at 3 hour intervals.

Figure 18 is in the same style as Figure 15 and is derived from the same 40 events as those used in Figure 15. The response of ground temperature to the arrival of the warm winter westerlies is similar to that of the air temperature, except it is smaller and not so sharp. The largest rise is 3.5°C in 3 hours compared to 12°C in 1 hour, and the overall rise is 9°C from 3 hours before the event, to 24 hours after, rather than 19.7°C from 3 hours before to 3 hours after.

5 Wind

The directional distribution of wind is shown in the wind roses of Figure 19 where for each season the frequencies of 3 speed ranges are plotted; 1–10 kt will be called light winds, 11–24 kt moderate and over 24 kt strong. The most notable feature is the strong directionality with almost all winds being either easterly or westerly. The scale is constant from season to season, and in Figure 19 it can easily be seen that the most frequent winds are the summer time moderate due easterlies, which occur about 12.5% of the time in summer. The seasons can be paired; autumn with winter, spring with summer. This latter pairing is probably exaggerated as more data is available for November than for September and October and less data for February than December and January.

In spring and summer moderate easterlies predominate; light easterlies and moderate westerlies are both half as frequent; the only strong winds are westerly and these are rare in the summer. In autumn and winter light easterlies predominate, these winds have much the same frequency throughout the year; moderate easterlies, moderate westerlies and strong westerlies have approximately equal frequency which is about half that of the light easterlies. However, for much of the time in autumn and winter there is no wind. The essential difference between the 2 halves of the year is that the alternation in autumn and winter of calm periods and strong westerlies is replaced in the spring and summer by periods of moderate easterlies.

The question arises about the time distribution of the calms and strong westerlies of winter time, and the moderate easterlies of summer time. Do the winds persist for long periods or do they occur regularly at a particular time of day? Since the winds are either easterly or westerly, they can be grouped accordingly and the seasonal changes in their diurnal variation and that of calms can be examined as in Figure 20. There is a quadrant of the circle for each season and within each quadrant, each of 4 directions represents a period of the day i.e. proceeding clockwise, night (N), morning (M), afternoon (A) and

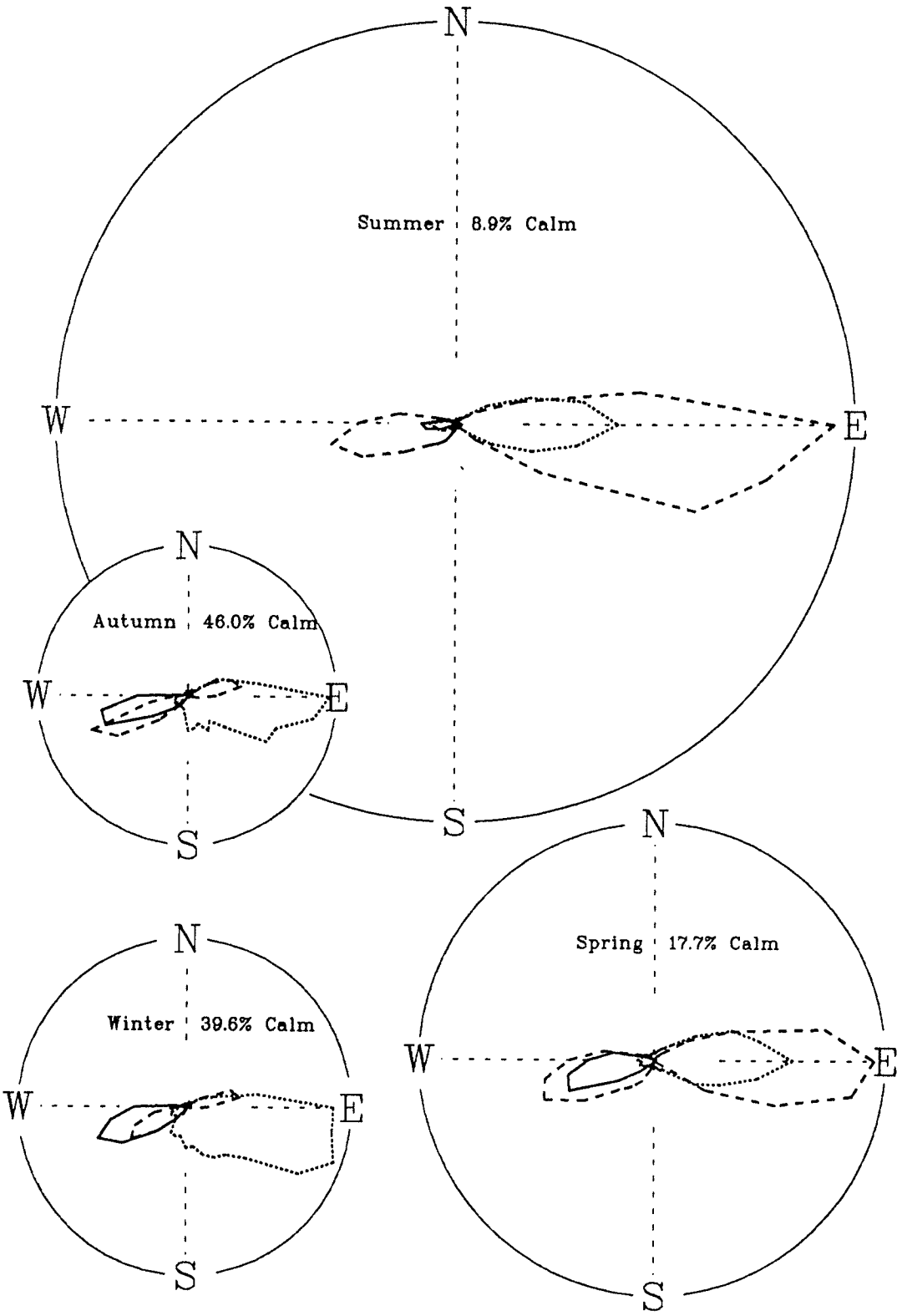

Figure 19: Seasonal wind roses for Lake Vanda

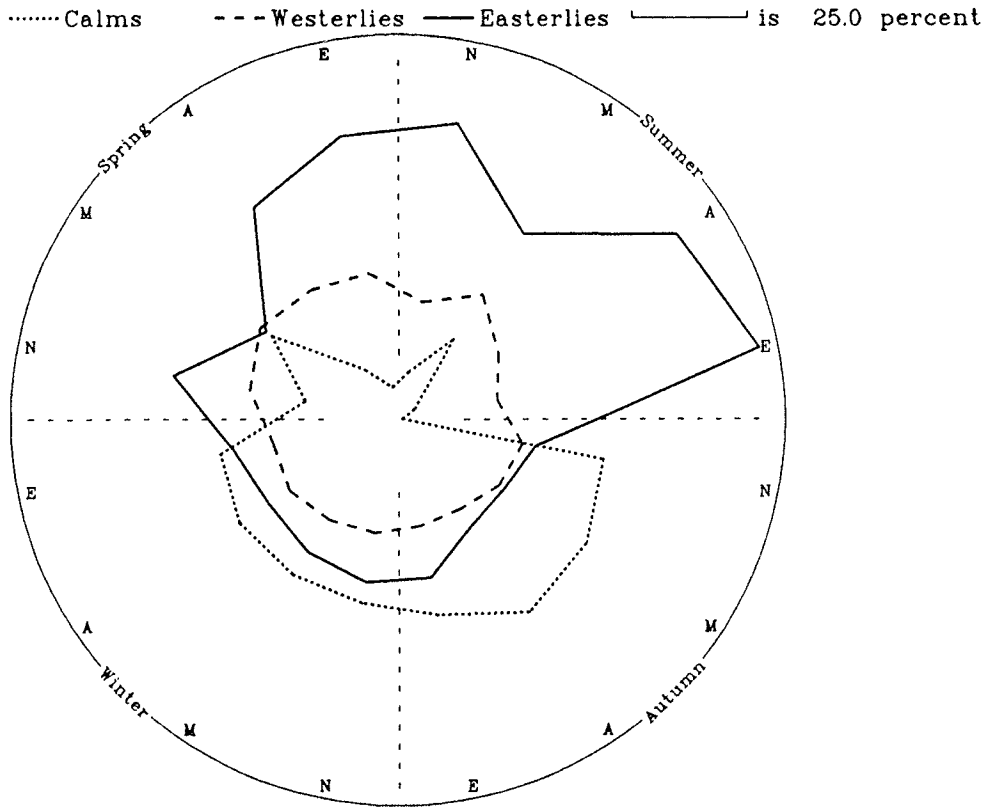

Figure 20: Seasonal and diurnal variation of the frequency of wind direction

evening (E), where each period is as defined in Figure 21. Thus, for each season and time of day, the frequencies of easterlies, westerlies and calms are plotted as radial distances.

If there were no diurnal and seasonal variation, then a perfect circle would result. The closest approach to a circle is for the westerlies, but calms and easterlies in autumn and winter also appear to have little diurnal variation. Even in spring and summer the diurnal variation of easterlies is not large, a small decrease in the morning occurs when calms, and to a lesser extent westerlies, become more frequent. Figure 20 contains no information on the diurnal variation of winds of different strength, whereas in Figure 21 there is a circle for westerlies and another for easterlies. Thus, for each wind direction, season and time of day the frequencies of 3 wind strengths are now plotted as radial distances — 1–10 kt will still be called light, but moderate is now 11–20 kt and strong is now over 20 kt.

The closest approach to a circle (i.e. no diurnal and seasonal variation) in Figure 21 is for strong westerlies, but it is broken by the smaller frequencies of summer. However, for

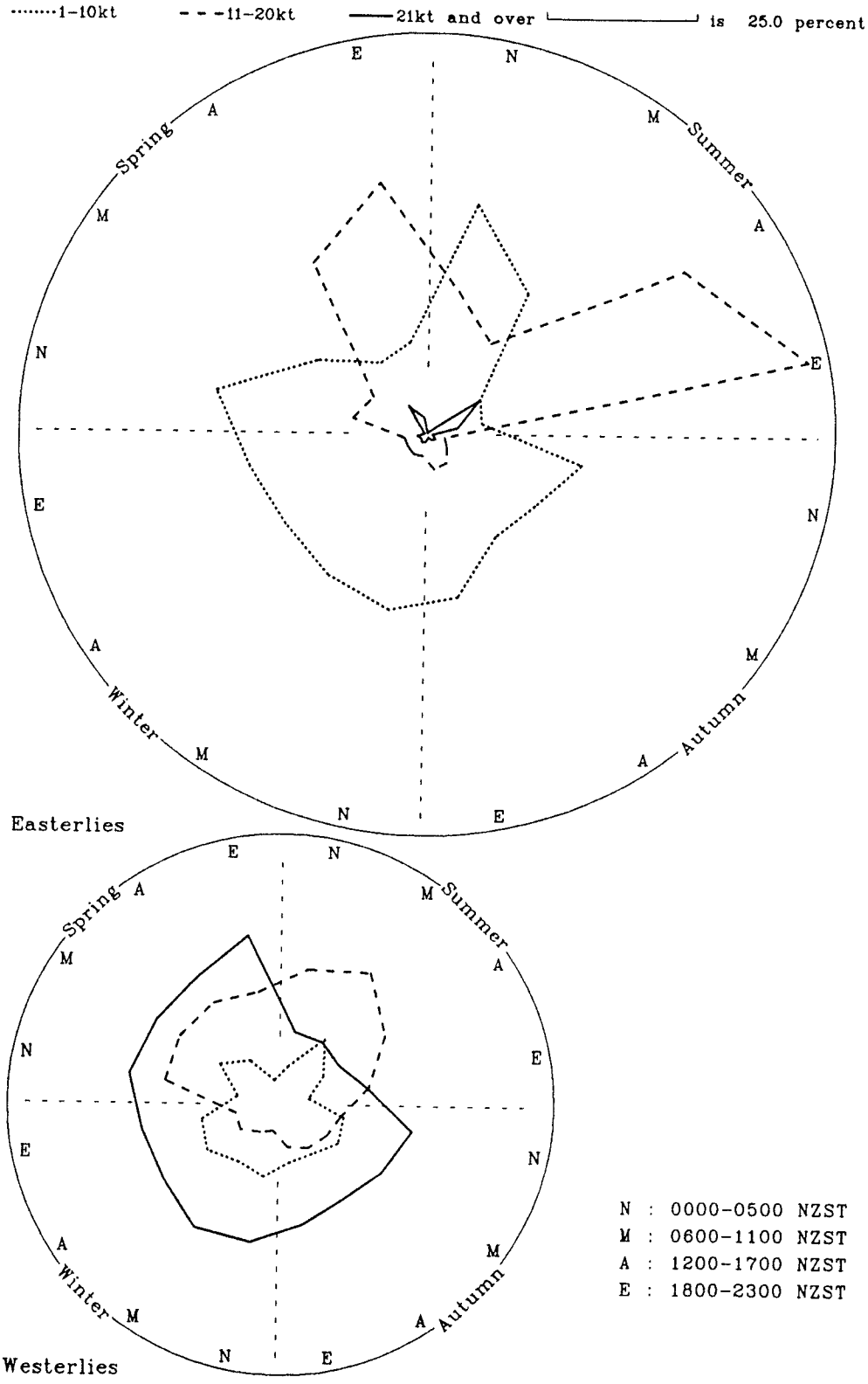

Figure 21: Seasonal and diurnal variation of the frequency of wind direction and strength classes

all westerlies little diurnal variation can be seen, even the slight decrease in the evening and night of the spring and summer light westerlies is not significant. In winter and to a lesser extent in autumn, moderate westerlies are the least frequent, which together with the high frequency of calms suggests that from March to September there is either little wind or there are strong westerly winds. Also, the strong westerlies are not tied to the diurnal cycle, which is to be expected during the Antarctic night. Thus it is possible that they occur in long periods interspersed with long calm periods. More will be said about the strong westerlies later.

Figure 21 shows that no diurnal variation exists in autumn and winter for easterly winds, whereas a large daily cycle can be seen in spring and particulary in summer. In both spring and summer, light easterlies are most frequent in the night and morning however, moderate easterlies predominate in the afternoon and evening, the frequency of strong easterlies is also higher then. This sort of diurnal variation looks very similar to that of a mid-latitude sea-breeze circulation, where day time heating forces an exchange of air over the land and over the sea. Even though the dynamics of this variation may be essentially different to that of the sea-breeze, this daily cycle is undoubtedly thermally driven.

In addition to the variability of wind direction as depicted in Figures 20 and 21, there is a diurnal variation in mean wind speed as shown in Figure 22 where no differentiation has been made between easterlies and westerlies. Each month is plotted separately with a dotted line, but they fall into 3 groups :

November, December and January which is labelled 'Summer' in the figure

March to September inclusive labelled 'Winter'

October and February.

The range of the summer group is indicated by the horizontally hatched area, and the mean by the heavy line through this area. Similarly, for the winter group with the range now vertically hatched, and the mean as before. The transitional months of October and

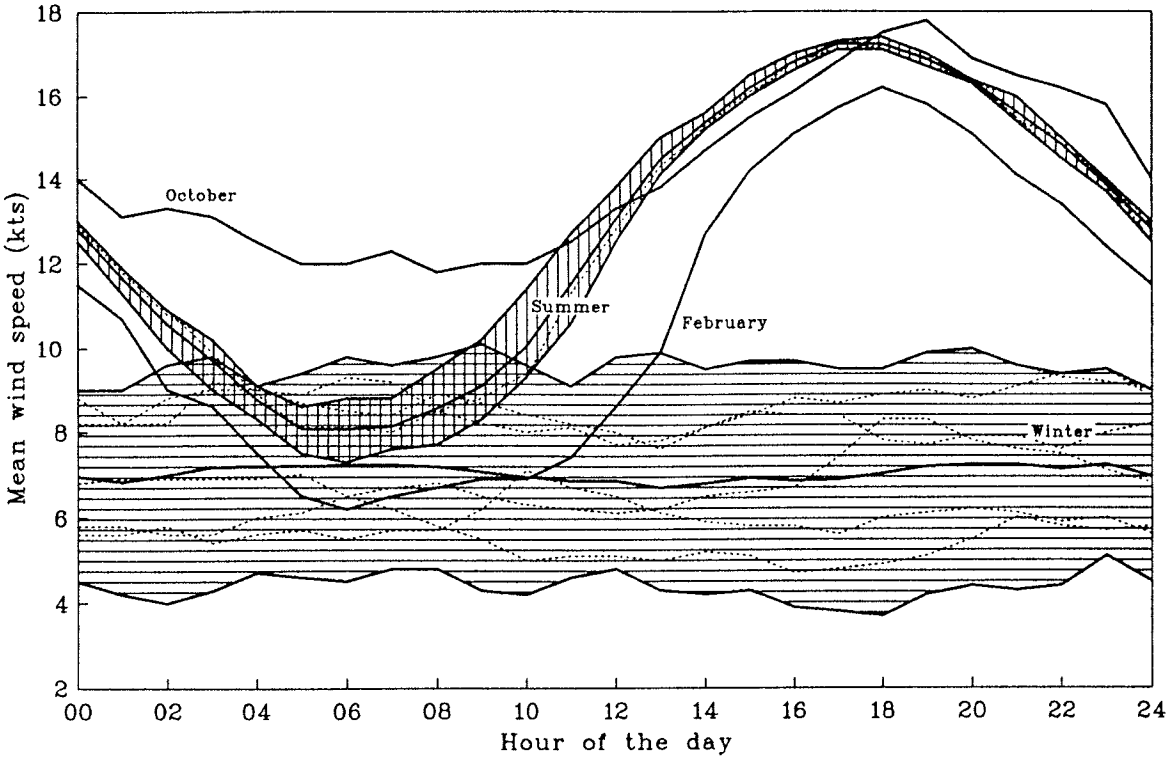

Figure 22: Diurnal variation of the mean wind speed for different times of the year

February are more like summer than winter, but October has a much lower amplitude cycle and February has generally lower values; neither's cycle is as smooth as the summer cycle. These months are biased towards the end and beginning of the month respectively as the summer observing season is from, at earliest, late October to, at the latest, early February. Therefore the transitional months are more like summer than winter.

If Figure 22 is compared to Figures 10, 14 and 17 the distinct seasons and transitional months are similar but the mean wind speed is absolute and not relative to a daily mean. In summer the least windy time of day is 5–7 a.m. when the mean wind speed is about 8 kt and the windiest is 6 p.m. with a wind speed of about 17 kt. In winter the mean wind speed for any hour of the day is about 7 kt, but it ranges from 4.5 kt to 9.5 kt. However, since in winter it seems that long periods of calm or light winds are interspersed with periods of strong westerlies, the mean wind speed has little meaning, and the strong westerlies will be examined separately.

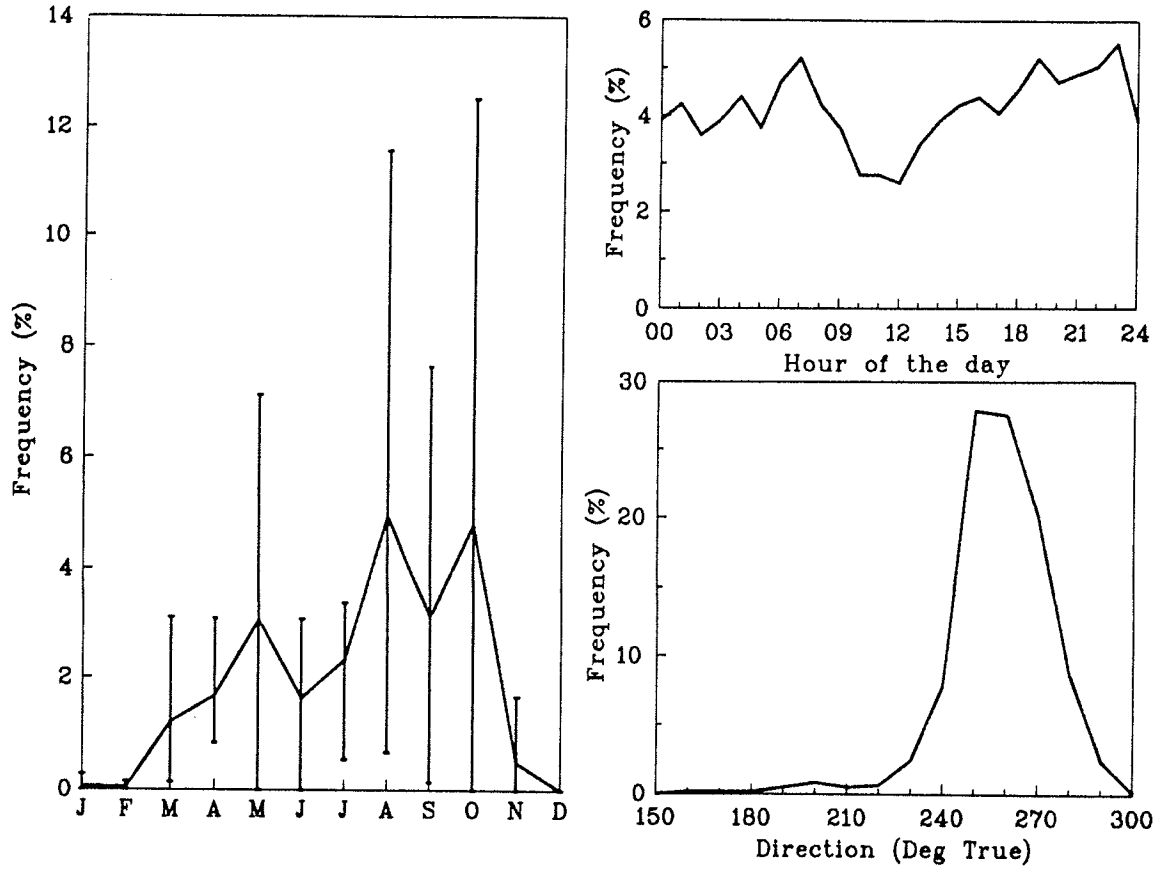

Figure 23: Gale force wind statistics

Figure 23 shows statistics for all winds (not just westerlies) with a speed of over 36 kt. It can be seen from the lower right hand side that most of these are westerlies, with over half coming from 250° and 260°. The upper right part of the figure shows the diurnal variation to be small and if the hypothesis that there is no diurnal variation is tested using a χ^2 test, the hypothesis cannot be rejected. Finally, the figure shows on the left the seasonal variation of the frequency of gales; December, January and February have very few, but from March until October there appears to be an increase in the mean frequency. The ranges, which are indicated by the vertical lines, are very large and the amount of data small, thus the trend may be more apparent than real.

The lower right part of Figure 23 shows that most strong winds come from between 210 and 300° and so, in Figure 24 these limits are used to define the westerly direction. The heights of the vertical lines in this figure indicate, for the years 1969 and 1970, the actual lengths of periods of westerly winds, while the mean wind speed over the period

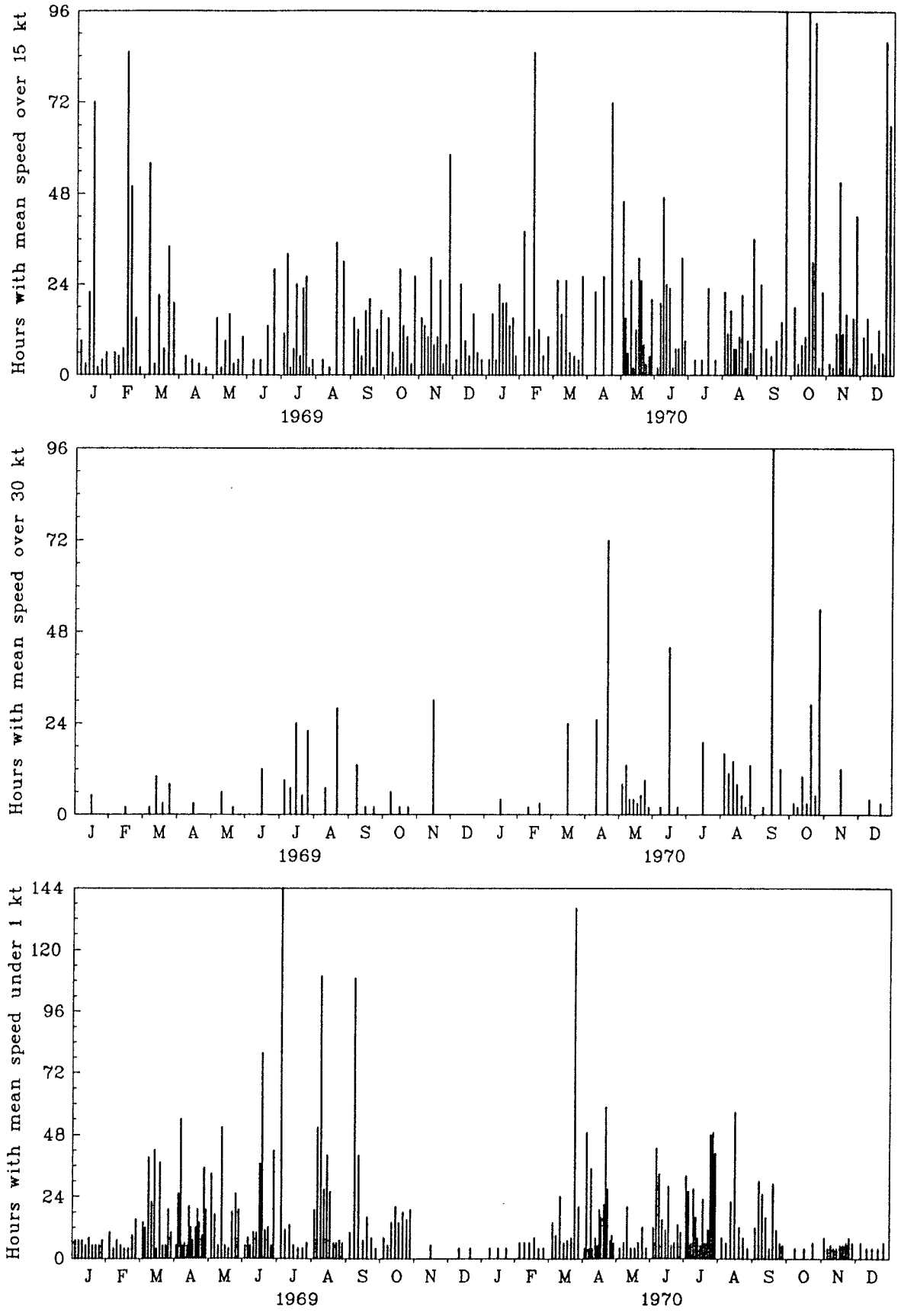

Figure 24: Actual durations of moderate and strong westerlies and of light winds

exceeds, in the top part, 15 kt and, in the middle part, 30 kt. For example, in January 1969 the first period of westerlies, through which the mean wind speed was over 15 kt, lasted for 8 hours and the next for 2 hours, then 23 hours etc. The periods, are of at least 2 hours duration and are drawn evenly spaced and in the right time order through each month. The lower part of the figure is in a similar style to the upper parts and shows the lengths of time during which the wind did not exceed 1 kt from any direction; only periods of at least 4 hours are drawn.

The top part of Figure 24 shows little seasonal variation in the moderate or more westerlies and although the 3 most persistent periods are in the September (151 hours) and October (96 and 93 hours) of 1970, the next 4 most persistent are in December, January or February. However, the middle part of the figure shows that for strong westerlies there is a preference for March to October inclusive. The most persistent strong westerly in the 2 year period was 107 hours in September 1970. The lower part of Figure 24 shows that periods with winds under 1 kt also have a seasonal pattern with longer and more frequent calm periods from March to October inclusive. The longest period with winds under 1 kt was for 184 hours in June 1969.

In Figure 25 the 20 longest periods of strong westerly have been plotted after being slightly smoothed, one of these periods is from November, the rest are from March to October. They have been aligned about the time in each event when the wind speed first exceeded 30 kt; negative wind speeds refer to winds from directions outside of 210–300°. There appears to be 2 classes of westerly; firstly, those where the wind speed increases from calm or light easterly to over 30 kt westerly within a few hours and secondly, those where the wind slowly increases from 20 kt to 30 kt in 12–24 hours. Both of these slowly decrease subsequently over a period of up to a few days, but at some stage the wind speed drops within an hour to near calm conditions. The heavy line in Figure 25 shows the mean response for the first class up to 3 hours prior to the time origin and, for all winds from then on and until the sudden drop to near calm. For the second class of event, in

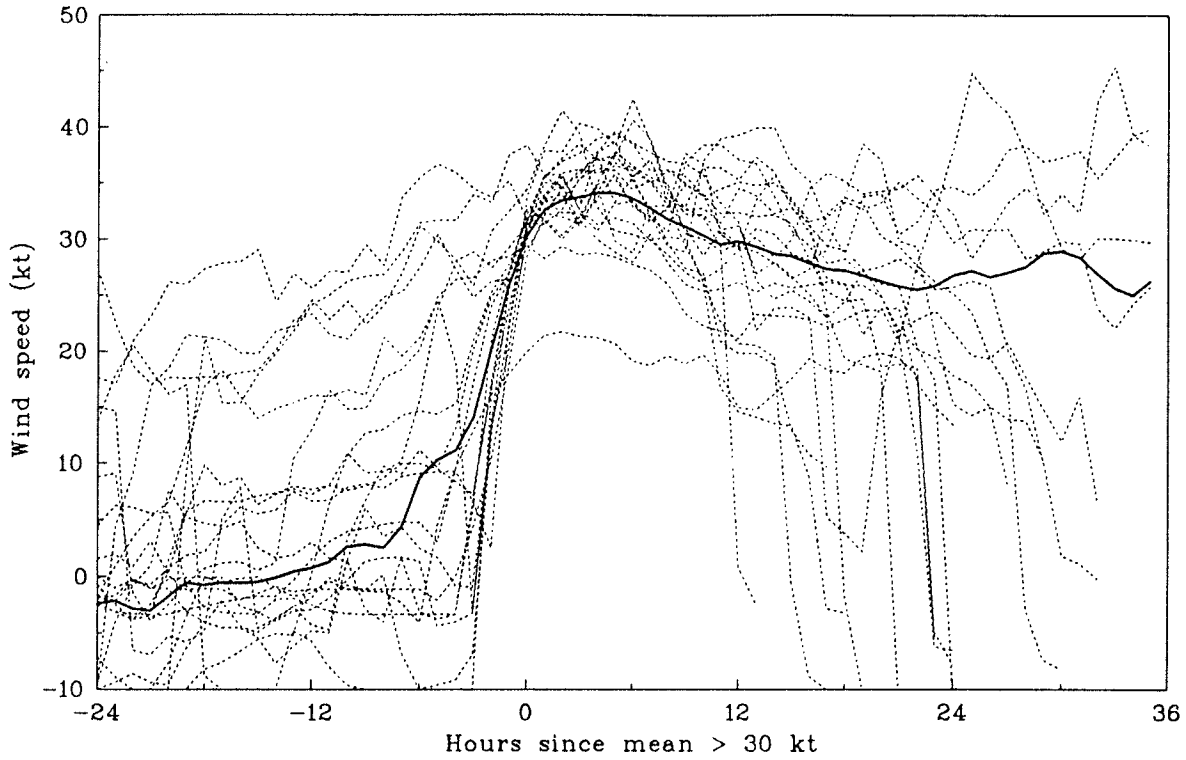

Figure 25: Actual and mean life histories of strong winter westerlies

most cases, a rise in wind speed within a few hours from near calm to about 20 kt can be seen at the left hand side of Figure 25 thus these are probably not essentially different to the first class.

At many Antarctic coastal locations, strong cold katabatic winds are common, these are generated by dense cold air from the Antarctic Plateau draining down valleys. The Wright valley leads from the Plateau to McMurdo Sound to the east, and katabatic westerlies were expected. However, as noted in the previous section the strong westerlies at Lake Vanda are comparatively warm and also dry. The process involved at Lake Vanda is one of compressive warming, in which air from one altitude is forced downwards and compressed so that its temperature rises and its relative humidity falls as a consequence.

Prior to a period of strong westerlies, blowing snow is observed to the far west at the head of the Wright valley. Some 6–8 hours later the westerly arrives at Lake Vanda with a strength qualitatively in proportion to the observed quantity of blowing snow. This

snow is always observed to be blowing from south to north, and often streamers of snow are seen to be blown off the Asgaard Range tops, also from south to north. The westerly generally arrives at Lake Vanda as a wall of dust, snow and grit or sand; temperatures rise rapidly and relative humidities fall. The vertical extent of these strong westerlies has not been measured in any systematic way, but on many occasions personnel on field trips have walked out of the strong westerlies as they have ascended the sides of the Wright Valley. Winds decreased steadily with height, and by about 500–600 m conditions were often near calm but from observing snow streamers higher up the ranges, it seems likely that this calm region is also fairly shallow, as strong southerlies prevail about the tops of the ranges.

Small whirls of about 20–60 m high, 10–30 m base diameter and lasting a few minutes are observed with every strong westerly, although they are much more common about the passes and glaciers of the Asgaard Range than on the valley floor. Less often, whirls over 100 m high occur, and on a few occasions heights of 500–1000 m have been observed. These large whirls originate to the west of Lake Vanda in the South Fork area and move eastwards a few kilometres over the valley floor before dissipating. They leave behind tracks up to 10 cm deep and 30 m wide and signs that boulders of about 1 m diameter have been moved several metres. The formation mechanism of these large whirls is not clear, but probably involves the vertical tilting of horizontal eddies by the particular land formation of the South Fork area.

Apart from these winter time whirls associated with strong westerlies, dust whirls are common in the summer time. In some favoured places, these can be observed most days in the late mornings of December and January before the afternoon fresh easterly wind commences. They are generally small, only 10–20 m high and 3–5 m in diameter, but a few up to 300–400 m have been seen. The formation of these summer time whirls involves the heating of air near the ground leading to strong thermals which, when suitably triggered, generate the whirls.

6 Correlations

In the previous sections of this report meteorological parameters have in general been examined singly; the exception to this was the strong winter westerlies with large temperature and humidity changes at the onset of these winds. However, there can be no doubt that physical dependencies do exist between meteorological parameters. Crudely, radiation heats the ground this in turn heats the air which can set up thermally forced winds, and given a source of moisture, air temperature together with wind and radiation cause evaporation and hence increased humidity.

An indication of what takes place can be gleaned from the summer time diurnal variations shown in Figures 6, 10, 14, 17 and 22, where it appears that changes in the parameters are not necessarily contemporary. Thus, any investigation must examine dependency over a few hours at least but need not extend to more than 12 hours. This is not to say that long term dependencies extending over several days, months or years, do not exist or are not important at Lake Vanda but such dependencies could only be defined if many years of data were available. The validity of the definition of short term dependencies from the 1 or 2 years data currently available is questionable, but it seems likely that broad outlines should be definable.

The simplest dependency that can be assumed between measurable quantities is one of linearity in which case the rate of change of one quantity is constant with respect to another. It must be noted that the hourly measurements available from Lake Vanda are unlikely to form a closed system. For example, although a dependence undoubtedly exists between the air temperature and the net radiation, other factors influence temperature and some of these are likely to have arisen from outside of the immediate Lake Vanda area. Thus, any linear dependence between two meteorological parameters will be confused by other dependencies and statistical rather then deterministic dependencies will be apparent. The correlation coefficient measures the amount of linear dependence between two quantities.

Figures 26–30 are all in the same style; for a particular parameter, correlation coefficients have been determined between it and other parameters for every month of the year.

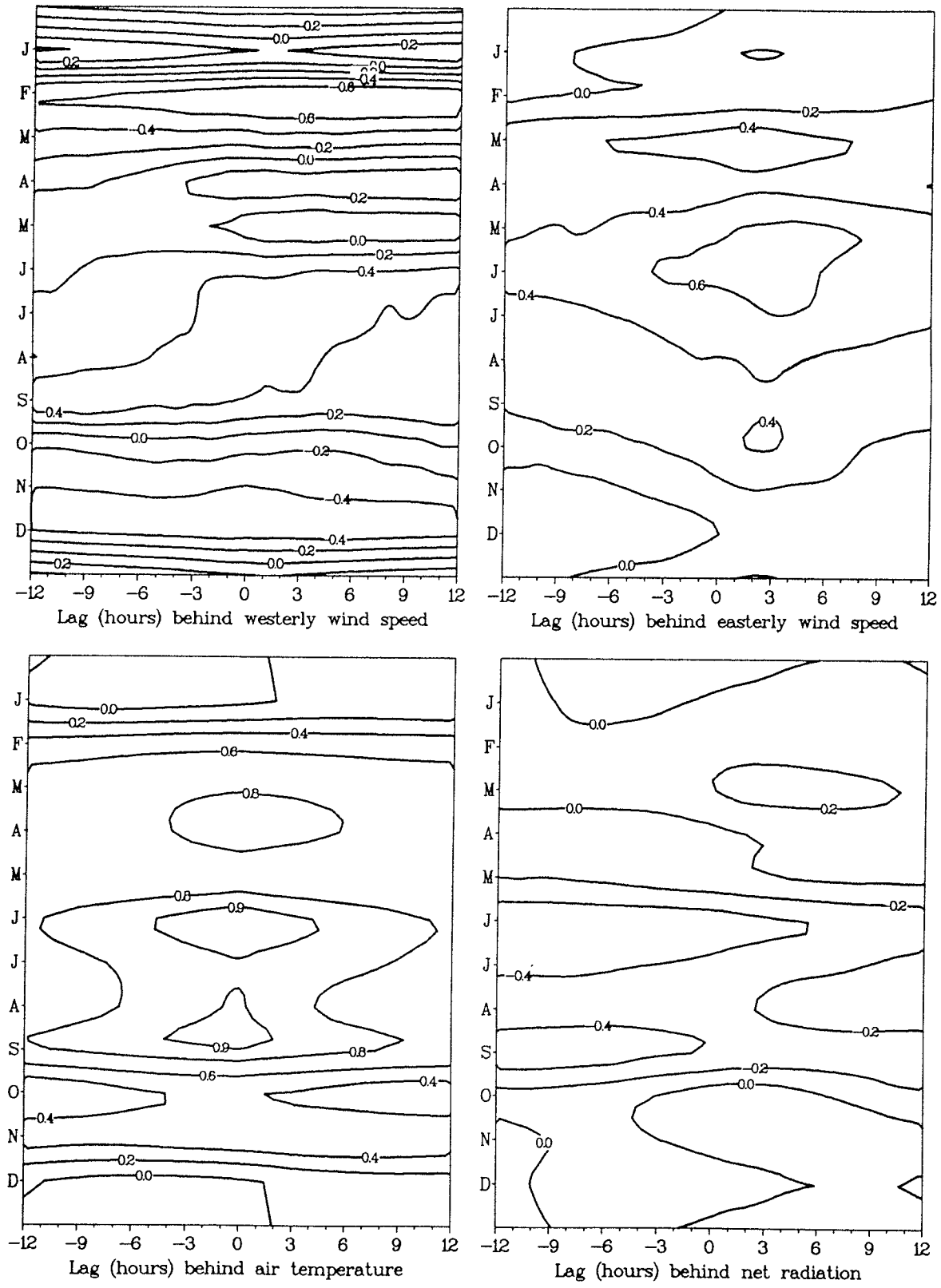

Figure 26: Monthly variation of the correlation between vapour pressure and the parameters shown for the lag and lead times shown

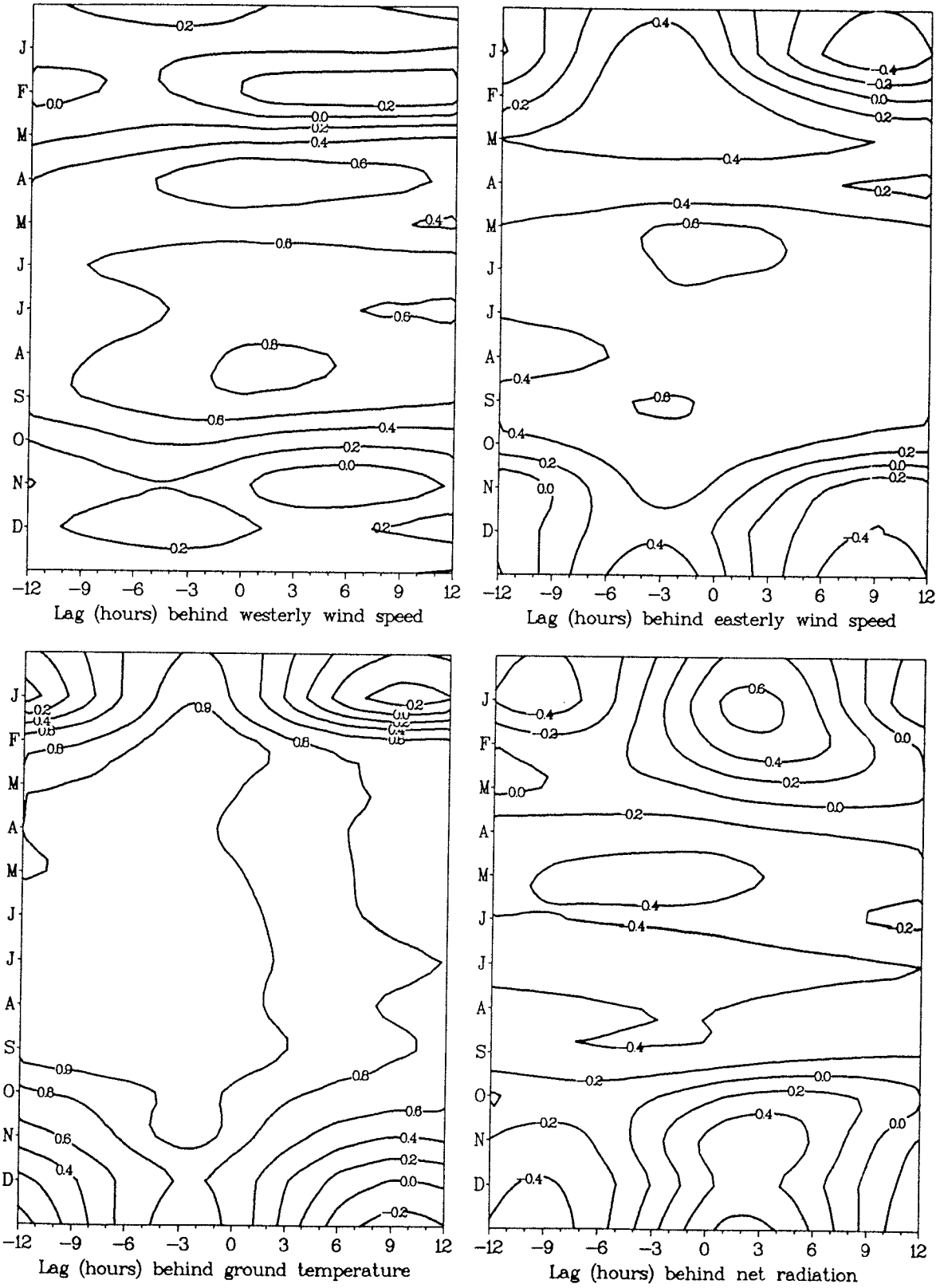

Figure 27: Monthly variation of the correlation between air temperature and the parameters shown for the lag and lead times shown

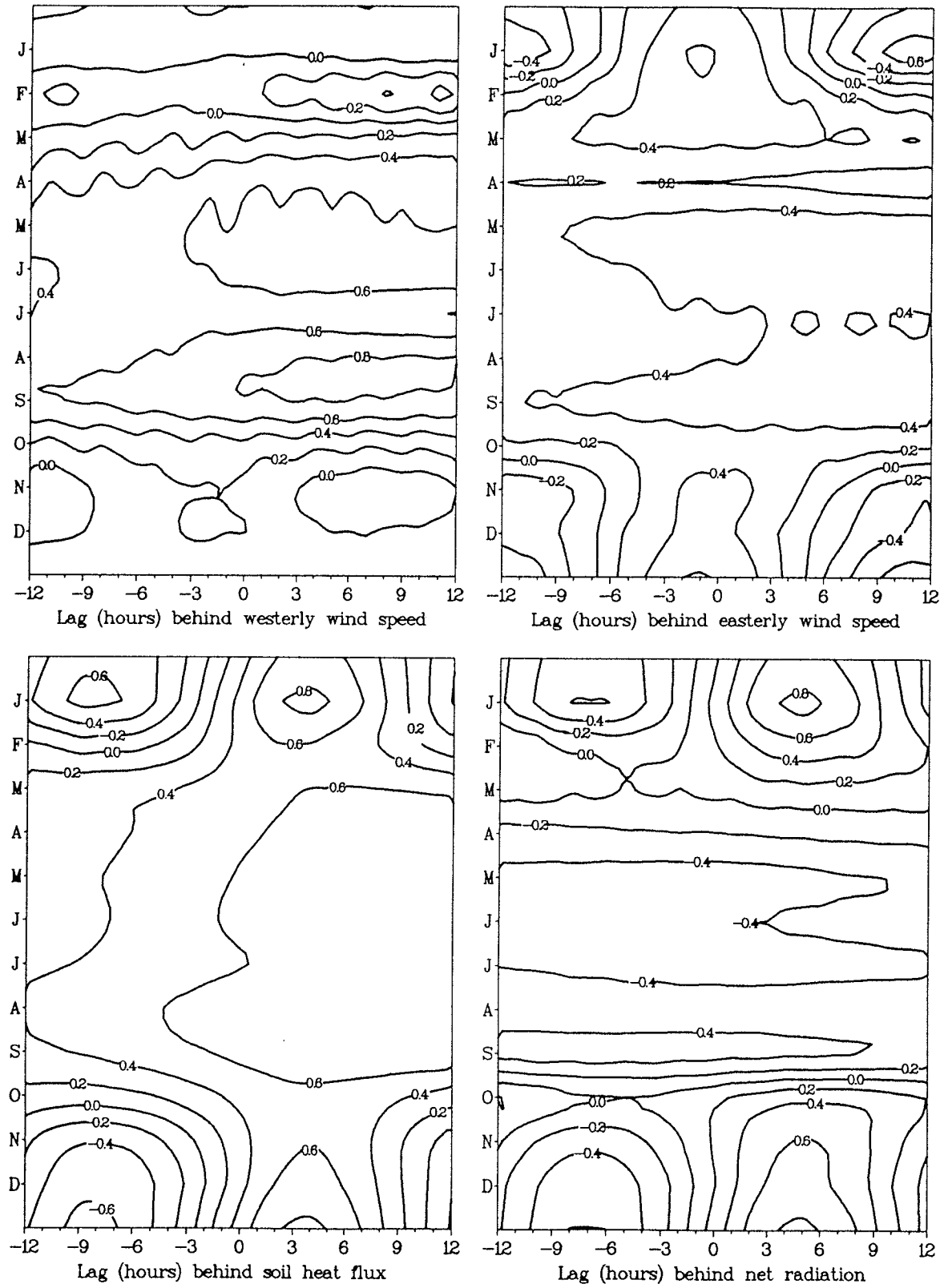

Figure 28: Monthly variation of the correlation between ground temperature and the parameters shown for the lag and lead times shown

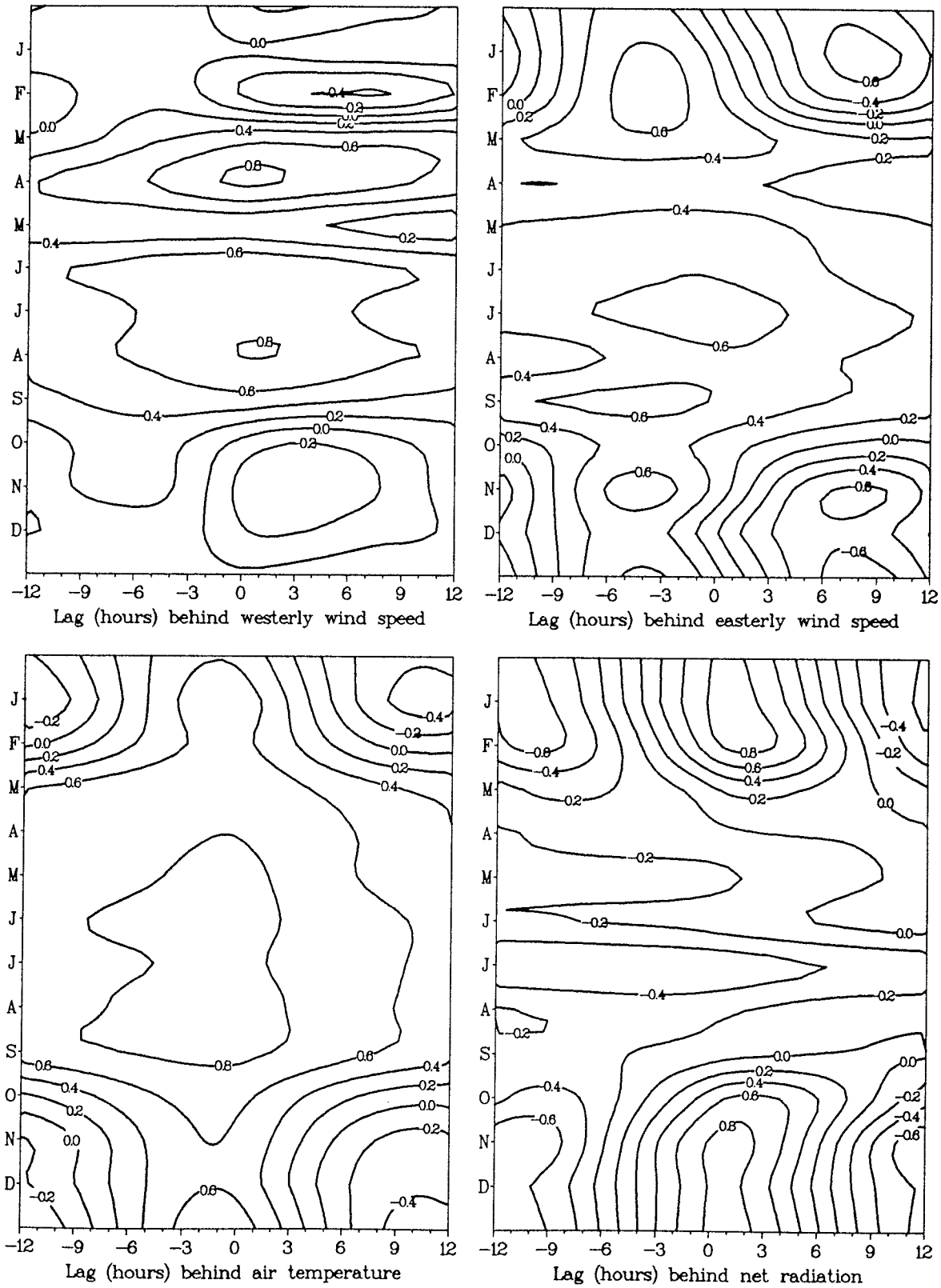

Figure 29: Monthly variation of the correlation between soil heat flux and the parameters shown for the lag and lead times shown

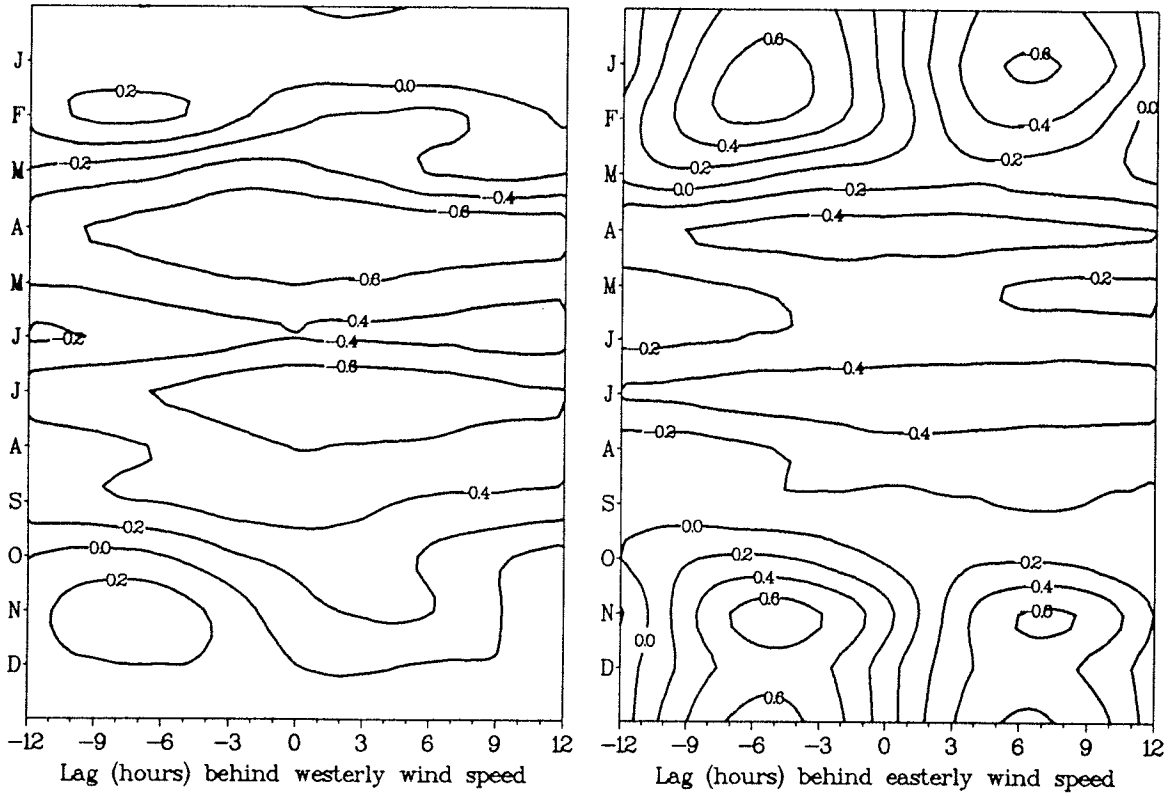

Figure 30: Monthly variation of the correlation between net radiation and the parameters shown for the lag and lead times shown

Not only have the contemporary coefficients been derived, but also those in which each parameter has been lagged by 1 to 12 hours with respect to the other. A 1 hour lagged coefficient is that in which the correlation is between measurements of the quantities that are 1 hour apart. Thus, each part of these figures is a contoured representation of 12×25 coefficients with contours at every 0.2 from -0.8 to 0.8 and also at 0.9 where necessary.

The number of pairs of values that these coefficients derive from is generally very high, reaching nearly 1500 several times; is usually several hundred and only falls below 100 a few times. The least number of pairs is for the July coefficients in the vapour pressure and westerly wind speed correlation with still 73–77 pairs available. However, as the coefficients in this case are 0.3–0.5, their statistical significance is very high; there is only a 1 in a 100 chance that these values arose randomly. The case just examined is the worst case, and most coefficients have much higher significance.

The meteorological parameters available with hourly values are; wind, solar radiation, net radiation, relative humidity, air temperature, ground temperature and soil heat flux.

Wind data contain information on both direction and speed, but as winds at Lake Vanda are either westerly or easterly these directions were used to define 2 new parameters i.e. westerly wind speed and easterly wind speed. Solar radiation and net radiation are closely related, but net radiation contains information on the solar energy available and so was chosen as the radiation parameter in preference to the other. In order to free the moisture parameter from any temperature dependence, the relative humidities were processed into vapour pressures using Magnus's formula. The other listed parameters were left unchanged.

Choosing 2 parameters at a time from the 7 available gave a total of 20 combinations, after allowing for westerly and easterly winds being mutually exclusive. The two combinations, of vapour pressure with ground temperature and with soil heat flux, were also excluded since any apparent dependencies would be through other more direct ones; probably with air temperature in these cases. In order to rationalise the remaining 18 combinations the parameters were sorted into dependent ones and independent ones. Net radiation which derives primarily from the sun, and the wind parameters which derive to a large extent from weather patterns over an area much larger than the Wright Valley, are all basically independent and control the others. Thus, in Figures 26–29 the correlations of the dependent parameters (vapour pressure, air temperature, ground temperature and soil heat flux) with the independent parameters (westerly wind speed, easterly wind speed and net radiation) are displayed plus a correlation with one of the other dependent parameters. Figure 30 shows the correlation between the dependent parameters.

In Figure 26 there are no strong lag or lead dependencies, unlike most of Figures 27–30, where often in the summer (i.e. October to February inclusive) a large variation in correlation exists with lag or lead. However, there still appears to be a difference between summer and winter in Figure 26 with generally higher correlations in the winter than the summer. Thus, in summer (apart from January but especially in February) as the westerly wind increases, the vapour pressure decreases, and early and late in the season, vapour pressure increases with air temperature, but the correlations with easterly wind speed and net radiation are weak. In winter the vapour pressure increases, as both the

westerly and easterly wind speeds and especially the air temperature increase, but tends to decrease before the net radiation increases.

In winter, the net radiation is just the outgoing radiation thus, a vapour pressure increase is followed by an increase in outgoing radiation. This effect is probably due to the high correlation between air temperature and vapour pressure which is to be expected, as within a closed system these parameters would be, from thermodynamic theory, strictly proportional. Thus, the essential features of Figure 26 are; the increase of vapour pressure with both easterly and westerly wind speed in the winter; its decrease with westerly wind speed in summer; the independence of vapour pressure from air temperature in mid-summer.

In all parts of Figure 27, a difference exists between the summer season of October to February and the rest of the year and, apart from the variation with westerly wind speed, strong lag and lead relationships exist in the summer. Although the dependencies are not so strong with westerly wind speed in the summer, they are similar to those of the easterly wind speed, where air temperature tends to increase 3–4 hours prior to an increase of wind speed, but decreases 6–9 hours after the wind's increase. Also in the winter, the effects of both westerly and easterly wind speeds are similar, with air temperature increasing with wind speed except that the westerly wind speed dependency is now the stronger. This stronger relationship is undoubtedly due to the westerly winds actually bringing warmer air to Lake Vanda, whereas the easterly wind only breaks down any surface inversion (i.e. temperatures increase with altitude). The summer situation is different with air temperatures increasing in light winds before the wind freshens and then temperatures fall later.

A strong dependency exists all year between air and ground temperatures with increases in the latter occurring 3 hours after increases in the former. However, a tendency increases through the summer for ground temperatures to be become less correlated to air temperatures 9 hours prior until in January ground temperatures tend to decrease 9 hours after air temperatures increase. The last part of Figure 27 shows that in winter as air temperature increases the net radiation decreases or, as only winter is being considered,

outgoing radiation increases. However, in summer an increase in net radiation tends to be followed 2–3 hours later by an increase in air temperature.

Therefore, the essential features of Figure 27 are; winter wind speed increases raise air temperatures by mixing with easterly winds and by advection of compressively warmed air with westerly winds; ground temperatures closely follow air temperatures after a 3 hour lag; winter time outgoing radiation increases with air temperature; the summer time diurnal cycles can be seen with net radiation increases preceding by 2–3 hours air temperature rises and 3–4 hours later a freshening of the easterly wind.

Figure 28 is very similar to Figure 27 because of the very high correlation between air and ground temperatures, only the variation with soil heat flux could be discussed but its variation with air temperature is shown in Figure 29. This figure is also similar to Figure 27 with lag and lead dependencies showing the effect of diurnal changes in the summer, but not in the winter. The reason for this similarity can be seen in the high correlation through the year of the soil heat flux with the air temperature (i.e. its dependency with wind speed is through the air temperature). Even the correlations with net radiation are similar to those of air temperature with net radiation; outgoing radiation increases with soil heat flux in the winter and net radiation precedes an increase of soil heat flux in the summer by 1–2 hours. Thus, the essential features of Figures 28 and 29 are explained by the high correlations between soil heat flux and air and ground temperatures.

In Figure 30 the correlations between net radiation and wind speeds are examined. As before, a distinct difference exists between winter and summer, the summer time westerlies are not correlated to net radiation but the easterlies, because of their diurnal cycle, show strong lag and lead dependencies. In winter, net radiation decreases or outgoing radiation increases as both wind speeds increase. This winter dependency is due to wind speed increases raising air temperature, and hence ground temperature and hence more outgoing radiation. Thus, the 3 parameters involved in Figure 30 are not independent of each other except for net radiation and summer time westerlies.

7 Conclusion

"What is Lake Vanda's weather like and why?" can only be partially answered. Tradition, prejudice and economy have all played their part in determining the scope of the observational programme at Lake Vanda, and over the period of the programme some measurements have been dropped and others started. Now it seems appropriate and perhaps overdue to highlight just what further observations would be most beneficial in increasing our understanding of Lake Vanda's climate and so refining the answers to the questions above.

Firstly, what is the weather and climate like? The evident extreme difference between mid-summer and mid-winter can be extended such that, although quantitatively a gradual change in parameters takes place as the year progresses, the year may be divided qualitatively into a 'summer' season of October to February inclusive and a 'winter' season of March to September. This division can be seen in the figures showing diurnal variations and in the correlation figures. In Figures 14 and 17 summer time conditions are seen to occur in March and September but in Figure 6, 10 and 22 are shown to be not fully established in February and October. Thus, the division of the year cannot be taken too strictly.

In summer, diurnal changes which have a sinusoid shape over the 24 hour period and an appreciable amplitude when compared to the general level of the parameters concerned, take place as follows :

Meteorological parameter	Amplitude	Time of minimum	Time of maximum
Solar radiation	1.6 MJ/sq m	1 a.m.	Noon
Net radiation	1.0 MJ/sq m	1 a.m.	Noon
Soil heat flux	0.1 MJ/sq m	1 a.m.	Noon
Air temperature	5°C	4 a.m.	3 p.m.
Ground temperature	6°C	6 a.m.	6 p.m.
Wind speed	9 kt	6 a.m.	6 p.m.
Vapour pressure	0.2 hPa	8 a.m.	8 p.m.

The diurnal cycles appear to be constant throughout the summer with the exception of vapour pressure, which in February and October, has a minimum near 4 a.m. and a maximum about noon. Since vapour pressure is dependent upon both temperature and wind, this difference is probably due to the different lengths of their summer seasons. In the list above, there is no entry for wind direction since little diurnal variation in direction exists; at most there is a small decrease in the frequency of easterlies in the morning, with a consequent small increase in calms and westerlies. However, a strong diurnal variation in the speed of easterly winds does exist, such that the wind speed entry in the above list may be considered applicable solely to easterlies.

The summer time correlational patterns confirm these diurnal cycles, and the links in the causal chain; radiation parameters increase and cause air temperatures to rise 2–3 hours later then, 3–4 hours later still, this causes the easterly wind to freshen. The apparent coincidence of ground temperatures and wind speed changes merely shows that the time delay in surface temperatures effecting temperatures at a depth of 8 cm and that in the thermally forced wind becoming fully established are approximately the same. The timing of the vapour pressure cycle is not easily explained and is further complicated since vapour pressure decreases as westerly winds increase especially in early and late summer and it is not correlated to air temperature in mid-summer.

The diurnal cycle of solar radiation is controlled purely by the sun, but the net radiation is controlled by local conditions. The total time there is a net gain of radiant energy varies from 20% in September to 90% in December and back to 20% in April; also from October to February, half the time at least 10% of the solar radiation is not re-emitted, and over half the time 90% of this net radiation heats the air rather than the ground. These values can be completely attributed to the ice-free nature of the Wright Valley and the consequent low albedo, which means that for the latitude concerned, more than usual solar radiation is available. This energy input, together with the local topography, which strongly channels any wind, give rise to the summer time pattern of regular cycles of tem-

perature and wind throughout the day. However, these daily cycles probably contribute little to maintaining the ice-free conditions.

In winter, radiation effects become less important as the incoming radiation is zero and the net radiation is *controlled* by temperature rather than *controlling* it. The output of radiant energy appears to be fairly constant through the winter at about 4 MJ/sq m each month with only 0.6 MJ/sq m of this coming from the ground; half the time ground losses account for 30% of the outgoing radiation. In the summer, about 0.6 MJ/sq m each month is input into the ground and the outgoing radiation amounts to about 14 MJ/sq m each month. It is doubtful that these monthly heat totals do really switch from one value to another at the change of the season. However, there does seem to be a definite switch from the summer time diurnal cycles to the winter time regime of calms and periods of strong, relatively warm westerly winds.

No diurnal cycles can be found in any parameter including the westerly wind during the winter; calms and strong westerlies are much more frequent than in summer whereas moderate westerlies have constant frequency throughout the year. The calms and westerlies of winter occur aperiodically for varying lengths of time some of which are very long. Often, after a period of light winds, a strong westerly will come to full force within a few hours, last for 12 hours, or may be a few days, and then die away within a few hours. At the onset of the westerly, temperatures rise, on average, about 13°C in an hour, but rises of over 20°C have been seen; relative humidities fall by 20–30%. By stirring the air, an increase in easterly wind speed also leads to higher temperatures and similarly an increase in any wind speed raises vapour pressure in the winter. Because of the high correlation of ground temperature and soil heat flux with air temperature both of these respond to the onset of the westerly wind.

This westerly wind is a local effect, as it occurs when the airflow on the Antarctic Plateau to the west and the free atmosphere above the Wright Valley is southerly. The local topography channels the wind flow into a westerly along the valley, but in just a

shallow layer 500–600 m thick, and forces the air downwards to be compressively warmed and dried as occurs with a föhn wind. Thus, unlike the summer time diurnal cycles which are a result of the ice-free nature of the Wright Valley, the winter time westerlies result from conditions outside the dry valleys. It has been noted that any snow lying or rime frost quickly clear when the westerly wind starts; the ablation of ice from the lake becomes eight times that in light wind conditions.

Thus, the winter westerlies appear to be responsible for keeping the valley ice-free. However, the amount of precipitation received at Lake Vanda must be taken into consideration because if this was to increase sufficiently the westerly wind could no longer effect clearance. Atmospheric humidity at Lake Vanda was compatible with its latitude, any apparent dryness was just an expression of its unusual annual temperature cycle. Summer temperatures are 5–7°C warmer than Scott Base, and winter temperatures are 4–5°C colder. These differences are simply due to the ice-free ground at Lake Vanda retaining more solar radiation in summer and outputting more during the winter. However, Scott Base has twice the number of days of snow and is about 50% cloudier than Lake Vanda; at both stations summer and autumn tend to be 'wetter' than winter and spring. The difference between the stations is explained by their different exposures with Scott Base on the coast and Lake Vanda in a deep inland valley. Therefore, Lake Vanda's position not only receives less precipitation but the local topography channels and enhances the westerly wind which clears any precipitation.

Leaving aside how the conditions originated, this explanation of how Lake Vanda maintains its ice-free state deals only with Lake Vanda's visibly obvious difference to neighbouring regions. As mentioned above, Lake Vanda is drier in terms of precipitation but not atmospheric moisture. Despite being cloudier, Scott Base receives more solar radiation, probably due to Lake Vanda's higher horizon profile but the net radiation shows an annual gain because of the low albedo of ice-free ground. Monthly mean temperatures are closely related to those at Scott Base, provided allowance is made for the warm

winter westerlies, when a multiple regression has a 93% coefficient of determination. The 'coreless' winter behaviour can be seen in both air temperatures and ground temperatures down to 90 cm. Wind behaviour is too locally controlled by the station being in a deep east to west oriented valley to be compared to anywhere else. Thus, other aspects of Lake Vanda's climate appear to compare well with Scott Base.

In the light of this report the following suggestions for future investigations are made :

1. Investigate further the currently available information particularly temperatures and winds from other sites in the Wright Valley.

2. Continue a programme of standard meteorological observations in the summer which should preferably include the whole of October and February.

3. Institute a winter time observing program for at least 3 years and preferably 5–10 years. This need not be a full programme but should include air temperature, wind run, net radiation and vapour pressure on an hourly resolution, some indication of snow or ice cover is also needed.

4. The prime meteorological problems, in order of importance, are :

   (a) The winter westerlies — their origin and influence.

   (b) The dynamics of the summer time wind circulation.

   (c) Moisture and heat balances especially in the summer time.

   The study of these problems not only requires the implementation of special observing programmes but also theoretical modelling.