ROYAL OBSERVATORY, HONG KONG

TECHNICAL NOTE NO. 45

ESTIMATION OF WIND SPEEDS NEAR SEA-LEVEL DURING TROPICAL CYCLONE CONDITIONS IN HONG KONG

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CONTENTS

FIGURES

TABLES

1. INTRODUCTION

Measurements of wind direction and speed are made at the Royal Observatory and several other meteorological stations in Hong Kong. Because of the differences in exposure and heights of measuring instruments above mean sea-level, observations from these stations are not directly comparable. The rapid rate of urbanization in Hong Kong during recent years together with changes in instrumental sites have also affected the representativeness of some of the anemometer readings. This paper attempts to analyse the effects of these factors with the aim of developing some criteria for estimating the representative wind flow near sea-level from station records.

2. WIND MEASUREMENTS IN HONG KONG

Automatic measurements of wind direction and speed were first made in Hong Kong on 1 March 1884. The instrument used was a Beckley cup-anemometer, made "extra strong" so that it would work as well in a typhoon as in the gentle breeze. The instrument was fixed to the top of a teak wood turrent, 2.8 metres high in the centre of the roof of the Royal Observatory building. The cup was 15 metres above the ground and 53 metres above mean sea level.

In January 1910, a Dines-Baxendall pressure-tube anemometer was installed about 3.3 metres northeast of the Beckley cups with its vane about 0.15 metre higher and a series of comparisons between the two instruments was maintained until 1938 when the Beckley anemometer was dismantled. The results of the comparisons show that the early Beckley readings were slightly over-estimated and a new correction factor for converting "run of the wind" into "velocity" was made. An additional Dines anemometer was also used for recording maximum gusts during tropical cyclones from 1938 until the outbreak of the Pacific War in 1941. The latter instrument continued to be in operation after the occupation of Hong Kong by the Japanese.

Because of the uncertainty in the accuracy of the Beckley measurements, monthly mean velocities were only computed from the Dines observations after 1911. The readings taken at the Royal Observatory have been used as official records for Hong Kong and are published in the annual volumes of Meteorological Results Part I.

Dines anemometers were also installed at the other out-stations of the Royal Observatory and the period of records available from each of these stations is given in Figure 1.

3. REPRESENTATIVENESS OF ROYAL OBSERVATORY WIND SPEED

Although the Royal Observatory station has the longest series of wind observations for Hong Kong, the data are by no means homogeneous. Apart from changes in instrumentation described in the previous section, the Dines anemometer head was also raised from 47.4 metres to 60.9 metres above mean sea-level in July 1959.

Figure 2 is a plot of the annual mean wind speed recorded at the Royal Observatory during the post-war period 1947-1975. The variation from year to year is considerable but the most significant feature is the abrupt fall after 1961. This feature is of particular interest since it is also revealed in the monthly mean speed profiles depicted in Figure 3 and is not readily explainable in terms of natural changes. The heterogeneous nature of the post-war data is also reflected in Figure 4 which shows the annual total number of hours with mean wind speed equal to or greater than 22 knots for the period 1948 to 1975. The number of hours with hourly mean speed greater than or equal to 22 knots was greater than 100 in nearly every year before 1958 but only in one year during the subsequent 17-year period. This indicates the need for care when analysing the time series of the Royal Observatory wind observations.

4. WIND DATA FROM OTHER STATIONS

Particulars of other stations in Hong Kong at which wind measurements have been made are given by Chen (1975). A survey of the locations, exposure and instrumentation of these stations indicates that Waglan Island is the only station with uninterrupted observations, which is not significantly affected by urbanization. Waglan Island has a comparatively long series of records and its environmental conditions have remained practically unchanged since its establishment in 1952. However there have been a change in the site of the Dines anemometer and two minor alterations in the height of the wind vane during this period. The instrument was removed from the roof of the meteorological station (70.1 m above M.S.L.) to the roof of the signal tower about 38 metres to the south-southwest of the meteorological station (anemometer head 68.3 m above M.S.L.) in January 1964. The anemometer head was rised to 74.6 metres above mean sea-level in July 1966. A further raise to 74.8 metres above mean sea-level was made in December 1971.

Since wind observations were made only during day-light hours primarily for aeronautical purposes, they were not published and have only been analysed at 3-hourly intervals. However, hourly data has been extracted in connection with a separate investigation by Chen (1975) and these observations were used in the present study to examine the effect of the site change of the anemometer.

Figure 5 depicts the variation of the annual hourly mean wind speed for Waglan Island for the period 1952-1975. It is seen that the amplitude of fluctuation from year to year is very similar to that observed for the Royal Observatory prior to 1960. However, there is little sign of any abrupt change or secular trend in the subsequent years.

5. SELECTION OF A REFERENCE OBSERVATION SERIES

To assess the change of representativeness of wind speed observations made at a particular station with respect to time, it is necessary that a comparison of their readings be made against a homogeneous time series of wind data over an extended period. Unfortunately, such a series is not available because none of the records from existing surface reporting stations are free from the effects of urbanization or exposure changes. In order to derive some quantitative estimates of these effects, recourse has been made to upper-air wind observations carried out at the King's Park Meteorological Station. Upper-wind measurements by radar were started at this station in 1952 and winds for different heights and pressure levels have been measured four times a day since 1954 by the plane displacement of a meteorological balloon in the time interval of two to three minutes chosen so that the mid-point time almost coincides with the moment at which the balloon attains a particular height or pressure level. The method of observation and the site of measurement have remained unchanged since the establishment of this station and despite the fact that the observations represent only the mean winds of a layer of the atmosphere over a time interval of a few minutes, the data form a uniform time series which can usefully be employed as a reference standard for comparison purposes. To minimise the effect of topography, winds at 900-m level have been selected which is assumed to be above the surface boundary layer. Figure 6 shows the variation of the annual scalar mean wind speed at this level for the period 1952-1975. As in the case of Waglan winds, no sharp discontinuities are noted in the profile and it appears reasonable to assume that changes from year to year are primarily caused by natural weather events.

6. COMPARISON ANALYSES

(a) Royal Observatory winds

High-rise buildings started to be built around the Royal Observatory from 1958 onwards. To test their effects on the wind measurements at the Observatory, the wind data available for the present study were divided into two 6-year periods, 1952-1957 and 1969-1974 for comparison with the 900-m winds. Due to the excessive amount of labour needed for data processing, only those observations taken during the occasions when the strong wind signal or higher was hoisted in Hong Kong were analysed.

The data were classified into eight groups according to the 8-point compass and correlation coefficients and regression equations were derived for four of these groups, viz. northerly, northeasterly, easterly and southeasterly, which comprise more than 95% of the total number of observations. The results are given below :-

(i) For the period 1952-1957

$$U_9 = 1.551\ RO_N + 5.593 \quad (n = 18\ ;\ r = 0.799) \qquad (1)$$

$$U_9 = 0.843\ RO_{NE} + 13.995 \quad (n = 7\ ;\ r = 0.653) \qquad (2)$$

$$U_9 = 1.059\ RO_E + 10.978 \quad (n = 83\ ;\ r = 0.660) \qquad (3)$$

$$U_9 = 0.853\ RO_{SE} + 13.408 \quad (n = 26\ ;\ r = 0.610) \qquad (4)$$

(ii) For the period 1969-1974

$$U_9 = 1.706\ RO_N + 14.808 \quad (n = 37\ ;\ r = 0.258) \qquad (5)$$

$$U_9 = 1.111\ RO_{NE} + 20.835 \quad (n = 24\ ;\ r = 0.683) \qquad (6)$$

$$U_9 = 1.564\ RO_E + 12.232 \quad (n = 63\ ;\ r = 0.797) \qquad (7)$$

$$U_9 = 1.719\ RO_{SE} + 5.701 \quad (n = 6\ ;\ r = 0.961) \qquad (8)$$

where U_9 denotes wind speed at 900-m level, RO winds at the Royal Observatory and the subscripts refer to the direction of wind (N = north, NE = northeast etc.), n is the number of observations used and r is the value of correlation coefficient.

For comparison purposes, a listing of Royal Observatory values corresponding to some specified 900-m wind speeds as computed from the above equations is given in Table 1.

TABLE 1. RELATIONSHIP BETWEEN 900-m LEVEL AND ROYAL OBSERVATORY WIND SPEEDS FOR THE TWO PERIODS 1952-1957 AND 1969-1974

900-m Wind Speed (kn)	Royal Observatory Wind Speed (kn)		Variation of Royal Observatory Wind Speed (%) $(\frac{a-b}{a})$
	1952-1957 (a)	1969-1974 (b)	
a. Northerly Winds at the Royal Observatory			
25	12.5	6.0	52.0
30	15.7	8.9	43.3
35	19.0	11.8	37.9
40	22.2	14.8	33.3
45	25.4	17.7	30.3
50	28.6	20.6	28.0
55	31.9	23.6	26.0
60	35.1	26.5	24.5
b. Northeasterly Wind at the Royal Observatory			
25	13.1	3.7	71.7
30	19.0	8.2	56.8
35	24.9	12.7	49.0
40	30.8	17.3	43.8
45	36.8	21.8	40.8
50	42.7	26.2	38.6
55	48.6	30.7	36.8
60	54.6	35.3	35.3
c. Easterly Winds at the Royal Observatory			
25	13.2	8.2	37.9
30	18.0	11.4	36.7
35	22.7	14.6	35.7
40	27.4	17.8	35.0
45	32.1	21.0	34.6
50	36.8	24.1	34.5
55	41.6	27.3	34.4
60	46.3	30.5	34.1
d. Southeasterly Winds at the Royal Observatory			
25	13.6	11.2	17.6
30	19.5	14.1	27.7
35	25.3	17.0	32.8
40	31.2	20.0	35.9
45	37.0	22.9	38.1
50	42.0	25.8	39.9
55	48.8	28.7	41.2
60	54.6	31.6	42.1

(b) Waglan Island winds

Analyses similar to those described in the previous section were carried out for Waglan Island. In this case, apart from the change in instrument site in January 1964, there are no other known causes which may significantly affect the representativeness of wind observations at this station. To enable a direct comparison with the Royal Observatory data to be made, the same two periods, i.e. 1952-1957 and 1969-1974, were chosen for the correlation study and the resultant regression equations obtained are given below :

(i) For the period 1952-1957

$$U_9 = 0.762\ WL_N + 11.732 \quad (n = 23\ ;\ r = 0.650) \qquad (9)$$

$$U_9 = 0.894\ WL_{NE} + 11.255 \quad (n = 8\ ;\ r = 0.935) \qquad (10)$$

$$U_9 = 1.120\ WL_E + 4.656 \quad (n = 62\ ;\ r = 0.751) \qquad (11)$$

$$U_9 = 0.971\ WL_{SE} + 10.202 \quad (n = 33\ ;\ r = 0.707) \qquad (12)$$

(ii) For the period 1969-1974

$$U_9 = 0.831\ WL_N + 6.856 \quad (n = 33\ ;\ r = 0.635) \qquad (13)$$

$$U_9 = 0.944\ WL_{NE} + 7.332 \quad (n = 30\ ;\ r = 0.891) \qquad (14)$$

$$U_9 = 0.901\ WL_E + 8.536 \quad (n = 66\ ;\ r = 0.760) \qquad (15)$$

$$U_9 = 0.884\ WL_{SE} + 12.124 \quad (n = 10\ ;\ r = 0.745) \qquad (16)$$

where WL denotes winds recorded at Waglan Island.

Wind speed values at Waglan Island corresponding to some specified 900-m winds have also been computed from the above equations and are listed in Table 2.

TABLE 2. RELATIONSHIP BETWEEN 900-m LEVEL AND WAGLAN ISLAND WIND SPEEDS FOR THE TWO PERIODS 1952-1957 AND 1969-1974

900-m Wind Speed (kn)	Waglan Island Wind Speed (kn)		Variation of Waglan Island Wind Speed (%) $(\frac{a-b}{a})$
	1952-1957 (a)	1969-1974 (b)	
a. Northerly Winds at Waglan Island			
25	17.4	21.8	-25.3
30	24.0	27.9	-16.3
35	30.5	33.9	-11.1
40	37.1	39.9	- 7.5
45	43.7	45.9	- 5.0
50	50.2	51.9	- 3.4
55	56.8	57.9	- 1.9
60	63.3	64.0	- 1.1
b. Northeasterly Winds at Waglan Island			
25	15.4	18.7	-21.4
30	21.0	24.0	-14.3
35	26.6	29.3	-10.1
40	32.2	34.6	- 7.5
45	37.7	39.9	- 5.8
50	43.3	45.2	- 4.4
55	48.9	50.5	- 3.3
60	54.5	55.8	- 2.4
c. Easterly Winds at Waglan Island			
25	18.1	18.2	- 0.6
30	22.6	23.8	- 5.3
35	27.1	29.4	- 8.5
40	31.6	34.9	-10.4
45	36.0	40.5	-12.5
50	40.5	46.0	-13.6
55	44.9	51.6	-14.9
60	49.4	57.1	-15.6
d. Southeasterly Winds at Waglan Island			
25	15.2	14.6	3.9
30	20.4	20.2	1.0
35	25.5	25.9	- 1.6
40	30.7	31.5	- 2.6
45	35.8	37.2	- 3.9
50	41.0	42.8	- 4.4
55	46.1	48.5	- 5.2
60	51.3	54.2	- 5.6

7. REDUCTION OF WAGLAN ISLAND WINDS TO STANDARD REFERENCE LEVEL

Since the head of the Dines anemometer at Waglan Island is located at 74.8 m above mean sea-level, the readings from this instrument cannot be used as such to report strong winds, gales etc. near the sea-level as defined in the official warnings of the Royal Observatory. A height reduction of these observations is required.

The most frequently used wind-height relationship for the surface boundary layer given in the literatures is probably the power law written in the form :

$$U = U_1 \left(\frac{Z}{Z_1}\right)^p \tag{17}$$

where U and U_1 are the mean wind speed at height Z and Z_1 respectively, and p is an empirical exponent.

Different values of p has been suggested by various research workers and the most commonly used is p = 0.14. Davenport (1967) found that a value of p = 0.16 fitted his measurements of vertical wind profile over a flat open country whilst Mackey (1973, 1975) examined the wind records collected from the experimental building at Cape D'Aguilar, Hong Kong during strong monsoon and tropical cyclone conditions and recommended a value of 0.19 for p. Another wind-height relationship proposed in the Handbook for Meteorological Instruments (1956) is that due to Hellmann and takes the form

$$U/U_{10} = 0.233 + 0.656 \log_{10} (Z-4.75) \tag{18}$$

where U_{10} is the wind speed at 10 m above a level ground or open sea surface and U is the wind speed at height Z.

More elaborate approaches have also been attempted by several other workers, but they all involve the measurement of other additional parameters at different levels which are generally not observed at a synoptic or aeronautical station.

Assuming that the effective height of the anemometer at Waglan Island is 74.8 m, Table 3 lists the equivalent wind speeds recorded by this anemometer corresponding to strong, gale and hurricane force winds at 10 m above mean sea-level.

TABLE 3. EQUIVALENT WIND SPEEDS AT 74.8 m ABOVE MEAN SEA-LEVEL CORRESPONDING TO STRONG, GALE AND HURRICANE FORCE WINDS AT 10 m ABOVE MEAN SEA-LEVEL COMPUTED FROM VARIOUS HEIGHT REDUCTION FORMULAE

Equivalent Wind Speed at 74.8 m above M.S.L.	Wind Speed at 10 m above M.S.L. (kn)		
	22 (strong)	34 (gale)	64 (hurricane)
Hellmann	32.6	50.3	94.7
Power Law p = 0.14	29.3	45.3	85.2
Power Law p = 0.16	30.4	46.9	88.3
Power Law p = 0.19	32.3	49.8	93.8

In the Central Forecasting Office at the Royal Observatory, a value of 28 knots has been adopted as the equivalent wind speed at Waglan Island for strong winds near the sea-level with a sustained speed of 22 knots. This value was derived from the Hellmann's formula using the assumption that winds recorded at the Royal Observatory (anemometer head 47.4 m above mean sea-level) are representative of the surface air flow at 10 metres above ground level and that the effective height of the anemometer at Waglan Island was 32.7 metres (70.1 - (47.4-10)). If this relationship is used to define gale and hurricane force winds at Waglan Island, then the equivalent wind speeds will be respectively 43 and 81 knots. These values are generally lower than those listed in Table 3.

Since the establishment of the Meteorological Station at Waglan Island in 1952, the highest hourly mean winds recorded were 80 knots which occurred during Typhoons Wanda and Ruby in 1962 and 1964 respectively. On the first occasion, the maximum winds measured at the Royal Observatory were 72 knots from the north and the minimum mean sea-level pressure recorded (953.2 mbar) was higher than that at Waglan by 9.2 mbar. In view of the continued deterioration in the representativeness of Observatory wind readings after 1957, the reported value, which is in excess of hurricane force, would most probably still represent an underestimate of the surface wind over the locality. During the passage of Typhoon Ruby, the Observatory recorded maximum hourly winds of 59 knots and a minimum mean sea-level pressure of 968.2 mbar which was higher than the Waglan minimum by 8.2 mbar. In this case, records from other stations indicate that hurricane force winds were general over the territory and the air flow over south Kowloon must also have exceeded the value reported by the Observatory.

An examination of tropical cyclone records shows that during the period 1952-1957 when building development in south Kowloon has not significantly affected the wind measurements at the Royal Observatory, there was only one typhoon, Gloria, which passed within 30 miles of the station. On this occasion, the maximum hourly winds recorded at the Royal Observatory were 62 knots from the east and the corresponding value at Waglan Island 61 knots. The minimum mean sea-level pressures recorded at these stations were respectively 984.3 and 981.9 mbar. By the use of Hellmann's formula with a reduced effective height, the wind measurements at Waglan Island would be grossly underestimated. Similar findings were noted when less intense tropical cyclones were considered.

From the above considerations, it appears that none of the height-reduction formulae discussed can be effectively used to transform Waglan Island wind readings into sea-level values during tropical cyclone conditions. The equivalent surface wind speeds determined from these formulae are found to be incompatible when compared with existing records.

8. DETERMINATION OF CRITERIA FOR DEFINING STRONG, GALE AND HURRICANE FORCE SURFACE WINDS

All the height-reduction formulae discussed in the previous section postulate an increase of wind strength with height in the surface boundary layer. While this is generally valid in most situations, the magnitude of variation may not necessarily follow these formulae under extreme wind conditions. Observational evidence to support the validity of these formulae in the gale to hurricane force speed range appears to be lacking. Bates (1977) noted that in tropical cyclones, the turbulent momentum exchanges at high wind speeds may offset the effect of increasing surface drag. This would cause the wind speed profile not to fall off so rapidly with decreasing elevation. He therefore concluded that the greater the wind speed, the less the shear would be between wind speeds at different altitudes. Bunting (1955) has found that in tropical cyclones, winds at the surface are faster than those at greater heights. Sherlock (1953) also pointed out that in typhoon regions, it is proper to accept a constant velocity profile within the height range of buildings. Bell (1961) examined wind speed data from aircraft reconnaissances and considered that in tropical cyclone conditions, the wind speed should increase from the surface for 30-60 metres, change little for the next 600 metres and then begin to decrease with height.

In the light of these findings an attempt was made to derive some criteria for defining strong, gale and hurricane force winds near sea-level in terms of Waglan Island observations by means of a different approach. The method used is based on the assumption that readings taken from the Royal Observatory during the period 1952-1957 could be used to represent the surface wind flow at 10 m above mean sea-level in the harbour area. An examination of the topographical features in the vicinity of the Observatory indicates that this assumption, while not justified in all cases, may be valid in easterly wind conditions. Table 4 presents the gustiness factors for winds from different directions with speeds greater than or equal to 22 knots recorded at the Royal Observatory and shows that the smallest mean value is associated with easterlies which prevail on 86% of all occasions studied.

TABLE 4. GUSTINESS FACTORS FOR WINDS FROM DIFFERENT DIRECTIONS WITH SPEEDS GREATER THAN OR EQUAL TO 22 KNOTS RECORDED AT THE ROYAL OBSERVATORY DURING THE MONTHS MAY-OCTOBER 1952-1957

Wind Direction / Year	N	NE	E	SE	S	SW	W	NW
1952	-	1.933 (4)	1.720 (77)	2.022 (4)	1.800(1)	-	1.733(1)	1.636(1)
1953	1.865 (5)	2.048 (7)	1.778 (78)	-	-	1.912 (4)	1.900(2)	1.957(1)
1954	-	-	1.694 (57)	-	-	-	-	-
1955	-	2.296 (2)	1.863 (44)	1.583 (1)	-	1.969 (3)	-	-
1956	-	-	1.673 (77)	-	-	1.773 (3)	-	-
1957	2.073 (6)	2.169 (4)	1.827 (70)	1.834 (7)	2.448(3)	2.239 (8)	-	-
Mean	1.978(11)	2.123(13)	1.753(403)	1.920(12)	2.286(4)	2.044(18)	1.858(3)	1.797(2)

Note : Number of observations is in parenthesis

All observations of winds blowing between 070 and 110 degrees recorded at the Royal Observatory during the period 1952-1957 were therefore extracted to provide a reference series for estimating the general wind flow near the sea-level at Waglan Island. The procedure of deriving equivalent surface wind speeds for Waglan Island from this series is as follows :

(1) Waglan Island hourly mean wind data were first correlated with the 900-m wind speeds for the two periods 1952-1957 and 1969-1974 to evaluate the effect of change in instrumental site which took place in 1964 (the effect of raising the anemometer head in 1966 and 1974 was found to be insignificant).

(2) Regression equations were computed to relate Waglan Island hourly mean winds with those at the Royal Observatory for the period 1952-1957. By means of such a relationship, and the results obtained in (1), equivalent wind speeds recorded at Waglan Island during 1969-1974 corresponding to Royal Observatory readings of 22, 34 and 64 knots recorded prior to 1957 were then evaluated.

A diagrammatic representation of the steps involved is given in Figure 7.

9. DISCUSSION OF RESULTS

The relationship between Royal Observatory winds and Waglan Island winds for the period 1952-1957 for the four wind directions, N, NE, E and SE is given by the following regression equations :

$$WL_N = 1.363\ RO + 3.494 \quad (n = 32\ ;\ r = 0.782) \qquad (19)$$

$$WL_{NE} = 1.220\ RO + 6.764 \quad (n = 18\ ;\ r = 0.911) \qquad (20)$$

$$WL_E = 0.991\ RO + 4.796 \quad (n = 98\ ;\ r = 0.814) \qquad (21)$$

$$WL_{SE} = 0.961\ RO + 1.252 \quad (n = 58\ ;\ r = 0.877) \qquad (22)$$

The equivalent wind speeds at Waglan Island corresponding to 22-, 34-and 64-knot winds at the Royal Observatory during the period 1952-1957 are given in Table 5 which provides evidence on the sheltering of the Royal Observatory site from north to northeast winds and also lends support to the belief that winds from the southeast are generally overestimated at the Royal Observatory because of the funnelling effect of Lei Yue Mun at the southeast approach to the Victoria Harbour.

TABLE 5. EQUIVALENT WAGLAN ISLAND WIND SPEEDS CORRESPONDING TO 22-, 34-AND 64-KNOT WINDS RECORDED AT THE ROYAL OBSERVATORY FOR THE PERIOD 1952-1957

Royal Observatory Wind Speed (kn)	Waglan Island Wind Direction and Speed			
	N	NE	E	SE
22	33.5	33.6	26.6	22.4
34	49.8	48.2	38.5	33.9
64	90.7	84.8	68.2	62.8

When Waglan Island observations for the later period 1969-1974 are used, Equations (9) to (16) may be applied to derive the corresponding equivalent wind speeds and the results are presented in Table 6.

TABLE 6. EQUIVALENT 1969-1974 WAGLAN ISLAND WIND SPEEDS CORRESPONDING TO 22-, 34-AND 64-KNOT WINDS RECORDED AT THE ROYAL OBSERVATORY IN 1952-1957

Royal Observatory Wind Speed (kn)	Waglan Island Wind Direction and Speed			
	N	NE	E	SE
22	36.6	36.0	34.2	22.6
34	51.5	49.8	47.2	35.2
64	89.0	84.4	79.7	67.0

It is seen from the table that if only easterly winds at the Royal Observatory are considered representative of the air flow near sea-level then the equivalent near sea-level wind speeds at Waglan Island for strong, gale and hurricane force winds become respectively 34, 47 and 80 knots. These values are comparable with those derived from the Hellmann's formula with a reduced effective height but for reasons given in the previous section, are still considered excessive. On a closer examination of the data used in the correlation study, it was found that simultaneous readings from both Waglan Island and King's Park stations were extremely few when winds from the former reached 45 knots or above. This was due to the difficulties in launching balloons for upper-wind measurements and also to the requirement to secure the wind-finding radar under extreme wind conditions. As a result, the linear fitting previously carried out was mainly based on the observations within a narrow speed range of 15 to 40 knots and a linear extrapolation beyond this range may not be justified.

To overcome this difficulty, the "nearly uniform" wind concept discussed in the previous section was used to maximize the data sample in the high-speed range by the addition of "bogus readings" to constrain the slope of the regression lines. It was assumed that in extreme wind conditions, the variation of winds with height below 900-m level would become insignificant and could be ignored for practical purposes.

To test the validity of the assumption, wind observations taken at King's Park Meteorological Station have been used to compute the ratio between surface winds and those at 900 m for different ranges of wind speed. Since air flow reaching the station is least "perturbed" from the southwest, only occasions with uniform southwesterlies from the surface to 900-m level have been considered and the results are given in Figure 8. It is clear that the ratio increase with wind speed and from the trend noted in the figure it seems reasonable that at a speed of about 80 knots the ratio should approach unity.

Using 80 knots as a threshold value for a nearly uniform flow between surface and 900-m level, "bogus data" have been added to the original pairs of wind observation series used in the derivation of Equations (1)-(16) in accordance with the following scheme :

TABLE 7. DATA MAXIMIZATION SCHEME

Number of observations in each series	Number of pairs of bogus observations added	Values of bogus pairs (kn/kn)
<25	1	80/80
25 to 50	2	80/80; 85/85
51 to 75	3	80/80; 85/85; 90/90
>75	4	80/80; 85/85; 90/90; 95/95

Regression equations were then re-computed from the maximised series for both the 1952-1957 and 1969-1974 periods and are given below :

(1) Relationship between winds recorded at the Royal Observatory and Waglan Island in a 6-year period 1952-1957

$$WL_N = 0.919\ RO + 9.409 \quad (n = 34\ ;\ r = 0.935) \qquad (23)$$

$$WL_{NE} = 0.950\ RO + 10.375 \quad (n = 19\ ;\ r = 0.943) \qquad (24)$$

$$WL_E = 0.946\ RO + 5.611 \quad (n = 102\ ;\ r = 0.943) \qquad (25)$$

$$WL_{SE} = 0.987\ RO + 0.841 \quad (n = 61\ ;\ r = 0.979) \qquad (26)$$

(2) Regression equations relating 900-m winds and

(i) winds recorded at Waglan Island during the period 1952-1957

$U_9 = 0.836\ WL_N + 10.347$ (n = 24 ; r = 0.830) (27)

$U_9 = 0.859\ WL_{NE} + 11.947$ (n = 9 ; r = 0.979) (28)

$U_9 = 0.927\ WL_E + 8.641$ (n = 65 ; r = 0.915) (29)

$U_9 = 0.870\ WL_{SE} + 11.698$ (n = 35 ; r = 0.920) (30)

(ii) winds recorded at Waglan Island during the period 1969-1974

$U_9 = 0.930\ WL_N + 4.368$ (n = 35 ; r = 0.893) (31)

$U_9 = 0.911\ WL_{NE} + 8.119$ (n = 32 ; r = 0.962) (32)

$U_9 = 0.910\ WL_E + 8.124$ (n = 69 ; r = 0.899) (33)

$U_9 = 0.839\ WL_{SE} + 13.185$ (n = 11 ; r = 0.947) (34)

(3) From Equations (27) to (34), the following relationship between winds recorded at Waglan Island in the two 6-year periods 1952-1957 and 1969-1974 is obtained

$WL_N\ (69\text{-}74) = 0.899\ WL_N\ (52\text{-}57) + 6.430$ (35)

$WL_{NE}(69\text{-}74) = 0.943\ WL_{NE}(52\text{-}57) + 4.204$ (36)

$WL_E\ (69\text{-}74) = 1.109\ WL_E\ (52\text{-}57) + 0.568$ (37)

$WL_{SE}(69\text{-}74) = 1.036\ WL_{SE}(52\text{-}57) + 1.772$ (38)

Equivalent values for 22-, 34- and 64-knot winds at the Observatory from the four directions N, NE, E and SE recorded at Waglan Island derived from the recomputed equations are presented in Table 8.

TABLE 8. RECOMPUTED 1952-1957 AND 1969-1974 EQUIVALENT WAGLAN ISLAND WIND SPEEDS CORRESPONDING TO 22-, 34-AND 64-KNOT WINDS AT THE OBSERVATORY IN 1952-1957

Royal Observatory Wind Speed (kn) \ Waglan Island Wind Speed (kn)	Waglan Island Wind Direction							
	N		NE		E		SE	
	52-57	69-74	52-57	69-74	52-57	69-74	52-57	69-74
22	29.6	33.0	31.2	33.6	26.4	27.5	22.5	21.5
34	40.7	43.0	42.7	44.5	37.8	39.1	34.4	33.9
64	68.2	67.7	71.2	71.4	66.1	67.9	64.0	64.5

Using the values listed in Table 8 as criteria, the computed number of tropical cyclones causing strong, gale and hurricane force winds from the four directions, N, NE, E and SE at the Royal Observatory during the period 1952-1957 based on Waglan Island records were determined and are presented in Table 9, together with the number recorded at the Royal Observatory.

TABLE 9. NUMBER OF TROPICAL CYCLONES CAUSING STRONG, GALE AND HURRICANE FORCE WINDS FROM THE FOUR DIRECTIONS, N, NE, E AND SE AT THE ROYAL OBSERVATORY DURING 1952-1957 (BASED ON TABLE 8)

Data source	Number of tropical cyclones causing			Total
	Strong wind	Gale	Hurricane force wind	
Royal Observatory observations	19	4	0	23
Waglan Island observations	19	5	0	24

Note : a gale producing tropical cyclone is not counted under the "Strong Wind" column.

The close agreement in the number of strong wind and gale producing tropical cyclones observed between the two stations is remarkable. It is also noted that the equivalent values for 64-knot northerly and easterly winds adequately account for the "discrepency" of estimated Waglan Island winds derived from other wind reduction formulae during Typhoons Wanda and Ruby as discussed in Section 7.

Gales from the other four directions viz. south, southwest, west and northwest are extremely rare in Hong Kong. An examination of the existing hourly mean wind records during the 6-year period 1952-1957 reveals that there were only 6 occasions in which the hourly mean speeds at Waglan Island exceeded 33 knots and their particulars are listed below :

Date	Hour	Name of tropical cyclone	Wind direction and speed: Royal Observatory	Wind direction and speed: Waglan Island
2/9/53	0500H	Typhoon Rita	270/23	280/34
2/9/53	0600H	Typhoon Rita	270/30	270/37
2/9/53	0700H	Typhoon Rita	250/28	250/36
2/9/53	0800H	Typhoon Rita	220/23	240/35
17/7/57	0500H	Typhoon Wendy	170/26	180/41
17/7/57	0600H	Typhoon Wendy	180/17	190/41

The above are clearly insufficient to derive a meaningful set of equivalent values for these wind directions. During Typhoon Rita in 1953, 10-min mean wind reports from two other meteorological stations, Cheung Chau and the Airport, indicated that winds over Hong Kong were only generally strong but did not reach gale force, as the maximum speeds recorded at these stations were only 23 and 26 knots respectively. In Typhoon Wendy in 1957, maximum hourly mean winds recorded were 37 knots at Cheung Chau, 34 knots at the Airport and the corresponding 10-min means at Royal Observatory and Waglan Island were respectively 28 and 44 knots. It would therefore seem probable that winds at Waglan Island exceeded gale force strength in Wendy but not in Rita.

For practical applications, it is considered that the criteria for defining surface easterly winds should be used for the directions from south through west to northwest. If all wind directions are considered then Table 9 will become Table 10 which is presented below :

TABLE 10. NUMBER OF TROPICAL CYCLONES CAUSING STRONG, GALE AND HURRICANE FORCE WINDS AT THE ROYAL OBSERVATORY DURING THE PERIOD 1952-1957 (BASED ON TABLE 8 AND ALL WIND DIRECTIONS CONSIDERED)

Data source	Number of tropical cyclones causing			Total
	Strong wind	Gale	Hurricane force wind	
Royal Observatory observations	21	4	0	25
Waglan Island observations	19	6	0	25

The good agreement shown in Table 10 provides a practicable means of up-dating the department's lists of 'Hong Kong Typhoons' and 'Tropical Cyclones which gave rise to persistent gales to the Royal Observatory' using Waglan Island records. However, the results obtained in the present study pertain to 'wind speed' only. No attempt has been made to examine the wind direction relationship between the Royal Observatory and Waglan Island although it is known from synoptic experience that under tropical cyclone conditions, the difference in wind direction reported by the two stations is generally insignificant except in northerlies and in extreme cases when the eye of a tropical cyclone is very close to one of the stations.

10. CONCLUSIONS

Because of building development in the vicinity of the Royal Observatory during recent years, wind measurements have been increasingly affected and it is no longer valid to use the Observatory's winds as a measure of the general air flow near sea-level.

The Meteorological Station at Waglan Island has experienced little change in its environment since 1952 when it was established and its wind readings have been found to provide a useful observational series for research purposes as well as for operational requirements. By comparison with winds at 900-m level measured at King's Park, the change in representativeness of Waglan observations due to a resiting of the anemometer in 1964 was evaluated. The 900-m wind observations were also maximised and utilized to establish the criteria for defining surface strong, gale and hurricane force winds in terms of Waglan Island measurements.

Because of differences in exposure of the Royal Observatory and Waglan Island stations, the wind data studied have been stratified into four main groups (comprising 95% of total observations) in accordance with wind direction, viz. northerly, northeasterly, easterly and southeasterly and regression equations were computed for each group. The analyses show that easterly winds recorded at the Royal Observatory were the least perturbed and observations of winds from this direction during the period 1952-1957, which were assumed to approximate the surface air flow in the harbour area, were used for carrying out height reduction of Waglan Island wind records.

It is proposed that hourly wind speeds of 28, 39 and 68 knots recorded by the Waglan Island anemometer be used to define strong, gale and hurricane force winds near sea-level respectively over the locality. Table 11 below has been constructed to include both the hourly and 10-minute values of equivalent strong, gale and hurricane force winds at Waglan Island based on the conversion factors developed by Bell (1961).

TABLE 11. PROPOSED EQUIVALENT 10-MIN AND HOURLY MEAN WIND SPEEDS RECORDED AT WAGLAN ISLAND CORRESPONDING TO STRONG, GALE AND HURRICANE FORCE WINDS NEAR THE SEA-LEVEL

Wind speed near sea-level (kn)	Waglan wind speed (kn)	
	10-min mean	Hourly mean
22 (strong)	30	28
34 (gale)	41	39
64 (hurricane force)	72	68

The results in Table 11 should be used as a guide for forecasters as well as for the climatology of tropical cyclones.

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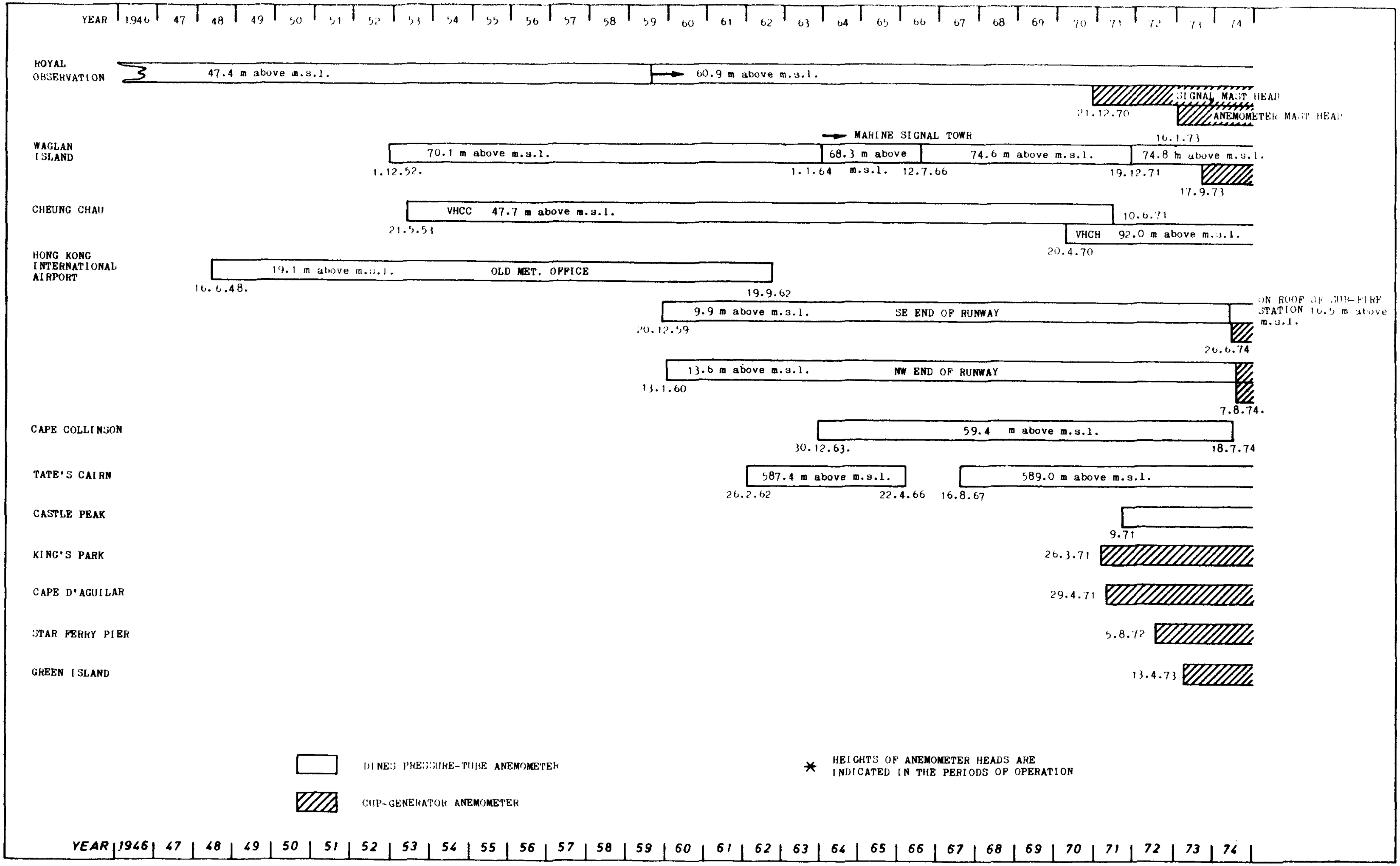


FIGURE 1. WIND RECORDS AVAILABLE AT VARIOUS STATIONS IN HONG KONG

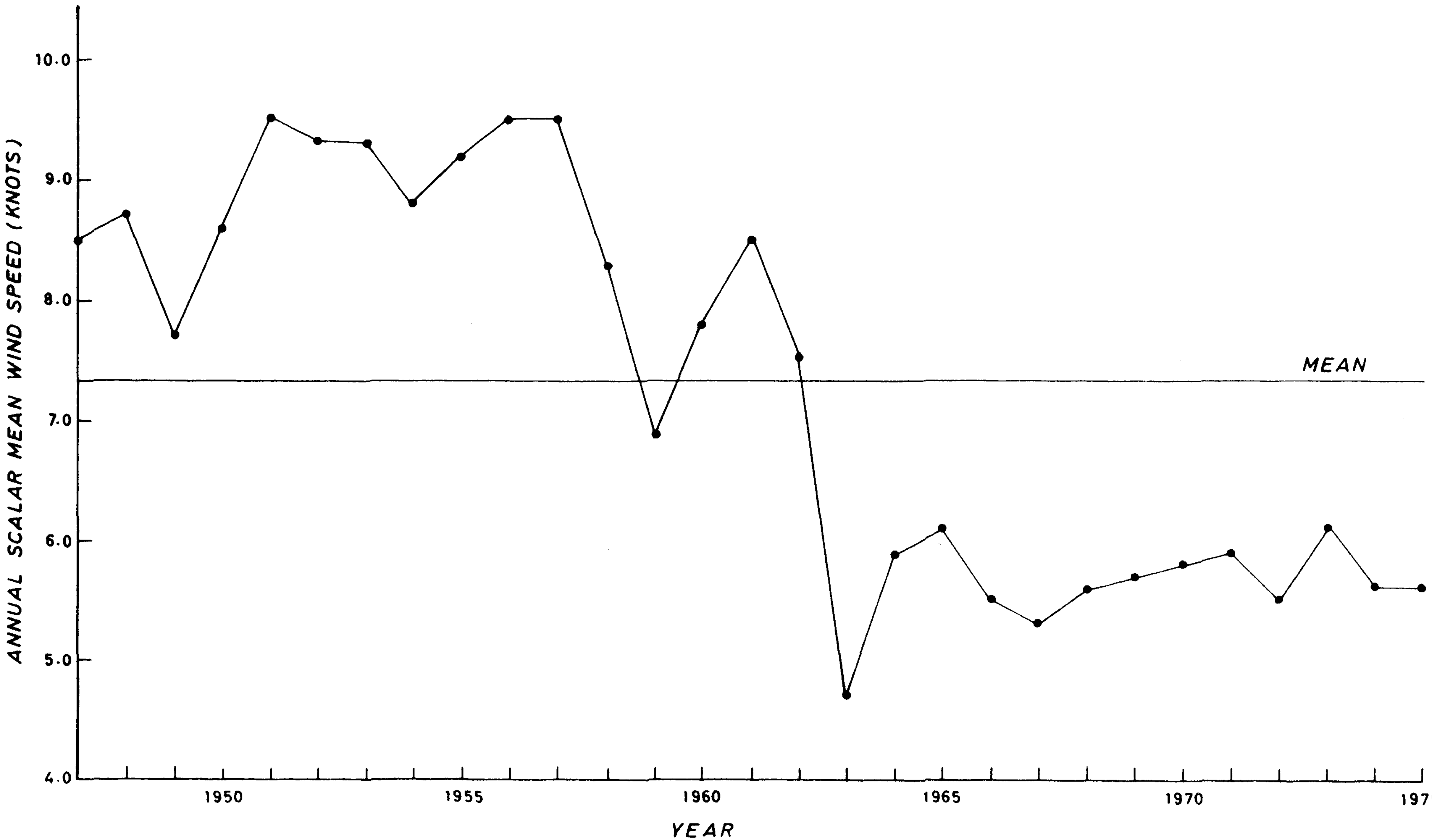


FIGURE 2. ANNUAL SCALAR MEAN WIND SPEED RECORDED AT THE ROYAL OBSRVATORY (1947 - 1975)

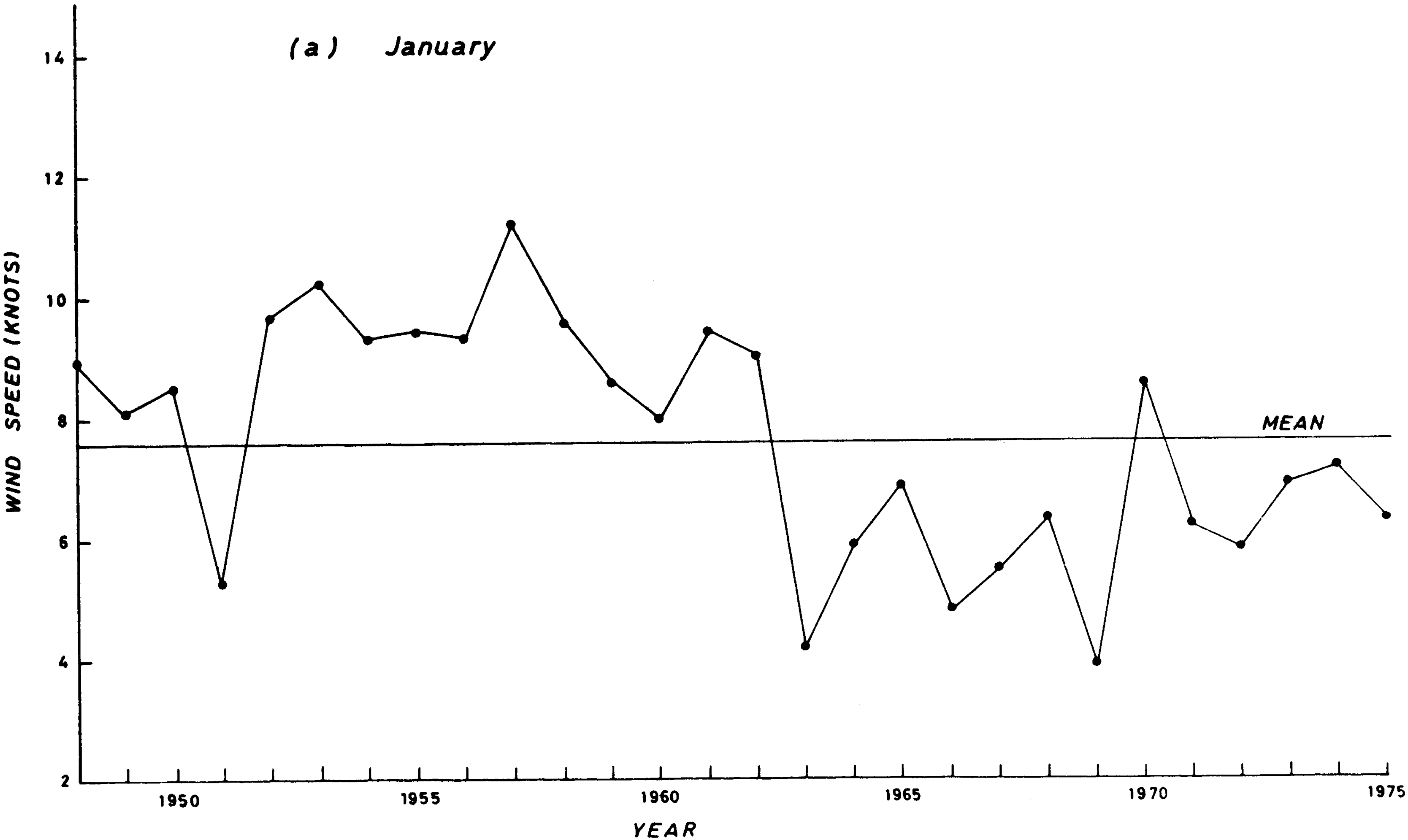
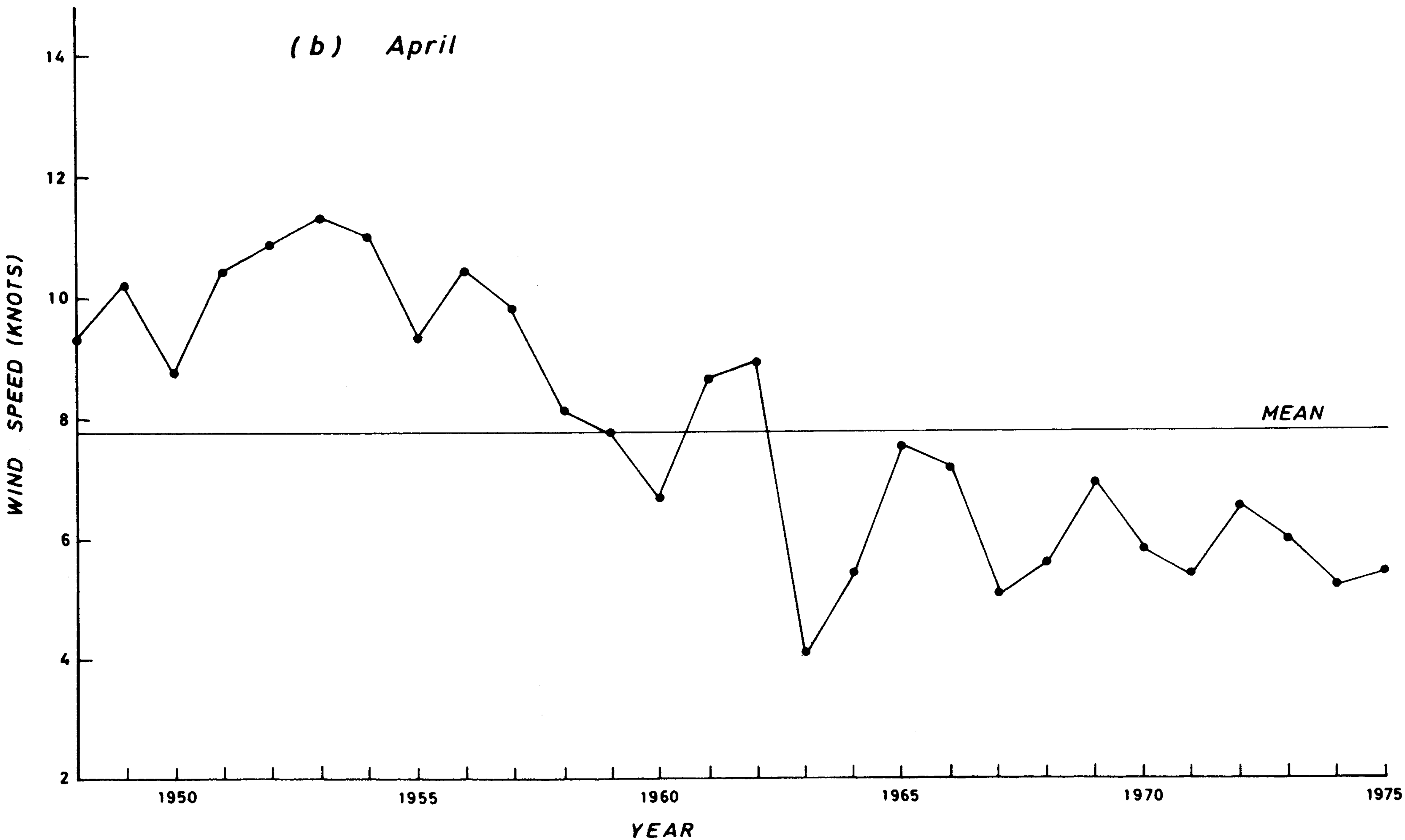
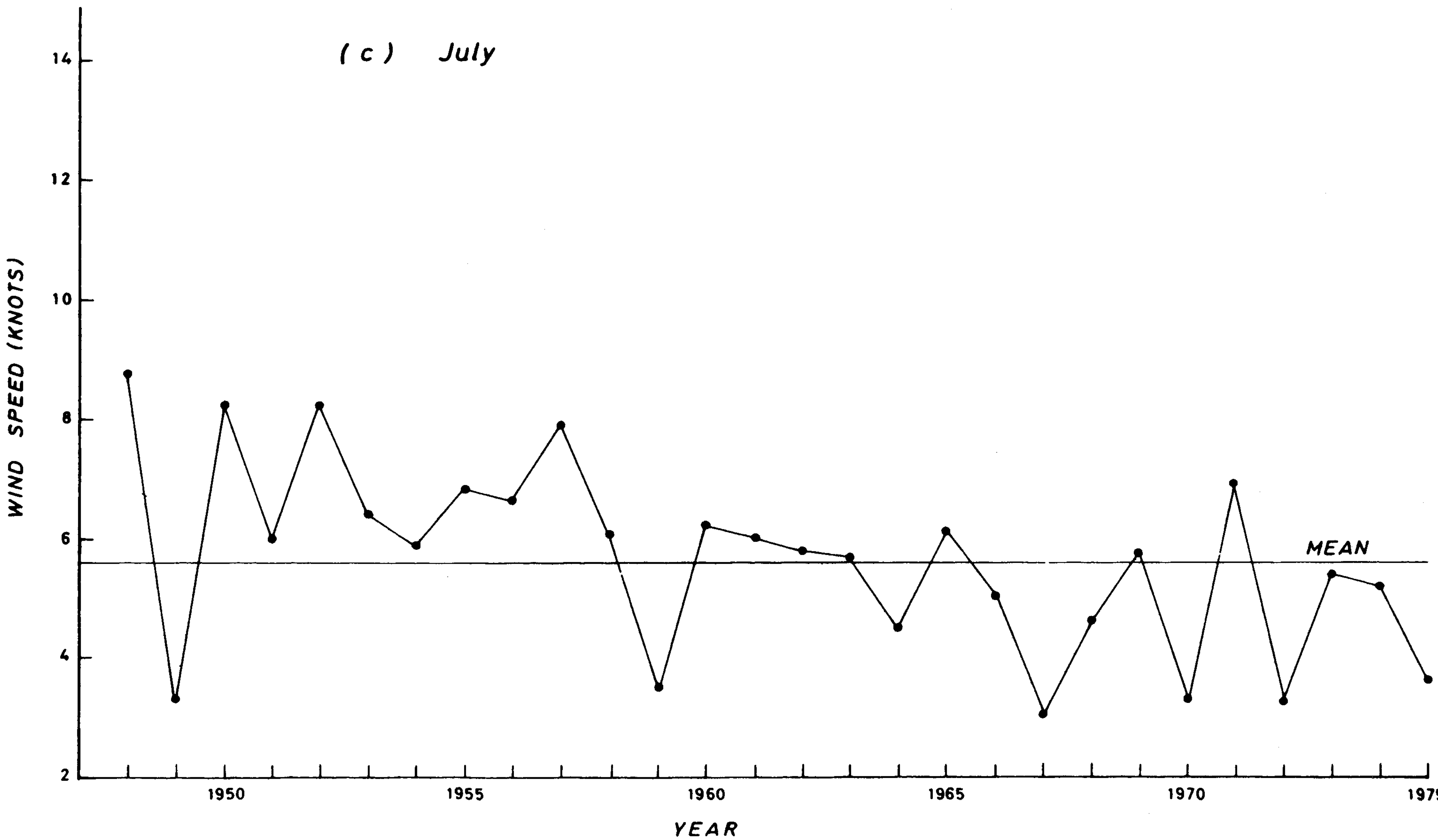
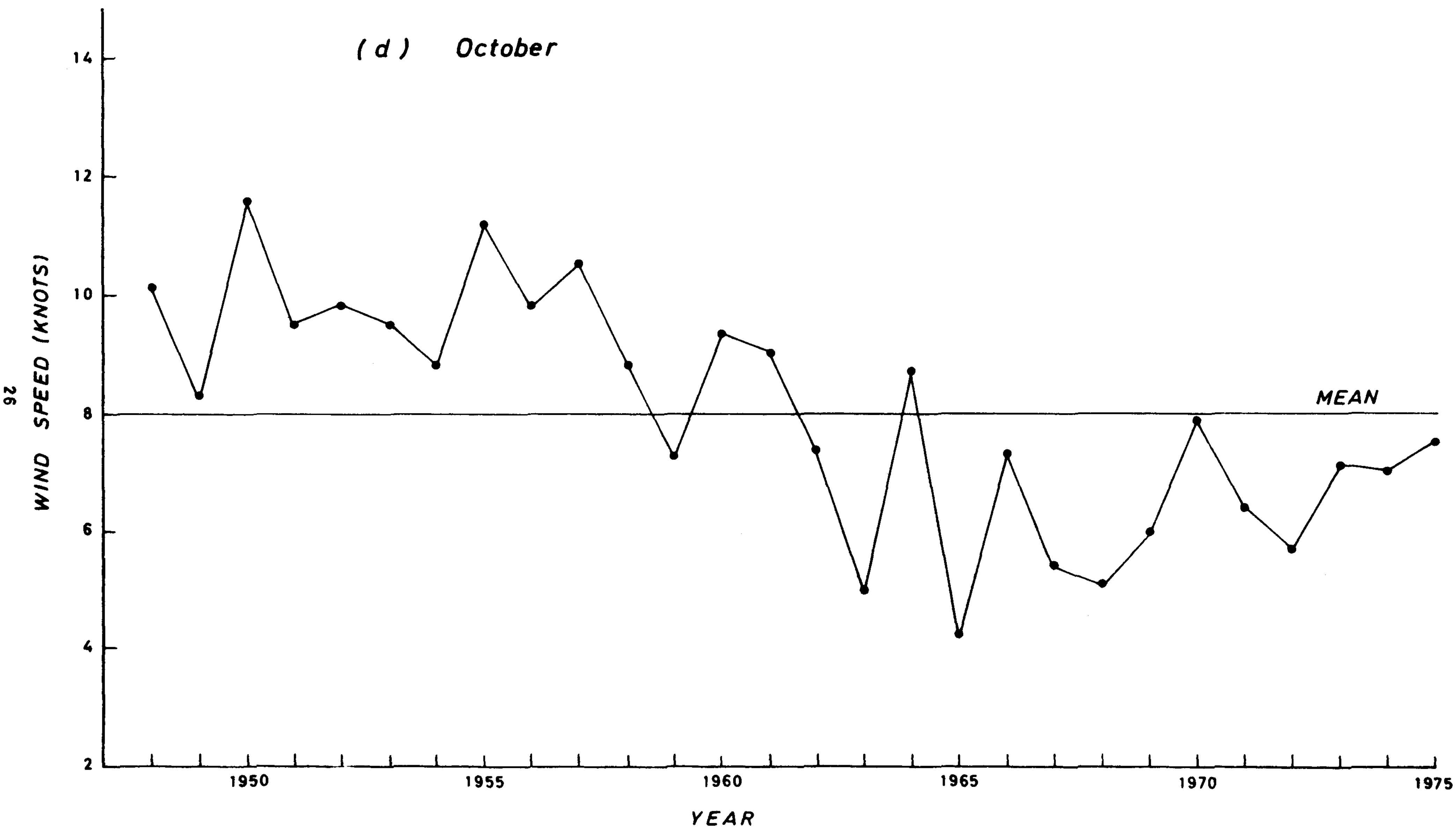


FIGURE 3. ANNUAL VARIATION OF MONTHLY SCALAR MEAN SPEED OF ROYAL OBSERVATORY WINDS (1948-1975)


(b) April
WIND SPEED (KNOTS)
14
12
10
8
6
4
2
MEAN
1950
1955
1960
1965
1970
1975
YEAR



(c) July
WIND SPEED (KNOTS)
14
12
10
8
6
4
2
MEAN
1950
1955
1960
1965
1970
1975
YEAR


(d) October
WIND SPEED (KNOTS)
14
12
10
8
6
4
2
MEAN
1950
1955
1960
1965
1970
1975
YEAR

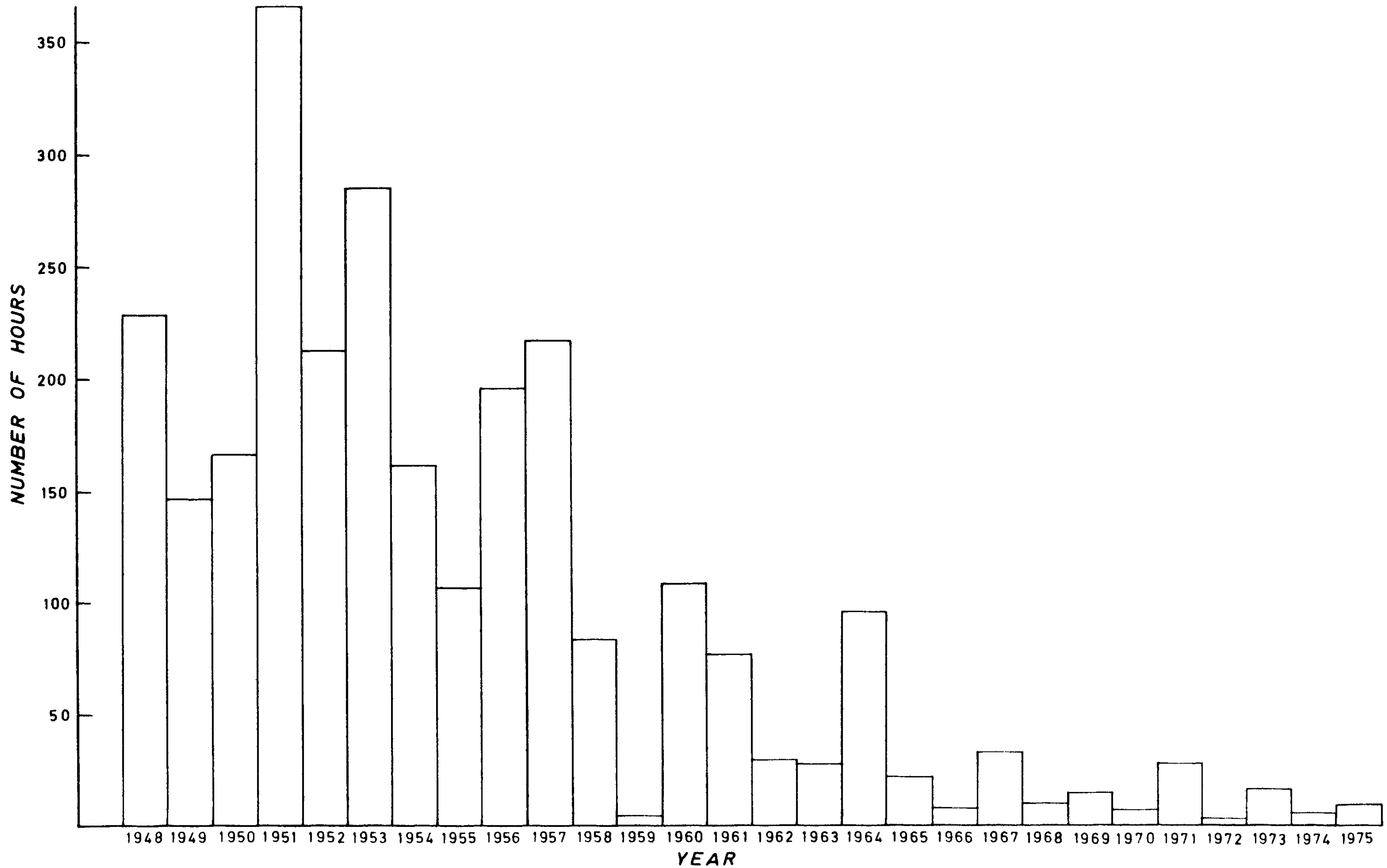


FIGURE 4. ANNUAL TOTAL NUMBER OF HOURS WITH MEAN WIND SPEED EQUAL TO OR GREATER THAN 22 KNOTS AT THE ROYAL OBSERVATORY (1948 - 1975)

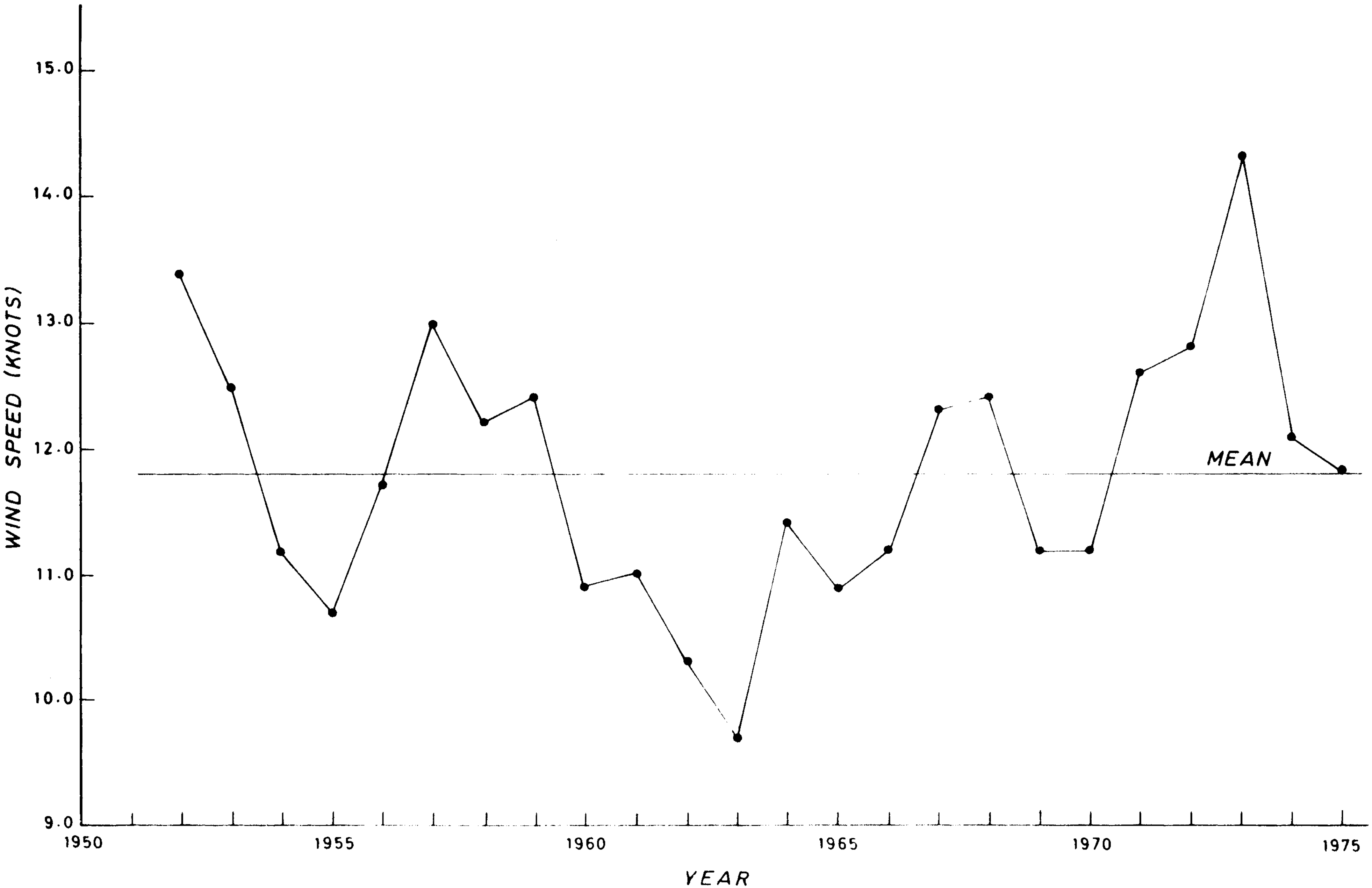


FIGURE 5. VARIATION OF THE ANNUAL SCALAR MEAN WIND SPEED RECORDED AT WAGLAN ISLAND (1952 - 1975)

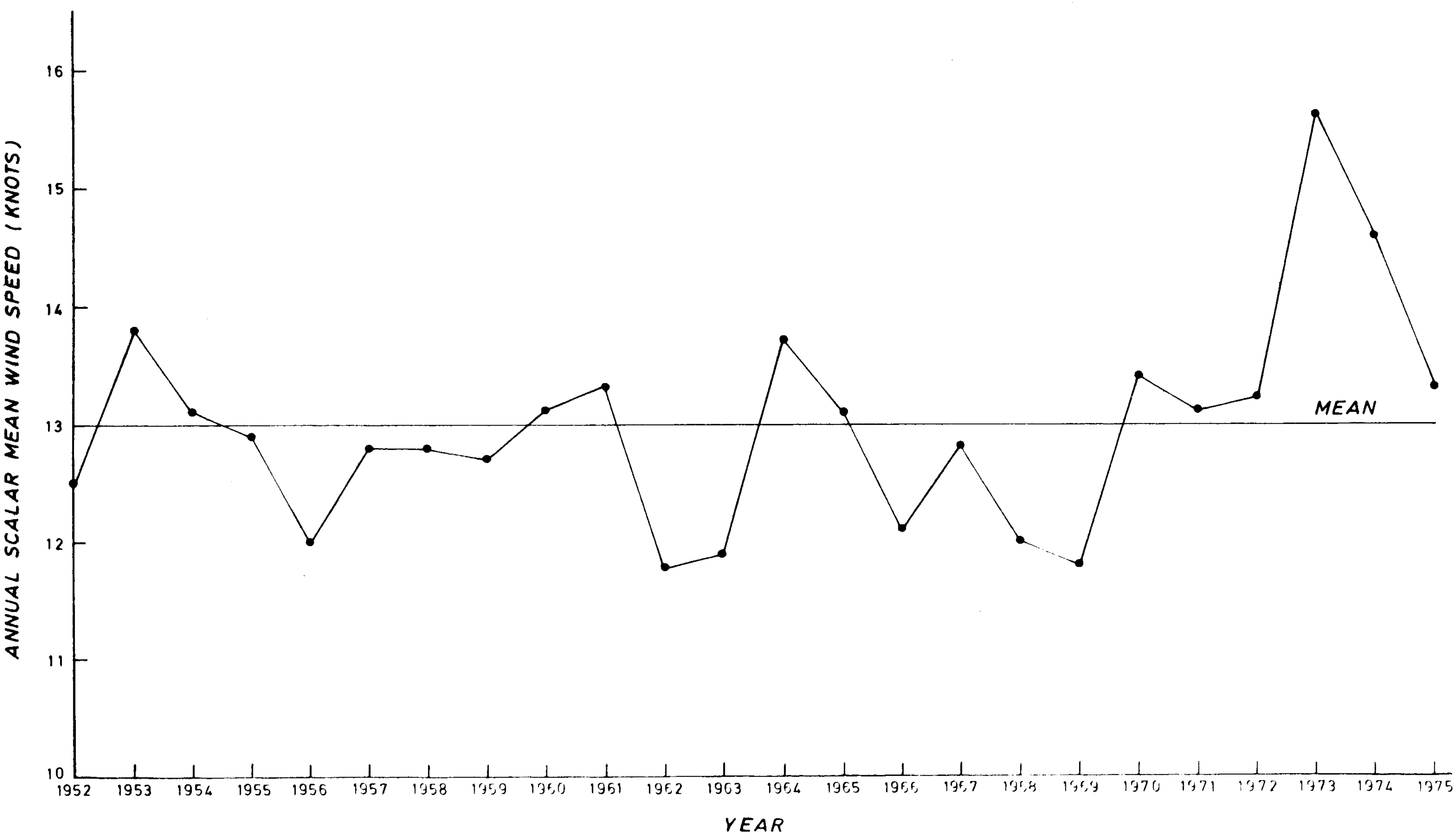


FIGURE 6. VARIATION OF THE ANNUAL SCALAR MEAN WIND SPEED AT 900-m LEVEL OVER HONG KONG (1952 - 1975)

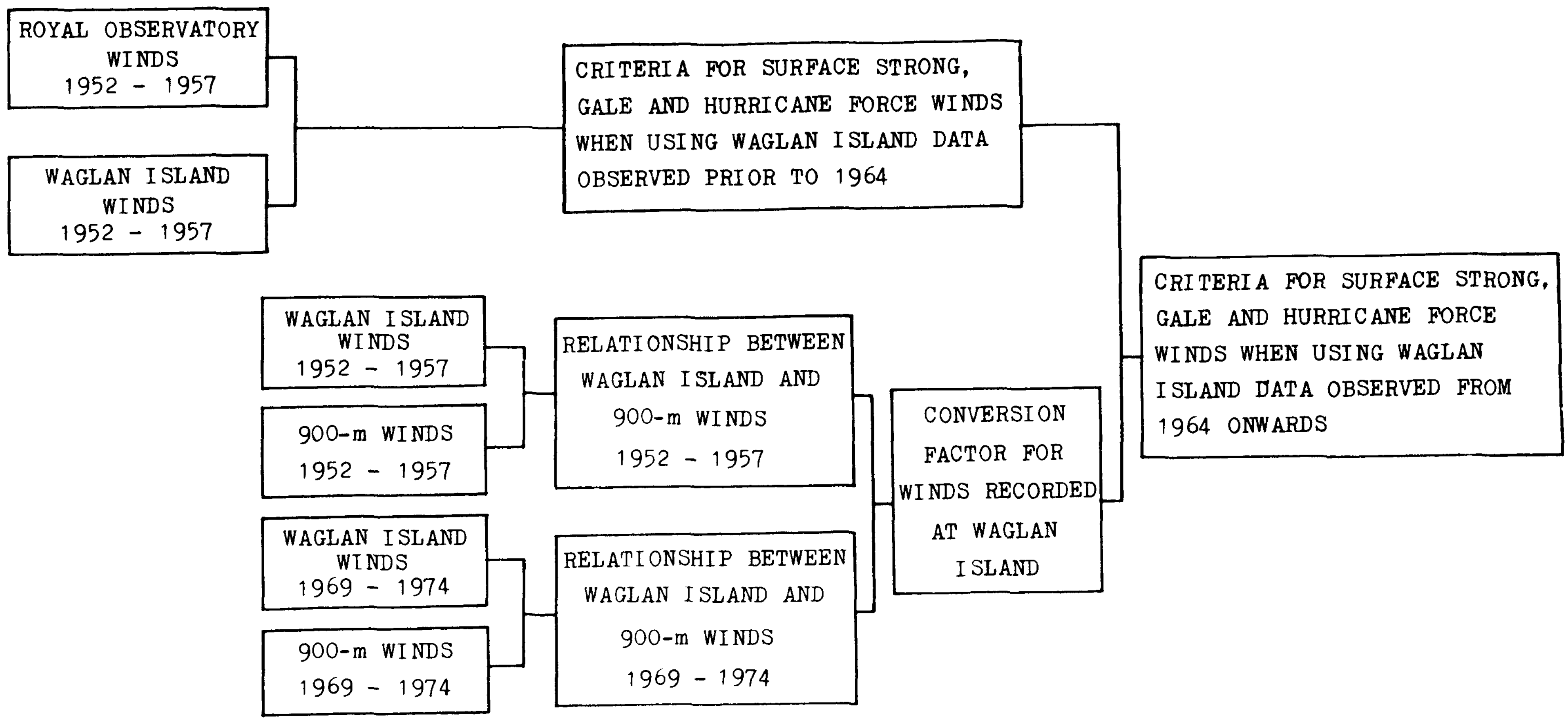


FIGURE 7. A DIAGRAMMATIC REPRESENTATION OF THE STEPS INVOLVED IN DEFINING THE CRITERIA FOR SURFACE STRONG, GALE AND HURRICANE FORCE WINDS

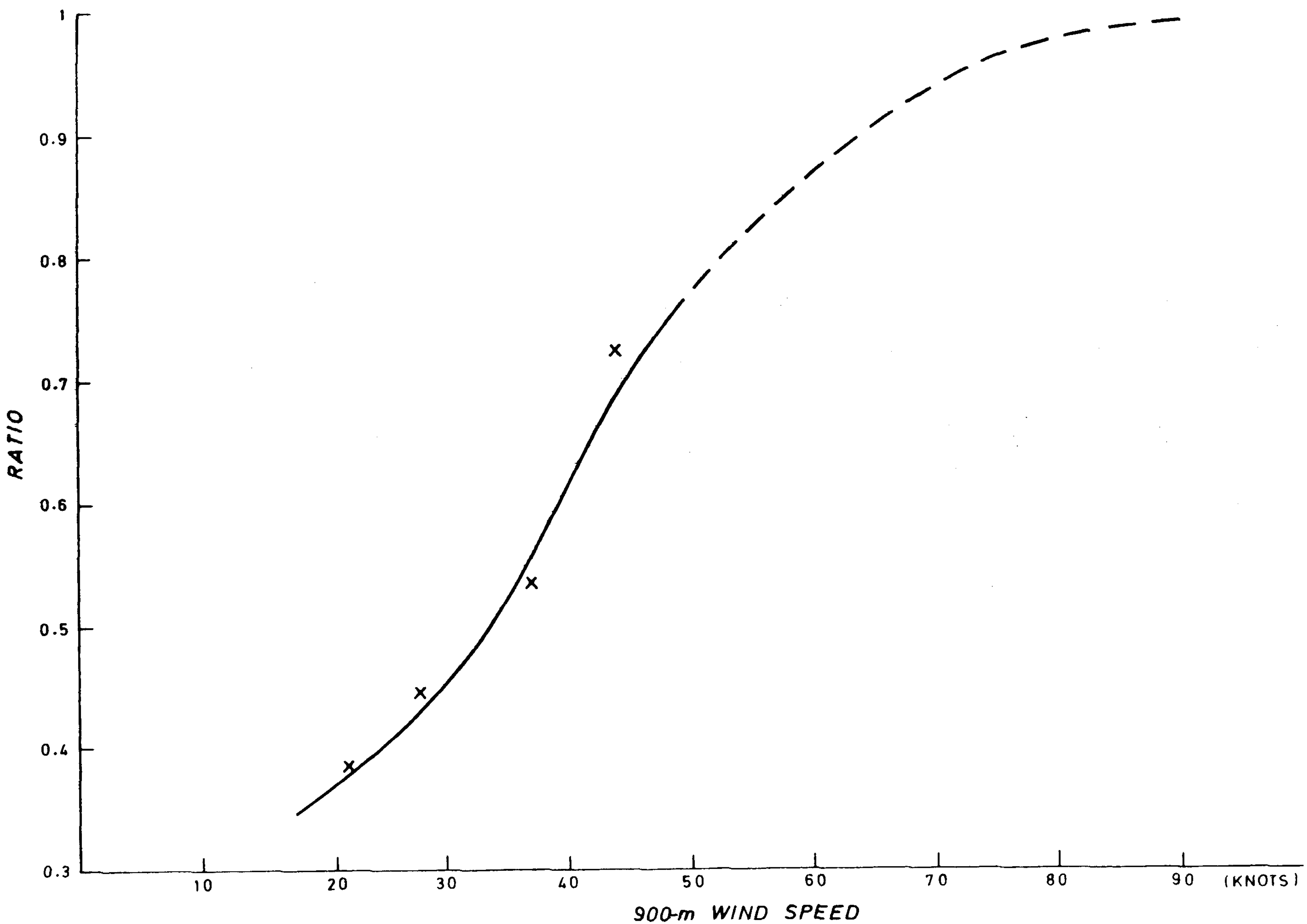


FIGURE 8. RATIO OF SURFACE/900-m WIND SPEEDS IN SOUTHWESTERLIES RECORDED AT KING'S PARK METEOROLOGICAL STATION (1969 - 1974)