HONG KONG OBSERVATORY

Technical Note (Local) No. 77

WIND STATISTICS IN HONG KONG

IN RELATION TO WIND POWER

by

M.S. Wong & W.K. Kwan

Published March 2002

Prepared by

Hong Kong Observatory
134A Nathan Road
Kowloon
Hong Kong

551.55:621.45(512.317)

摘要

本報告根據香港13個氣象站的風速資料，以統計方法對本地風能資源作出評估。

結果顯示本地的風能資源分布變化很大，當中以離島及山頂的風能潛力最高，平均風能功率超過每平方米150瓦特，而大帽山更高達每平方米485瓦特；市區方面，由於風力受到高樓大廈的阻擋，能提供的風能資源明顯較小。

用維泊爾(Weibull)概率分布擬合風速分析時，大部份氣象站風速的分布形狀參數值都接近2，合符風能計算的假設。

Abstract

This note presents the results of a statistical study of wind energy resource in Hong Kong based on wind data at 13 weather stations.

The study shows significant variation in the wind energy resource over the territory. The most promising locations are offshore islands and hilltops where mean wind power density exceeds 150 W/m^2 and can be as high as 485 W/m^2 at Tai Mo Shan. Wind energy resource is significantly lower in urban areas because of tall buildings moderating the flow.

The winds at the majority of these stations when fitted to the Weibull distribution give shape factors close to 2, a value usually assumed for wind energy calculations.

CONTENTS

FIGURES

FIGURES (cont'd)

TABLES

1. INTRODUCTION

The wind has long been exploited as a source of energy. Mariners have made use of it to sail across the seas since ancient times. There is a long history of utilizing windmills to turn grain into flour. Using wind energy to pump water for irrigation purposes is likewise something that goes back many years.

Harnessing energy from the wind has received much attention since the oil crisis in the seventies. Wind energy is non-polluting, and its exploitation has gathered further momentum given the concern for global warming caused by the burning of fossil fuels to generate electricity.

To gauge the potential for wind energy exploitation in the territory, a statistical study of wind data from the Hong Kong Observatory's weather stations was conducted. Out of the 45 stations with wind measurements, 13 stations meeting certain data period and wind speed criteria (discussed in Section 2) were selected for detailed study.

Hourly wind data at these stations across the territory were analysed statistically to estimate the available mean wind power density. In addition, wind speed distributions as well as percentage of wind speed exceeding specified values at these stations were also calculated and presented for reference in future wind energy studies.

2. DATA

45 weather stations with wind measurements have been established at various locations in Hong Kong for monitoring the weather and to meet the public's increasing demand for regional meteorological information. Stations meeting certain criteria in data period as well as wind speed were selected for the investigation of wind energy resource in Hong Kong.

In this note, unless otherwise specified, wind speed *u* is defined as the 10-minute mean wind speed taken before the hour. 60-minute mean wind speed or other longer averaging speed are not suitable as it would under-estimate the corresponding wind energy (Jensen et al, 1984). Other derived quantities, such as the annual average wind speed commonly referred to in wind turbine operation, are calculated from the value of *u*.

To take into account the variability of wind speed from one year to another, data should cover a period of at least 5 years so that a reliable annual mean value can be obtained at a given location (Justus et el, 1976 & Janardan and Nelson, 1994). Of the 45 stations, 30 met this criterion.

Since in general, an annual average wind speed of 3 m/s is required to operate a small wind turbine (AWEA, 1995 & Qian et al, 1992), only 13 of the above 30 stations with annual average wind speeds exceeding this threshold were selected for further investigation.

The station type, data period, anemometer height (above mean sea-level) and annual average wind speed of these 13 stations are listed in Table 1. Their locations are shown in Figure 1.

Because of the hilly terrain in Hong Kong, information on the exposure of the stations to the prevailing flow is important when it comes to siting of wind turbines. Wind roses for the 13 stations are therefore given in this report in Figures 2-14. The notation used is explained in Figure 15.

3. WIND POWER DENSITY IN HONG KONG

3.1. Mean wind power density

The mass of a uniform air stream moving with speed u and crossing an area A per unit time is $A\rho u$ where ρ is the air density. The available wind power of this moving air mass is (Walker and Jenkins, 1997):

$$P = \frac{1}{2} \rho A u^3 \qquad (3.1)$$

where

P is power (in watts);
ρ is air density (in kg/m^3) and is taken to be 1.225;
A is area exposed to the wind (in m^2);
u is the 10-minute mean wind speed (m/s)

The wind power is therefore proportional to the cube of wind speed. Thus, doubling the wind speed would increase the wind power by a factor of eight. The wind power per unit area, *P/A*, is called the wind power density (Spera, 1994) which is a term frequently used to estimate how energetic the winds are during a period of time (Gipe, 1993).

For assessing wind energy resource, usually the mean wind power density, $\overline{P}/A$, averaged over a certain time period (e.g., a month, a year, or several years) is used (Janardan and Nelson, 1994). Thus,

$$\overline{P}/A = \frac{1}{2} \rho \overline{u^3} \qquad (3.2)$$

where the overbar denotes the time average.

For this study, $\overline{P}/A$ for each of the 13 stations in Table 1 is calculated over the data period for that station. The mean wind power densities so obtained are shown in Table 2. Please note that mean wind power densities shown in Table 2 correspond to the respective anemometer heights and that a constant air density for all stations is assumed. Adjustment for variations in height and air density may be necessary for specific installations. For example, the decrease of air density for a 1 km increase in elevation would reduce the wind power density by about 10%.

It can be seen from Table 2 that the highest wind power densities are generally associated with sites at hilltops and outlying islands. The rooftop of Central Plaza, at 378 m above mean sea-level, is the third highest site of the 13. However, its wind power density ranks 6th and attests to the importance of exposure on wind power density.

Mean wind power densities are usually grouped into different classes for the assessment of wind energy resource (Elliott et al, 1991). These classes are shown in Appendix A. Class 1 (below 100 W/m^2) is generally unsuitable for wind power applications. Class 2 (100-150 W/m^2) is marginally suitable while Class 3 (150 W/m^2) and above are suitable.

In accordance with this classification, only the first six sites in Table 2 can be regarded as suitable for wind power development. With the exception of Central Plaza, all are either outlying islands or hilltops.

3.2. Usable wind power

In evaluating wind resources, it is important to distinguish between the available wind power as shown in Equation (3.1) and usable wind power as discussed below.

Equation (3.1) yields the theoretical amount of power available as determined by the kinetic energy of the wind. It is not possible to convert all the available kinetic energy into usable energy as the air must flow out from a wind turbine with a non-zero speed. The usable power P_U that can be extracted from P is (Gipe, 1995):

$$P_U = C_p C_r P \qquad (3.3)$$

In Equation (3.3), C_p is coefficient of performance and C_r is a coefficient representing the combined effects of the operating characteristics of the turbine. C_p has an upper limit of 0.59 which is known as th*e* Betz limit (Walker and Jenkins 1997), and $C_r < 1$. Modern wind turbines are capable of extracting about 30% of the available power (Gipe, 1993).

3.3 Wind speed thresholds for wind power generation

Turbines are used to convert wind power into electrical power. In general, an initial wind speed of 3 m/s or more is required for the small wind turbine while 4-5 m/s or more is required for the larger ones to generate electricity (Gipe, 1993). The frequencies of occurrence of winds above these threshold values are therefore important considerations for wind power generation. These frequencies are listed in Table 3.

It is observed that nearly all stations record winds of 3 m/s or more for over 50% of the time. For outlying islands and hilltops, this percentage is higher and is over 75 %. For 4 m/s, the probability is about 65% for outlying islands and hilltops, but only about 30% for urban sites. For 5 m/s, the respective probabilities are 50% for outlying islands and hilltops, and about 20% for urban sites.

3.4. Application of the Weibull Probability Function

The Weibull probability function is generally considered the best approximation of the distribution of wind speeds over time at sites around the world. The use of the Weibull distribution enables wind power estimates to be made easily without resorting to the basic wind data. In cases where only the mean wind is known but individual wind reports are not available, wind power estimates can be made by assuming a Weibull distribution of certain shape.

The Weibull distribution is characterized by two parameters: one for shape (k) and the other for scale (c). The probability density function is

$$f(u) = (k/c)(u/c)^{k-1} \exp[-(u/c)^k] \qquad (3.4)$$

where u is the wind speed; $k > 0$, $u > 0$, $c > 1$. When k equals to 2, the Weibull distribution degenerates to the Rayleigh distribution.

The cumulative distribution function $F(u)$ is given by

$$F(u) = 1 - exp[-(u/c)^k] \qquad (3.5)$$

The wind power density is given by (Hennessey, 1977):

$$\overline{P}/A = \frac{1}{2}\rho\,\overline{u^3} = \frac{1}{2}\rho\, c^3\, \Gamma\,(1+3/k) \qquad (3.6)$$

where Γ is the gamma function.

The values of Weibull parameters k and c for the 13 stations obtained through maximum likelihood estimates are listed in Table 4. Wind speed distributions of the 13 stations are shown in Figures 16-28.

The values of k vary between 1.6 and 2.1, which are within the range of 1.5 and 2.5 found by Jensen et al (1984). Moreover, most of them are close to the value of 2 (corresponding to the Rayleigh distribution) used for wind resource estimation in WMO (1981) and found by Schwartz (1999) for many coastal areas of southeastern China.

4. CONCLUSIONS

Among the stations listed in Table 1, about half of them (6 out of 13) have mean wind power densities exceeding the generally accepted threshold of 150 W/m^2 for wind turbine applications. These stations are situated at hilltops, offshore islands or tall building.

The percentages of occurrence of wind speed exceeding 3 m/s, 4 m/s and 5 m/s at stations located at exposed outlying islands and hilltops are generally more than 75%, 65% and 50% respectively. Wind speed distributions of these stations generally follow Weibull distribution with the shape factor k close to 2, which is widely used in wind energy studies worldwide. This information may be useful in the proper siting of wind turbines.

REFERENCES

1.	American Wind Energy Association (AWEA)	1995	The most frequently asked questions about wind energy
2.	Elliott D.L., C.G. Holladay, W.R. Barchet, H.P. Foote and W.F. Sandusky	1991	"Wind energy resource atlas of the United States", Solar Technical Information Program, Solar Energy Research Institute, Golden, Colorado.
3.	Gipe, Paul	1993	"Wind power for home and business : renewable energy for the 1990s and beyond", Chelsea Green Publishing Company, Vermont.
4.	Gipe, Paul	1995	"Wind energy comes of age", Wiley, New York.
5.	Guzzi R. and C.G. Justus	1988	Physical climatology for solar and wind energy : Miramare - Trieste, Italy, 21 Apr - 16 May 1986. pp. 291-320, World Scientific, Singapore.
6.	Hennessey, J.P.	1977	Some aspects of wind power statistics, Journal of Applied Meteorology, Vol. 16, pp. 119-128.
7.	Janardan S. Rohatgi and V. Nelson	1994	"Wind characteristics : an analysis for the generation of wind power", Alternative Energy Institute, West Texas A&M University, Canyon, Texas.

8.	Jensen N.O., E.L. Petersen and I. Troen	1984	Extrapolation of mean wind statistics with special regard to wind energy applications, WMO WCP 86.
9.	Justus C.G., W.R. Hargraves and Ali Yalcin	1976	Nationwide assessment of potential output from wind-powered generators, Journal of Applied Meteorology, Vol. 15, pp. 673-678.
10.	Qian Guangming, Wu Kaijia and Luo Jinling	1992	A study of the resources of wind energy on the coast of Guangdong, Journal of Tropical Meteorology, Vol. 8, No. 3, pp.227-236.
11.	Schwartz M.	1999	Wind Resource Estimation and Mapping at the National Renewable Energy Laboratory, presented at the ASES Solar '99 Conference Portland, Maine, June 12-16, 1999.
12.	Spera, David A.	1994	"Wind turbine technology : fundamental concepts of wind turbine engineering", ASME Press, New York.
13.	Walker, J. F. and N. Jenkins	1997	"Wind energy technology", John Wiley & Sons, Chichester.
14.	WMO, Geneva	1981	Meteorological aspects of the utilization of wind as an energy source, WMO Technical Note 175.

APPENDIX A

Classes of wind power density

The following table is extracted from Elliott et al (1991) at 10 metres above ground level.

Wind power class	Mean wind power density (W/m^2)	Mean wind speed (m/s)
1	0-100	0-4.4
2	100-150	4.4-5.1
3	150-200	5.1-5.6
4	200-250	5.6-6.0
5	250-300	6.0-6.4
6	300-400	6.4-7.0
7	400-1000	7.0-9.4

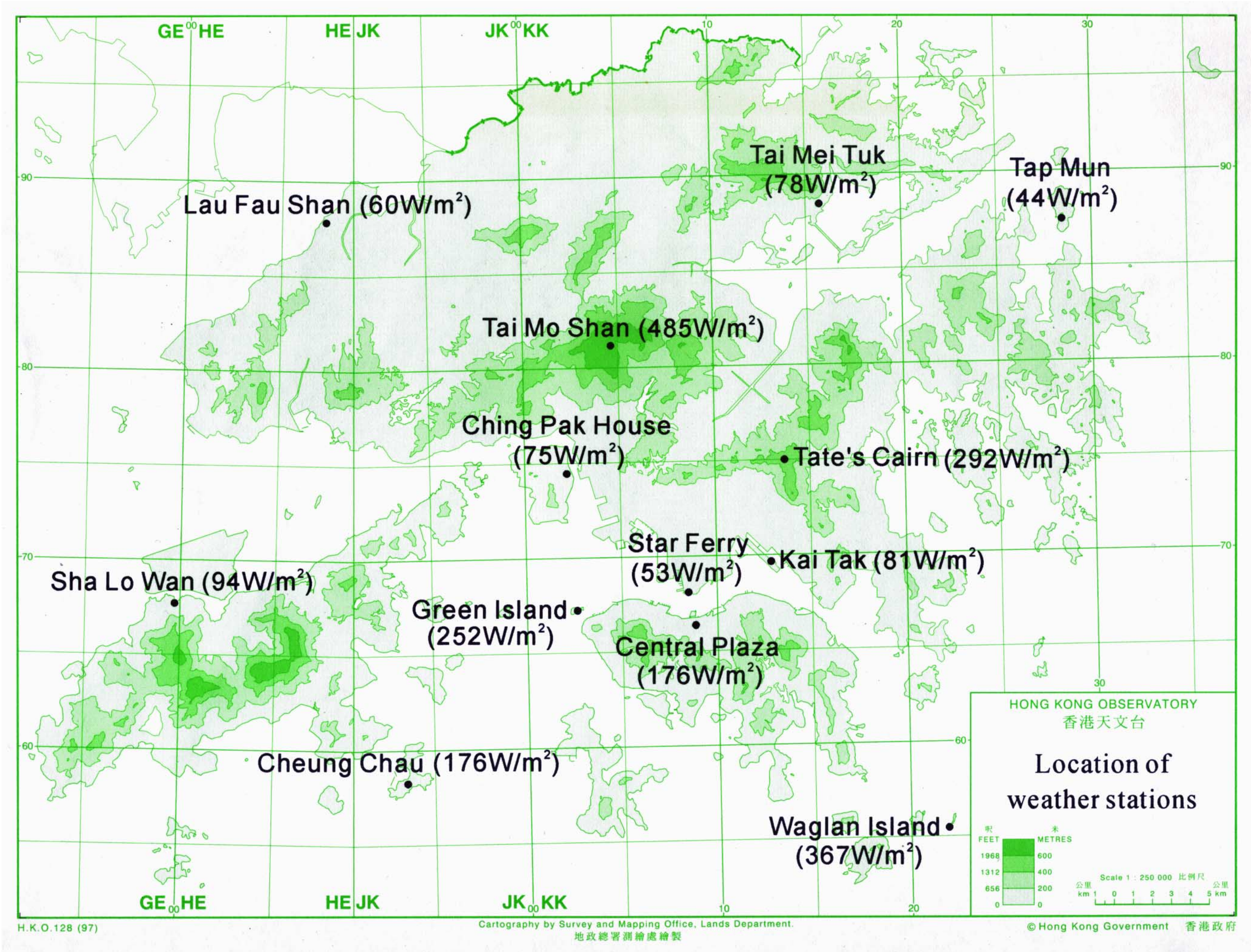

Fig. 1 Location of the 13 weather stations used to assess wind power density in Hong Kong (mean wind power density in brackets)

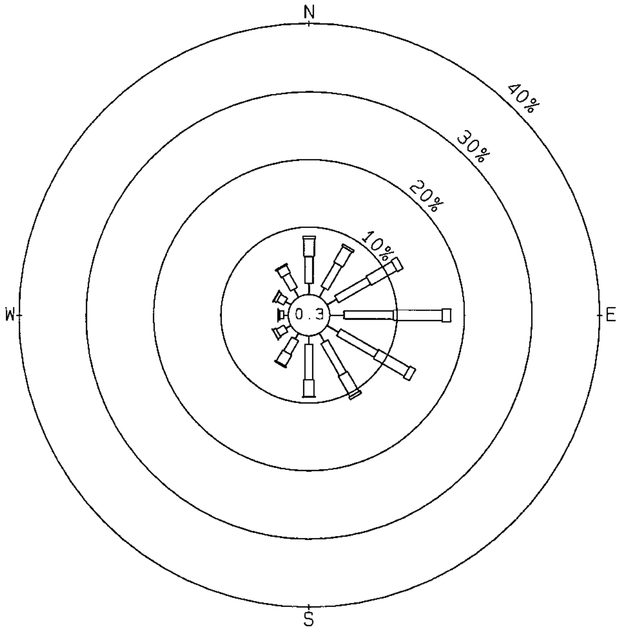

Fig. 2 Wind roses of Tai Mo Shan (TMS), 1988-2000

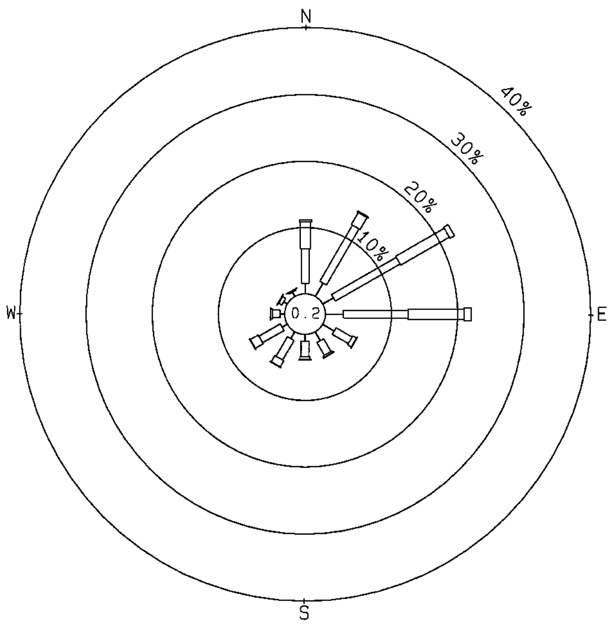

Fig. 3 Wind roses of Waglan Island (WGL), 1990-2000

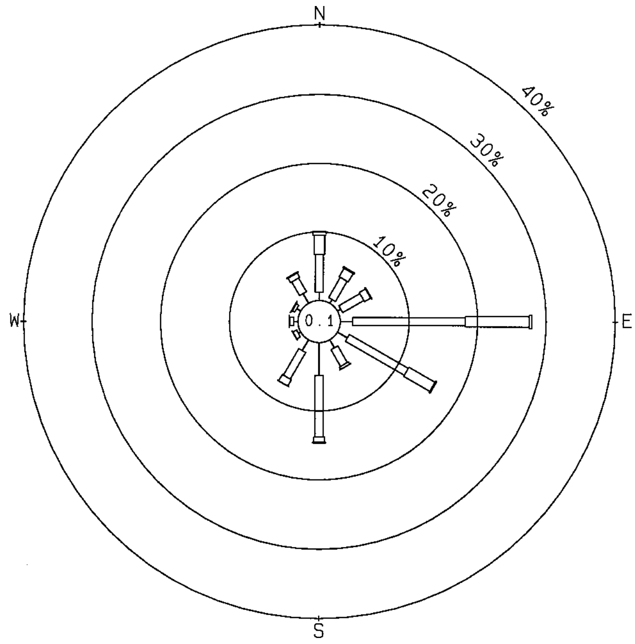

Fig. 4   Wind roses of Tate's Cairn (TC), 1988-2000

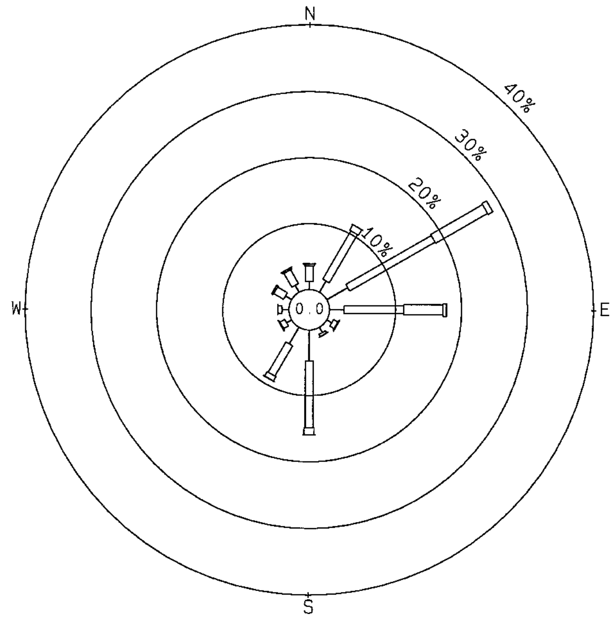

Fig. 5   Wind roses of Green Island (GI), 1990-2000

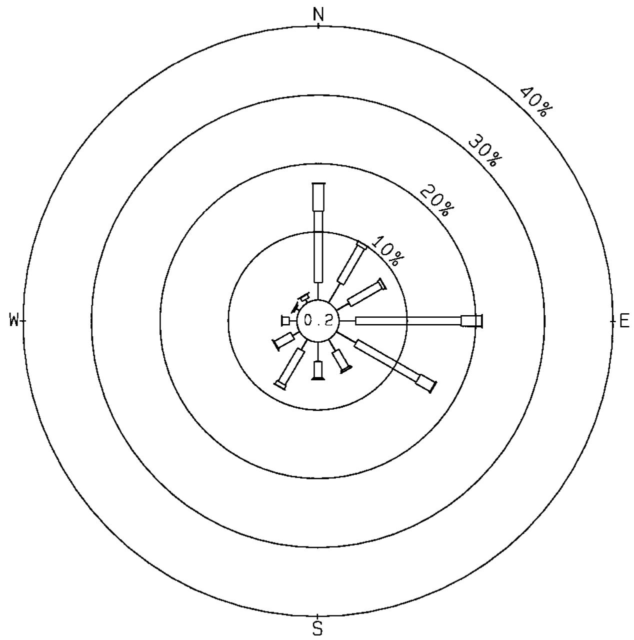

Fig. 6　Wind roses of Cheung Chau (CCH), 1993-2000

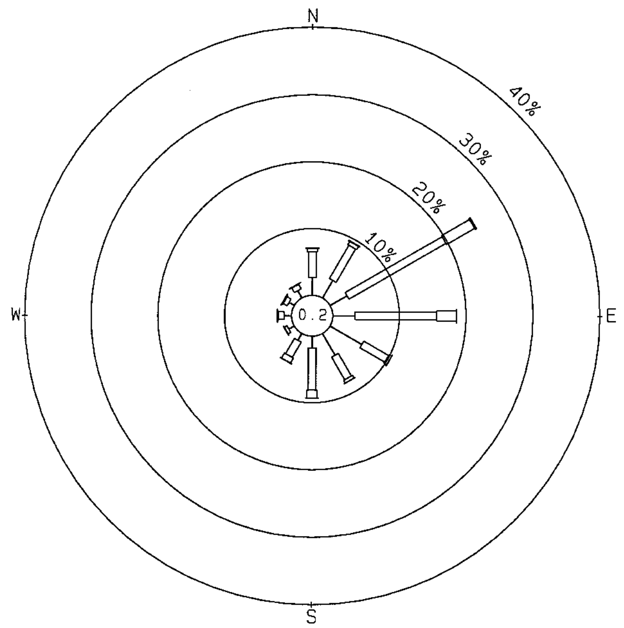

Fig. 7　Wind roses of Central Plaza in Wan Chai (WCN), 1994-2000

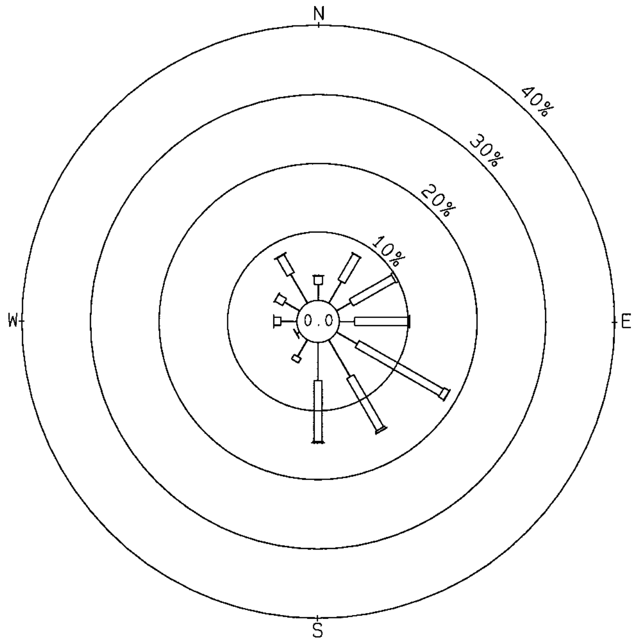

Fig. 8 Wind roses of Ching Pak House in Tsing Yi (CPH), 1988-2000

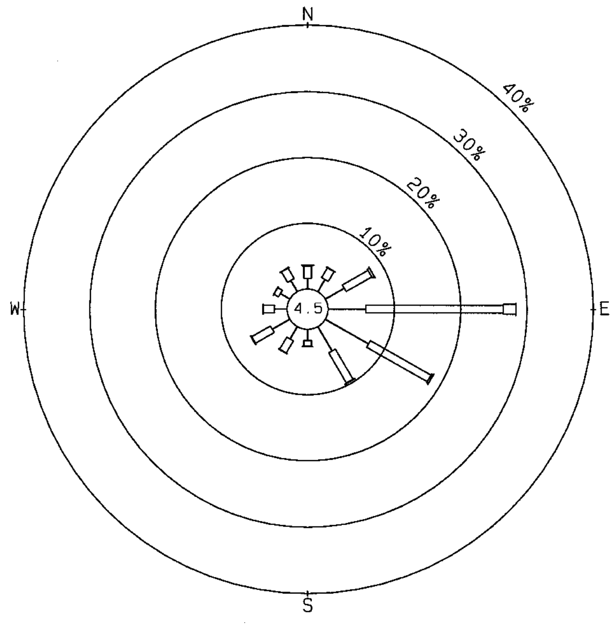

Fig. 9 Wind roses of Kai Tak (KT), 1968-1997

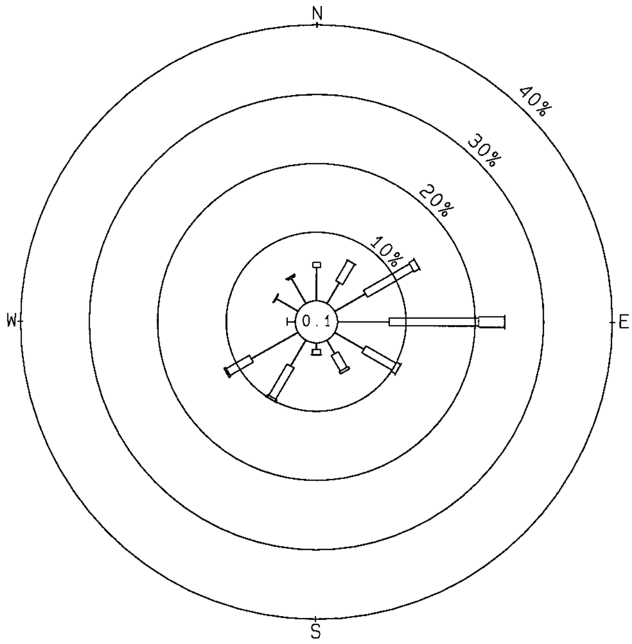

Fig. 10   Wind roses of Sha Lo Wan (SLW), 1994-2000

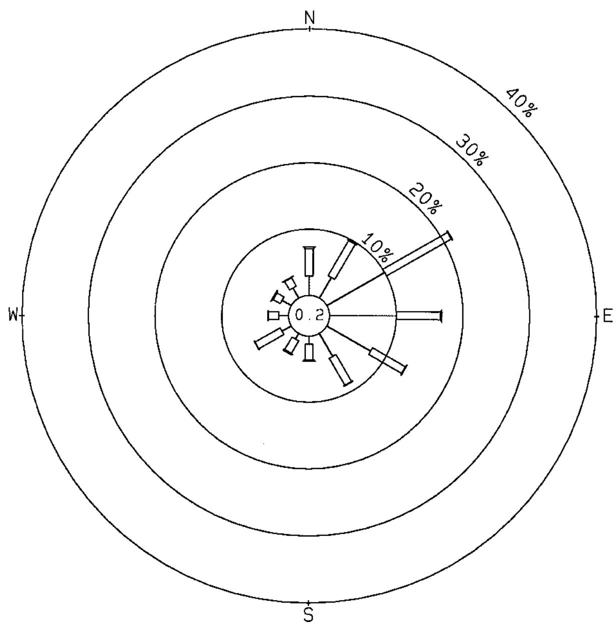

Fig. 11   Wind roses of Lau Fau Shan (LFS), 1986-2000

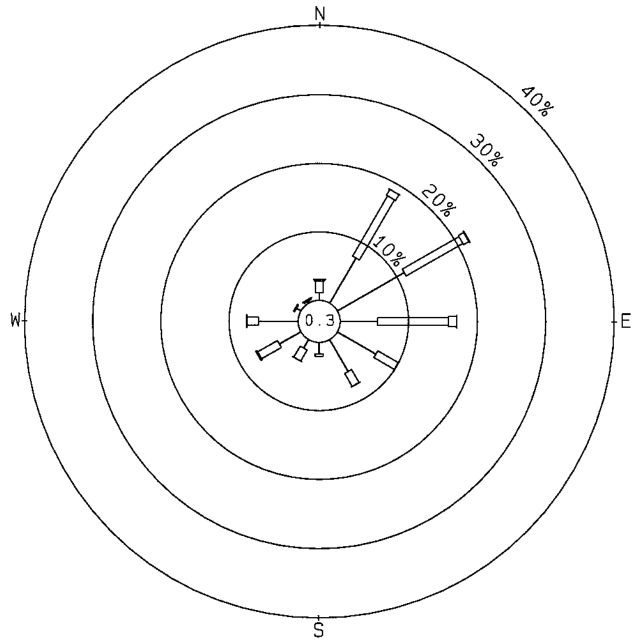

Fig. 12 Wind roses of Tai Mei Tuk (PLC), 1993-2000

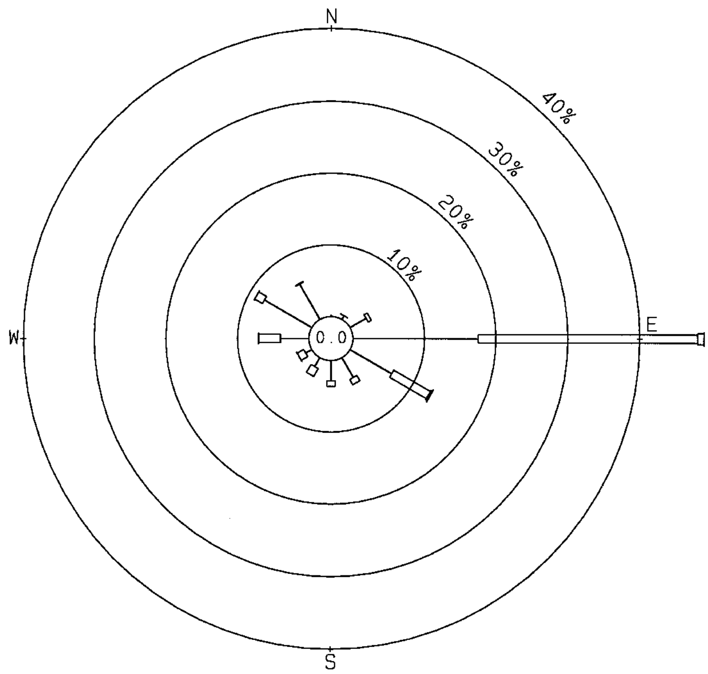

Fig. 13 Wind roses of Star Ferry in Tsim Sha Tsui (SF), 1988-2000

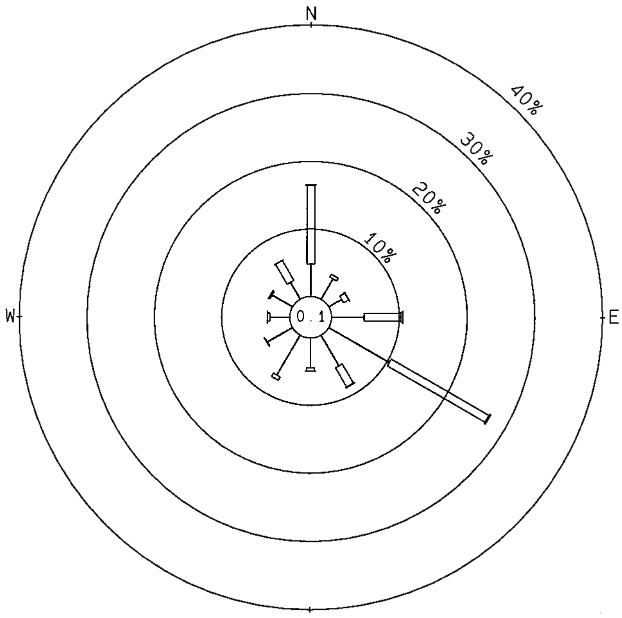

Fig. 14 Wind roses of Tap Mun (TAP), 1994-2000

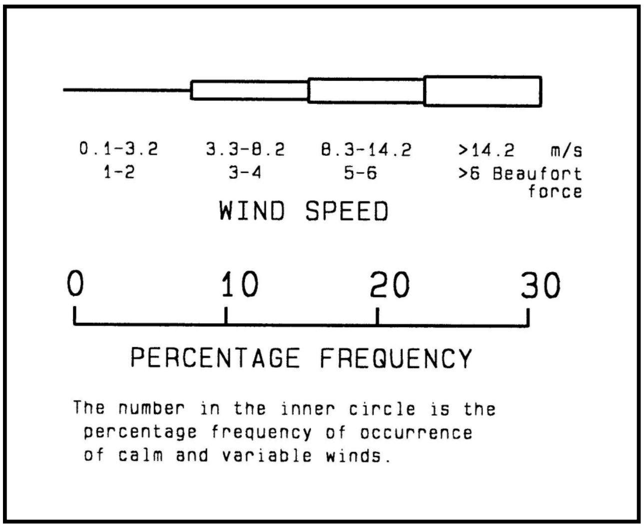

Fig. 15 Notation of wind roses used in Figures 2-14

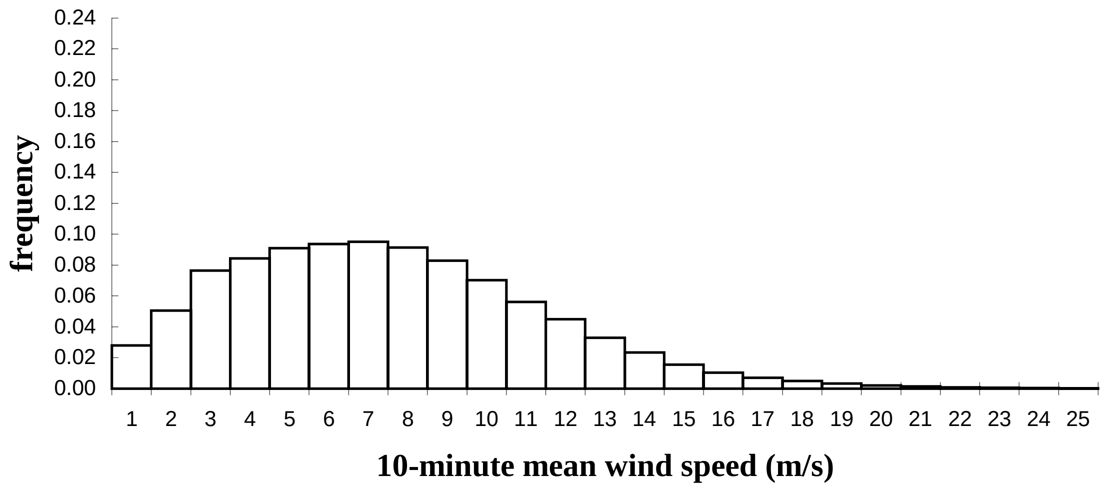

Fig. 16 Wind speed distribution of Tai Mo Shan (TMS), 1988-2000

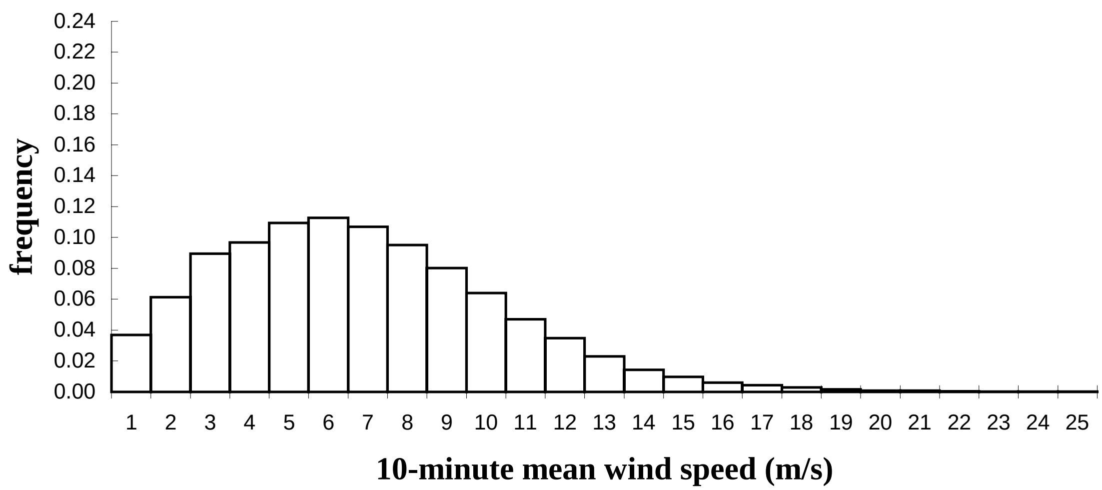

Fig. 17 Wind speed distribution of Waglan Island (WGL), 1990-2000

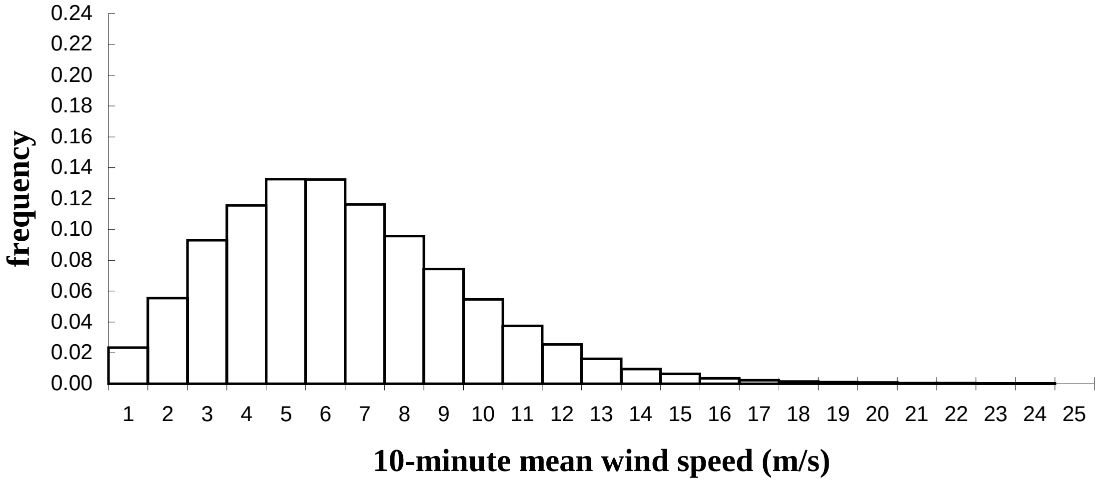

Fig. 18 Wind speed distribution of Tate's Cairn (TC), 1988-2000

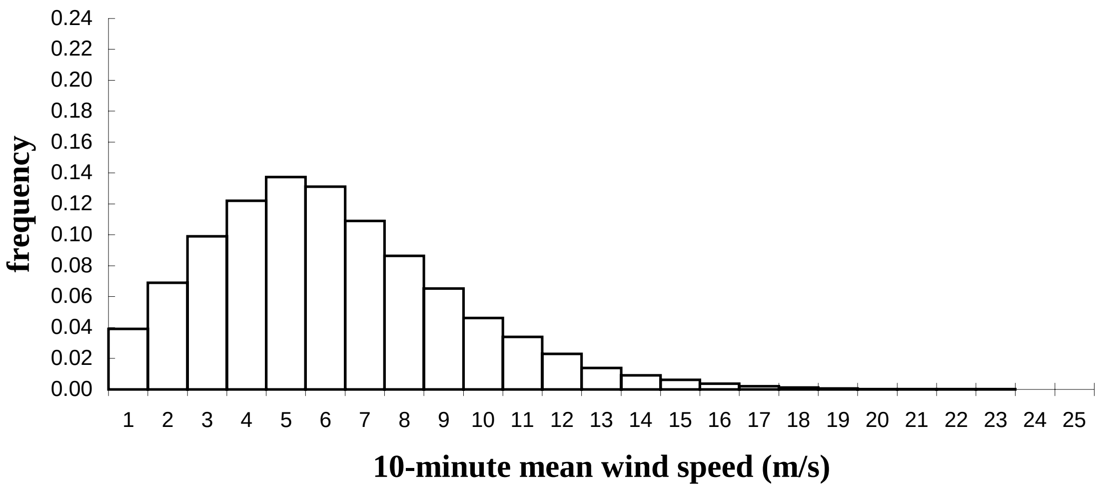

Fig. 19 Wind speed distribution of Green Island (GI), 1990-2000

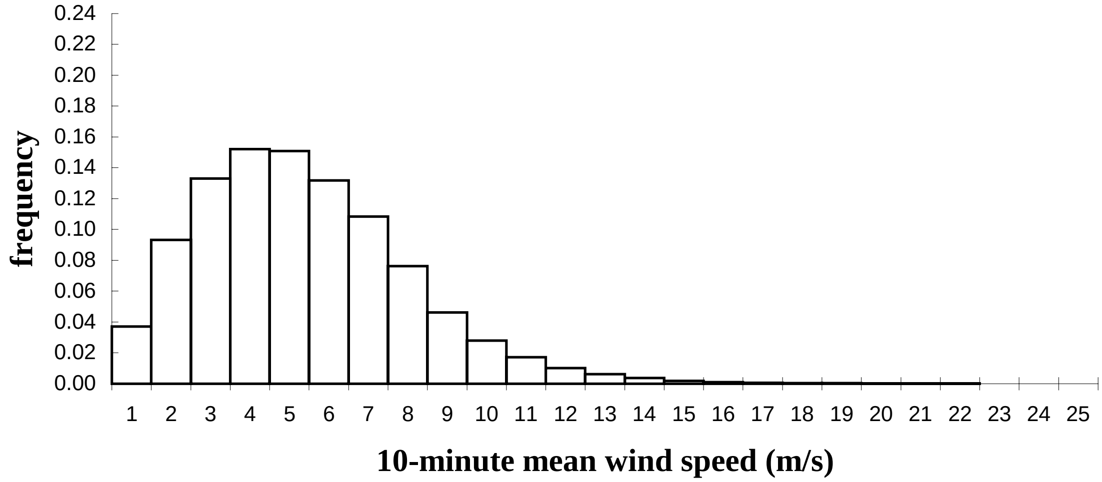

Fig. 20 Wind speed distribution of Cheung Chau (CCH), 1993-2000

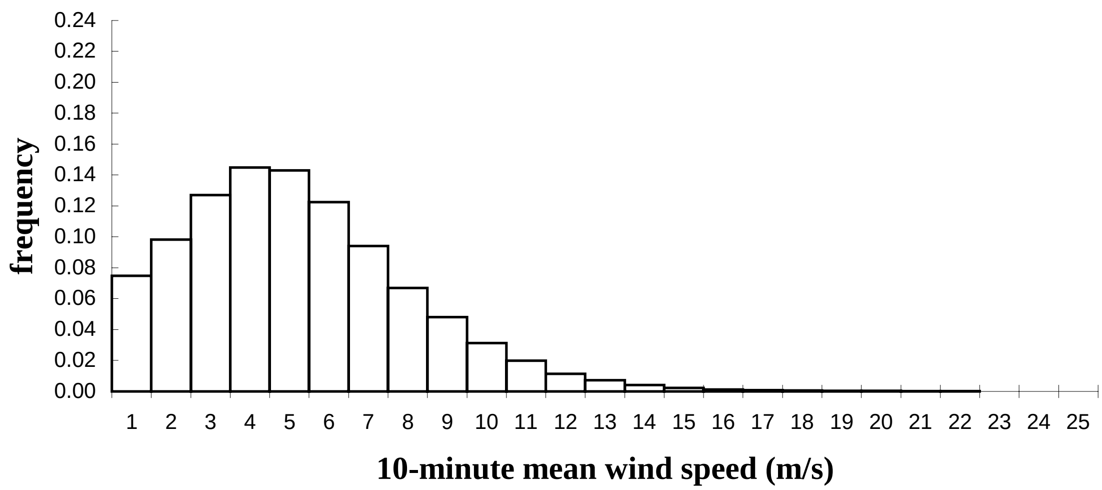

Fig. 21 Wind speed distribution of Central Plaza in Wan Chai (WCN), 1994-2000

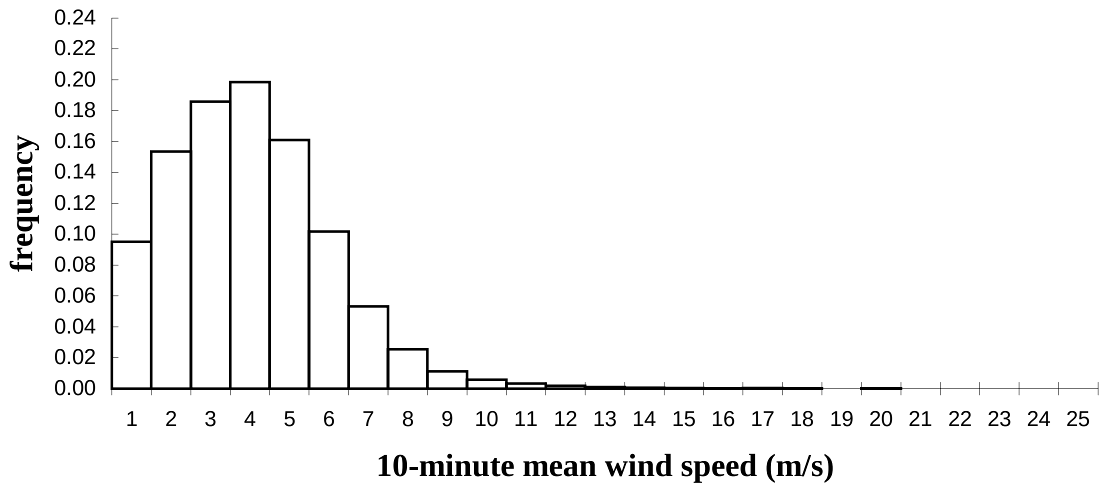

Fig.22 Wind speed distribution of Ching Pak House in Tsing Yi (CPH), 1988-2000

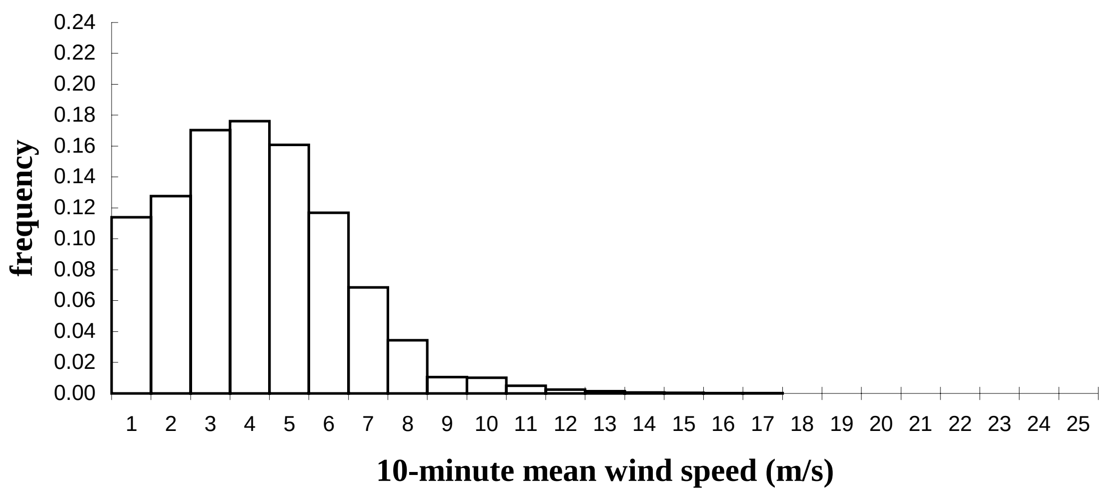

Fig. 23 Wind speed distribution of Kai Tak (KT), 1968-1997

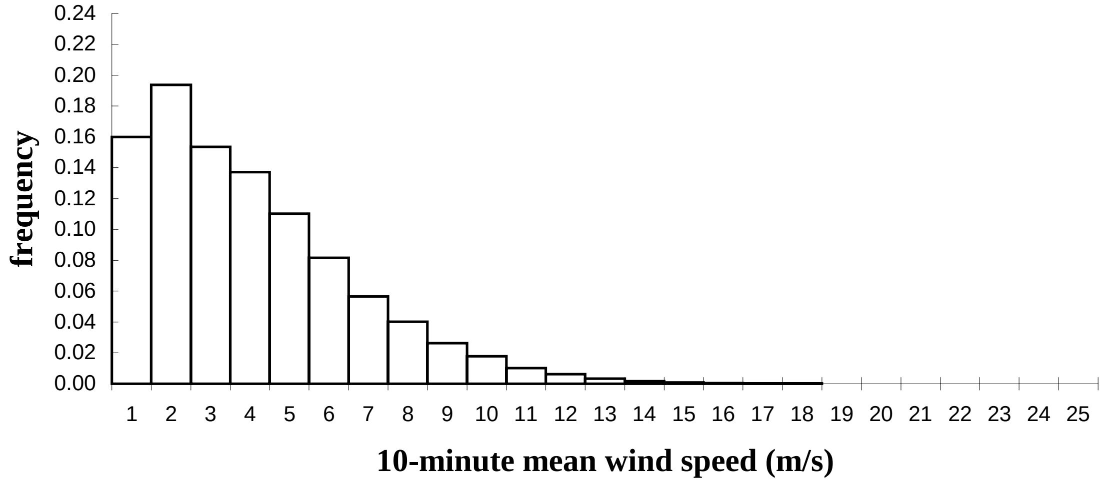

Fig. 24 Wind speed distribution of Sha Lo Wan (SLW), 1994-2000

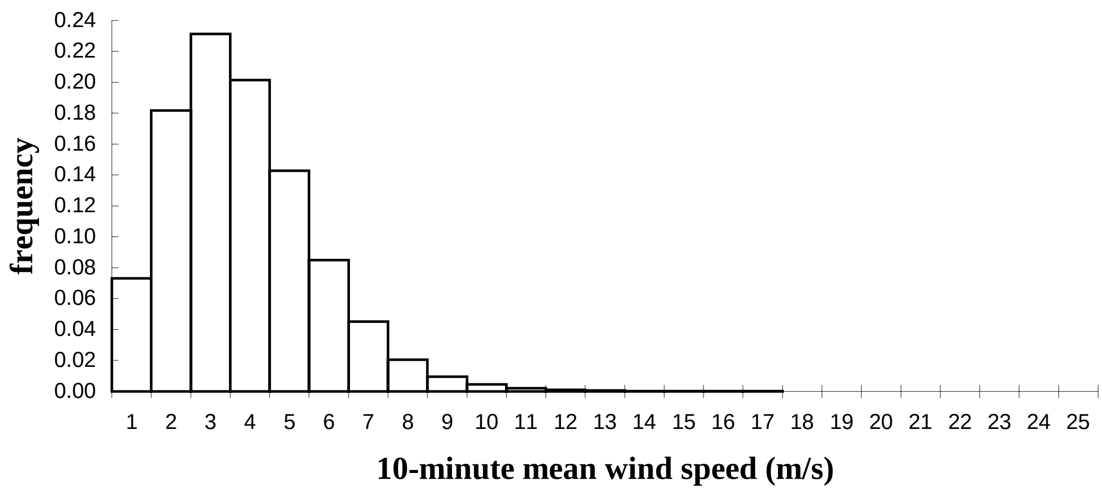

Fig. 25 Wind speed distribution of Lau Fau Shan (LFS), 1986-2000

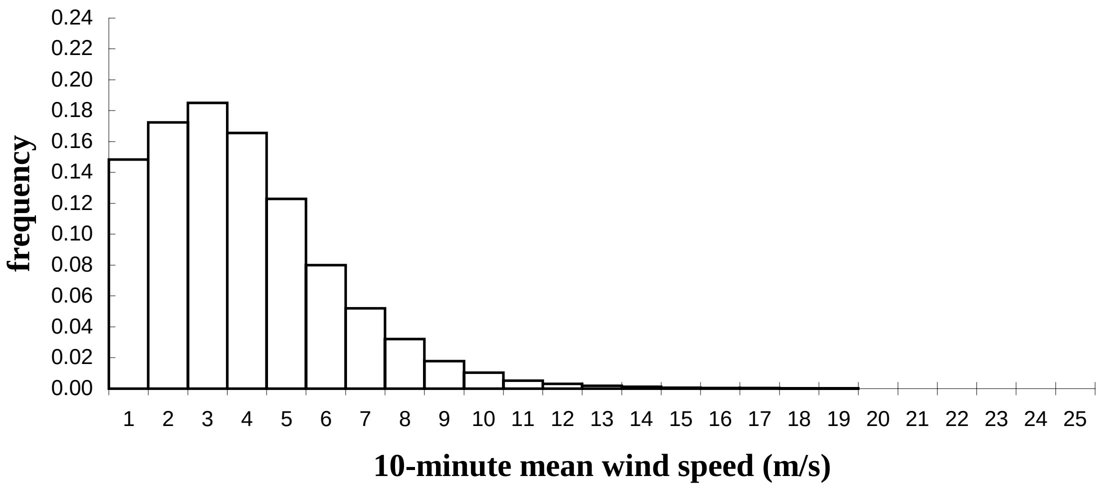

Fig. 26 Wind speed distribution of Tai Mei Tuk (PLC), 1993-2000

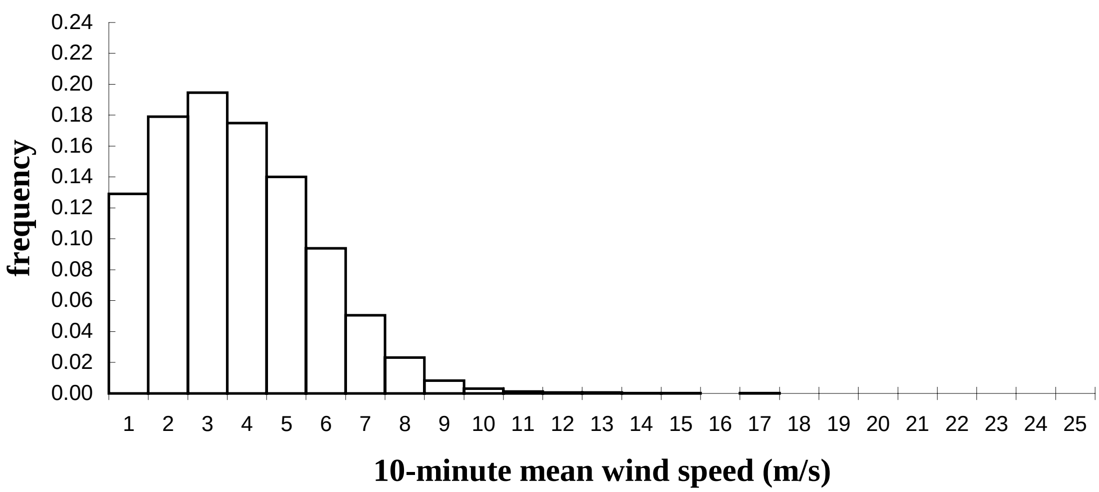

Fig. 27 Wind speed distribution of Star Ferry in Tsim Sha Tsui (SF), 1988-2000

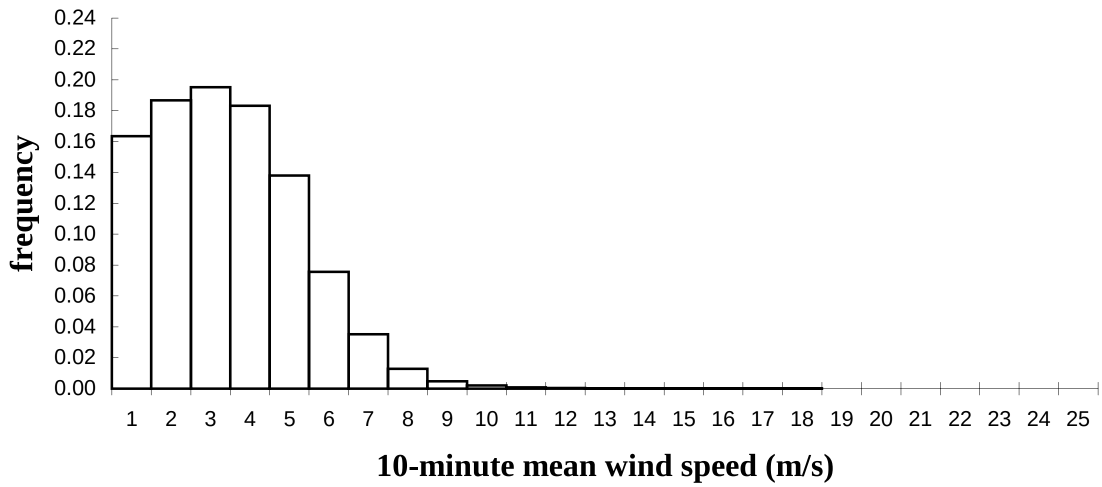

Fig. 28 Wind speed distribution of Tap Mun (TAP), 1994-2000

TABLE 1

SELECTED STATIONS WITH AVERAGE WIND SPEED (OVER THE ENTIRE DATA PERIOD) EQUAL TO OR GREATER THAN 3 m/s

Station	Type	Data Period	Average wind speed (m/s)	Anemometer height above mean sea-level (m)
Tai Mo Shan (TMS)	hilltop	1988-2000	7.3	969
Waglan Island (WGL)	offshore	1990-2000	6.7	82
Tate's Cairn (TC)	hilltop	1988-2000	6.2	588
Green Island (GI)	offshore	1990-2000	5.8	105
Cheung Chau (CCH)	offshore	1993-2000	5.2	99
Central Plaza in Wan Chai (WCN)	tall tower	1994-2000	5.0	378
Ching Pak House in Tsing Yi (CPH)	urban	1988-2000	3.9	136
Kai Tak (KT)	urban	1968-1997	3.9	16
Sha Lo Wan (SLW)	rural	1994-2000	3.8	71
Lau Fau Shan (LFS)	rural	1986-2000	3.6	50
Tai Mei Tuk (PLC)	rural	1993-2000	3.5	71
Star Ferry in Tsim Sha Tsui (SF)	urban	1988-2000	3.3	18
Tap Mun (TAP)	rural	1994-2000	3.1	37

TABLE 2

MEAN WIND POWER DENSITY AT SELECTED STATIONS

Station	Mean wind power density (W/m^2)
Tai Mo Shan (TMS)	485
Waglan Island (WGL)	367
Tate's Cairn (TC)	292
Green Island (GI)	252
Cheung Chau (CCH)	176
Central Plaza in Wan Chai (WCN)	176
Ching Pak House in Tsing Yi (CPH)	75
Kai Tak (KT)	81
Sha Lo Wan (SLW)	94
Lau Fau Shan (LFS)	60
Tai Mei Tuk (PLC)	78
Star Ferry in Tsim Sha Tsui (SF)	53
Tap Mun (TAP)	44

TABLE 3

PERCENTAGE OF TIME AT SELECTED STATIONS WITH WIND SPEED EQUAL TO OR GREATER THAN SPECIFIED VALUES

Station	Percentage of wind speed >= 3 m/s	Percentage of wind speed >= 4 m/s	Percentage of wind speed >= 5 m/s
Tai Mo Shan (TMS)	85.4	77.3	68.5
Waglan Island (WGL)	84.8	76.0	65.5
Tate's Cairn (TC)	85.1	74.9	62.7
Green Island (GI)	80.0	69.6	57.0
Cheung Chau (CCH)	79.2	64.8	49.9
Central Plaza in Wan Chai (WCN)	74.4	60.9	46.7
Ching Pak House in Tsing Yi (CPH)	65.0	45.8	27.4
Kai Tak (KT)	67.0	50.5	34.9
Sha Lo Wan (SLW)	54.0	40.1	28.3
Lau Fau Shan (LFS)	60.5	39.0	22.4
Tai Mei Tuk (PLC)	54.3	37.6	24.1
Star Ferry in Tsim Sha Tsui (SF)	52.6	36.0	21.9
Tap Mun (TAP)	49.6	32.2	17.5

TABLE 4

VALUES OF WEIBULL PARAMETERS FOR SELECTED STATIONS

Station	Weibull shape parameter (*k*)	Weibull scale parameter (*c*)
Tai Mo Shan (TMS)	2.0	8.4
Waglan Island (WGL)	2.0	7.7
Tate's Cairn (TC)	2.1	7.3
Green Island (GI)	2.0	6.9
Cheung Chau (CCH)	2.1	6.0
Central Plaza in Wan Chai (WCN)	1.9	5.8
Ching Pak House in Tsing Yi (CPH)	2.0	4.5
Kai Tak (KT)	1.7	4.5
Sha Lo Wan (SLW)	1.6	4.4
Lau Fau Shan (LFS)	2.1	4.3
Tai Mei Tuk (PLC)	1.7	4.3
Star Ferry in Tsim Sha Tsui (SF)	1.9	4.1
Tap Mun (TAP)	1.9	3.8