

Regional and Seasonal Variations of the Characteristics of Gust Factor in Hong Kong and Recent Observed Long Term Trend

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Abstract-The design of buildings and structural systems requires consideration of winds and gusts. Among the wind parameters, the gust factor, which reflects the degree of wind turbulence or gustiness, is one of the critical parameters widely employed in codes and standards for estimating the wind loading effect. Hong Kong, located at the coast of south China, has a sub-tropical climate with significant seasonal variation. Different weather systems characterize different seasons, resulting in a marked seasonal variation in wind speed and prevailing wind direction. Climatologically, high wind and gust conditions in summer are attributed to the passage of tropical cyclones while those in winter are attributed to intense winter monsoons. In addition to seasonal variation, the wind pattern in Hong Kong is complicated by the complex terrain and the densely distributed high-rise buildings constructed in the past few decades. This study analyses the wind data measured at different locations of the territory by a network of anemometers, the aim being to examine the characteristics of the gust factors in summer and winter in different regions as well as to determine the long-term trend, if any, of the gust factors.

Keywords- Gust Factor; Trend; Regional Variations; Seasonal Variations; Hong Kong

I. INTRODUCTION

The design of buildings and structural systems requires consideration of winds and gusts. Among the wind parameters, the gust factor (GF), which reflects the degree of wind turbulence or gustiness, is one of the critical parameters widely employed in codes and standards for estimating the wind loading effect. This GF can be used to estimate the effects of turbulence in typically producing higher but shorter-acting winds of greater significance for causing damage [1].

While it is generally recognized that GF is inversely related to mean wind speed and is influenced by terrain effect [2], [3] suggested that the mean GFs appear to be independent of the static and dynamic stability of atmosphere. Regarding the possible differences between GF related to tropical cyclones and that related to extra-tropical systems, [4] noted that the mean GFs in tropical regimes were higher than that in extra-tropical environment.

Hong Kong, located at the coast of south China, has a sub-tropical climate with significant seasonal variation. Different weather systems characterize different seasons, resulting in a marked seasonal variation in wind speed and prevailing wind direction. Climatologically, high wind and gust conditions in summer are attributed to the passage of tropical cyclones while those in winter are attributed to intense winter monsoons [5]. In addition to seasonal variation, the winds in Hong Kong are complicated by the complex terrain and the densely distributed high-rise buildings constructed in the past few decades. For example, while [6] showed that GFs at different stations in Hong Kong were different, [7] illustrated a sharp rise in gustiness in urban areas because of the increase in roughness.

Making use of the wind data collected in the past couple of decades by a network of anemometers operated by the Hong Kong Observatory in the territory, this study examined the characteristics of the GF in Hong Kong in both summer and winter at different locations of Hong Kong to determine if there are any seasonal and regional variations. Furthermore, the long-term trends, if any, of the GFs at different locations of the territory were also studied.

II. DATA SET AND METHODS

The wind data collected at thirteen automatic weather stations (Fig. 1) were used for this study.

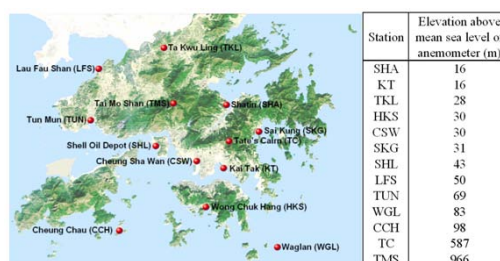


Fig. 1 Locations of stations used in the study. Station codes are in brackets. The insert gives the elevations of anemometers

Results at the two high ground stations at Tai Mo Shan (TMS) and Tate's Cairn (TC) reflect the conditions near or above the boundary layer and that at Waglan (WGL), which has good exposure with open seas in all direction and no changes in environmental condition in the study period, can be used as reference for comparison with the results of the other ten near sea-level stations distributed over the territory of Hong Kong with different degrees of sheltering by nearby topographic features and/or buildings. The study period was from 1990 to 2011 but not earlier in order to maximize the number of automatic weather stations with good data availability and minimal changes in the anemometer positions and altitudes. Although the anemometer at Cheung Chau (CCH) was raised from 92 m to its present altitude of 98 m above mean sea level in 1992 and the Sai Kung station (SKG) started operation in 1993, these two stations (wind data from 1992 at CCH and from 1993 at SKG) were included in this study in order to attain a better spatial coverage. For the same reason, weather station at Cheung Sha Wan (CSW) was also included in the study although it was terminated in mid-December 2010.

Similar to [8], 1-second gust was used for analysis in this study. In this study, the GFs in an hour (or simply GF hereafter), which is defined as the ratio of the maximum 1-second gust to the hourly mean wind speed of the hour, for wind speeds of 0.5 m/s or higher (i.e. at winds higher than force F1 (in the Beaufort Scale) were computed for analysis.

For examining seasonal variation, the GFs in the summer months from May to October and the winter months from November to April next year were analyzed to cater for the difference in the attributing factors to high wind and gust conditions arising from the passage of tropical cyclones in the summer months and intense winter monsoons in the winter months.

As preliminary analysis showed that the monthly distributions of the GFs and hourly mean wind speeds were positively skewed, and the arithmetic mean tends to over-estimate the actual central tendency, the monthly GF and monthly wind speeds were described in terms of median (or 50th percentile) of all the GF and hourly mean wind speeds of the month respectively. The 95th percentile of the GF (GF₉₅) for each month was used to characterize the extreme values of the GF.

The mean values of GF and wind speed for periods longer than a month in this study (such as seasonal average) were respectively calculated by the arithmetic mean of the monthly GF values and monthly wind speed values within the corresponding periods.

Besides the mean values of GF, the frequency distribution of the GF and the variation of GF with wind speed at all the thirteen stations in both the summer and winter months were analyzed to examine the regional and seasonal variations in the characteristics of GF, if any.

For trend analysis, linear trend, if any, was determined using the regression method with the significance of trend tested by t-test [9]. Significance level of 5 % was adopted in the study.

III. RESULTS

The mean GFs, mean GF₉₅, and the mean wind speeds for the summer and winter months at the thirteen stations during the study period are summarized in Table I. To examine specifically the gust factors in tropical cyclone (TC) conditions, the mean GFs with Tropical Cyclone Signal Number 3 or above in effect in the summer months were also compiled and shown in Table I.

A. Variation of Mean GF and Mean GF₉₅

1) Regional Variation:

Table I shows the regional variations of the mean GF and mean GF₉₅ in Hong Kong. The mean GF (GF₉₅) ranged from 1.3 to 1.4 (1.8 to 2.2) at WGL to 2.7 (4.7) at TUN. The mean GFs and mean GF₉₅ at the offshore island stations (WGL and CCH) and high ground stations (TMS and TC) were relatively smaller as compared with the nine stations at the Hong Kong Island (HKS), Kowloon Peninsula (CSW and KT) and the New Territories (LFS, SKG, SHA, SHL, TKL and TUN) where the mean wind speeds were also relatively smaller, generally. The regional variation of GF highlights an inverse relationship with wind speed such that GF tends to be smaller when the wind speed is higher.

The variations of the mean GF at WGL and TUN were further examined to depict the variations in GF as a function of wind speed. Two stations were considered for simplicity, and WGL and TUN were chosen for their pronounced contrast in the mean GF. As shown clearly in Fig.2, the mean GFs generally decreased with increasing wind speeds and stabilized towards an apparent constant value at high wind speed. The fluctuation at wind speeds exceeding F3 for TUN can be attributed to limited number of cases at high wind speeds (say stronger than F3, see right panel Fig.2). It can be seen that at the same wind speed, the mean GF at TUN was greater than at WGL, signifying the difference in local turbulence. Similar observations were found at other stations (not shown).

Of the two high ground stations near or above the boundary layer, the mean GF and mean GF₉₅ at TMS of higher altitude was in general smaller than that at TC. This phenomenon is in line with the observations of [10] that gust factor decreases with increasing altitude. However, similar phenomenon was not observed for the other stations near mean sea-level as their variation was associated with the difference in topographic effect more than the difference in altitude. For example, despite at

lower altitude, the mean GF and mean GF₉₅ at WGL was smaller than that at CCH, possibly due to better exposure at WGL.

TABLE I COMPARISON OF MEAN GF, MEAN GF₉₅ AND MEAN WIND SPEED (M/S) AT THE THIRTEEN STATIONS. VALUES WITH SIGNIFICANT DIFFERENCE BETWEEN WINTER AND SUMMER MONTHS AT THE 5 % LEVEL BASED ON T-TEST ARE SHADED.

Conditions		Stations												
		WGL	TMS	TC	CCH	LFS	KT	SKG	SHL	TKL	SHA	HKS	CSW	TUN
Mean GF	Winter	1.3	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.5	2.6	2.7	2.7
	Summer	1.4	1.5	1.8	1.6	1.8	2.0	2.2	2.3	2.5	2.4	2.5	2.5	2.7
Mean GF ₉₅	Winter	1.8	2.7	2.5	2.3	2.7	3.4	3.9	3.9	3.9	4.0	4.4	4.3	4.7
	Summer	2.2	2.6	3.0	2.4	2.9	3.5	4.0	3.8	4.3	4.4	4.5	4.1	4.7
Mean Wind Speed	Winter	6.6	6.6	6.4	4.8	3.3	3.5	2.5	2.3	2.2	2.1	2.2	2.1	2.1
	Summer	5.7	6.7	5.3	4.8	3.4	3.4	2.6	2.5	1.8	2.1	2.2	2.3	2.3

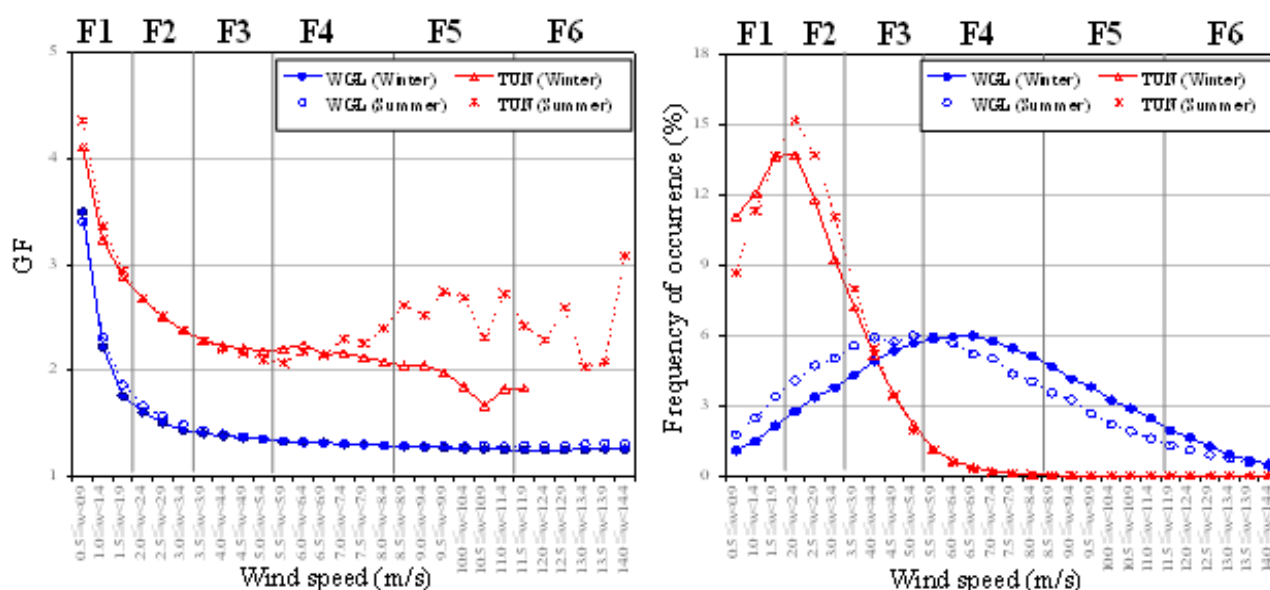


Fig. 2 Relationship between mean GF and wind speed (limited to < 14.4 m/s) at WGL and TUN (left), the frequency of occurrence of different wind speeds (right). Wind strength in Beaufort Force scale and gust factor are included for referencing.

For the nine stations at the Hong Kong Island, Kowloon Peninsula, and the New Territories, the mean GF of seven of them exceeded 2.0. According to [11], a gust factor exceeding 2.0 is considered as large and significant in terms of the degree of gustiness. The results thus indicate the highly gusty nature of most parts of the territory of Hong Kong except at offshore islands and high ground where there is good exposure.

The regional variation in the mean GFs was more significant in TC conditions. Table II shows that the mean GFs of five stations (KT, SHL, SHA, CSW and TUN) in TC conditions were apparent higher (significant at the 5 % level) than the respective mean values in the summer months. This reveals that the gustiness was higher at these stations with higher mean wind speed under the influence of TCs. There were no apparent change in the mean GFs in TC conditions at the two offshore island stations (WGL and CCH) and the two high ground stations (TMS and TC).

WGL and TUN were again chosen to illustrate in more detail the variation in gust factors in TC conditions. Fig.3 shows the scatter plots of the hourly wind speeds and the corresponding maximum 1-second gust recorded at WGL and TUN in the summer months with those recorded when Tropical Cyclone Signals Number 3 or above (considered as under TC condition) were in effect highlighted in black.

It can be seen that winds could be up to Storm force (F10) or above at WGL in TC conditions with the corresponding gust factors ranging between 1.2 and 2.0. Compared with WGL, winds at TUN were generally weaker and wind speed per hour exceeding F5 were rare unless in TC conditions. However, it was possible for TUN to experience higher gust factors compared with WGL especially in TC conditions during which the gust factors varied roughly between 2.0 and 4.0. It can also be seen that the gust factors in TC conditions at TUN was generally higher than the overall mean values in the summer months (Table II). Higher degree of gustiness during TC conditions as compared with normal time was apparent at TUN.

Mean GF₉₅ was not compared since extreme GF was prone to be observed at lower mean wind speed (see also Fig. 3) so that the mean GF₉₅ in TC condition would likely to be smaller.

TABLE II COMPARISON OF MEAN GF AND MEAN WIND SPEED (M/S) AT THE THIRTEEN STATIONS. VALUES WITH SIGNIFICANT DIFFERENCE BETWEEN TC CONDITION AND SUMMER MONTHS AT THE 5 % LEVEL BASED ON T-TEST ARE SHADED.

Conditions		Stations												
		WGL	TMS	TC	CCH	LFS	KT	SKG	SHL	TKL	SHA	HKS	CSW	TUN
Mean	Summer	1.4	1.5	1.8	1.6	1.8	2.0	2.2	2.3	2.5	2.4	2.5	2.5	2.7
GF	TC	1.4	1.5	1.7	1.7	1.9	2.2	2.0	2.7	2.6	2.8	2.6	2.9	3.2
Mean	Summer	5.7	6.7	5.3	4.8	3.4	3.4	2.6	2.5	1.8	2.1	2.2	2.3	2.3
Wind Speed	TC	15.7	17.7	15.3	13.5	7.3	7.9	8.8	5.2	4.8	4.6	5.8	4.4	3.6

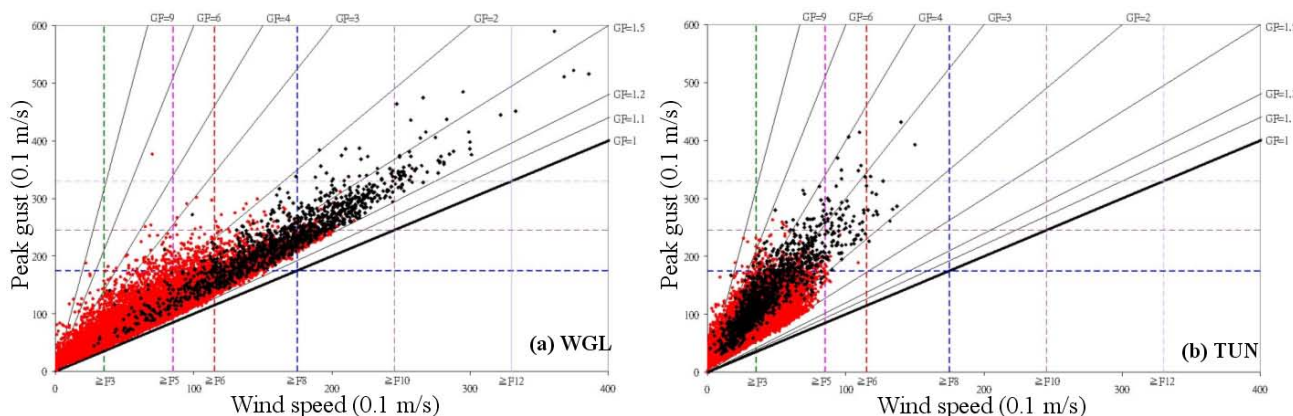


Fig. 3 Scatter plot of peak gust and hourly wind speed at (a) WGL and (b) TUN in summer. Black dot represents TC condition (i.e., Tropical Cyclone Signal Number 3 or above was in effect). Wind strength in Beaufort Force scale and gust factor are included for referencing

2) Seasonal Variation:

Despite difference in the attributing factors to high wind and gust conditions, Table I shows that not all stations had significant seasonal difference in mean GF and mean GF₉₅.

For mean GF, nine of the thirteen stations did not exhibit any significant seasonal difference in mean GF. These included the offshore island station WGL and the high ground station TMS with good exposure in all directions. Even for the four stations that had significant seasonal difference in mean GF, they did not show the same sign of difference. Among them, two (TC and TKL) had higher mean GF and two (CCH and CSW) had smaller mean GF in the summer months than in the winter months.

There were only three stations (WGL, TC, and TKL) with significant seasonal difference in GF₉₅. All of them had higher mean GF₉₅ in the summer months.

B. Variation in Frequency Distribution of GF

Besides the mean GF and mean GF₉₅, the frequency distribution of the GFs at each station was also examined in terms of the skewness and kurtosis. Using k-means cluster analysis technique (e.g., [12]) performed by the commercial package XLSTAT, the thirteen stations could be classified into three groups in terms of skewness and kurtosis (Table III).

TABLE III GROUPING OF THE THIRTEEN STATIONS IN TERMS OF KURTOSIS AND SKEWNESS OF THE FREQUENCY DISTRIBUTIONS OF THE GFS USING K-MEANS CLUSTER ANALYSIS TECHNIQUE.

Group	Winter	Summer
1	WGL	WGL
2	TMS, TC, CCH	TMS, TC, CCH, LFS, KT
3	LFS, KT, SKG, SHL, TKL, SHA, HKS, CSW, TUN	SKG, SHL, TKL, SHA, HKS, CSW, TUN

It can be seen that, the classification of the thirteen stations was more or less in line with the degree of exposure or complexity of the topography in the vicinity of the stations. The frequency distribution of GFs at WGL which has good exposure with open sea surface areas in all directions was significantly different from those at other stations in both the summer and winter months. For the other stations, the high ground stations TMS and TC as well as the other offshore island station CCH which also have rather good exposure were classified as the same group in both seasons. The frequency distributions of the GFs of these three stations were distinguishable from those located near mean sea level at the Hong Kong Island, Kowloon Peninsula and the New Territories except LFS and KT which showed seasonal variation in the frequency

distribution of the GFs.

Fig.4 shows the frequency distributions of GFs for WGL, TUN (the two stations with the smallest and highest mean GFs respectively among the thirteen stations) and CCH (a station of Group 2 near mean sea-level) in the summer months and winter months in the study period in 0.1 intervals. It can be seen that the frequency distributions at the three stations were positively skewed to a significant degree (refers to [13] for the estimation of significance). Besides the medians, the frequency distributions were also significantly different. Of the three stations, WGL had the sharpest peak and TUN had the flattest pattern. For example, in the winter months, more than 82 % of the GF at WGL ranged from 1.2 to 1.6 but the same frequency of occurrence ranged from 1.3 to 3.6 at TUN. Furthermore, the lowest GF observed at TUN was >1.3 and only 0.04 % of the GF at TUN were smaller than 1.5 as compared to 84 % at WGL.

C. Long Term Trends of GF

The long-term trends of the mean GFs in the summer and winter months of the thirteen stations were examined. Results show that the long term trends also exhibited regional variations. Of the thirteen stations, seven, namely WGL, SHA, CSW, KT, SHL, TMS and TC, had significant trends in the summer and/or winter months, while no significant trends were observed at CCH, LFS, TKL, HKS, SKG and TUN in both seasons. Table IV summarizes the average rates of change of the mean GFs in the summer and winter months of the seven stations with significant trends in either/both seasons. The trends of wind speeds for stations with significant increasing or decreasing trends of wind speed at 5 % level during the same period are also shown in brackets in the table.

For the two offshore island stations, the mean GF at WGL had decreasing trends in both summer and winter months while that at CCH did not have any significant trends. Regarding the high ground stations, the mean GFs at both TMS and TC had rising trends in summer months, while in winter months, rising trend was only observed at TC. For the other stations with significant trends in mean GF, SHA had significant decreasing trends and KT and SHL had significant rising trends in both seasons.

According to [14], gust factor decreases with increasing wind speed and vice versa. This relationship was apparent at SHA, KT and SHL where the decreasing trend of mean GF at SHA and the increasing trends of mean GFs at KT and SHL were accompanied with the respective increasing and decreasing trends in mean wind speed during the period. On the other hand, this relationship was not apparent at the other four stations (WGL, CSW, TMS and TC). They had significant trends in mean GF but had no significant trends in mean wind speed during the study period, indicating that other factors such as surface roughness [15], temperature and relative humidity [16] as well as concentration of aerosol in air [17] also attributed to the observed changes in mean GFs at these stations. However, further study is required to resolve precisely the contributing factors for the observed changes in the mean GFs

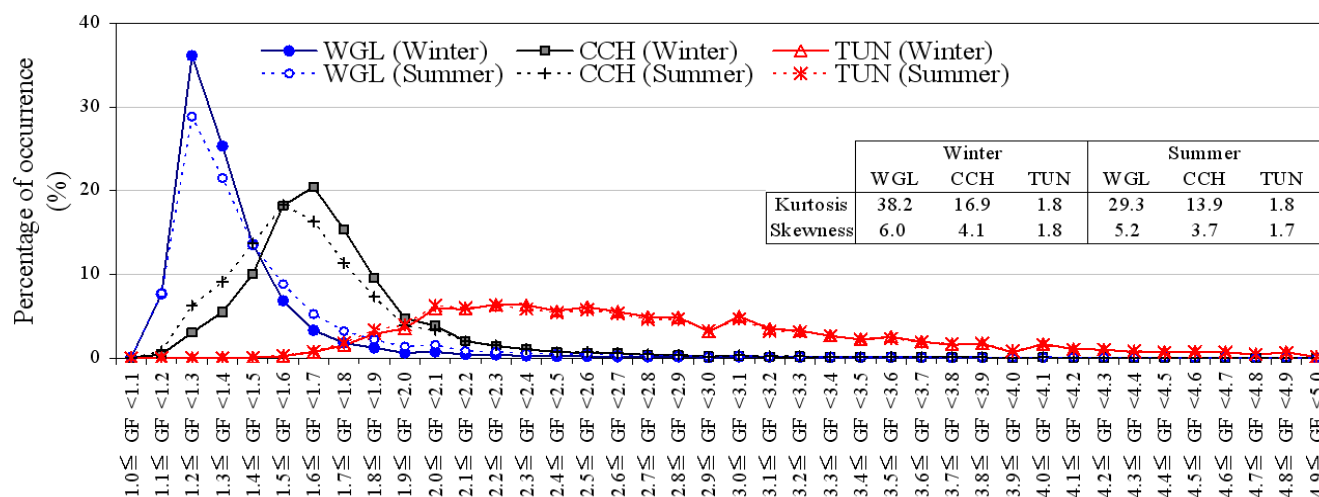


Fig. 4 Distributions of GF (limited to < 5.0) for WGL and TUN. The insert gives the skewness and kurtosis of the distributions.

TABLE IV THE LONG TERM TREND OF SEASONAL MEAN GFS AT WGL, SHA, CSW, KT, SHL, TMS AND TC. THE TRENDS ARE EXPRESSED IN UNIT OF % (RELATIVE TO THE AVERAGE IN 1990-2011) PER YEAR. NEGATIVE VALUES ARE SHADED. TRENDS FOR WIND SPEED IN 0.1 M/S FOR STATIONS WITH SIGNIFICANT (AT 5 % LEVEL) INCREASING OR DECREASING TRENDS OF WIND SPEED ARE SHOWN IN BRACKETS.

Season	Stations						
	WGL	SHA	CSW	KT	SHL	TMS	TC
Winter	-0.29	-1.08 (0.4)	Insignificant	0.80 (-0.5)	1.09 (-0.7)	Insignificant	0.11
Summer	-0.33	-1.08 (0.4)	-0.31	0.46 (-0.4)	1.64 (-0.5)	0.32	0.25

IV. CONCLUSION

The seasonal and regional variations of the gust factors in Hong Kong were studied using the wind speed data recorded from 1990 to 2011 at thirteen automatic weather stations distributed over the territory. The results indicate that despite differences in factors attributable to high wind and gust conditions, most of the stations did not have significant seasonal differences in the mean values of the gust factors. On the other hand, owing to the complexity of the topography, significant regional variation in the gust factors, in terms of both the mean values and the frequency distribution as a whole, was observed. The mean values of the gust factors were significantly lower at the offshore islands and high ground with good exposure as compared with those located at the Hong Kong Island, Kowloon Peninsula, and the New Territories, which generally have more complex topography and/or buildings in the vicinity. The gustiness at most of these places, particularly during summer and tropical cyclone conditions, was considered large with the mean gust factors exceeding 2.0. While the wind climatology at Waglan Island is generally used for engineering designs of buildings and infrastructures in Hong Kong due to its long history of record, the engineering community has taken particular note of this regional variation in gust factors over the territory of Hong Kong.

The long term trends of the gust factors at the 13 stations during the study period from 1990 to 2011 were also location specific. The gust factors in the summer and/or winter months had statistically significant decreasing trends at Waglan Island, Shatin and Cheung Sha Wan but statistically significant rising trends at Tai Mo Shan, Tate's Cairn, Shell Oil Depot and Kai Tak. No significant trends were observed at the other six stations in either the summer or winter month.

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