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Lake Okanagan Evaporation Study

by

Neil B.A. Trivett

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1984

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FINAL REPORT

LAKE OKANAGAN EVAPORATION STUDY

by

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ABSTRACT

The mass transfer coefficient for Okanagan Lake was estimated from eddy correlation measurements of lake evaporation. The coefficient (M = 0.024) agrees well with other studies of deep lakes. The spatial pattern of lake surface temperature was obtained from thermal imaging line scanner data during three aircraft flights. The spatial and temporal distribution of temperature and wind speed were obtained from special climate stations established at the edge of the lake. The annual water loss from Okanagan Lake estimated from the mass transfer equation is approximately 63% of that derived from the Class A pan data. During the warm period, May to October, the corresponding figure is 54%. Recommendations are included for estimating water loss using the mass transfer approach on an operational basis.

RÈSUMÈ

Le coefficient de transfert massique pour le lac Okanagan a été estimé à partir de mesures de l'évaporation du lac par la méthode de corrélation des flux turbulents. Le coefficient (M = 0,024) est en bon accord avec d'autres études de lacs profonds. Le patron spatial de la température de surface du lac a été obtenu de données extraites par un détecteur de ligne thermique à balayage durant trois vols d'avoin. La distribution spatiale et temporelle de la température et de la vitesse du vent ont été obtenues de stations climatiques établies au bord du lac. La perte anuelle d'eau du lac Okanagan, estimée de l'équation de transfert massique, est approximativement 63% de celle dérivée des données d'évaporation de classe A. Durant la période chaude, Mai à Octobre, la valeur correspondente est de 54%. On a inclus des recommendations pour l'estimation de la perte d'eau en utilisant l'approche de transfert massique sur une base opérationelle.

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Dr. G. den Hartog and Mr. W. Kobelka, of the Boundary Layer Research Division (AES) made the eddy correlation measurements. A special thank you goes to the professional and technical staff of the Hydrometeorology Division, in particular, Mr. J. Metcalfe who participated in the field work, Mr. S. Ishida who abstracted the chart data and Mrs. Lou-Ann Hotz who patiently typed the manuscript.

Neil B.A. Trivett
Project Coordinator
Okanagan Lake Evaporation Study

EXECUTIVE SUMMARY

During the previous Okanagan Study (1974) estimates were made of monthly evaporation but no actual measurements were made nor was any check possible. There is considerable doubt, therefore, as to the accuracy of these estimates. Since the plan for water management calls for efficient use of the available supply, a better knowledge of these losses from evaporation was considered necessary in the long term operation of the Okanagan Flood Control System.

This evaporation study, as approved by the Implementation Board, was carried out over an 18-month period in 1980 and 1981 by the Hydrometeorology Division, Canadian Climate Centre, Atmospheric Environment Service, Environment Canada. The overall objective of the study was to provide a suitably precise yet practical method of estimating evaporation from Okanagan Lake for periods as long as one month and possibly as short as one week.

Previous estimates for evaporation from Okanagan Lake have been based on the Class "A" evaporation pan method commonly used to estimate evaporation from shallow lakes and ponds. These pans are normally located at airport weather stations and do not necessarily reflect the same meteorological conditions encountered over large lake surfaces. Okanagan Lake, for example, is essentially ice free during most winters, and continues to lose water to the atmosphere throughout the winter when the evaporation pan network has ceased operation due to freezing temperatures. Comparable studies on other lakes have also shown that the Class "A" pan method does not provide a reliable estimate of evaporation losses.

Of the many current methods for estimating evaporation from a lake surface, the one preferred by most hydrometeorologists is the mass transfer approach because of its simplicity and the general availability of the required data. This approach was used to calculate evaporation as a function of the humidity gradient over the lake and the wind speed through the following relationships:

$$E = M(e_s - e_a) \cdot u,$$

where E is the evaporation rate (gmm day^{-1}), M is the mass transfer coefficient, e_s (mb) is the saturation vapour pressure at the temperature of the water surface, e_a is the ambient humidity over the lake and u (km hr^{-1}) is the wind speed. Although attempts have been made to generalize the mass transfer coefficient, this study used the eddy correlation technique to calibrate the mass transfer equation for Okanagan Lake. The eddy correlation technique is considered to be the most precise method of measuring evaporation rates but is not suited to long term or operational use because of the extensive instrumentation required. The mass transfer coefficient for Lake Okanagan was found to be M=0.0240 which agrees well with other studies of deep lakes.

Surface water temperatures were obtained through temperature measurements taken around the shoreline on a regular basis by volunteer observers, and through airborne thermal imagery involving a number of flights at different times of the year. While the normal trend in air temperatures is usually one of increasing temperatures to the south, the surface temperatures of Okanagan Lake consistantly show just the reverse trend with water temperatures generally warmer in the north and west arm segments.

Areally Weighted Means of Lake Surface Temperature
(°C) Obtained From Thermal Line Scanner Imagery

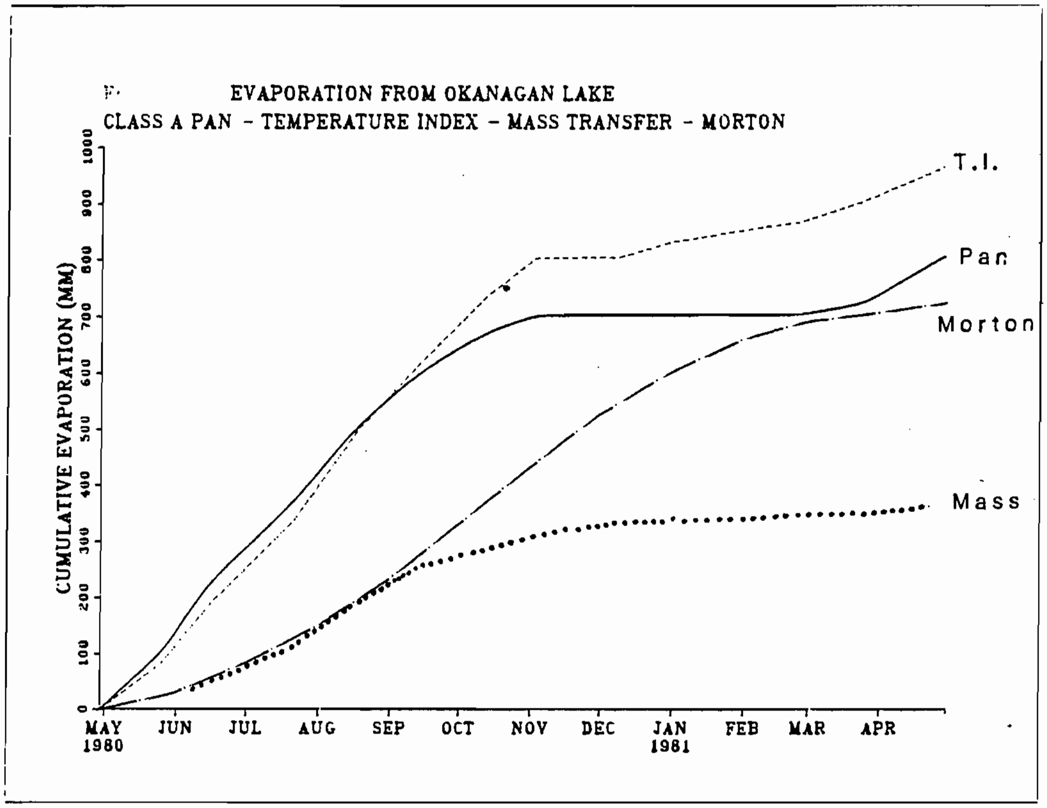
	Lake	South	Central	North	West Arm
November 1, 1979	9.7	9.3	9.3	10.2	9.3
April 26, 1980	11.0	9.9	10.4	12.2	11.7
September 8, 1980	16.9	16.0	16.7	17.6	17.7

The evaporation rates calculated by the mass transfer technique were affected by the input parameters in the following order of increasing importance - atmospheric humidity, surface water temperature and wind speed. Of these three parameters the wind speed was found to be the most variable from place to place, to have the largest range of values, and to have the most direct effect on the calculated evaporation rate.

A comparison of climatic data from Penticton and Kelowna airports to stations located on the lake itself indicated that the substitution of airport data may give questionable results as each of the three major segments of the lake appears to have a different wind regime and a different surface water temperature. If substitution of data is used to avoid establishing new climatic stations, then Penticton Airport vapour pressure and wind speed could be used, providing actual lake water temperatures are measured at one or more locations around the lake.

Estimated totals of evaporation from Okanagan Lake were calculated from the mass transfer equation using Penticton Marina data and are compared in the accompanying Figure with estimates of lake evaporation from the Class A pan and the temperature correlation method currently used by the B.C. Ministry of Environment.

The estimated evaporation loss using the mass transfer method is less than half that estimated from the older Class "A" pan method or the temperature correlation method currently used by B.C. Ministry of Environment. The May through September losses due to evaporation account for 75% of the annual loss. These evaporation rates as calculated by the mass transfer method do not appear to be unusually low when compared with the results of studies from other lakes.



In summary, this study indicates that the evaporation losses from Okanagan Lake are considerably less than those estimated during the previous Okanagan Study and used for water management purposes to date. Moreover, there is considerable difference between the timing and magnitude of evaporation rates using the mass transfer technique as compared to the older Class "A" pan method. In particular, the Class "A" pan method greatly overestimates lake evaporation in the spring when air temperatures are warm but the lake temperature still cold.

INTRODUCTION

The Okanagan Basin lies in the south central plateau area of British Columbia. The major drainage feature of the Basin is a chain of lakes stretching from the northern end of the Basin near Vernon to the State of Washington border. Okanagan Lake, which is the largest and deepest of these lakes, is a fundamental component of the water balance of the region. It is the major source of water for both industrial and residential uses as well as for irrigation.

The climate of the Basin may be described as a moderate continental type with rather mild winters and hot dry summers. Much of the valley bottom is semi-arid with Oliver near the International border receiving an average of only 272 mm of precipitation per year. The long frost free period (150-200 days), high temperatures (2000-2500 growing degree days) and fertile soils make the Basin one of the more favoured areas of the province for growing temperature sensitive crops. Because of the limited precipitation during the growing season, it is necessary to irrigate in most areas to sustain commercial agriculture. The excellent climate also attracts many people to the Basin both as tourists and as new residents. Consequently, there is an increasing demand for the area's somewhat limited water resources.

In response to the increasing concern of the local residents the Province of British Columbia and the Federal Government of Canada signed an agreement in October, 1969 which set out the purpose and terms of reference for a pilot study to develop and test new techniques for water resource planning. This study was to incorporate both the social and economic aspects of resource planning in order to maintain a high level of environmental quality consistent with predicted growth trends for the development of the Basin. The findings of this comprehensive study were published in 1974 by the Canada-British Columbia Consultative Board.

During the Okanagan Basin Agreement the various components of the water balance were studied in detail and models were developed to estimate evaporation from both the lake and land surfaces. Since no measurements of actual evaporation were made, these models were based either directly on evaporation pan data or indirectly by correlating pan data with the mean temperature (refered to here as the temperature index method). In a hot and dry environment like that of the Okanagan Basin an evaporimiter, such as the Class A pan, with a small thermal mass would initially lose large amounts of water to the atmosphere at a much faster rate than would a deep water body with a large thermal mass. There was, therefore, some doubt as to their accuracy. Since the plan for water management in the Basin calls for efficient use of the available water supply, the Okanagan Basin Implementation Board initiated the following study of the evaporation from Okanagan Lake.

This study, initiated at the request of the B.C. Ministry of Environment, was funded jointly by the Province of British Columbia and the Federal Government under the Okanagan Basin Agreement. The Okanagan Basin Implementation Board allocated the funds to cover the installation and maintenance of the climate stations and the operational costs of the research programs. The Atmospheric Environment Service provided the scientific and support staff required for the data collection and analysis. Various municipal, provincial and other federal agencies, also contributed to the project by providing special data and/or other needed facilities. The study was carried out by the Atmospheric Environment Service during an eighteen month period from April 1980 to September 1981.

The overall objective of this study was to provide a suitably precise, yet still practical method of estimating evaporation from Lake Okanagan for periods as long as one month and possibly as short as one week. The method should not depend upon the Class A evaporation pan commonly used to estimate evaporation from shallow lakes and ponds. Lake Okanagan, which is essentially ice-free during most winters, continues to lose water to the atmosphere throughout the winter when the evaporation pan network has ceased operation due to freezing temperatures.

The specific objectives of this study were to answer or provide further insight to the following questions:

1. Is the mass transfer function for Lake Okanagan significantly different from those reported in the literature?

2. To what extent are the temperature, humidity and wind speed measured over the lake different from the corresponding parameters measured at the nearby airports?

3. What is the spatial and temporal distribution of water surface temperature in Lake Okanagan and how may it be estimated or measured operationally?

4. What spatial and temporal variations in evaporation might be expected over the lake and can the average for the lake be estimated from one or more selected points?

BACKGROUND

The commonly used techniques for determining evaporation losses from open water surfaces may be divided into two general categories: those which provide an areally averaged or integrated estimate; and, those which provide an estimate at a point. If a method which falls into the last category is used, some technique is required to provide a spatial average from one or more point values. Methods for estimating evaporation are discussed in detail elsewhere (WMO, 1966 and 1973; Hounam, 1961) and are only briefly outlined below.

SYMBOLS AND DEFINITIONS

c_p - specific heat of air

C_E, C_H - the bulk transfer coefficients for water vapour and sensible heat

$\dot{E}$ - evaporation rate

e_a, e_s - vapour pressure of the air at some level z and at the surface of the water

H - sensible heat flux

M - mass transfer coefficient

p - pressure

P - precipitation

q - specific humidity

R - runoff

S - storage

T - temperature

u - horizontal wind speed

w - vertical wind speed

β - Bowen's ratio

ρ - density of air

θ - potential temperature

λ - latent heat of vapourization

a) Water Budget Method

With the water budget method, evaporation is calculated as a residual in the water balance equation, viz:

$$E = P + I - O + \Delta S \tag{1}$$

where E = evaporation from the lake
P = precipitation over the lake
I = inflow to the lake (surface and subsurface)
O = outflow from the lake (surface and subsurface)
ΔS = change in storage in the lake

While the water budget method is simple in principle, the various parameters in the equation cannot be measured or calculated with sufficient accuracy for short periods or in some cases even on an annual basis. For example, the error in calculating the outflow of Franklin D. Roosevelt Lake on the Columbia River is 10 times the evaporation (WMO, 1966). In addition, precipitation over the lake and lateral flows into the lake cannot be measured or estimated with sufficient accuracy, in most cases, to warrant the use of the water budget method for the time interval under consideration.

b) Energy Budget Method

The energy budget method is similar in concept to the water budget, e.g.,

$$Q_E = Q^* + Q_V + \Delta Q_S - Q_H - Q_W \tag{2}$$

where Q_E = energy used in evaporation
Q^* = net radiation over the lake
Q_V = net energy brought into the lake by inflow and precipitation
ΔQ_S = change in energy stored in the lake
Q_H = sensible heat lost from the lake
Q_W = energy carried away by the evaporated water

As in the water budget, all of the errors in the other terms in the equation are combined into the error in the evaporation term.

c) Energy Partitioning Method

The energy partitioning method was first suggested by Bowen (1926) and is commonly accepted to be accurate for periods as short as one hour (or less in exceptional circumstances). Many investigators favour this approach as a reliable method of estimating lake evaporation. The Bowen ratio, defined as:

$$\beta = \frac{Q_H}{Q_E} = \frac{c_P}{\lambda} \frac{\Delta T}{\Delta q} \tag{3}$$

where c_p = specific heat of air at constant pressure
λ = latent heat of vapourization
Δq = specific humidity gradient
ΔT = temperature gradient

may be determined from measurements of the surface temperature of the water and the temperatue and specific humidity at one level above it. The evaporation rate is then calculated from:

$$Q_E = \frac{Q^* - Q_S}{\lambda} \frac{(1)}{1 + \beta} \tag{4}$$

The energy partition or Bowen ratio method requires the measurement of net radiation at a point, Q^*, considered to be representative of a larger area and an estimate of the storage term Q_S. Both of these terms are difficult to measure or estimate very accurately. Since this method is a point estimate the usual problems of spatial extrapolation must be resolved.

d) Eddy Correlation Method

The rate of evaporation from the surface of the lake may be determined directly from the co-variance of the vertical wind and the concentration of water vapour in the air. Similarly the heat lost to the atmosphere from the surface of the lake may be determined from the co-variance of the vertical wind and temperature, thus:

$$E = \overline{\rho w'q'} \approx \bar{\rho}\ \overline{w'q'} \tag{5}$$

$$Q_H = c_p\ \overline{\rho' w' T'} \approx c_p\ \bar{\rho}\ \overline{w'T'} \tag{6}$$

where ρ = the average density of the air
$w'q'T'$ = the instantaneous deviations from the mean vertical wind w specific humidity, q, and temperature, T, respectively and the horizontal bar denotes a time average.

The eddy-correlation method is the only method to give a direct estimate of the evaporation rate. However, the equipment is expensive, sensitive to maintain and not yet suitable for long periods of unattended use. Like the Bowen ratio method it is a point measurement and requires an extrapolation scheme for spatial averaging.

e) Mass Transfer Methods

The mass transfer methods, often referred to as the "bulk aerodynamic methods", are derived from the Dalton equation for evaporation from a free water surface:

$$E = f(u)\,(e_s - e_a) \tag{7}$$

where f(u) is an empirical wind function e_s and e_a are the vapour pressure at the surface of the water and at some reference level, z, above the water.

There are almost as many forms of the wind function as there are studies using the mass transfer technique but Harbeck (1962) generalized it to:

$$f(u) = 0.291\,A^{-0.05}u \tag{8}$$

where A = area of lake or reservoir in square metres
u = wind speed (ms^{-1}) measured at 2 metres

Using a generalized form of f(u) can result in a 25% or more error in the evaporation rate (WMO, 1966). Consequently, the determination of f(u) for each lake is almost manditory if short term estimates of evaporation are required.

f) The Combination Method

The combination method, more commonly called the Penman method, is based in part on the mass transfer method and the energy balance method where:

$$Q_E = \frac{\Delta}{\Delta + \delta}\,\frac{(Q^* - Q_s)}{\lambda} + \frac{\delta}{\Delta + \delta}\,f(u)\,(e_a - e_d) \tag{9}$$

where Δ = slope of the saturation vapour pressure curve at air temperature T_a
δ = psychrometric constant
e_a, e_d = saturation varpour pressure at ambient temperature of the air, T_a, and dew point temperature of the air, T_d
f(u) = a function of the wind speed

There are various forms of the wind function, f(u), but Penman (1956) used:

$$f(u) = 0.35\,(0.5 + u_2/100) \tag{10}$$

where u_2 is the run of wind in miles per day at 2 metres

g) Evaporation Pans

There is sufficient evidence (Hounam, 1961 and 1968; Kohler, 1954; and WMO 1954 and 1973) to show that evaporation pans are a good indicator of evaporation from shallow lakes on a monthly basis. To obtain monthly estimates of lake evaporation the pan data need to be corrected for differences in storage characteristics, surface water temperature, turbulence characteristics and vapour pressure gradients over the water surfaces. This is normally done with a simple correction factor which varies with the time of year. The correction factor used by AES is given in Appendix A.

Of the many methods for estimating evaporation outlined above, the one preferred by most hydrometeorologists for operational use is the mass transfer approach because of its simplicity and the general availability of the required data.

METHODS OF CALCULATING THE MASS TRANSFER COEFFICIENT

Finding the definitive value of the mass transfer coefficient has been the subject of many studies (see Table 1). Harbeck (1962) incorporated area to allow for the effect of lake size on the meteorological parameters. This formula would be difficult to apply directly to Lake Okanagan because of its non-circular shape (see Figure 1). Because the generalized form of the transfer function can result in an error of 25% or more in the evaporation rate (WMO, 1966) due to topographic influences, the determination of M for each lake is almost mandatory if short-term estimates of evaporation are required.

The mass transfer equation requires temperature, humidity, and wind speed data over the surface of the lake as well as lake surface temperature. With a long, narrow and deep lake such as Okanagan, these parameters could vary significantly from one end to the other, and consequently, so would the evaporation rates. Since the evaporation rate is calculated from point meteorological data, it is necessary to know the spatial variability of these data in order to assess their representativeness for estimating evaporation from the lake.

The list of some of the mass transfer functions in Table 1 is taken from Helferty (1981). The wind speeds have been standardized to a 10 metre level using the power formula $u_{10} = u_z (10/z)^{-0.15}$. For comparison, evaporation rates are calculated for wind speeds of 10 and 20 km hr^{-1} with a vapour pressure gradient of 10 mb. The area of Lake Okanagan, assumed to be 348 km, is used to obtain equation T.18. Several methods of calibrating the mass transfer equation are outlined below.

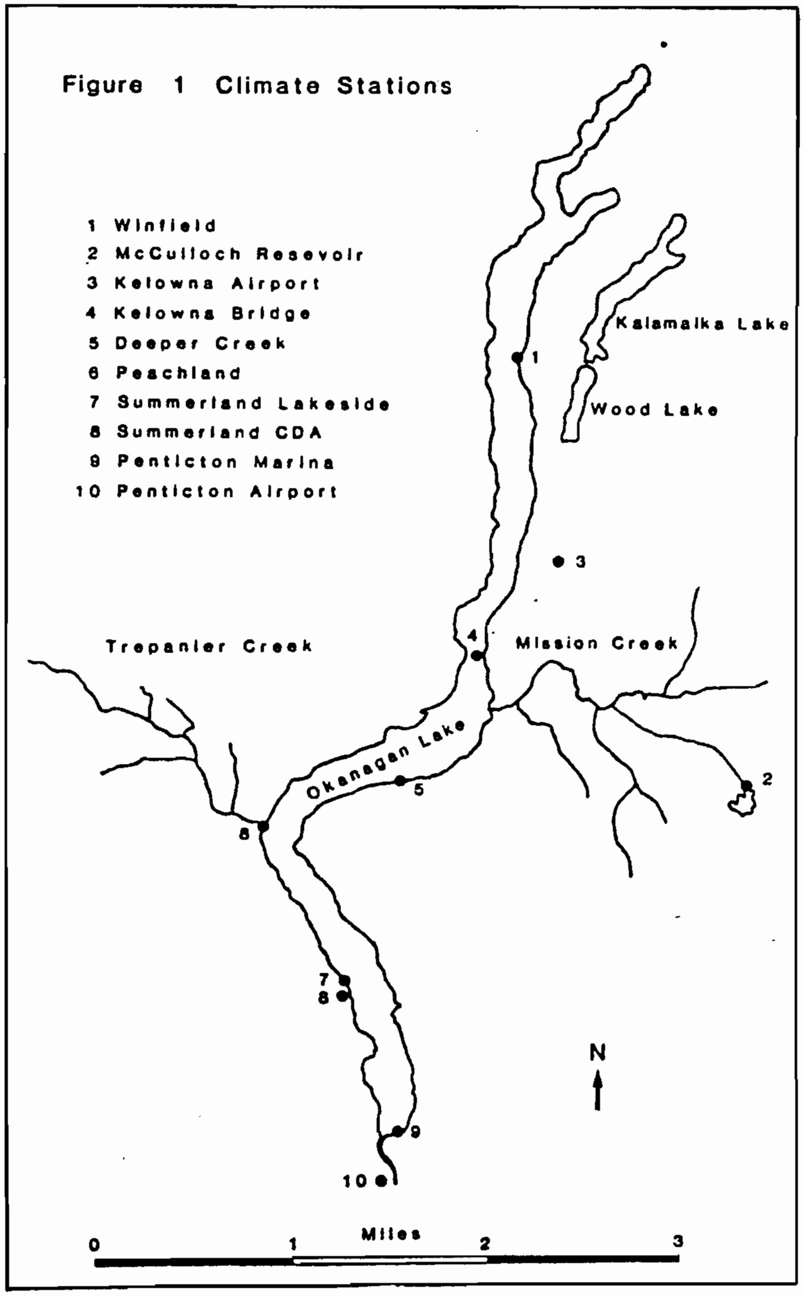


Figure 1 Climate Stations

TABLE 1
A Comparison of Mass Transfer Functions
(from Helferty, 1981)

	M(u)	E	E	Source	
		mm/day	mm/day		
T.1	0.3 (1 + 0.0885 u)	5.7	8.3	Fitzgerald	1886
T.2	0.312 (1 + 0.0482 u)	4.6	6.1	Horton	1917
T.3	0.231 (1 + 0.131 u)	5.3	8.4	Rohwer	1931
T.4	0.241 (1 + 0.118 u)	5.3	8.1	Rohwer	1931
T.5	0.2455 (1 + 0.0597 u)	3.9	5.4	Meyer	1942
T.6	0.259 (1 + 0.072 u)	4.S	6.3	Penman	1948
T.7	0.0255 u	2.6	5.1	Marciano	1952
T.8	0.0261 u	2.6	5.2	L. Hefner	1954
T.9	0.131 (1 + 0.234 u)	4.4	7.4	Pernman	1956
T.10	0.148 (1 + 0.125 u)	3.3	S.2	Kuzmin	1957
T.11	0.13 (1 + 0.157 u)	3.3	5.4	WMO	1966
T.12	0.0286 u	2.9	5.7	WMO	1966
T.13	0.0318 u	3.2	6.4	WMO	1966
T.14	0.0332 u	3.3	6.6	WMO	1966
T.15	0.051 (1 + 0.406 u)	2.6	4.7	Barry	1975
T.16	0.0380 u	3.8	7.6	Ferguson	1975
T.17	0.0405 u (A = 1 km)	4.1	8.2	Harbeck	1962
T.18	0.0302 u (A = 348 km)	3.0	6.0	Harbeck	1962

a) Water Balance Method

The classical method of determining the value of M was to calculate the unknown evaporation E as the residual in the water balance equation. Because of the difficulty of obtaining the other water balance parameters accurately this technique is best suited to monthly data in most cases. In the case of reservoirs where the runoff and storage might be known more precisely, the water balance could be used for periods as short as one day. However, for a system as large as Lake Okanagan with its many unmeasured inflows and extractions and suspected ground water leakage, the water balance would be a challenge to apply with confidence even on a monthly basis.

b) Profile Method

From the profile theory of turbulent transfer in the surface boundary layer, the flux of a property is related to its gradient and the motion of the transport medium, thus in finite difference form:

$$Q_E = \rho\lambda\ C_E u\ (q_1 - q_2) \qquad (11)$$

and

$$Q_H = \rho\ c_p\ \ C_H\ u\ (\theta_1 - \theta_2) \qquad (12)$$

where C_E and C_H are referred to as the "bulk" transfer coefficients. The definition of the symbols and their common units are given in the list of symbols. Since vapour pressure is often used to express humidity in hydrometeorology and the pressure correction for potential temperature is negligible between measurement levels, Equations 11 and 12 may be rewritten as:

$$Q_E = \frac{0.62}{p} \cdot \rho\lambda\, C_E\, u\, (e_s - e_a) \qquad (13)$$

$$Q_H = \rho\, c_p\, C_H\, u\, (T_s - T_a) \qquad (14)$$

where 0.62 is the ratio of the molar masses of water and air. The vapour pressure at the surface is assumed to be the saturation vapour pressure at the surface temperature of the water (T_s). It can be readily seen from Equations 7 and 13 that the "mass" transfer coefficient is related to the "bulk" transfer coefficient by:

$$M = 0.62\, \frac{\rho}{p} \cdot C_E \cdot 86.4 \qquad (15)$$

where 86.4 is the conversion from g $m^{-2}s^{-1}$ to mm day^{-1}. The relationship between M and C_E is primarily temperature dependent varying from 68.3 at 0°C to 61.6 at 30°C and may be approximated by:

$$M = (68.2 - 0.225\ T) \cdot C_E \qquad (16)$$

Many workers have tried to calculate C_E from profile theory (Dyer, 1974; Paulson, 1970) by assuming the $C_E = C_H$ and deriving a stability correction term. Quinn (1979) adopted this approach to derive stability dependent values of C_E for the Great Lakes. The major advantage claimed for this approach by Quinn is an "increase in calculated evaporation during unstable, high-evaporation months and a reduction in condensation during the stable late spring months to more realistic levels". Table 2 gives Quinn's comparison of his recommmended procedure with two workers who recommended a constant C_E (no stability correction) and with two others who do include a stability correction. There is still some controversy over the assumption that $C_E = C_H$ or even that C_E is dependent upon stability (see Anderson and Smith, 1981).

TABLE 2
Comparison of Evaporation Procedures for Lake Ontario Monthly Evaporation in Millimeters

	Donelan et al (1974)	Holland et al (1979)	Quinn (1979)	Phillips (1978)	Businger et al (1971)
	$C_E = 1.43\text{x}10^{-3}$	$C_E = 1.5\text{x}10^{-3}$			
May	-1	-1	0	-1	-1
June	-7	-7	-2	-5	-2
July	21	22	20	21	25
August	52	54	49	51	64
September	86	91	90	86	118
October	101	106	118	108	159
November	89	93	108	96	147
Total	341	358	383	356	512

*Note - meteorological parameters measured or estimated for a 3 metre height

c) Eddy Correlation Method

A more direct approach to estimating the mass transfer coefficient is to use the eddy correlation technique. The evaporation rate and sensible heat flux are determined from the covariance of the vertical wind and humidity and the covariance of the vertical wind and temperature respectively (see Equations 5 and 6). This is the method adapted for this study and is discussed in more detail in the next section.

MASS TRANSFER COEFFICIENT FOR OKANAGAN LAKE

During a 14 day intensive field study period in September of 1980, 59 half hour averages of sensible heat flux and latent heat flux were obtained at the Deeper Creek experimental site (see Figure 1) with a Kaijo Denki sonic annemometer, a micro bead thermister and a Lyman-Alpha humidity sensor. The data from these fast response sensors were recorded on magnetic tape for later analysis by a PDP 11/34 minicomputer in the laboratory. The temperature and humidity of the air over the water were obtained from the climate station installed on a platform over the water. Wind speed and direction at 4 metres were also measured from a tower on the same platform. The water temperatue at 2 cm was monitored using an Analogue Devices temperature sensor from a floating ring buoy moored several hundred feet offshore in about 35 feet of water. The sensor was connected to the climate station data logger on shore by a signal cable strung along the lake bottom. These data are given in Table 3.

The study period was predominantly one of light winds with air temperatures in the morning 2-4°C lower than the water temperature rising to within 1°C of the water temperature by early afternoon. As a consequence the range of evaporation rates is small. The data in Table 3 are divided into 3 groups

TABLE 3

Half hourly estimates at latent and sensible heat fluxes and amounted climate data

DATE	TIME	λE	H	T_a	e	T_s	u	d	E
		Wm^{-2}	Wm^{-2}	°C	mb	°C	ms^{-1}	deg	$10^{-2}gm^{-2}s^{-1}$
September 8	0930	55	31	12.5	4.7	16.8	2.31	81	2.23
	1000	56	36	13.0	9.8	16.7	2.6	92	2.27
	1030	60	21	13.6	9.4	16.3	2.4	90	2.43
	1100	63	30	14.2	4.2	17.0	2.2	85	2.55
	1130	31	17	14.7	9.1	16.1	1.8	100	1.26
	1200	41	17	15.0	9.2	16.8	2.0	76	1.66
	1230	54	24	15.3	9.7	16.9	1.8	84	2.19
	1300	32	13	15.0	10.3	17.4	1.3	87	1.30
	1330	31	9	16.2	10.2	17.4	1.2	79	1.26
	1400	23	26	16.8	9.9	18.0	1.4	95	0.93
	1430	39	7	17.4	9.9	17.2	1.4	85	1.59
	1500	35	7	17.9	9.4	17.8	1.2	65	1.42
	1530	32	2	18.4	9.6	18.2	1.6	86	1.30
9	1030	68	24	14.4	10.5	17.0	2.5	77	2.76
	1100	59	16	14.9	10.2	17.0	2.4	82	2.39
	1130	68	15	15.6	10.5	17.5	2.1	93	2.76
	1200	67	10	16.1	11.0	17.6	2.3	88	2.72
	1230	49	6	16.5	11.2	17.3	2.6	88	1.99
	1300	69	6	17.2	11.3	17.5	3.0	88	2.80
	1330	57	5	17.4	12.3	17.3	3.4	89	2.32
	1400	56	4	18.0	12.1	18.4	3.2	87	2.28
	1430	36	0	18.5	12.7	18.4	3.4	90	1.47
	1500	19	-2	18.8	13.4	18.6	3.1	96	0.74
10	0930	36	14	14.2	11.4	16.0	1.7	73	1.46
	1000	33	10	14.6	11.5	15.8	1.5	87	1.34
	1030	31	7	15.1	11.8	16.3	1.2	75	1.26
	1100	43	12	15.6	11.6	16.4	1.4	76	1.74
	1130	28	5	16.1	11.8	16.0	2.1	85	1.14
	1200	43	2	16.8	12.4	15.2	2.4	77	1.75
	1230	30	5	17.1	12.6	16.6	0.5	31	1.22
11	1100	38	4	17.2	13.6	17.7	2.4	M	1.54
	1130	38	1	17.9	13.7	17.8	M	M	1.22
	1200	24	-1	18.4	14.0	18.0	3.6	135	0.48
	1230	18	-4	19.0	14.0	18.1	3.8	133	0.73
12	1000	53	9	16.5	10.8	17.6	1.8	100	2.15
	1030	53	8	16.8	10.0	17.6	2.8	110	2.15
	1100	50	8	16.9	10.5	17.6	2.8	115	2.03
	1130	72	8	17.2	11.1	17.7	2.8	106	2.43
	1200	81	4	17.5	11.3	17.8	2.4	113	3.29
	1230	31	6	17.9	11.1	18.0	1.8	114	1.26
14	0930	54	30	14.2	11.9	17.1	2.7	121	2.19
	1000	72	28	14.6	11.4	17.2	2.8	94	2.42
	1100	45	15	15.1	11.4	17.2	2.9	87	1.82
	1130	40	8	15.9	10.8	17.3	2.2	74	1.62
	1200	37	9	15.6	11.2	17.3	1.7	76	1.50

TABLE 3

Half hourly estimates at latent and sensible heat fluxes and amounted climate data

DATE	TIME	λE	H	T_a	e	T_s	u	d	E
		Wm^{-2}	Wm^{-2}	°C	mb	°C	ms^{-1}	deg	$10^{-2}gm^{-2}s^{-1}$
September 15	1000	55	2	14.4	10.4	16.7	2.4	84	2.23
	1100	27	1	15.7	10.8	16.8	1.7	87	1.10
	1130	30	-1	16.3	10.5	16.8	2.0	88	1.22
	1200	26	3	16.8	10.1	16.9	2.0	86	1.06
	1330	38	-1	17.9	4.9	17.0	2.8	87	1.55
	1400	21	0	18.2	10.1	17.1	2.6	80	0.85
17	1100	102	-42	21.0	11.1	17.6	3.4	262	4.16
	1130	40	-5	20.7	11.9	17.6	3.0	253	1.63
	1200	89	0	22.8	9.6	17.8	3.1	223	3.63
	1230	138	-32	21.4	4.4	17.0	3.0	228	5.63
	1300	128	-35	21.6	11.7	17.8	2.5	272	5.22
	1330	171	-8	20.9	13.1	18.0	2.0	252	6.98

based on the predominant wind direction during the 1/2 hour run. When the winds were nearly along the shore (78-88 clockwise from north or 273-283 clockwise from north), the fetch was classified as only acceptable and winds in the sector 88-273 degrees where classified as unacceptable because the winds were off the land. The remaining sector 288 degrees through north to 78 degrees were classified as excellent.

Although there is considerable scatter in Figure 2 the correlation coefficient of 0.70 for the regression equation given below is significant at the 0.5% level.

$$E = 0.0070 + 0.00064 \cdot u \cdot \Delta e \tag{17}$$

The slope of Equation 17 $(0.64 \pm 1.2)\times10^{-4}$ gives a bulk transfer coefficient of $C_E = (0.78 \pm 0.15)\times10^{-3}$ when adjusted for wind speeds measured at 10 metres using the logarithmic wind profile (Quinn, 1979). This is considerably smaller than the bulk transfer coefficients obtained by others using similar experimental procedures, for example, Bill et al (1980), $C_E = 1.19 \times 10^{-3}$ for a shallow lake in Florida and Anderson and Smith (1981), $C_E = 1.32 \times 10^{-3}$ from a large data set from 5 different experiments. For the study in Florida the sonic anemometer was mounted at 2.5 metres above the surface of the water. This could lead to underestimation of the evaporation rate due to the poor high frequency response characteristics of the anemometer. The low value for C_E reported by Bill et al (1980) would seem to support this contention when compared with value obtained by Anderson and Smith (1981) from the 5 sets of experimental data.

As the scatter in Figure 2 indicates, it is quite difficult to accurately measure small evaporation rates. One would expect that if the wind speed or humidity gradient were zero the rate of evaporation would be zero or at least negligible. The rather large intercept in Equation 17 is due in part to the very limited range of evaporation rates (1-3 $gm^{-2}s^{-1}$). When the regression equation is forced through zero; the bulk transfer coefficient increases to $C_E = (1.34 \pm 0.19)\times10^{-3}$ which agrees with the value of 1.32 x 10^{-3} obtained by Anderson and Smith (1981).

Because of the limited range of meteorological conditions experienced during the intensive field study period, the data from Sable Island are included with the Okanagan data in Figure 3. The resulting regression equation with a correlation coefficient of 0.95 is given below:

$$E = 0.0032 + 0.00086 \cdot u \cdot \Delta e \tag{18}$$

Once again the intercept is rather larger than expected. If the regression is forced through zero the slope increases to give $C_E = 1.30 \times 10^{-3}$ which is not significantly different from the value of 1.34×10^{-3} obtained from the Okanagan data alone.

The resulting mass transfer coefficients obtained from the Okanagan Lake data (M = 0.0240) are in good agreement with those reported in the literature for other large and deep lakes (Table 4).

FIGURE 2 MASS TRANSFER COEFFICIENT FROM LAKE OKANAGAN EDDY CORRELATION DATA

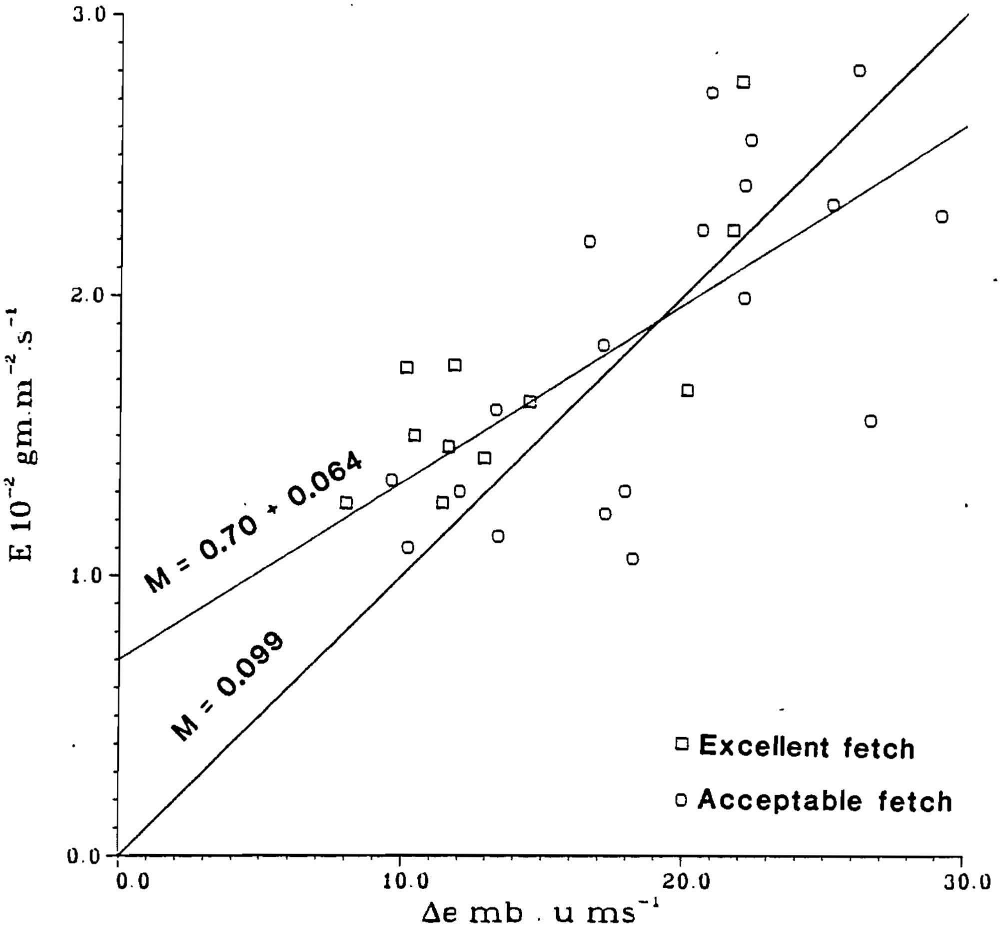


FIGURE 3 MASS TRANSFER COEFFICIENT FROM LAKE OKANAGAN AND SABLE ISLAND EDDY CORRELATION DATA

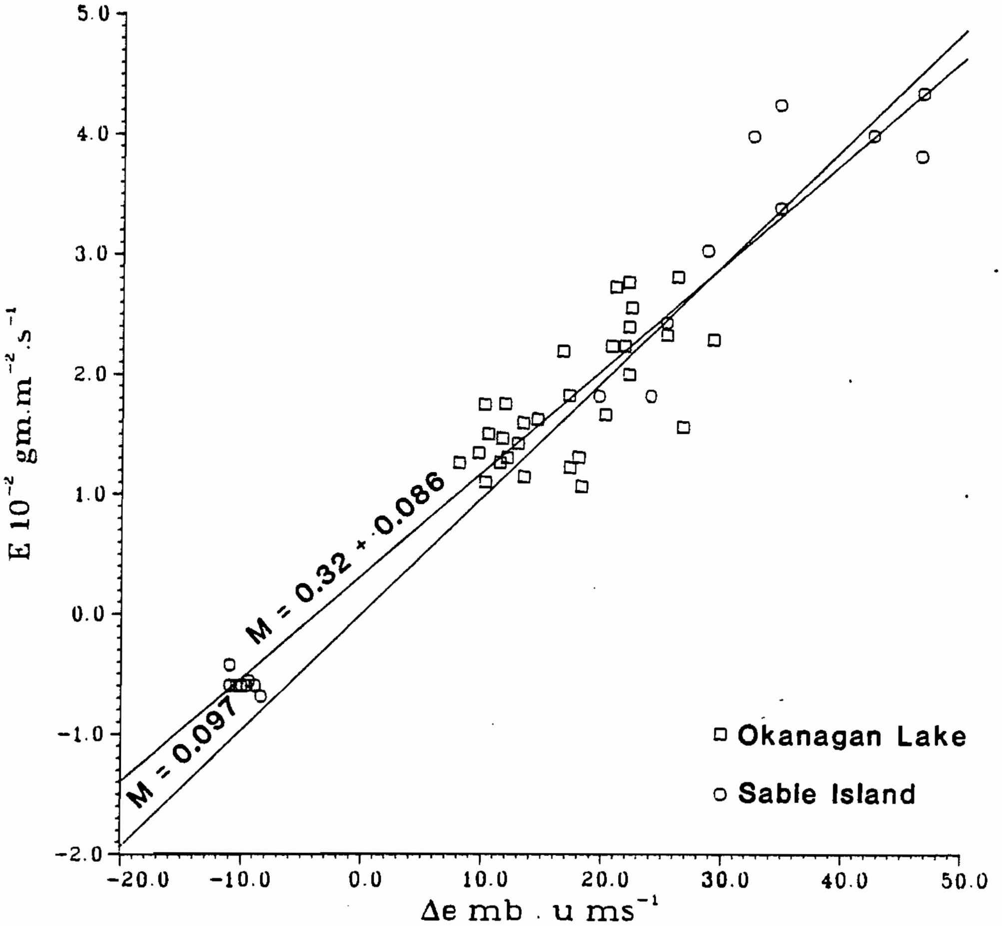


TABLE 4
Comparison of Mass Transfer Coefficients for Deep Lakes

This Study	With Sable Island	Lake Superior	Lake Ontario	Lake Hefner
0.0240	0.0233	0.0198-0.0239	0.0262-0.0275	0.0269

The mass transfer coefficients (M) in Table 4 were standardized to four metres where possible using the logarithmic wind profile. The evaporation rate is in mm day^{-1} when the wind speed is in km hr^{-1} and the humidity gradient is expressed in mb. The range of coefficients for Lake Superior were obtained from Derecki (1981), for Lake Ontario from Donelan et al (1974) and Holland et al (1979) respectively, and for Lake Hefner from the USGS study.

SENSITIVITY AND ERROR ANALYSIS

The sensitivity of a function (S_i) may be defined as the ratio of the change in the function produced by a unit change in one of the input parameters (X_i), thus;

$$S_i = \Delta E / \Delta X_i \tag{19}$$

It is often useful to know the sensitivity of the function relative to the magnitude of the calculated value. This may be expressed as a percentage change as follows:

$$R_i = \frac{\Delta E}{\Delta X_i} \cdot \frac{100}{E} \tag{20}$$

Quinn (1979) following some work by Coleman and De Coursey (1976) examined the sensitivity of the mass transfer equation to its various inputs in terms of the range of values for each parameter using the following expression for relative importance.

$$I_i = \frac{\Delta E}{\Delta X_i} \cdot \frac{X_{imax} - X_{imin}}{E} \tag{21}$$

The variance of the mass transfer equation may be calculated from

$$\sigma_E^2 = \left(\frac{\Delta E}{\Delta T_s} \cdot \sigma_{Ts} \right)^2 + \left(\frac{\Delta E}{\Delta h} \cdot \sigma_h \right)^2 + \left(\frac{\Delta E}{\Delta u} \cdot \sigma_u \right)^2 \tag{22}$$

where σ refers to the standard error of the respective parameters: water temperature (T_s), humidity (h) and wind speed (u). The standard error of measurement σ_m may be found from Equation 22 by substituting measurement limits for the standard error of each parameter. The standard error of estimate of the mean evaporation rate (averaged over time or space) may be calculated from Equation 22 by substituting the temporal or spatial standard errors for the respective parameters.

TABLE 5
Variation in Mass Transfer Input Parameters

	Mean	Standard Error	Maximum	Minimum
Summer				
Surface Temp (°C)	14.3	4.5	21.5	3.1
Humidity (mb)	10.4	2.4	17.0	5.2
Wind Speed (km hr^{-1})	9.0	3.0	21.9	3.9
Lake Evaporation (mm day^{-1})	1.27			
Winter				
Surface Temp (°C)	4.0	4.9	15.6	-0.2
Humidity (mb)	5.9	1.9	14.6	1.8
Wind Speed (km hr^{-1})	9.1	4.0	26.7	3.2
Lake Evaporation (mm day^{-1})	0.49			

Summer (May to September, 1980) and winter (October 1980 to March 1981) averages of water temperature, humidity and wind speed (for Penticton Marina) used in the sensitivity and error analysis of the mass transfer equation are given in Table 5. The water temperature at the Marina were supplemented by data from Deeper Creek since the recorder at the Marina did not operate continuously throughout the winter. Lake evaporation was calculated with M = 0.024. The measurement errors for water temperature, humidity and wind speed respectively were 1°C, 0.5 mb and 0.5 km hr^{-1}.

When the input data are averaged over the summer or winter seasons, the mass transfer equation appears to be less sensitive to wind speed than the other two parameters (see Table 6). While the sensitivity to both water temperature and humidity increases during the winter, the equation is more sensitive to the humidity. When the seasonal range of each parameter is taken into account, the wind speed remains the least important parameter. The water temperature is an important parameter in both summer and winter. The humidity is once again dominant in the winter months.

It must be remembered that the sensitivity refers to a unit change in each of the input parameters. The day to day variations in mean water temperature and humidity are less than that of the wind speed, particularly in winter. Whereas the day to day variations of water temperature and vapour pressure are typically 2°C and 2 mb respectively, the wind speed can easily be 2 or 3 times higher than the previous day. Because the mass transfer evaporation rate is linearly related to wind speed, doubling the wind speed doubles the evaporation rate. The spatial and temporal variability of the wind speed make it the most important parameter when the mass transfer equation is used on a daily basis.

TABLE 6
Error and Sensitivity Analysis at Okanagan Lake Data

	Relative Sensitivity %		Relative Importance		Measurement Error mm day^{-1}		Seasonal Error mm day^{-1}	
	S	W	S	W	S	W	S	W
Surface Temp	19	28	3.5	4.4	0.29	0.14	1.23	0.79
Humidity	-17	-45	-2.0	-5.8	0.11	0.23	0.53	0.84
Wind Speed	11	10	2.0	2.4	0.07	0.02	0.42	0.20

Error and sensitivity analysis of the mass transfer equation were calculated using the data from Table 5. The calculated mean evaporation for the summer period (S) with M = 0.0240 was 1.27 mm day^{-1} and for the winter (W) it was 0.49 mm day^{-1} giving an estimated annual total of 322 mm.

VARIABILITY BETWEEN CLIMATE STATIONS

While it is recognized that 18 months of data are insufficient to provide the definitive climate of Lake Okanagan itself, they are adequate to make some generalizations of consequence to the use of the mass transfer method for this particular lake.

The mass transfer equation requires humidity and wind speed over the water as well as water temperature, preferably measured, but often estimated from nearby shore stations. Since Lake Okanagan is in a long narrow mountain valley and often has a very steep shoreline, the extrapolation of shore-based climatological data over the surface of the lake should be approached with caution. The climatological data collected at lake-side stations will be compared to Kelowna and Penticton Airports, both of which measure temperature, humidity and wind speed routinely. Both stations have Class A evaporation pans.

In order to assess the representativeness of the airport stations for estimating conditions over the lake itself, five special climate stations were established on the shoreline (see Figure 1). These were from north to south: Winfield (#1), Deeper Creek (#5), Peachland, Yacht Club (#6), Summerland (#7) and Penticton Marina (#9). The anemometer at Kelowna Bridge (#4) had been installed for a previous study but required a recorder. The Kelowna weather office staff maintained the recorder and abstracted the data. Temperature, humidity, wind speed and direction were measured at all sites except Kelowna Bridge (wind only) and Summerland (temperature and humidity only). Water temperatures were measured at Winfield, Deeper Creek, Peachland and Penticton Marina.

Deeper Creek was chosen as the main site for further experimental work because of its reasonable exposure, protection from vandals and a willing landowner. Additional elements such as solar radiation and net radiation were also monitored at Deeper Creek on special data loggers. With the exception of Winfield, all data were measured either over the water, such as at Deeper Creek and Peachland Yacht Club, or within a meter of the high water mark. The Winfield site was a rocky prominatory with a steep two metre drop to the shoreline. Good exposure for this site was from the north only.

a) Differences Between Airports

In general terms weekly averages of temperature at Penticton were 1-3°C warmer than Kelowna in the summer (Figure 4) and this difference narrowed to less than a degree over the winter months. On any particular day, of course, these differences could be much larger. The humidity content of the air expressed as a vapour pressure tends also to be slightly higher at Penticton (about 1 mb) in the spring and early summer but this difference essentially disappears by the fall (Figure 5). The most significant difference between these two airports is the much stronger winds at Penticton (Figure 6). Kelowna Airport is in a smaller valley running roughly parallel to Lake Okanagan and separated from it by a high ridge. Penticton on the other hand is in the main valley at the southern end of the lake and is exposed to the full force of the valley winds. With the exception of the wind, the "climates" as measured at Kelowna and Penticton are essentially similar. The difference in the wind speeds makes a good case for the inclusion of siting characteristics when comparing climate station data.

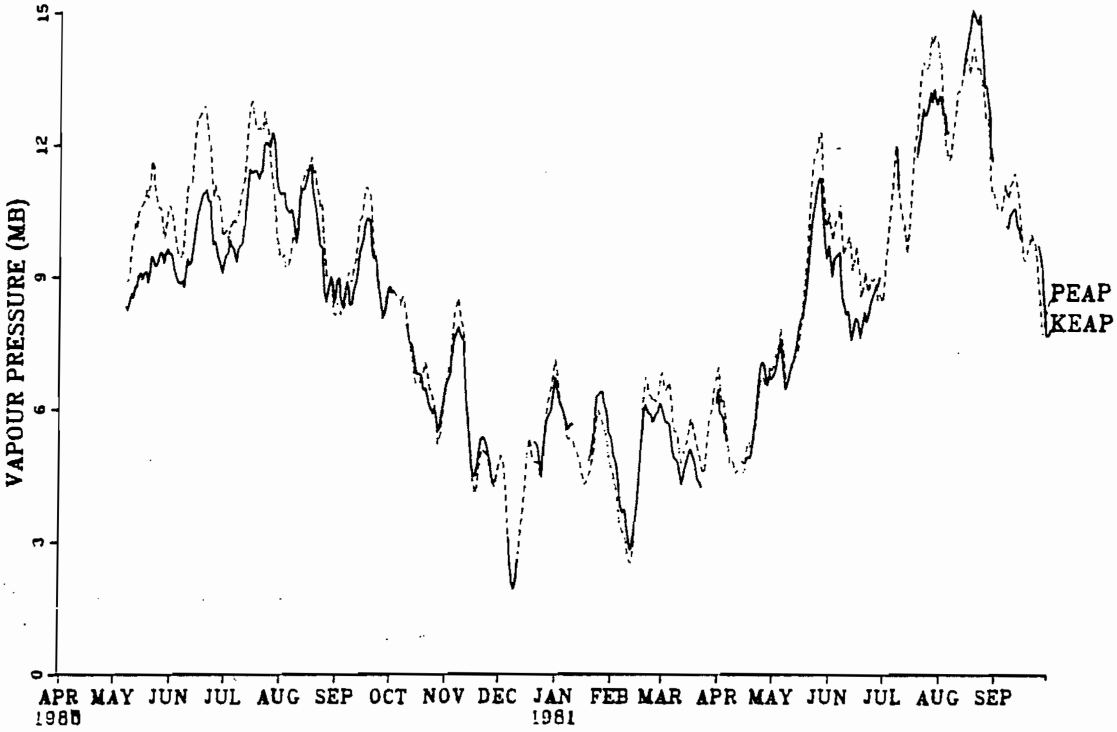
b) Differences Between Lake-Side Stations

Data from "lake-side" climate stations indicated that the greatest difference between stations for temperature and humidity occurs in the summer. Winfield is often 1-2°C warmer than Deeper Creek or Penticton Marina during the summer, whereas Deeper Creek appears to have higher vapour pressures than either Winfield or Penticton Marina (Figures 7 and 8). The more sheltered location of the Winfield station probably accounts for some of the temperature difference. The higher humidities at Deeper Creek may be due to the irrigation of the orchard. The Peachland Yacht Club with its southerly exposure on the north shore is generally warmer than either Penticton Marina or Deeper Creek.

With respect to water temperatures, Winfield was the warmest followed by Deeper Creek and Penticton Marina (Figure 9). As the summer season progressed the differences between Winfield and Deeper Creek were quickly reduced but Pencticton Marina remained significantly cooler until the end of June. Then during July, the water temperatures at the Marina exceeded even Winfield for several weeks. For the remainder of the summer the water temperatures at the Marina were within a degree of those at Deeper Creek. No comparisons between locations were possible during the winter months because the Penticton Marina and Winfield recorders were removed for safety reasons. However, the electronic water temperature recorder at Deeper Creek functioned throughout the winter. By the end of November, the surface water temperature had decreased to near 1°C and it continued a slow decline until mid February when it appears to have frozen during a short cold spell. The water

FIGURE 4 KELOWNA AIRPORT – PENTICTON AIRPORT
7 DAY RUNNING MEANS – AIR TEMPERATURE

FIGURE 5 KELOWNA AIRPORT – PENTICTON AIRPORT
7 DAY RUNNING MEANS – VAPOUR PRESSURE



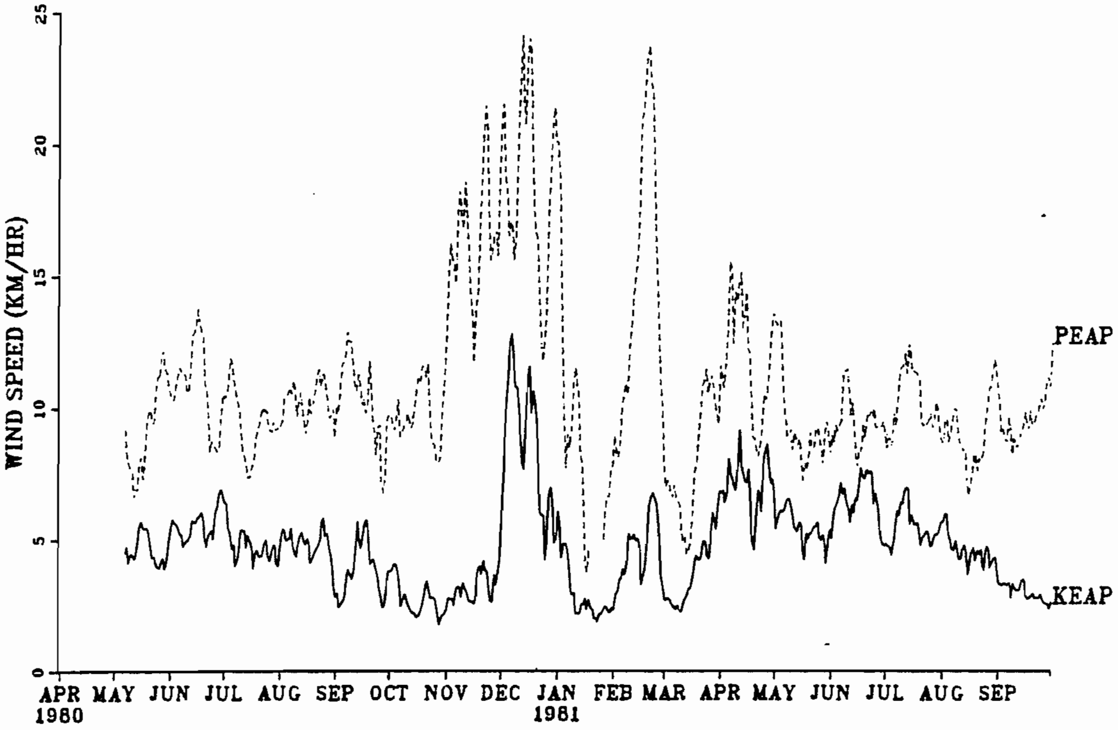


FIGURE 6 KELOWNA AIRPORT – PENTICTON AIRPORT
7 DAY RUNNING MEANS – WIND SPEED

FIGURE 7a LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - AIR TEMPERATURE

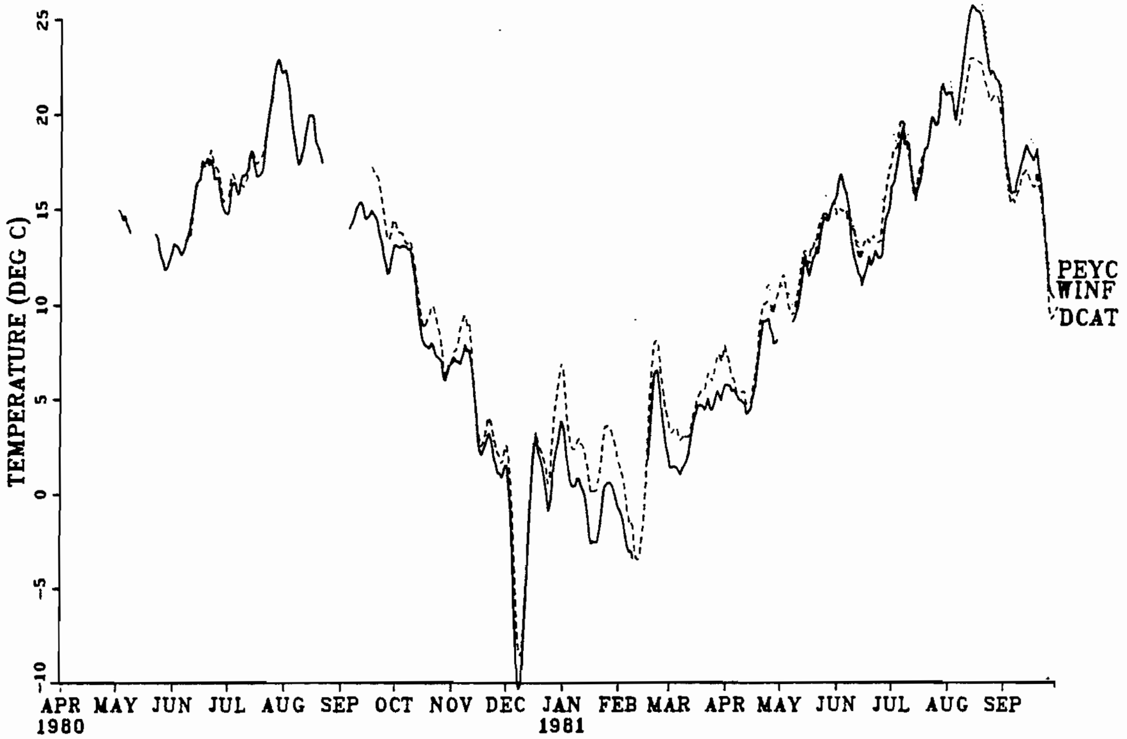


FIGURE 7b LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - AIR TEMPERATURE

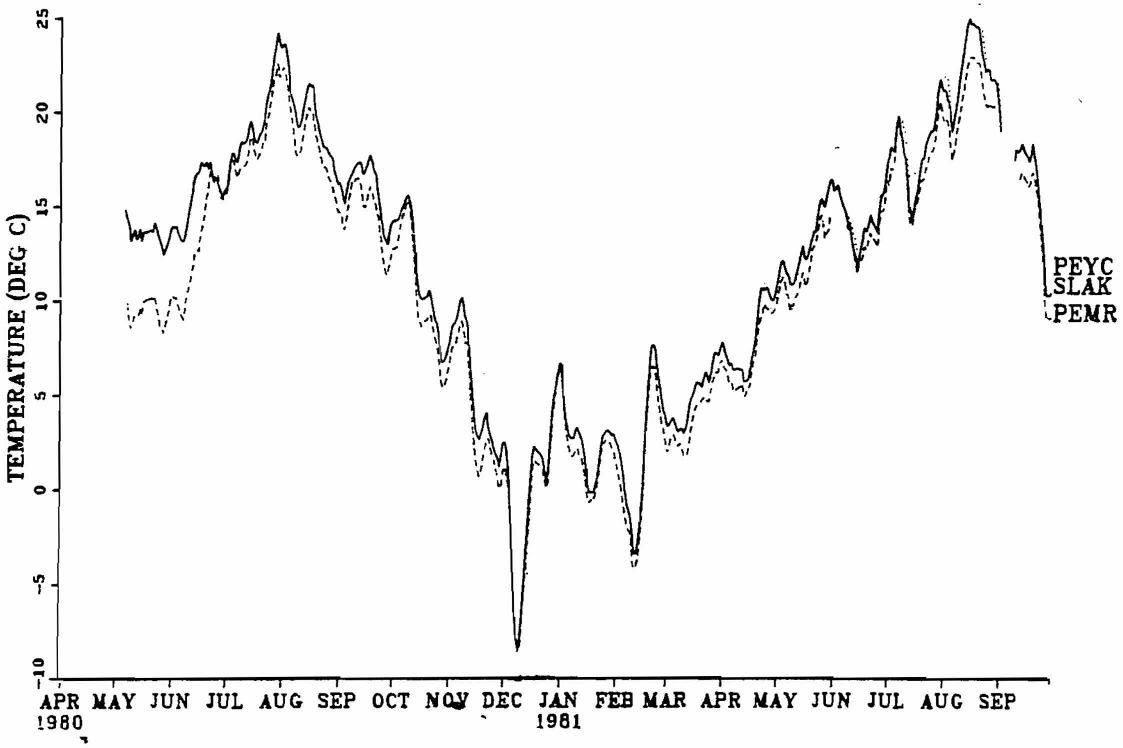


FIGURE 8a LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - VAPOUR PRESSURE

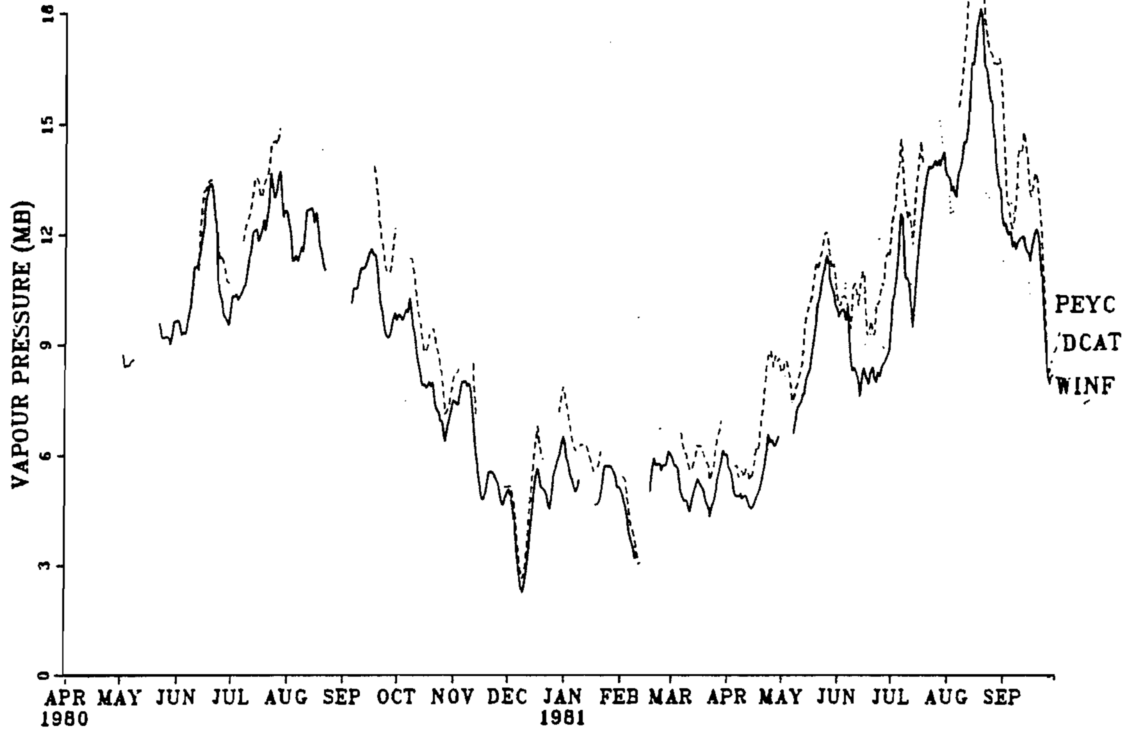


FIGURE 8b LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - VAPOUR PRESSURE

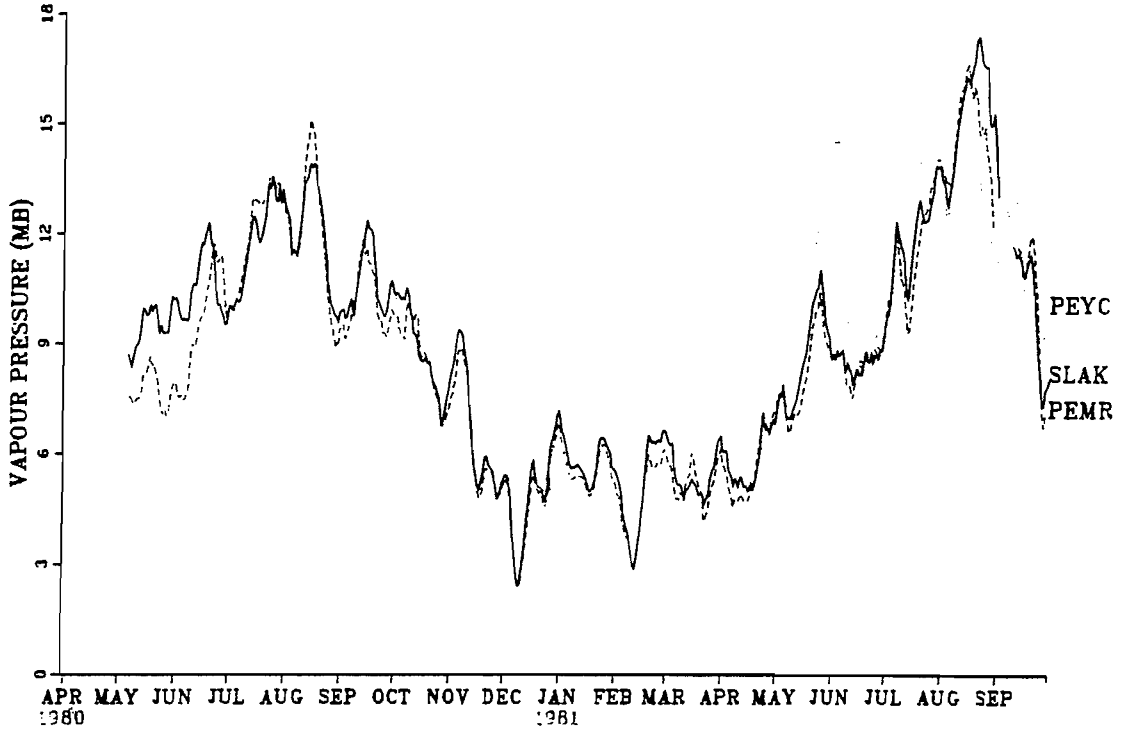


FIGURE 9a LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - WATER TEMPERATURE

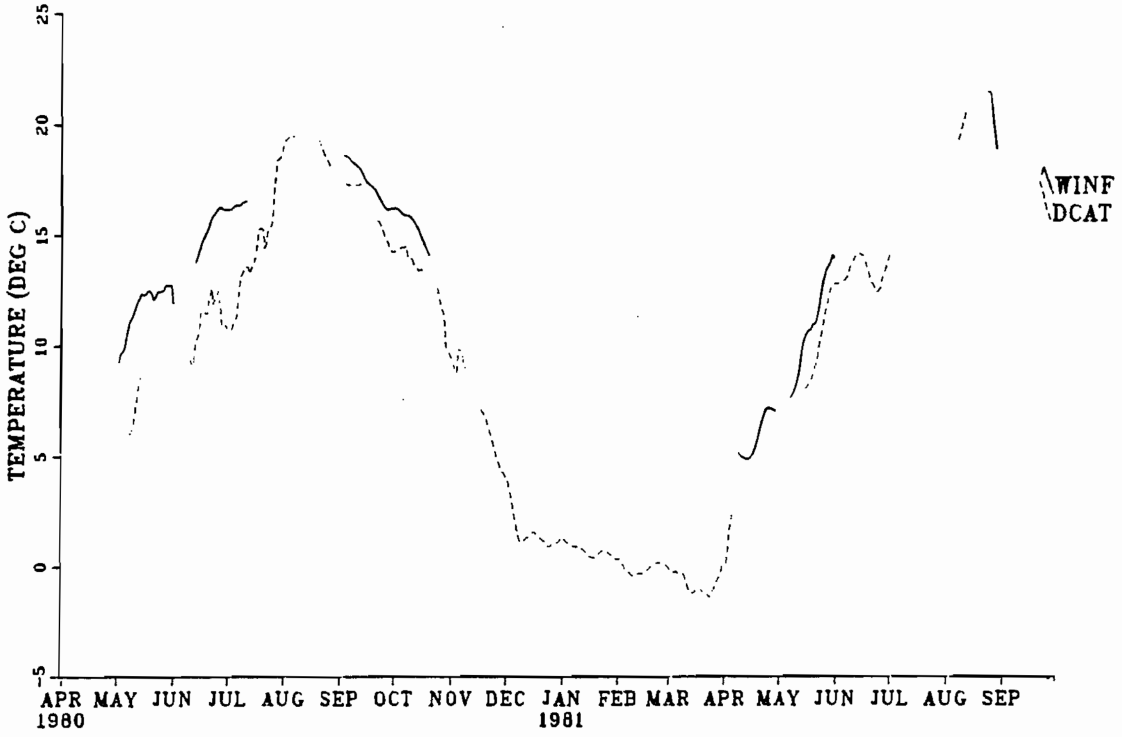
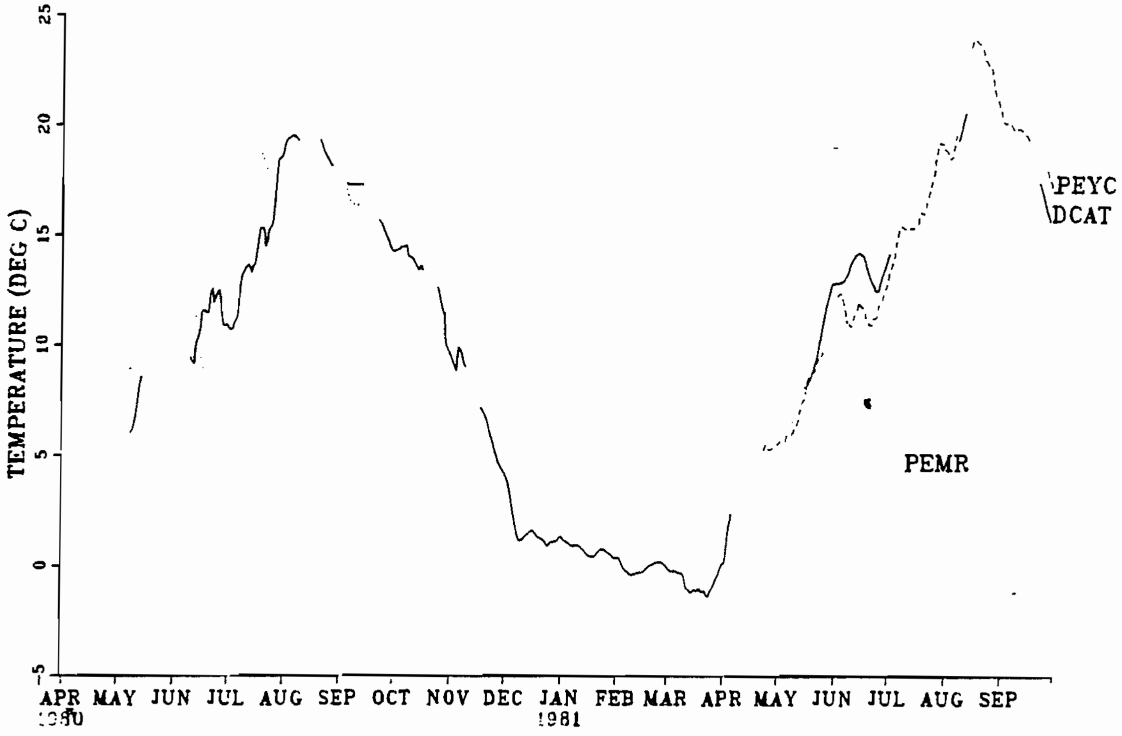


FIGURE 9b LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - WATER TEMPERATURE



temperature increased throughout the remainder of February and by the end of March was up to 6°C at Deeper Creek and 3°C at Penticton Marina. As in 1980 the spring water temperatures at Penticton Marina were significantly lower than Deeper Creek. Unfortunately the 1981 spring and summer water temperatures at the Marina are incomplete, first due to equipment malfunction and then to vandalism and theft.

The winds were noticeably stronger at the Penticton Marina site than either the Deeper Creek or Winfield sites (Figure 10). Even when wind direction is taken into account the wind speeds at Winfield are significantly lower that Deeper Creek which is significantly lower than Penticton Marina. This trend confirms my personal observation based on limited experience that the Peachland to Penticton section of the lake seemed to have much stronger winds than either of the other two sections of the lake. Even at the Deeper Creek site the winds near the centre of the lake appeared to be stronger than our shore based measurements indicated.

c) Substitution of Airport for Lake-Side Data

The question arises as to whether or not the climatological data collected at the airports may be substituted for the "lake-side" or "over-lake" climatological data. Figures 11-16 give comparisons between Kelowna Airport - Deeper Creek and Penticton Airport - Penticton Marina for temperature. humidity and wind speed. The weekly averaged temperatures at Deeper Creek tend to be slightly warmer than those at Kelowna Airport where as Penticton marina is somewhat cooler than Penticton Airport. Once again the cold water in the Peachland to Penticton segment of the lake noticeably depresses the temperature in the spring of 1980. Although the cool water during this period also lowered the humidity at the Marina (Figure 14), the humidities at lake-side stations were consistently higher than those at the airports. Wind speed comparisons show greater variability between stations than those for temperature or humidity. The wind speeds at Deeper Creek appear to be a consistent 2-5 km/hr higher than Kelowna Airport until the anemometer at Deeper Creek was replaced with a less sensitive type in April, 1981. In general the wind speeds at Penticton Airport are higher than those at the Marina, however due to sheltering effects at each site the northerly winds winds are noticeably stronger at the Marina whereas the southerly winds are stronger at the Airport (see Figure 7 and 8, Appendix A). The wind speeds at the Airport may be as much as 5-10 km/hr stronger than at the Marina.

The mass transfer equation is very sensitive to wind speed and vapour pressure gradient. If you double either, the evaporation rate will double. No one station is sufficient for the whole lake and there is no real substitute for data measured over the lake. If one had to substitute data, Penticton Airport vapour pressure and possibly wind speed could be substituted for the Marina data if water temperature is measured. For example, the calculated evaporation rate using the $M = 0.0240$ would be 1.20 mm/day using the Marina data versus 0.75 mm/day using the Airport data with measured water

FIGURE 10a LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - WIND SPEED

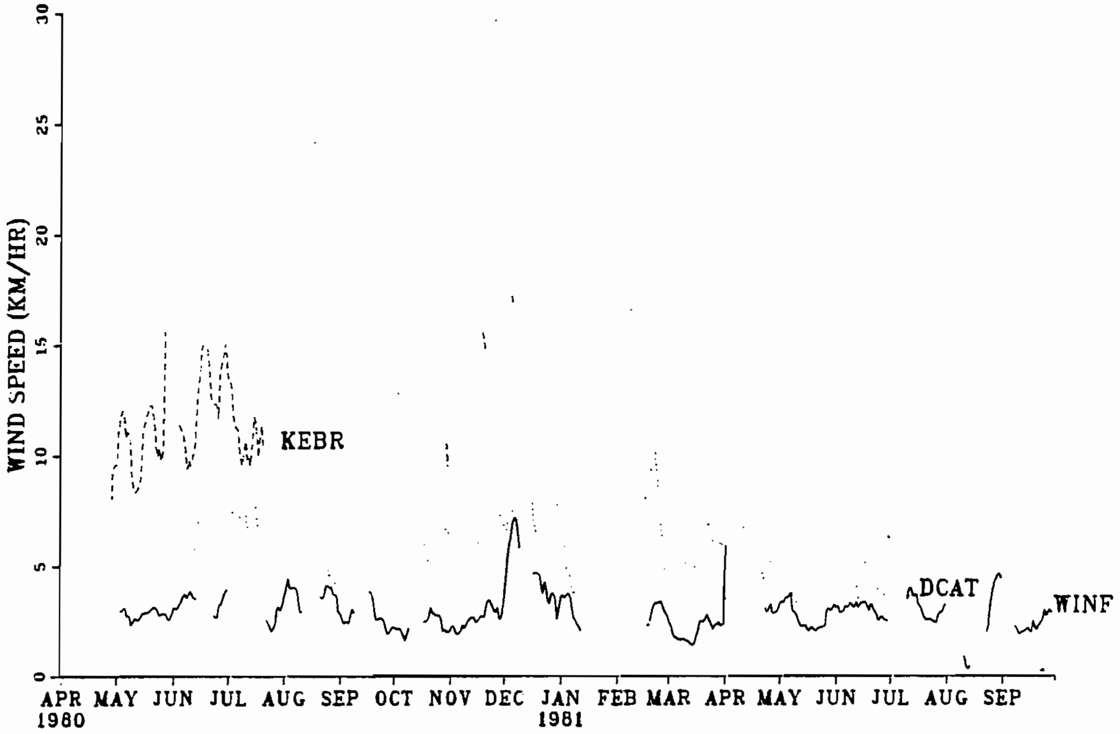


FIGURE 10b LAKE-SIDE STATIONS
7 DAY RUNNING MEANS - WIND SPEED

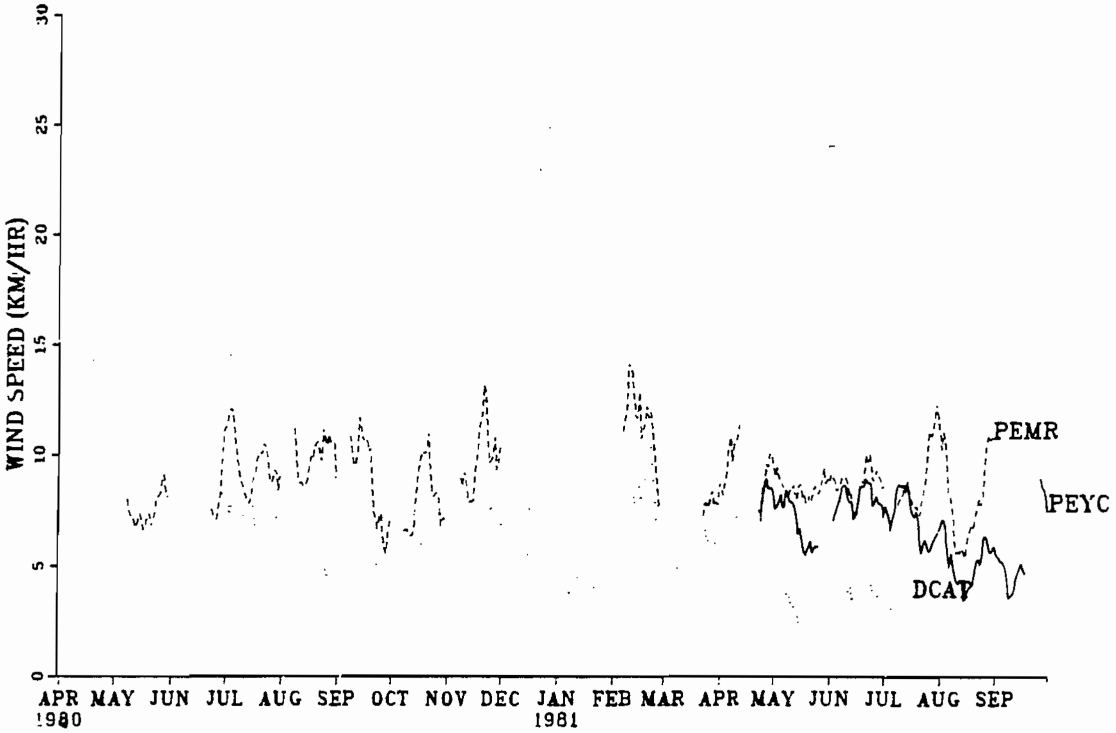


FIGURE 11 KELOWNA AIRPORT - DEEPER CREEK
7 DAY RUNNING MEANS - AIR TEMPERATURE

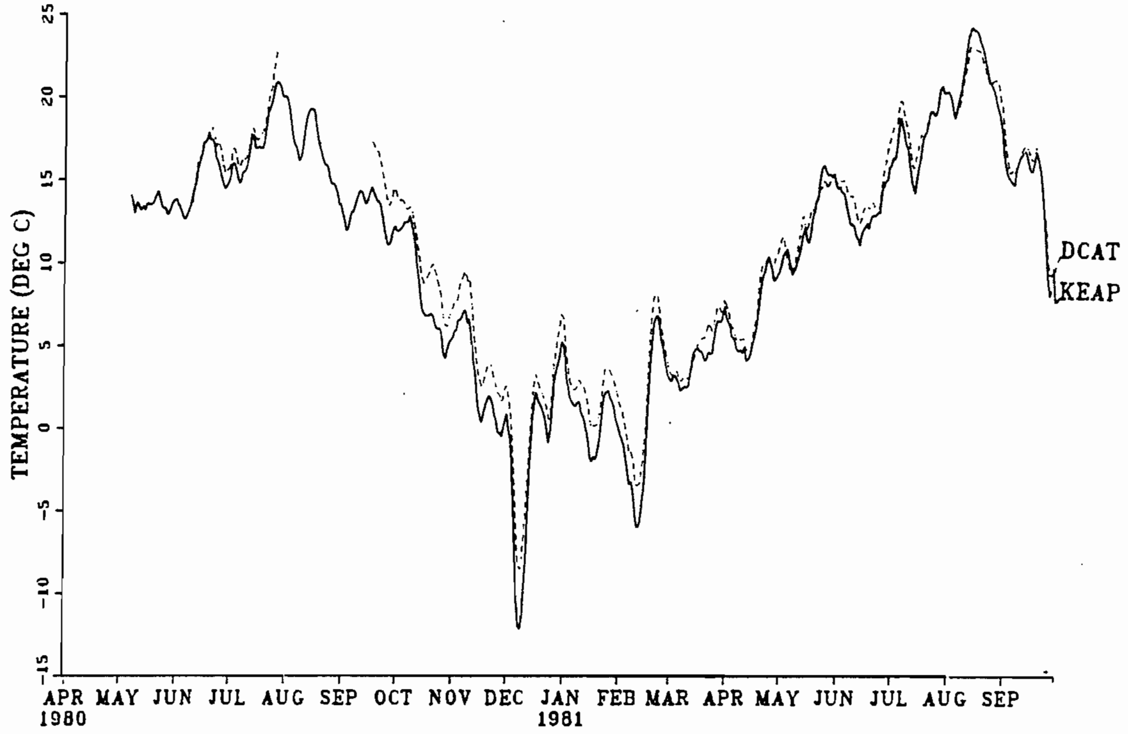
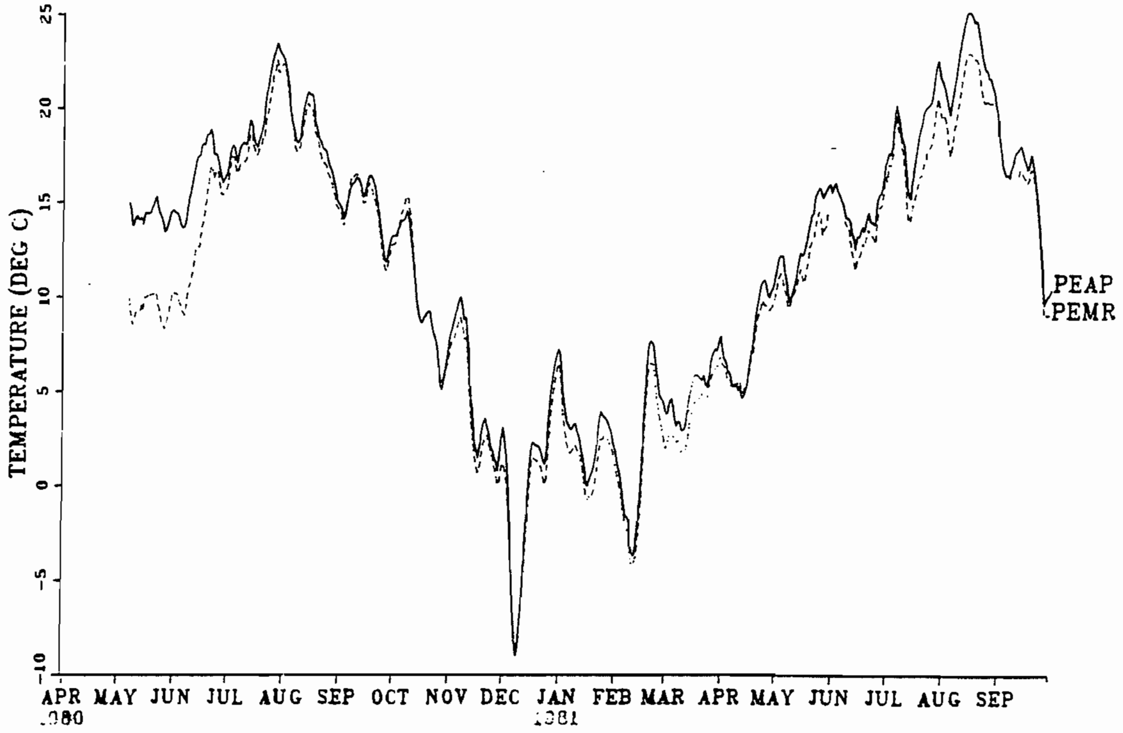


FIGURE 12 PENTICTON AIRPORT - MARINA
7 DAY RUNNING MEANS - AIR TEMPERATURE



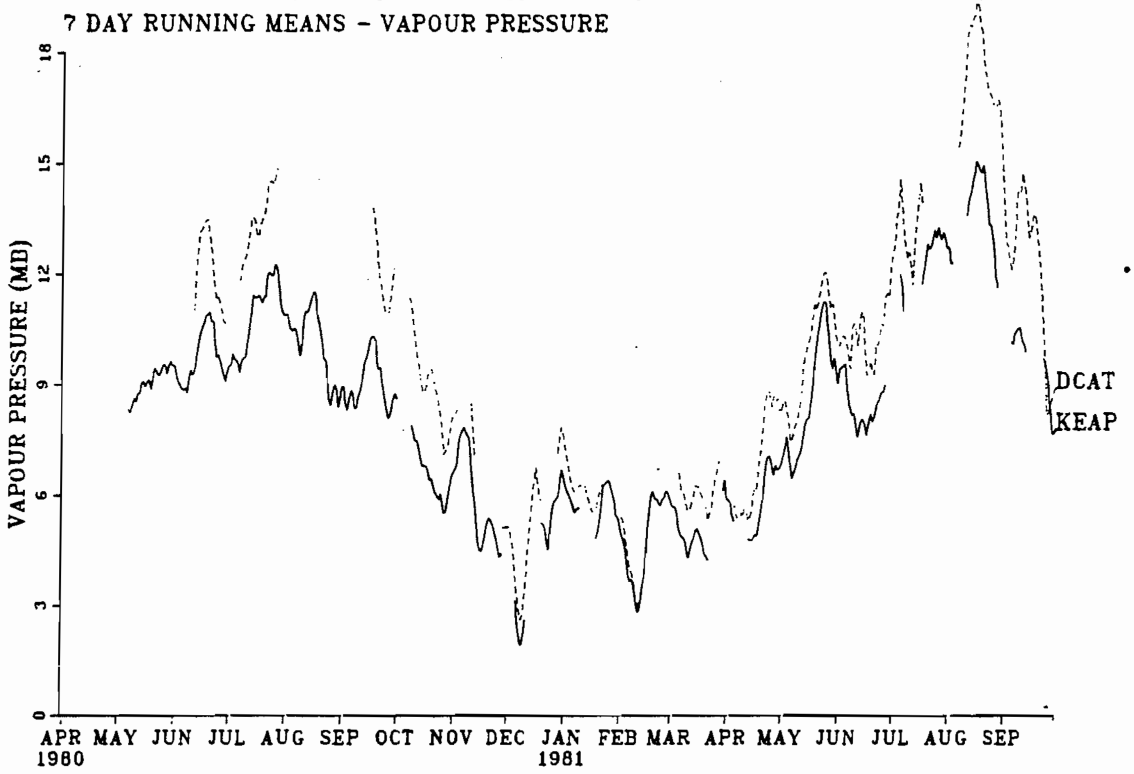


FIGURE 13 KELOWNA AIRPORT - DEEPER CREEK
7 DAY RUNNING MEANS - VAPOUR PRESSURE

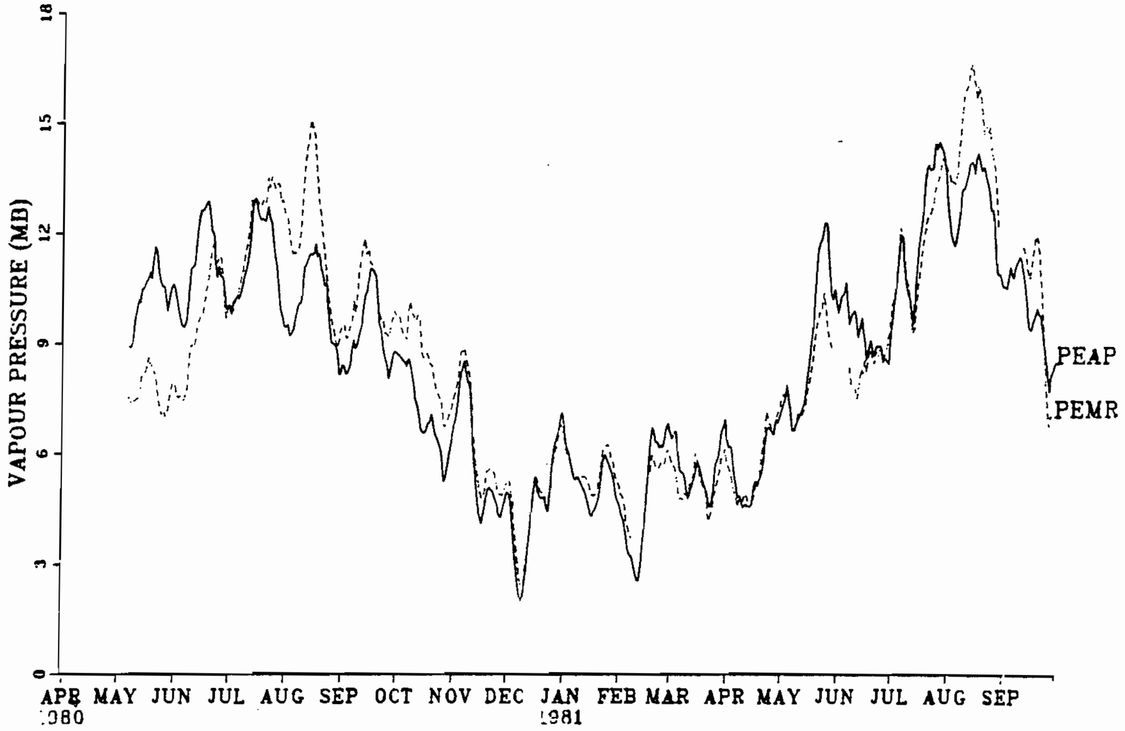


FIGURE 14 PENTICTON AIRPORT - MARINA
7 DAY RUNNING MEANS - VAPOUR PRESSURE

FIGURE 15 KELOWNA AIRPORT - DEEPER CREEK
7 DAY RUNNING MEANS - WIND SPEED

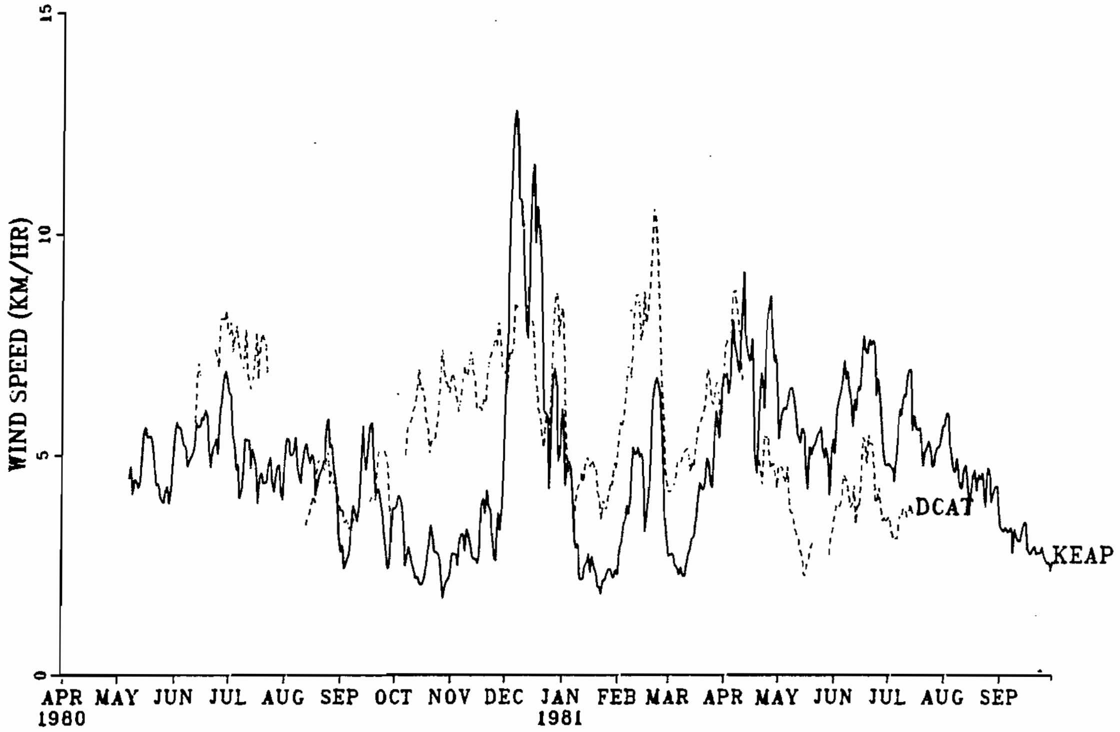
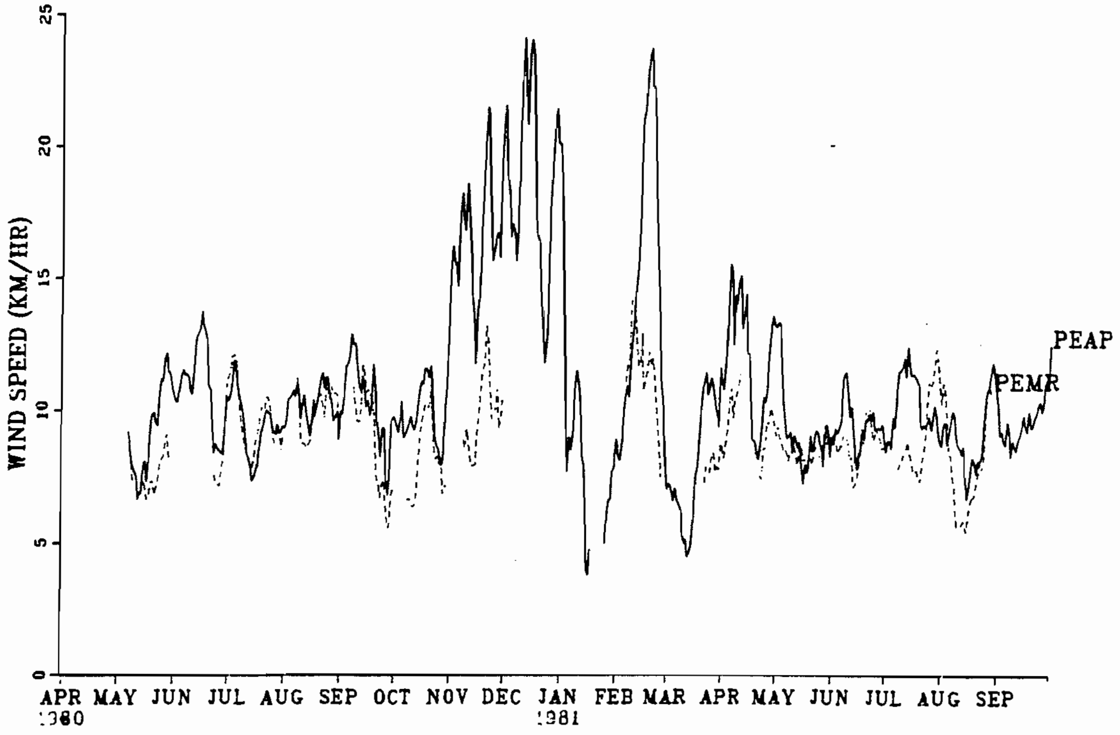


FIGURE 16 PENTICTON AIRPORT - MARINA
7 DAY RUNNING MEANS - WIND SPEED



temperature for the 7 day period ending on the 12 of May 1980. For the same period in 1981 the calculated evaporation rate of 0.58 is the same at both stations.

THE SPATIAL DISTRIBUTION OF LAKE SURFACE TEMPERATURES

Few evaporation studies have been able to address the problem of the spatial variability of water surface temperature. Water temperatures measured at one or more points on the lake are assumed to be "representative" of the whole lake. Airborne radiation thermometry (ART) has been used on the Great Lakes (Irbe, 1972) to monitor lake surface temperatures operationally for 13 years. Using an infrared thermometer, measurements of surface temperature are obtained from an aircraft along a series of flight lines. From this data an isoline map of surface temperature is constructed manually. The major problem with this technique is that the spatial detail must be constructed from essentially point data along the widely spaced survey lines. Thermal imagery obtained via satellite does provide spatial detail but there are problems of resolution, frequency of over-flights, and interference from clouds. Satellites such as the NOAA-6 and NOAA-7 do provide twice daily coverage of Lake Okanagan but the minimum pixel size or resolution is about 1 square kilometer. Landsat on the other hand does have acceptable resolution about 0.01 square kilometers but with a 19 day interval and the likelihood of partial or complete cloud cover, the probability of obtaining the data when required is not very high. In addition, the thermal band on Landsat is only in the near infrared and therefore is not suitable for monitoring surface temperatures.

a) Infrared Imagery

The thermal imaging line scanner, can provide both the spatial resolution required and provide the data when required. With this system the thermal sensor scans across the flight line and by flying at the appropriate altitude the whole width of the lake may be viewed at one time. Using a "warm" and a "cool" black body cavity to set the upper and lower delection limits of the scanner, the thermal "brightness" of the underlying surface is referenced to the known temperatures of the two black body cavities. The thermal brightness is translated into an analogue signal and recorded on magnetic tape for later processing onto computer compatible tape or through a photographic system to produce a film strip. The density of the film is directly related to the temperature through a density step wedge. The film strips may then be analysed with an image analysis system commonly referred to as a density slicer. With this system, temperatures are assigned to various density bands or gray scale levels and the areas in each temperature band are calculated to produce an areally weighted average surface temperature.

TABLE 7

The area in each temperature interval (in °C), obtained from the infrared imagery and expressed as a percentage, are given below for Lake Okanagan. The colours are assigned to the temperature intervals by the density slicer and correspond to those in the accompanying photographs in Figures 19 and 20 and the slides in Appendix G.

November 1979 I.R. Flight

	Temp.	South	Central	North	West Arm	Lake
Red	> 12	0.0	0.0	0.0	0.0	0.0
Yellow	11-12	0.0	0.0	0.0	0.0	0.0
Orange	10-11	21.2	3.8	64.6	12.1	35.0
Green	9-10	48.1	76.5	35.4	58.4	48.0
Violet	8-9	24.0	19.7	0.0	24.5	14.1
Cyan	7-8	6.6	0.0	0.0	3.9	2.9
Blue	6-7	0.0	0.0	0.0	1.2	0.1
Magenta	< 6	0.0	0.0	0.0	0.0	0.0
Average Lake Temp.		9.3	9.3	10.2	9.3	9.7

April 1980 I.R. Flight

	Temp.	South	Central	North	West Arm	Lake
Red	> 14	0.0	0.2	6.3	4.9	2.8
Yellow	13-14	4.5	4.0	29.5	22.9	15.1
Orange	12-13	6.4	8.9	22.2	16.3	13.9
Green	11-12	16.3	30.3	20.8	15.0	22.0
Violet	10-11	14.6	20.3	10.0	22.5	15.2
Cyan	9-10	22.5	14.8	8.8	16.7	14.6
Blue	8-9	23.0	11.6	1.6	1.3	10.0
Magenta	< 8	12.7	9.8	0.8	0.3	6.4
Average Lake Temp.		9.9	10.4	12.2	11.7	11.0

September 1980 I.R. Flight

	Temp.	South	Central	North	West Arm	Lake
Red	> 20	0.0	0.0	0.0	0.0	0.0
Yellow	19-20	0.0	0.0	3.5	0.0	1.2
Orange	18-19	0.0	2.0	23.5	32.1	11.1
Green	17-18	3.7	31.3	52.6	59.8	33.0
Violet	16-17	46.6	56.2	20.3	7.7	37.5
Cyan	15-16	40.7	8.9	0.2	0.3	14.2
Blue	14-15	9.0	1.6	0.0	0.0	3.0
Magenta	< 14	0.0	0.0	0.0	0.0	0.0
Average Lake Temp.		16.0	16.7	17.6	17.7	16.9

Intertech Remote Sensing Ltd. of Calgary was contracted to do a preliminary evaluation flight in November, 1979. Although the coverage of the lake was incomplete (due in part to misalignment of flight lines) the results were encouraging. The range of temperature (6-11°C) and the spatial variability was greater than expected. The temperature distribution by area is given in Figure 17 for the lake as a whole. The lake was further divided into four segments: south - from Penticton to Peachland; central - from Peachland to Kelowna Bridge; north - from Kelowna Bridge to Vernon; and the West Arm - from Whiteman to the north end of the lake. The temperature distributions for these segments are compared to the whole lake in Table 7. Details of analysis procedures and slides are given in Appendix G.

While the general trend in the climate is one of increasing temperatures to the south, on the basis of three surveys in the spring and fall surface temperatures of Lake Okanagan show just the reverse (see Table 7) with water temperatures generally warmer in the North and West Arm segments. This temperature trend is consistent in the three data sets analysed. These data have not been corrected for atmospheric attenuation of infrared radiation by aerosols, principally water vapour, between the aircraft and the surface. A computer program designed to correct thermal data obtained from satellites was used to estimate the temperature correction term given in Table 8.

TABLE 8

Table of surface temperature corrected for atmospheric attenuation between the aircraft and the surface (°C)

	Indicated Temperature												
	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
Corrected T_s													
April 26	8.7	9.9	11.2	12.4	13.6	14.8	16.0						
Sept. 9					14.8	16.1	17.3	18.5	19.7	20.9	22.3		

The infrared data from the line scanner does give an excellent representation of the spatial variability of the surface water temperature. While the temperature distributions given in Figures 17 do give an indication of the range of temperature and their relative importance, they do not give any insight to the complexity of the spatial pattern. For this reason one photograph for each flight from the slides in Appendix G has been included in this report. As these photographs clearly indicate, the spatial pattern for the April flight is much more complex than the September flight (the November imagery is similar to September). Moreover, the time scale of the pattern appears to be of relatively short duration. The imagery of the lake was obtained using seven separate flight lines with an average of 2-7 minutes between flight lines. This short time was sufficient in one case to make it difficult to match the pattern between flight lines when joining the photographs to make the mosaic.

FIGURE 17 – SURFACE TEMPERATURE DISTRIBUTION DERIVED FROM THERMAL IMAGING LINE SCANNER DATA

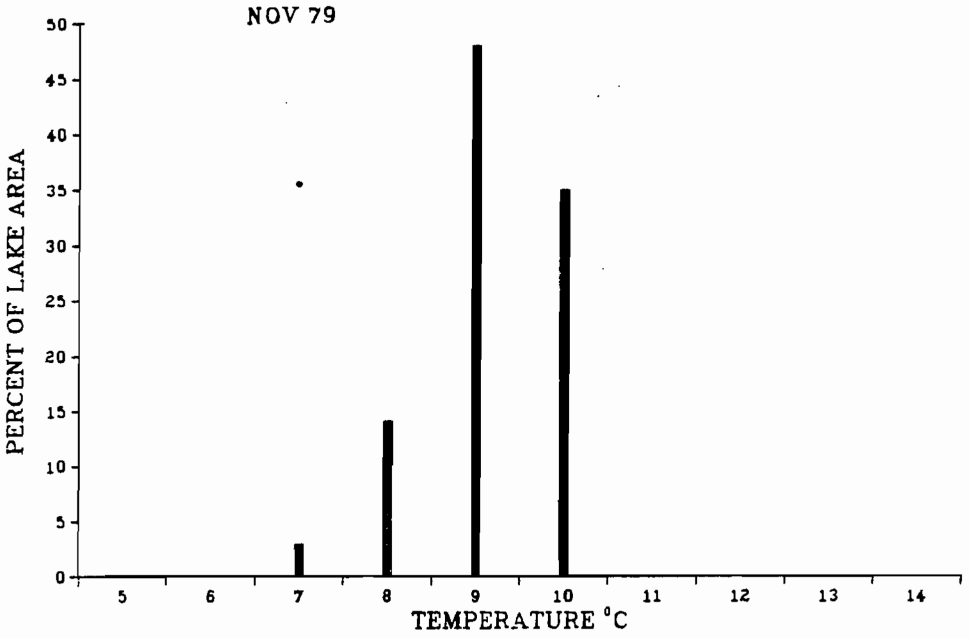
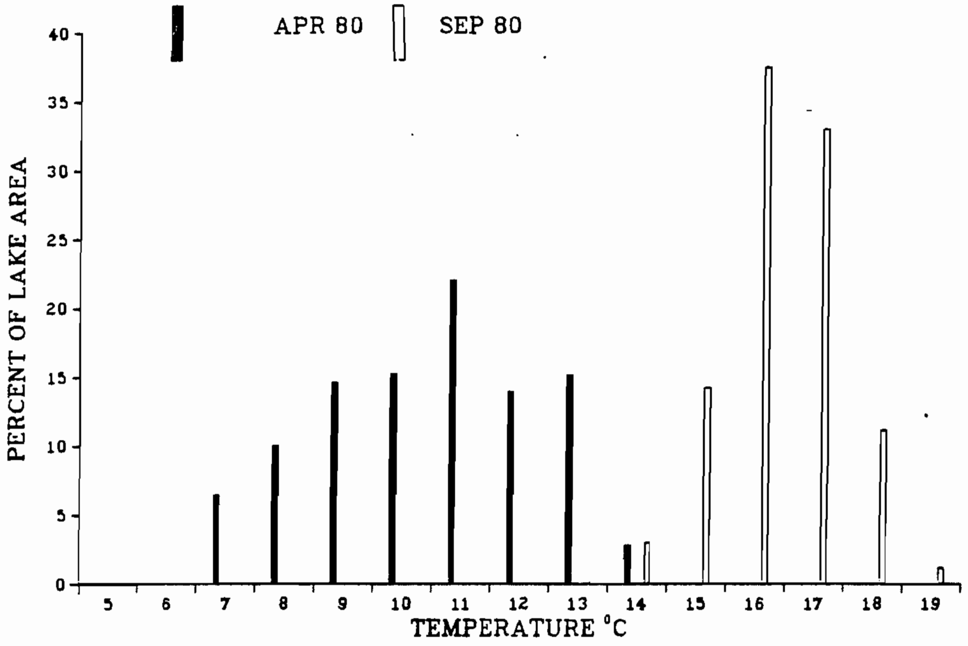


FIGURE 18 – SURFACE TEMPERATURE DISTRIBUTION DERIVED FROM THERMAL IMAGING LINE SCANNER DATA



Some of the features of the April temperature patterns are readily explained such as the large areas of cold water (magenta colour) at the outflows Trepanier and Trout Creeks. The thin line patterns in Figure 19 are the wakes of motor boats and are more clearly defined on the film strips. These wakes are 1-3°C cooler than the surrounding surface waters. In the spring months there is a strong thermal gradient in the water near the surface of the lake. Bathythermograph surveys conducted during the April and September field seasons showed that in April there was a 5°C decrease in the water temperature (11.5°C to 6.4°C) between the surface and the 5 metre depth, whereas in September the temperature decrease was only 0.6°C (17.8°C to 17.2°C). April 26 was a day of warm temperatures and strong solar heating with relatively light winds (southerly, 6 km/hr at Kelowna, northerly, 10 km/hr at Penticton). (The contrast in wind direction between Penticton and Kelowna Airports makes it difficult to extrapolate to winds over the lake.) The thermal imagery seems to indicate that areas like the south shore near Kelowna and some protected bays on the east and west shores in the reach from Penticton to Peachland have the warmer temperatures 11-13°C whereas the more exposed areas in the centre of the lake are cooler in the 8-10°C range. The extreme values of surface temperatures in the April imagery range from less than 8°C to greater than 14°C. Spot measurements with a hand held thermometer gave temperatures as low as 6°C near the mouth of Deeper Creek. With cold 5°C water lying just below the surface, warm air temperatures and strong solar heating, the detailed pattern in the April imagery is probably due to mixing of the surface waters by a combination of winds and currents.

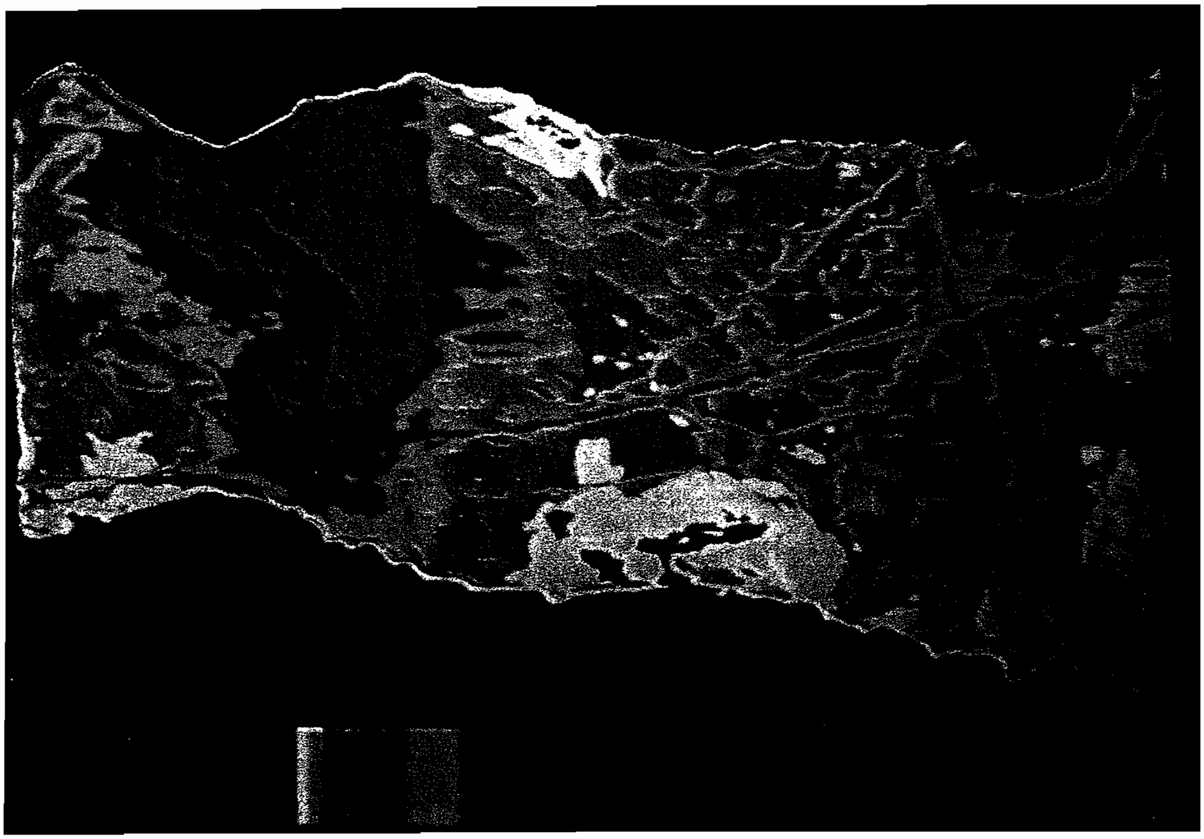
The temperature range for the September imagery is less than the April imagery, and the pattern is much more uniform with approximately 70% of the area of the lake in the 16-18°C temperature band (see Figure 20). The coldest segment of the lake is the South segment with about 90% of the surface temperatures between 15°C and 17°C. The North and West Arm segments have the strong peaks in the temperature distribution in the 17-18°C interval.

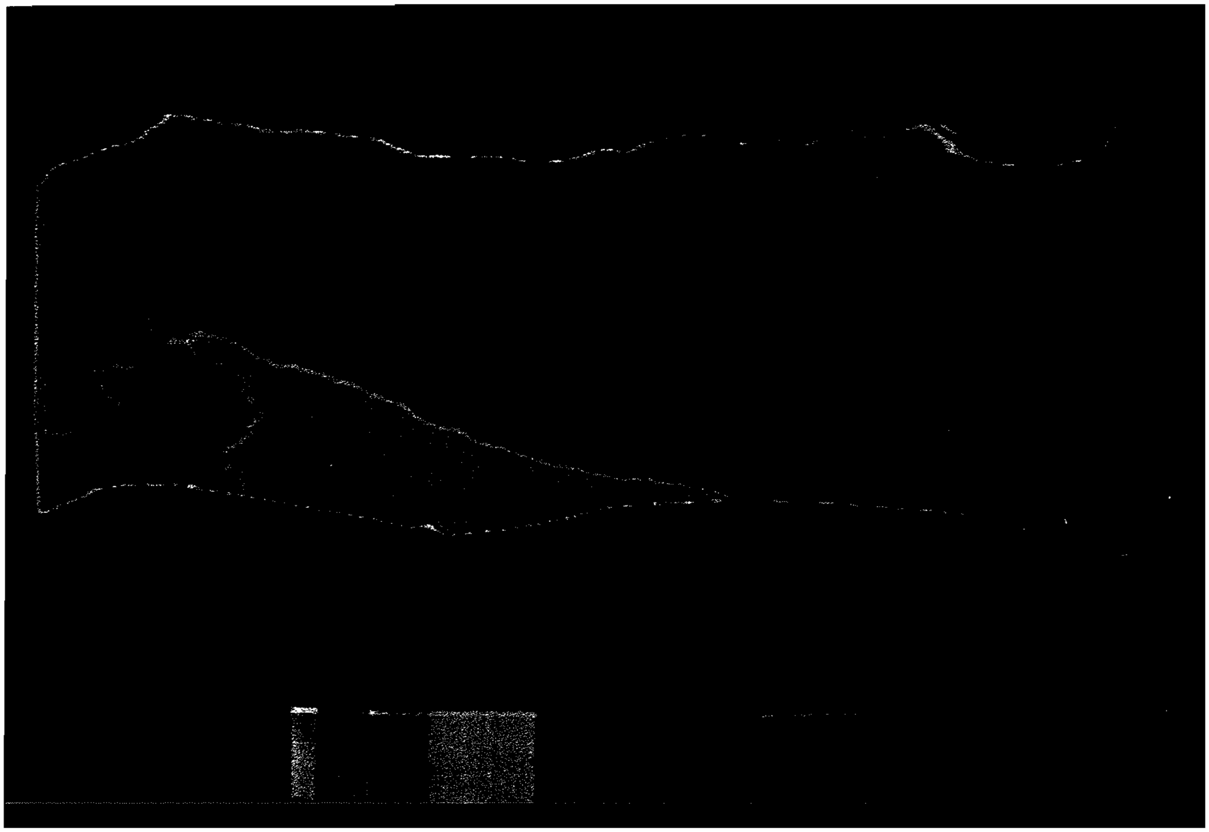
b) Floating Thermometers

Only the Winfield water temperature recorder was installed and working on April 26. The recorded maximum and minimum temperatures were 14.5°C and 6.9°C respectively. Although it is impossible to locate the Winfield water temperature recorder precisely on the imagery, the indicated temperatures in the area are 13-14°C and 12-13°C. Taking 13°C as the mid-point and using Table 8, the corrected temperature would be 14.8°C. The estimated accuracy of both the thermal imagery and the mechanical water temperature recorder is about ±0.5°C. The thermal imagery agrees with the Winfield measurement within the expected accuracy of both systems. Furthermore, the hand held thermometer temperatures obtained during the surface infrared thermometer surveys conducted from a motor boat ranged from 6.7°C near shore to 11.2°C near the middle of the lake while the infrared thermometer readings ranged from 11.6°C to 15°C. The hand held readings were obtained by stirring the surface water with the thermometer thereby, probably bringing colder water to the surface which accounts for the difference in temperatures between the two techniques. The thermal imagery temperatures along the infrared thermometer survey line range from 8-9°C to a high of 11-12°C.

FIGURE 19 COLOUR ENHANCED THERMAL IMAGERY -26 APRIL 1980
PEACHLAND TO MISSION CREEK (SEE TABLE 6 FOR COLOUR KEY)

FIGURE 20 COLOUR ENHANCED THERMAL IMAGERY -6 SEPTEMBER 1980
PEACHLAND TO MISSION CREEK (SEE TABLE 11 FOR COLOUR KEY)





During the September survey period three mechanical water temperature recorders were operational and the data are given in Table 9. Once again the maximum temperatures agree well with the indicated temperatures near each recorder: Penticton - (16-17°C), Deeper Creek - (16-18°C); and Winfield - (18-20°C). Thermometer readings taken from the boat during the bathythermograph surveys in the segment between Squally Point and Mission Creek ranged from 17.5°C to 18.2°C. The indicated temperatures at the approximate location of the survey points ranged from 16-17°C to 17-18°C. The corrected temperatures would be about 1.0-1.5°C higher but this is still within the expected accuracy of both sets of data.

TABLE 9

September 9, 1980 1 cm water temperatures (°C)

	Winfield	Deeper Creek	Penticton Marina
Maximum	20.4	18.4	17.5
Minimum	17.9	17.0	16.3
Average	19.2	17.2	16.9

As part of a limnological study of the mainstem lakes in the Okanagan Valley, Blanton and Ng (1972) obtained profiles of temperature at 19 sounding stations on Okanagan Lake from Penticton to Vernon. Their results are summarized in Figures 21 and 22 for six survey periods from April to October. These data lend further support to the observations of this study: the large range of surface temperature in the spring; the decrease in the range of temperatures during the summer and early autumn and the consistent trend of increasing water temperatures north from Penticton to Vernon. In the spring the spatial pattern of water temperature may be very complex as seen in the thermal imagery (Figure 19) and water temperatures measured by infrared techniques may be as much as 2-4°C higher than conventional measurements which are usually made just below the surface. However, this large difference between measurement techniques diminishes considerably on cloudy and windy days and as the surface layers of the lake become more isothermal as the heating season progresses into summer. The outflow areas of streams and near-shore shallow areas shoud be avoided when making spot readings of the lake temperature.

EVAPORATION FROM OKANAGAN LAKE

The temporal and spatial distribution of evaporation rates calculated by the mass transfer technique is a function of the distribution of the following input parameters listed in order of increasing variability - atmospheric humidity, surface water temperature and wind speed. As was discussed earlier, the vapour pressures at Kelowna and Penticton Airports were very similar to each other but generally lower than those of the special lake-side stations.

FIGURE 21 PROFILES OF LAKE TEMPERATURE – APRIL TO JUNE OBTAINED BY BLANTON AND NG (1972)

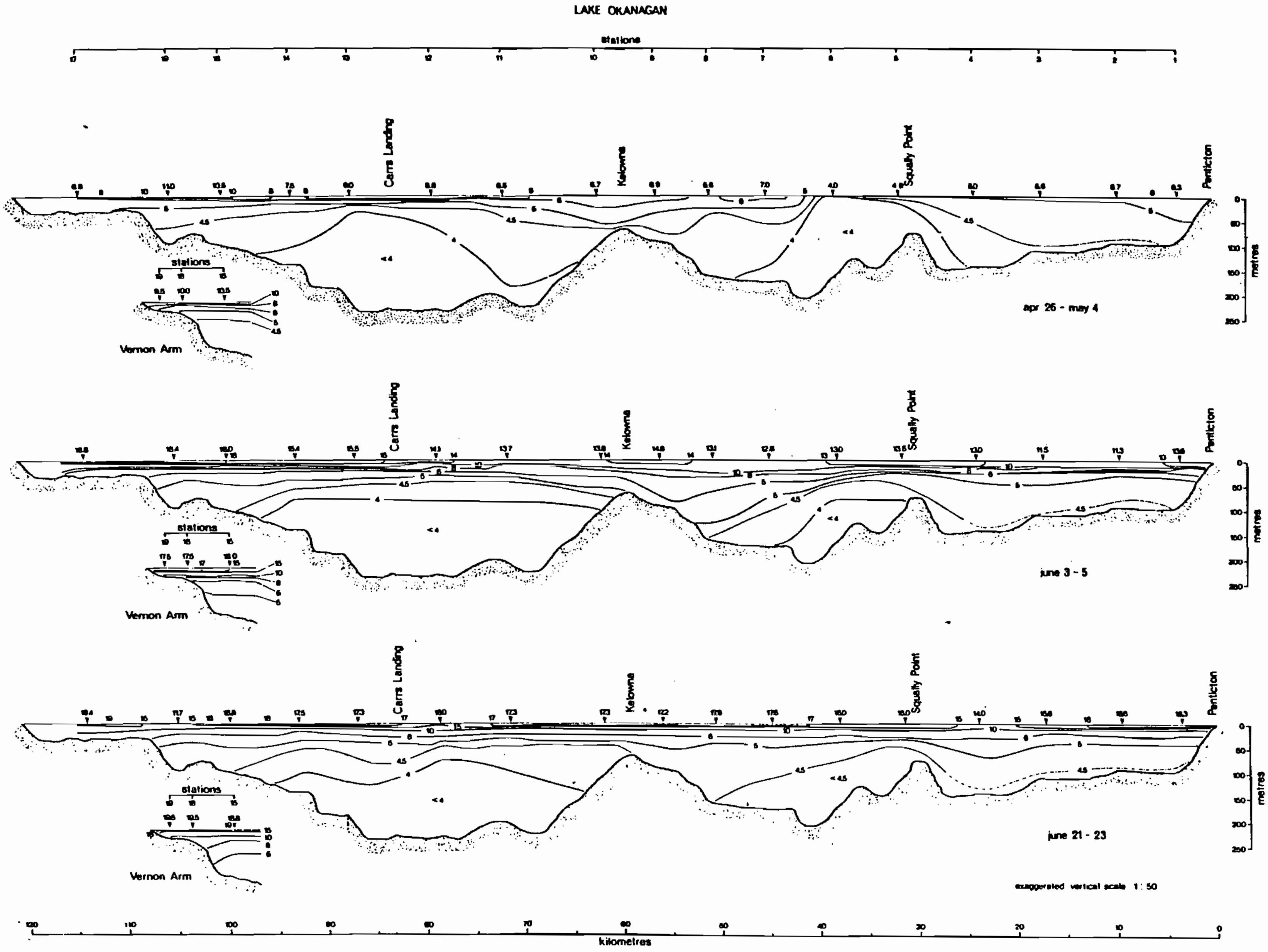
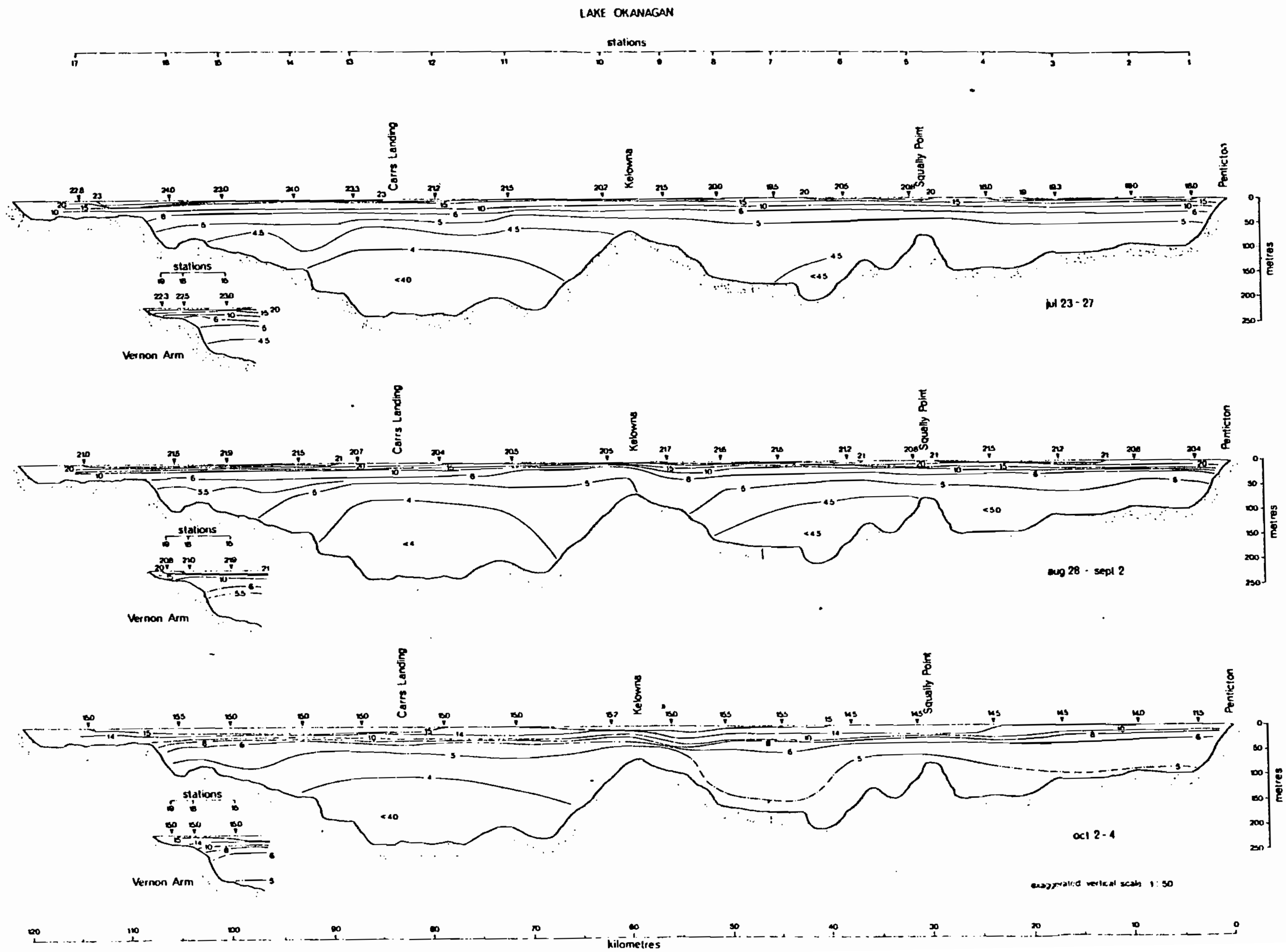


FIGURE 22 PROFILES OF LAKE TEMPERATURE – JULY TO OCTOBER OBTAINED BY BLANTON AND NG (1972)



a) Variability

Water surface temperature, which determines the surface vapour pressure, can vary 6-8°C across the lake in the spring; however, the September and November thermal imagery indicate that 2-4°C might be more typical of the summer and fall seasons. In the spring the diurnal change in the surface water temperature may be as much as 5-6°C whereas in the summer and autumn it is typically 1°C or less. Calculated evaporation rates are given in Table 10 for three vapour pressures typical of spring, summer and autumn for a corresponding range of water temperatures. The evaporation rate is calculated with a mass transfer coefficient of 0.024 and a wind speed of 10 km hr^{-1}. As expected, cool dry spring weather enhances the evaporation rates whereas warm moist conditions may lead to condensation (negative evaporation in Table 10). Warm sunny weather which leads to a large loss of water from the Class A evaporation pan does not necessarily result in correspondingly large evaporation rates from lakes, shallow or deep.

TABLE 10

The influence of surface water temperature (T_s) on the calculated evaporation rate is given for three ambient humdities.

T_s °C	e_a = 8 mb E mm day^{-1}	e_a = 10 mb E mm day^{-1}	e_a = 12 mb E mm day^{-1}
6	0.32	-0.15	-0.63
8	0.66	0.17	-0.31
10	1.02	0.54	0.06
12	1.44	0.97	0.49
14	1.92	1.43	0.95
16	2.46	1.96	1.48
18	3.03	2.55	2.08
20	3.70	3.23	2.75
22	4.44	3.96	3.48

Of the three input parameters, the wind speed is the most variable from place to place, has the largest range of values and, consequently, has an important influence on the calculated evaporation rate. It is not uncommon for there to be a 5-10 km/hr difference in wind speed from one point to another. One particular feature of Lake Okanagan is the strong winds at the centre of the lake blowing either up or down the valley. It is not unusual for there to be stronger winds in one segment of the lake when it is relatively calm in the other segments of the lake. Even if the humidities and surface temperatures were the same this would have a significant effect on the calculated evaporation rate. For example, evaporation rates are calculated for the two days in which thermal imagery is available for water temperatures (Table 11). Using the average lake temperature (T_{sa}), the mean of the appropriate segment of the lake (T_{ss}) and measured value (T_{sm}). Lake evaporation (E_L) computed from evaporation pan data are also given for comparison. The ratio of maximum to minimum calculated evaporation rates is 8:1 for both days. On April 26, the vapour pressure gradient at Penticton Airport, calculated using the areally weighted average surface temperature and airport humidity, was twice that calculated for Winfield and the wind speed at Penticton Airport was four times that at Winfield. For September, the difference in evaporation rates between Winfield and Penticton Airport is due almost entirely to the wind speed which was seven times stronger at the airport. Because of the sheltered location of the Winfield station, a more appropriate comparison would be between Kelowna Bridge and Penticton Airport or Marina. The corresponding evaporation ratios are reduced from 8:1 to approximately 2:1 in April and 1:1 in September for Penticton Airport and Kelowna Bridge.

TABLE 11

Evaporation (mm day^{-1}) calculated at each climate station with M=0.0240

	26 April 1980				9 Sept. 1980			
	E_L	$E_{T_{sa}}$	$E_{T_{ss}}$	$E_{T_{sm}}$	E_L	$E_{T_{sa}}$	$E_{T_{ss}}$	$E_{T_{sm}}$
Winfield		0.1	0.3	0.1		0.4	0.3	0.5
Kelowna A.P.	3.9	0.4	0.3		3.1	0.8	0.7	
Kelowna Bridge[1]		0.5	0.5			2.6	2.3	
Deeper Creek						0.8	0.7	0.9
Summerland[2]						0.8	0.7	
Penticton Marina						1.4	1.4	1.4
Penticton A.P.	4.3	1.0	0.8		2.8	2.7	2.5	

[1] Temperature and humidity from Kelowna Airport were used to calculate evaporation

[2] Wind speed from Penticton Marina was used to calculate evaporation

The total estimated evaporation loss from Lake Okanagan calculated using airport humidity and wind speeds with recorded water temperature from the nearest lake-side climate station is given in Table 12. The 12 month period is from 5 May 1980 to 4 May 1981. During the winter months Deeper Creek water temperature were substituted for Penticton Marina. The climatological data were averaged for a 7 day period and the evaporation rates were calculated from the 7 day averages. The estimates of lake evaporation from the Class A pan were calculated using the procedure outlined in Appendix A. This is the method used by the Atmospheric Environment Service to estimate lake evaporation from evaporation pan data.

TABLE 12

Evaporation (mm) using airport data with measured water temperatures

		E_L	E_M M=0.0240	E_M M=0.0269 (Lake Hefner)	E_M M=0.0332 (WMO, 1966)
Kelowna	5 May 80 29 Sept. 80	536	169	187	226
	30 Sept. 80 4 May 81	80	76	84	102
	Total	616	245	271	328
Penticton	5 May 80 27 Oct. 80	695	373	415	532
	28 Oct. 80 4 May 81	103	128	141	191
	Total	798	501	556	673

Of the two airports, the wind speed at Penticton is considered to be the better substitute for over-the-lake measurements because of its location in the main valley bottom. The Penticton Airport winds compare quite well with the Kelowna Bridge winds when the latter are reduced by 15% to account for the difference in height between the two sensors (see Figure 23). Nevertheless, the estimated evaporation loss by the mass transfer method for Penticton is only 61% of that estimated from pan data for the 12 month period using the mass transfer coefficient obtained in this study. Approximately 26% of the total evaporation (E_M) occurred during the "winter" months when the evaporation pans were not in service; therefore, the corresponding estimated "summer" evaporation loss by the mass transfer method with is only 49% of E_L.

b) Comparison with Other Deep Lakes

For most lakes in Canada the ice-free season is from May to November and for some it extends into December. With the exception of the Great Lakes, very few lakes have extensive open water sections throughout the winter season. Discussions with local residents indicate that ice formation in Lake Okanagan is usually limited to sheltered bay areas and in mild winters may not occur at all for any significant length of time. May to October estimates of evaporation from Lake Ontario vary from 252 mm to 275 mm (see Table 2) if the technique by Bussinger et al is not used. In a study of another lake similar to Okanagan, Spring and Schaefer (1973) estimated the May to October evaporation rate from Babine Lake to be 305 mm which is close to the 373 mm evaporation loss from Lake Okanagan estimated using Penticton Airport data.

FIGURE 23 KELOWNA BRIDGE–PENTICTON MARINA
7 DAY RUNNING MEANS – WIND SPEED

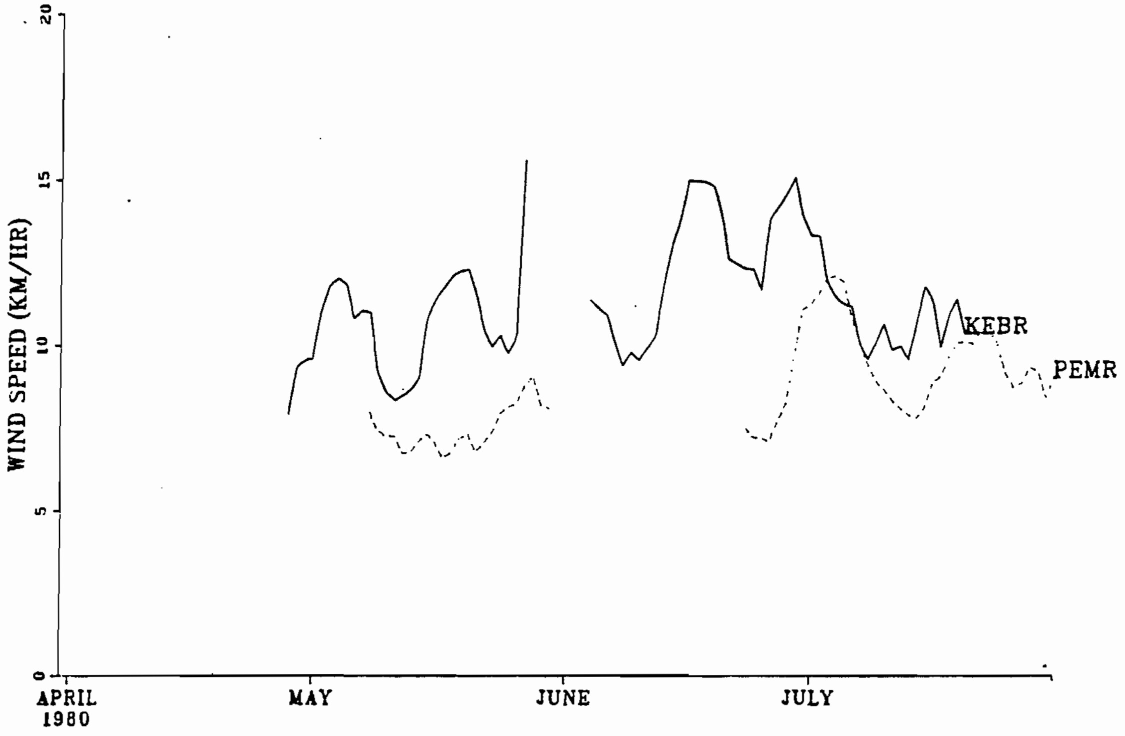
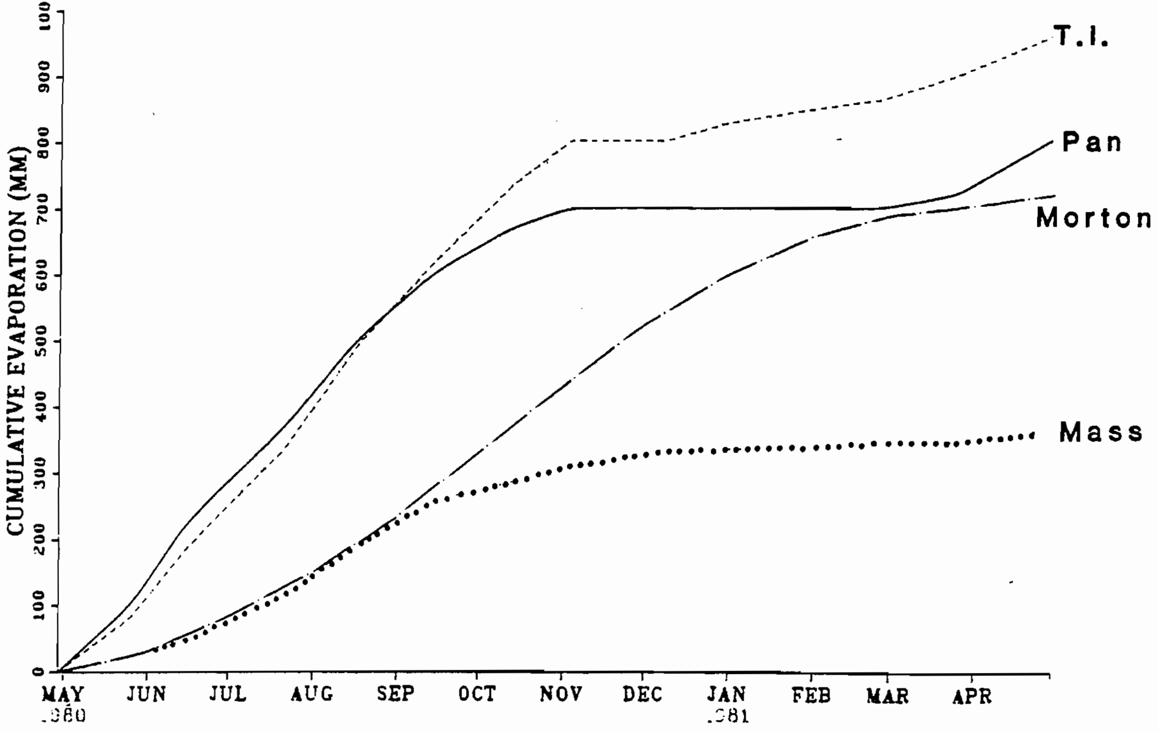


FIGURE 24 EVAPORATION FROM OKANAGAN LAKE
CLASS A PAN – TEMPERATURE INDEX – MASS TRANSFER – MORTON



While the magnitude of the water loss from Lakes Ontario, Babine and Okanagan are similar, there are some important differences in the annual distribution of evaporation. The May to October evaporation from Lake Ontario is approximately 38% of the annual water loss (Phillips, 1978). The corresponding losses for Babine and Okanagan are 74% and 75% of their respective annual rates. Since Babine Lake freezes over during the winter, the annual water loss of 379 mm for 1973 is less than the estimate of 501 mm for Lake Okanagan. Some care and interpretation is required when making comparisons between these three lakes when the data are from different years. However, condensation does appear to be much more significant in the evaporation regime of Lake Ontario than either Okanagan or Babine. The significant portion (62%) of the annual water loss for Lake Ontario occurs during the period November to April, whereas, it is only 26% and 25% for Lakes Babine and Okanagan respectively.

Earlier studies of evaporation from Okanagan Lake completed under the Okanagan Basin Agreement in 1974 estimated that the annual water loss from the lake was in the range of 730-1090 mm. This is consistent with the Class A pan estimates of lake evaporation published by Atmospheric Environment Service or the temperature correlation (with lake evaporation) method currently used by the B.C. Ministry of Environment (see Figure 24). Using Penticton Airport data these two methods are in good agreement with each other until September when the temperature correlation method overestimates due to the warm September temperatures. Whereas the Class A pan was removed at the end of October and reinstalled at the beginning of April, the temperature correlation method was continued throughout the winter months. During the May to October period and including the following April the temperature based method over estimated the pan derived lake evaporation by only 9% as compared to 21% for the annual period. Both the pan and the temperature methods over-estimate the annual estimate of the water loss by the mass transfer technique by 218% and 264% respectively.

An alternative approach to calculating annual water loss from deep lakes has been developed by Morton (personal communication). It is based on some earlier work by Morton (1980) and requires monthly means of air temperature, dew point temperature, and sunshine. Lake evaporation is calculated monthly by an iterative technique and summed for the annual total. This approach using Penticton Airport data over-estimates the mass transfer estimates at Penticton Marina by only 15% for the period April to September. The annual estimates, however, are much closer to those derived from Class A pan data. The good agreement between Morton's approach and the mass transfer technique during the spring, summer and early autumn months would suggest that this technique be further investigated.

SUMMARY

1) The mass transfer coefficient found in this study for Okanagan Lake (M = 0.0240) is essentially identifical to that found in other studies of deep water bodies in which the eddy correlation technique was used to measure actual evaporation rates (Anderson and Smith, 1981). It is also in good agreement with mass trasnfer coefficients found in the Great Lakes evaporation studies (see Table 3). The mass transfer coefficients for deep lakes are considerably smaller than those reported in the literature which include coefficients for shallow lakes and those derived by less direct means (see Table 1).

m = 0.024

2) As expected the air over the lake is cooler, more humid and the winds are stronger than over the land. Because of its location in a small side valley separated from the lake by a high ridge, Kelowna Airport climate data should not be used for estimating climatic conditions over the lake. Penticton Airport which is located in the main valley at the south end of the lake would appear to be more suitable for estimating humidities and wind speeds over the lake. The largest differences betweeen the lake-shore and the airport stations occurred in the spring of 1981 when the water in the lake north of Penticton Marina warmed very slowly. Temperatures were as much as 5-6 degrees C cooler at the Marina throughout May and the early part of June but a 1-2 degree C difference is more typical of the remainder of the summer. Humidity differences of 3-5 mb are not uncommon in the summer months but this reduces to 1 mb or less in the winter. Wind speeds measured at Penticton Airport are considered to be a good estimate of the winds over the lake when compared to the winds from Penticton Marina and Kelowna Bridge. Because of their more sheltered locations, Deeper Creek and Winfield sites are not suitable for routine measurements of wind speed.

Kelowna A X
Penticton A ✓
wind
humidity

3) In the spring the surface temperature of the lake can vary 8-10°C across the lake or from one end to the other. This was quite evident in the thermal imagery obtained on April 28, 1980. However, 2-4°C would seem to be more typical for the remainder of the summer as the heat absorbed by the lake is mixed to greater depths. Although no thermal imagery was obtained during the winter months and only one lake-side station continued to measure water temperatures, the temperature range in winter should be 1-3°C. In contrast to the air temperature over the land, the lake surface temperatures were warmer in the northern part of the lake than in the segment from Peachland to Penticton. Okanagan Lake is too narrow to be monitored via satellite and thermal surveys by aircraft are too costly. The lake is too long for surveys by boat to be practical. Relatively inexpensive hand-held infrared thermometers could be used to scan those parts of the lake accessible by road or at least viewable from the road. Permanent floating recording thermometers at several selected sites could then be used to obtain a continuous record of lake temperatures between survey periods.

4) Assuming a uniform wind field the evaporation rate can vary from 6:1 in the spring to 3:1 in the summer and early autumn due to the spatial variation in the surface water temperature. With every 1°C increase in water

temperature the evaporation rate increases by 0.26 mm for humidities in the range of 8-12 mb and a wind speed of 10 km/hr. Doubling the wind speed, of course, doubles the increase in evaporation rate (see Table 10). The areally weighted average surface temperature for the April 26 flight varied from 9.9°C for the south segment to 12.2°C for the north segment (see Table 7) with a mean lake temperature of 11.0°C. This gives rise to a ±20% variation in evaporation rate from that calculated using mean lake temperature. The corresponding variation for the September 9 flight is only ±12%. In practical terms, then, the large variation in lake temperature, as seen in the thermal imagery, do not translate into correspondingly large variations in evaporation rate when the data are areally weighted. Wind induced variations in the evaporation rate are equally important. Taking the difference in height into account the wind speed measured at Kelowna Bridge agree very well with respect to magnitude with those measured at Penticton Marina when averaged over a seven day period but as Figure 23 indicates the strongest winds at each site do not necessarily occur at the same time. There are differences in the wind fields in each segment of the lake. The degree of confidence in the calculated evaporation rates increases with the number of "evaporation" stations used. The required degree of confidence is related to the intended use of the evaporation rates.

RECOMMENDATIONS

To some degree these recommendations are tempered by the perceived use of the evaporation data and are arranged generally in decreasing order of preference.

1) The Class A pan or any of its derivative methods should not be used to estimate water losses from Okanagan Lake for any purpose.

2) Evaporation calculated using the mass transfer approach requires water temperatures which must be measured rather than estimated.

3) Kelowna Airport data, in particular, the wind speed, should not be used for any evaporation calculations for Okanagan Lake.

4) One or more special purpose climate stations should be installed. Ideally these would be floating buoy systems monitoring air temperature, humidity, wind speed and direction and water temperature with the data radioed back to a central receiving station. This procedure would give real-time access to the data which could serve other purposes such as recreational boating forecasts as well as monitoring evaporation rates. It would also allow the data to be collected in the most suitable locations out in the lake. Since the expense of this ideal system is probably not warranted, an acceptable alternative would be to install a climate station on Kelowna Bridge to monitor the same parameters and supplement this with similar climate stations installed at a number of marinas around the lake such as the Penticton Marina, Peachland Yacht Club and the Marina at Vernon. Such shore-based climate stations are rather inexpensive compared to the buoy systems and could also provide real-time information via telephone lines to the local weather offices and/or the B.C. Ministry of Environment in Victoria.

5) A less acceptable alternative to installing special climate stations would be to use the temperature, humidity and wind data from Penticton Airport supplemented by "bucket" temperature measurements of water temperature made at Penticton Marina for evaporation calculations at the south end of the lake. Kelowna Airport temperature and humidity could be used with the wind speed from Kelowna Bridge with surface temperature obtained via a bucket from the bridge. Similarly Vernon Airport data could be supplemented with a "bucket" water temperature at the local marina. With the airport data averaged over seven days the water temperature could be obtained only once per week although daily would be preferrable.

Penticton A
Ta, RH, U
Penticton marina
Ts

6) If estimates of evaporation are only required on a monthly basis, the approach of Morton could be used if some modification were made to the winter-time calculation.

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APPENDIX A

CALCULATION OF LAKE EVAPORATION FROM CLASS A PAN DATA

Appendix A

Calculation of Lake Evaporation in S.I. Units from Class A Pan Data

$E_L = 0.7\ [E_p + 0.00642\ p\ \alpha_p\ (.37 + 0.0025\ U_p)\ T]$

where: E_L = computed daily pan loss (mm)

E_p = net daily pan loss (mm)

$E_p = W_a - W_r + R$
W_a = water added (mm)
W_r = water removed (mm)
R = rainfall for past 24 hr (mm)

P = station pressure (kilopascal)

$P = 101.325\ (1 - 0.00002257\ Z)^{5.25}$
Z = station elevation (m)

α_p = fraction of advected energy (Class A) used for evaporation

$\alpha_p = 0.35 + 0.01044\ T_W + 0.000559\ U_p$ if $0 \leq U_p < 161$
$\alpha_p = 0.35 + 0.01044\ T_W + 0.08 + 0.000249\ (U_p - 161)$ if $161 \leq U_p < 322$
$\alpha_p = 0.35 + 0.01044\ T_W + 0.12 + 0.000124\ (U_p - 322)$ if $322 \leq U_p < 483$
$\alpha_p = 0.35 + 0.01044\ T_W + 0.14 + 0.000062\ (U_p - 483)$ if $U_p \geq 483$

U_p = daily wind run across pan (km)

T = mean water and air temperature difference function

$T = (T_W - T_a)^{.88}$ if $T_W > T_a$
$T = [(T_a - T_W)^{.88}]$ if $T_W < T_a$
$T = 0$ if $T_W = T_a$

T_W = mean water temperature (°C)

T_a = mean air temperature (°C)

Reference:

Kohler, M.A., T.J. Nordenson, and W.E. Fox, "Evaporation from Pans and Lakes", Research Paper No. 38, U.S. Weather Bureau, 1955.

APPENDIX B

FREQUENCY DISTRIBUTION OF MEAN DAILY WIND SPEED AND DIRECTION FOR EACH STATION

FIGURE 1 DISTRIBUTION OF MEAN DAILY WINDS FOR WINFIELD

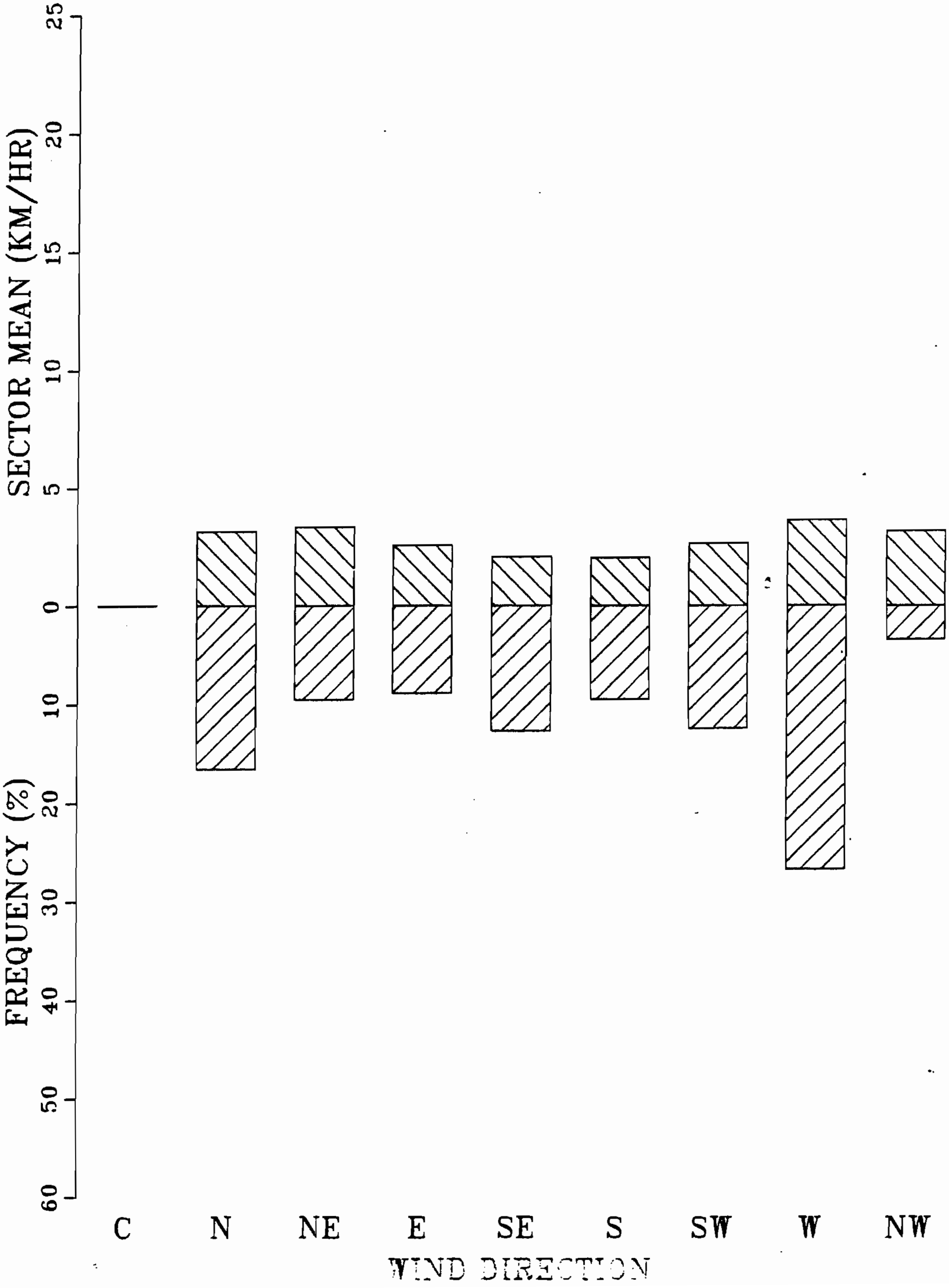


FIGURE 2 DISTRIBUTION OF MEAN DAILY WINDS FOR MCCULLOCH RESEVOIR

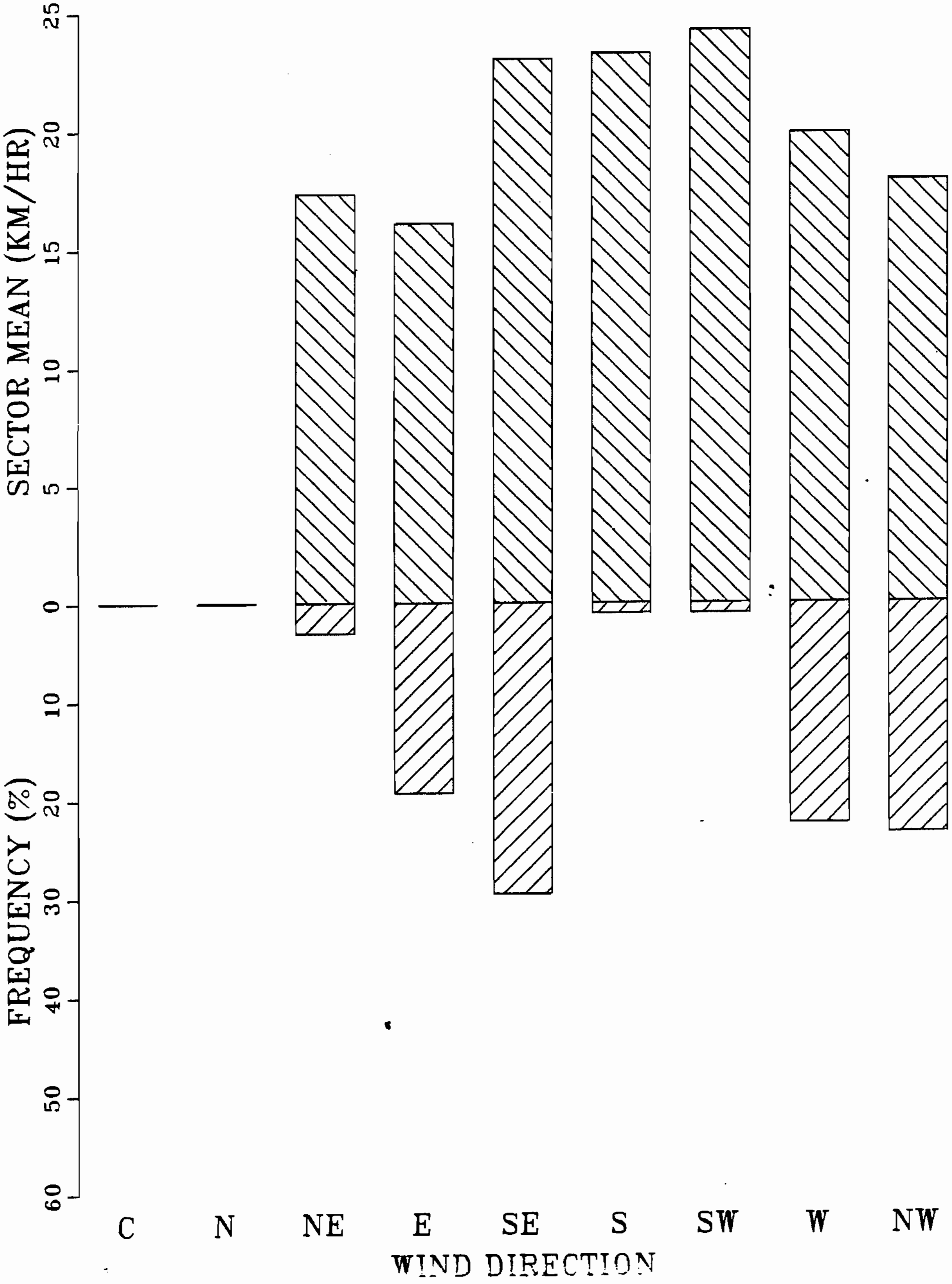


FIGURE 3 DISTRIBUTION OF MEAN DAILY WINDS FOR KELOWNA AIRPORT

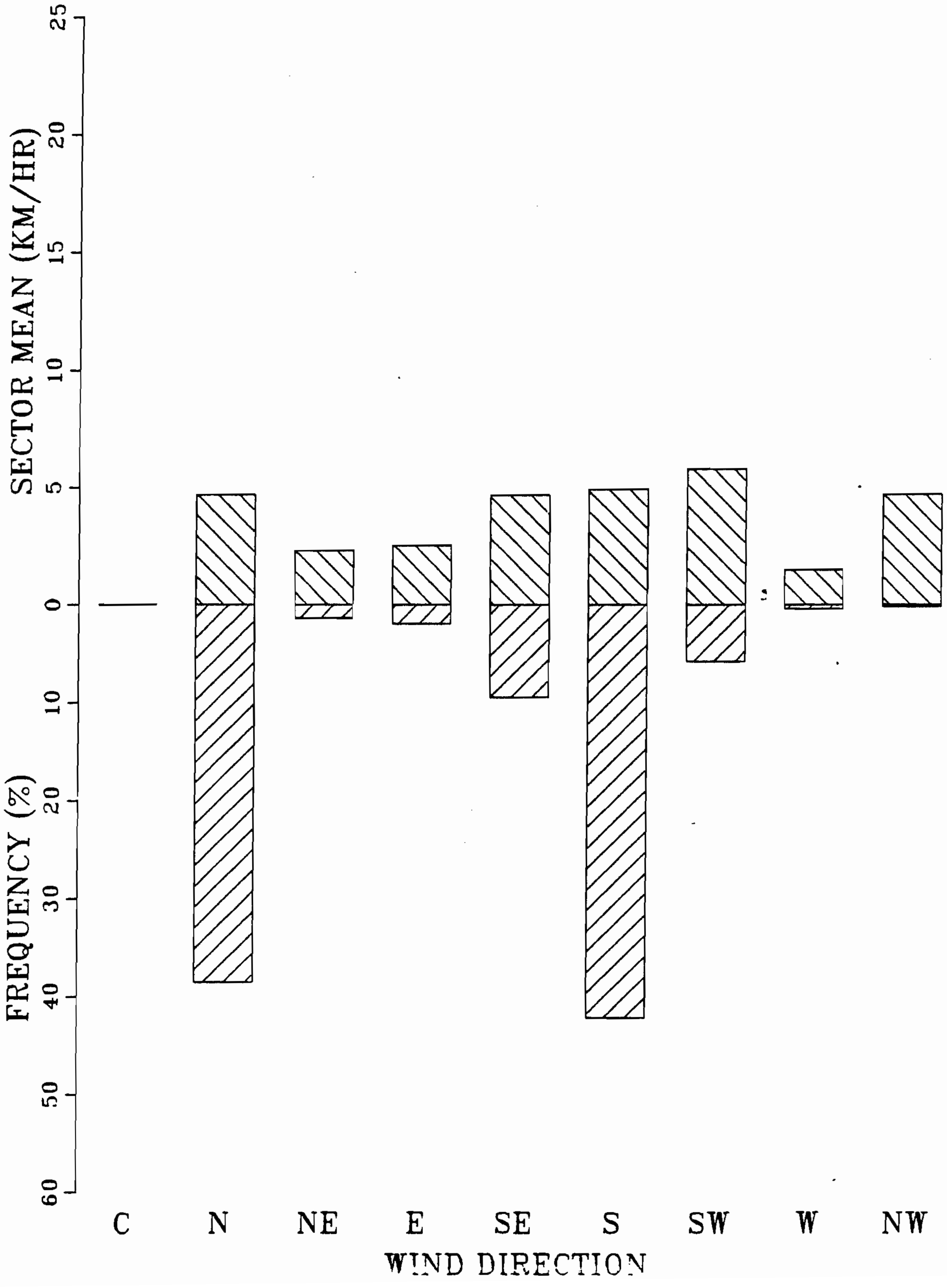


FIGURE 4 DISTRIBUTION OF MEAN DAILY WINDS FOR KELOWNA BRIDGE

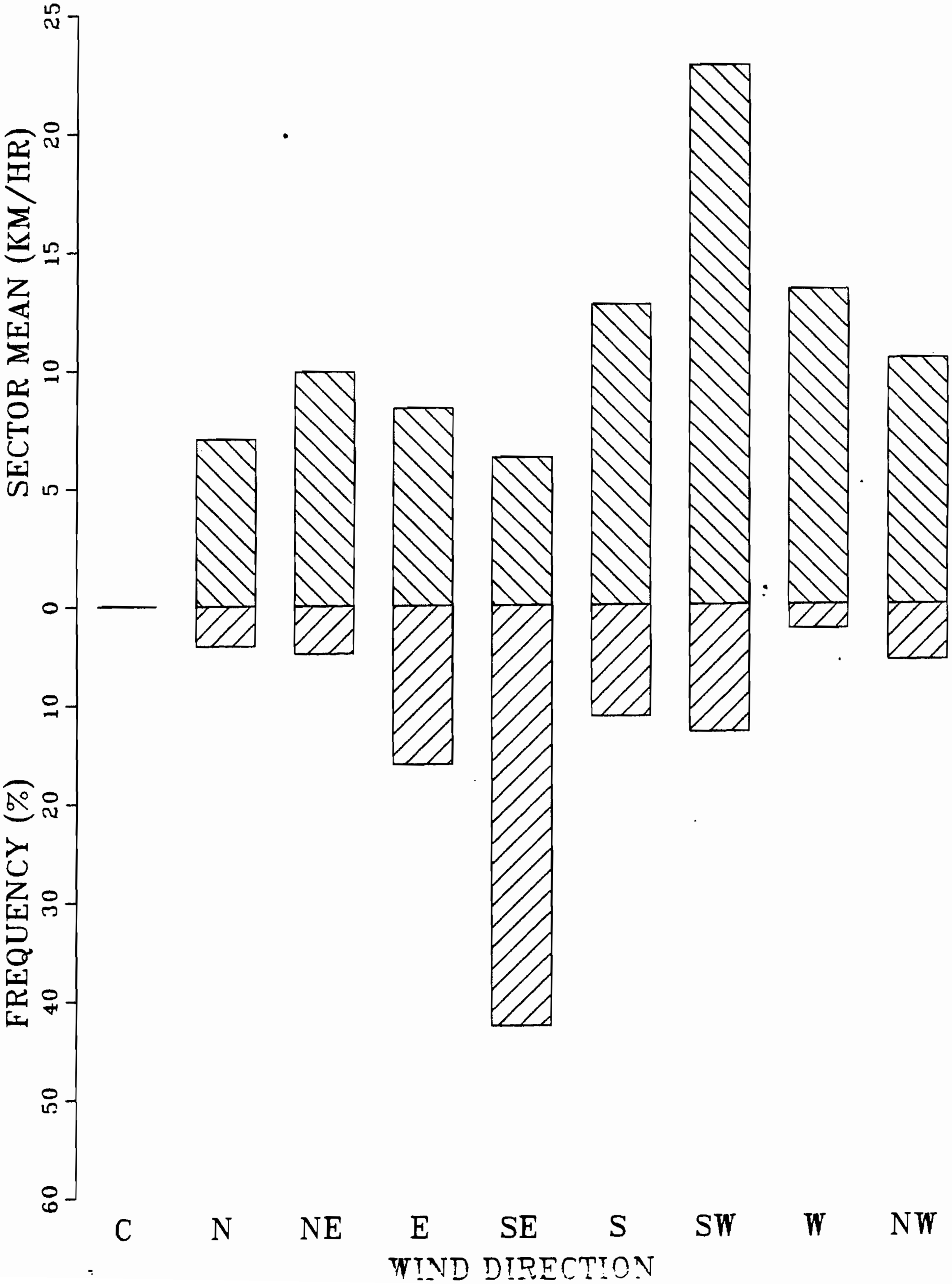


FIGURE 5 DISTRIBUTION OF MEAN DAILY WINDS FOR DEEPER CREEK

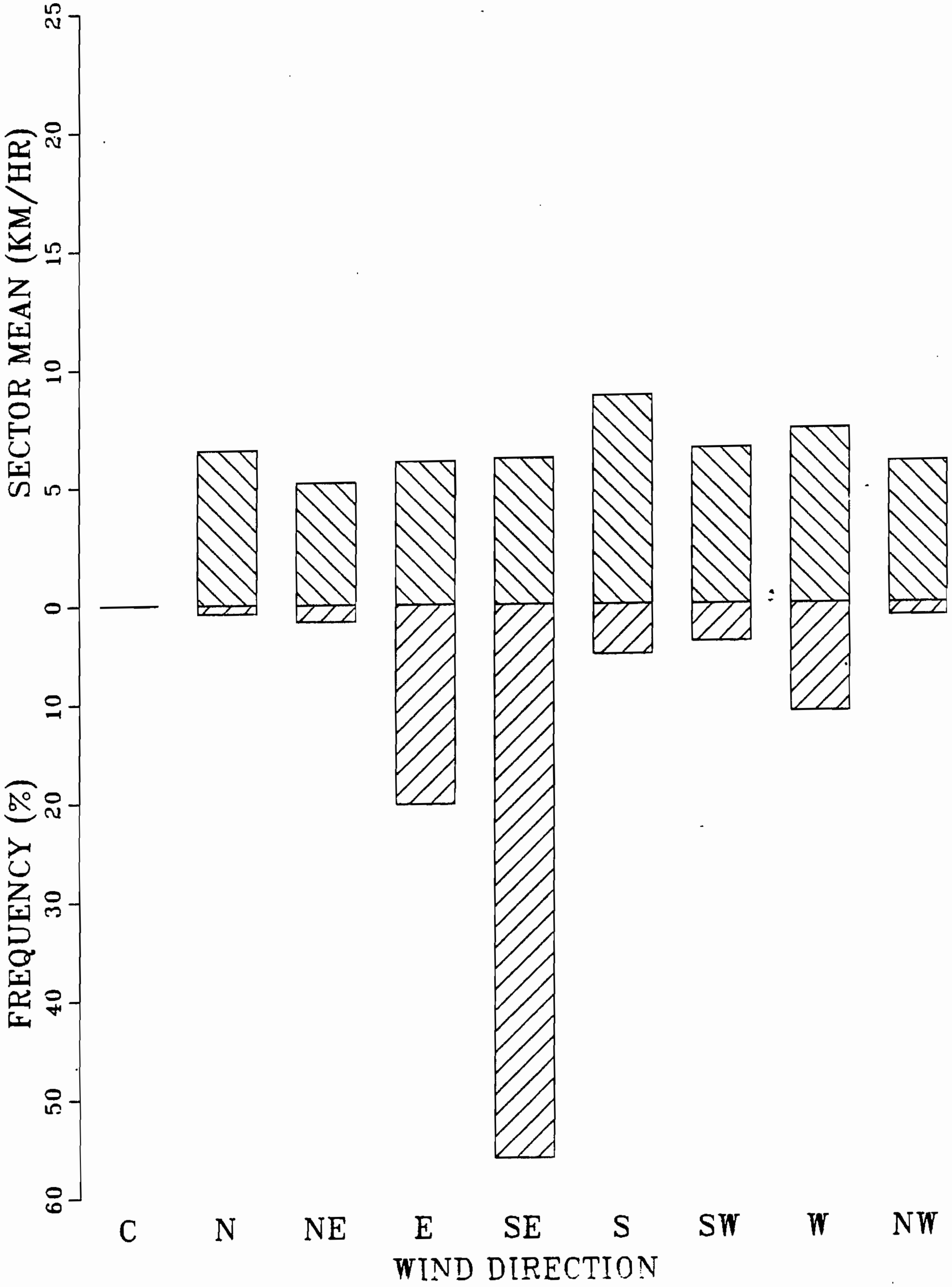


FIGURE 6 DISTRIBUTION OF MEAN DAILY WINDS FOR PEACHLAND YACHT CLUB

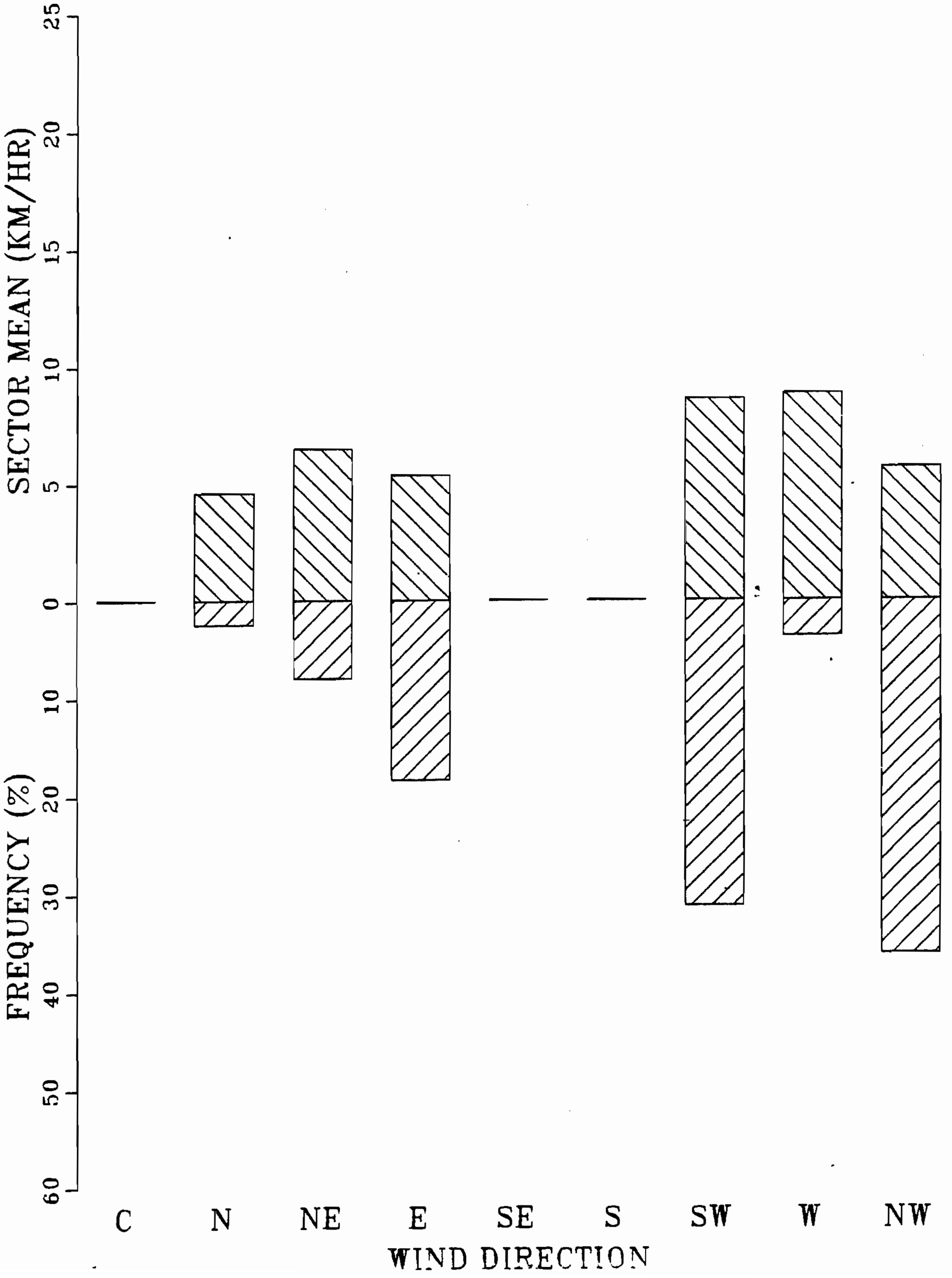


FIGURE 7 DISTRIBUTION OF MEAN DAILY WINDS FOR PENTICTON MARINA

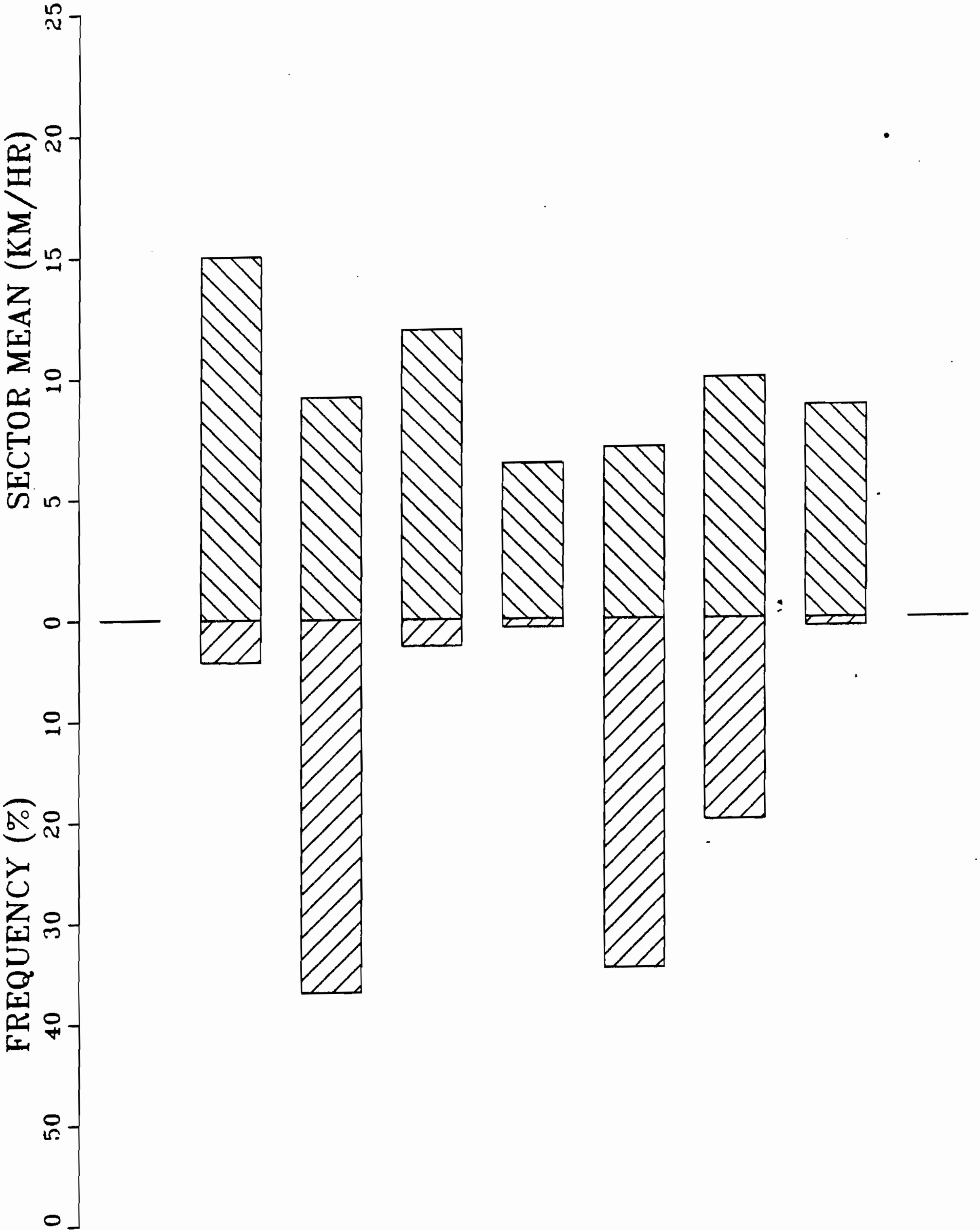
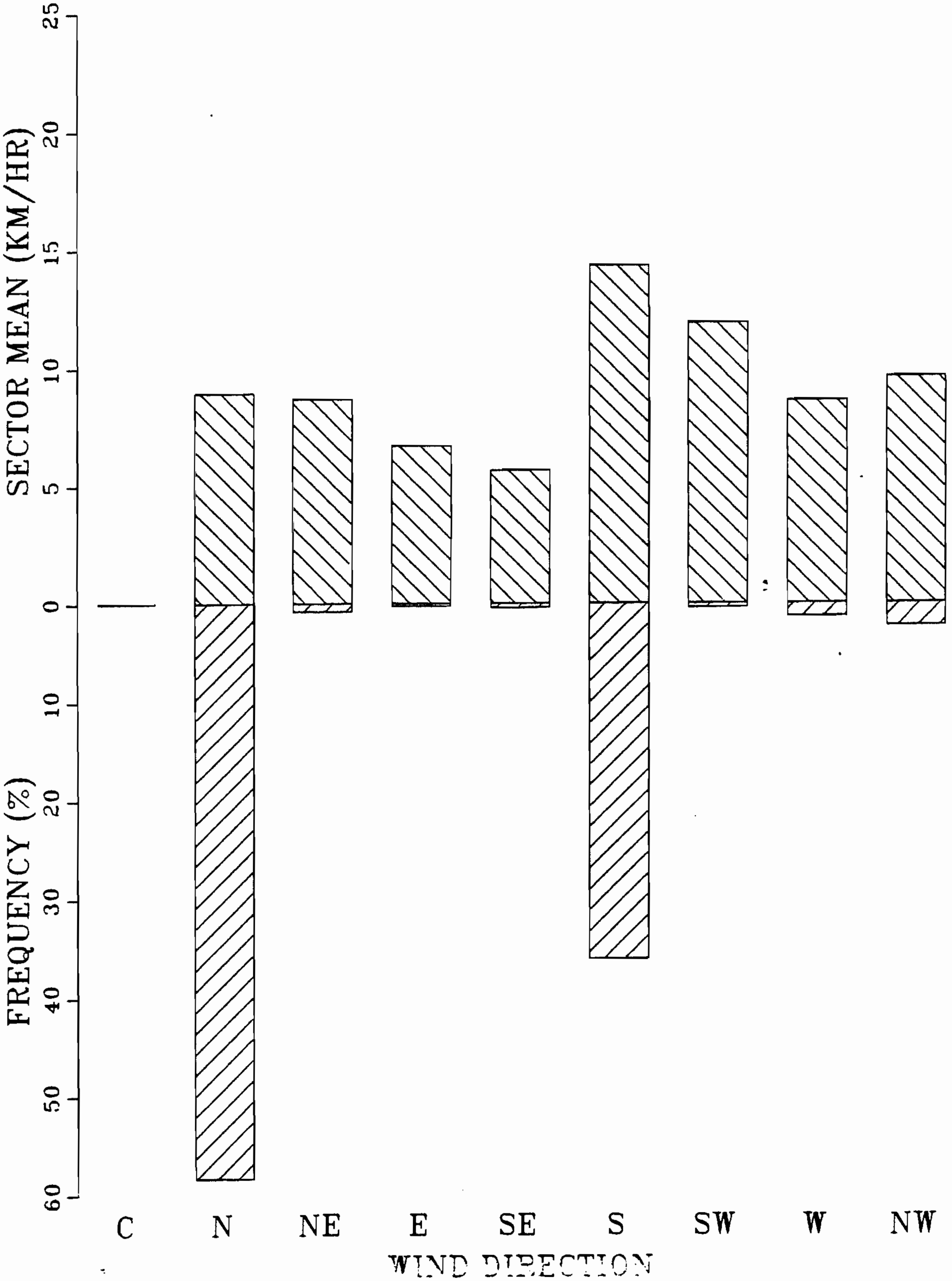


FIGURE 8 DISTRIBUTION OF MEAN DAILY WINDS
FOR PENTICTON AIRPORT



APPENDIX C

MEAN WIND SPEED AND FREQUENCY OF OCCURRENCE IN EACH OF EIGHT WIND DIRECTIONS BY STATION

FIGURE 1 DISTRIBUTION OF NORTH WINDS FOR OKANAGAN LAKE

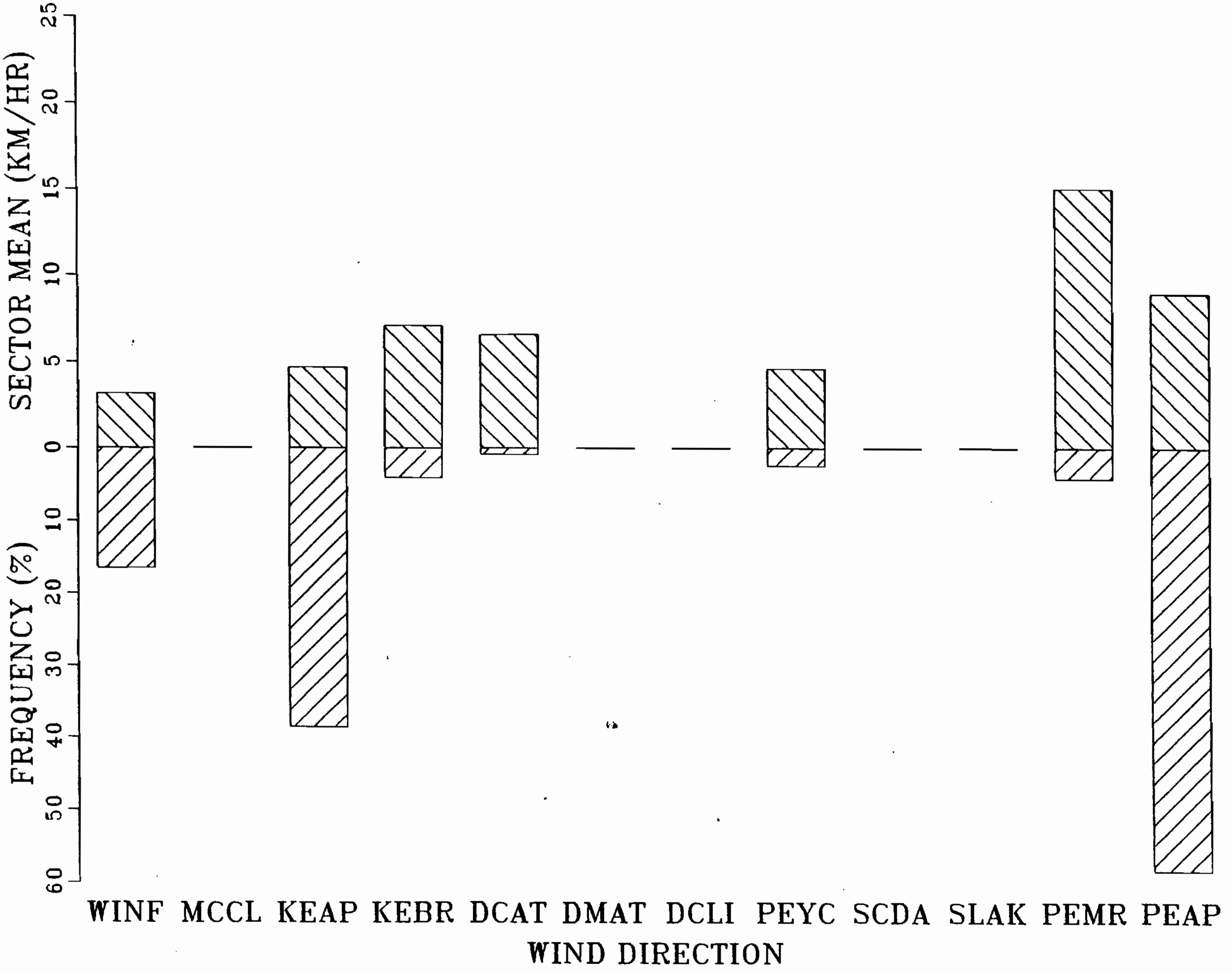


FIGURE 2 DISTRIBUTION OF NORTH-EAST WINDS
FOR OKANAGAN LAKE

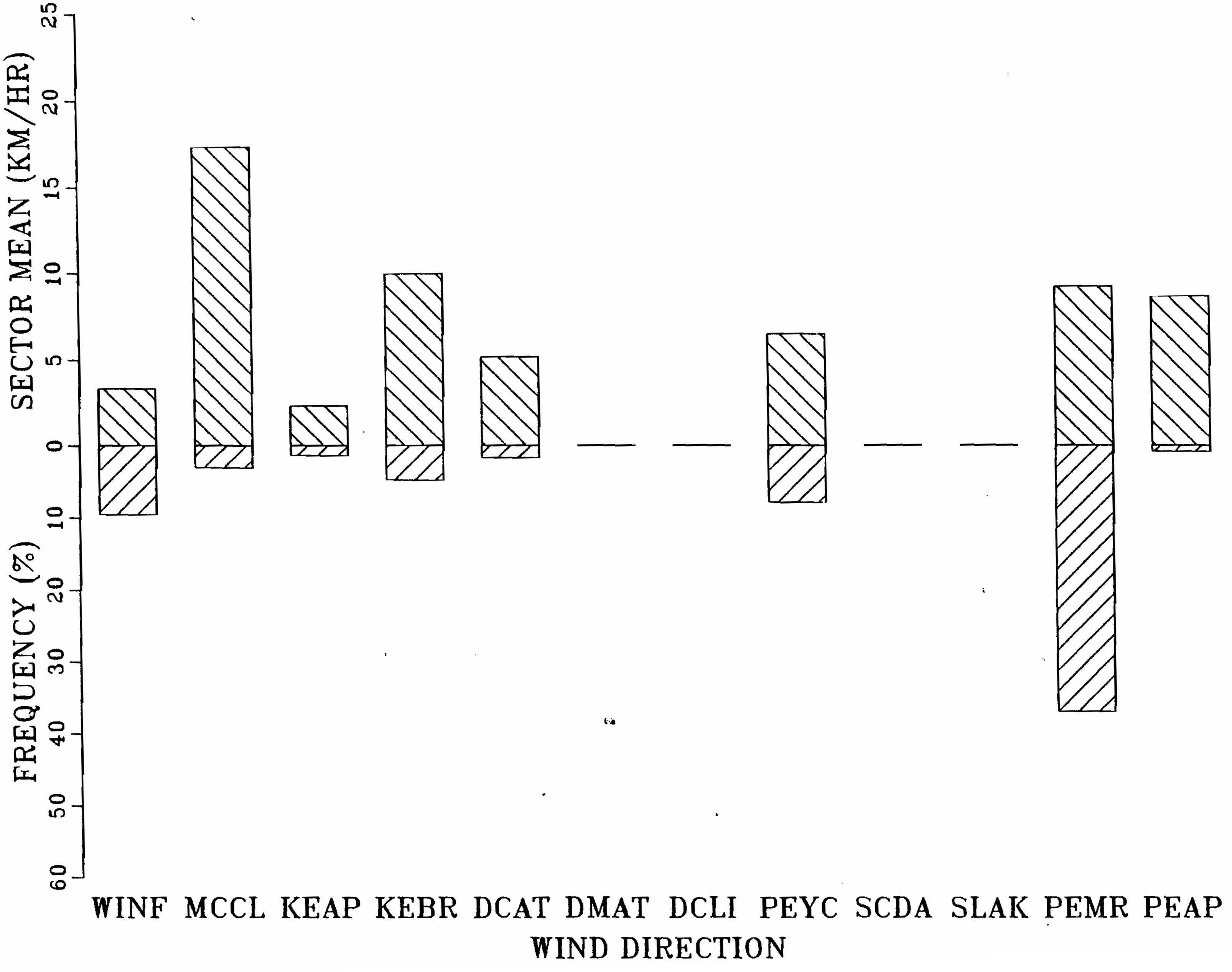


FIGURE 3 DISTRIBUTION OF EAST WINDS
FOR OKANAGAN LAKE

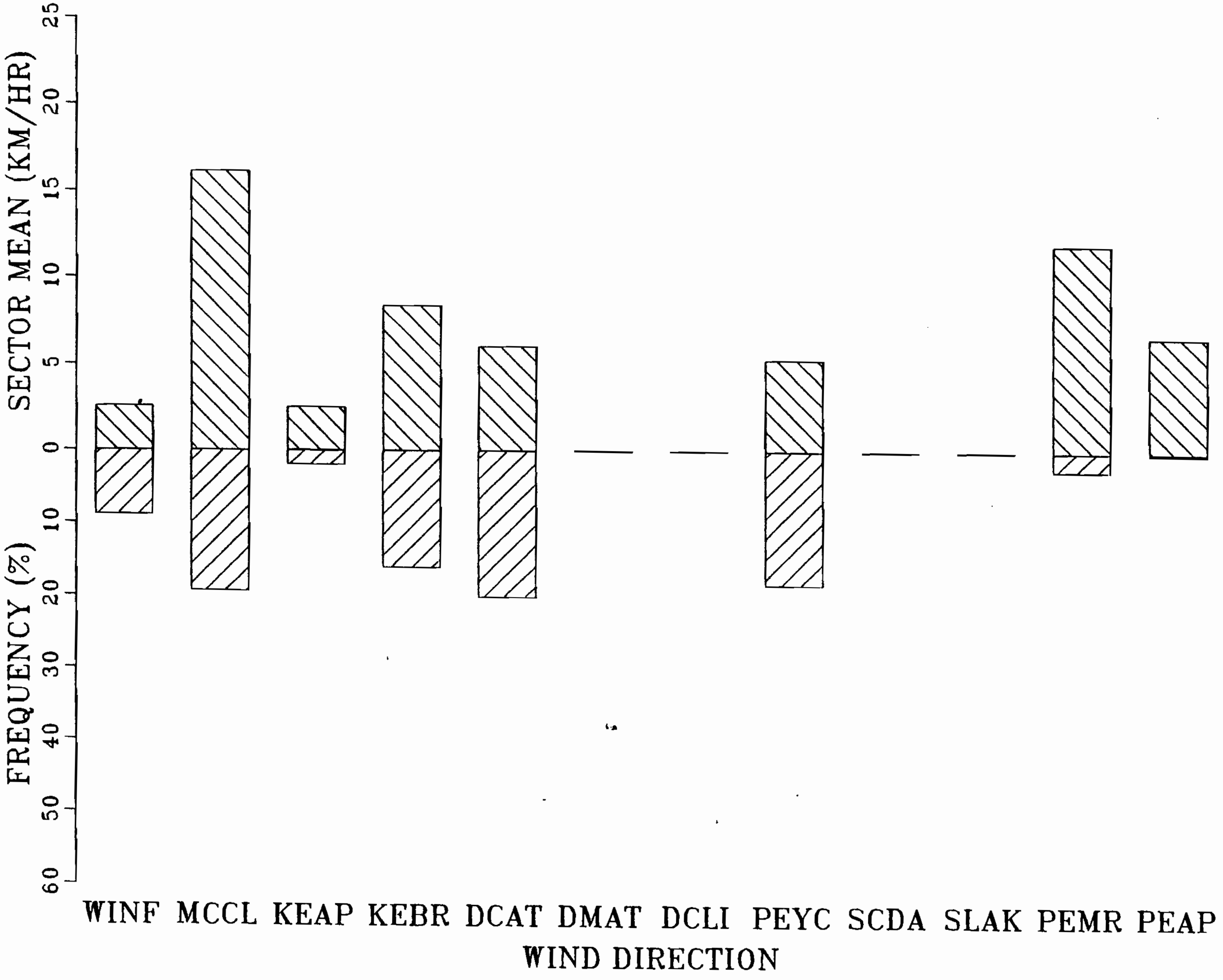


FIGURE 4 DISTRIBUTION OF SOUTH–EAST WINDS FOR OKANAGAN LAKE

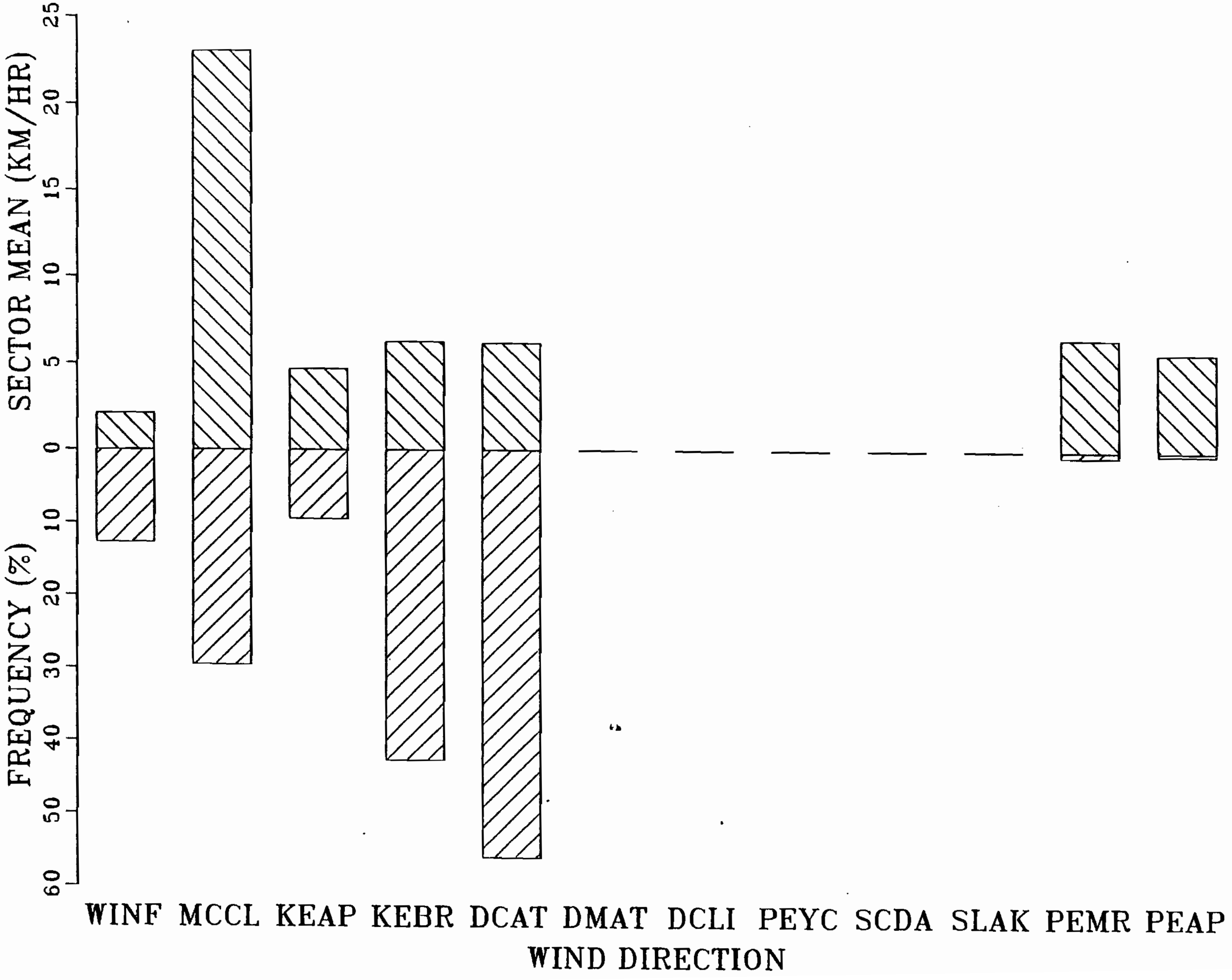


FIGURE 5 DISTRIBUTION OF SOUTH WINDS FOR OKANAGAN LAKE

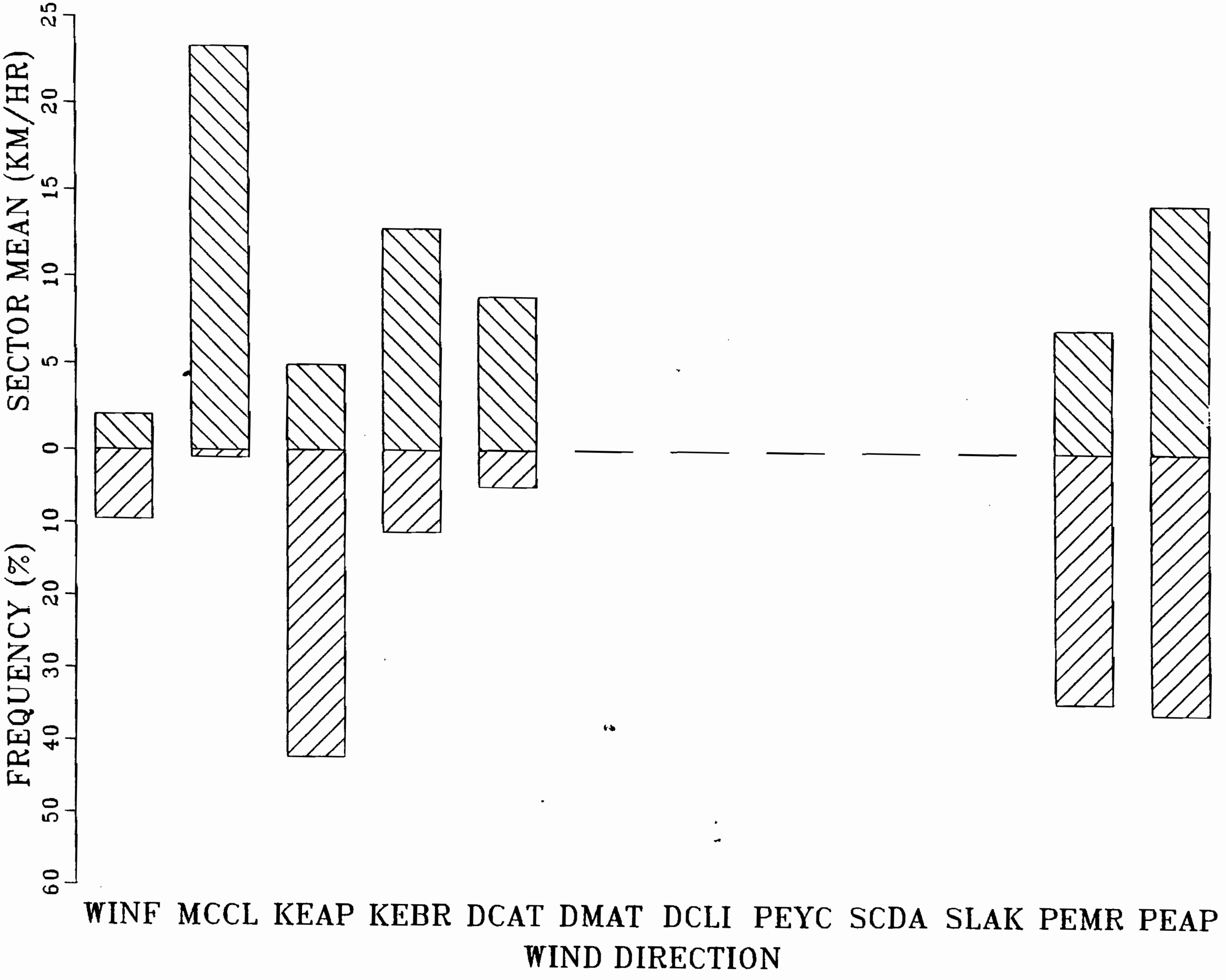


FIGURE 6 DISTRIBUTION OF SOUTH-WEST WINDS
FOR OKANAGAN LAKE

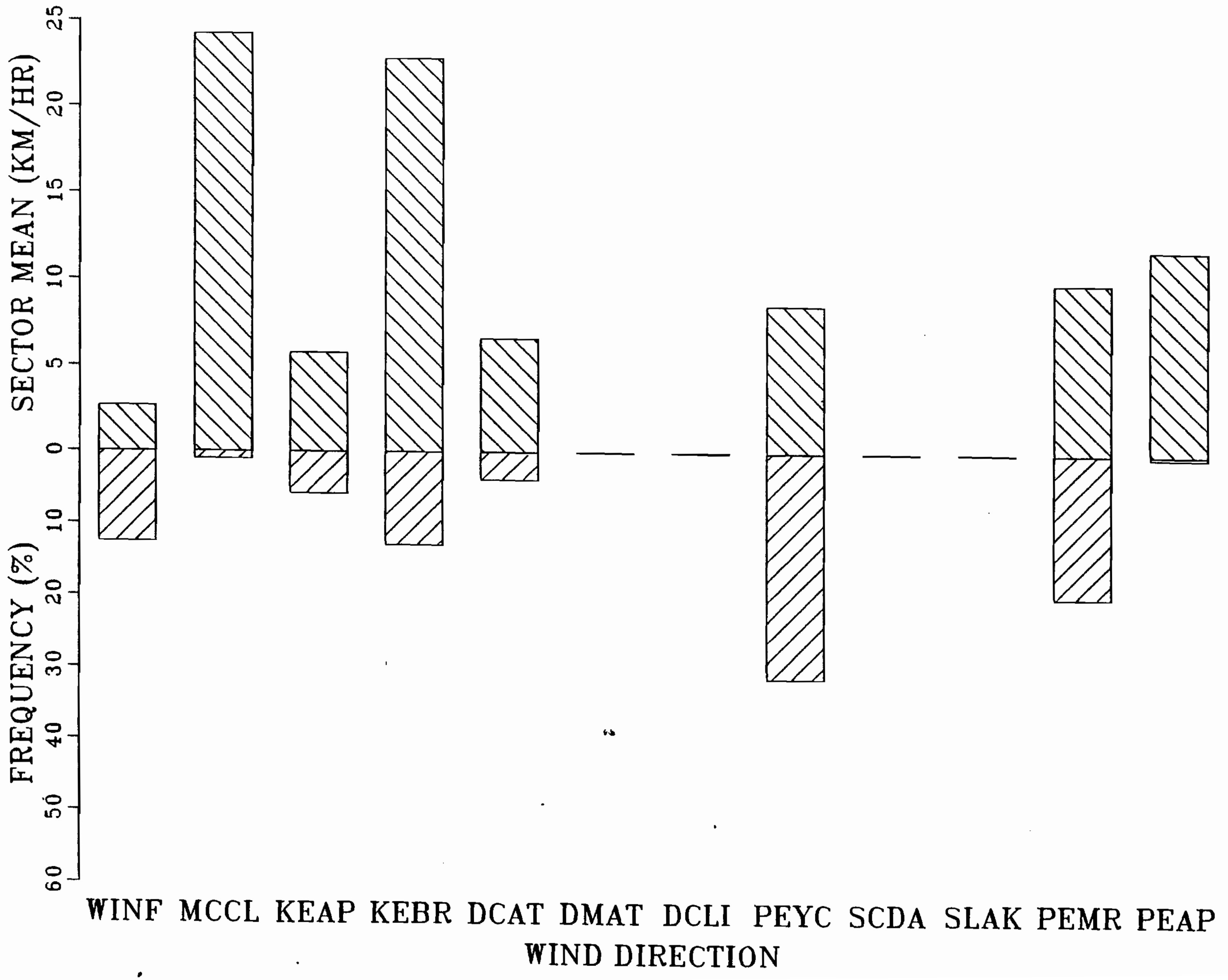


FIGURE 7 DISTRIBUTION OF WEST WINDS FOR OKANAGAN LAKE

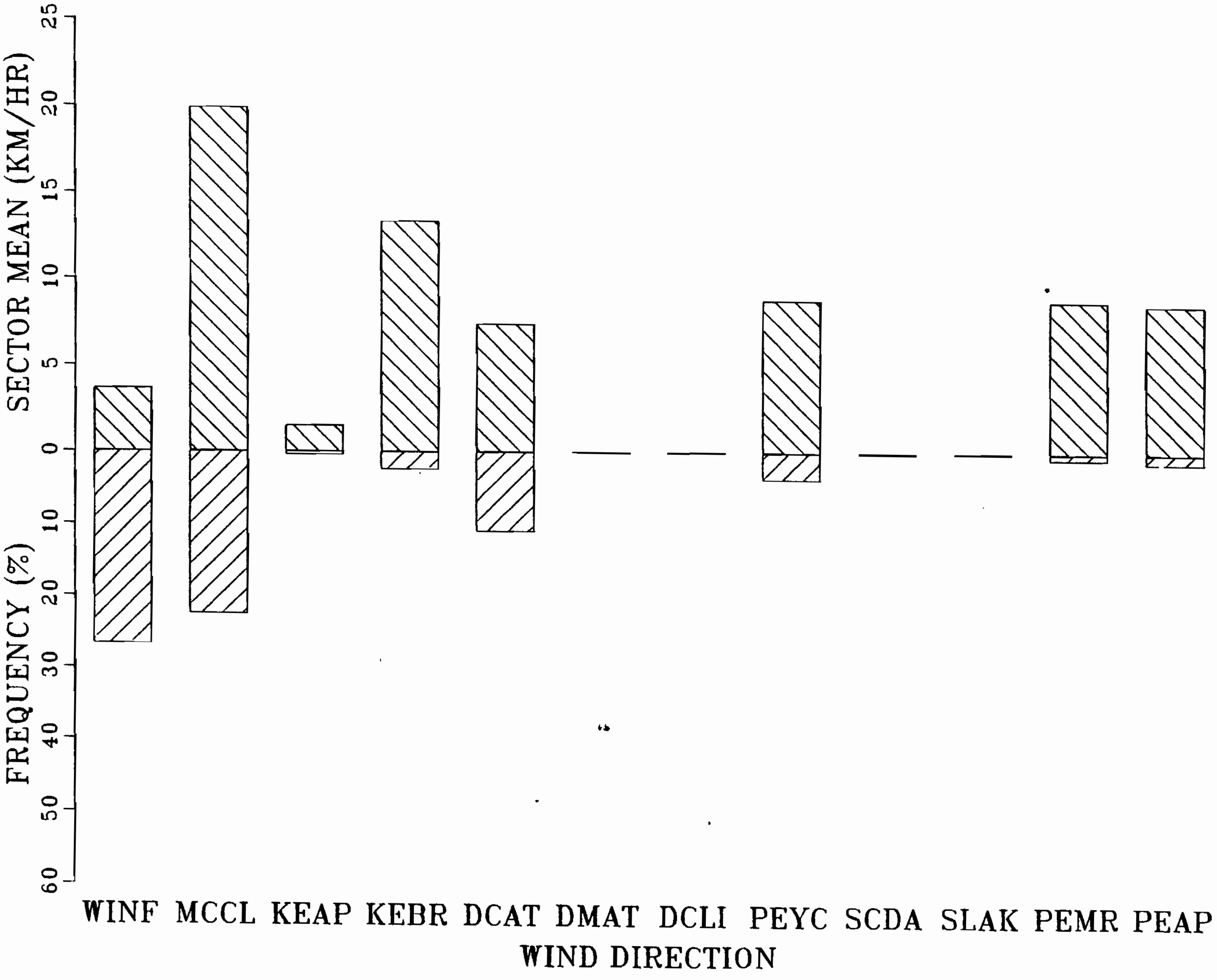
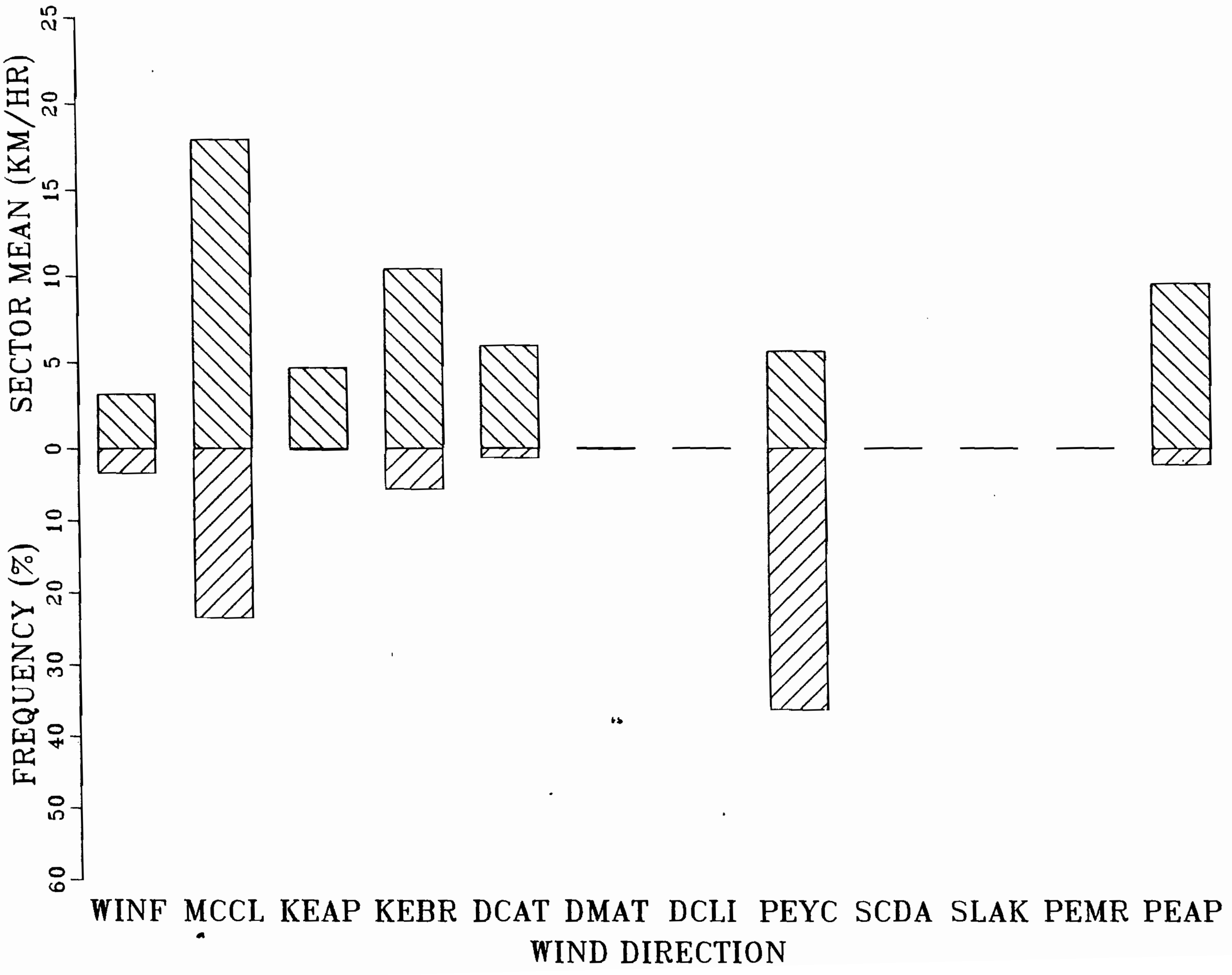


FIGURE 8 DISTRIBUTION OF NORTH-WEST WINDS FOR OKANAGAN LAKE



APPENDIX D

FREQUENCY DISTRIBUTION OF MEAN HOURLY WIND SPEED AND DIRECTION FOR EACH STATION

FIGURE 1

PREDOMINANT HOURLY WINDS FOR WINFIELD

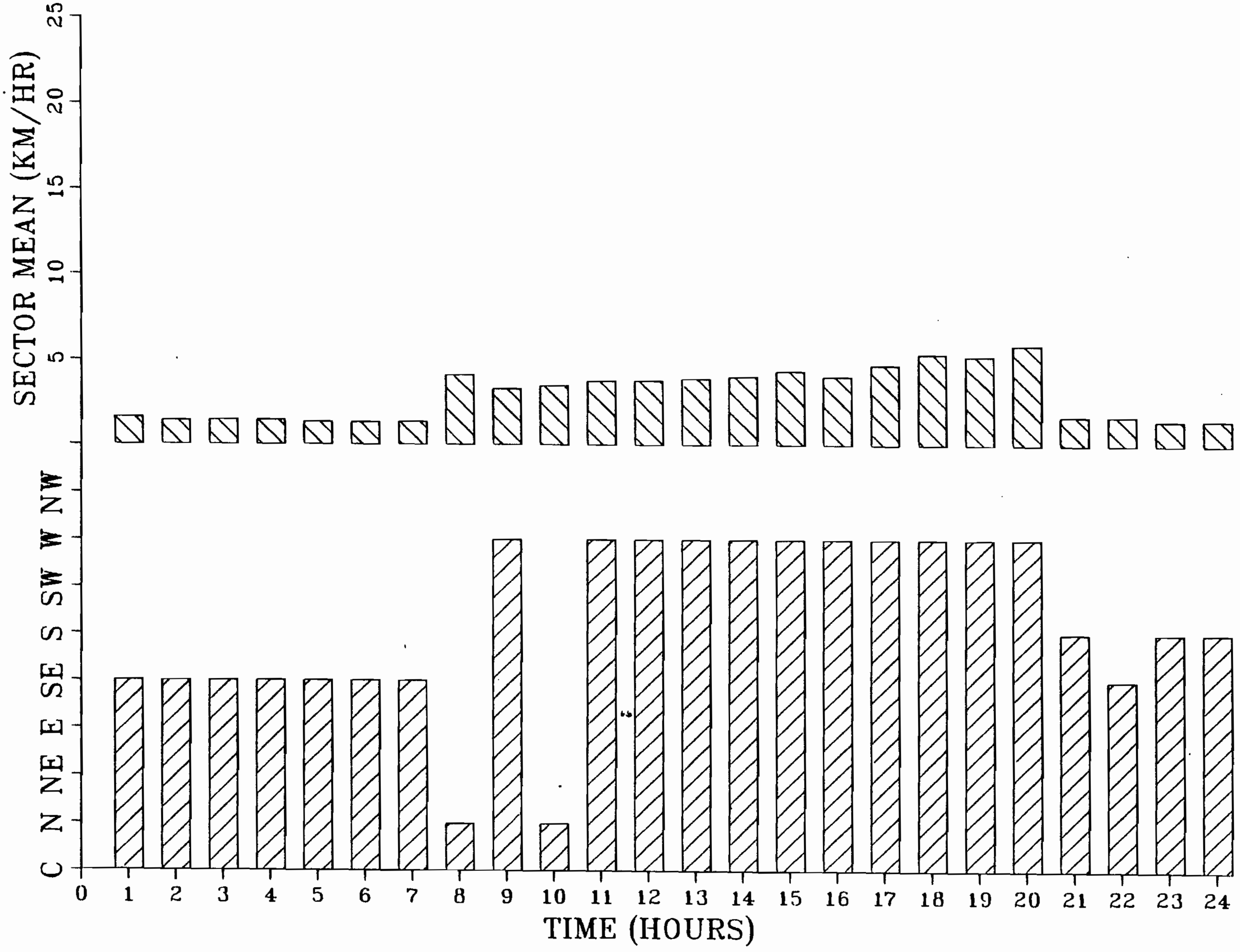


FIGURE 2

WINFIELD – ANNUAL OCCURRENCE OF CALMS

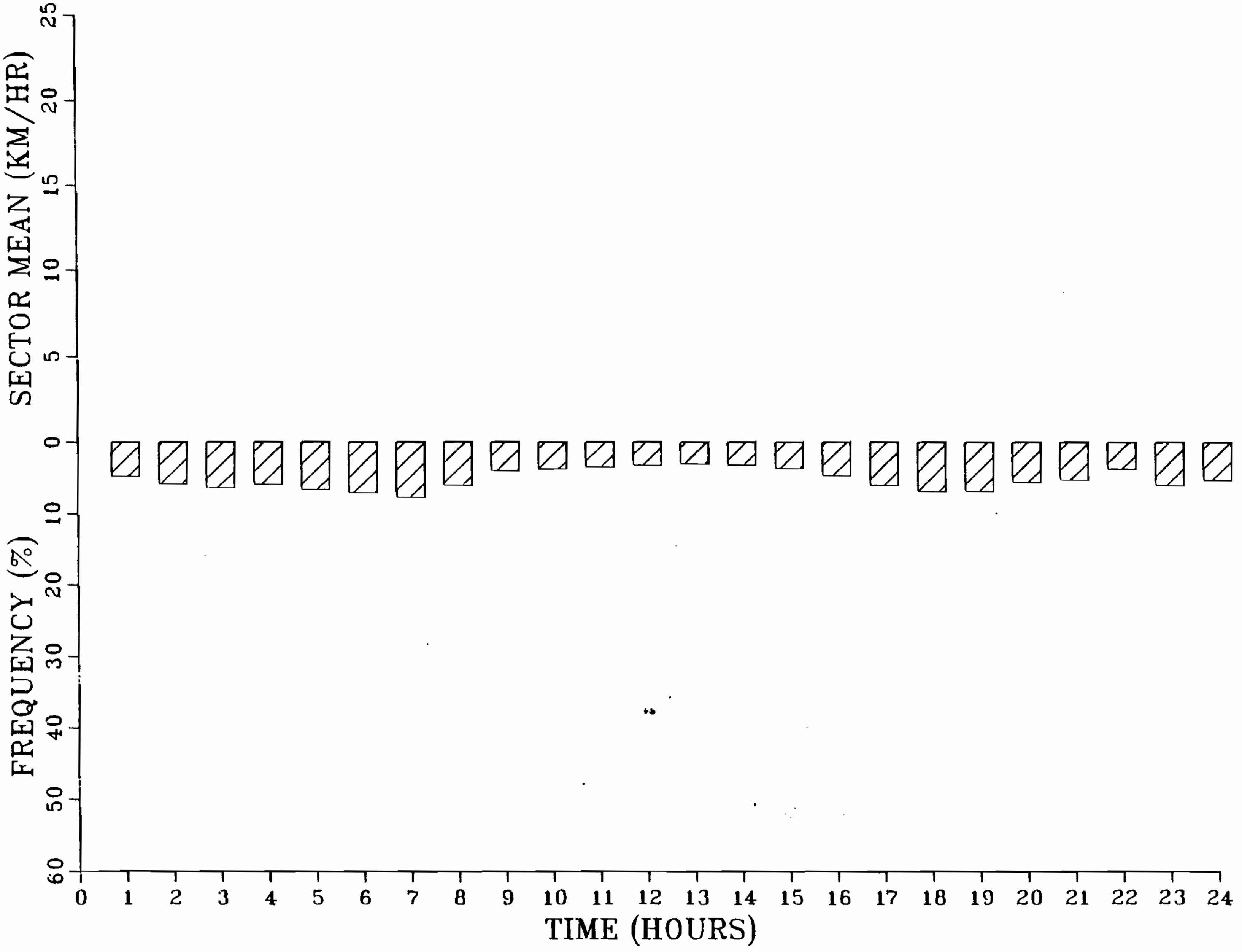


FIGURE 3
WINFIELD – ANNUAL OCCURRENCE OF NORTH WINDS

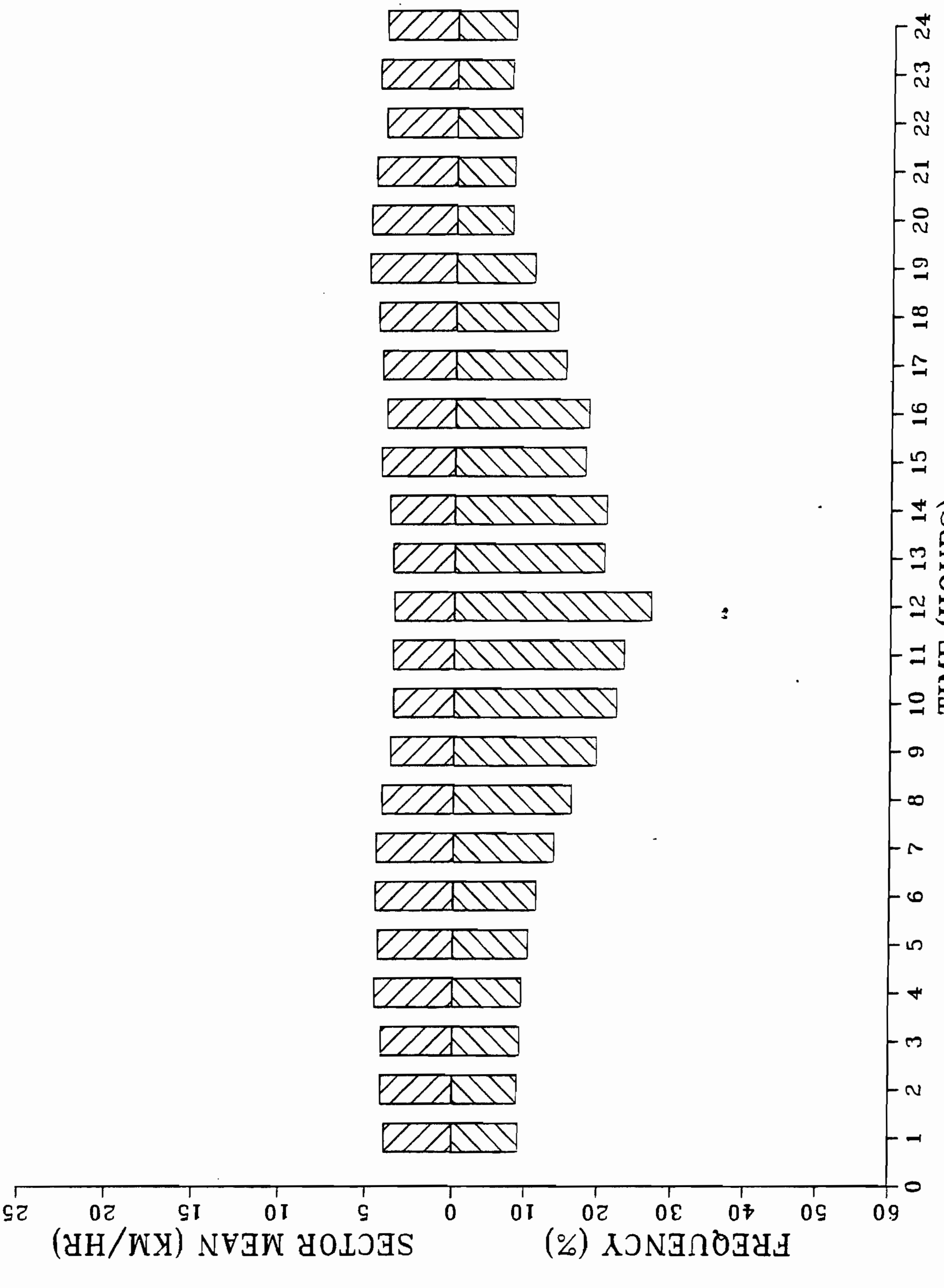


FIGURE 4

WINFIELD – ANNUAL OCCURRENCE OF NORTH–EAST WINDS

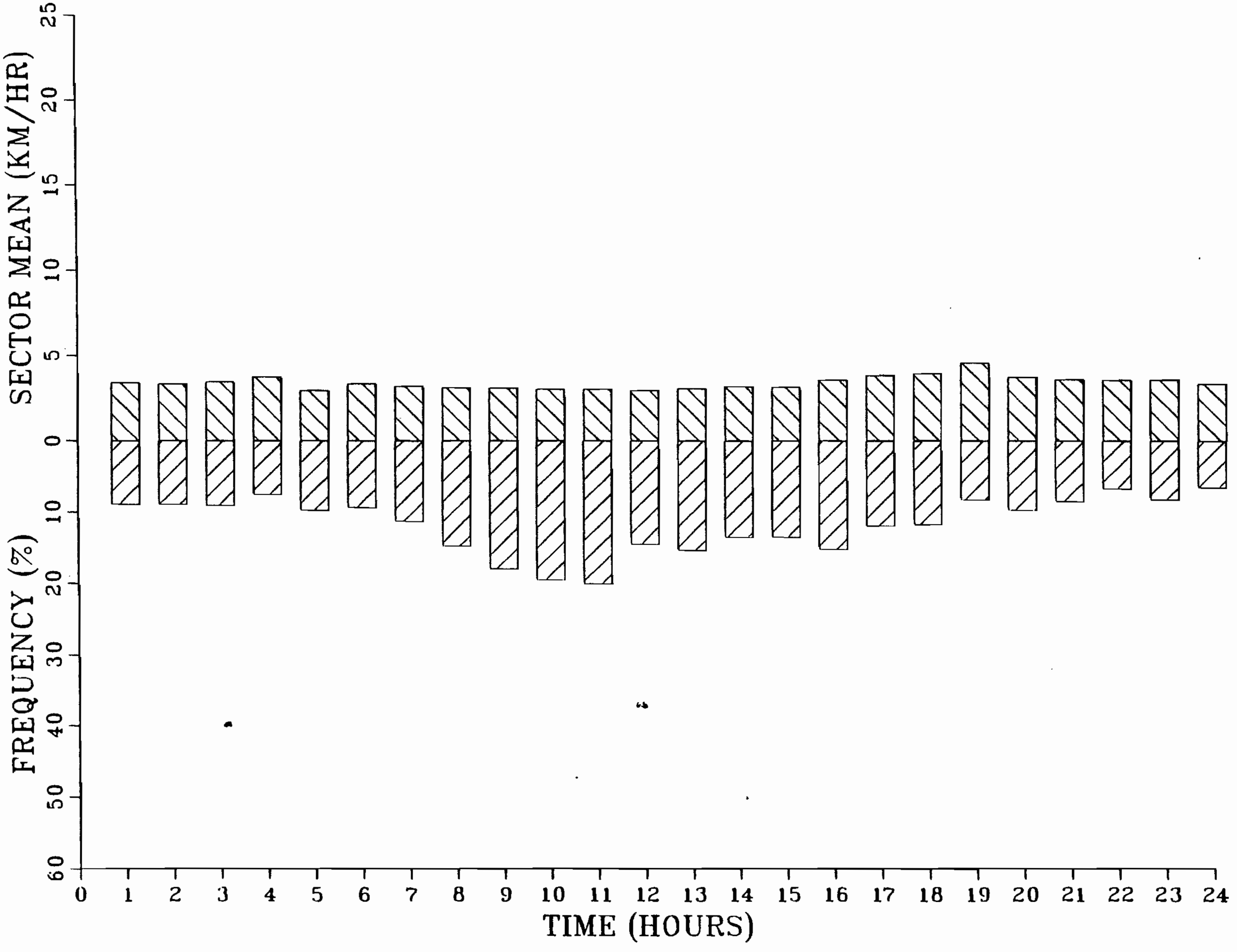


FIGURE 5

WINFIELD – ANNUAL OCCURRENCE OF EAST WINDS

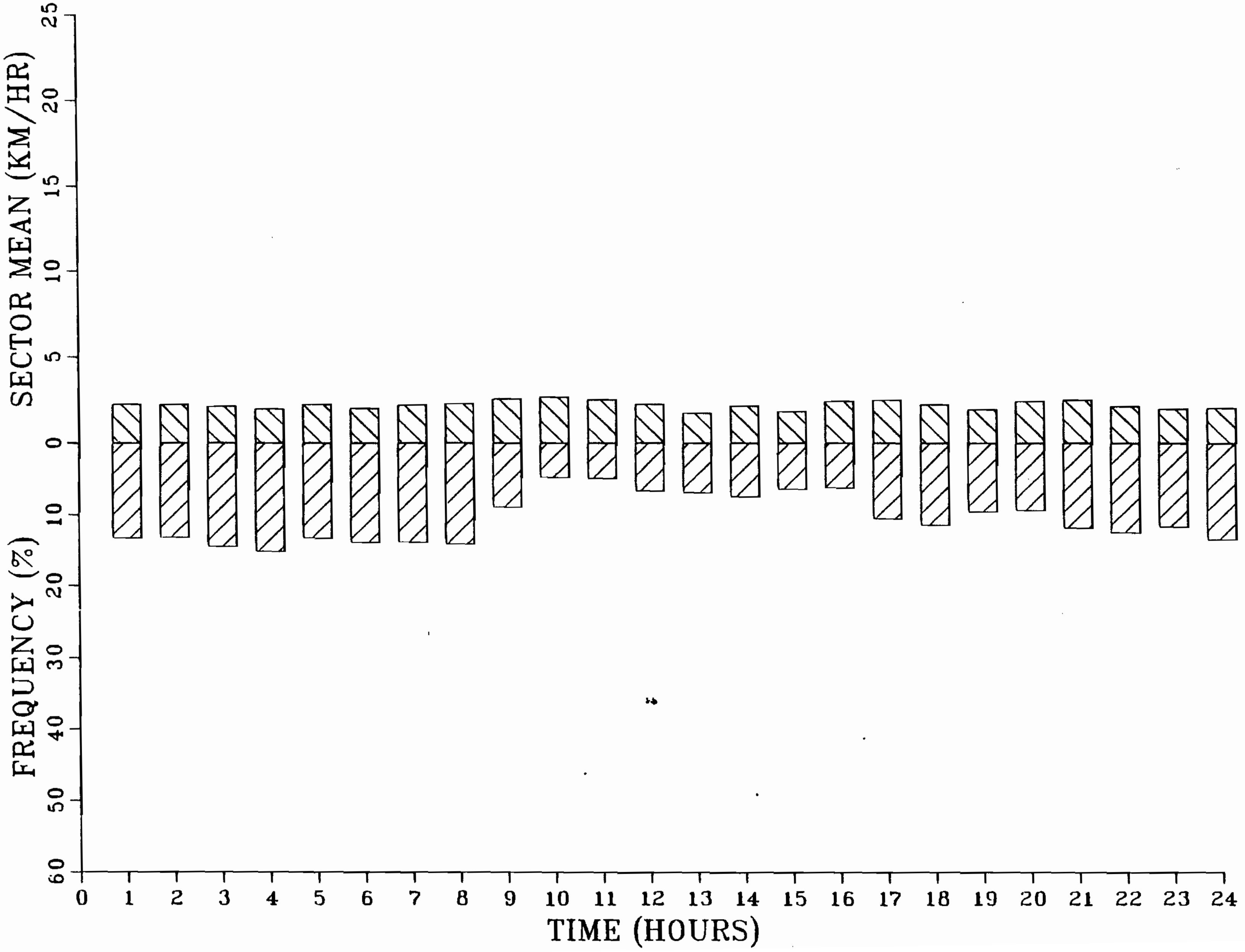


FIGURE 6

WINFIELD – ANNUAL OCCURRENCE OF SOUTH–EAST WINDS

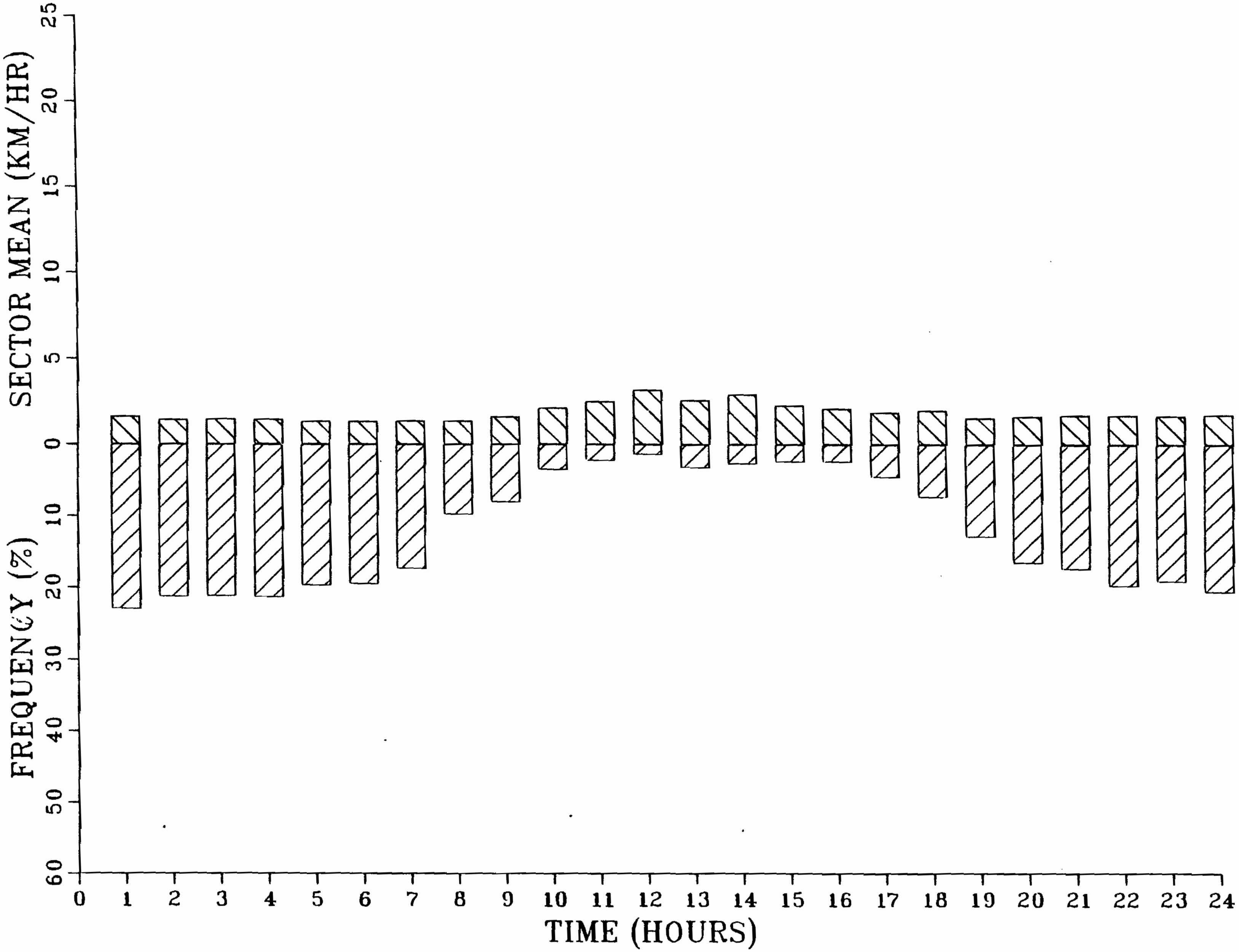


FIGURE 7

WINFIELD – ANNUAL OCCURRENCE OF SOUTH WINDS

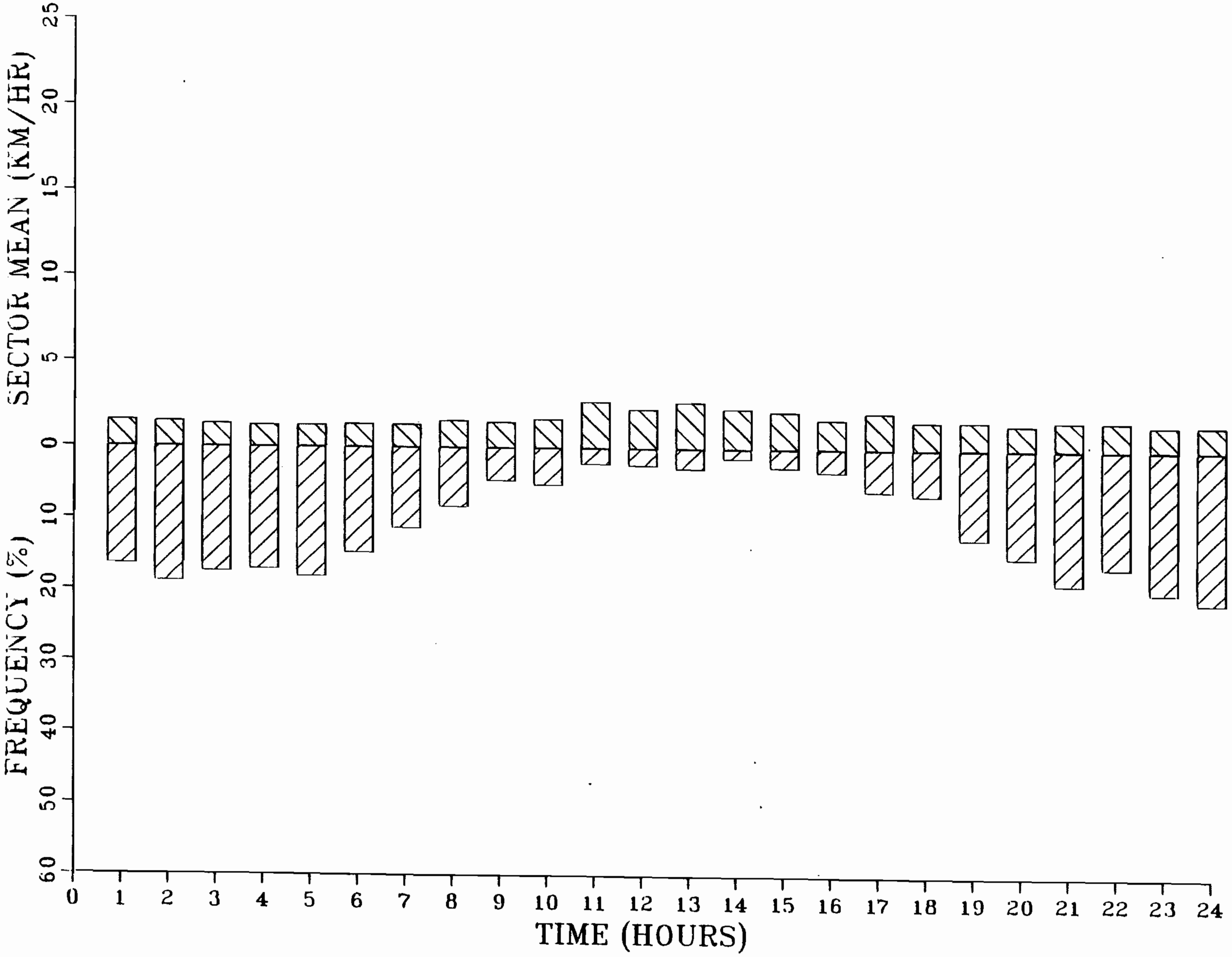


FIGURE 8

WINFIELD – ANNUAL OCCURRENCE OF SOUTH–WEST WINDS

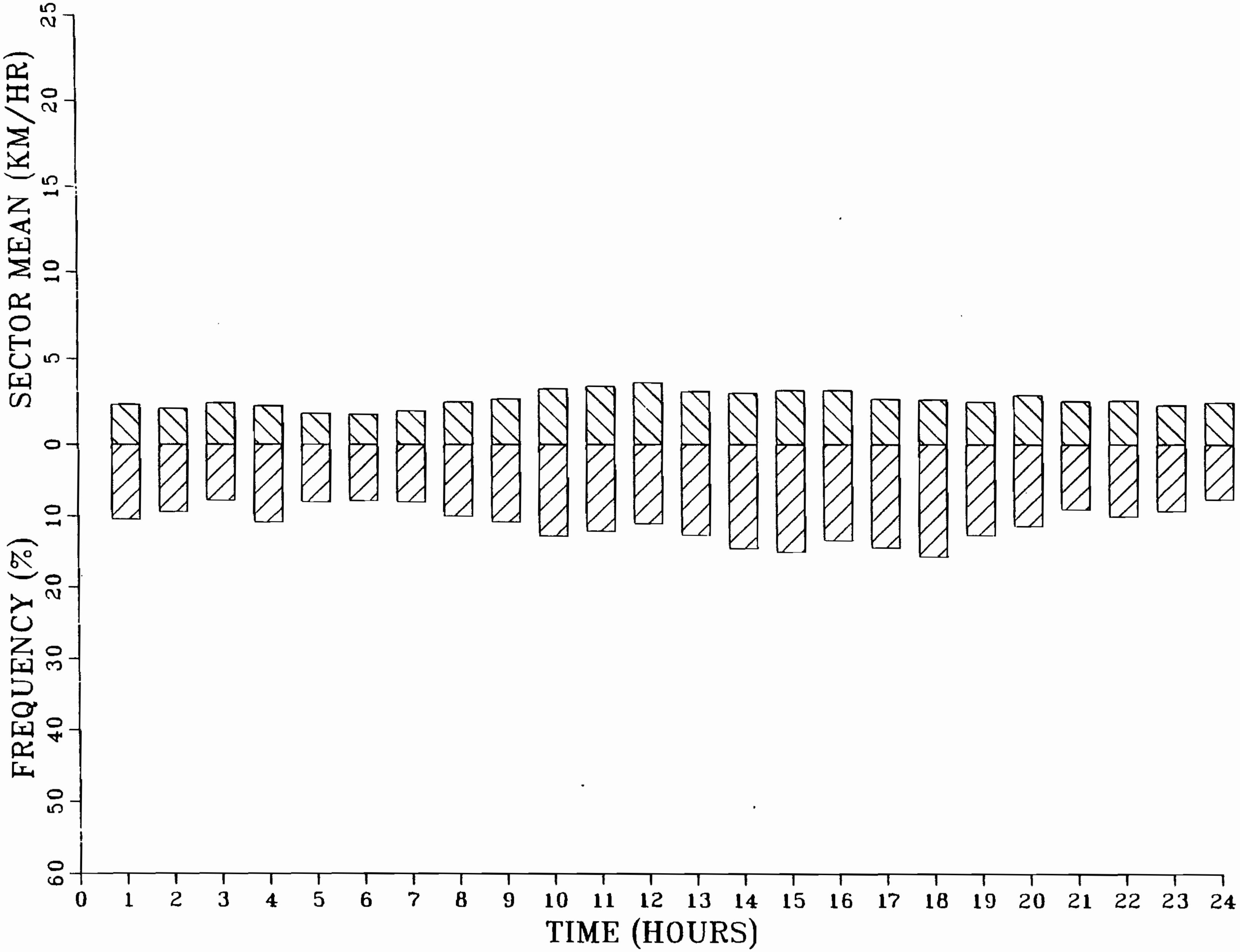


FIGURE 9

WINFIELD – ANNUAL OCCURRENCE OF WEST WINDS

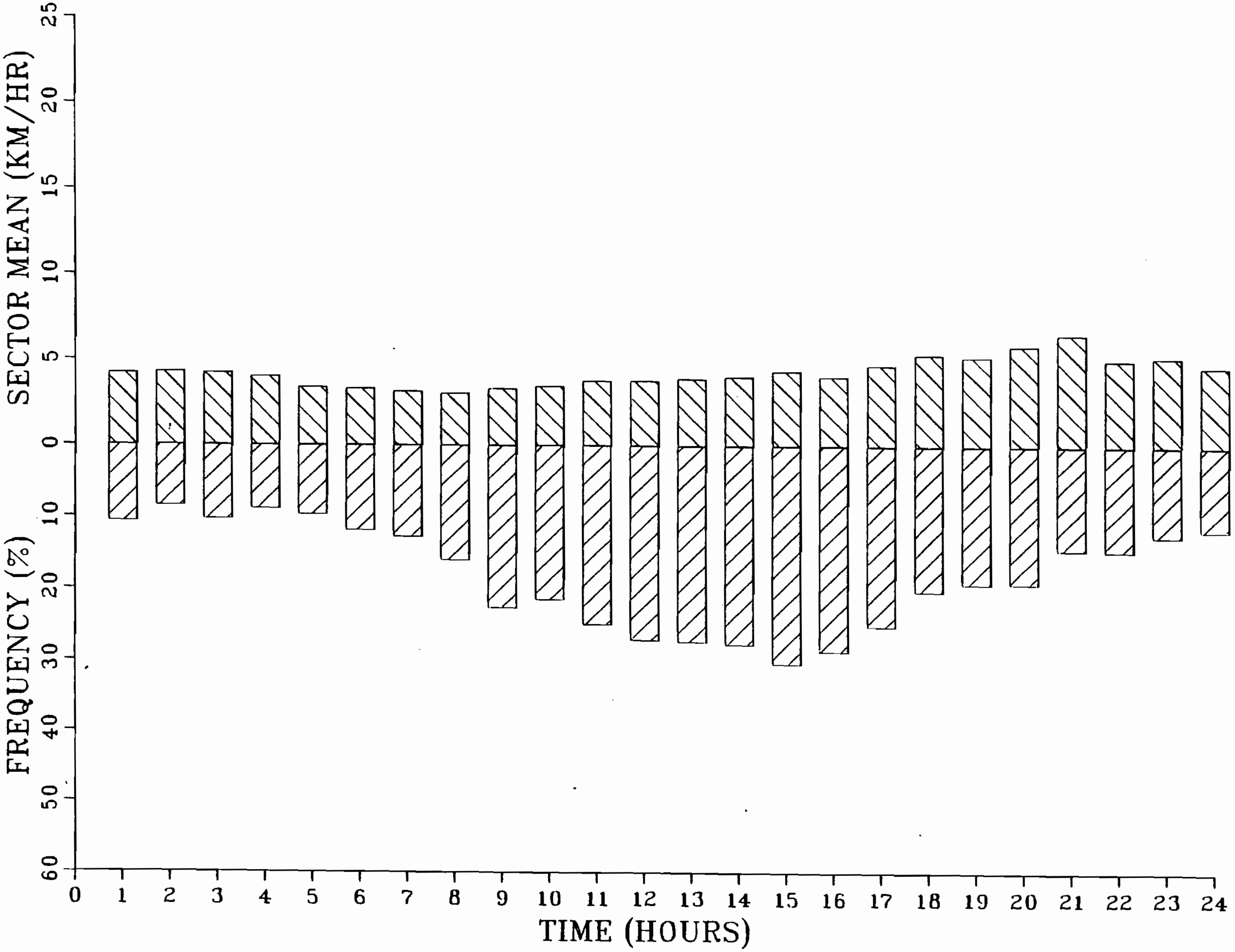


FIGURE 10

WINFIELD – ANNUAL OCCURRENCE OF NORTH–WEST WINDS

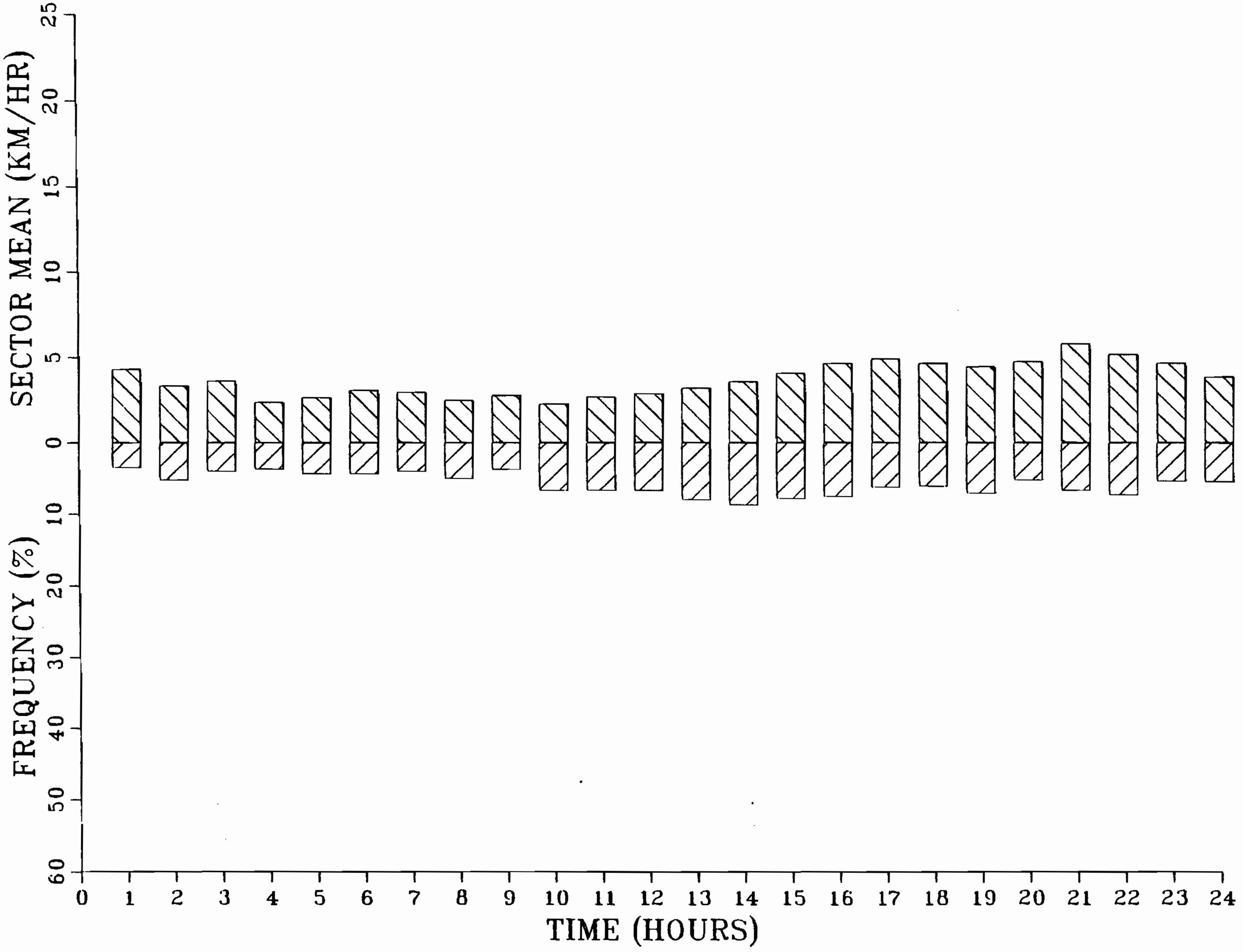


FIGURE 1

PREDOMINANT HOURLY WINDS FOR KELOWNA AIRPORT

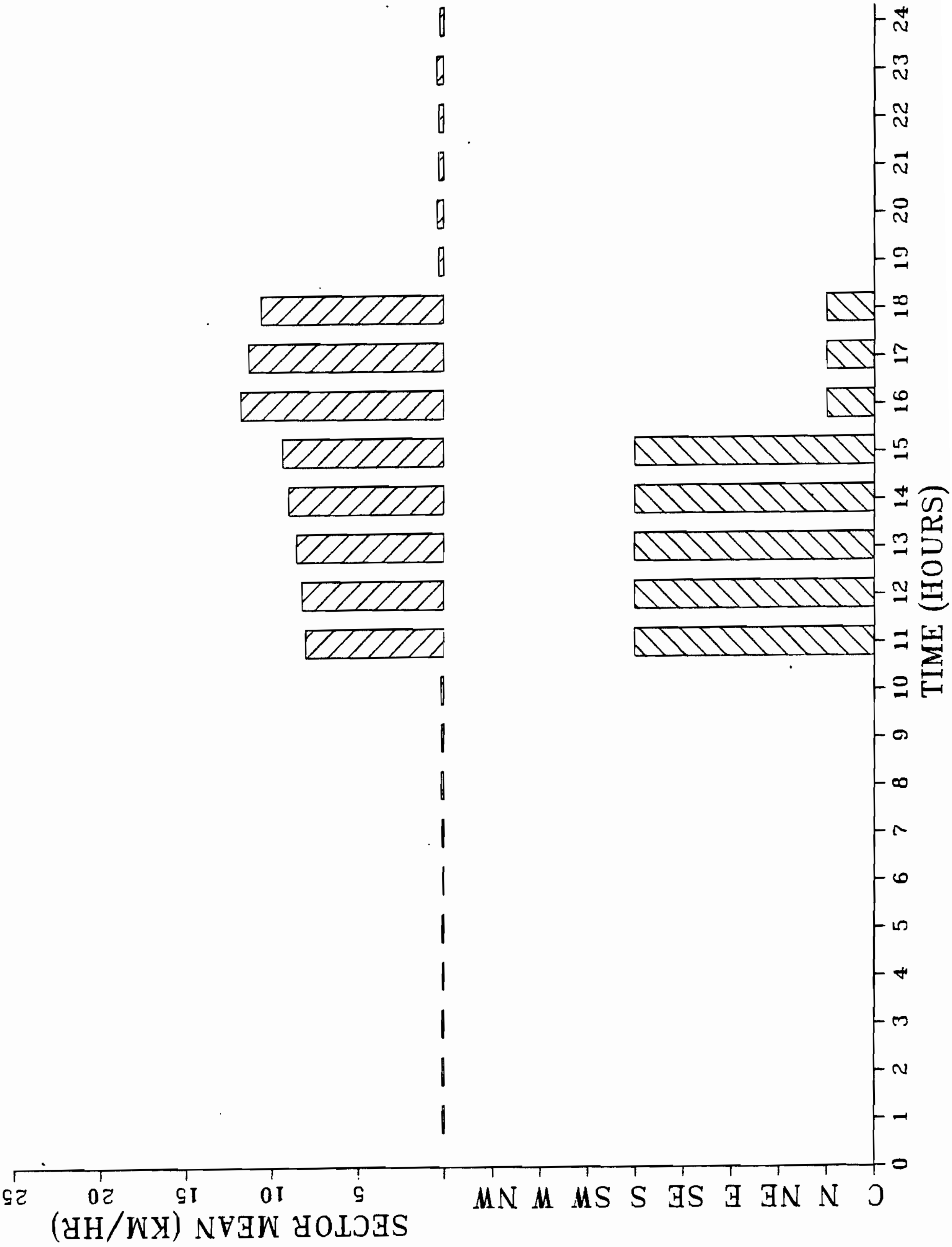


FIGURE 2

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF CALMS

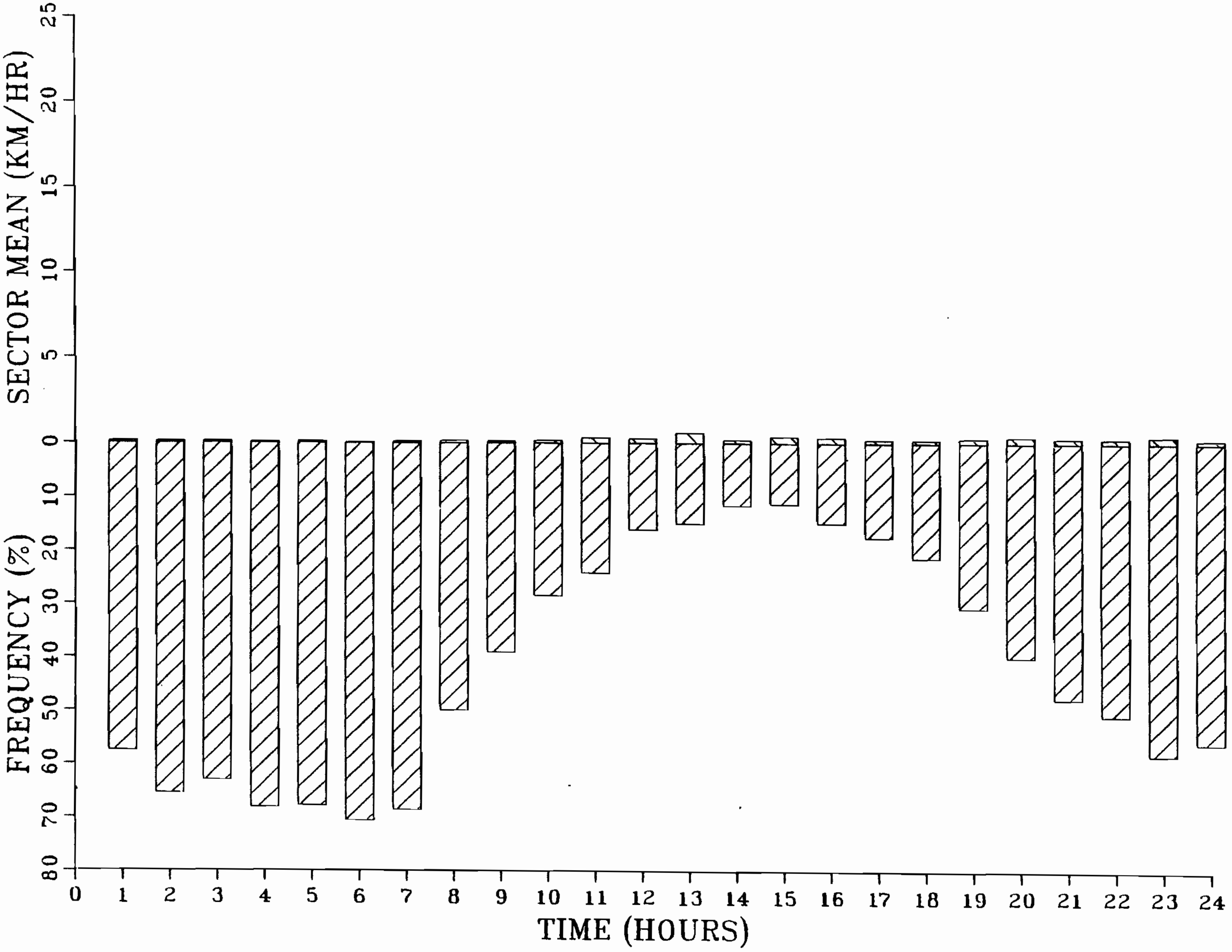


FIGURE 3

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF NORTH WINDS

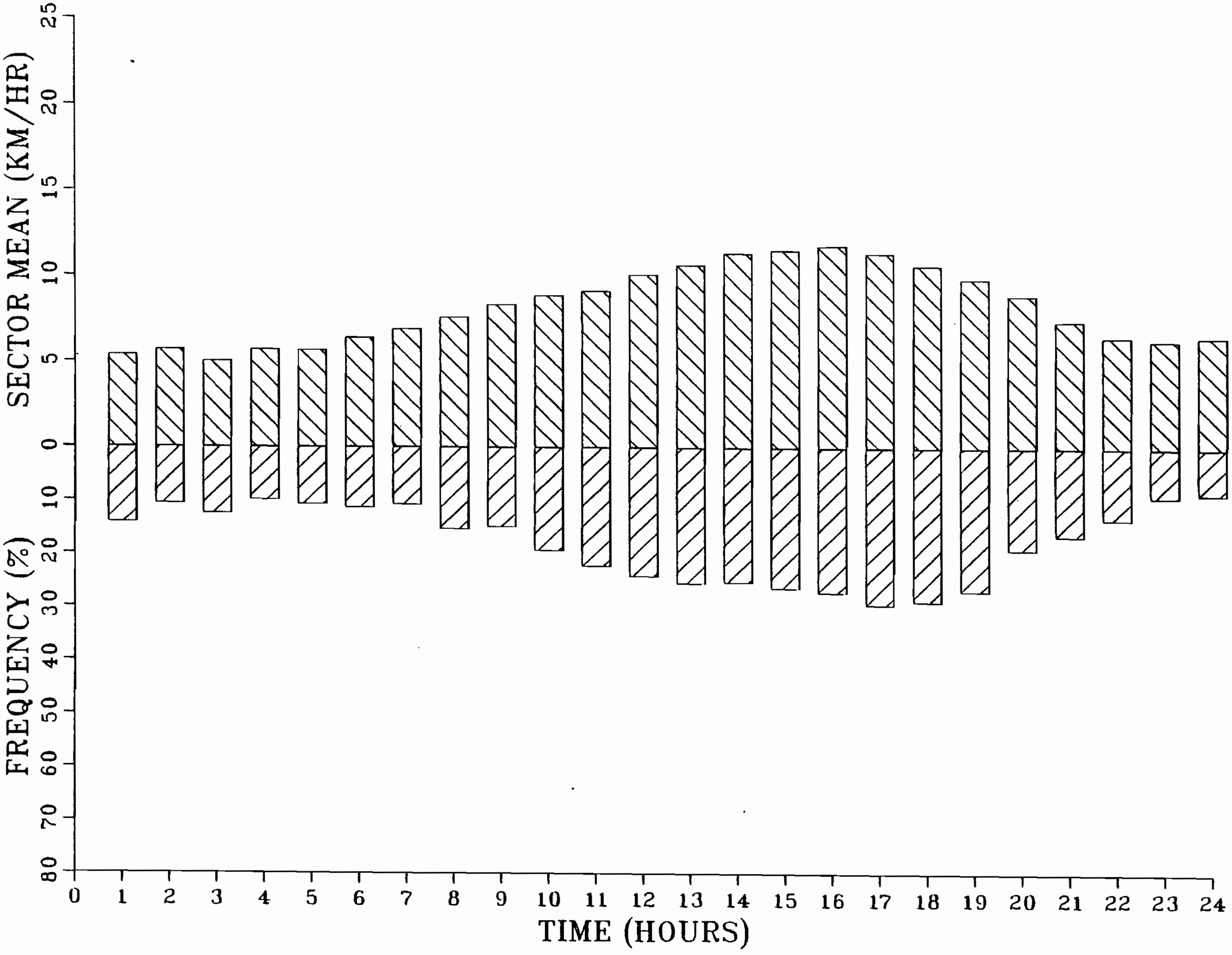


FIGURE 4

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF NORTH–EAST WINDS

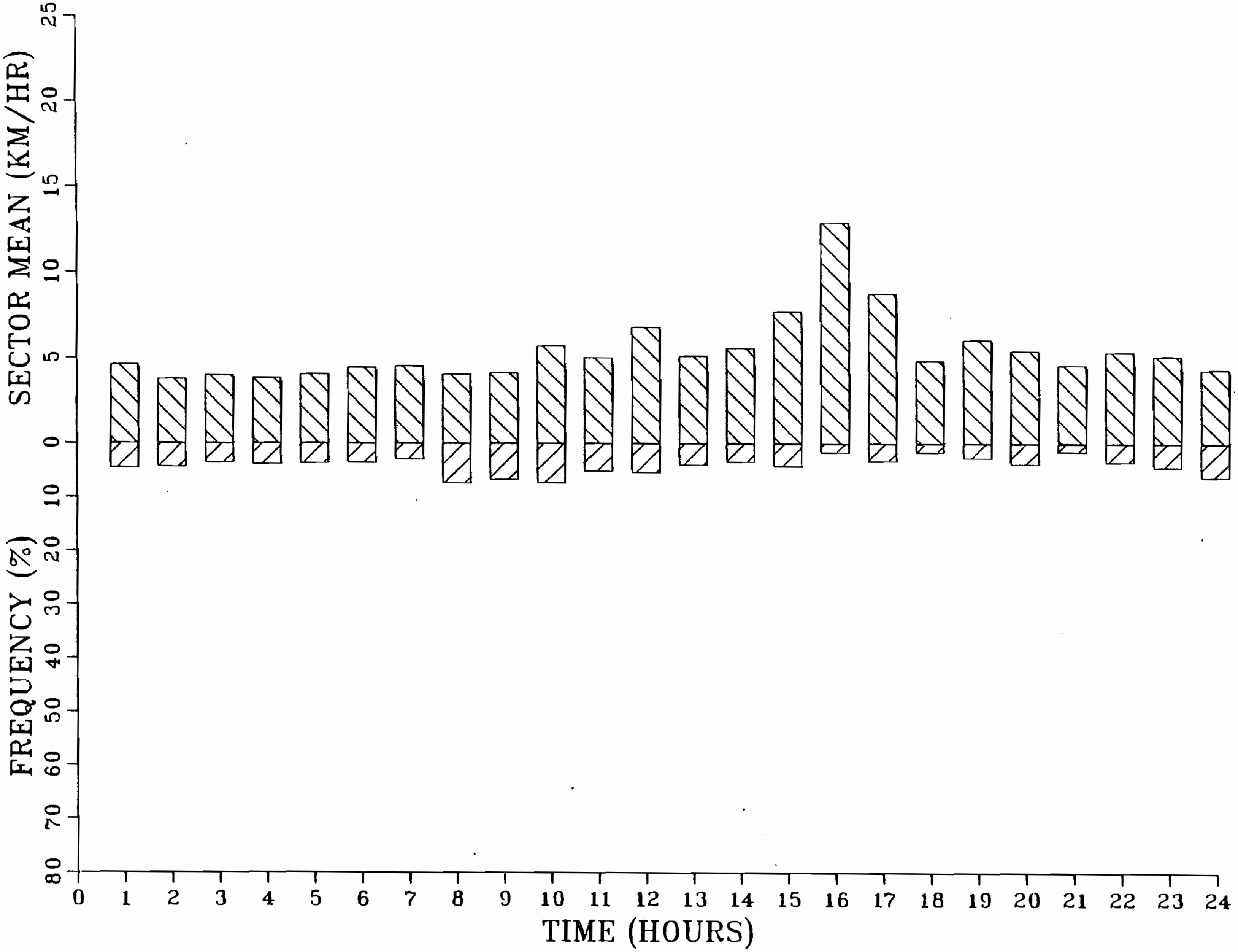


FIGURE 5

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF EAST WINDS

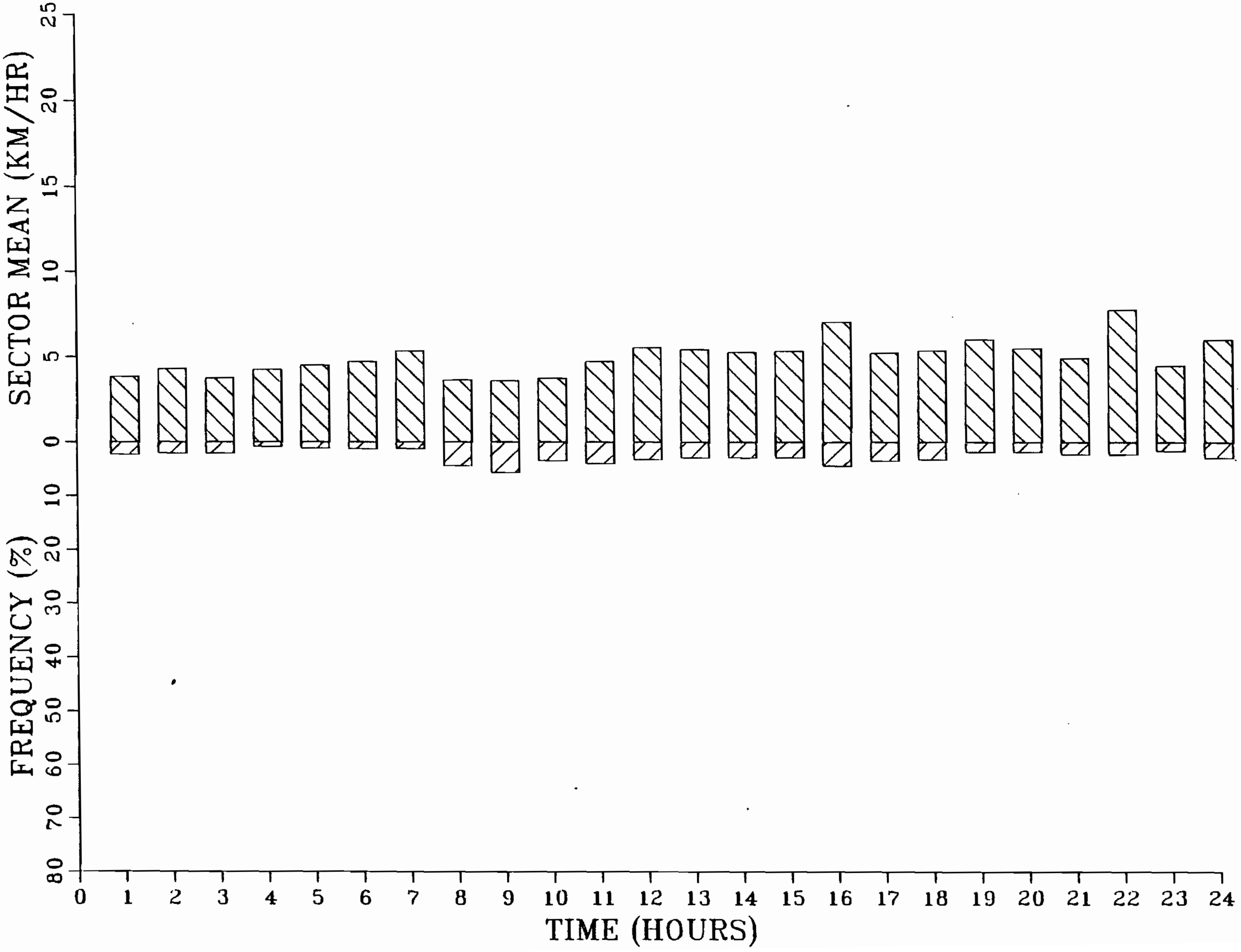


FIGURE 6

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF SOUTH–EAST WINDS

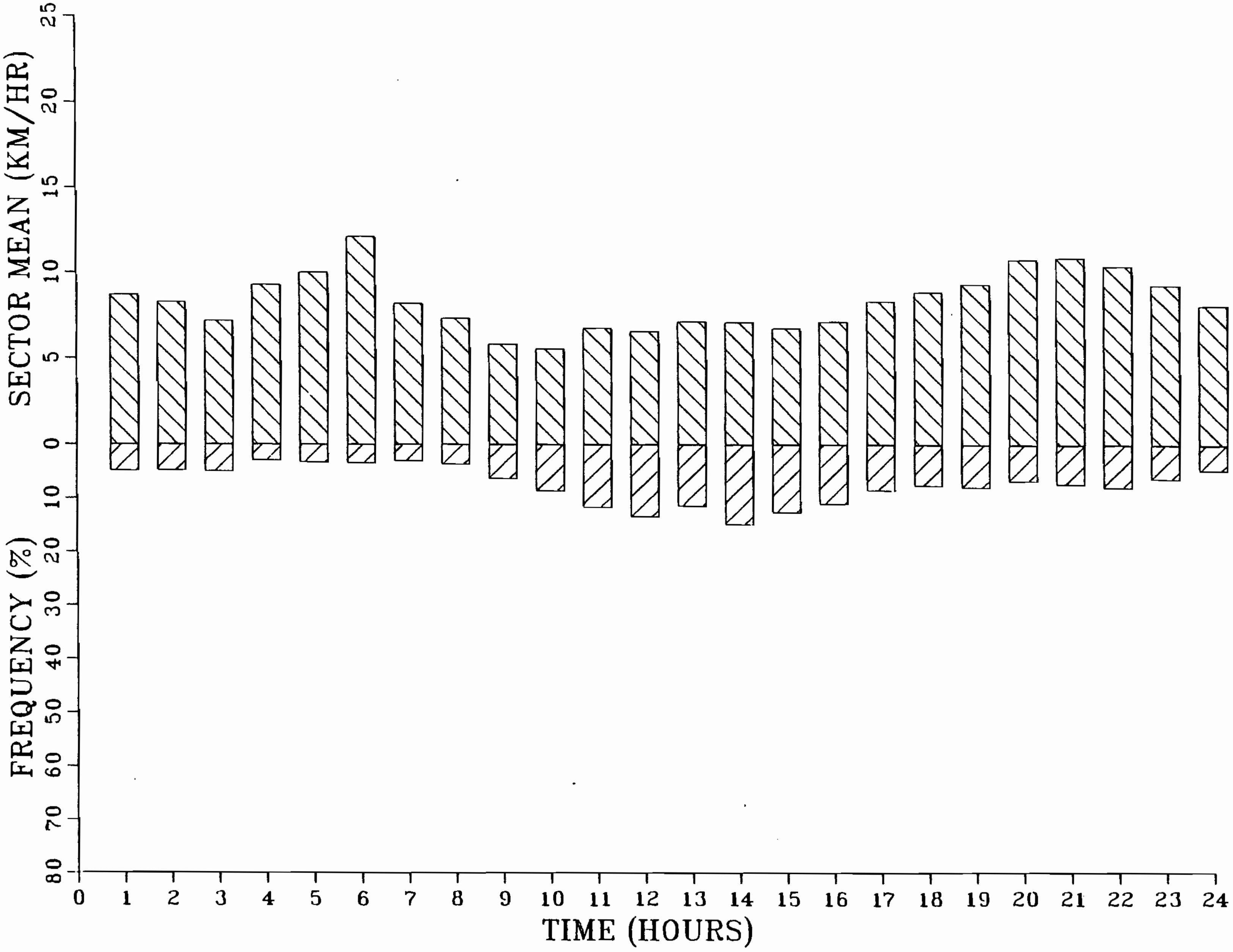


FIGURE 7

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF SOUTH WINDS

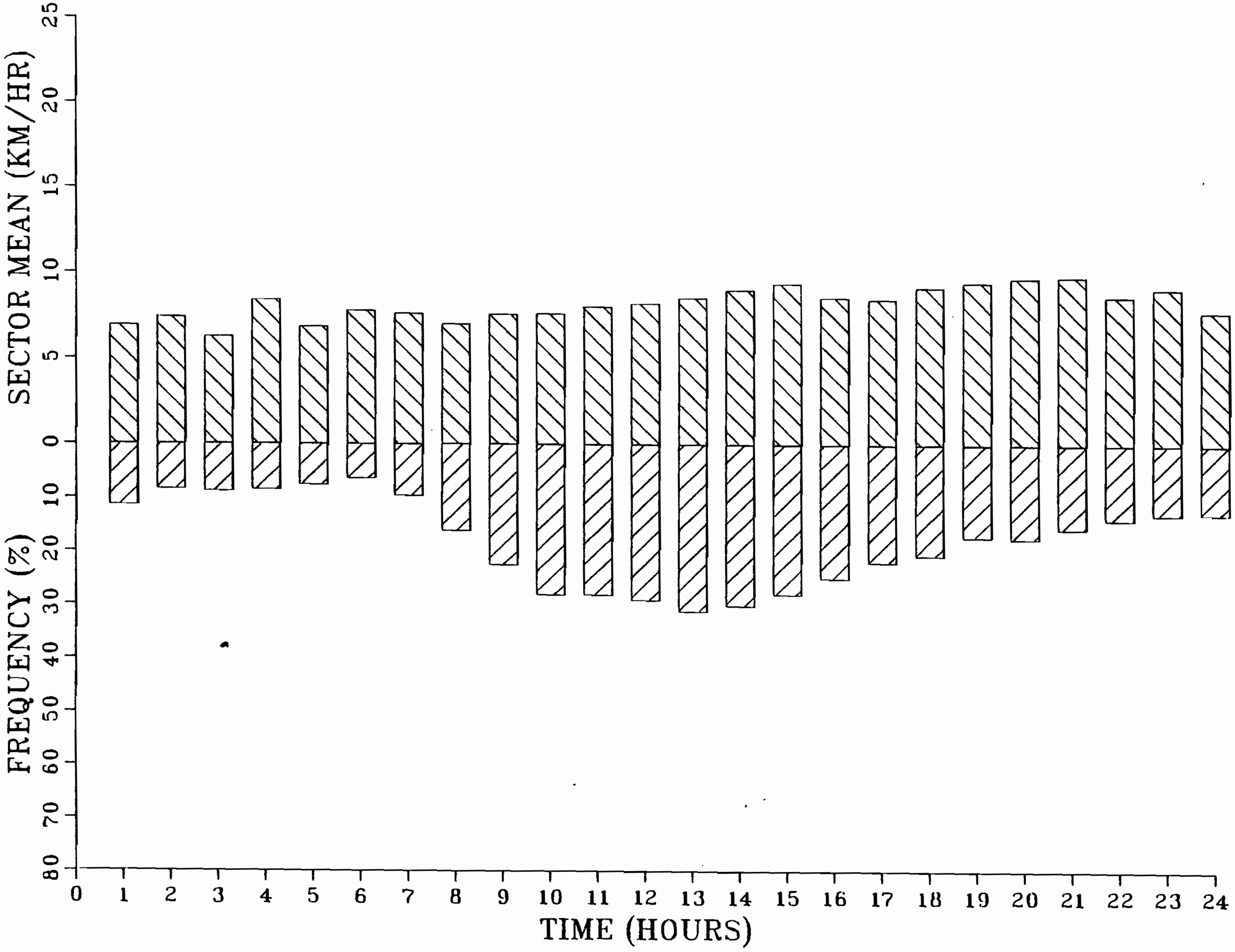


FIGURE 8

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF SOUTH-WEST WINDS

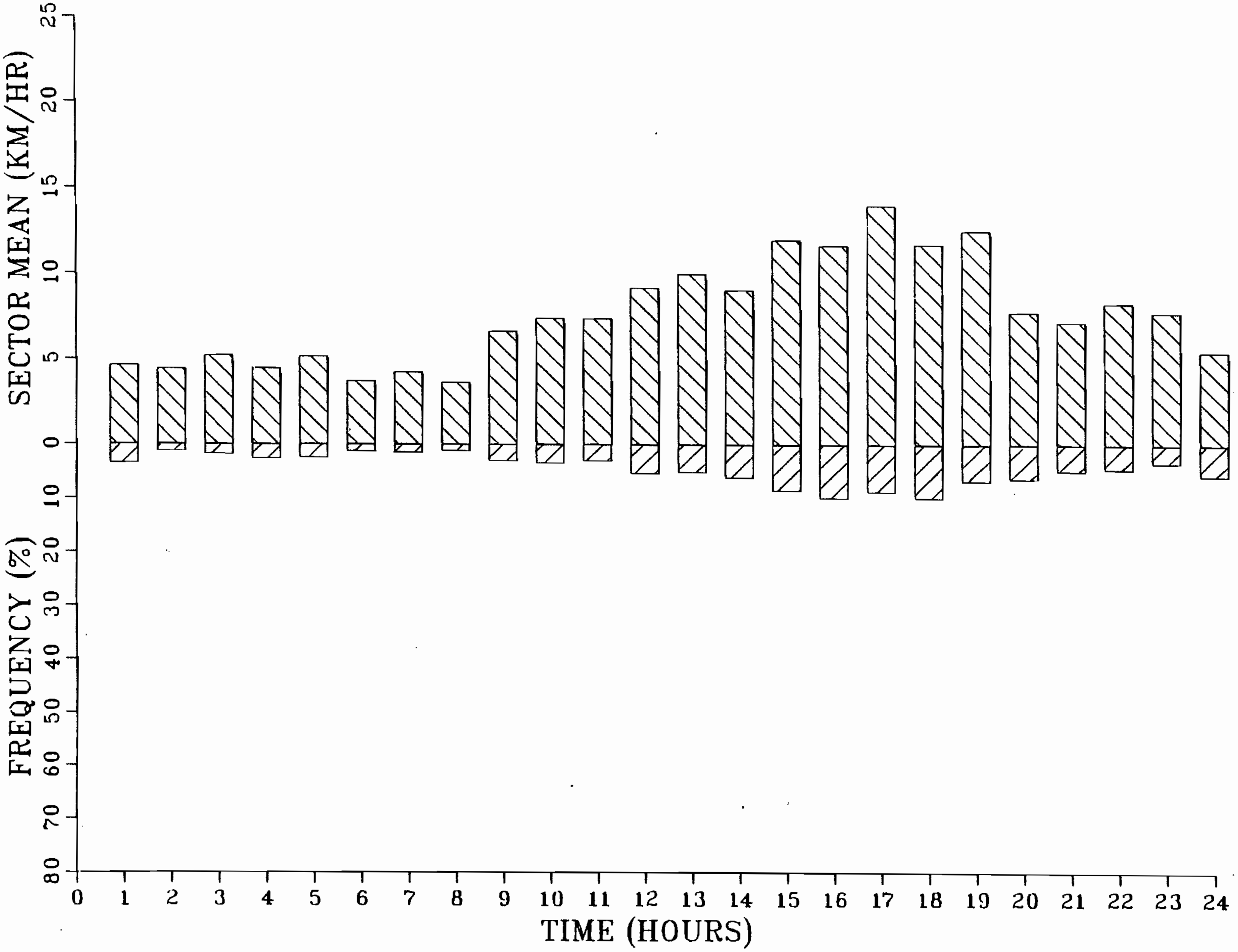


FIGURE 9

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF WEST WINDS

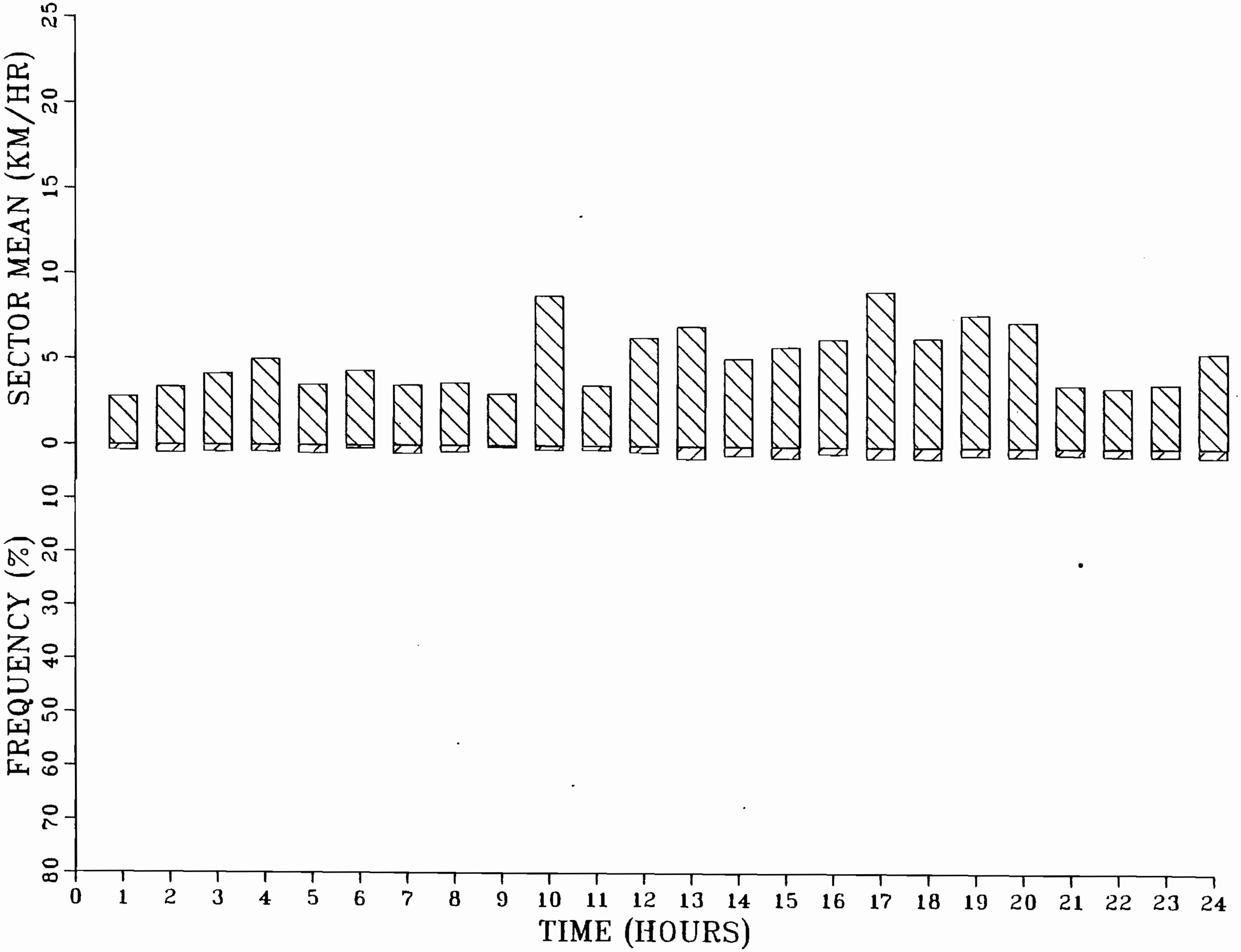


FIGURE 10

KELOWNA AIRPORT – ANNUAL OCCURRENCE OF NORTH-WEST WINDS

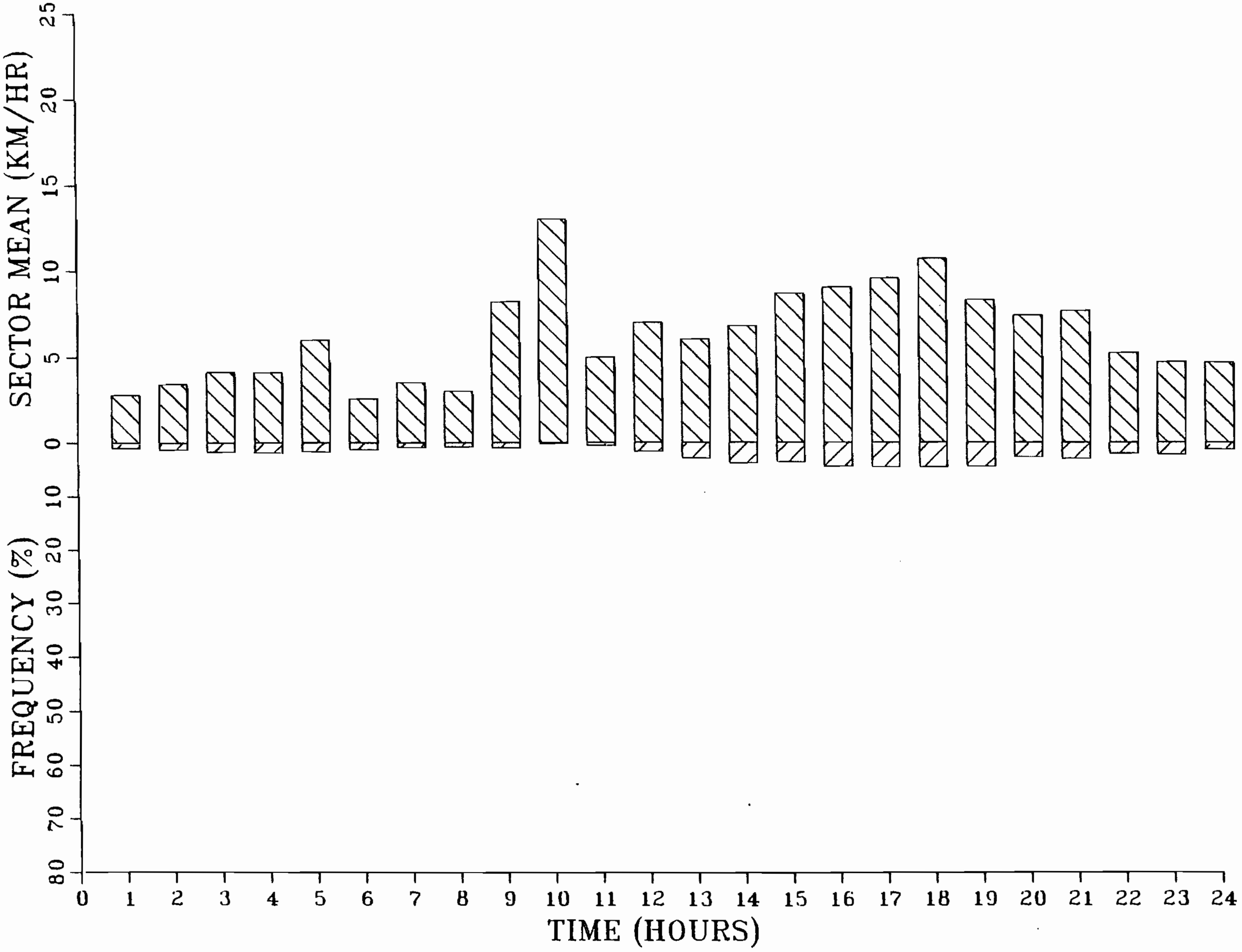


FIGURE 1

PREDOMINANT HOURLY WINDS FOR KELOWNA BRIDGE

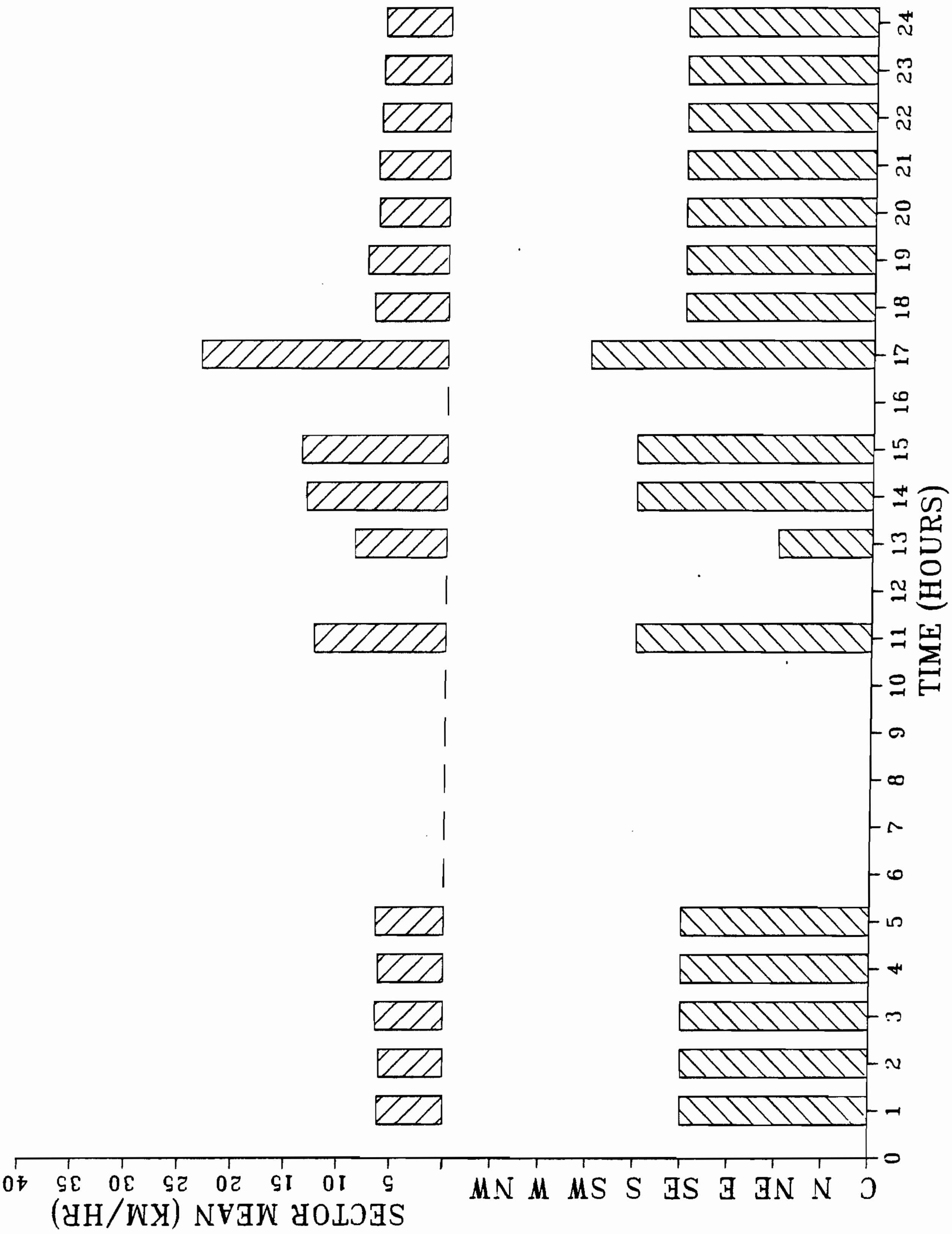


FIGURE 2

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF CALMS

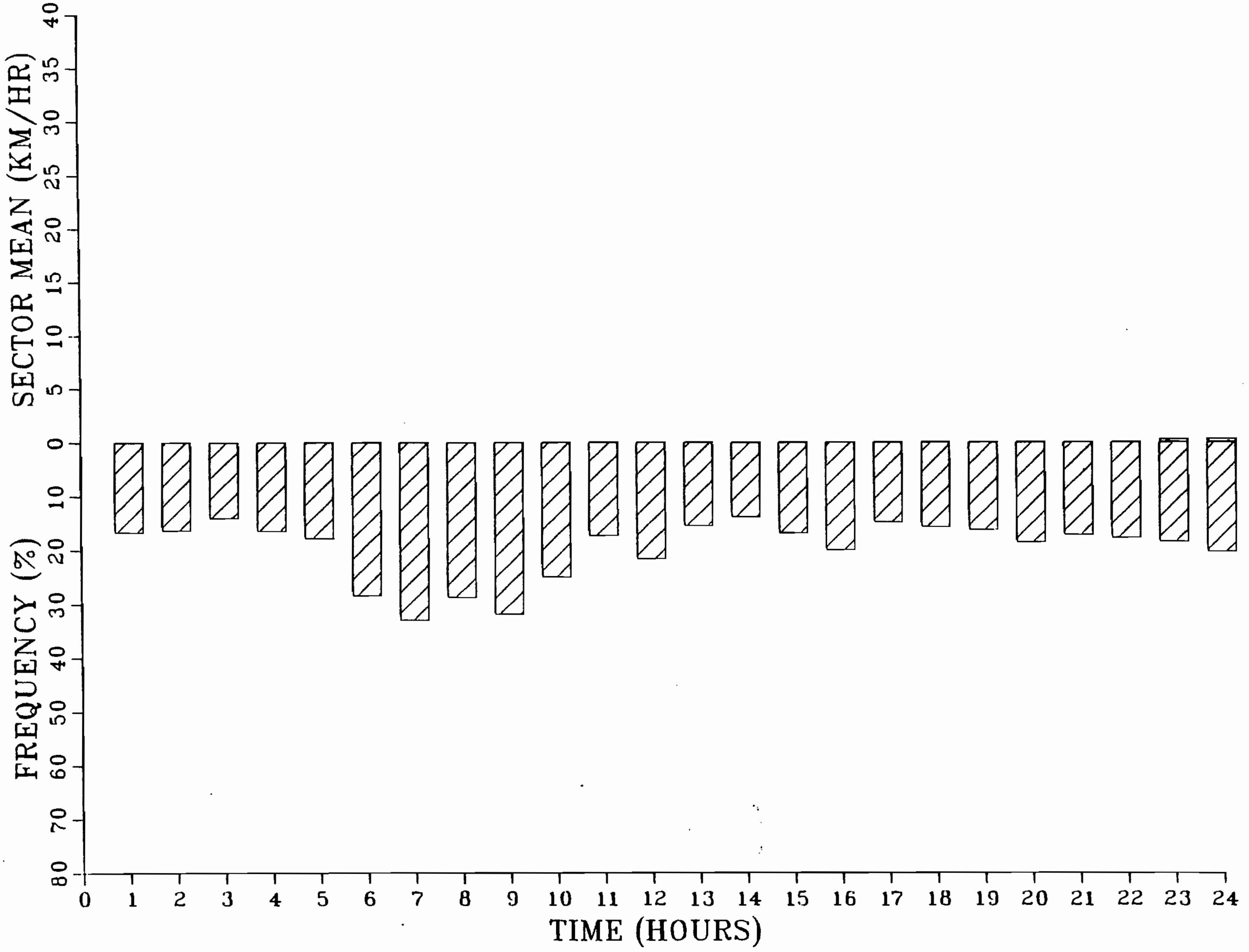


FIGURE 3

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF NORTH WINDS

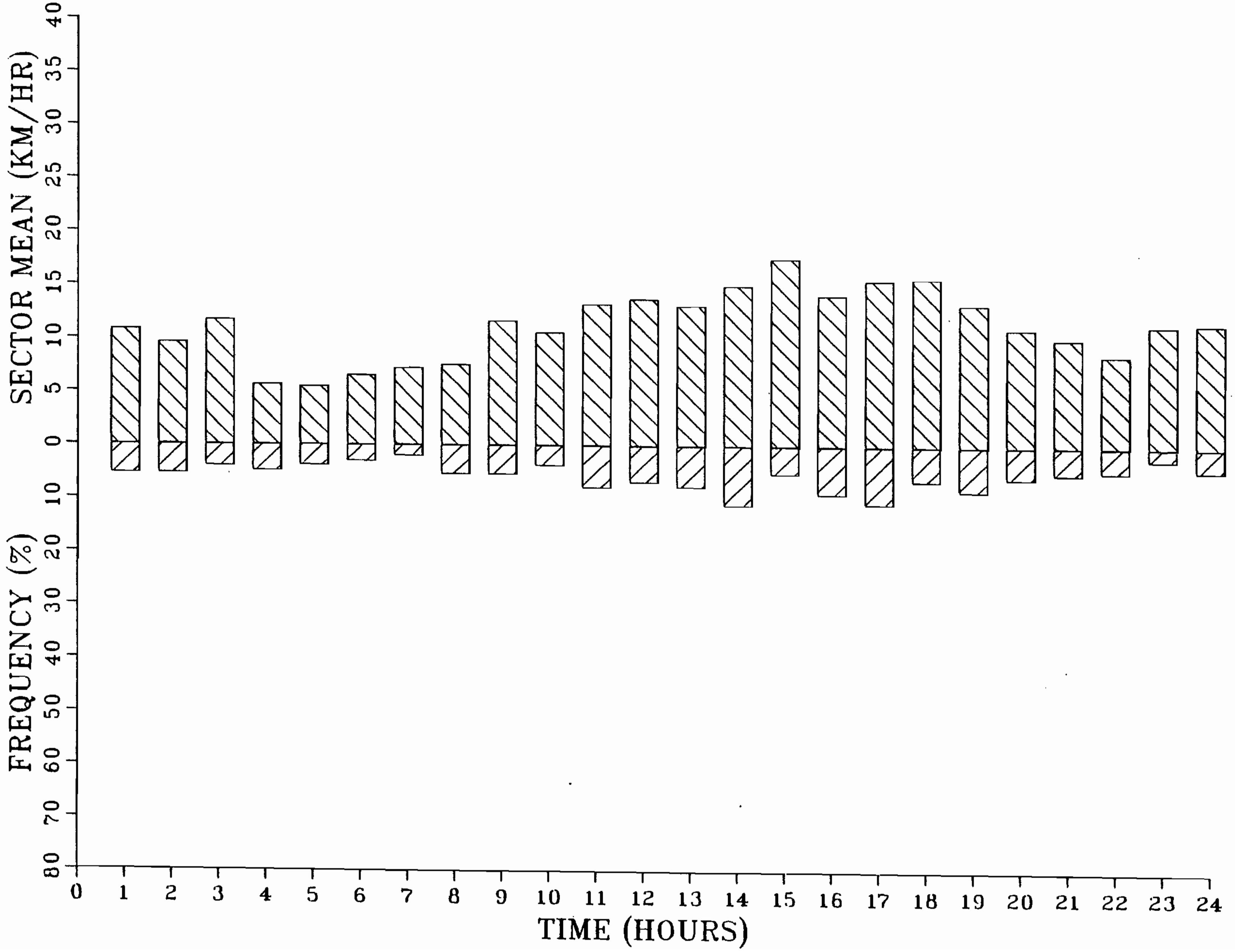


FIGURE 4

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF NORTH–EAST WINDS

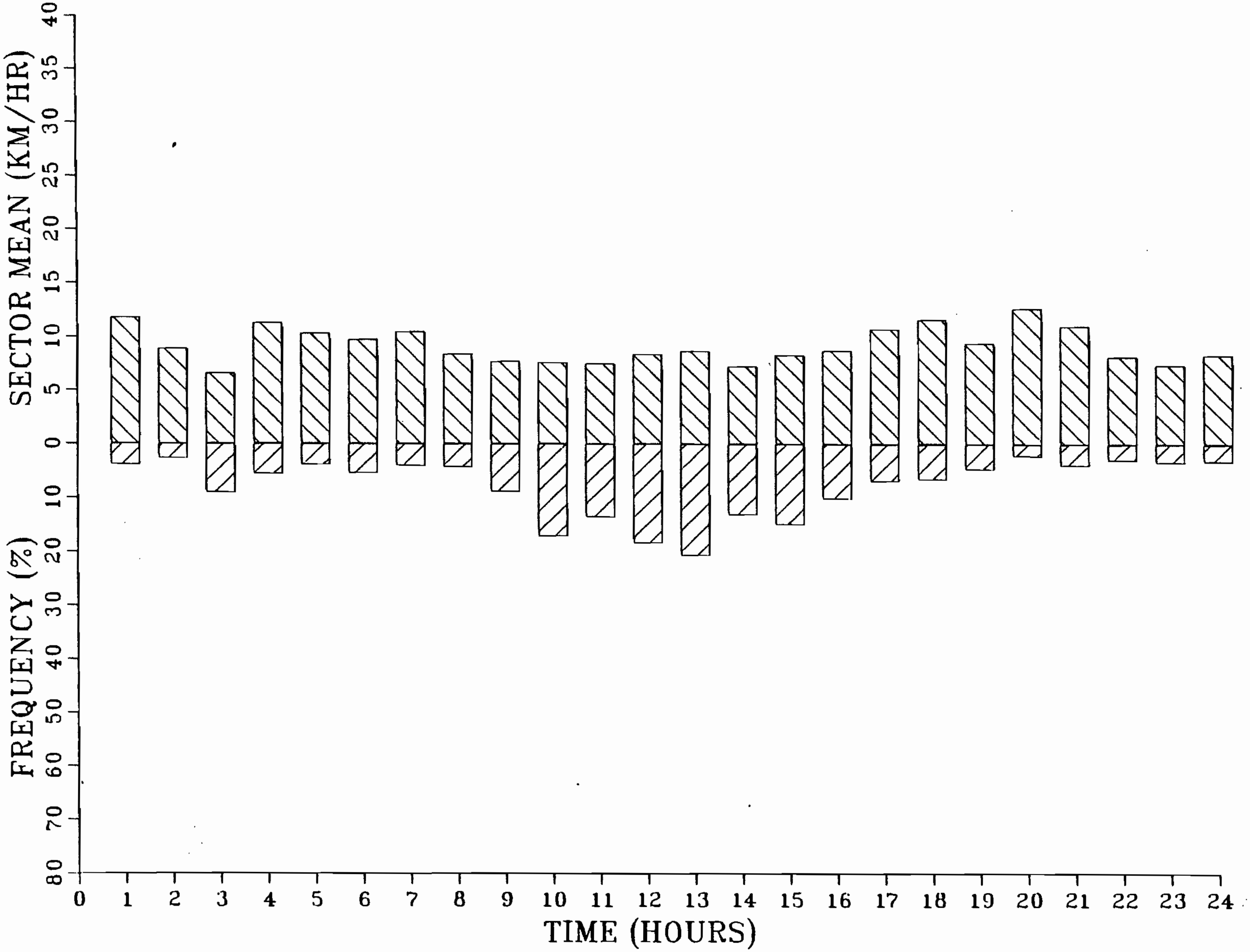


FIGURE 5

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF EAST WINDS

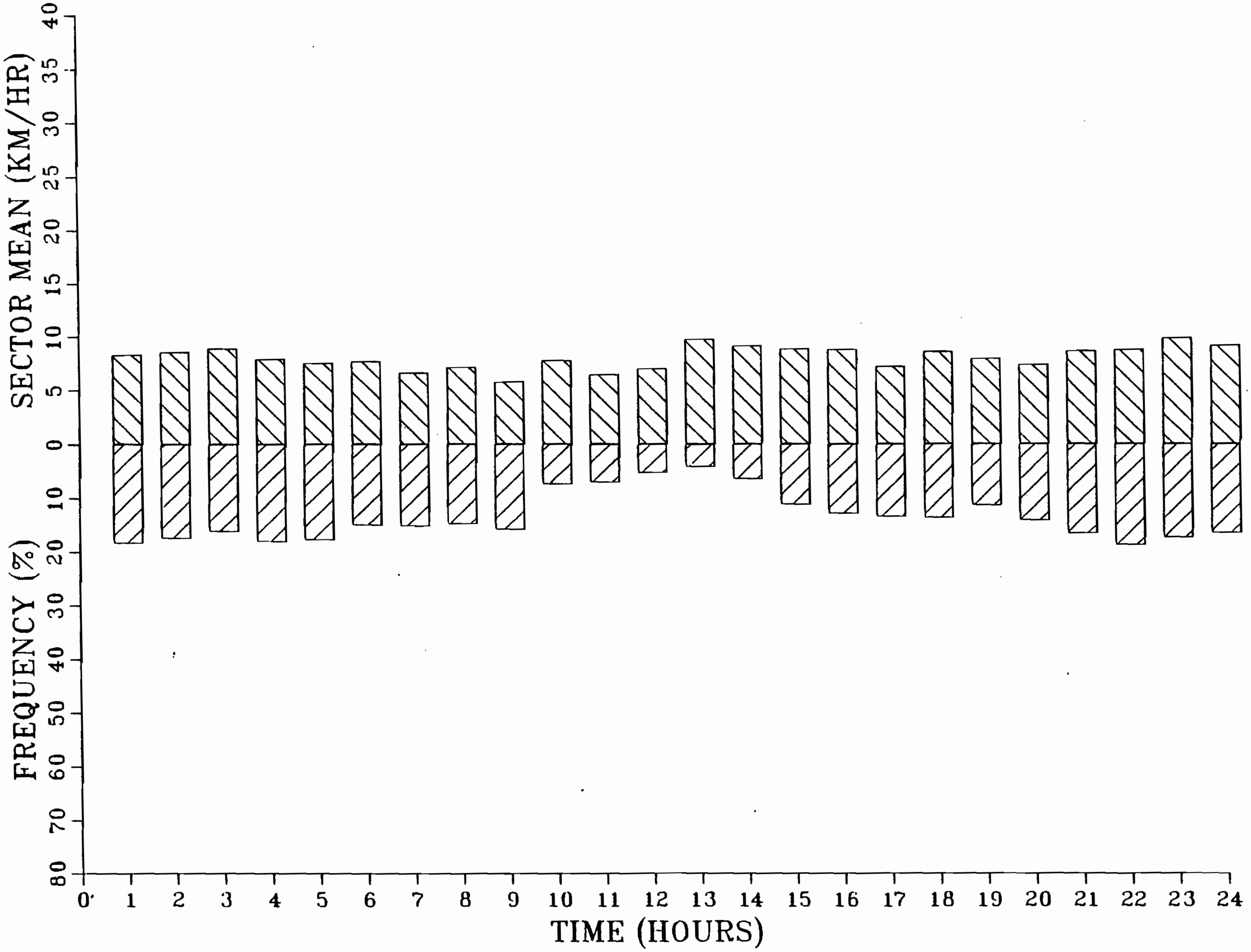


FIGURE 6

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF SOUTH-EAST WINDS

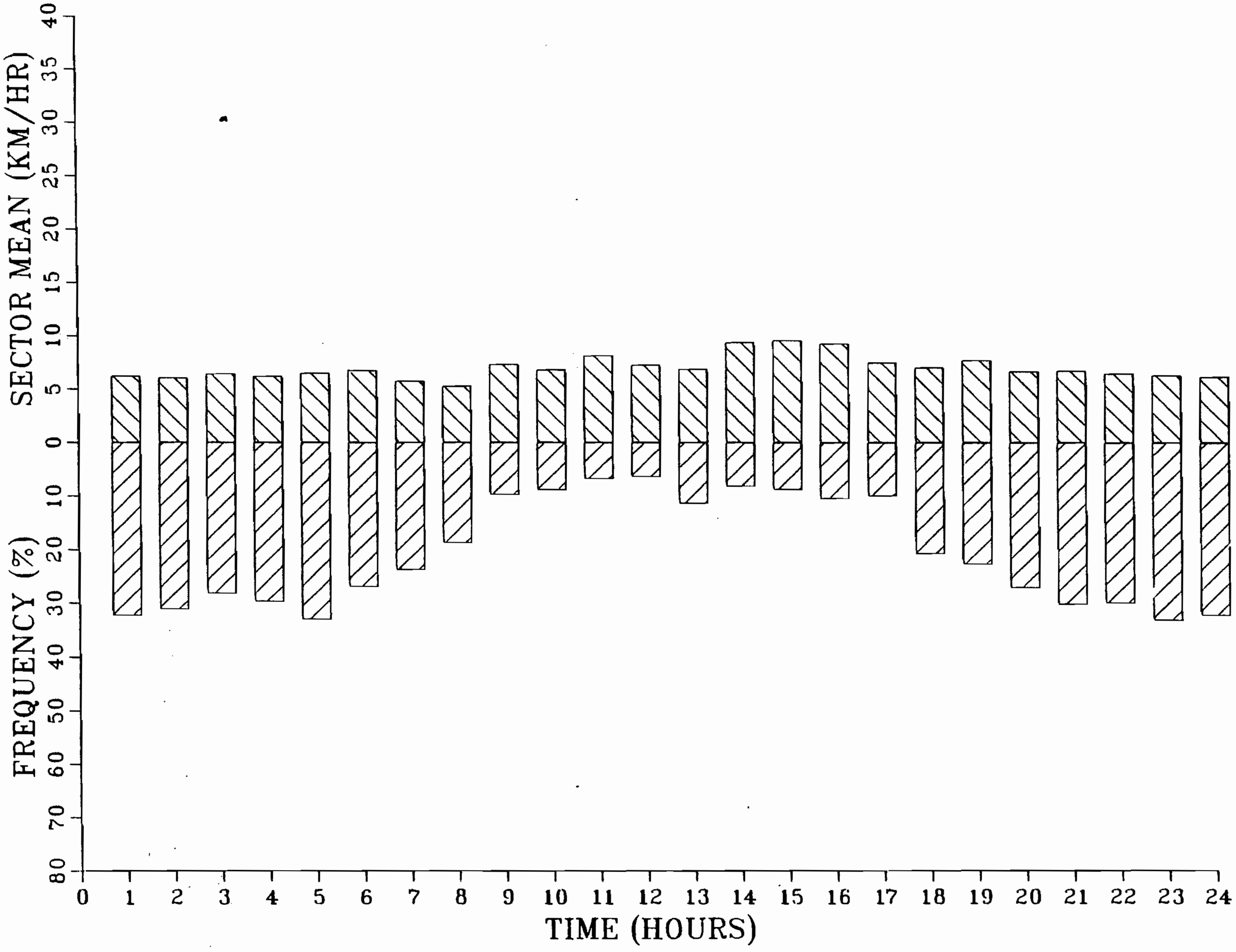


FIGURE 7

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF SOUTH WINDS

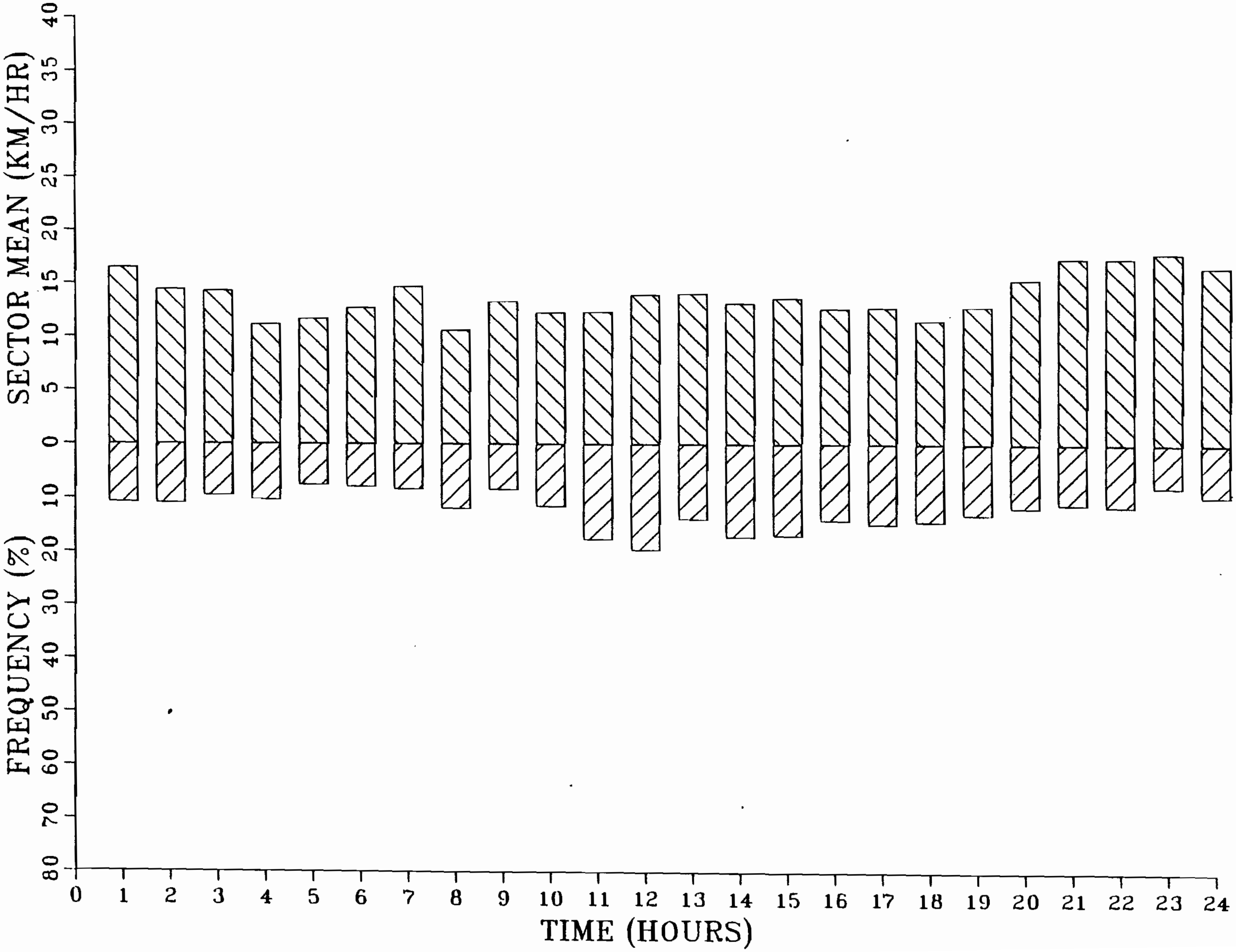


FIGURE 8

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF SOUTH–WEST WINDS

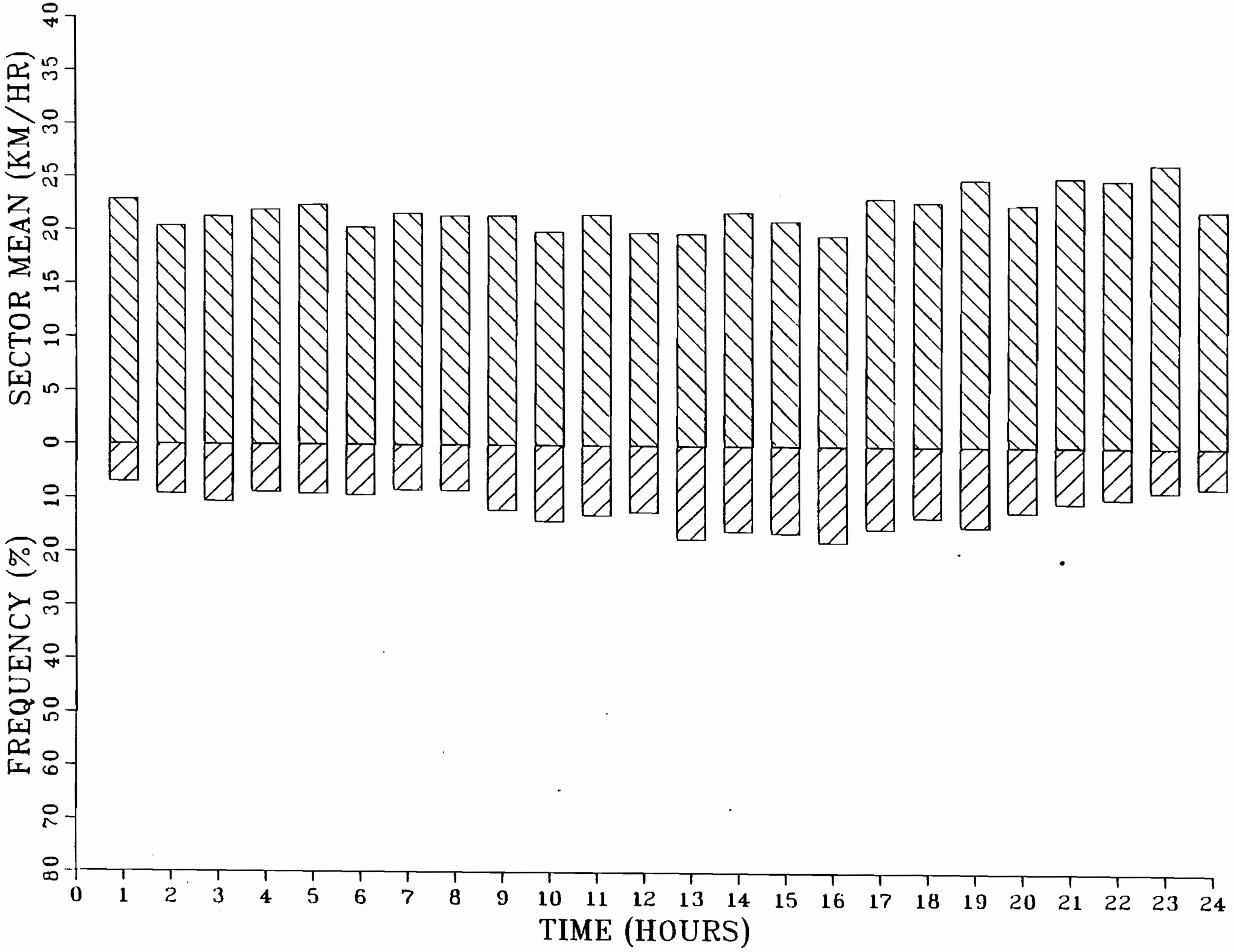


FIGURE 9

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF WEST WINDS

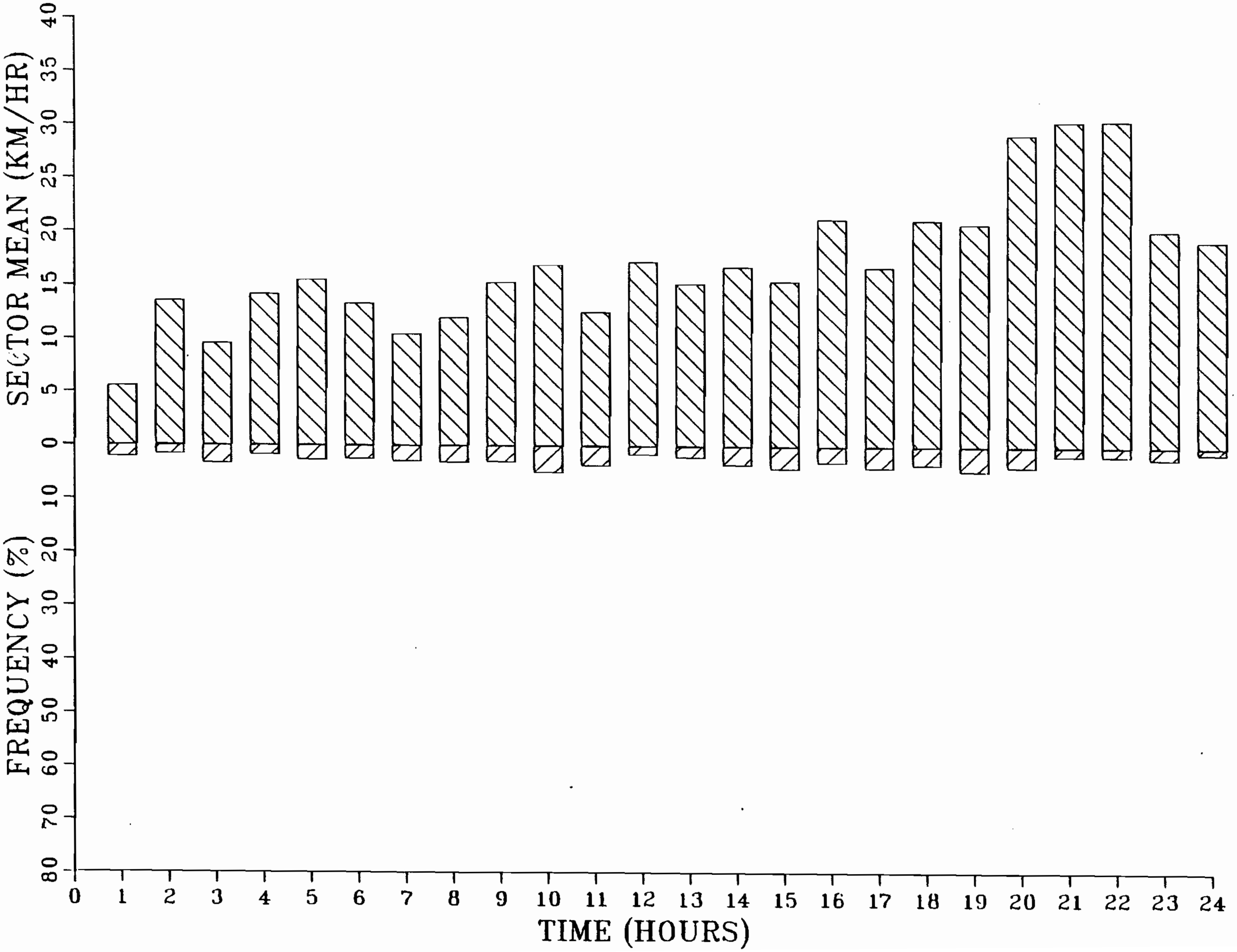


FIGURE 10

KELOWNA BRIDGE – ANNUAL OCCURRENCE OF NORTH–WEST WINDS

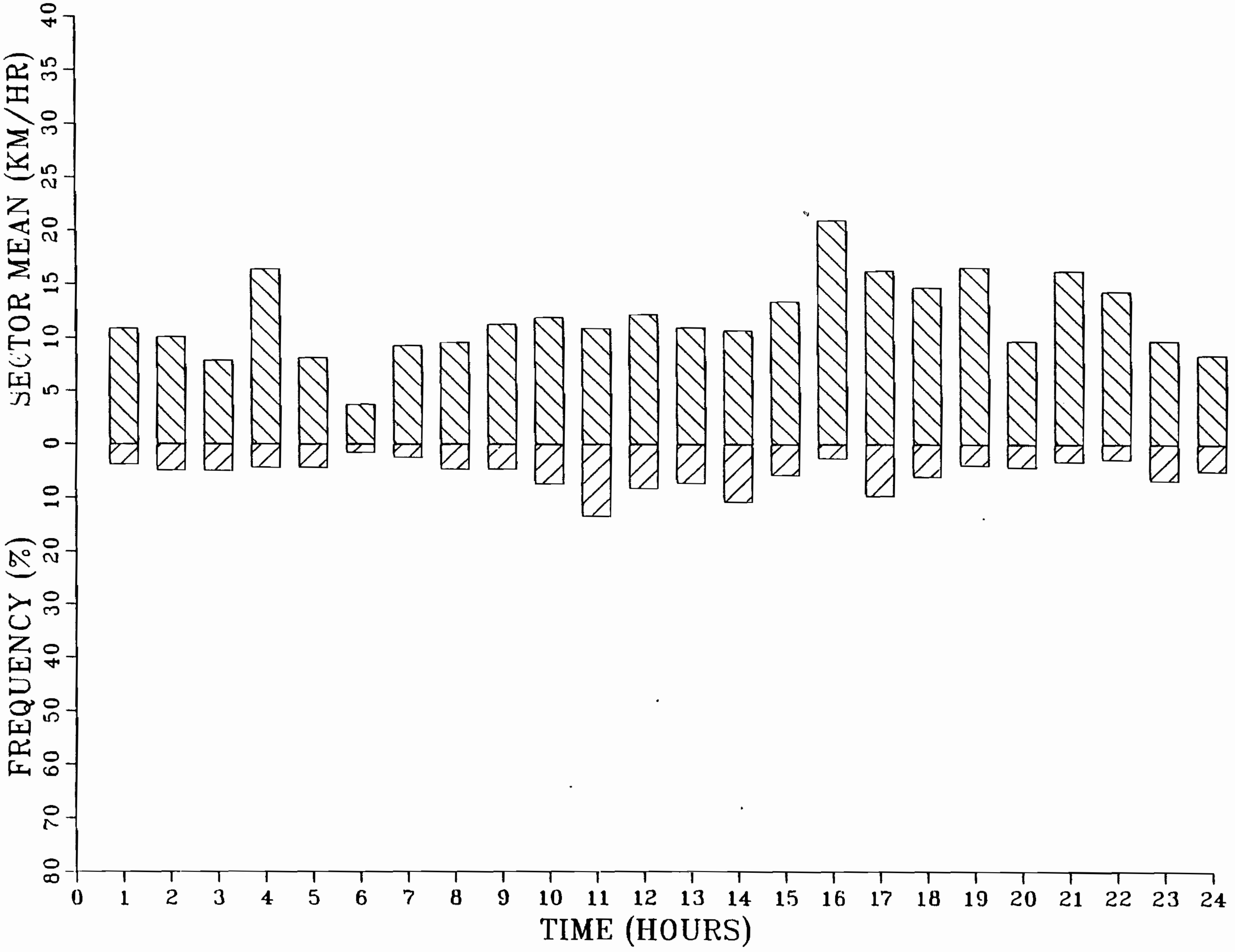


FIGURE 1

PREDOMINANT HOURLY WINDS FOR DEEPER CREEK

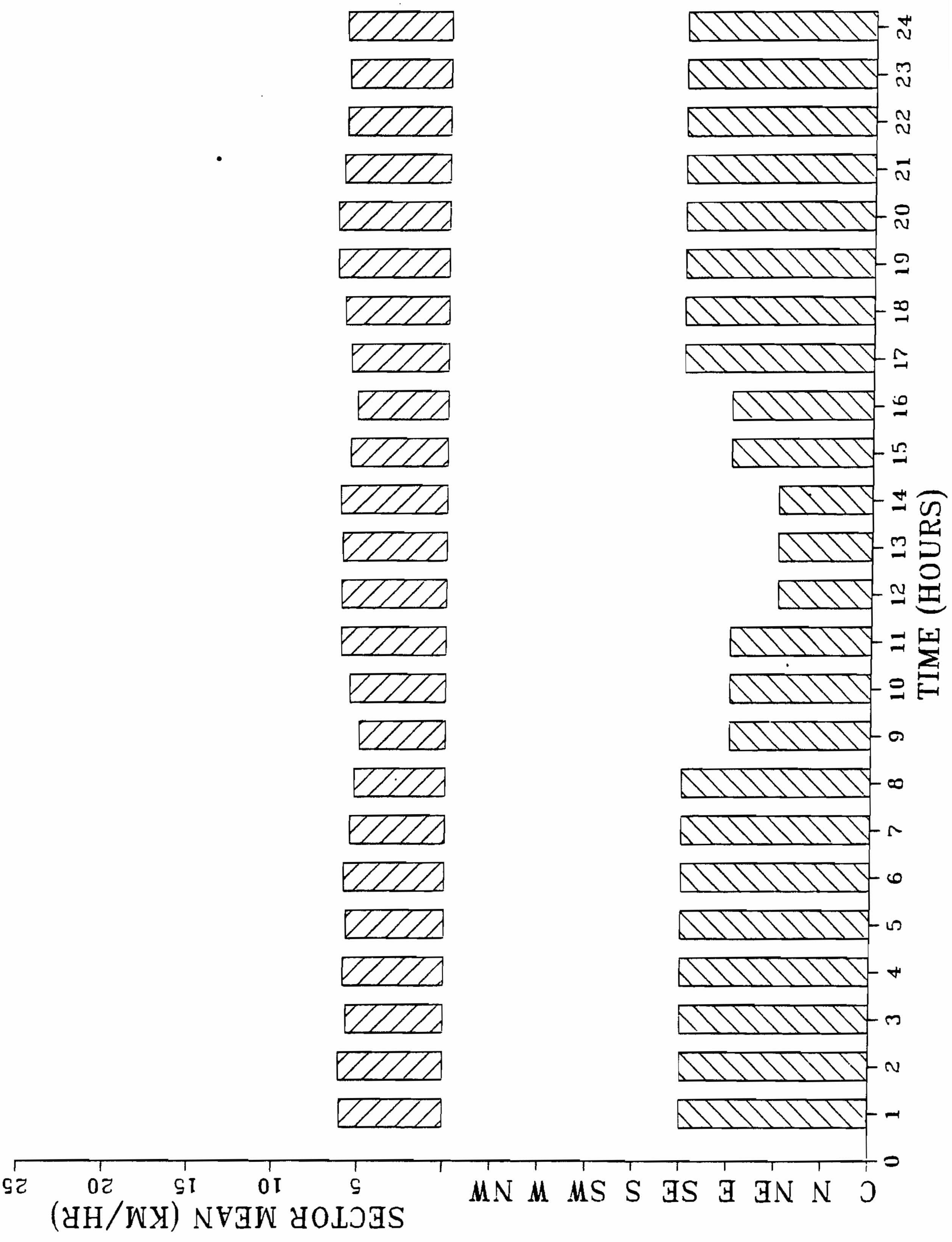


FIGURE 2

DEEPER CREEK – ANNUAL OCCURRENCE OF CALMS

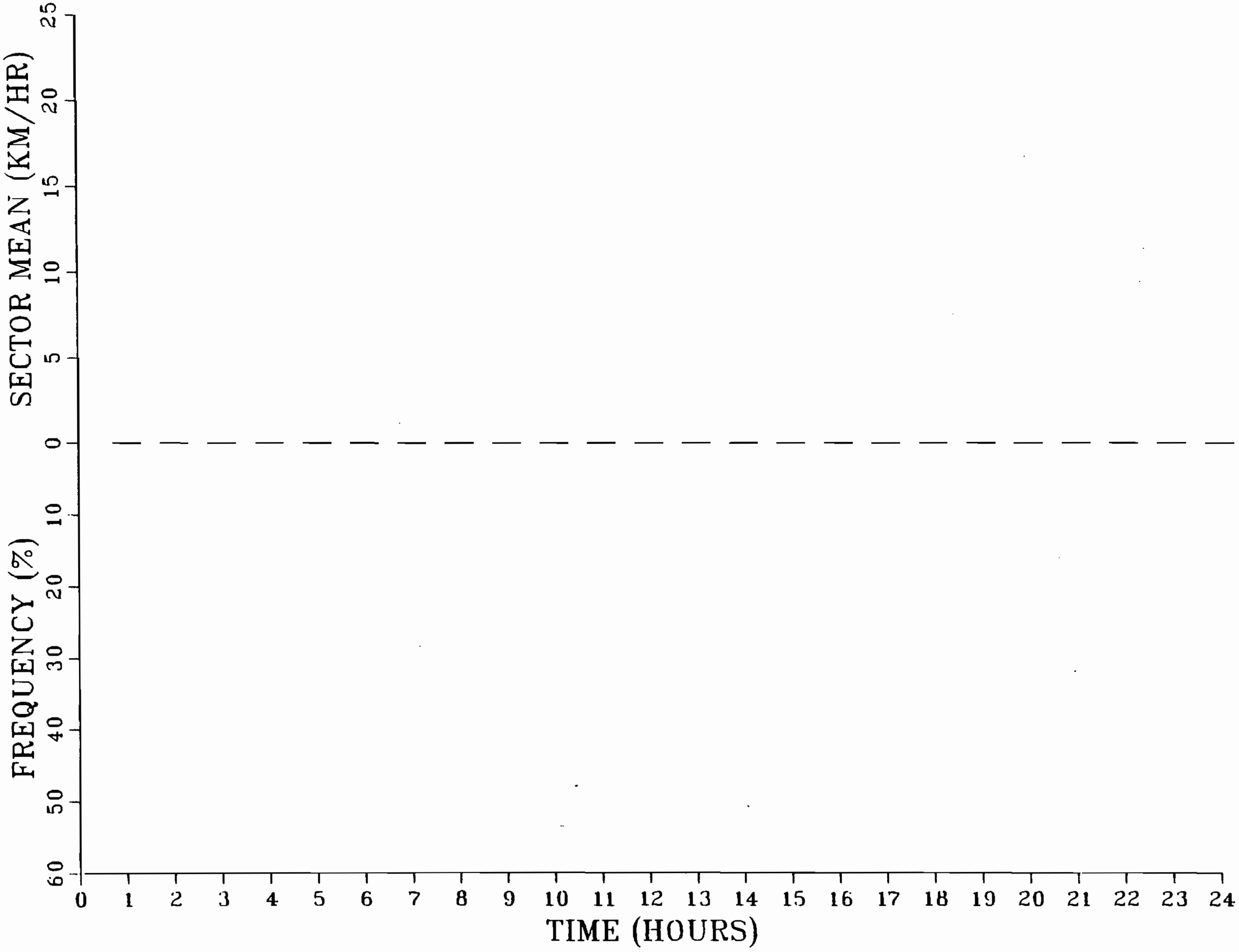


FIGURE 3

DEEPER CREEK – ANNUAL OCCURRENCE OF NORTH WINDS

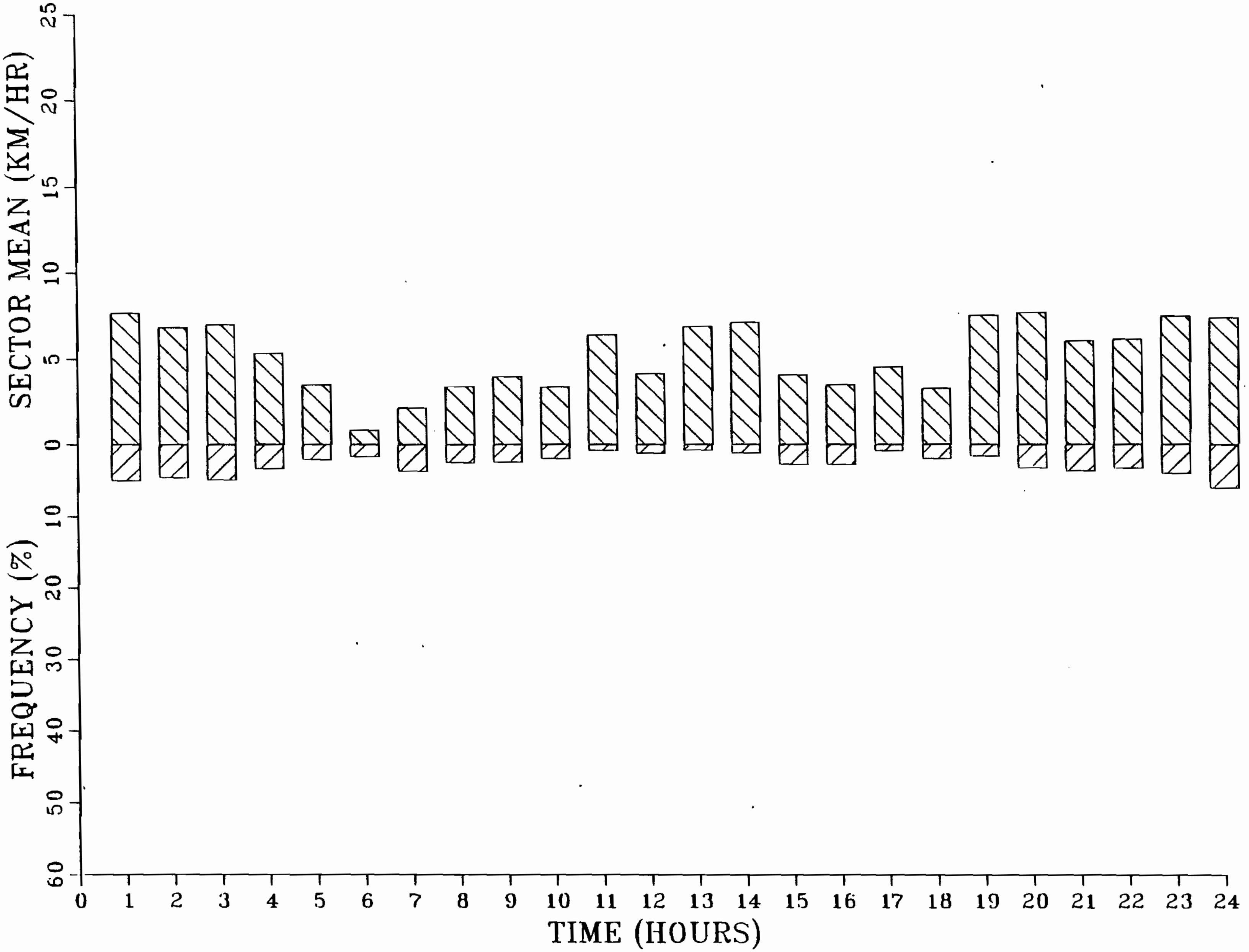


FIGURE 4

DEEPER CREEK – ANNUAL OCCURRENCE OF NORTH-EAST WINDS

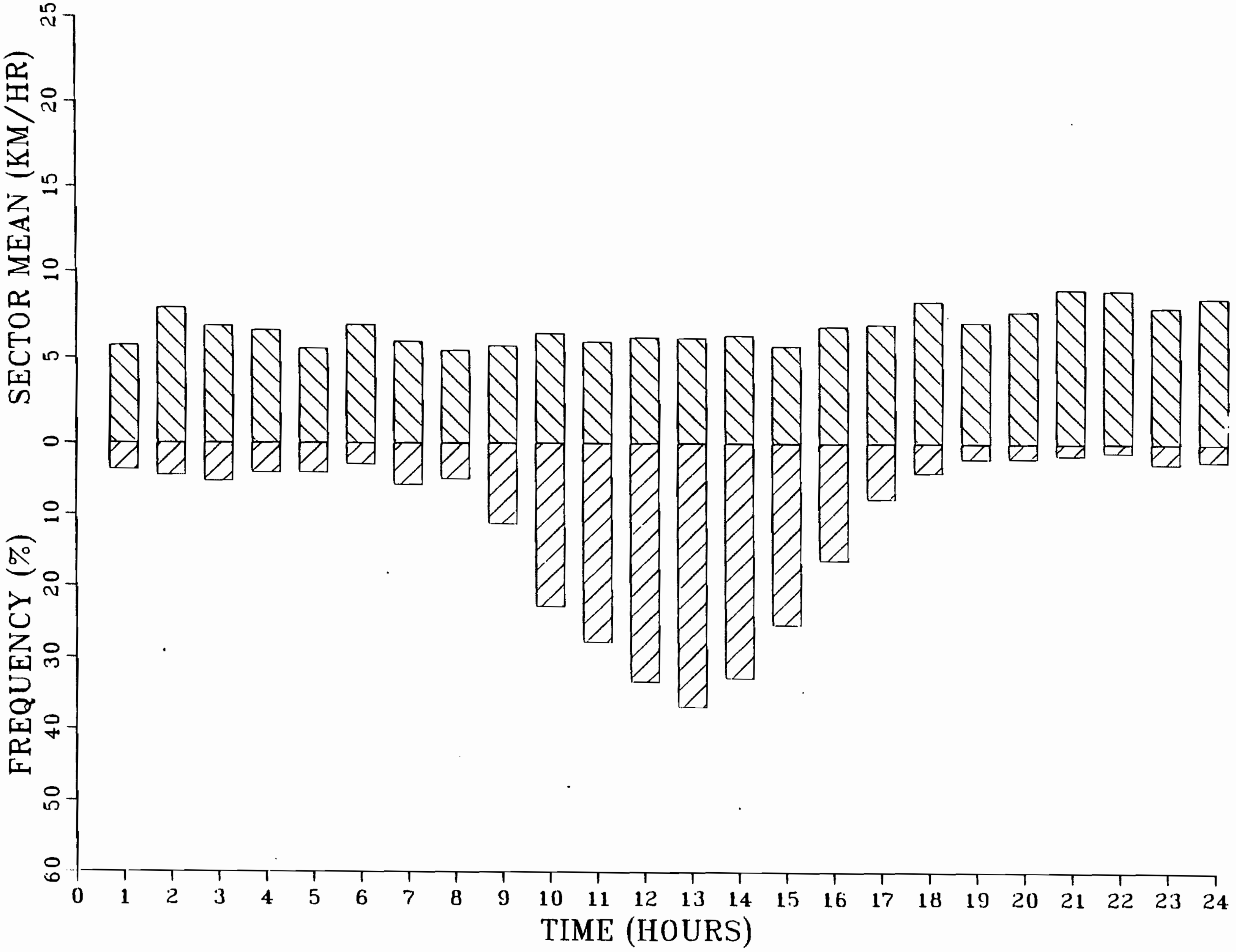


FIGURE 5

DEEPER CREEK - ANNUAL OCCURRENCE OF EAST WINDS

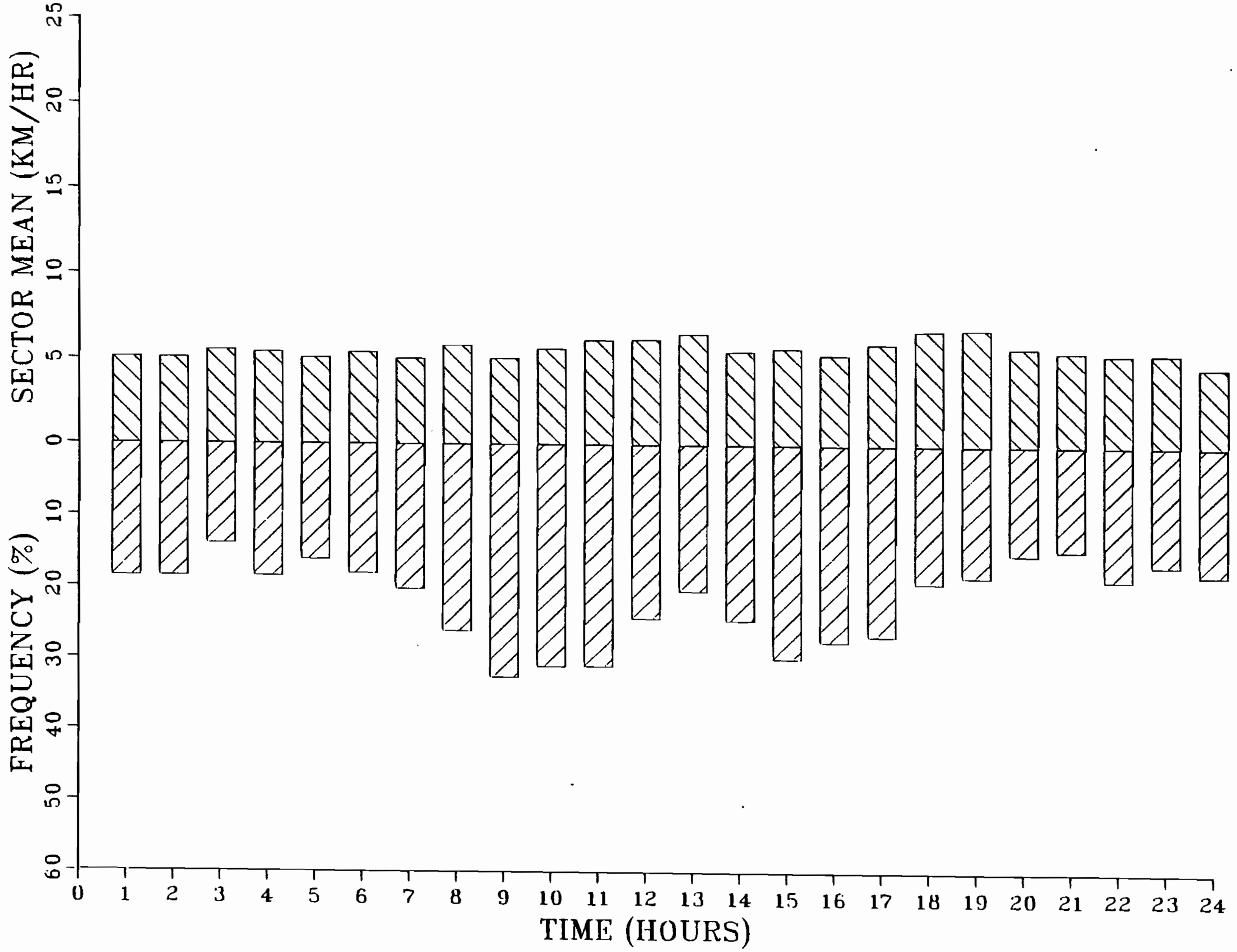


FIGURE 6

DEEPER CREEK – ANNUAL OCCURRENCE OF SOUTH–EAST WINDS

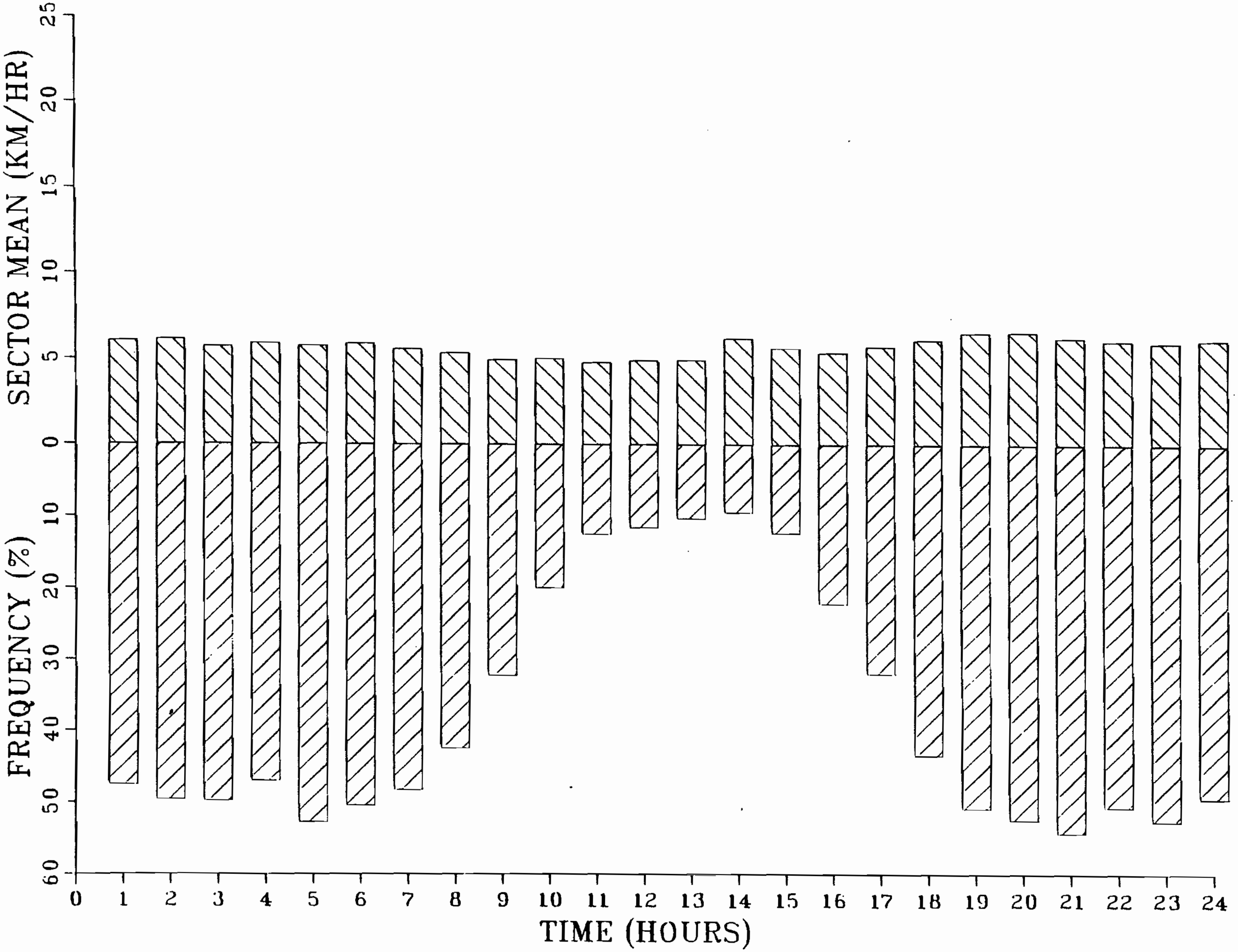


FIGURE 7

DEEPER CREEK – ANNUAL OCCURRENCE OF SOUTH WINDS

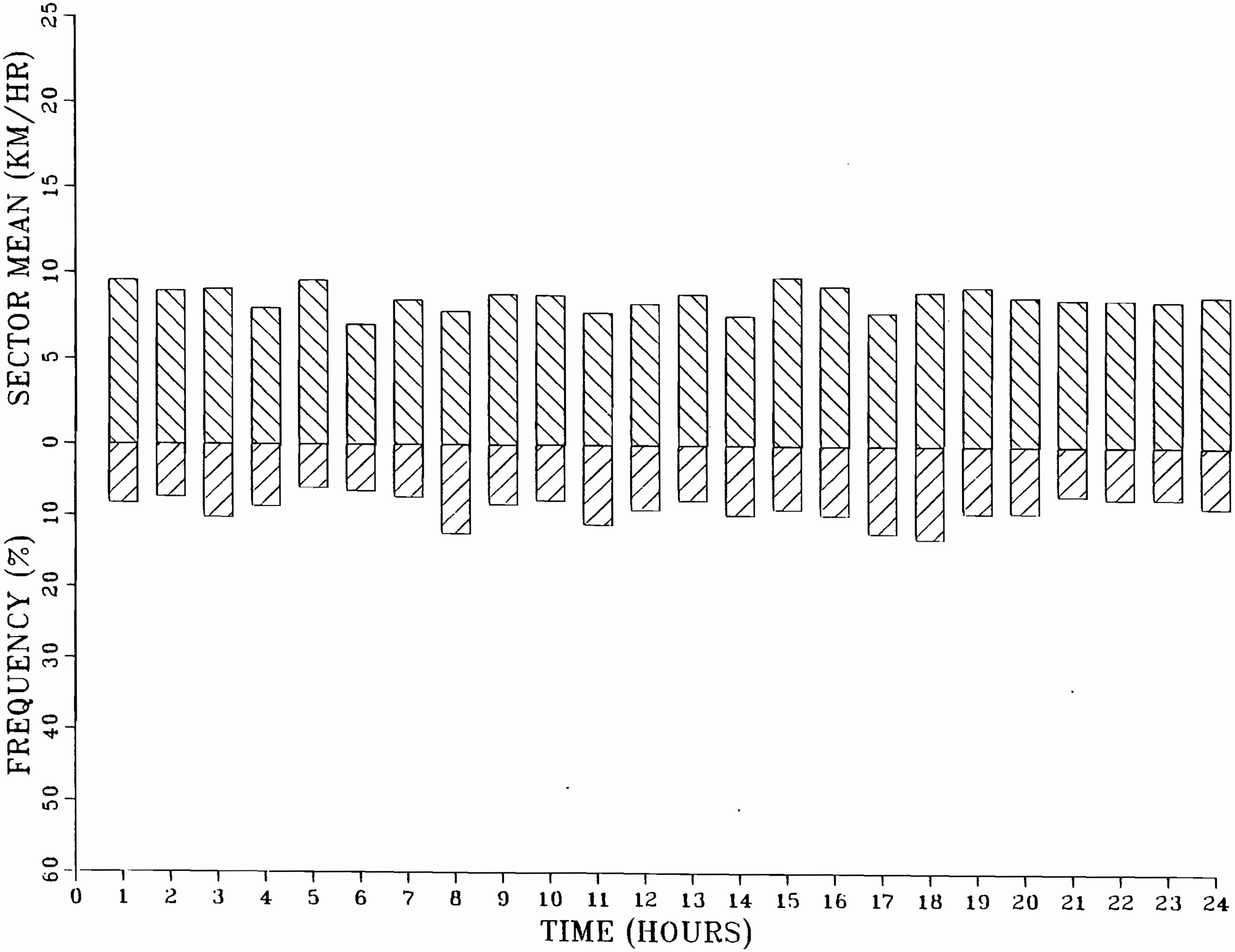


FIGURE 8

DEEPER CREEK – ANNUAL OCCURRENCE OF SOUTH–WEST WINDS

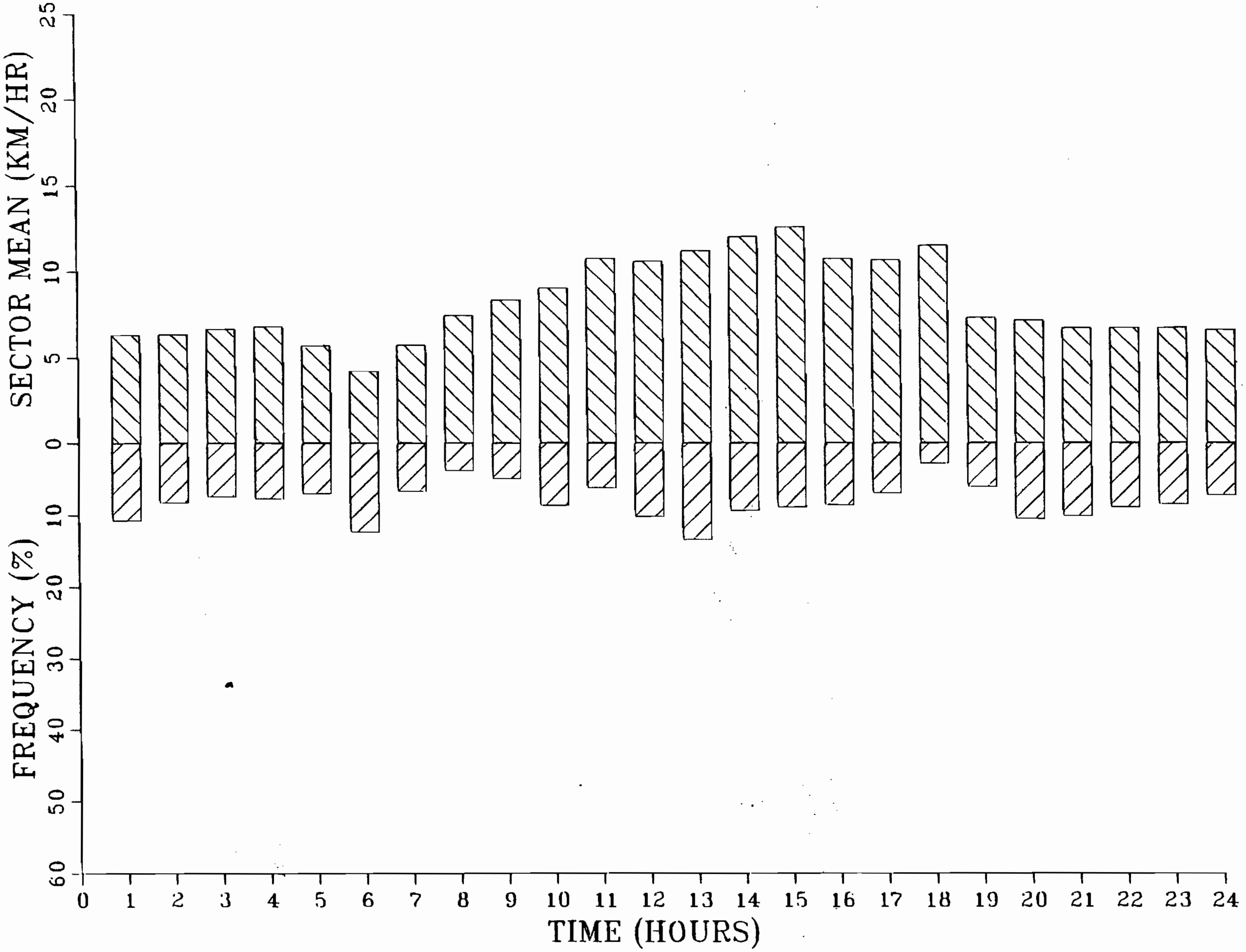


FIGURE 9

DEEPER CREEK – ANNUAL OCCURRENCE OF WEST WINDS

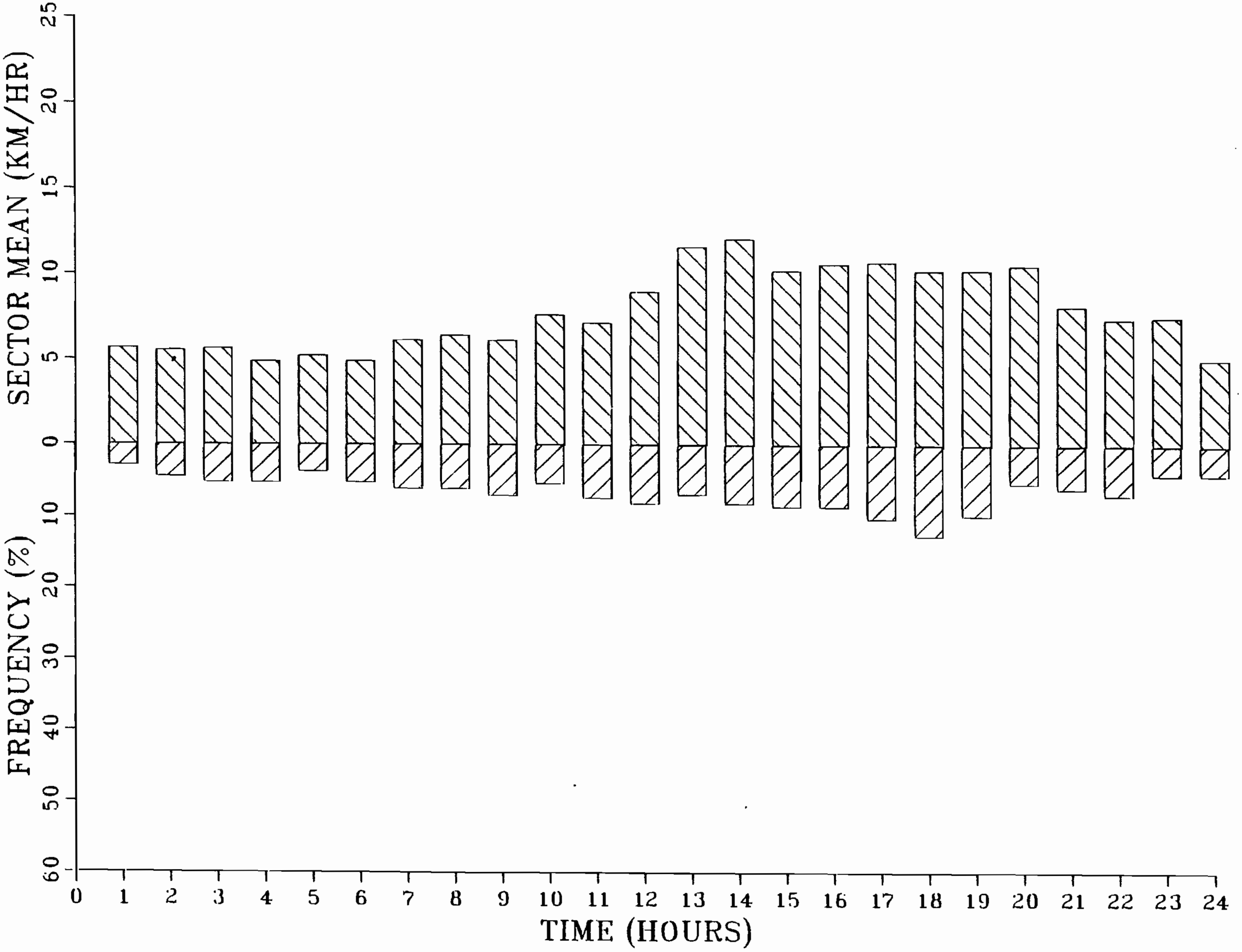


FIGURE 10

DEEPER CREEK – ANNUAL OCCURRENCE OF NORTH–WEST WINDS

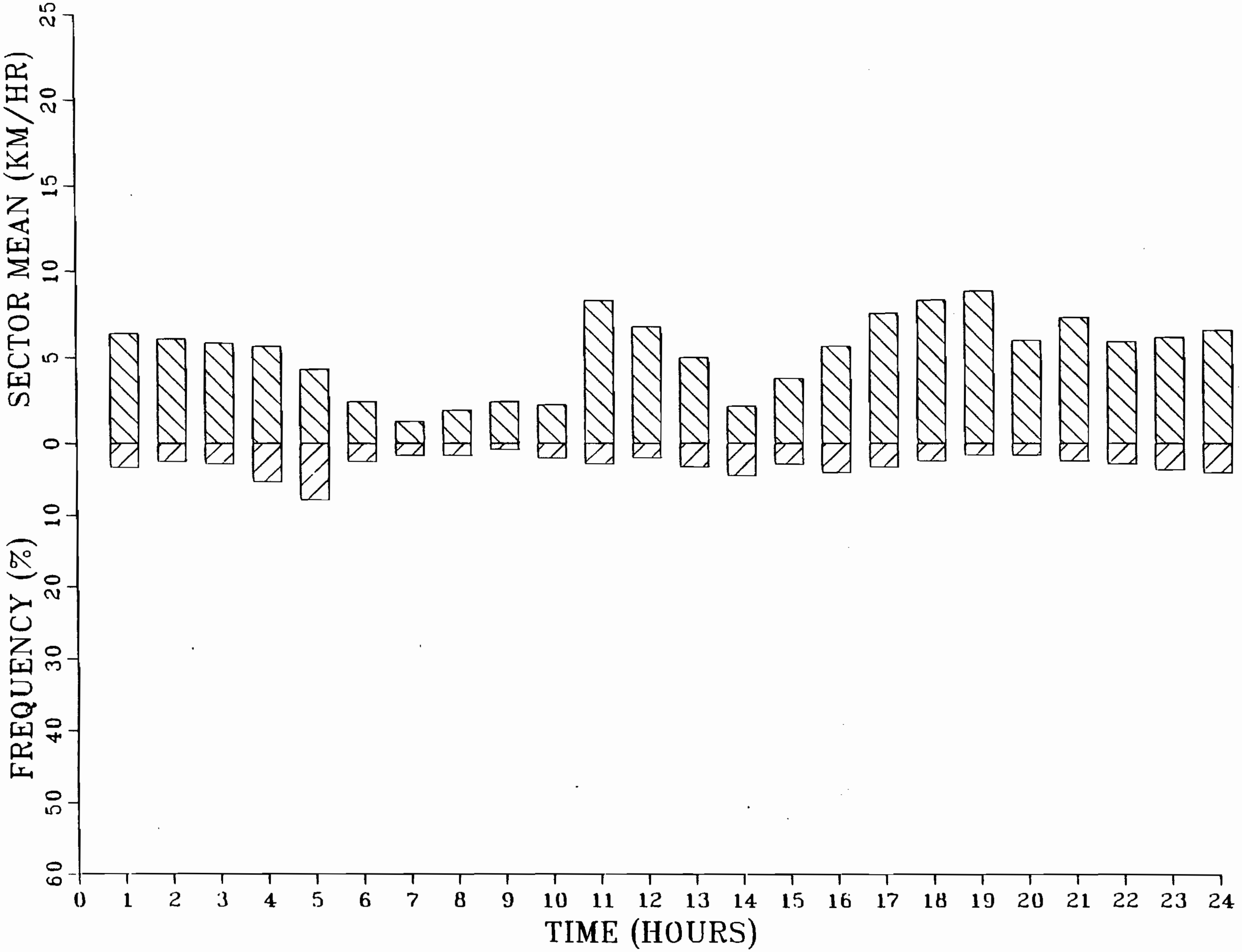


FIGURE 1

PREDOMINANT HOURLY WINDS FOR PENTICTON MARINA

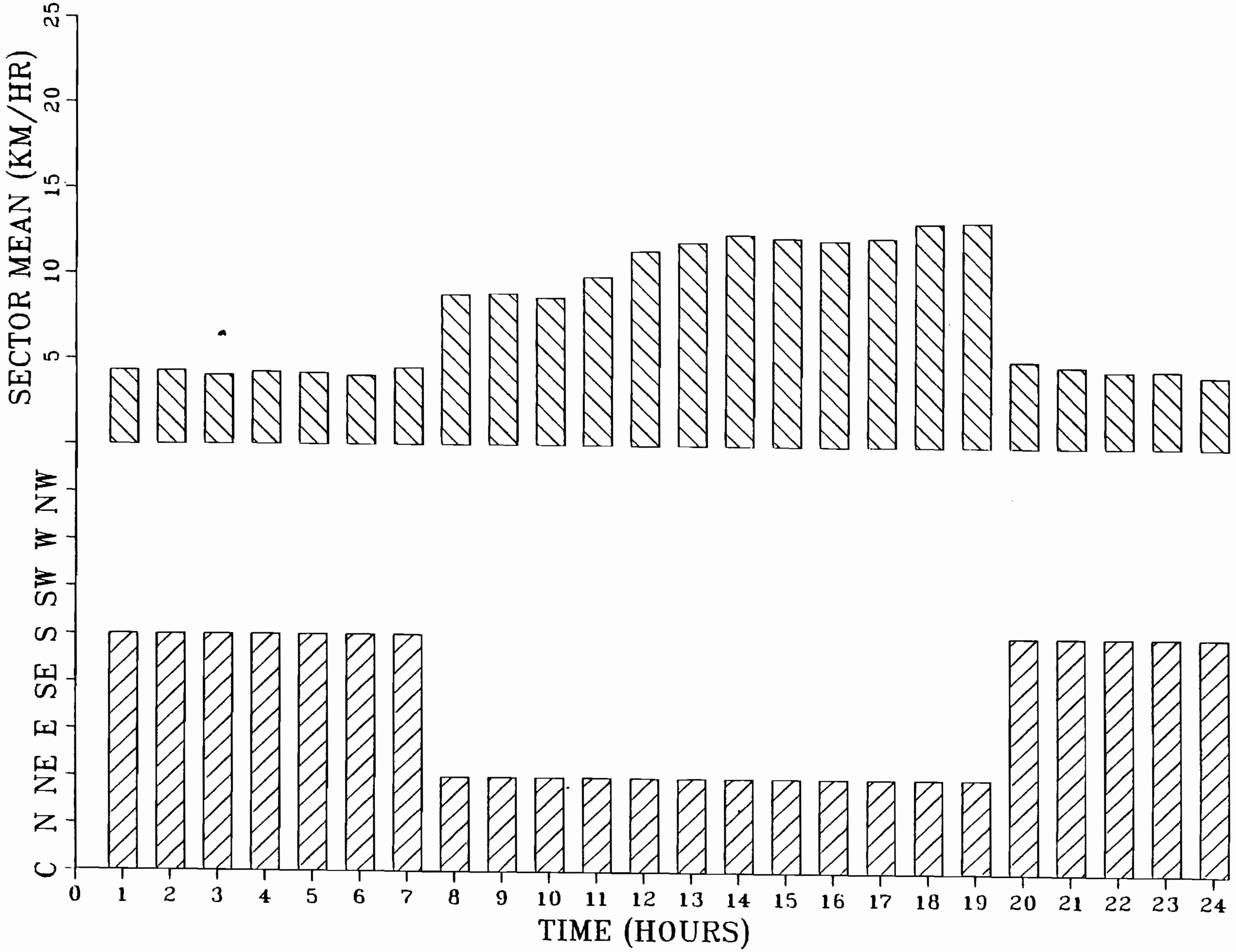


FIGURE 2

PENTICTON MARINA - ANNUAL OCCURRENCE OF CALMS

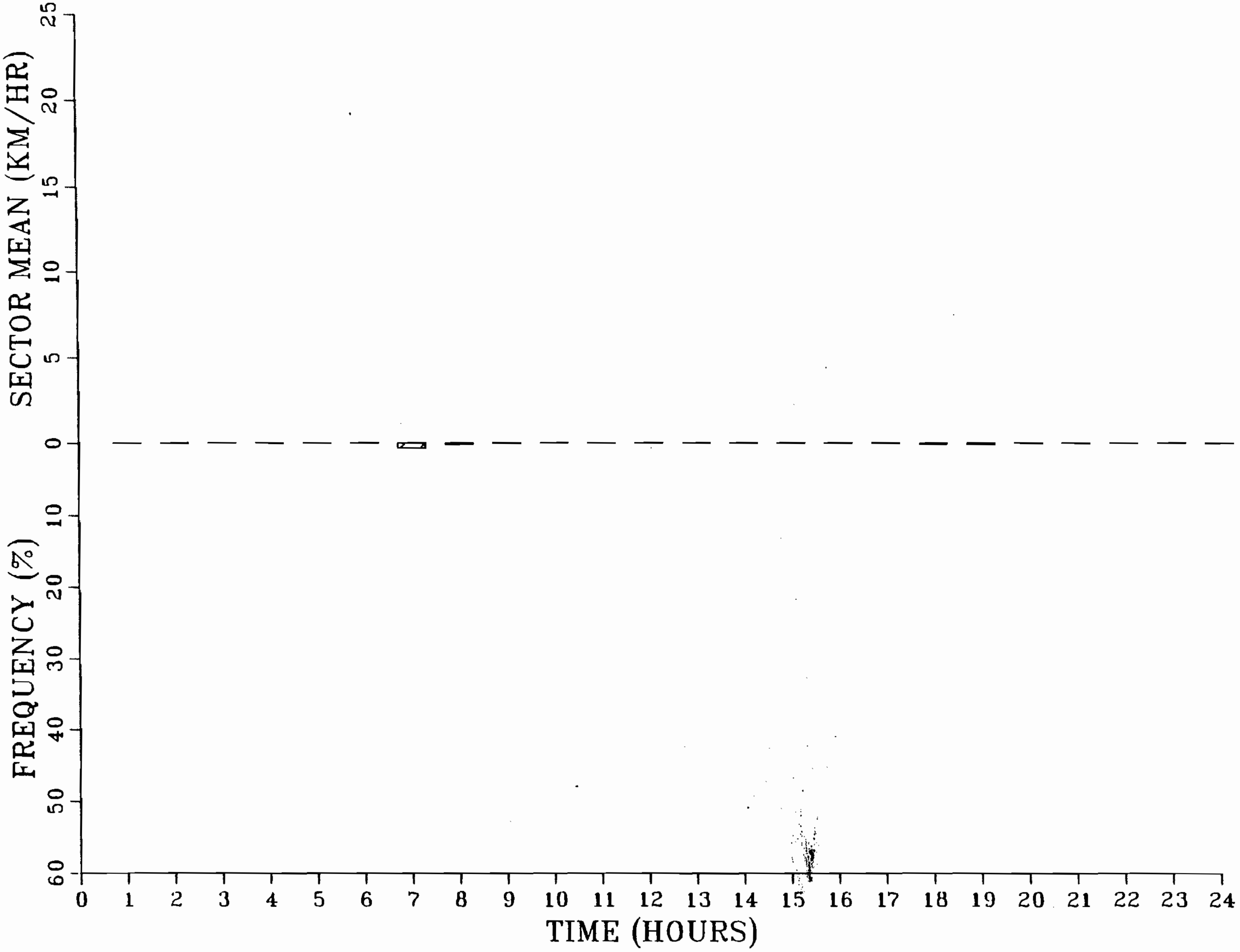


FIGURE 3

PENTICTON MARINA – ANNUAL OCCURRENCE OF NORTH WINDS

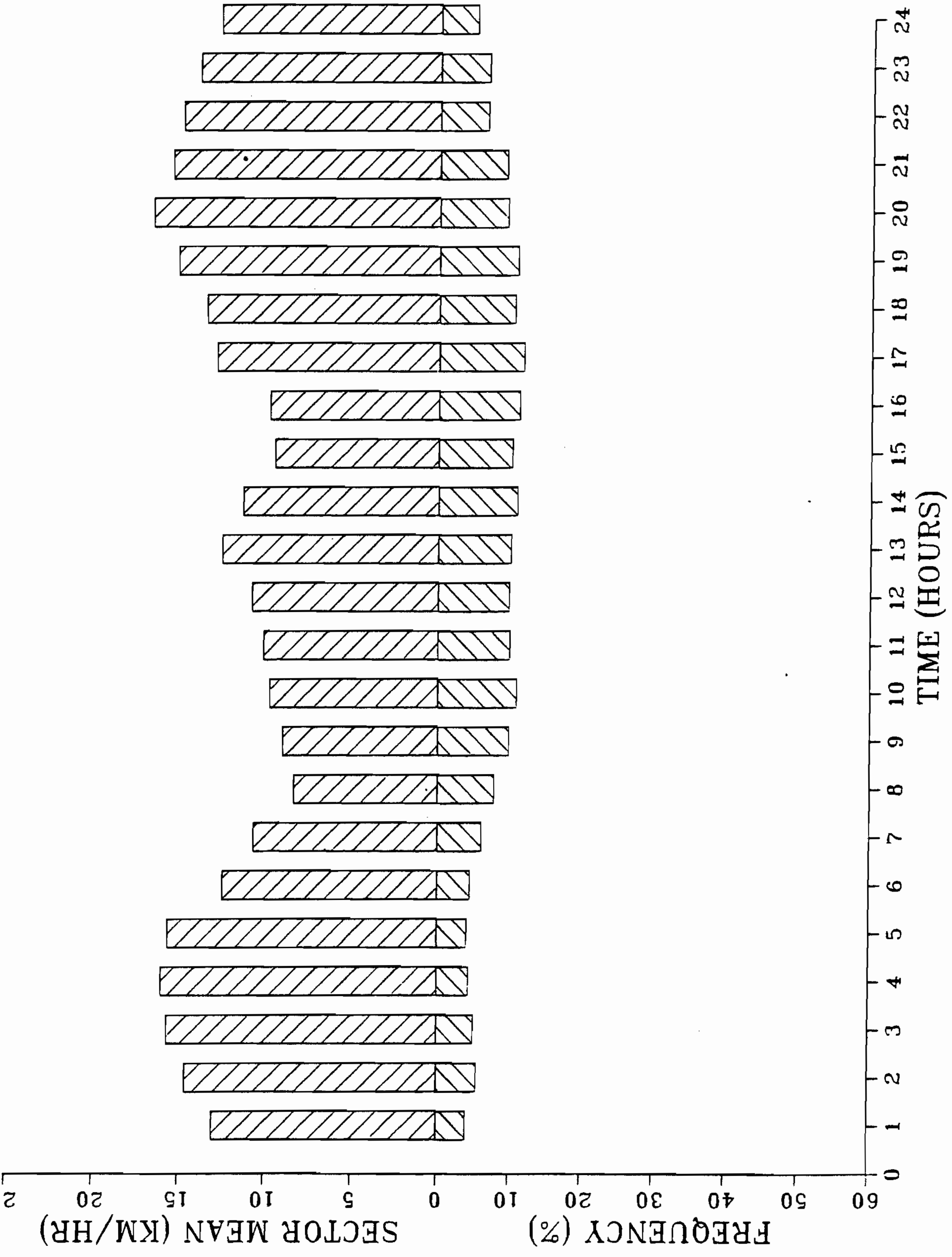


FIGURE 4

PENTICTON MARINA – ANNUAL OCCURRENCE OF NORTH–EAST WINDS

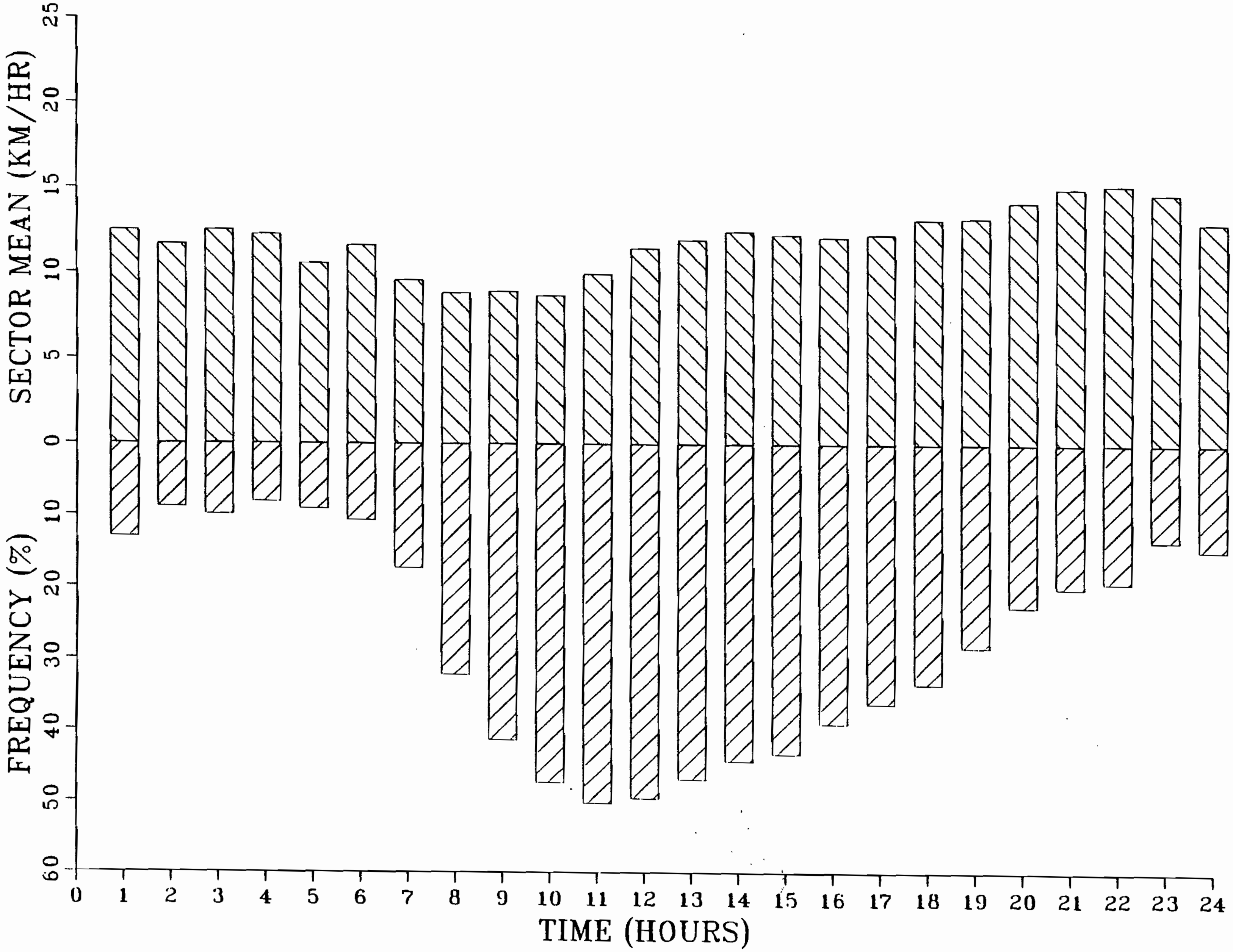


FIGURE 5

PENTICTON MARINA – ANNUAL OCCURRENCE OF EAST WINDS

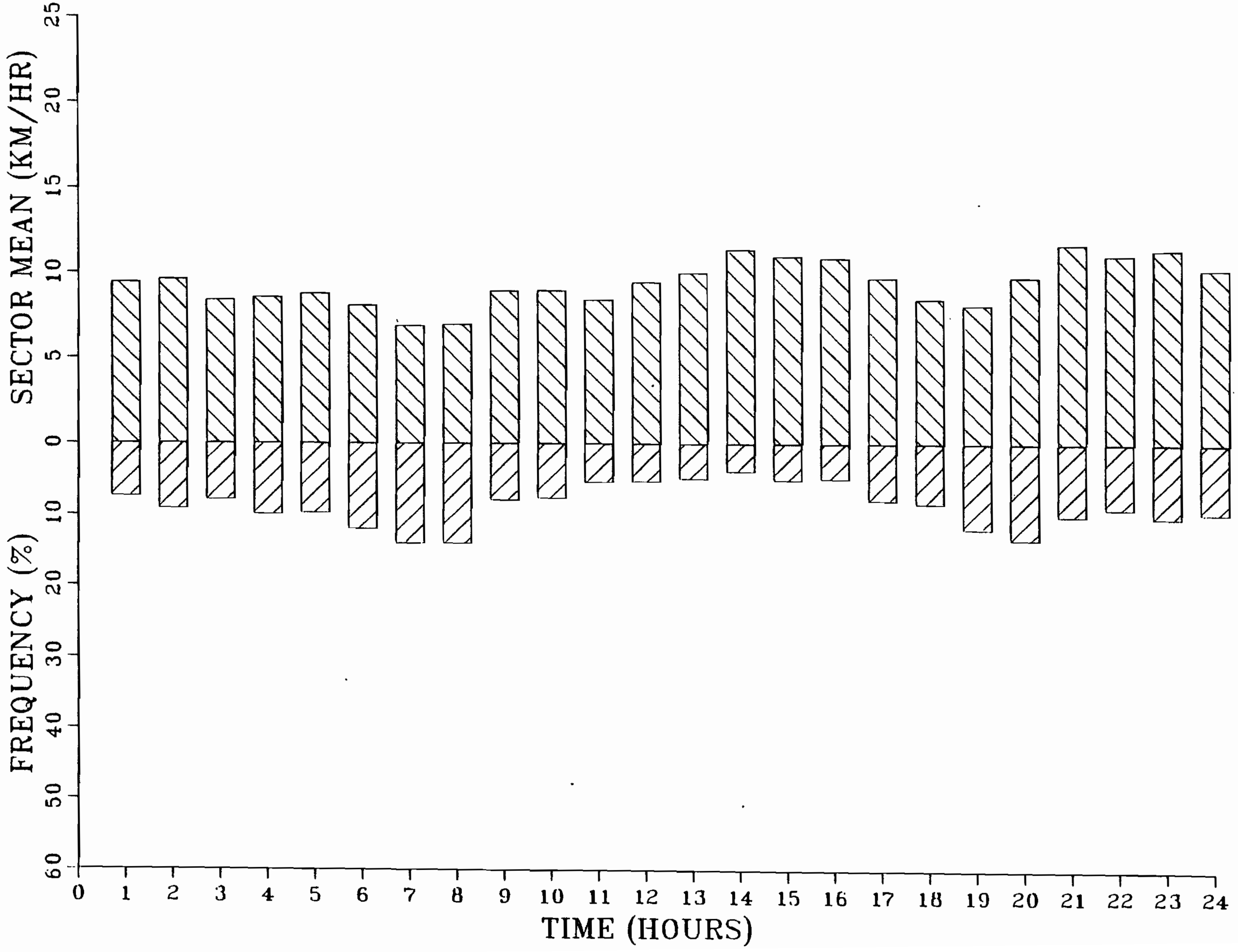


FIGURE 6

PENTICTON MARINA – ANNUAL OCCURRENCE OF SOUTH–EAST WINDS

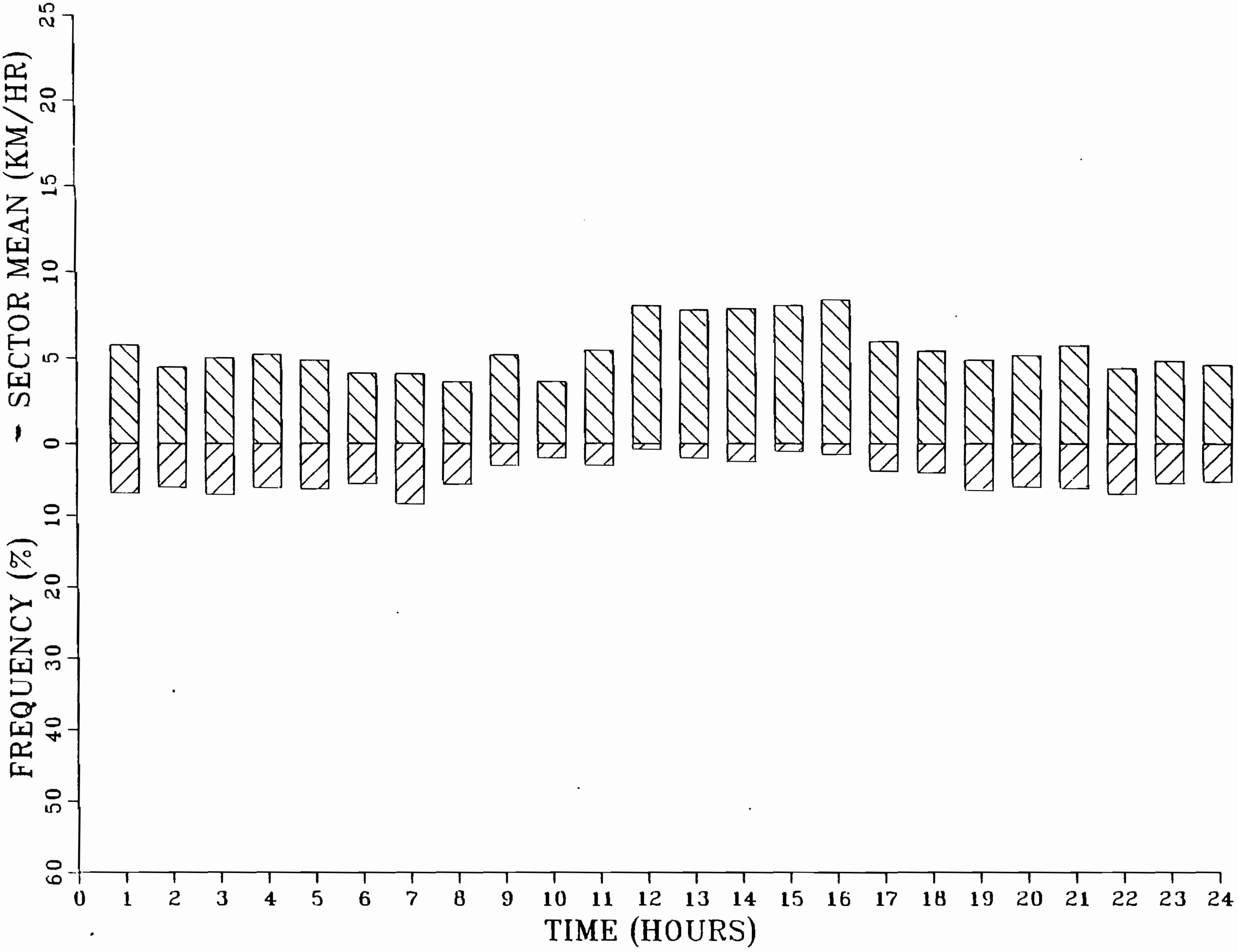


FIGURE 7

PENTICTON MARINA – ANNUAL OCCURRENCE OF SOUTH WINDS

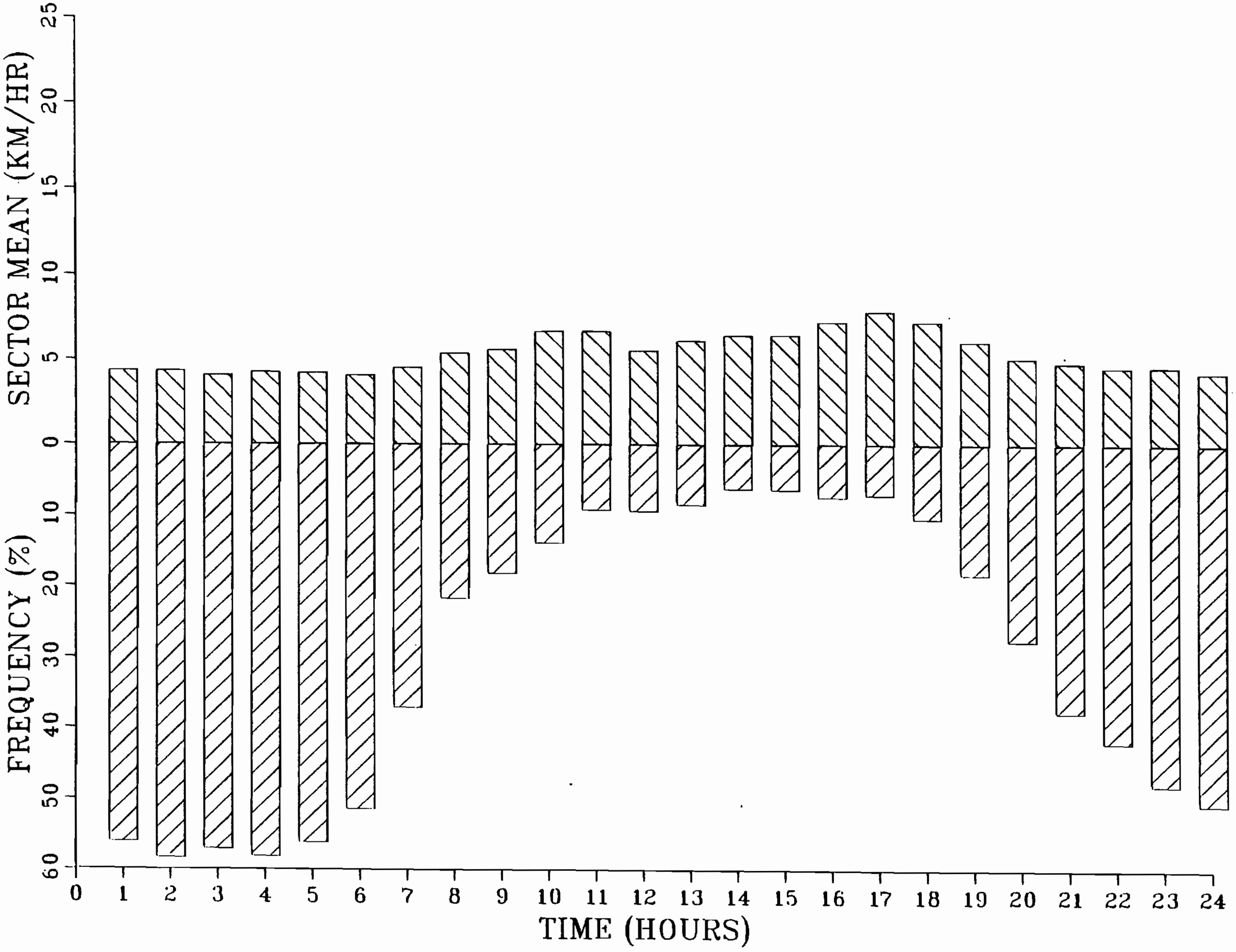


FIGURE 8

PENTICTON MARINA – ANNUAL OCCURRENCE OF SOUTH–WEST WINDS

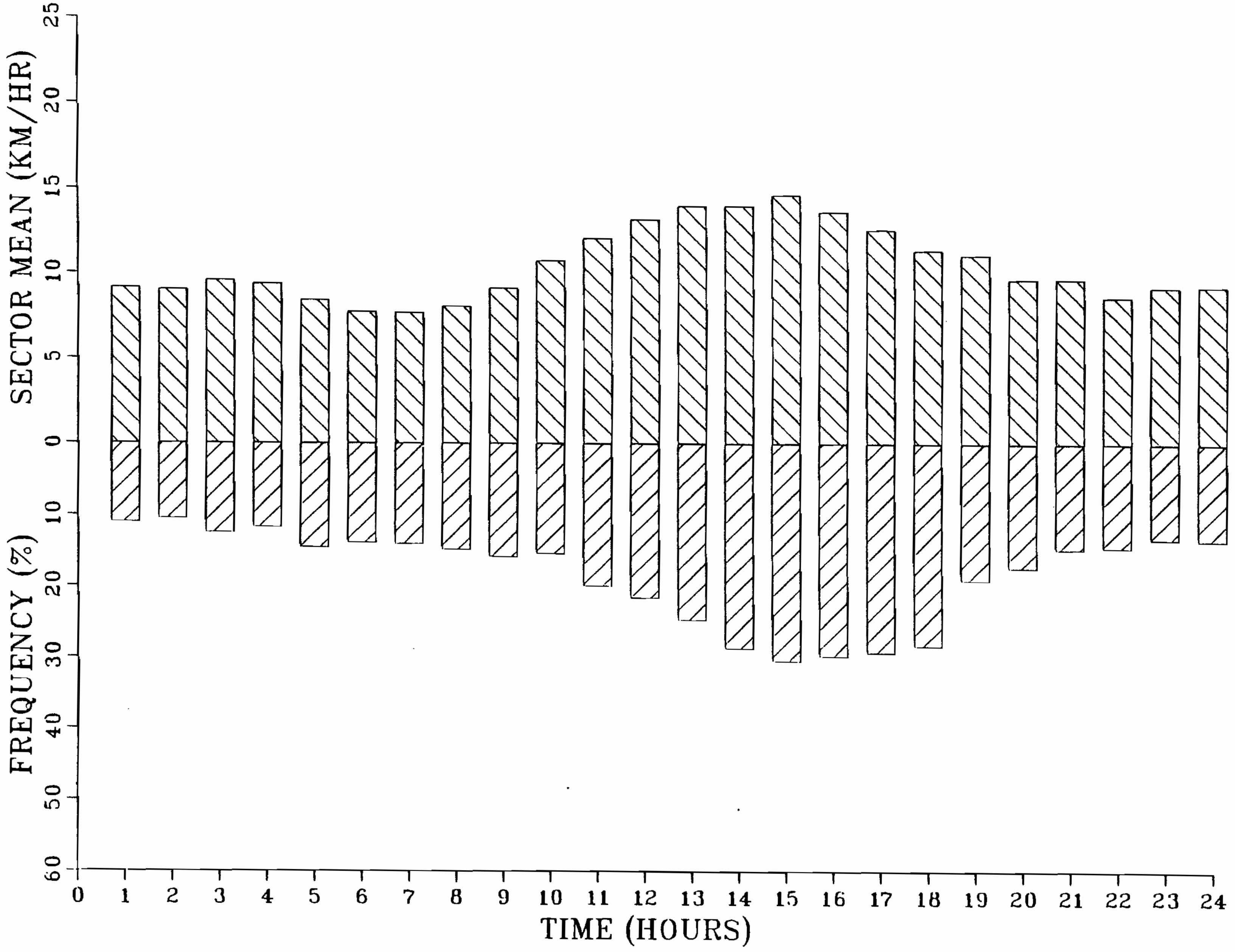


FIGURE 9

PENTICTON MARINA – ANNUAL OCCURRENCE OF WEST WINDS

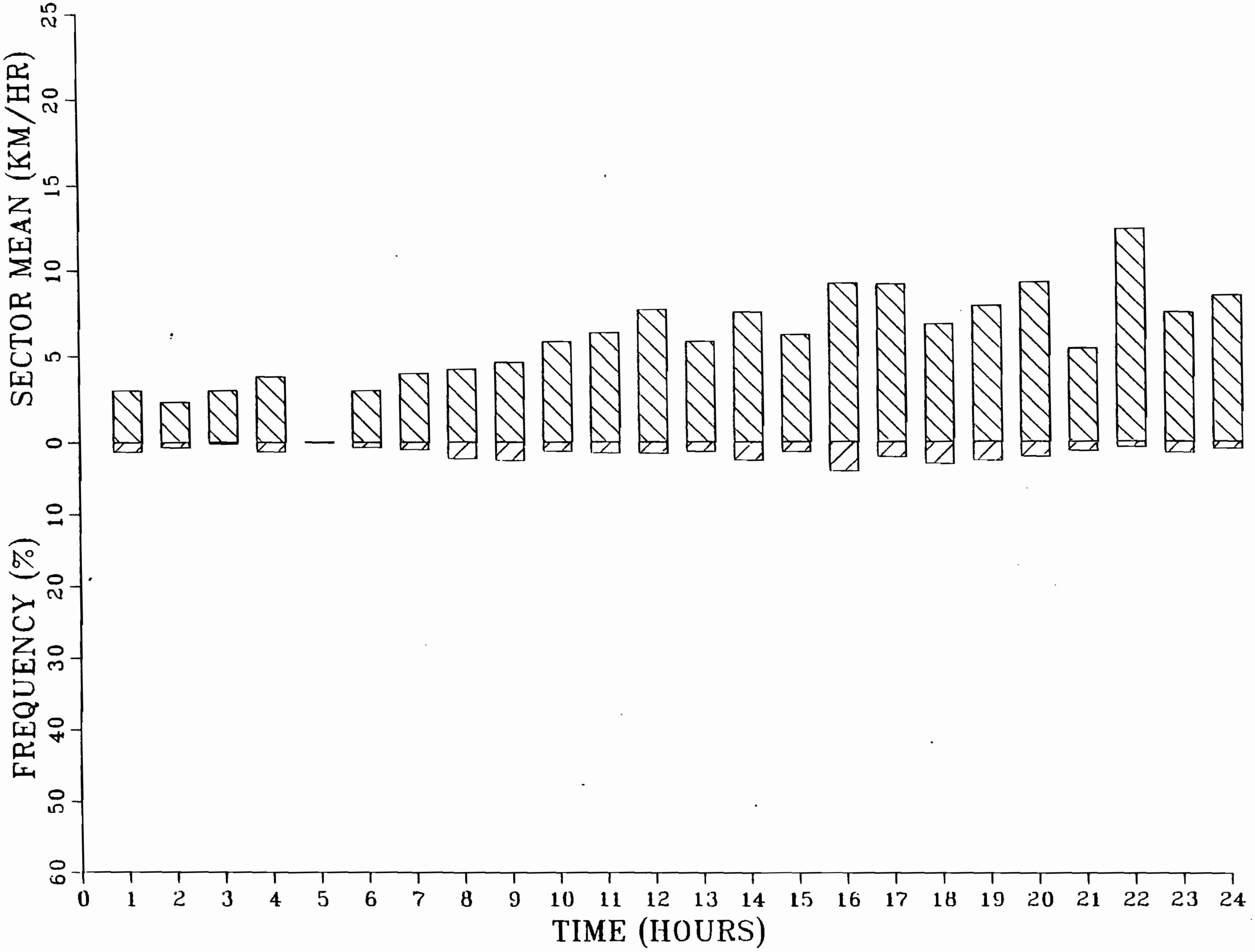


FIGURE 10

PENTICTON MARINA – ANNUAL OCCURRENCE OF NORTH–WEST WINDS

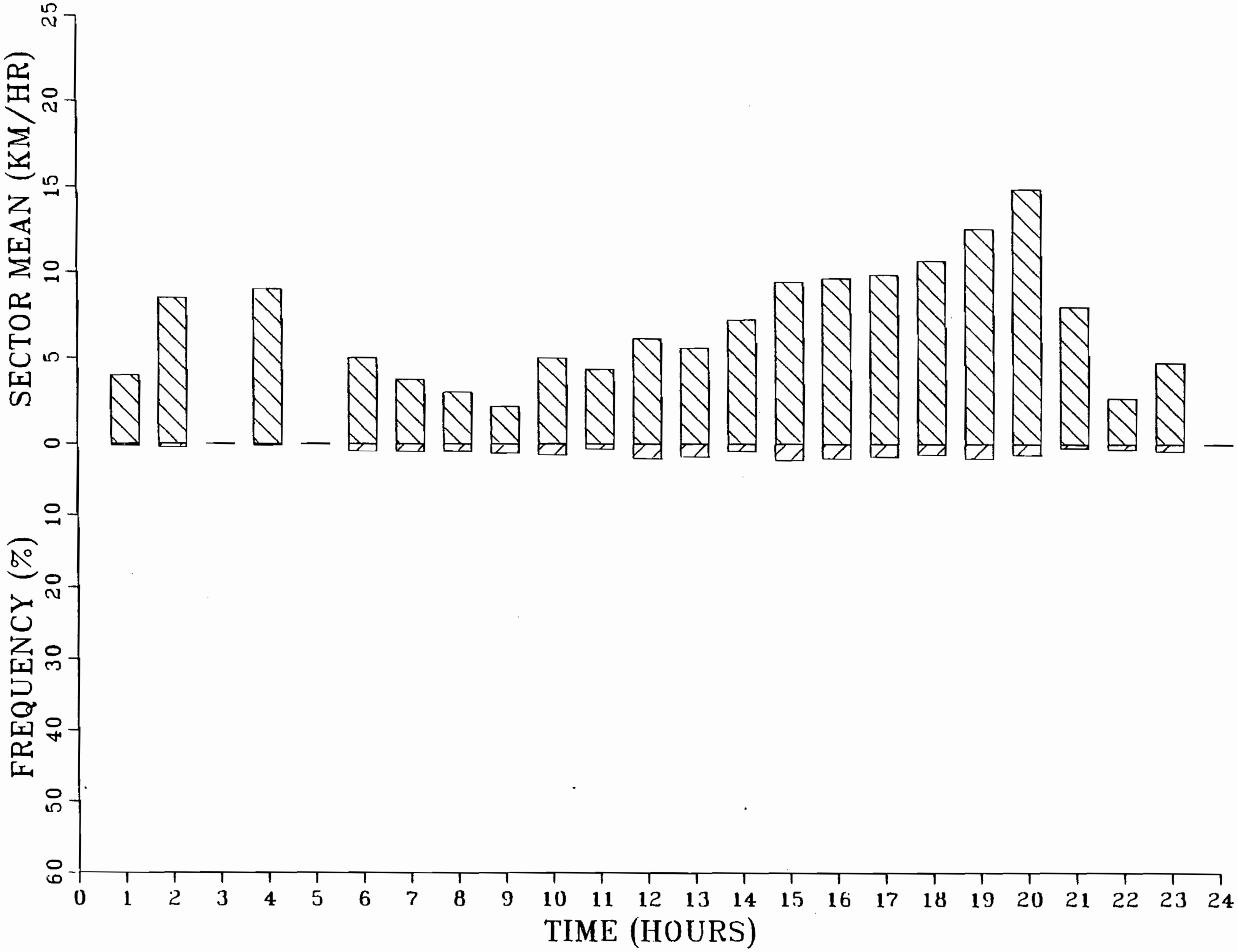


FIGURE 1
PREDOMINANT HOURLY WINDS FOR PENTICTON AIRPORT

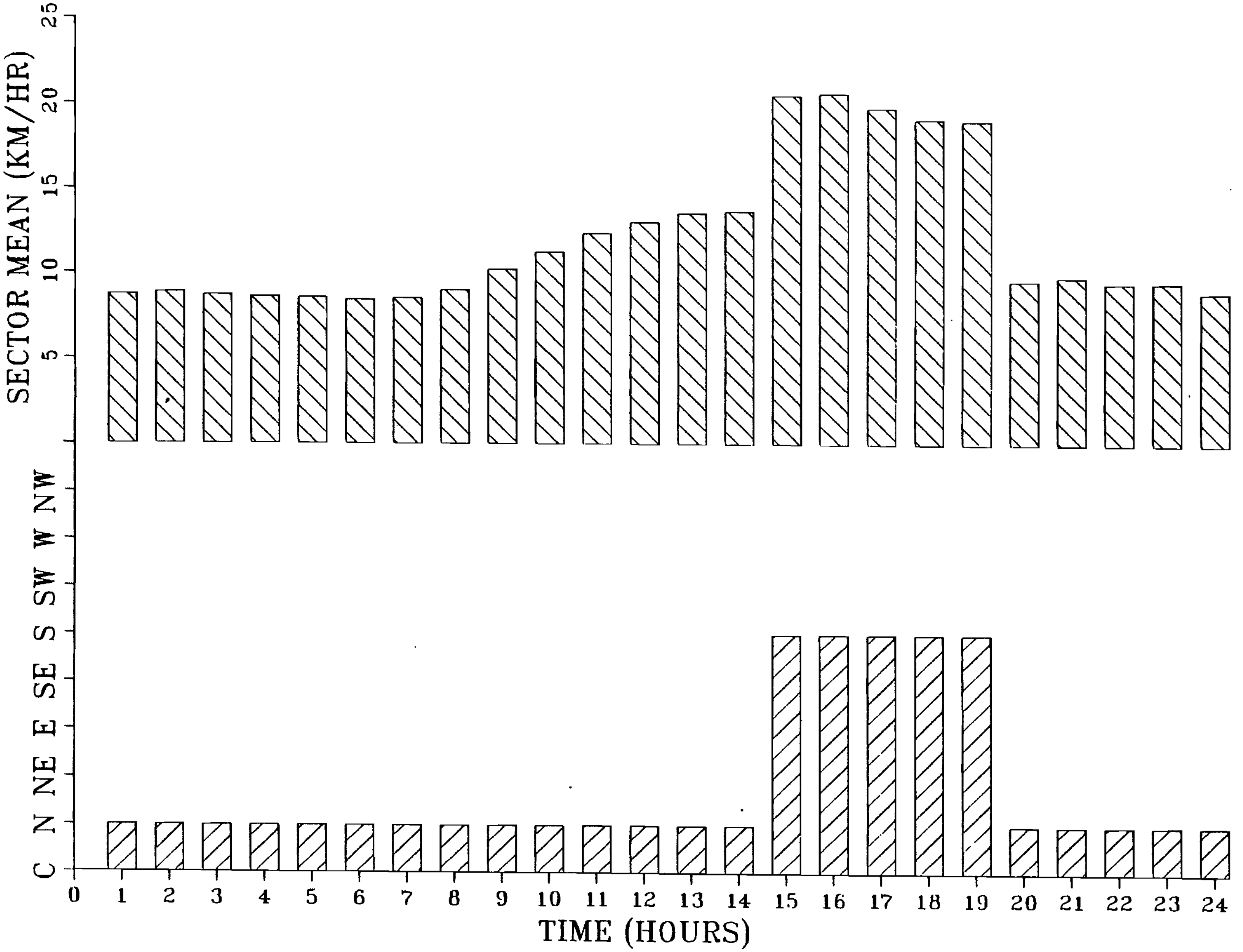


FIGURE 2

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF CALMS

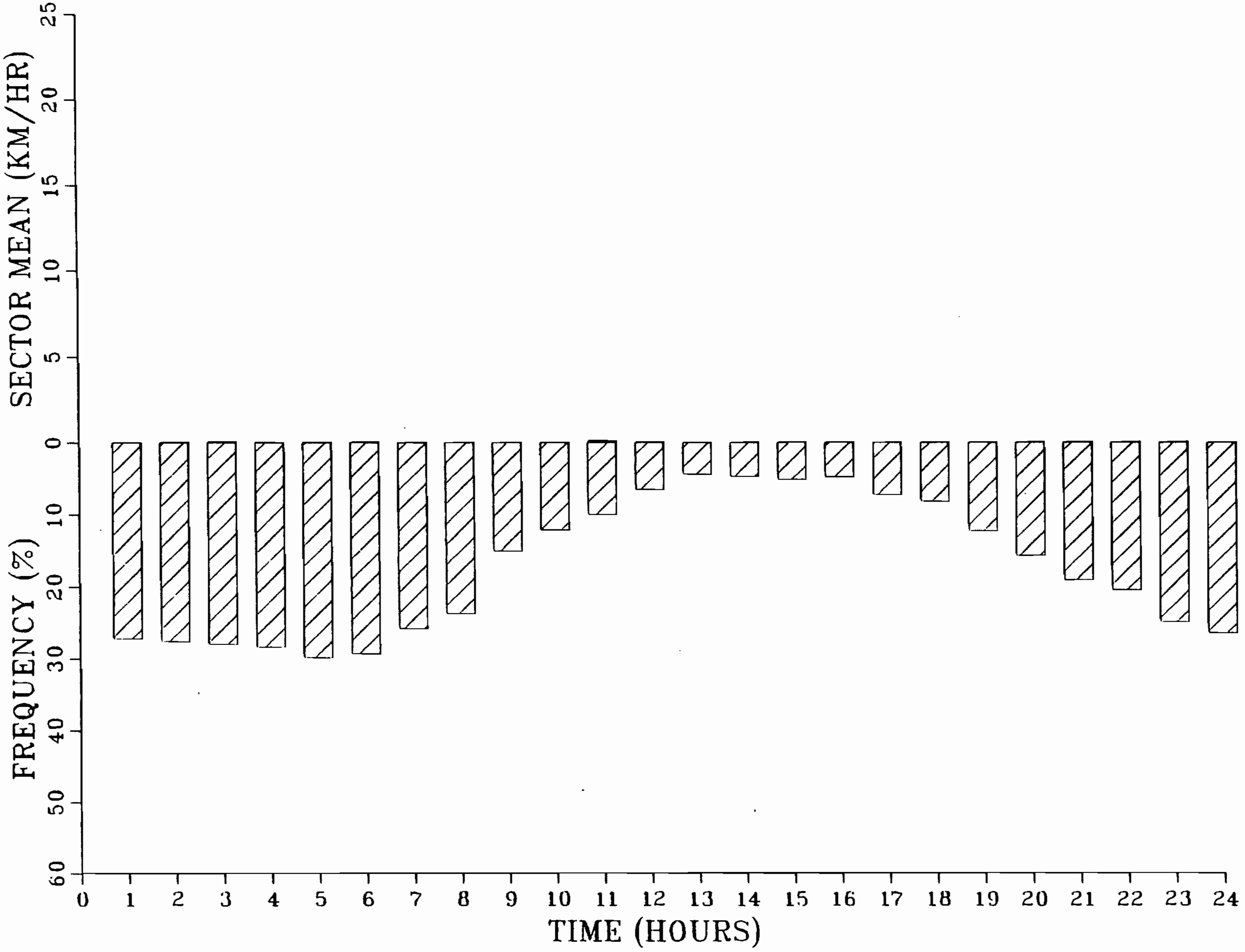


FIGURE 3

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF NORTH WINDS

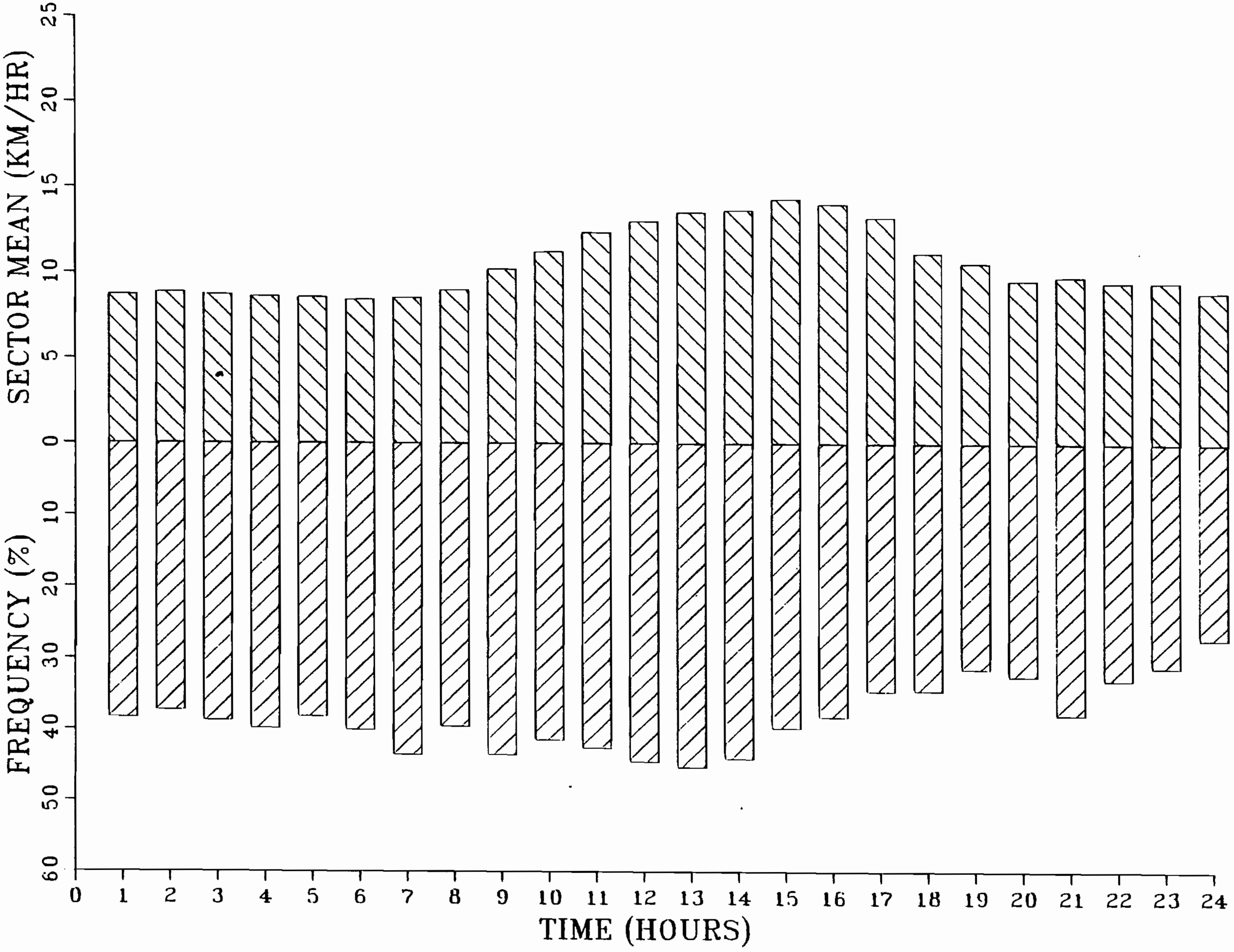


FIGURE 4

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF NORTH–EAST WINDS

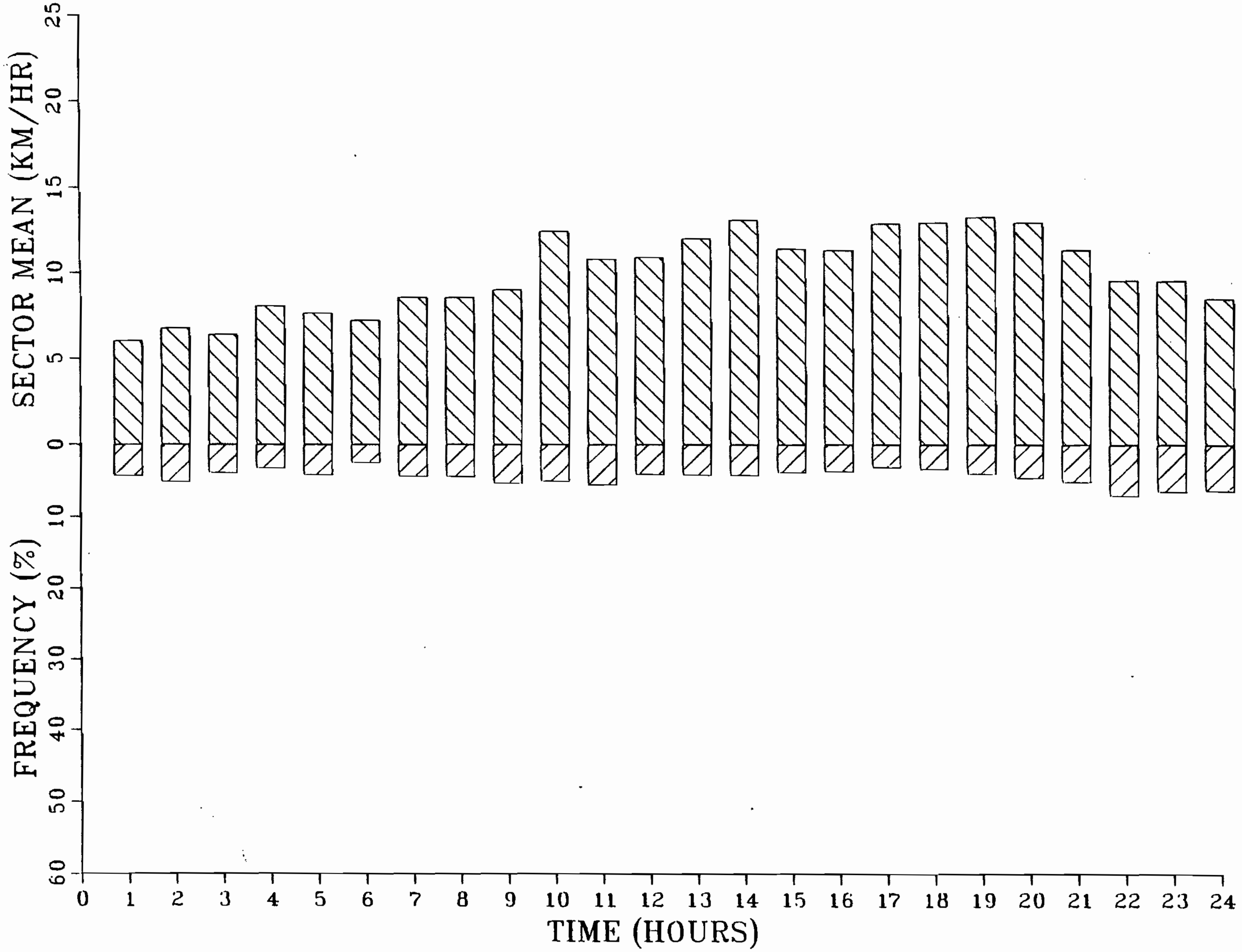


FIGURE 5

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF EAST WINDS

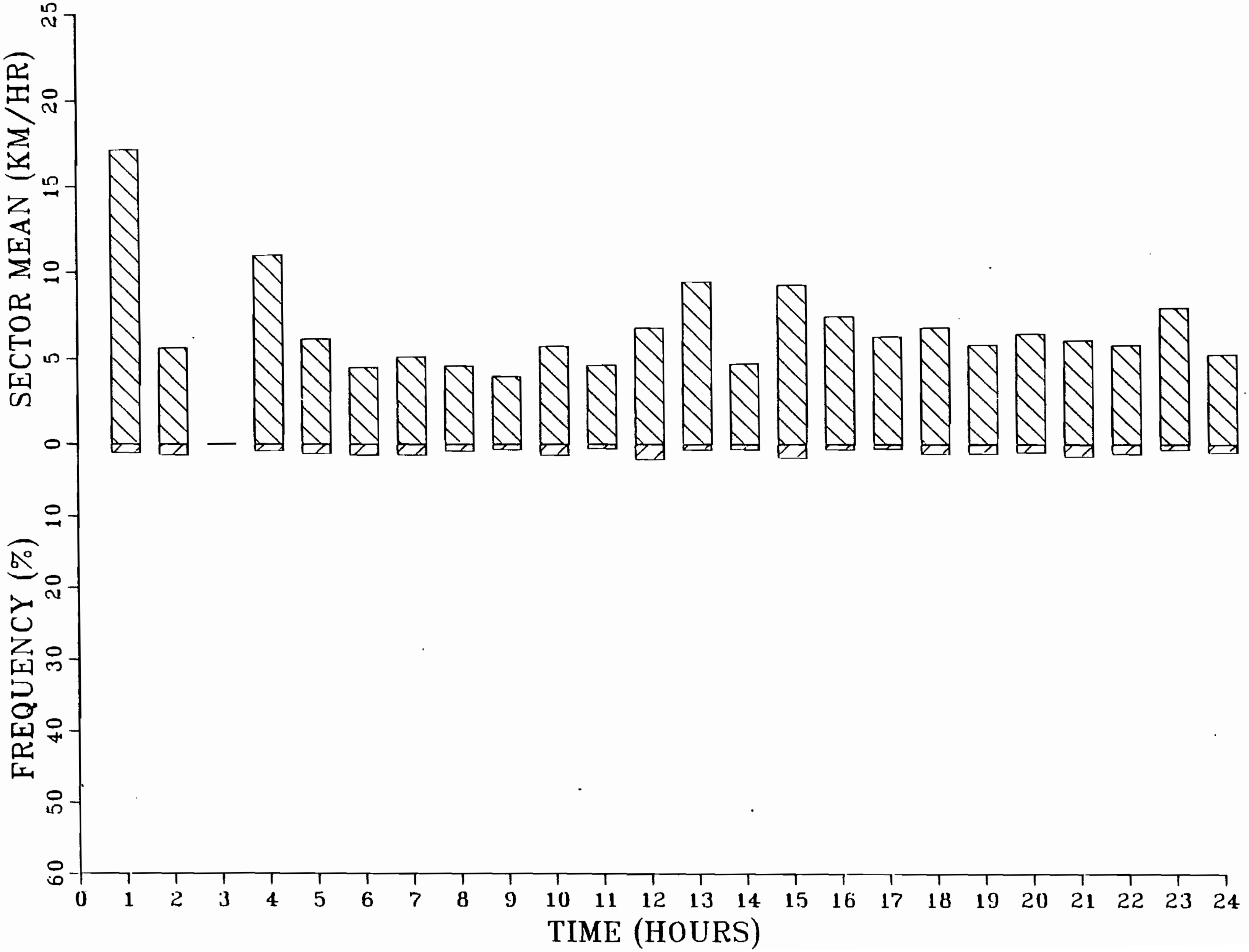


FIGURE 6

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF SOUTH–EAST WINDS

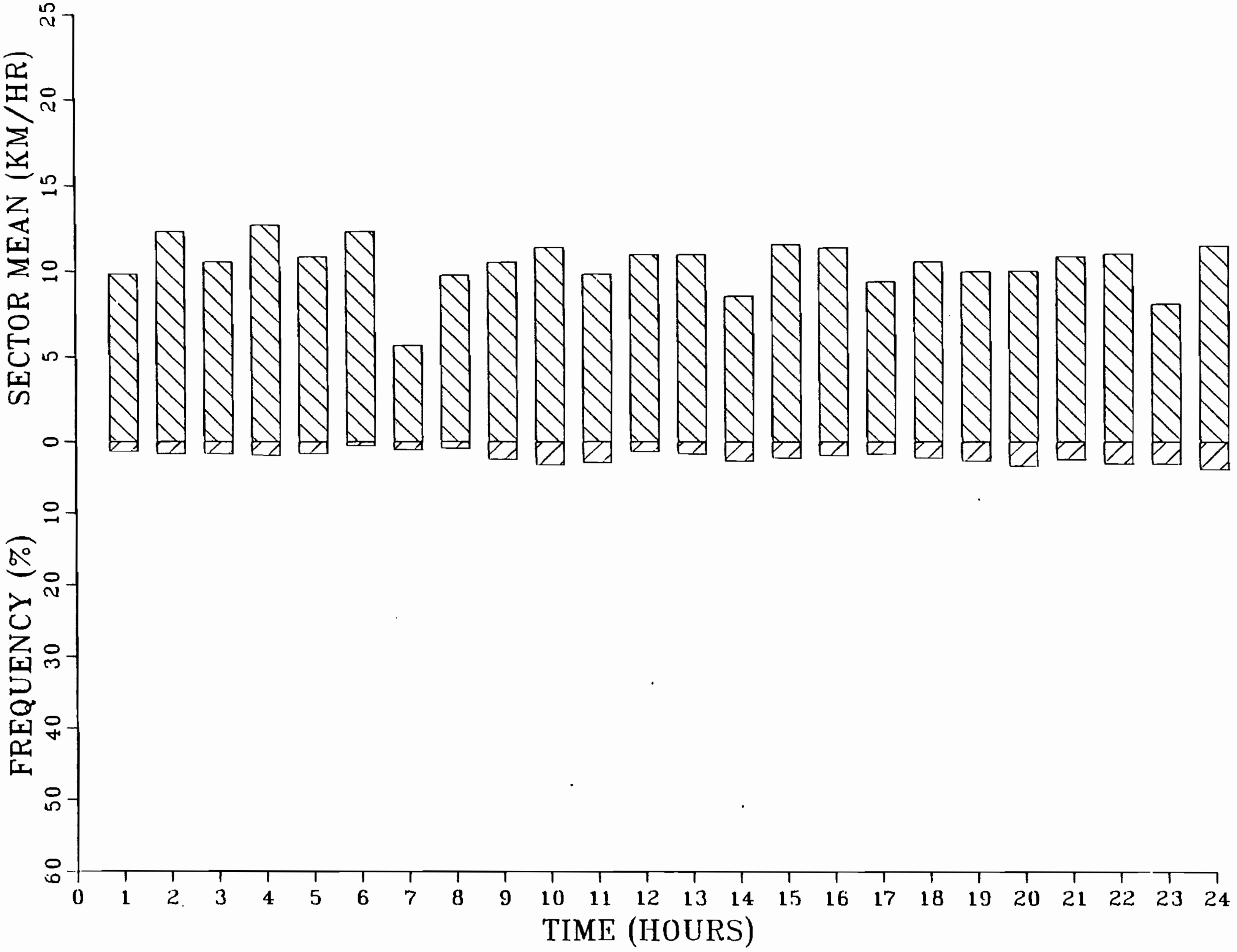


FIGURE 7

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF SOUTH WINDS

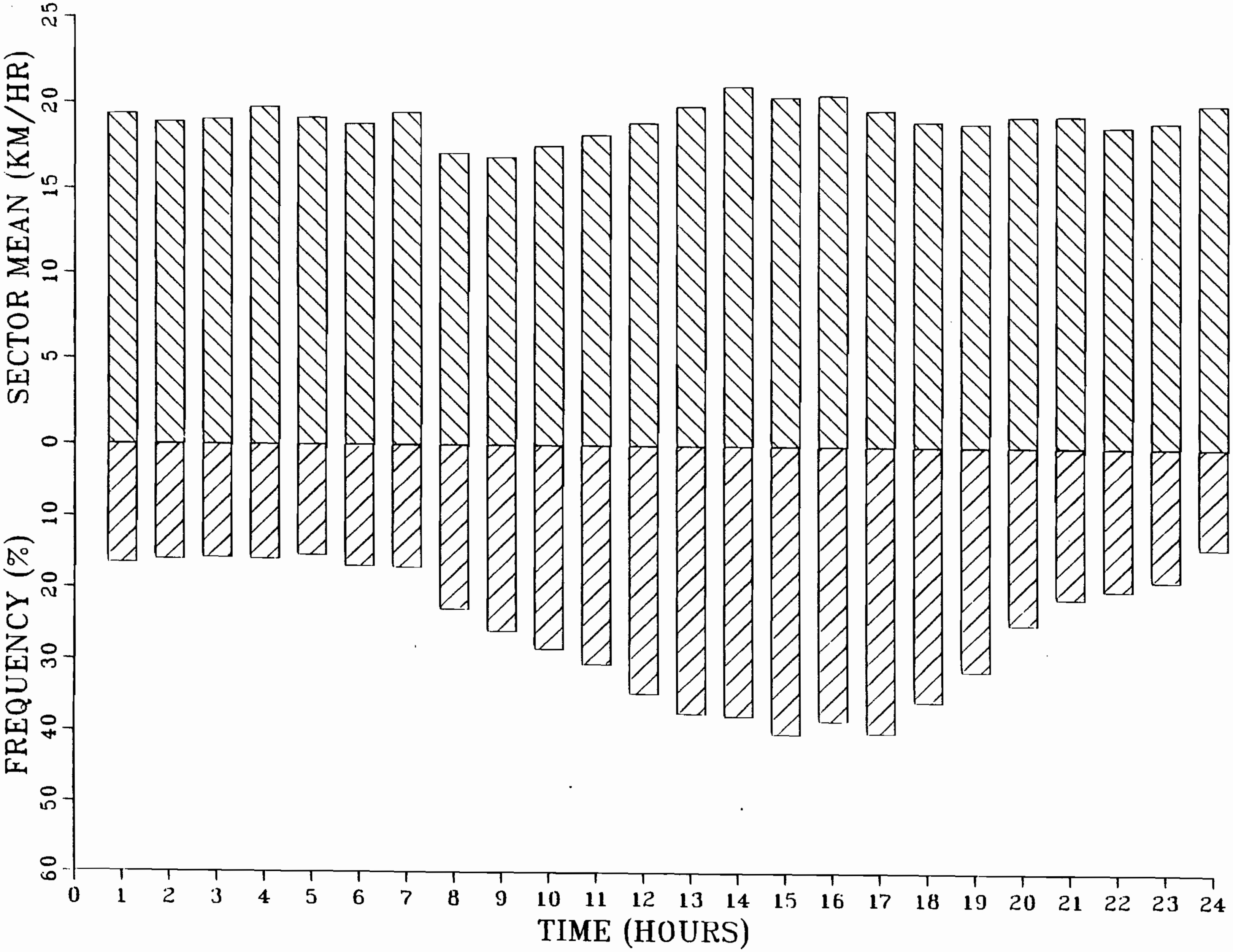


FIGURE 8

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF SOUTH–WEST WINDS

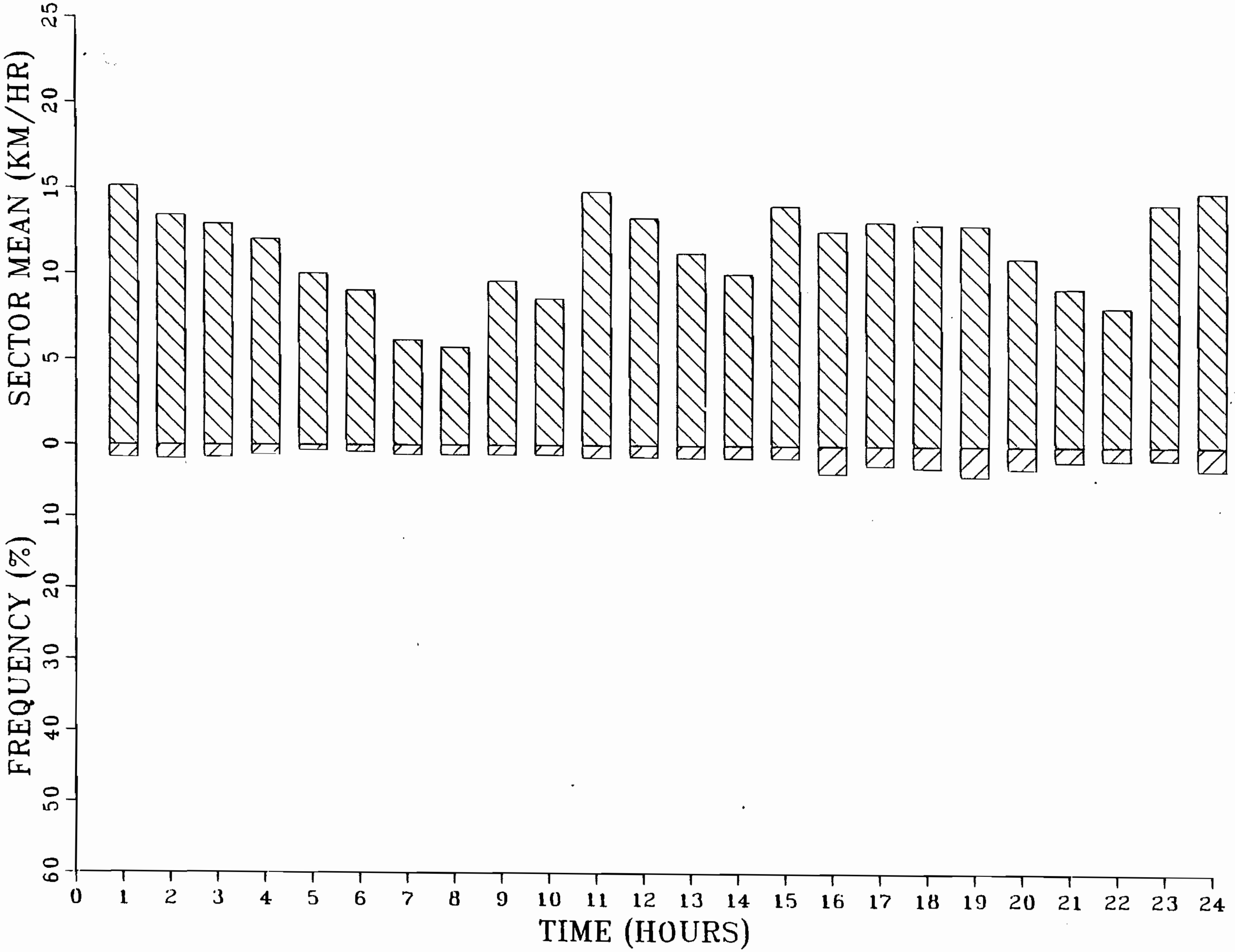


FIGURE 9

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF WEST WINDS

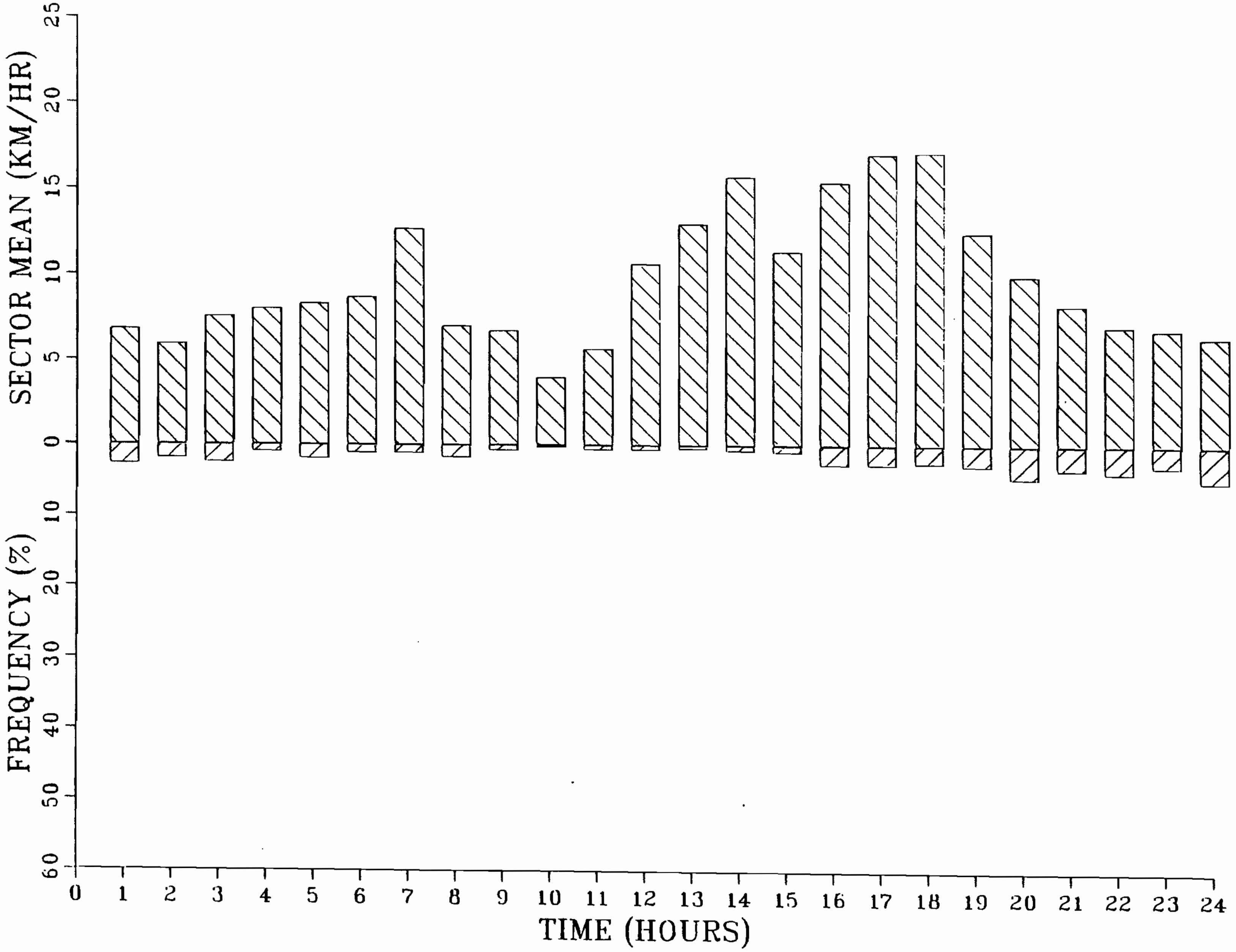
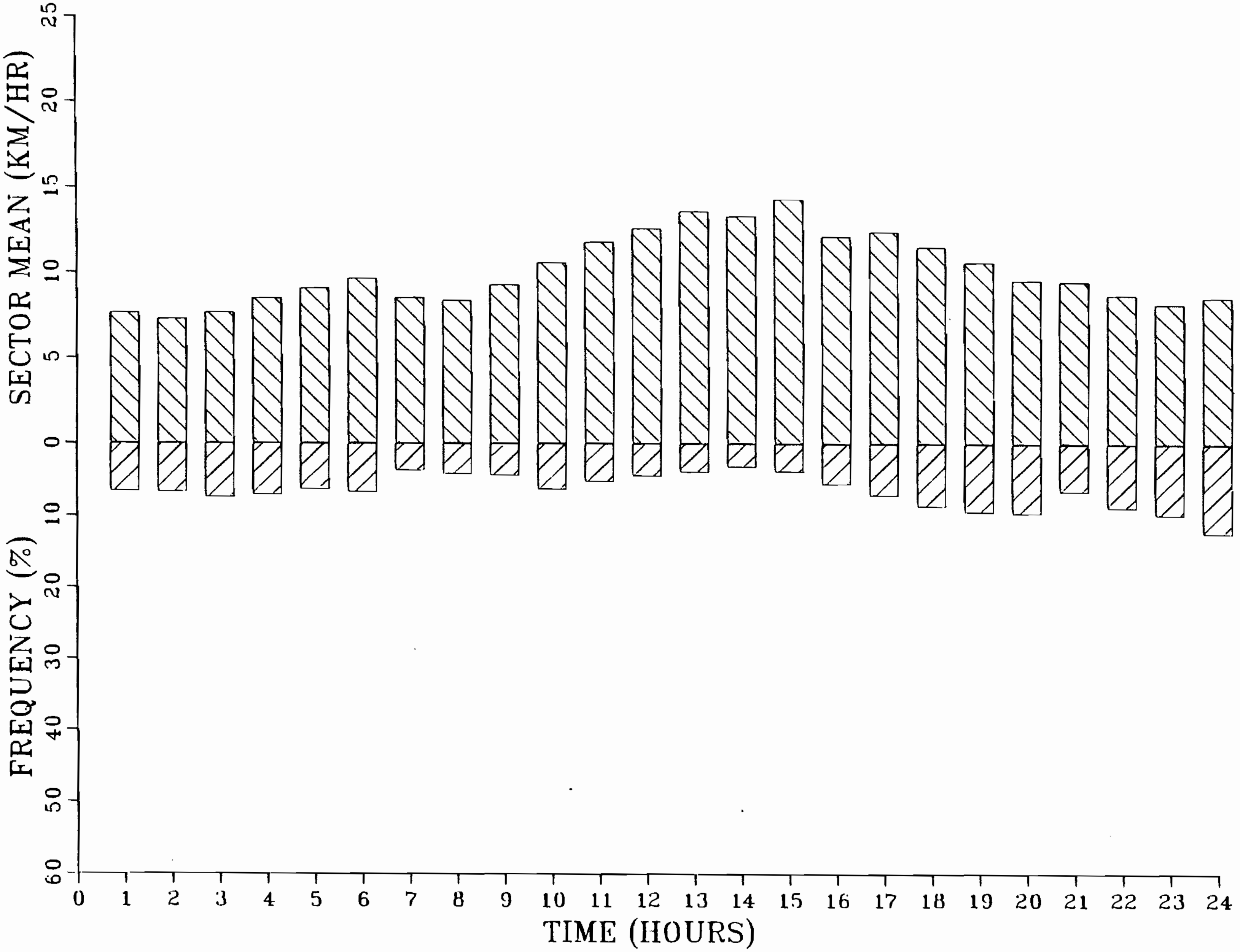


FIGURE 10

PENTICTON AIRPORT – ANNUAL OCCURRENCE OF NORTH-WEST WINDS



APPENDIX E

GRAPHICAL PRESENTATIONS OF AIR TEMPERATURE, RELATIVE HUMIDITY, WATER TEMPERATURE, VAPOUR PRESSURE GRADIENT AND WIND SPEED FOR EACH STATION

FIGURE 1 WINFIELD – AIR TEMPERATURE

5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

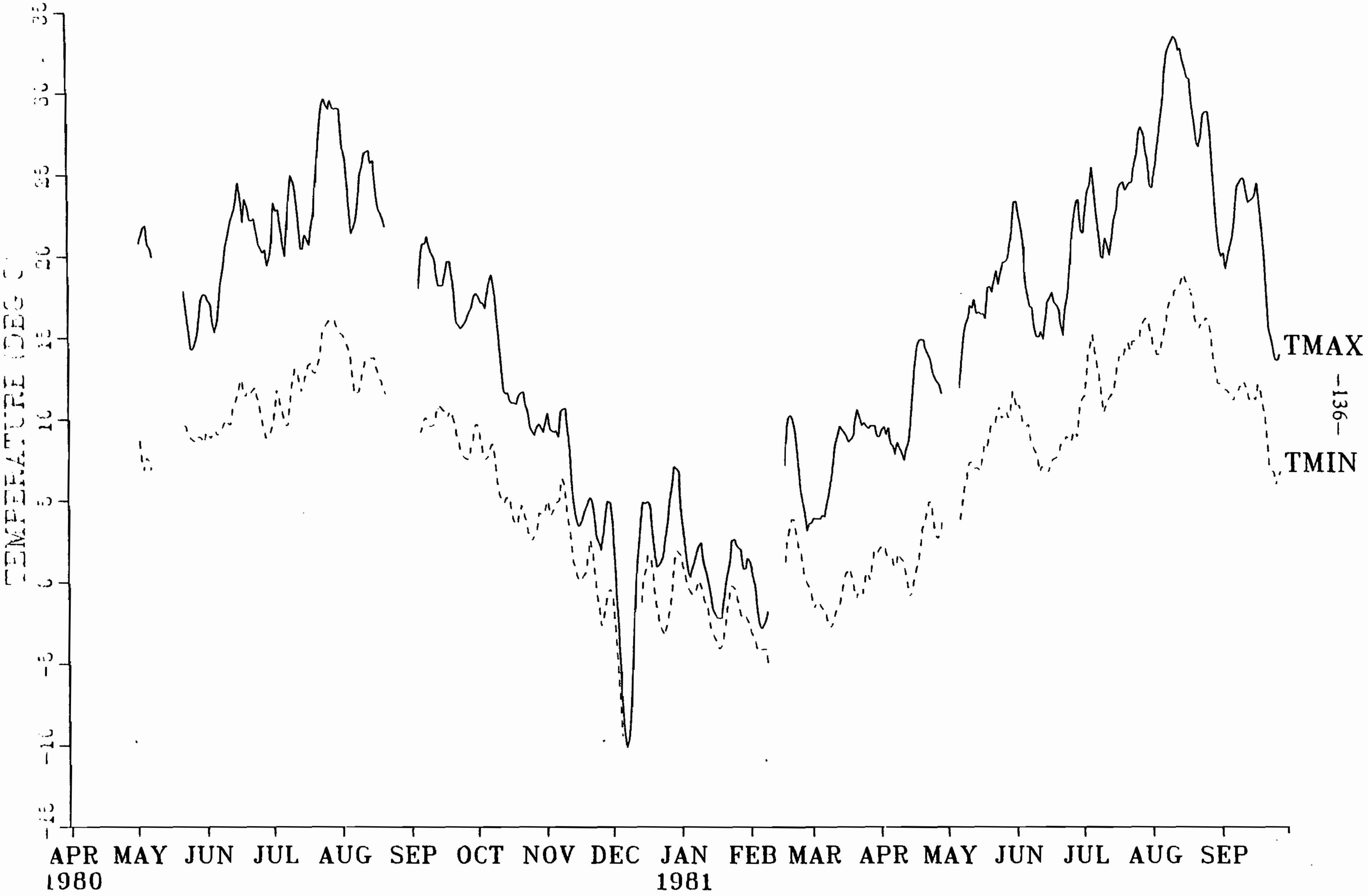


FIGURE 2 WINFIELD – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

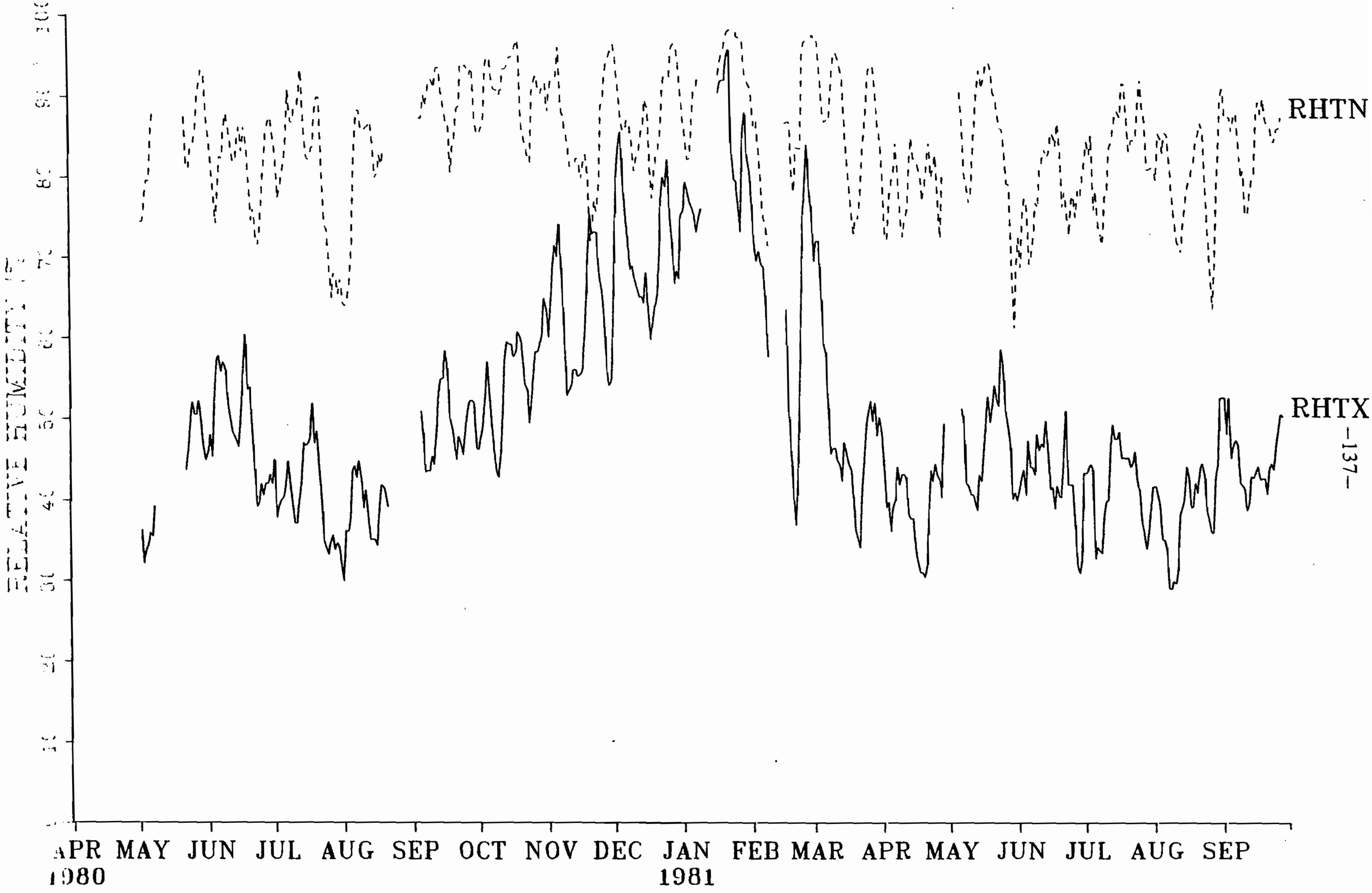


FIGURE 3 WINFIELD – WATER TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TSMX) AND MINIMUM (TSMN)

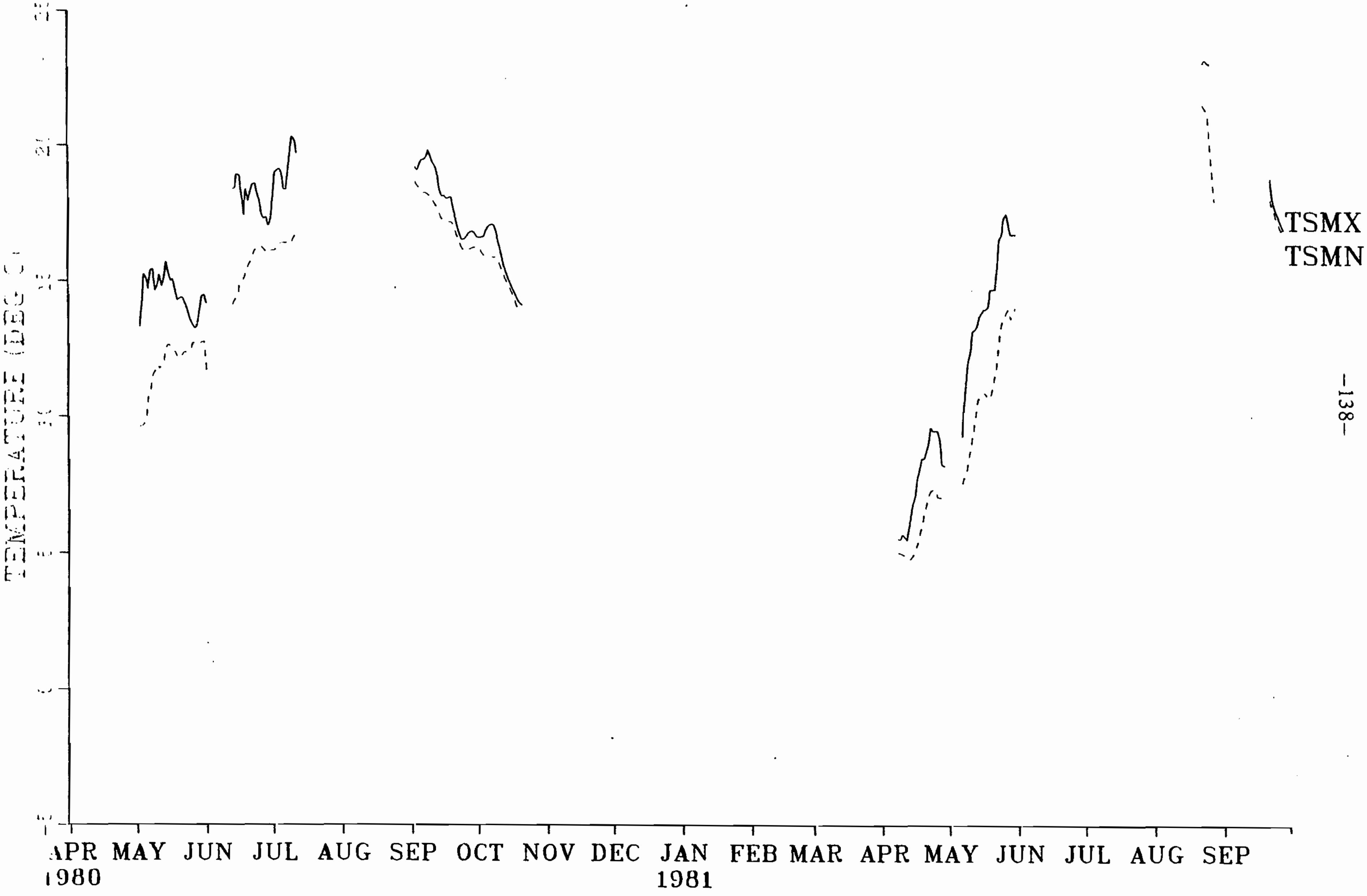


FIGURE 4 WINFIELD – AIR AND WATER TEMPERATURE
5 DAY RUNNING MEANS – AIR (TAVE) AND WATER (TSAV)

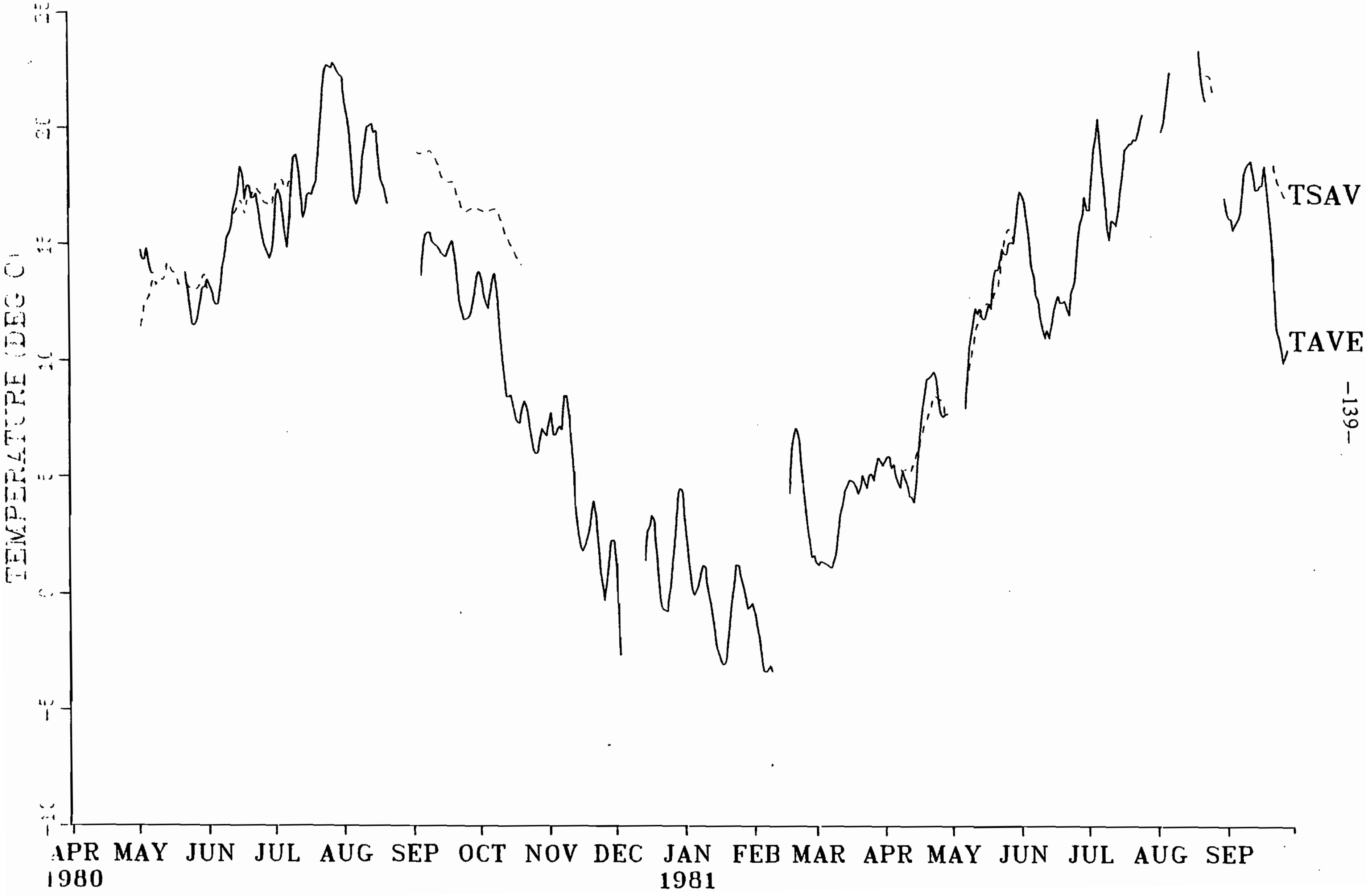


FIGURE 5 WINFIELD – VAPOUR PRESSURE

5 DAY RUNNING MEANS – SURFACE (VPSF) AND AMBIENT (VPMN)

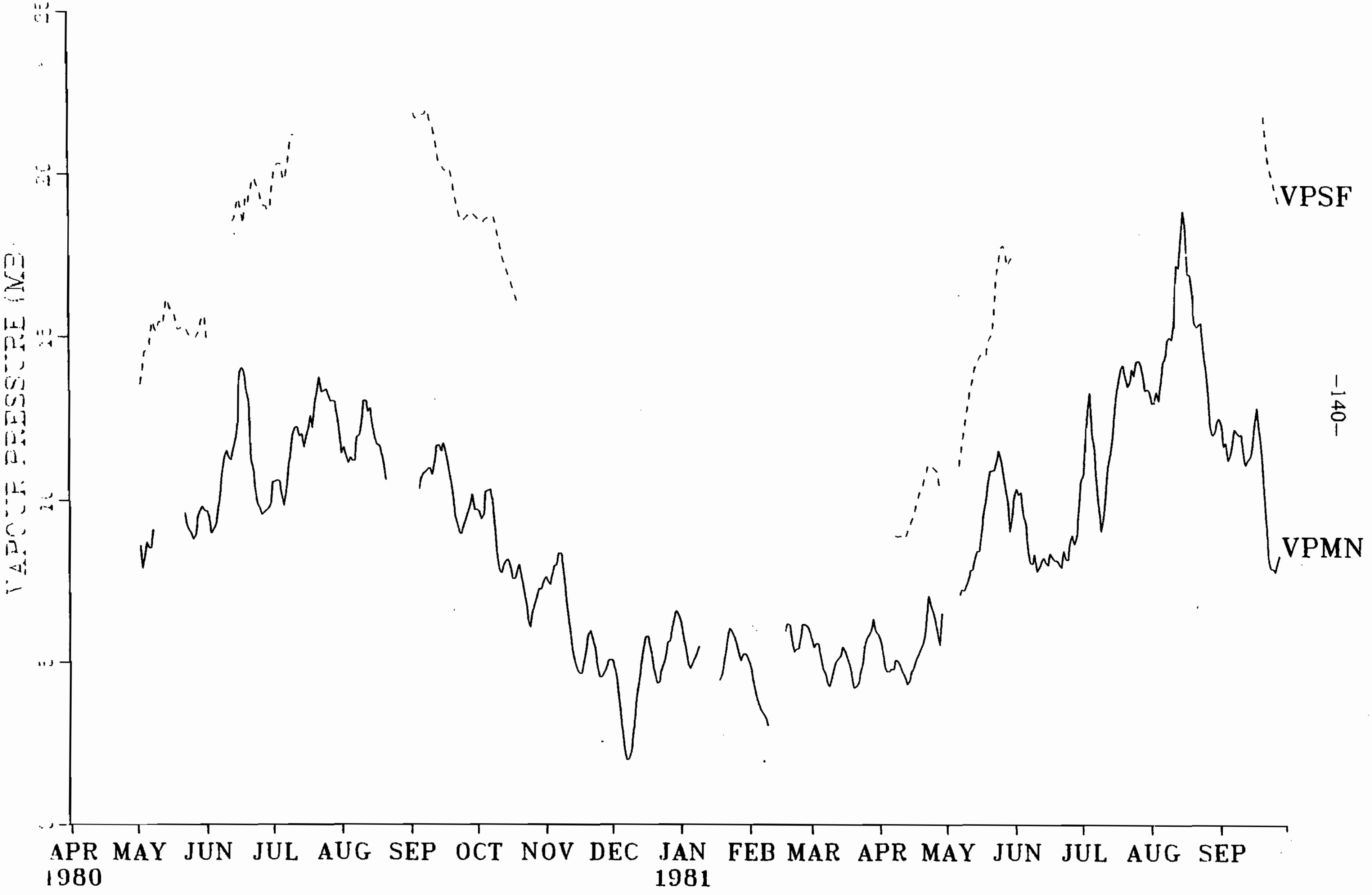


FIGURE 6 WINFIELD – WIND SPEED
5 DAY RUNNING MEANS – 4 METRES ABOVE MEAN LAKE LEVEL

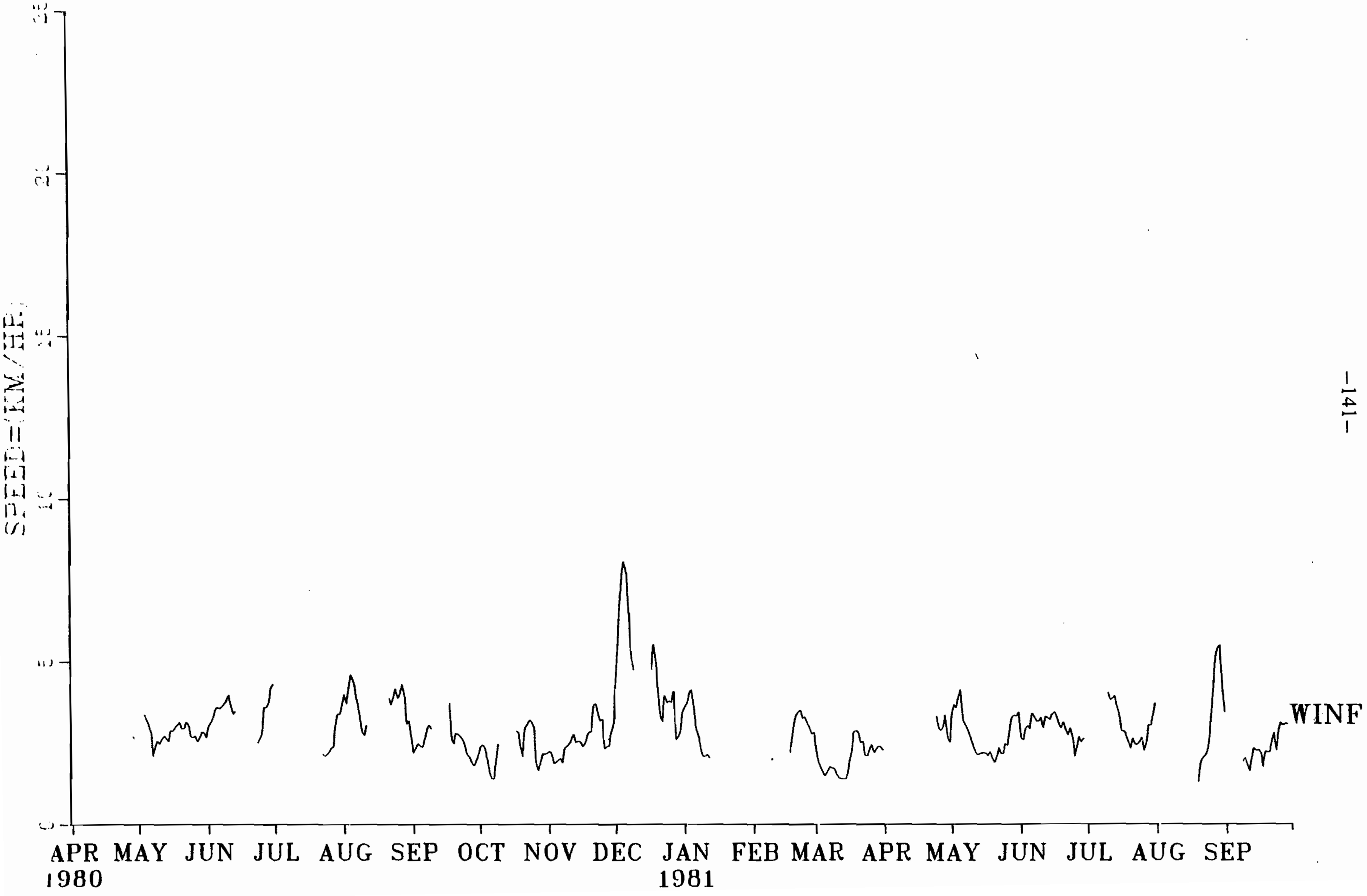


FIGURE 1 KELOWNA AIRPORT – AIR TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

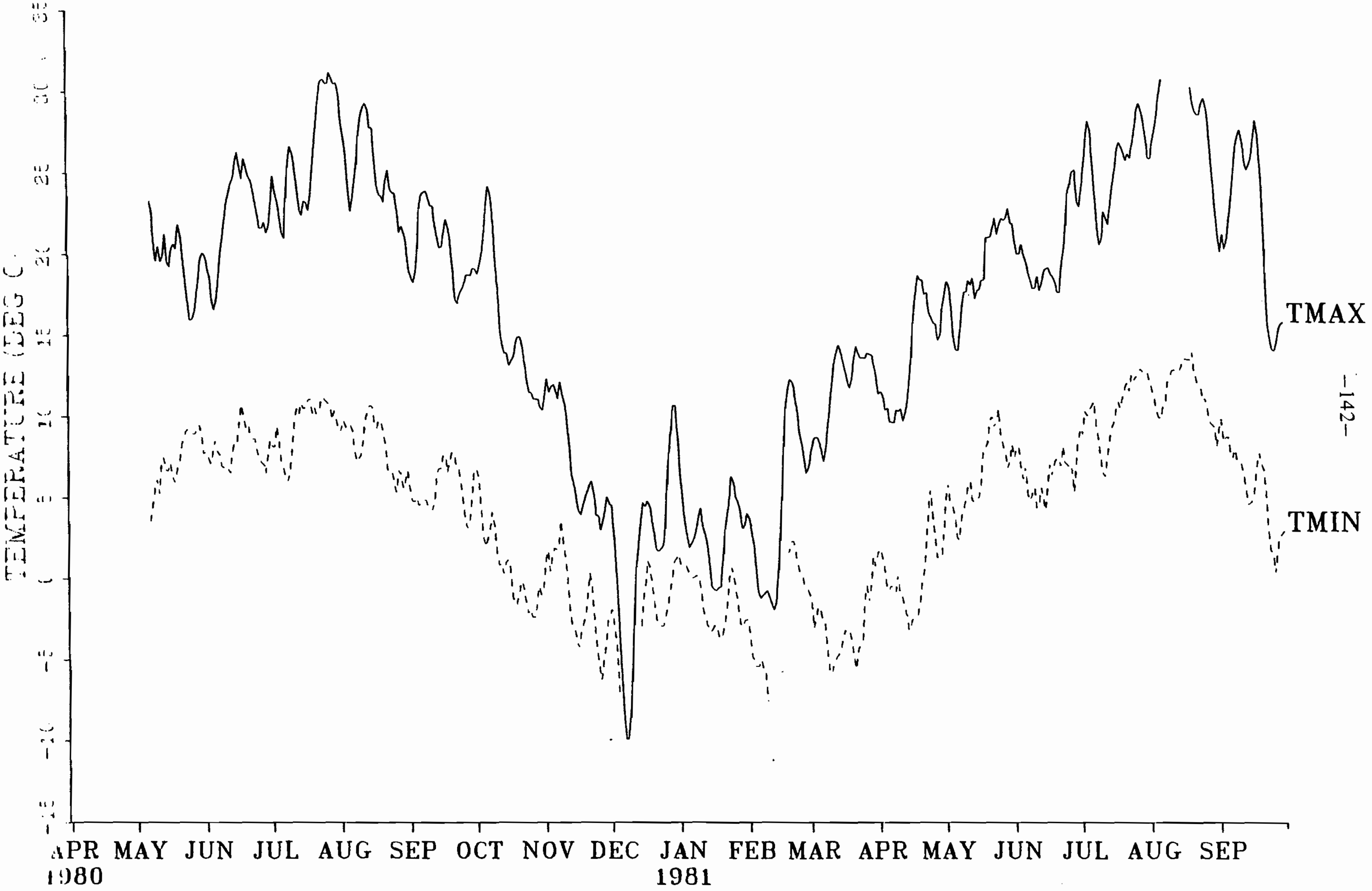


FIGURE 2 KELOWNA AIRPORT – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

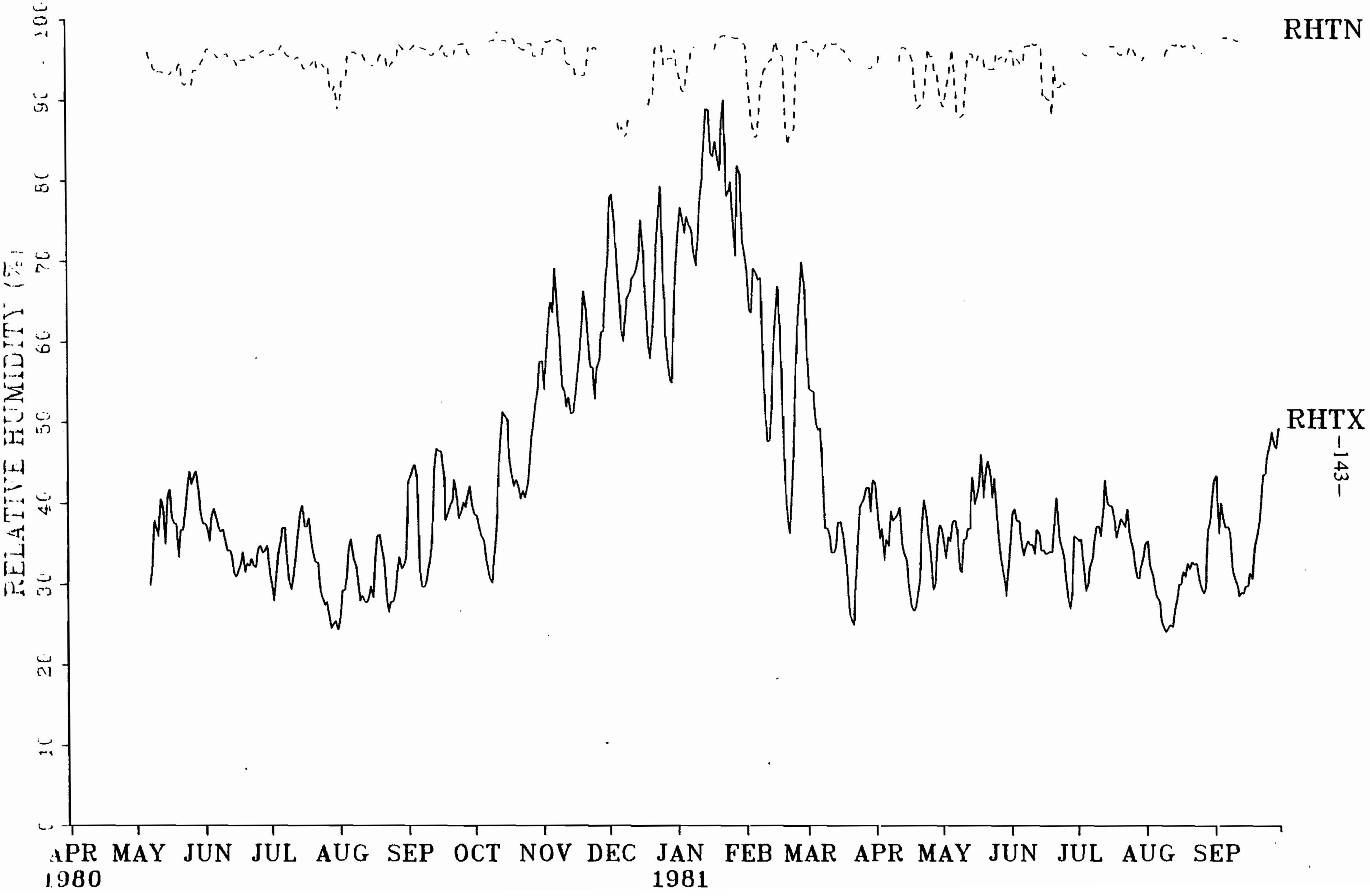


FIGURE 3 KELOWNA AIRPORT – DEEPER C. TEMPERATURE
5 DAY RUNNING MEANS – AIRPORT (KEAP) AND DEEPER C. (DCAT)

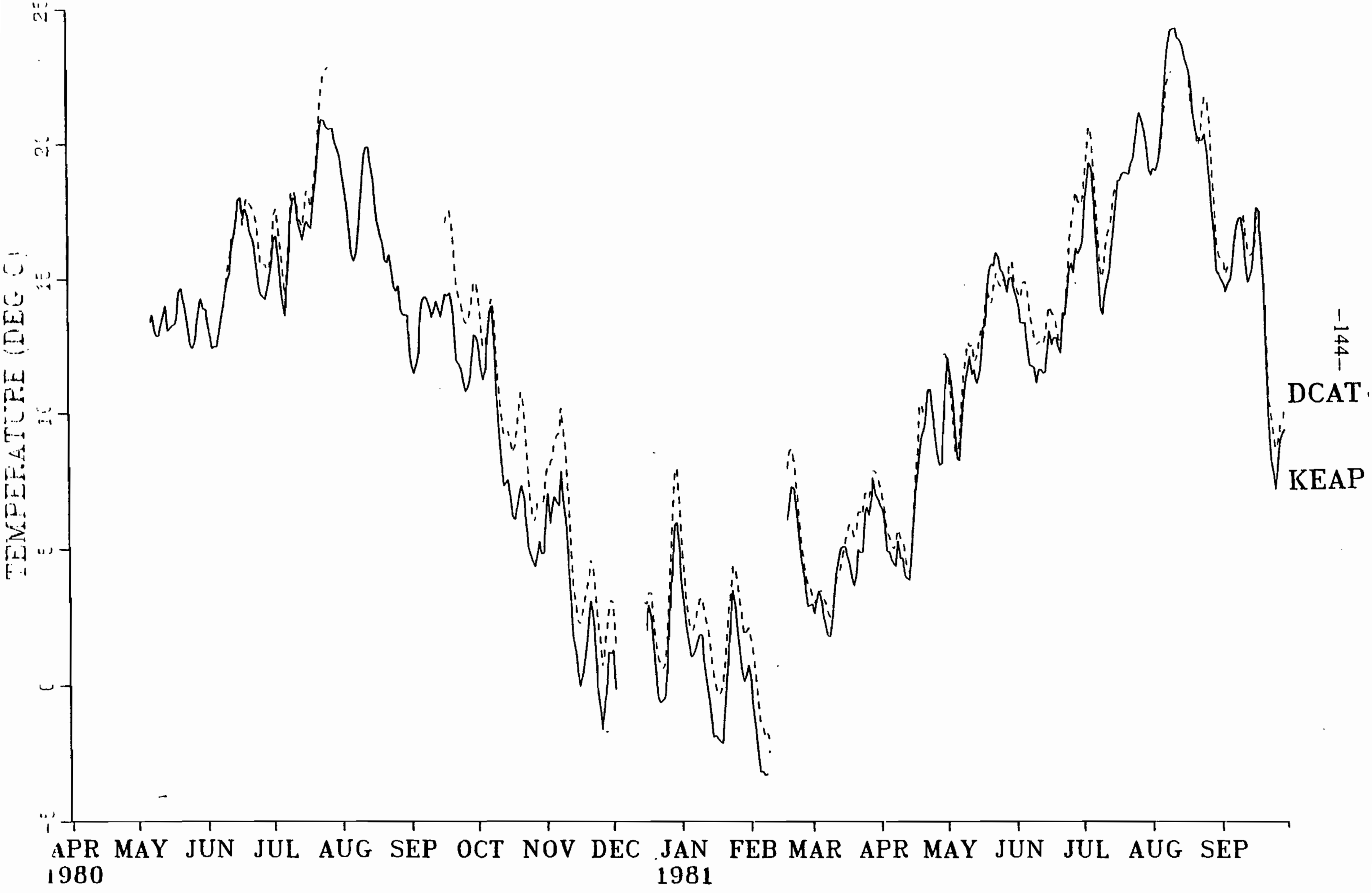


FIGURE 4 KELOWNA AIRPORT – DEEPER C. VAPOUR PRESSURE
5 DAY RUNNING MEANS – AIRPORT (PEAP) AND DEEPER C. (PEMR)

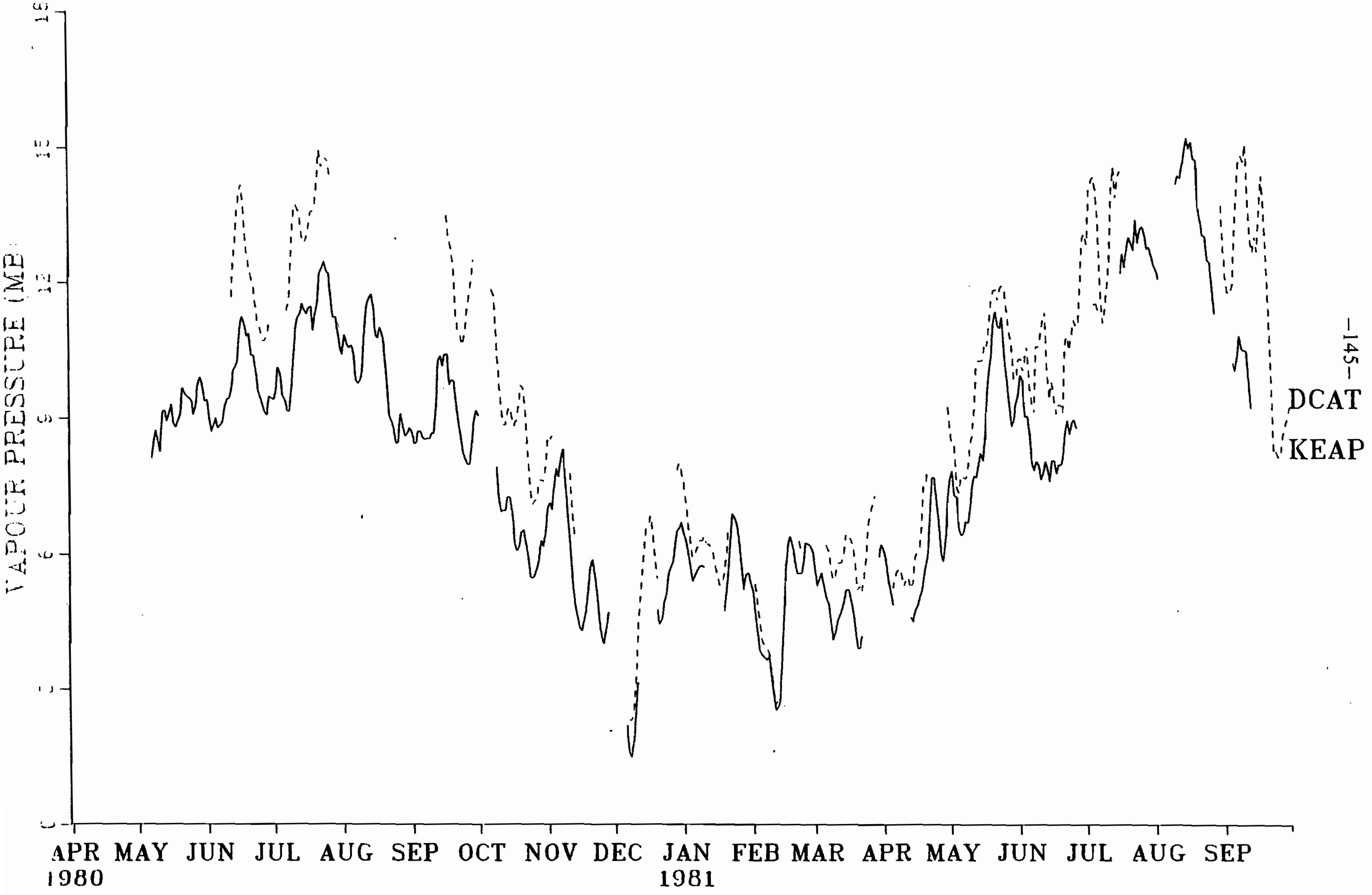


FIGURE 5 KELOWNA AIRPORT – DEEPER C. TEMPERATURE GRADIENT
5 DAY RUNNING MEANS – AIRPORT (TAVE) AND DEEPER C. (TSAV)

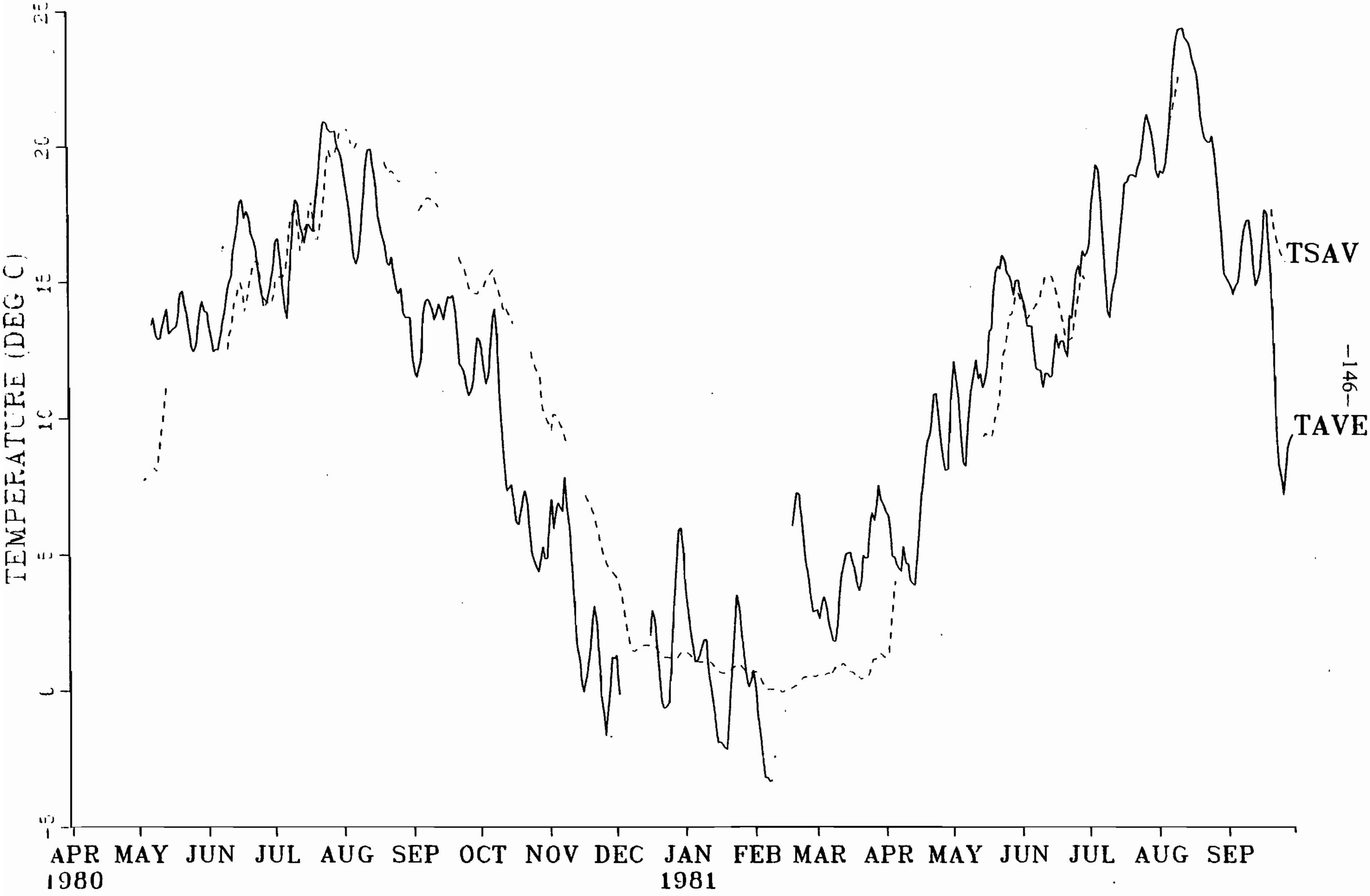


FIGURE 6 KELOWNA AIRPORT – DEEPER C. VAPOUR PRESSURE GRADIENT
5 DAY RUNNING MEANS – AIRPORT (VPMN) AND DEEPER C. (VPSF)

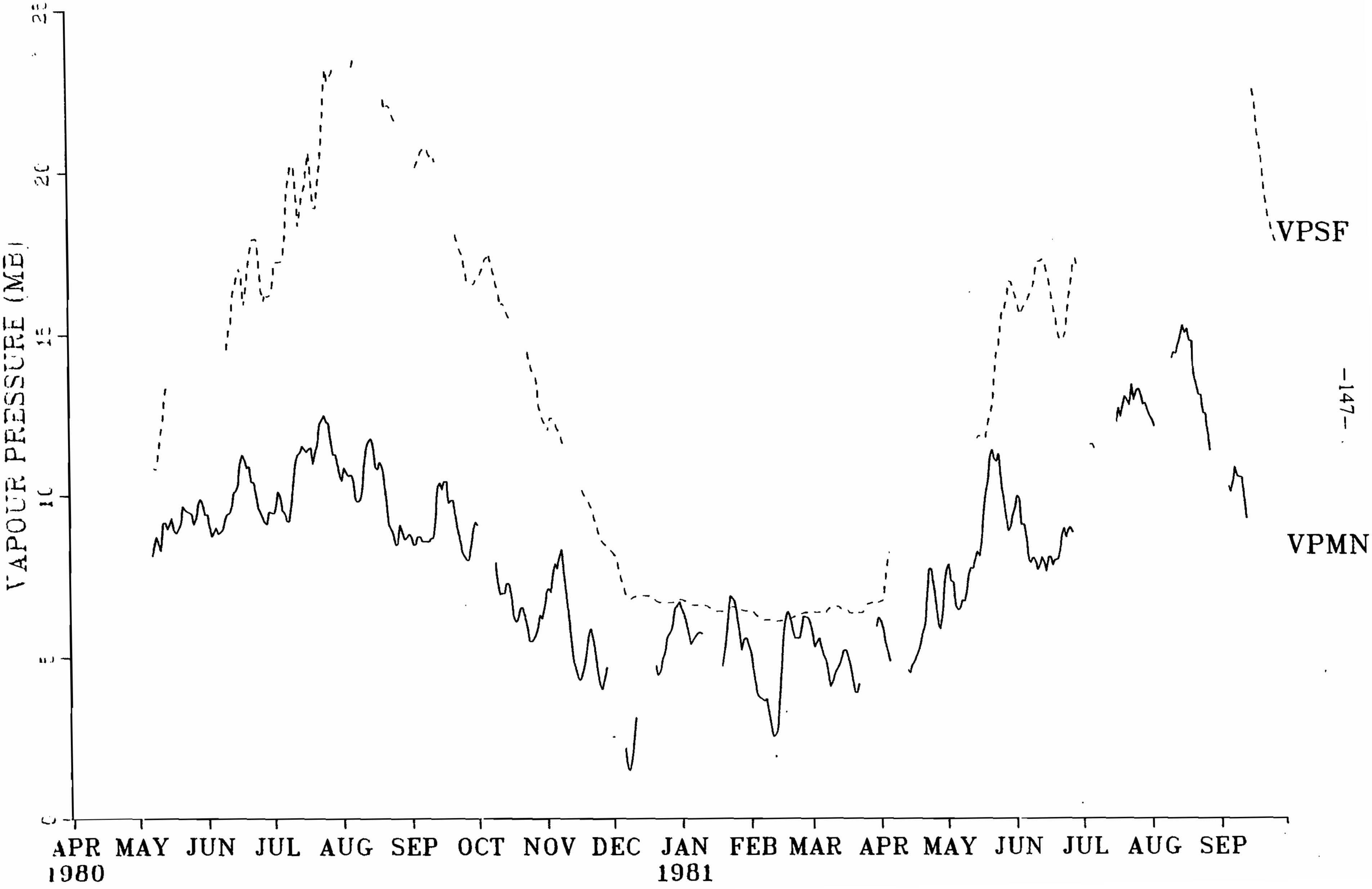


FIGURE 7 KELOWNA AIRPORT – DEEPER C. – WIND SPEED
5 DAY RUNNING MEANS – AIRPORT (PEAP) AND DEEPER C. (PEMR)

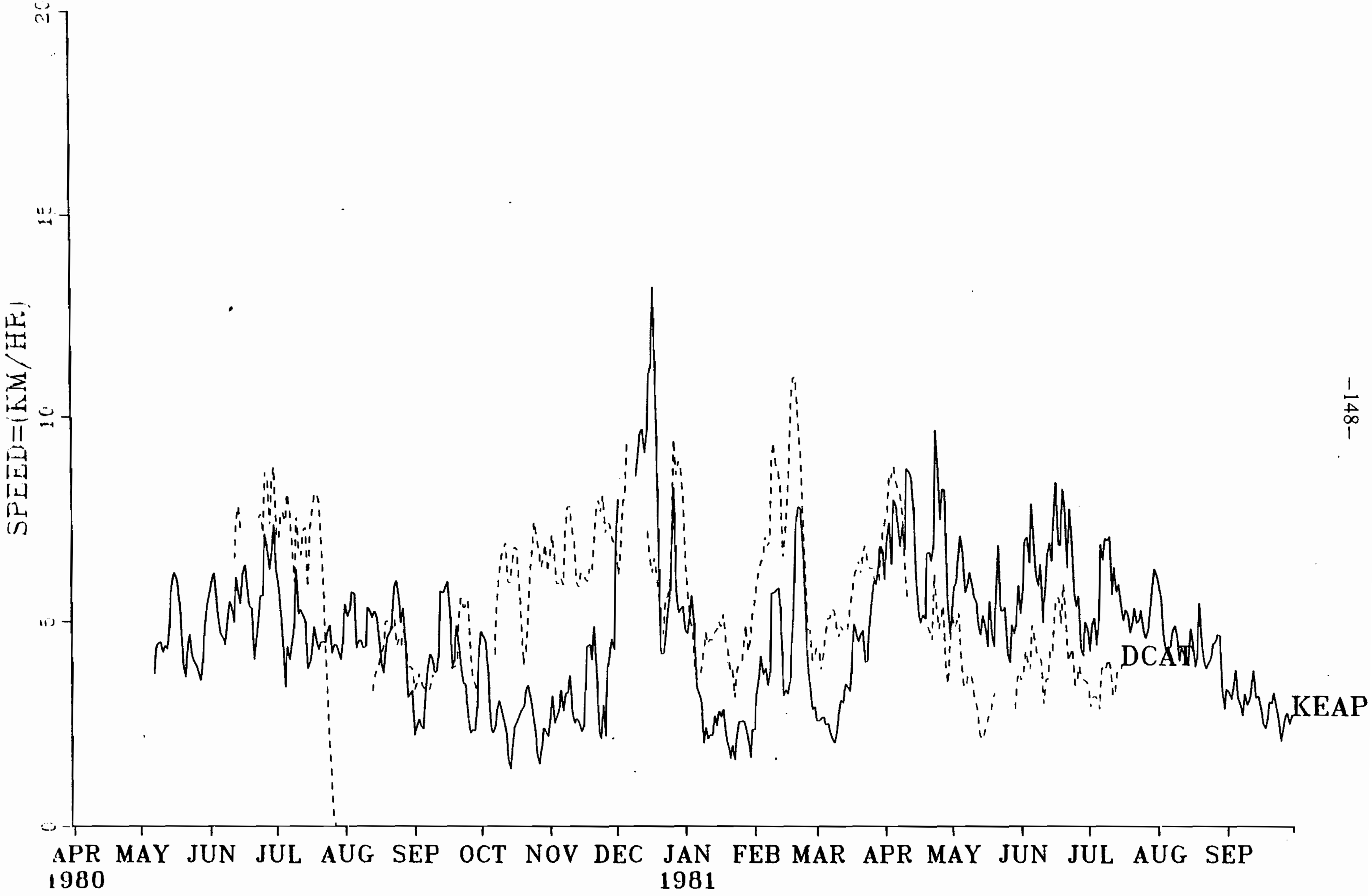


FIGURE 1 DEEPER CREEK (CAT) – AIR TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

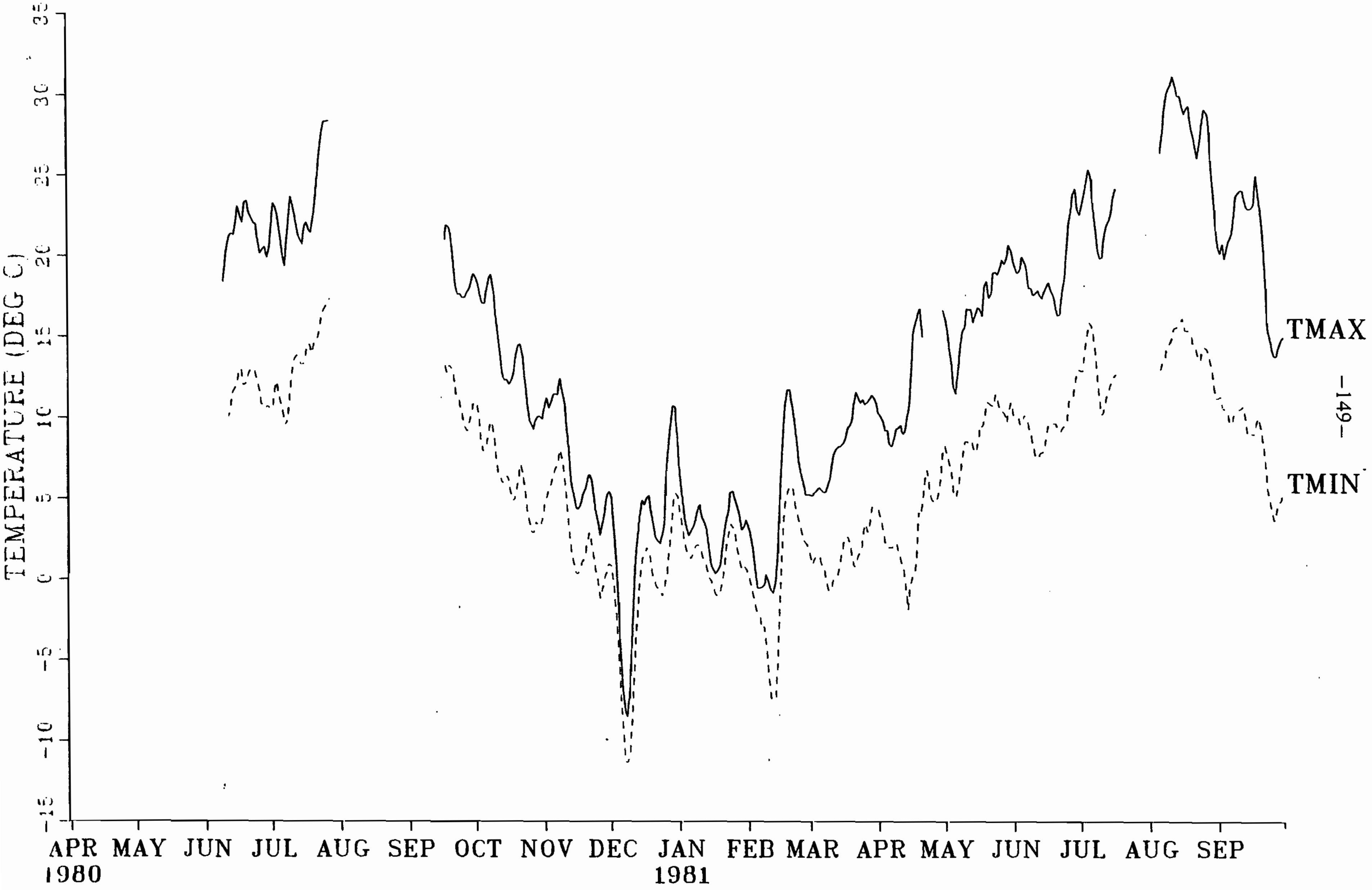


FIGURE 2 DEEPER CREEK (CAT) – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

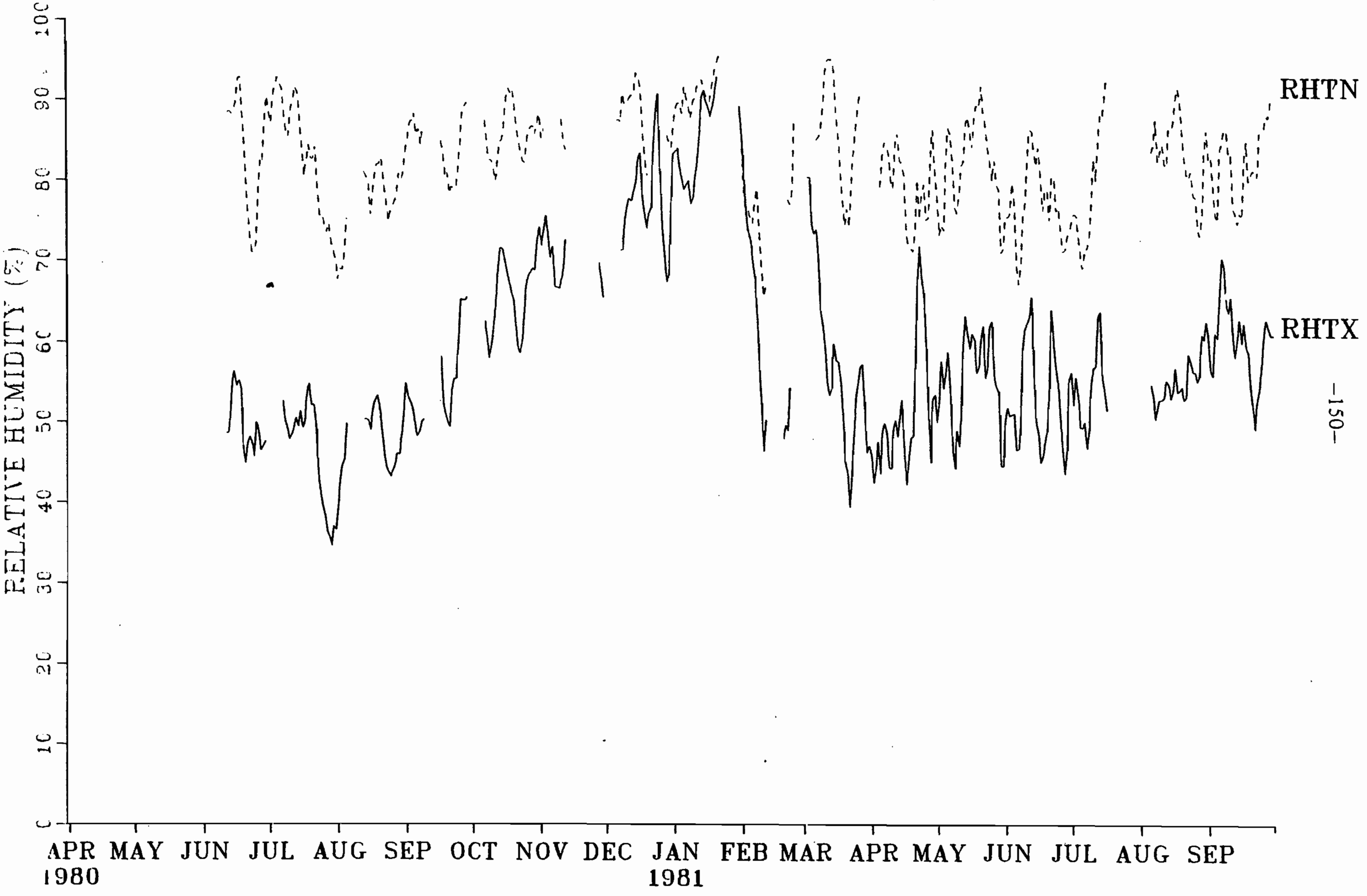


FIGURE 3 DEEPER CREEK (CAT) - WATER TEMPERATURE
5 DAY RUNNING MEANS - MAXIMUM (TSMX) AND MINIMUM (TSMN)

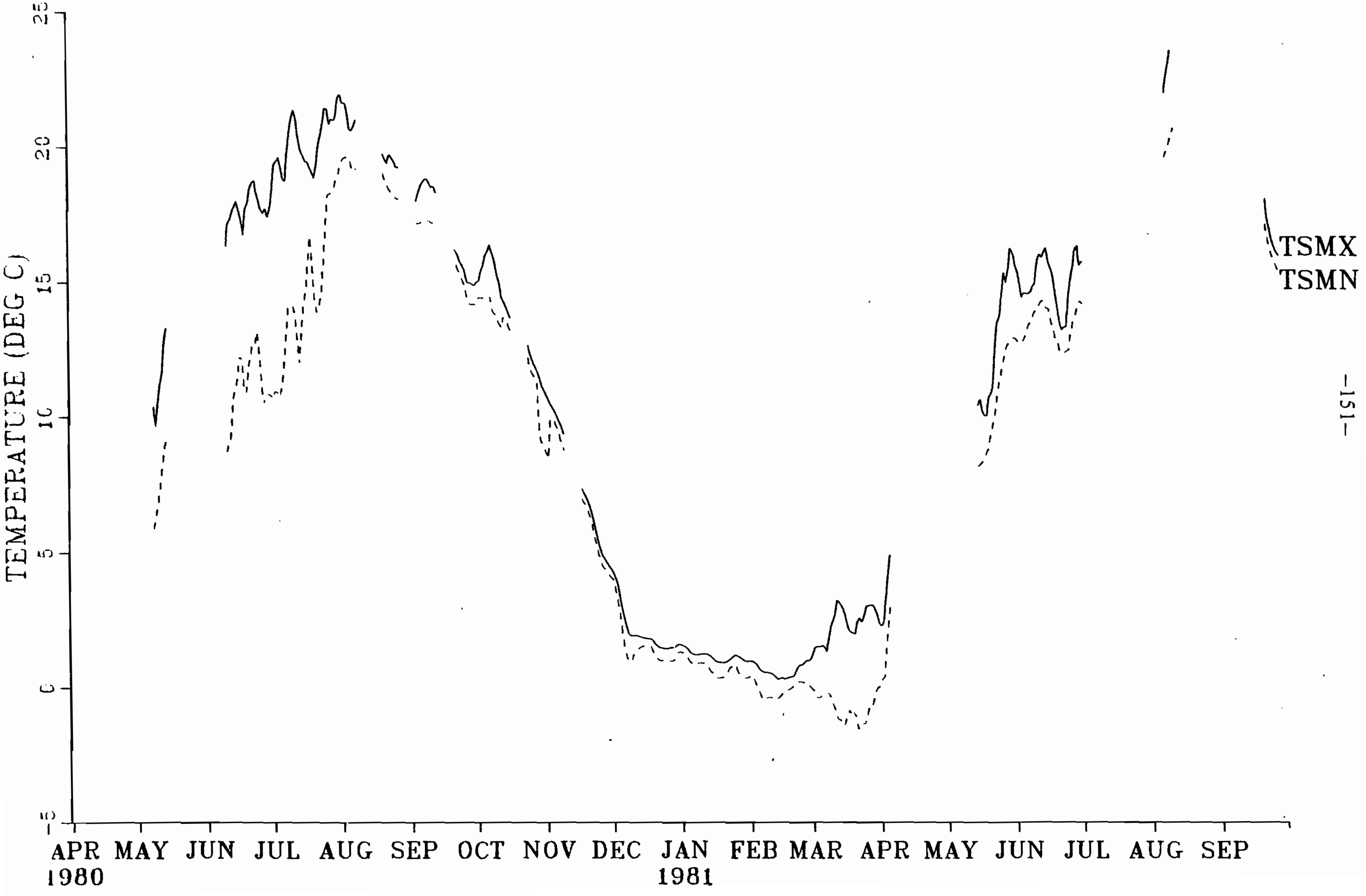


FIGURE 4 DEEPER CREEK (CAT) – AIR AND WATER TEMPERATURE
5 DAY RUNNING MEANS – AIR (TAVE) AND WATER (TSAV)

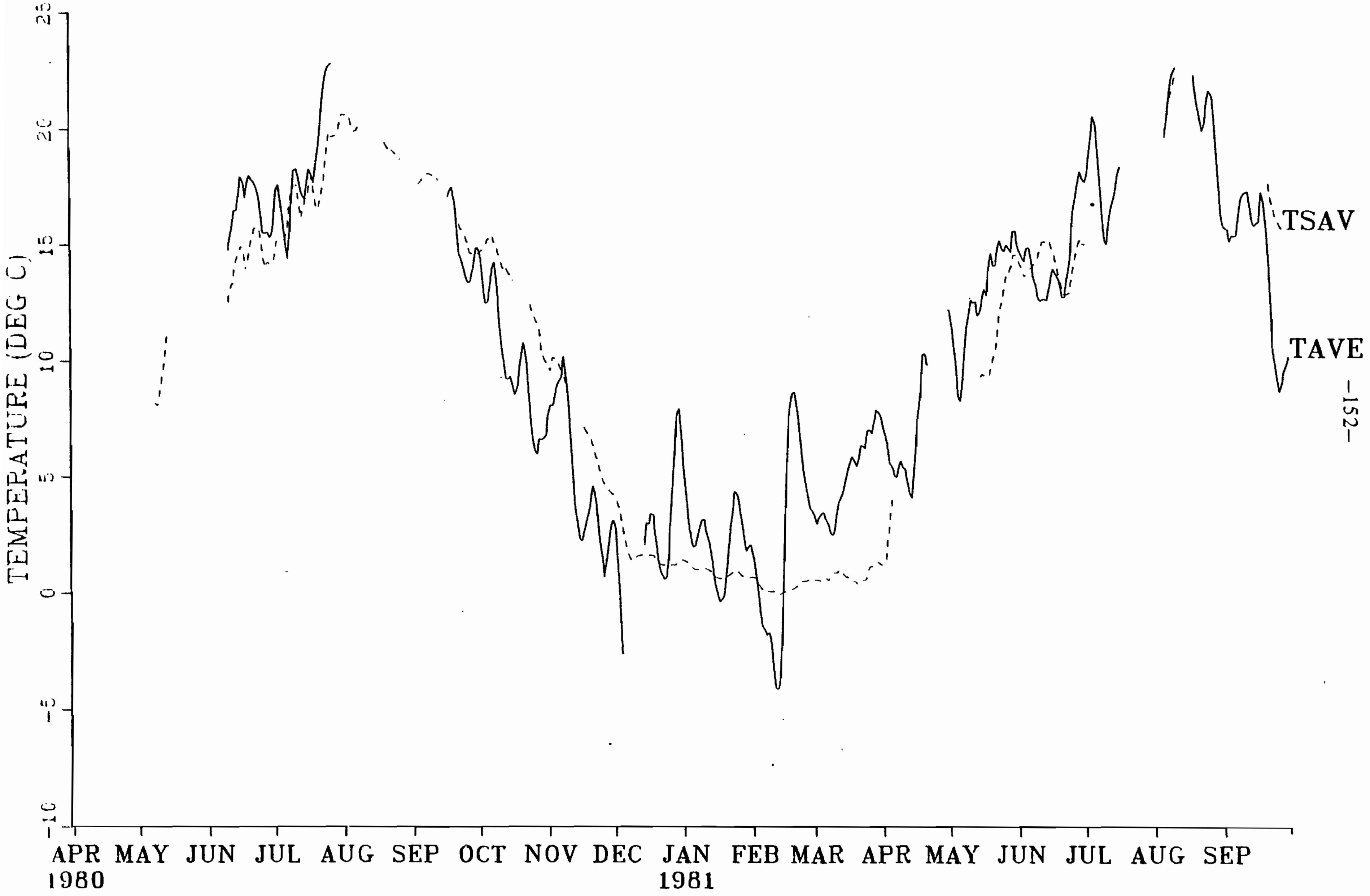


FIGURE 5 DEEPER CREEK (CAT) – VAPOUR PRESSURE
5 DAY RUNNING MEANS – SURFACE (VPSF) AND AMBIENT (VPMN)

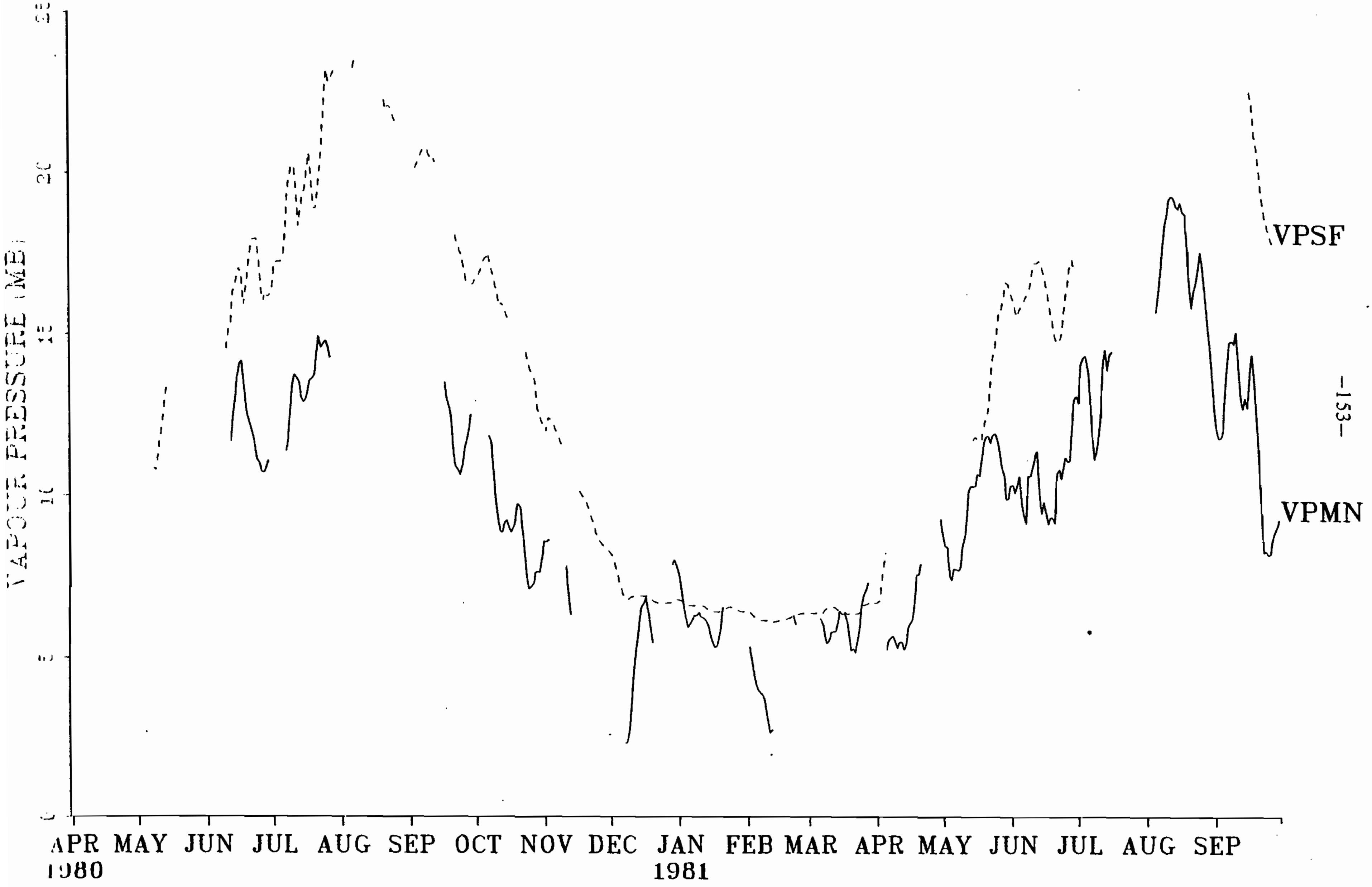


FIGURE 6 DEEPER CREEK (CAT) – WIND SPEED
5 DAY RUNNING MEANS – 4 METRES ABOVE MEAN LAKE LEVEL

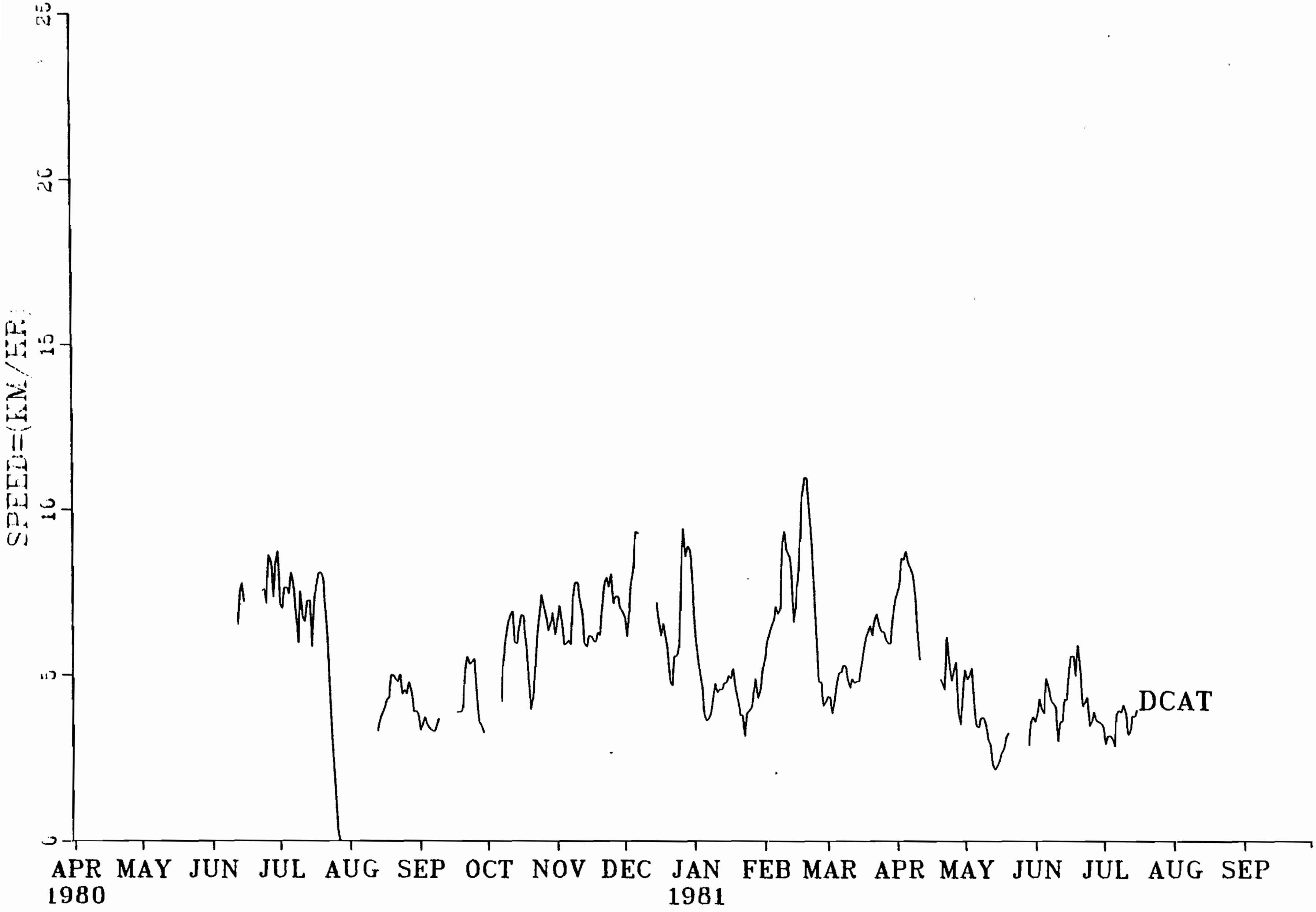


FIGURE 6 PEACHLAND YACHT CLUB – WIND SPEED
5 DAY RUNNING MEANS – 4 METRES ABOVE MEAN LAKE LEVEL

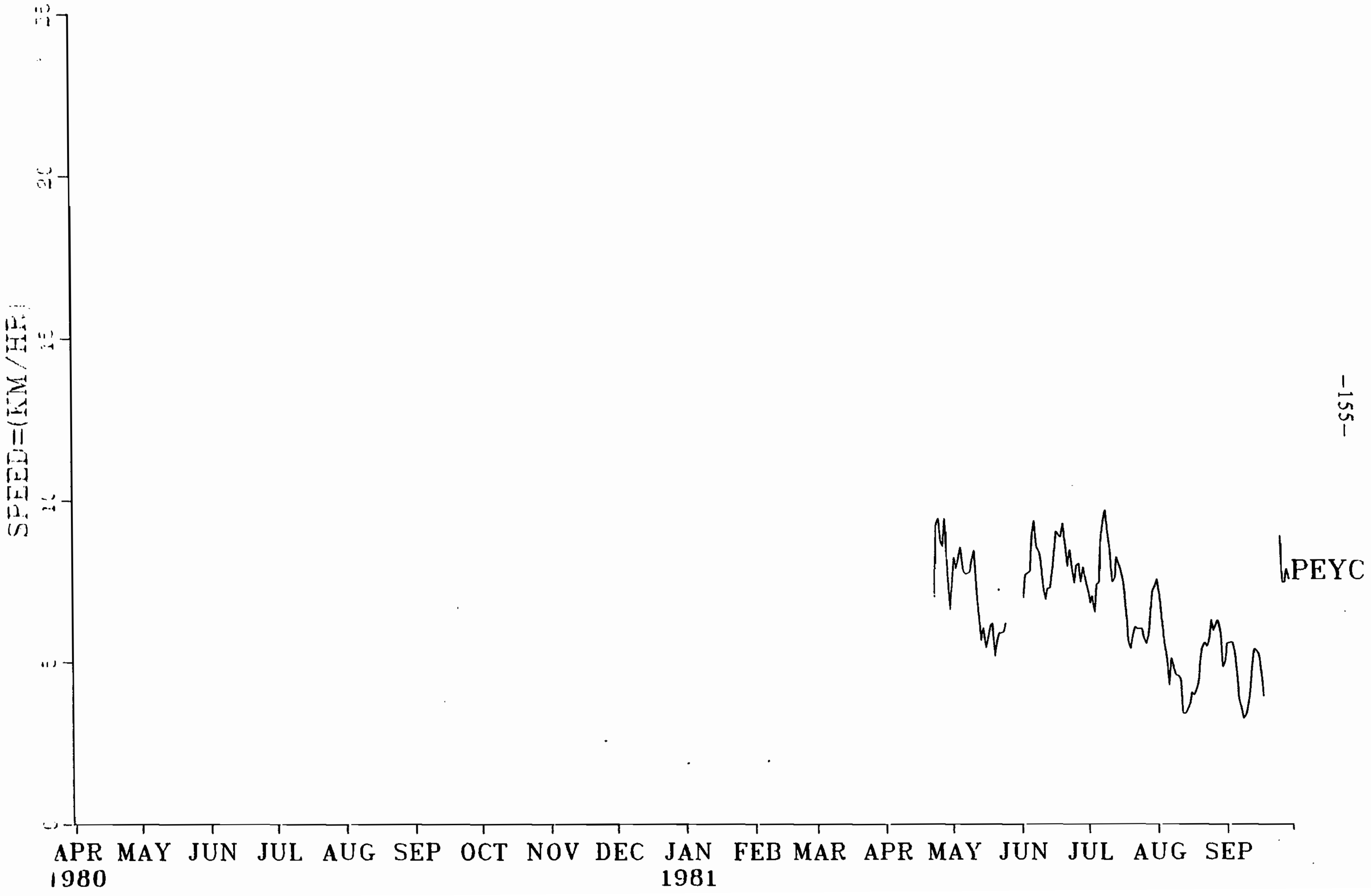


FIGURE 5 PEACHLAND YACHT CLUB – VAPOUR PRESSURE
5 DAY RUNNING MEANS – SURFACE (VPSF) AND AMBIENT (VPMN)

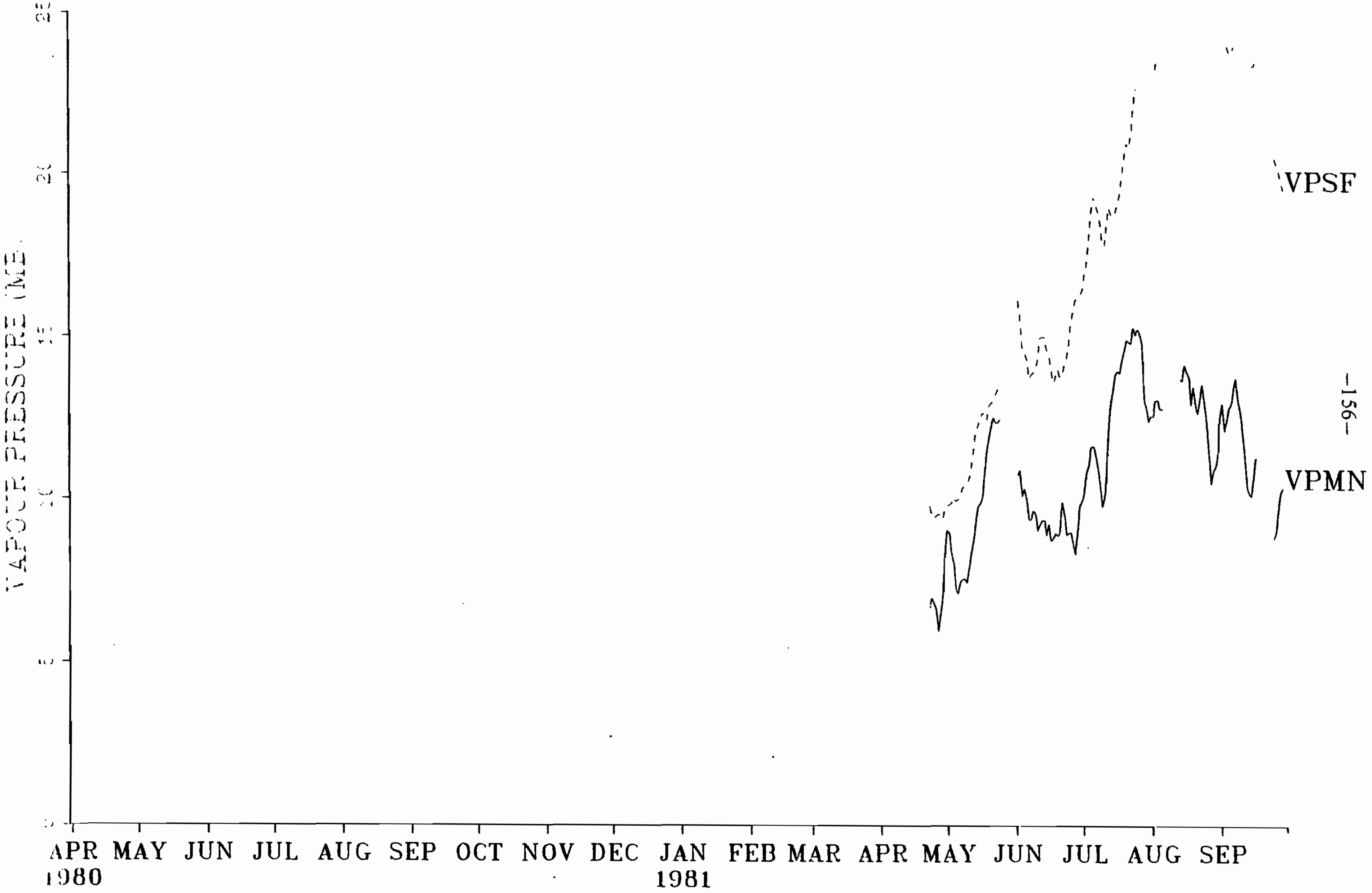


FIGURE 4 PEACHLAND YACHT CLUB – AIR AND WATER TEMPERATURE
5 DAY RUNNING MEANS – AIR (TAVE) AND WATER (TSAV)

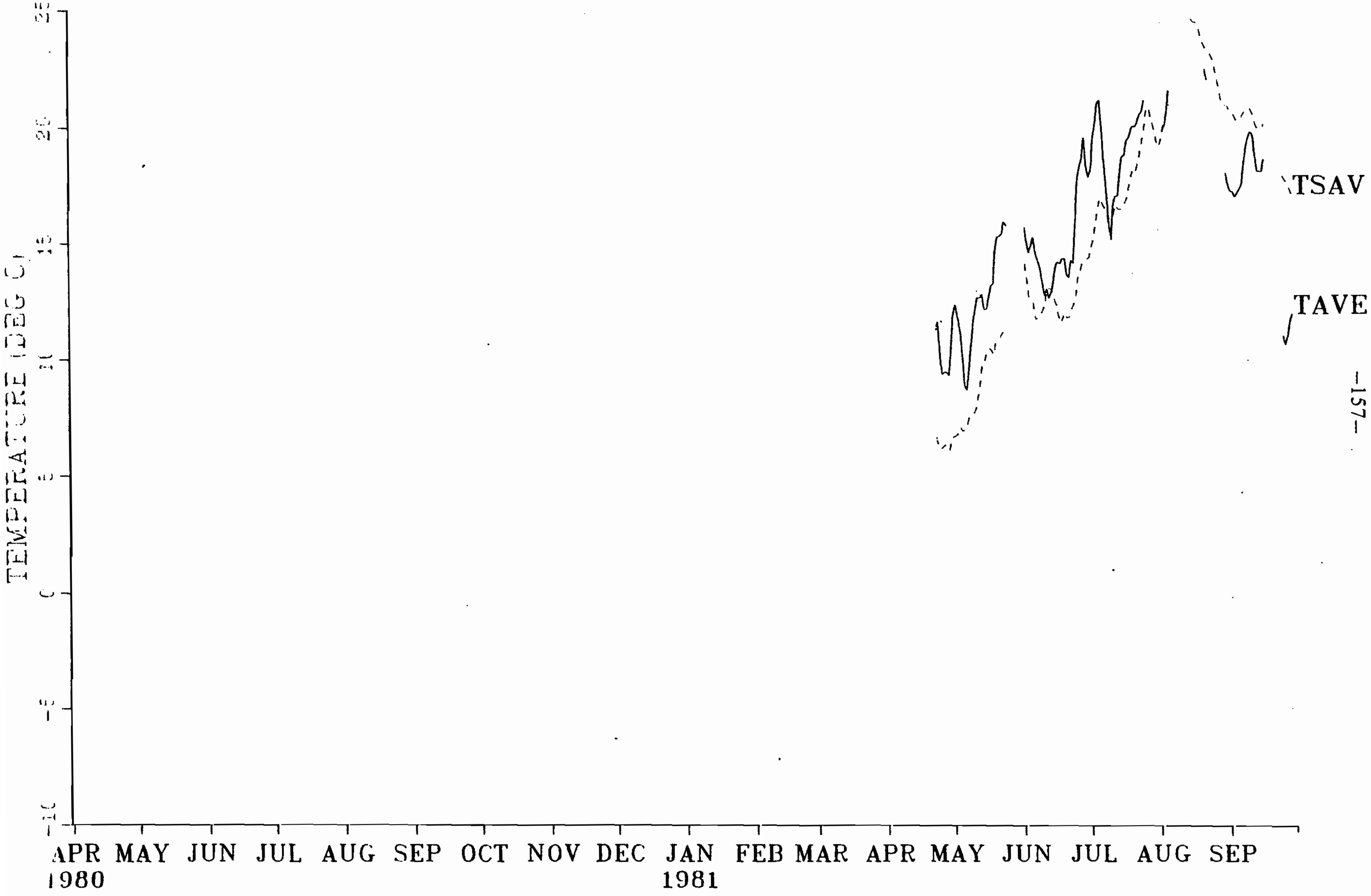


FIGURE 3 PEACHLAND YACHT CLUB – WATER TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TSMX) AND MINIMUM (TSMN)

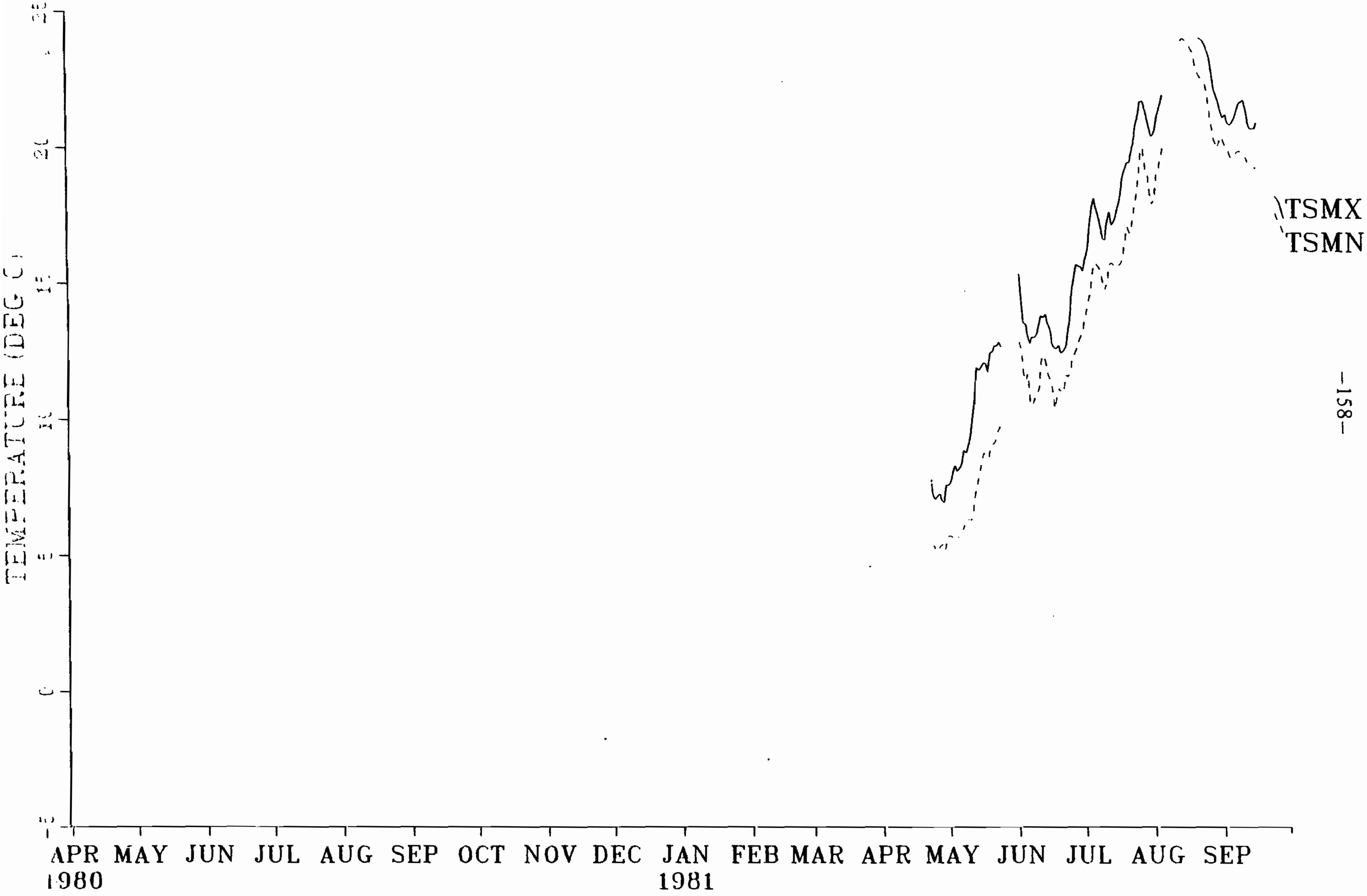


FIGURE 2 PEACHLAND YACHT CLUB – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

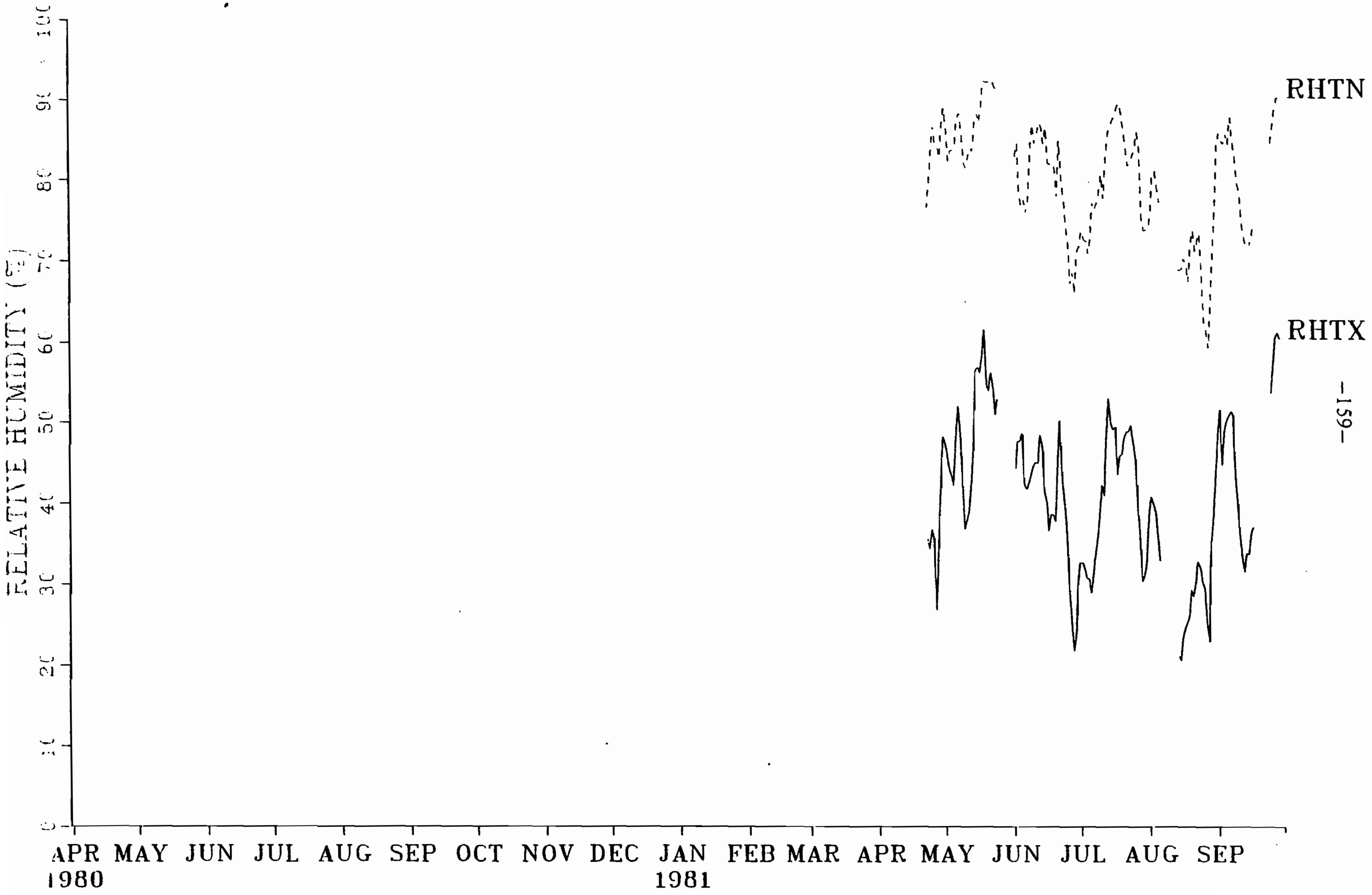


FIGURE 1 PEACHLAND YACHT CLUB – AIR TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

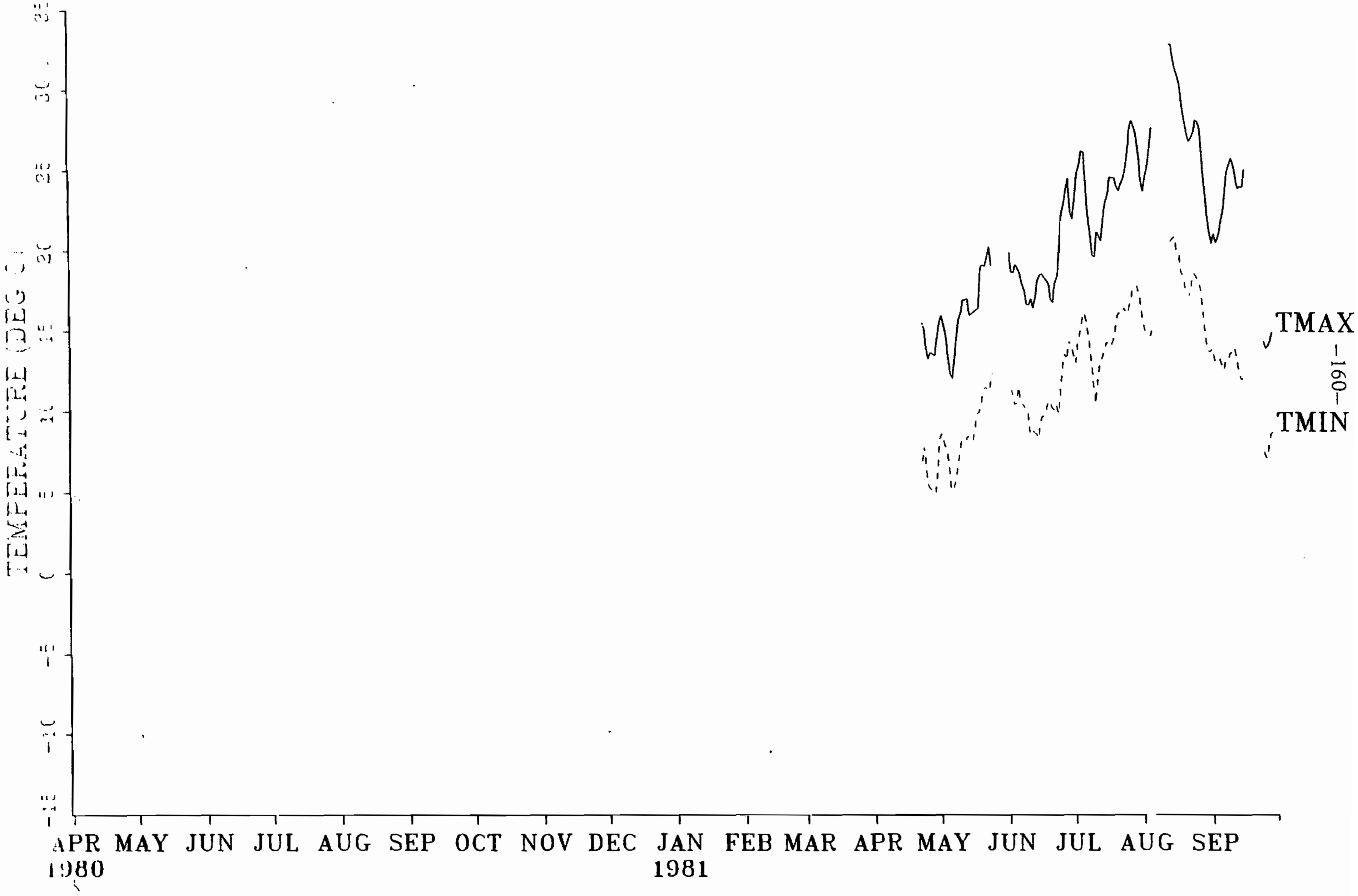


FIGURE 1 PENTICTON MARINA – AIR TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

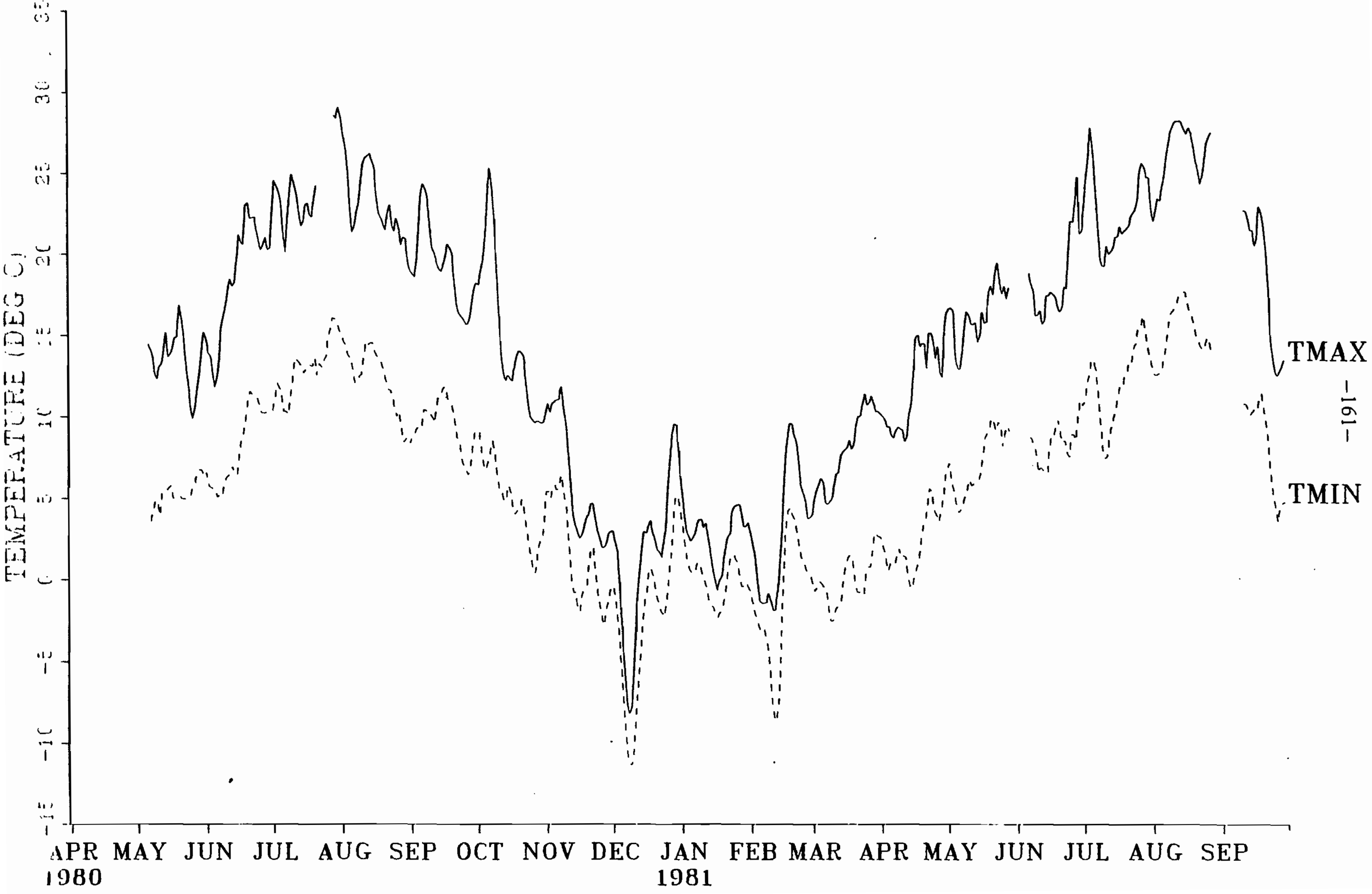


FIGURE 2 PENTICTON MARINA – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

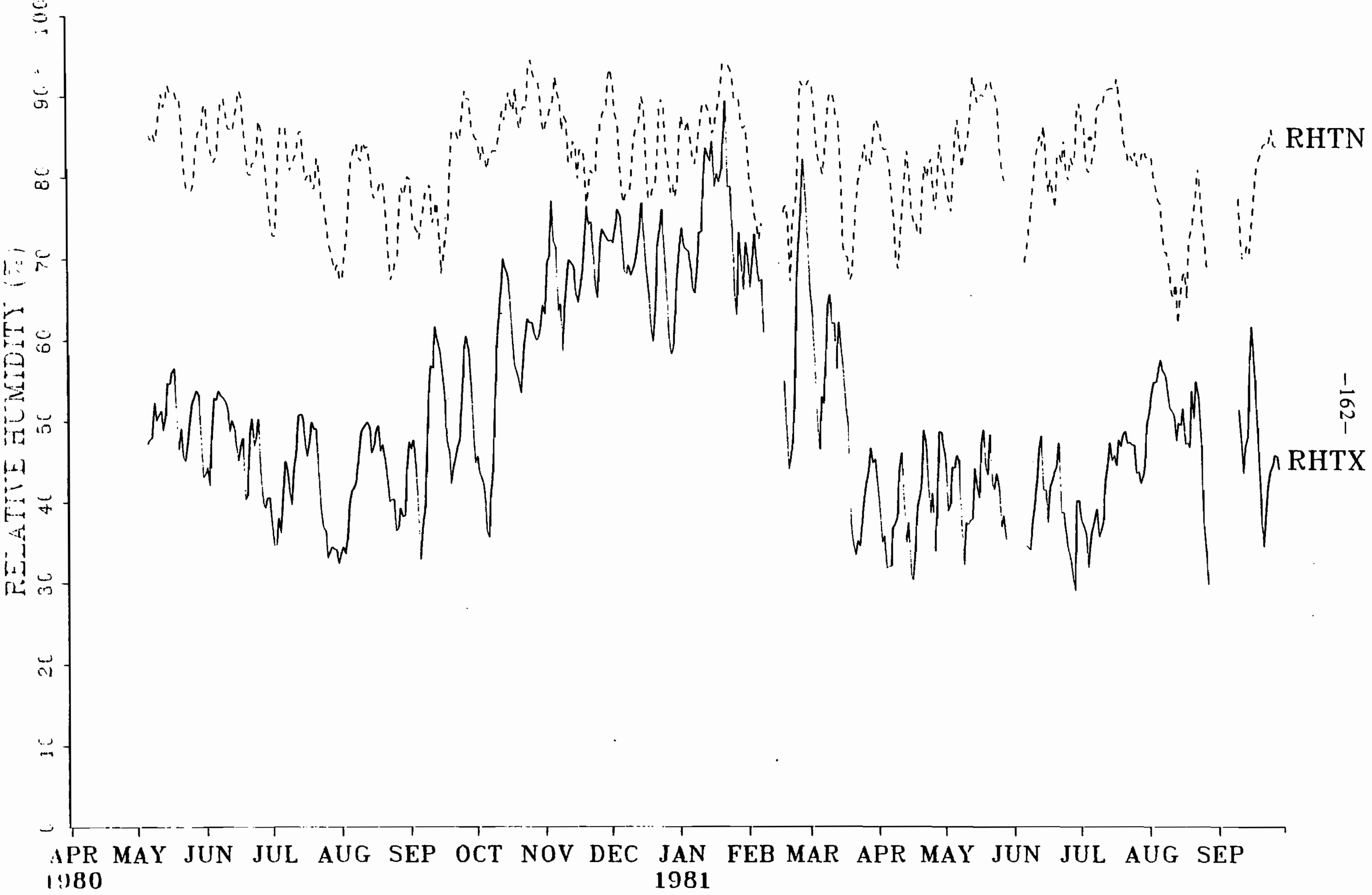


FIGURE 3 PENTICTON MARINA – WATER TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TSMX) AND MINIMUM (TSMN)

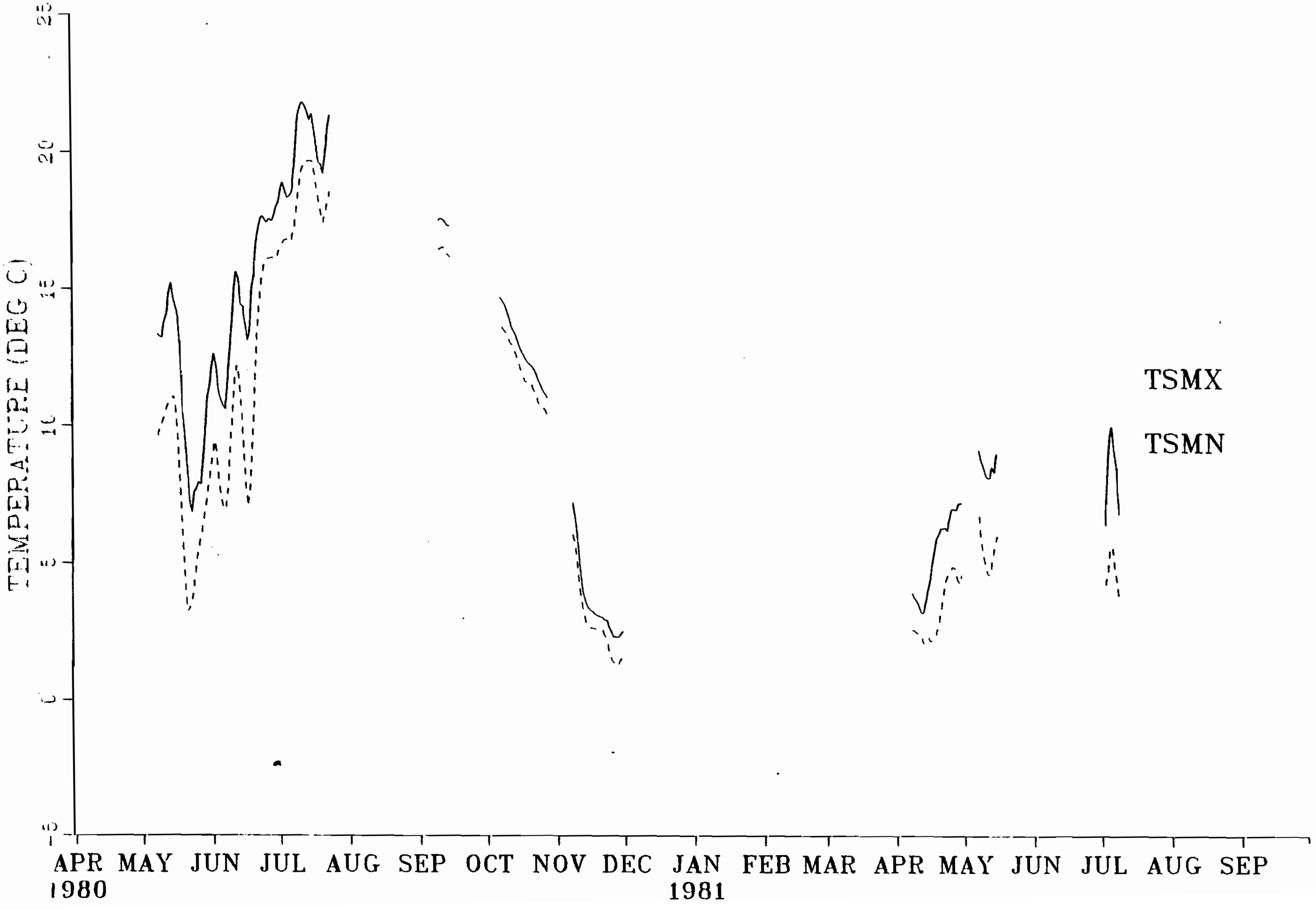


FIGURE 4 PENTICTON MARINA – AIR AND WATER TEMPERATURE
5 DAY RUNNING MEANS – AIR (TAVE) AND WATER (TSAV)

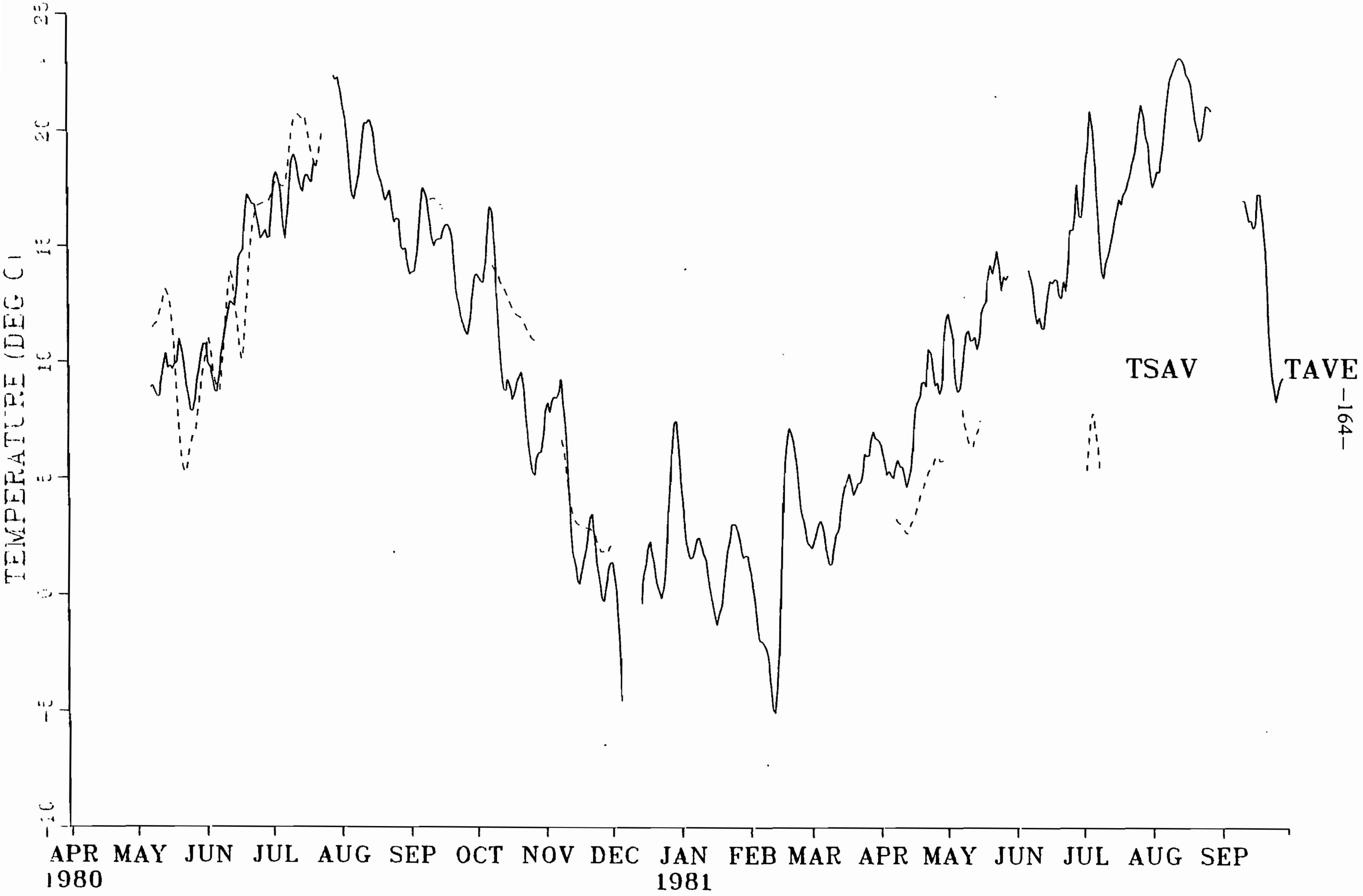


FIGURE 5 PENTICTON MARINA – VAPOUR PRESSURE
5 DAY RUNNING MEANS – SURFACE (VPSF) AND AMBIENT (VPMN)

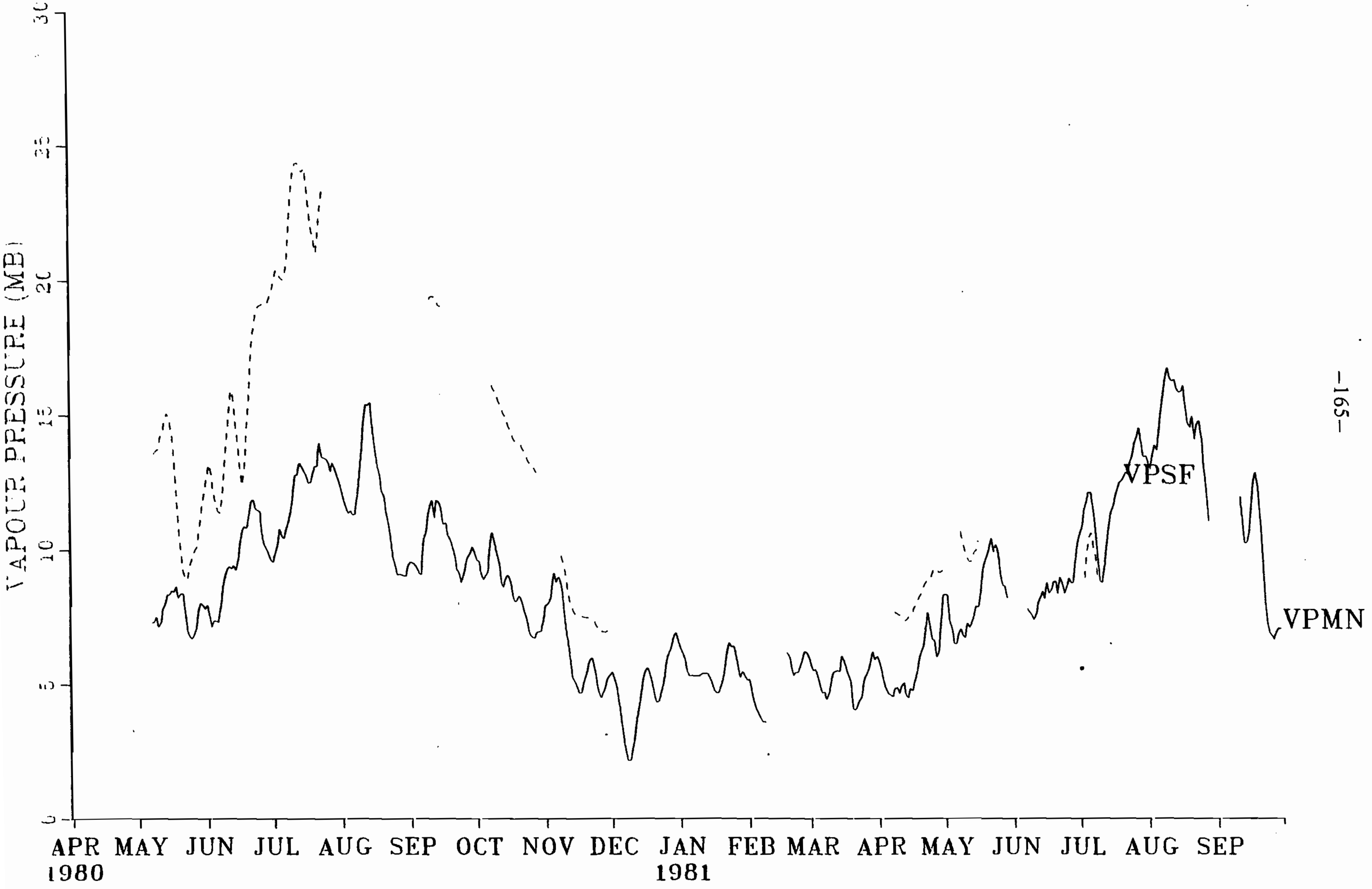


FIGURE 6 PENTICTON MARINA – WIND SPEED
5 DAY RUNNING MEANS – 4 METRES ABOVE MEAN LAKE LEVEL

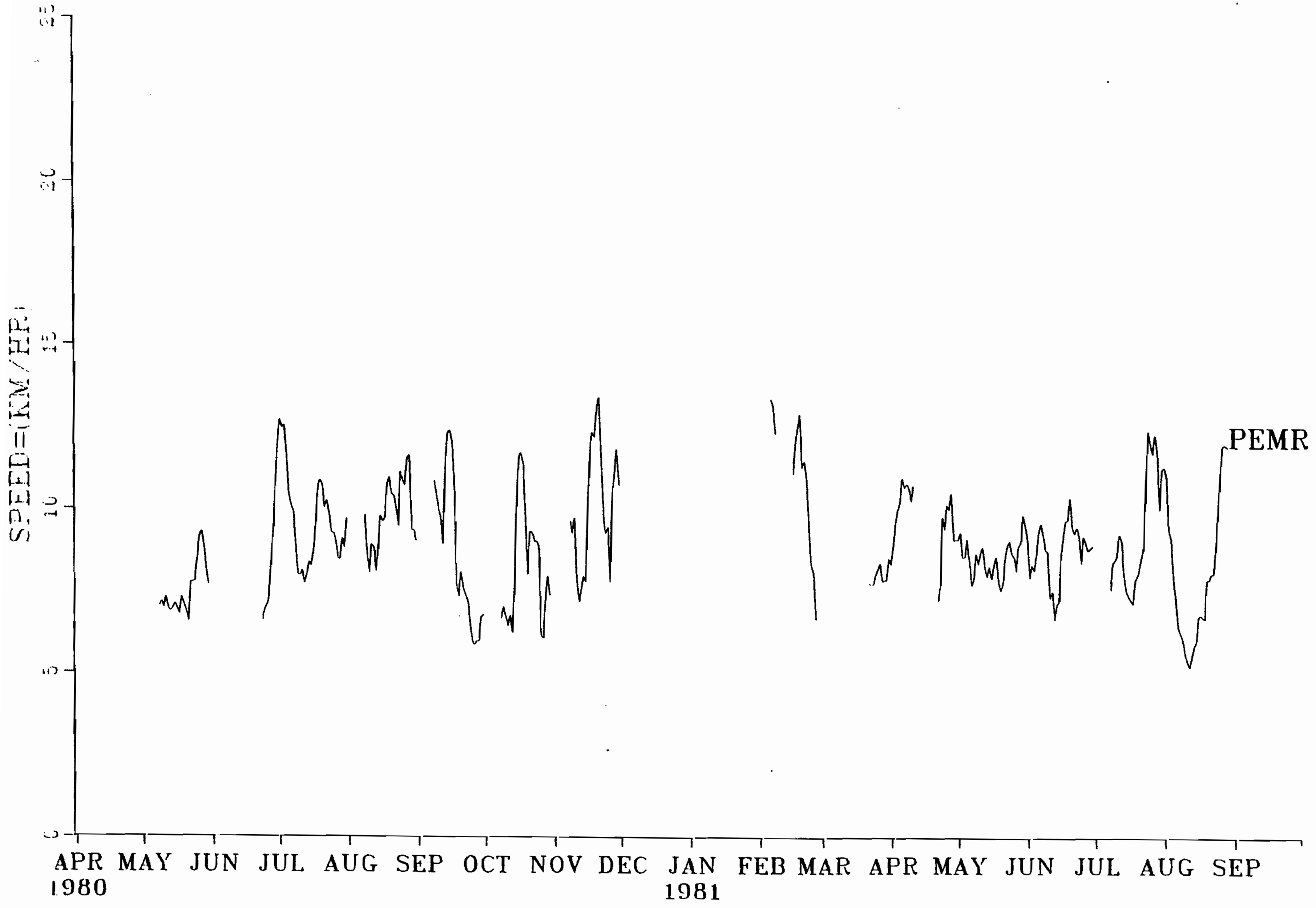


FIGURE 1 PENTICTON AIRPORT – AIR TEMPERATURE
5 DAY RUNNING MEANS – MAXIMUM (TMAX) AND MINIMUM (TMIN)

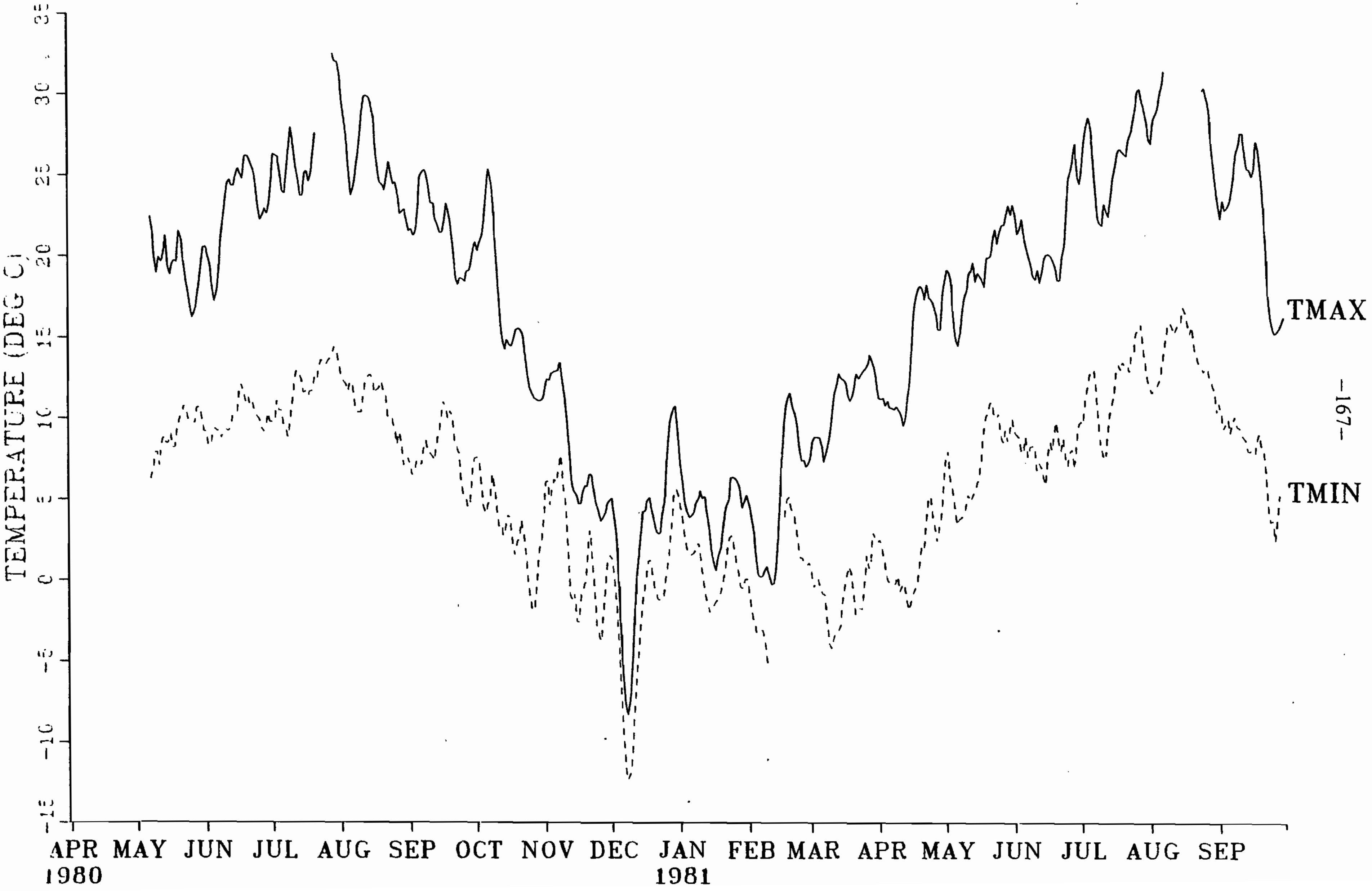


FIGURE 2 PENTICTON AIRPORT – RELATIVE HUMIDITY
5 DAY RUNNING MEANS – AT TMAX (RHTX) AND TMIN (RHTN)

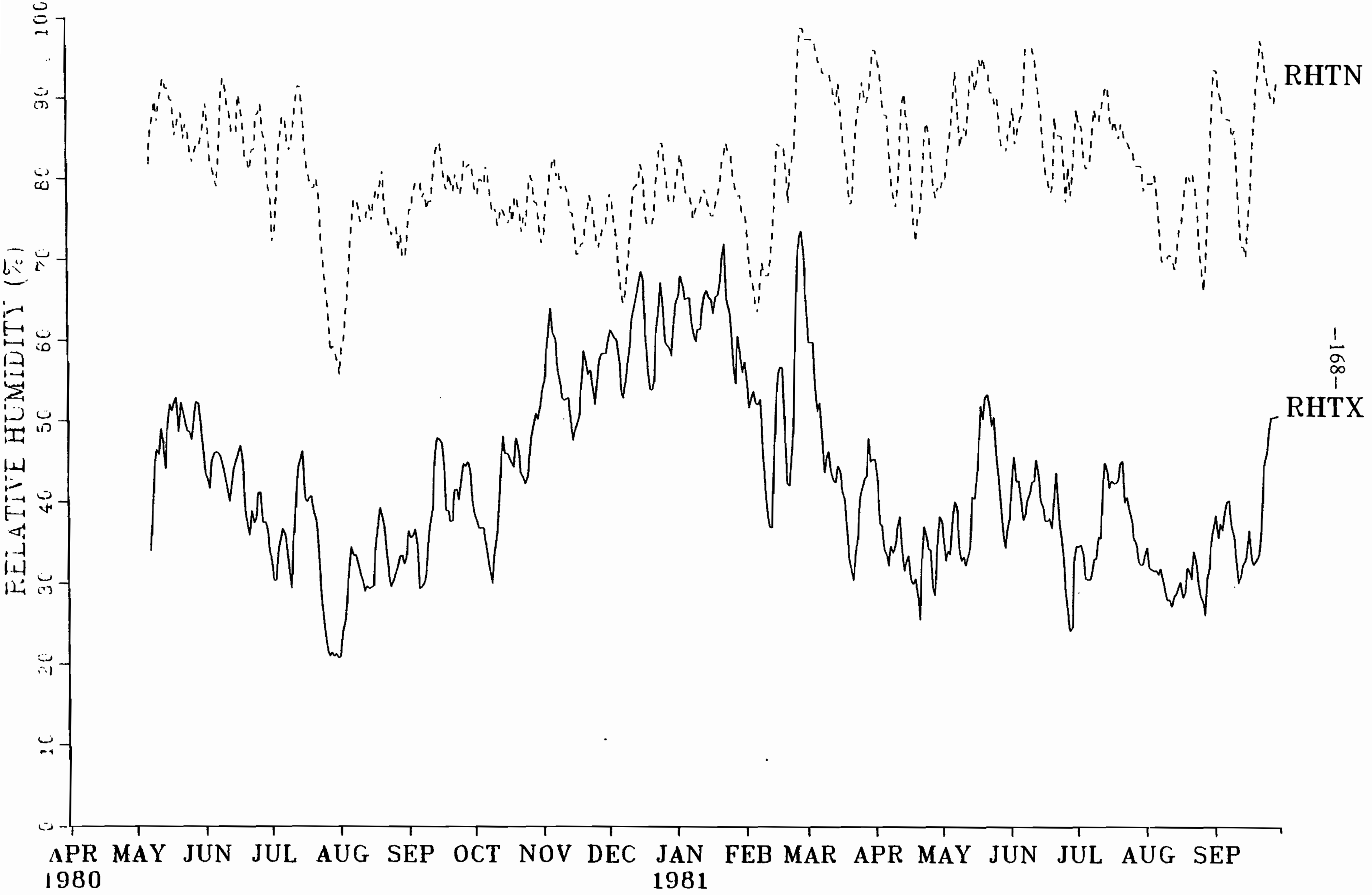


FIGURE 3 PENTICTON AIRPORT – MARINA TEMPERATURE
5 DAY RUNNING MEANS – AIRPORT (PEAP) AND MARINA (PEMR)

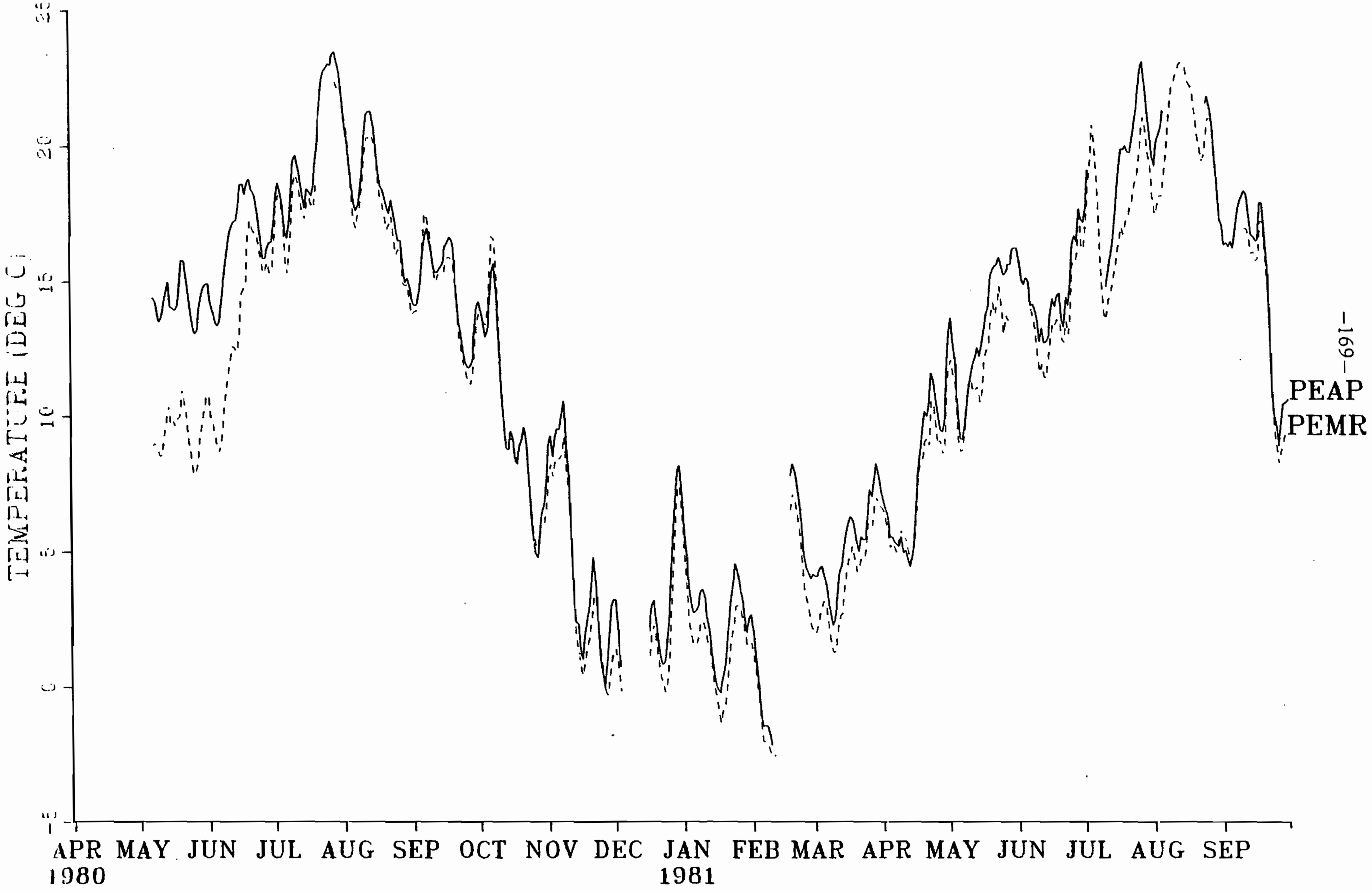


FIGURE 4 PENTICTON AIRPORT – MARINA VAPOUR PRESSURE
5 DAY RUNNING MEANS – AIRPORT (PEAP) AND MARINA (PEMR)

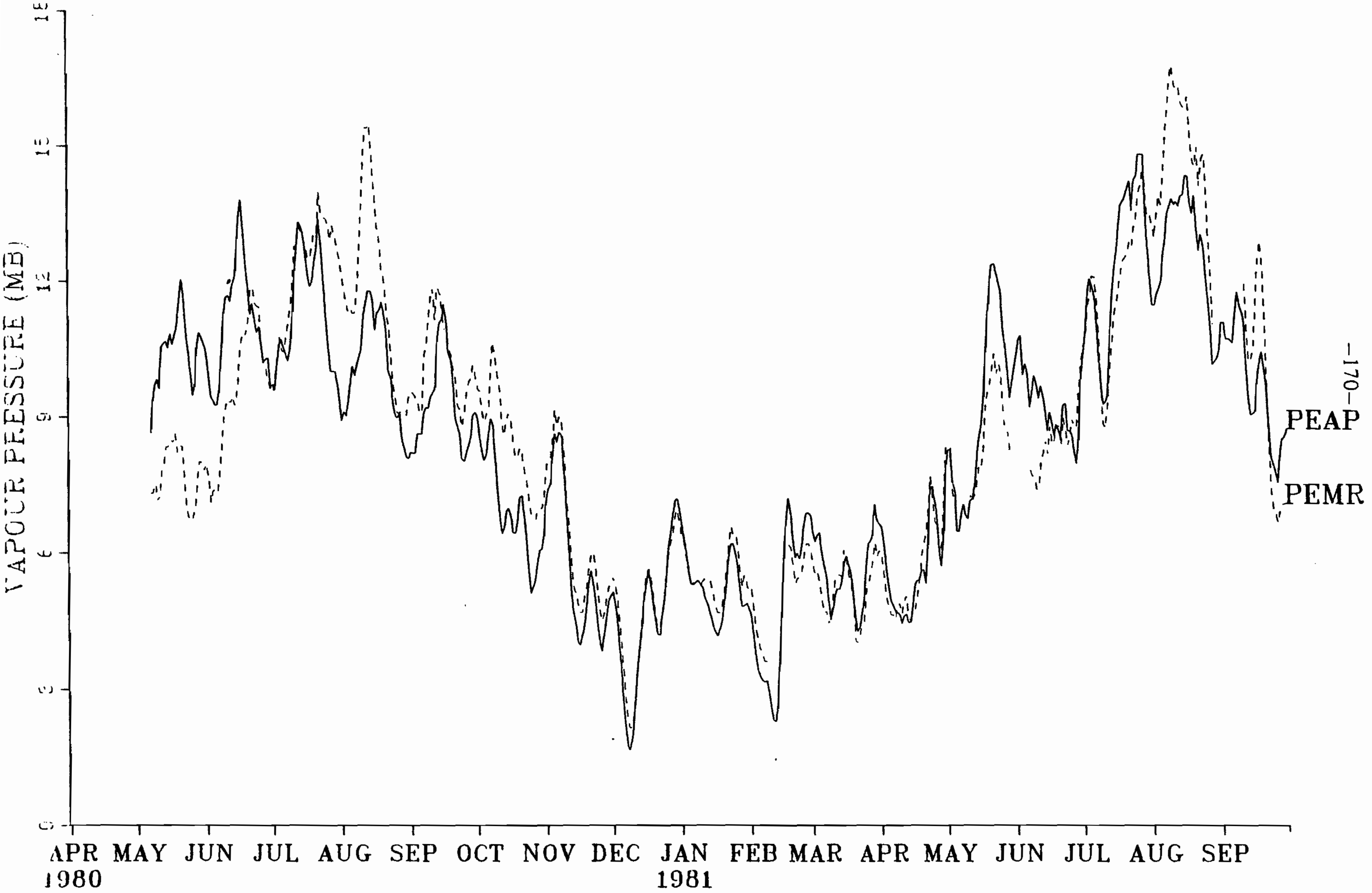


FIGURE 5 PENTICTON AIRPORT – MARINA TEMPERATURE GRADIENT
5 DAY RUNNING MEANS – AIRPORT (TAVE) AND MARINA (TSAV)

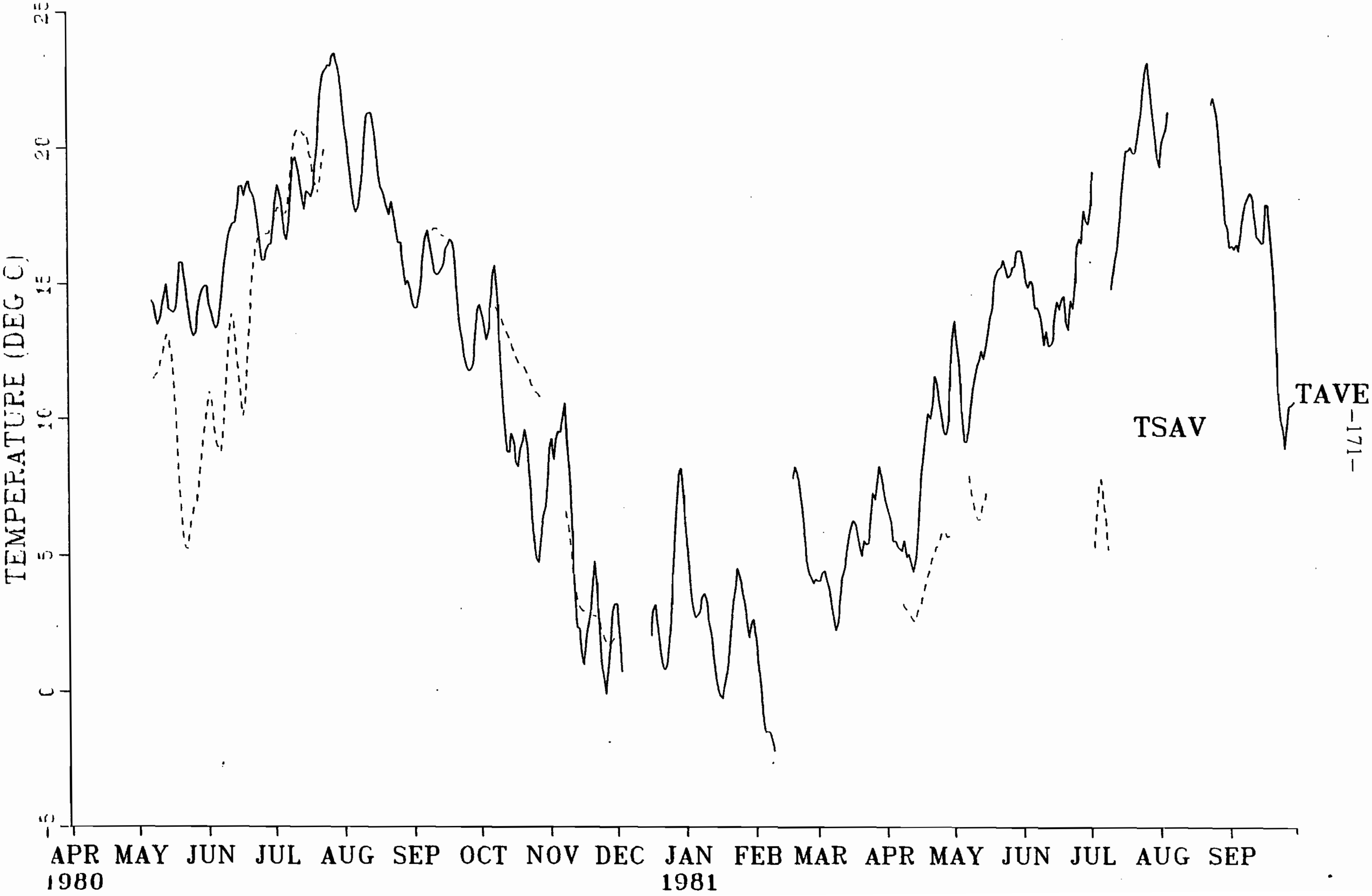


FIGURE 6 PENTICTON AIRPORT – MARINA VAPOUR PRESSURE GRADIENT
5 DAY RUNNING MEANS – AIRPORT (VPMN) AND MARINA (VPSF)

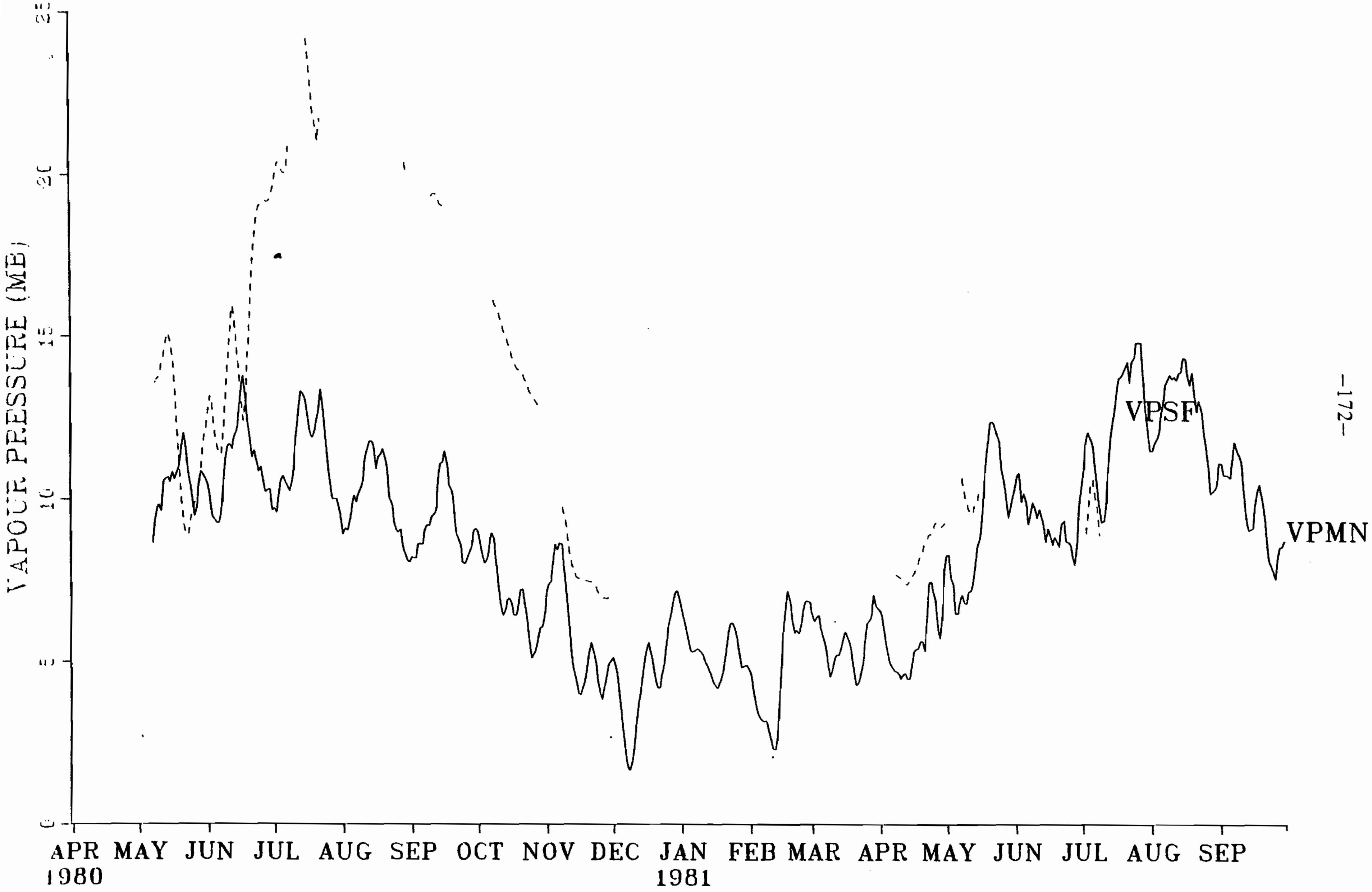
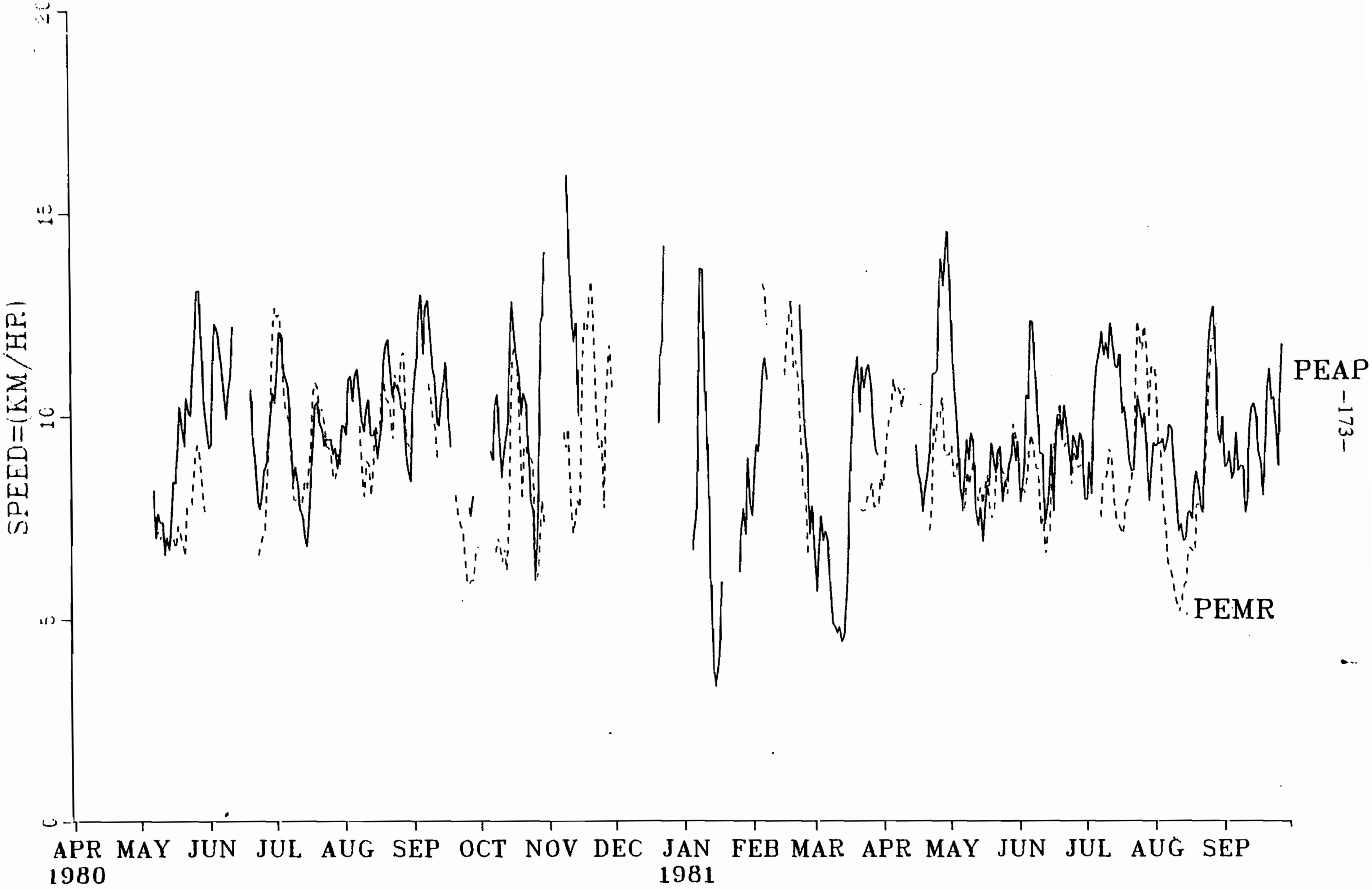


FIGURE 7 PENTICTON AIRPORT – MARINA – WIND SPEED
5 DAY RUNNING MEANS – AIRPORT (PEAP) AND MARINA (PEMR)



APPENDIX F

DAILY MEASUREMENT OF LAKE TEMPERATURE AT SELECTED STATIONS USING THE THERMOMETER AND BUCKET METHOD

Daily measurements of water temperature in Appendix F made by various municipal authorities using the bucket and thermometer technique. These data were measured between 8 a.m. and 9 a.m. where possible.

TABLE F.1
WATER TEMPERATURES IN APRIL

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
10		4.0		4.0			
23		6.0		4.0			

TABLE F.2
WATER TEMPERATURES IN MAY

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
1			10.0				8.0
2			11.5				8.5
3			10.0				
4			11.0				
5			12.0				9.0
6			13.0				10.0
7			11.5				10.5
8		12.0	13.0	9.0			12.0
9			13.5		15.3	12.0	10.0
10			12.5				10.0
11			12.0				13.0
12			13.0				11.5
13			13.5				13.0
14			13.5				13.0
15			13.5		10.3	9.3	12.0
16			13.0				7.0
17			14.5				8.5
18			14.5				10.0
19			14.5				8.0
20			14.5				8.0
21			13.5				8.5
22		12.5	13.0	13.5	13.0	12.5	10.0
23			14.5				10.0
24			14.5				10.0
25			14.0				10.0
26			14.0				10.0
27			14.0				7.0
28			13.5				8.0
29			13.0		12.5	12.5	8.5
30			14.0				10.5
31			14.0				13.0

TABLE F.3
WATER TEMPERATURES IN JUNE

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
1							10.5
2							11.5
3							11.0
4							11.0
5		18.0		13.0			10.5
6					13.5	14.8	12.5
7							12.0
8							13.5
9							13.5
10							14.0
11							14.0
12					17.3	16.8	15.0
13							15.0
14							12.0
15							14.5
16							14.0
17							13.0
18							14.0
19		17.0		15.0	17.5	18.5	15.0
20			17.0				17.0
21			18.0				17.5
22			17.5				16.5
23			17.0				13.5
24			17.5				14.5
25			17.0				14.5
26			17.0		17.3	15.5	16.0
27			17.5				15.0
28			17.0				15.5
29			17.5				16.0
30			17.5				15.0

TABLE F.4
WATER TEMPERATURES IN JULY

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
1			17.5				16.0
2			18.0				17.0
3		19.0	18.0	17.0	18.5	17.5	17.0
4			17.5				17.0
5			17.5				16.0
6			18.0				16.5
7			17.0				16.5
8	20.3		19.5				17.0
9	20.5		17.5				18.0
10	19.6		19.0		20.0	17.0	17.5
11	19.2		18.0				17.5
12			18.5				17.5
13			19.0				18.0
14	20.0		18.5				17.0
15	20.0		18.0				17.0
16	19.5		19.0				17.0
17	19.8	21.0	18.5	21.5			17.0
18	19.7		18.0				17.5
19			18.0		18.5	17.3	17.5
20			19.0				18.5
21	21.3		19.0				19.0
22	21.0		19.0				20.0
23	21.6		20.0				20.0
24	22.5		20.0		22.5	22.0	20.0
25	22.4		20.0				19.5
26			20.5				21.0
27			21.0				21.0
28	23.7		20.5				20.0
29	24.0		20.0				20.0
30	22.8		21.0				19.5
31	23.3		21.0		23.5	22.0	20.0

TABLE F.5
WATER TEMPERATURES IN AUGUST

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
1	23.0	23.0	21.0	23.5			20.5
2			21.0				20.5
3			20.5				19.5
4			20.0				18.0
5	20.7		20.0				18.5
6	20.3		20.0				18.0
7	20.7		20.0		20.5	20.0	18.5
8	20.9		20.5				18.5
9							19.5
10							19.5
11	21.2						19.5
12	20.4						19.5
13	20.7						19.5
15	21.4						21.0
16							21.0
17							19.0
18	20.2						18.5
19	20.5						18.5
20	20.7						18.0
21	20.0						18.0
22	19.6						18.5
23							18.5
24							17.5
25	19.3				20.5	19.5	17.5
26	19.7						18.5
27	19.3						17.5
28	18.6	23.0		23.0	18.8	18.0	17.0
29	19.2						17.5
30							17.0
31							18.5

TABLE F.6
WATER TEMPERATURES IN SEPTEMBER

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
1							16.0
2							16.0
3							16.0
4					18.5	17.8	16.0
5							17.5
6							18.0
7							17.5
8							16.0
9							16.0
10							16.5
11		20.0		20.0	19.3	19.0	16.5
12							17.5
13							17.0
14							16.0
15							16.0
16							16.0
17							16.0
18					17.6	17.6	16.0
19							16.0
20							
21							
22							15.0
23							15.5
24							15.0
25		18.5		19.5			14.0
26					16.2	16.0	14.0
27							
28							
29							14.5
30							14.5

TABLE F.7
WATER TEMPERATURES IN OCTOBER

Date	Vernon Yacht Club	Vernon Arm	Ellison Provincial Park	Okanagan Centre	Traders Cove	Gellatly Pier	Summerland Provincial Park
9		16.0		16.0			

APPENDIX G

ANALYSIS OF SURFACE TEMEPRATURES FROM THERMAL IMAGING LINE SCANNER IMAGERY USING A DENSITY SLICER

The thermal imagery of Lake Okanagan was obtained under contract by INTERTEC which in a subsidiary of INTERA of Calgary. This imagery was on film which had been "digitally sliced" by INTERTEC at 1°C intervals. The system used to obtain the imagery is described below.

An instrument known as a density slicer was used to calculate the area in a given interval of film density corresponding to the desired temperature interval. The density-to-temperature conversion is given by the density wedge produced at the start of each flight where black corresponds to the temperature of the warm black body (or warmer), white corresponds to the temperature of the cool black body (or cooler), and the in between temperatures are divided into 6 equal intervals. Figure G.1 shows a black and white segment of the flight line and Figure G.2 shows the same segement on the colour monitor after the colour temperature assignments. Figure G.3 shows the variation in density across the image at the top of the colour band in Figure G.2. The area in each temperature interval (each colour) is measured as a percentage of the lake in the segment. An areally weighted mean is then calculated by summing the areas in each interval for each segment. The area and temperature interval are given in Figures G.4-G.7 for this segment as an example.

The complete analysis has been recorded on slides in Appendix H.

Thermography

The thermal line-scanner used for this project was a Daedalus DS-1230 dual channel model, manufactured by Daedalus Enterprises of Ann Arbor, Michigan. The scan system has a spatial resolution of 1.7 milliradians and a thermal resolution of 0.2°C. The detector is sensitive in the 8-14 micron region with a spectral response curve given in Figure G.8.

The scanning mirror within the scan system, rotates at a rate of 80 scans per second. During each scan-line cycle the mirror views two adjustable temperature black body reference sources. The field of view beneath the aircraft is 77°20' (Figure G.9). The mirror focuses emitted thermal radiation from the ground surface and reference sources on the detectors. The output of information from one scan appears as in Figure G.10. All data is recorded on magnetic tape for playback at a ground processing station.

Processing of Thermal Imagery

The ground processing unit is capable of producing a hard-copy film product from the stored tape signal. An analogue, or continuous tone output is available for interpretation of thermal information. The analogue output provides an image that resembles a black and white aerial photograph and is best suited to the interpretation of small-detailed thermal information.

"Level slicing" of the thermal data is a method of providing information of a semi-quantitative nature. The processing unit does this by defining a two reference level calibration range, (as a voltage) comparing the ground scene voltages to that range and finally subdividing the range into six equal iso-levels. The iso-levels are each given a grey tone in the printing unit.

Figure G.11 shows a signal from the Scanner which has calibrated thermal reference sources producing voltages V_{BBI} and V_{BB2}. Electronic sample-hold circuits extract V_{BBI} and V_{BB2} from the input signal for use as calibration reference voltages. The difference between V_{BBI} and V_{BB2} represents the full calibration range of the instrument. The voltages V_{BBI} and V_{BB2} are applied to opposite ends of a precision voltage divider to create six equal voltage increments within the full calibration range. Ranges are then defined as in Figure G.11 by numbers representing the divisions between voltage increments; such as range 1-2, range 2-5, or the full calibration range 1-7.

Once an appropriate range is selected, the processor automatically subdivides the signal into six equal voltage increments which corresponds to the isolevels shown on Figure G.11. Whenever the ground scene level is within a given isolevel increment, an output voltage is supplied to the Film Printer Unit to give an appropriate gray level on film. Signals above and below the selected range from the darkest and lightest levels on film to give 8-level-sliced processing.

Again using Figure G.11 as an example, examination of a "master set" of the 8 gray levels might lead to a desire for greater processing detail within that range. This can be accomplished by making additional "subset" passes. If the scanner operator had adjusted the reference source temperature properly so the total calibration range 1-7 was utilized by the ground scene in Figure G.11, 36 calibrated levels could have been achieved. System noise limits the practical number of sublevels to something less than 36 levels and the smallest temperature difference to 0.25°C.

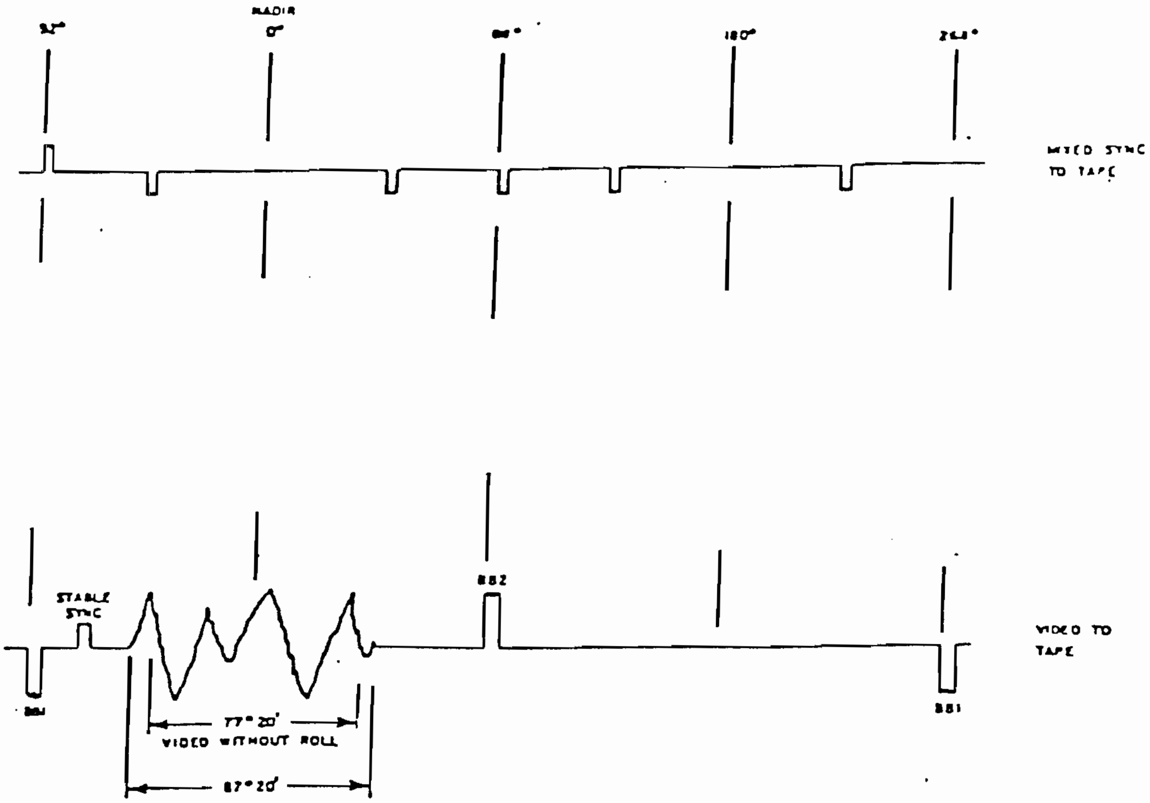
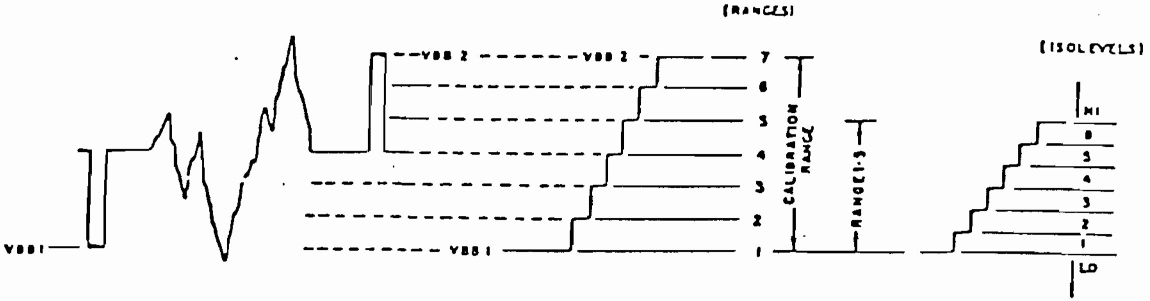


FIGURE G.10 The output from a single scan sequence is illustrated above. As the mirror turns the detector records the incoming radiation from one temperature reference, the ground scene and then the other reference. As the mirror continues its circuit the mirror "looks" at the inside of the scanning unit and no information is seen. At each event in the circuit, timing marks are recorded. These timing marks are for the syncronization of the signals during the playback mode.



					6-7
				5-6	5-7
			4-5	4-6	4-7
		3-4	3-5	3-6	3-7
	2-3	2-4	2-5	2-6	2-7
1-2	1-3	1-4	1-5	1-6	1-7

FIGURE G.11 The calibration range of the input signal is determined by the two reference temperatures BB_1 and BB_2. The processor automatically divides the input range in Hi-Lo and six equal levels in between. The master range 1-7 provides the largest span between levels because the 1-7 ranges uses BB_1 and BB_2 as the upper and lower end of the level-slice. From the master range any combination of sub-ranges can also be broken into the Hi-6-Lo isolevel product. Thirty-six possible combinations are available and depending on the temperature spread between BB_1 and BB_2 the smallest level possible is 0.25°C. (Daedalus 1977).