Observational Study of Wind Velocity and Structures during Supertyphoons and Convective Gales over Land Based on a 356-m-High Meteorological Gradient Tower

QIAN-JIN ZHOU, a LEI LI, a,b,c PAK-WAI CHAN, d XUE-LING CHENG, e CHANG-XING LAN, a,b,c JIA-CHEN SU, a YU-QING HE, a and HONG-LONG YANG, b

a School of Atmospheric Sciences, Sun Yat-Sen University, and Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, China
b Guangdong Provincial Observation and Research Station for Climate Environment and Air Quality Change in the Pearl River Estuary, Zhuhai, China
c Key Laboratory of Tropical Atmosphere-Ocean System, Sun Yat-Sen University, Ministry of Education, Zhuhai, China
d Hong Kong Observatory, Hong Kong, China
e Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
f Key Laboratory of Tropical Atmosphere-Ocean System, Sun Yat-Sen University, Ministry of Education, Zhuhai, China

g Institute of Meteorology and Climate Research–Atmospheric Environmental Research, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
h Shenzhen National Climate Observatory, Shenzhen, China

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ABSTRACT: Supertyphoons (STs) and strong convection gales (SCGs) are extremely hazardous weather events over land. Knowledge of their processes is crucial for various applications, such as intensity forecasts of gales and the design of high-rise construction and infrastructure. Here, an observational analysis of two strong SCGs and two STs is presented based on data from the Shenzhen meteorological gradient tower, the tallest in Asia. Differences in the intrinsic physical characteristics measured at each event can be associated with different disaster-causing mechanisms. Wind speeds during STs are comparatively much larger but feature slower variations, while those of SCGs are more abrupt. Unlike what is seen in the ST energy spectrum distribution, a clear process of energy increase and decrease could be observed in SCGs during gale evolution. Nonetheless, both SCGs and STs exhibited a high downward transfer of turbulent momentum flux at a 320 m height, which could be attributed to the pulsation of the gusts rather than to the large-scale base flow.

SIGNIFICANCE STATEMENT: Strong gales induced by typhoons and severe convection have potential serious impacts on human society. The current study compares and analyzes the characteristics of the gales induced by the two different weather systems using the data observed by a 356-m-tall tower in South China. This paper also shows the relationship between gusts of the near-surface wind and the turbulent momentum fluxes, thus suggesting a possible mechanism leading to destructive forces in surface winds. In terms of social value, this study would contribute to increase the awareness of gales (the instantaneous wind speed over 17 m s⁻¹) and improve the prediction and prevention of different types of gales, as well as the wind-resistant design of high-rise buildings.

KEYWORDS: Turbulence; Vertical motion; In situ atmospheric observations

1. Introduction

Modeling the physical characteristics of the behavior of different types of gales, such as those formed by typhoons or strong convection, is of great importance for hazard identification, risk management, and various other applications across fields (Shu et al. 2021, 2020). The high wind speed and long lifetime of typhoons, especially supertyphoons (STs), can lead to high annual economic costs and loss of life in coastal regions. Global warming has led to a global increase in tropical cyclone intensity and to landfalling typhoons lasting for a longer duration, further intensifying the vulnerability of coastal regions (Li et al. 2019). However, gales are not exclusively caused by STs but also by strong convection, which is more complex and difficult to characterize owing to its abrupt changes. Relative to typhoons, the duration of convection gales is much shorter, but they are no less severe (Solari et al. 2015). Extensive studies have been conducted on the statistical characteristics of typhoons, covering wind speeds, directions, gusts, turbulence intensities, peak, and power spectra, etc. (W. Li et al. 2020; X. Li et al. 2021). However, research on strong convection gales (SCGs), especially in comparison with STs, is relatively scarce. A thorough investigation of characteristics of various types of gales in the atmospheric boundary layer (ABL) is a prerequisite for understanding the intrinsic physical characteristics of the
wind, as well as for wind-resistant design of buildings and model simulation in such hazardous conditions.

For the past half-century, numerous studies have been conducted on gales that occur in the midlatitudes, with more complex types of gales found in subtropical regions. Most disasters caused by gales are related to typhoons or strong convection. In general, typhoons take on a nearly elliptical structure, while the structures of strong convections are complex and sometimes appear as a striped structure. Over land, observations are the most direct and reliable way to understand the various characteristics of wind, such as the wind speed and turbulence profiles of gales. In recent years, studies have been conducted based on anemometers installed on surface weather stations, buildings, and stations (Li et al. 2019; Shu et al. 2015). For data collected in these studies, unlike the data collected from aircraft (Sparks et al. 2019), the multilevel mean wind profile and turbulence structure, including the upper levels, are currently unknown because the datasets containing wind and turbulence information are recorded from ground weather stations or instrument towers, with heights typically at or below 15 m (Fernández-Caban et al. 2019). Similarly, some anemometers on buildings are ineffective because of building-caused flow distortion (Wang et al. 2020). Further, remote sensing techniques in adverse weather conditions are not without challenges (Liao et al. 2020).

In contrast to the aforementioned methods, meteorological towers equipped with various instruments can offer promising multilevel data such as wind records and flux with high fidelity (Fang et al. 2020). Unfortunately, the high construction costs of meteorological towers make them uncommon. With the rapid development of construction, numerous high-rise buildings over 160 m have been built, while most previous studies on the structure of gales used datasets from meteorological towers lower than 130 m (Fang et al. 2019). Therefore, reports of continuous wind variation over vertical profiles are quite rare, and production of wind profiles of different gale types, which would allow a better understanding of the physical mechanisms of gale development, are yet to be fully understood because of the lack of high-level observations in the 0–320-m range where the impact of gusts could extend. To date, the characteristics of turbulence and flux in the ST and SCG boundary layers over wide altitudinal-range areas are less known. However, with the rapid economic development and increased vulnerability of coastal cities, a better understanding of the physical characteristics of STs and SCGs is urgently required, driving the need for high-quality, multilevel wind datasets.

At 356 m, the Shenzhen meteorological gradient tower (SZMGT) offers a unique opportunity to collect observational data for studying the features based on vertical profiles of various types of gales. On the basis of the multilevel, 10-Hz observational records from the SZMGT, similarities and differences in the high-resolution wind speed and momentum flux between STs and SCGs are investigated. The outcome of this study is expected to provide a better understanding of the various characteristics of vertical wind components, which can aid in both atmospheric and engineering applications such as weather forecasting and wind resistance design. The data involved in this study were obtained over the course of two ST and SCG events from four fast-response sonic anemometers installed at the SZMGT. In section 2, the background information on the STs and SCGs will be introduced further, together with the methods of data collection and processing from the SZMGT. The analysis of the measured wind and gust characteristics of the two types of gale processes will be presented in section 3. In section 4, the major conclusions and efforts needed in future research will be summarized.

2. Data and methods

a. Data

The data used in this study were collected during four disaster events, namely, two ST cases and two severe convective events in the last decade. South China coastal regions have undergone numerous destructive ST and SCG events during these four events. The STs Hato and Mangkhut, which occurred in 2017 and 2018, respectively, are the focus of this study. Both had maximum wind speeds exceeding 45 m s⁻¹. Similarly, two SCG events that took place on 10 May 2020 and 3 March 2019 were studied. Each event had wind speeds ≥ 17.2 m s⁻¹, accompanied by thunderstorms and short-duration heavy precipitation. Typhoon Hato was generated in the northwest Pacific Ocean, and its intensity increased while passing the South China Sea with wind speeds 48 m s⁻¹ before landing in Zhuhai City, Guangdong Province, China. The maximum 10-min mean wind speed and the 3-s gust wind speed recorded at SZMGT were 25.1 and 32.3 m s⁻¹, respectively. Similarly, Typhoon Mangkhut formed on the northwest Pacific Ocean and caused fierce winds and high damage during its passage over Shenzhen. The SZMGT recorded a maximum 10-min mean wind speed of 40.7 m s⁻¹ and a 3-s gust wind speed of 46.6 m s⁻¹ (He et al. 2021; Q. S. Li et al. 2021). As compared with STs, SCGs often occur in weather systems with small horizontal scales of 12–300 km in a short lifetime of 1–12 h. They are caused by the strong vertical movement of air and often considered the fourth-most-damaging natural disaster after tropical cyclones, earthquakes, and floods (Zhang et al. 2007).

In this study, the analysis of gale characteristics under different weather processes was focused on the aforementioned STs and SCGs. Notably, the physical mechanisms of STs and SCGs are quite different, especially considering the lifetime of gales. An average typhoon life cycle is approximately 1 week, while the life cycle of a strong convective process is relatively short: approximately 1–12 h. This study focused on the relevant wind elements of the exact days when typhoon transit and strong convection occurred, particularly the maximum wind speed phase during landfall. Therefore, we only used the datasets related to the days of typhoon landfall and strong convection occurrence. Based on a large amount of measured data, the physics difference between ST and SCG is discussed through the analysis of wind speed distribution, vertical structure, and momentum flux. Table 1 shows the details of the four events.

Figure 1a shows photographs of the SZMGT, which is located near the Tiegang Reservoir in Shenzhen, China (22°38′59″N,
The surrounding topography and terrain are shown in Fig. 1; Figs. 1b–d show that the SZMGT is deployed at a relatively rougher site when compared with the surroundings where no major obstacles (e.g., tall buildings) exist. The area 1–2 km northeast of the tower is covered by cropland or water, while buildings with heights between 10 and 30 m interspersed within forests were seen in distant suburban areas. The terrain up to 5 km to the south and northwest of the tower is generally smooth and almost entirely covered by woods and lakes.

SZMGT is the tallest meteorological tower in Asia: a 356-m-high steel tower with a lattice structure that is cable stayed at 65, 130, 195, and 325 m. In this study, the measurements were taken at heights of 10, 40, 160, and 320 m, using fast-response systems consisting of four CSAT3 3D sonic anemometers (Campbell Scientific, Inc.). These instruments recorded various parameters, such as the three orthogonal wind components ($u_x$, $u_y$, and $u_z$) and water-vapor mixing ratio, 10 times per second. The tower is also equipped with a standard meteorological measurement system consisting of 13 Vaisala WMT703 wind sensors (Vaisala Oyj), which measured the meteorological elements (wind speed, wind direction, and temperature; He et al. 2022). Installations were spaced at 10-m intervals from 10 up to 360 m above ground level as shown in Fig. 1e.

To ensure the validity of the data, we compared the 320-m data from SZMGT with the 367-m data from the nearest wind-profiling radar (WPR). All time series were normalized using the equation $X_{\text{norm}} = (X_i - X_{\text{min}})/(X_{\text{max}} - X_{\text{min}})$. It was revealed that, although the instruments and measurement methods were different, the obtained correlation coefficient (cor) between the two data series was high enough to pass the significance test. Also, the wind speed variations observed by

<table>
<thead>
<tr>
<th>Year</th>
<th>Start</th>
<th>End</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>0000 23 Aug</td>
<td>2359 23 Aug</td>
<td>Hato</td>
</tr>
<tr>
<td>2018</td>
<td>0000 16 Sep</td>
<td>2359 16 Sep</td>
<td>Mangkhut</td>
</tr>
<tr>
<td>2019</td>
<td>0000 3 Mar</td>
<td>2359 3 Mar</td>
<td>SCG1</td>
</tr>
<tr>
<td>2020</td>
<td>0000 10 May</td>
<td>2359 10 May</td>
<td>SCG2</td>
</tr>
</tbody>
</table>

Table 1. Observation periods considered in this paper (UTC).

Fig. 1. (a) Satellite imagery of the SZMGT (2021; Google), (b)–(d) photographs of SZMGT, and (e) the layout of instruments on SZMGT. “Standard” indicates standard meteorological measurement, and “flux” indicates flux and turbulence measurement.
the two instruments followed similar trends, especially the almost-identical wind speed peak values recorded by both instruments. See the details in Fig. 2.

b. Methods

1) QUALITY CONTROL

Missing or invalid points may occur during measurement of a landfalling ST or SCG. During periods of high rain rates, CSAT3 systems may face challenges, such as water accumulation on the sensor of sonic anemometers and condensation of water vapor on the sensor. These conditions may result in data loss or spikes (or random pulsations). Hence, to ensure data quality, the raw data require preprocessing following the general recommendations outlined in Foken and Wichura (1996). Quality control, data processing, and interpolation were performed as follows.

1) Physical rationality judgment: To ensure the physical rationality of the observed wind speed data, the threshold values are set as $100 \text{ m s}^{-1}$ for horizontal wind speed and $10 \text{ m s}^{-1}$ for vertical wind speed. The reason why $100 \text{ m s}^{-1}$ is set as the threshold value for horizontal wind speed is that the maximum ground-level wind speed caused by typhoons landing on China since 1949 is $72 \text{ m s}^{-1}$ (Ying et al. 2014). Considering that the height of observation can reach as high as 320 m in the current study, the threshold value is enlarged to $100 \text{ m s}^{-1}$, and the data larger than this value will be removed and marked with missing flags. Note that, in the dataset used in the current study, the maximum wind speed is $43.38 \text{ m s}^{-1}$, which appeared at the height of 320 m at 1424 LST 16 September 2018. Therefore, the quality-control module of physical rationality has not been actually triggered in this study.

2) Random pulsation elimination: Owing to the condensation of water vapor on the sensor, the data-receiving and data-transmission systems may generate random pulses. First, the probability density distribution and variance of the pulsation ($\Delta X = X_{t+1} - X_t$) were presented. If $|\Delta X| > n\sigma$, the corresponding value will be considered a random pulse (Højstrup 1993; Vickers and Mahrt 1997). Because of the prevalence of turbulent intermittency and coherent structures, asymmetries are often observed in the probability density distribution of actual atmospheric turbulence data, with potential occurrence of large skewness, leading to a long-tail phenomenon. To protect the original data to the maximum extent and to avoid erroneous elimination of intermittent signals, $n$ was set to 5, and $\sigma$ was the standard deviation. The random pulses were eliminated during quality control. 

3) Coordinate rotation: To ensure the mean wind components are aligned with the $x$ axis, the coordinate system was aligned with the direction of the mean wind using the double rotation method (Tanner and Thurtell 1969) for each 1-min sample datum. The along- ($u_1$), cross- ($u_2$), and vertical- ($u_3$) velocity components are transformed into $U$, $V$, and $W$, respectively, where the average of 1-min $V$ and $W$ is close to 0. Here, $U$, $V$, and $W$ are assumed to be the along-wind, crosswind, and vertical velocities, respectively (horizontal and stationary flow).

4) Interpolation of missing values: After quality control and coordinate rotation excluded anomalous results, gaps had to be filled before analysis. While the Newton interpolation formula performs well for a single missed point, it is not suitable for multiple points. To avoid data divergence, a simulation interpolation method based on the Weierstrass–Mandelbrot function was used to fill continuous missing values (Liu et al. 2013):

$$R(t) = Re \, W(t)$$

$$= A \sum_n \left[ \frac{\cos\phi_n - \cos\phi \cos\gamma t}{\gamma^{2-D\mu}} + \frac{\sin\phi_n - \sin\phi \gamma t}{\gamma^{2-D\mu}} \right] .$$

(1)
values missing more than 600 continuous measurements (1 min) were not interpolated. Here we need to mention that the missing data [more than 600 consecutive measurements (1 min)] accounted for 1.8% of the total data.

In this study, 828,000 data points were used for each case, with the details of the case data shown in Table 2. Of the four cases, the Mangkhut case had the lowest proportion of valid data use at 66.5%. To ensure the validity of the interpolated data, we selected 1 h of complete data from the Mangkhut process, randomly removed 35% of the original data, and then compared the differences in statistical characteristics between the interpolated and original data, as shown in Fig. 3a. The two datasets were statistically consistent, with a correlation coefficient of 0.92. Our study focused on gusts, and the results shown in Fig. 3a reveal that the corrected gust data fit well with the original gust data, with a correlation coefficient approaching 1. Furthermore, the probability density distribution results in Fig. 3b show that the corrected gust data are almost identical to the original data distribution and cover all peaks of the original data. These results indicate that the corrected data reflect the relevant physical and statistical characteristics of the original data to a certain extent and, therefore, basically meet the requirements of this study, which are primarily based on the statistical characteristics of the data.

In section 2b(1), the raw velocity components were transformed to $U$, $V$, and $W$, which were uniformly considered as $f(t)$ in this study. However, the observed wind speed data were actually the superposition of multiple wind signals. Therefore, the wind speed needs to be decomposed to study the physical properties of the wind in a more effective manner. The time series of $f(t)$ is divided into three parts (basic flow and fluctuations) through Fourier transformation, as shown in

$$F(t) = \bar{f(t)} + f_g(t) + f_i(t) + \delta \quad \text{and (2a)}$$

$$f' = f_g + f_i + \delta. \quad \text{(2b)}$$

Turbulence consists of turbulent vortices of different size scales, with large-scale turbulence generally dominating the energy transfer of turbulent momentum and one of the causes of high-frequency turbulence (Kolmogorov 1991; Lan et al. 2022). Here, $\bar{f(t)}$ refers to the mean flow, or basic flow, with a frequency of $<0.00167$ and a period of $>10$ min. Various symbols were used to distinguish different scales of turbulence, where $f_g(t)$ denotes the large-scale turbulence at the low frequency and $f_i(t)$ denotes smaller-scale turbulence at higher frequencies, as shown in Eq. (2b). According to previous studies, the frequency of gusts falls roughly in the range of $0.00167$–$0.0167$ Hz, which corresponds to a period of 1–10 min (Zeng et al. 2010). The frequency of $f_i(t)$ is in the range of 0.0167–10 Hz. The $\delta$ refers to turbulent flows with frequencies of $>10$ Hz, which are not considered in this study because of the limitations of the maximum sampling frequency of the instrument. In wind-resistant design, it is generally accepted that the impacts of wind usually manifest as a static response influenced by the basic wind speed (deformation of the structure due to an increase in a given wind speed) and a buffeting

<table>
<thead>
<tr>
<th>Cases</th>
<th>Valid data (%)</th>
<th>Interpolated data (%)</th>
<th>Discarded data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Aug 2017</td>
<td>89.8</td>
<td>9.72</td>
<td>0.48</td>
</tr>
<tr>
<td>16 Sep 2018</td>
<td>66.5</td>
<td>30.2</td>
<td>3.3</td>
</tr>
<tr>
<td>3 Mar 2019</td>
<td>95.1</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>10 May 2020</td>
<td>97.6</td>
<td>0.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 2. Data information for each case.
response caused by pulsations (forced vibrations of the structure caused by pulsations; Isyumov 2012). The maximum amplitude of the buffeting response has a strong relationship with wind gusts because of the existing resonance frequency in the structure and winds over different averaging periods (Cao et al. 2015). Given the importance of gusts in wind-resistant design, the $f_g(t)$ was carefully considered in this study.

3. Analysis of wind characteristics

a. Evolution of half-hourly wind speeds during the whole day

Typhoons and convective cell storms are often accompanied by gales at landfall, and various evolutionary characteristics of gales may cause different potential impacts and damage to high-rise buildings and power facilities. Therefore, first, we conducted a relevant study on wind characteristics. The horizontal velocity of air motion spans a wide area, with that of typhoons reaching between 500 and 1000 km and that of convection reaching approximately 300 km (Ming et al. 2014; Zhang et al. 2018). The evolution of the half-hourly horizontal mean wind speed of the four gale events measured by CSAT3 is plotted in Fig. 4 at heights of 10, 40, 160, and 320 m. The missing points in Fig. 4 were caused by excessive loss of measurements, and the maximum hourly wind speed period (MHP) is shaded. The wind speed of each event increased with height within 330 m of the ground. The strongest half-hourly wind speeds occurred almost simultaneously at the four height levels, and when the ST/SCG passed, the increase of the magnitude of the wind speed during the gale periods was found to be significantly different between STs and SCGs. The evolution of wind speed varied in individual events; the increase in wind speeds of STs showed a gradual uptrend at the four heights during the MHP; however, a strong increase in wind speed occurred in SCGs, especially at the highest height (320 m). Considering the differences in MHP among the two gale events, three hours each from hours before MPH (P-MHP), hours after MPH (L-MHP), and including the MHP were chosen for an in-depth analysis. These periods are henceforth called “gale time.”

b. Statistics of the wind characteristics during gale time

Because turbulence is composed of high-frequency signals, its physical characteristics can be captured more realistically only by using 10-Hz raw data. The detailed evolutions of the gale time were shown in Figs. 5a–p, where, the gray line represents the original velocity $U$, the red line shows the velocity $U_g$ filtered by high-frequency signals $T_{1 \text{ min}}$, whose evolutionary features are similar to gusts $u_g$, and the last blue line (MS) is the 3-h average velocity. The shaded area indicates the time period with maximum hourly mean wind speed. The $U_g$ and $U$ are defined as

$$U_g = \overline{U} + u_g \quad \text{(3a)}$$

$$\overline{U} = \frac{\sum U}{n} \quad \text{(3b)}$$

As shown in the bottom panels of Fig. 5, the heat map reflects the change in linear regression coefficients (LRCs) for the results of 5 min of data under 1-min sliding, which represents the slope of the fluctuation, while the shades of color reflect the sharpness of the overall wind speed change in a 5-min time frame. Figures 5a–d show the wind speed evolution characteristics of Hato at four heights. The mean wind speed increased with height, and the wind speed pulsation superimposed on the mean flow fluctuated modestly, with no substantial and abrupt changes in wind speed. As shown in Figs. 5e and 5f, the mean wind speed of Mangkhut also increased with height, but the increase was greater and the wind speed pulsation was stronger relative to Hato. While transitioning to gale, strong, abrupt wind speed changes occurred at 160 and 320 m, as shown in Figs. 5g, 5h, and 5b. Figures 5i–l show the event for
SCG1, with a small but increasing trend in mean wind speed change from low to high levels. There was a clear, abrupt change in wind speed as it transitioned to gale, with more drastic changes at higher levels. When the wind speed reached the maximum, it slowly weakened, as shown in Figs. 5i–l and the bottom-right panel of Fig. 5. For SCG2, as shown in Figs. 5m–p, the average wind speed at each level was relatively close. However, abrupt changes in wind speed appeared when it transitioned to gale, and the changes were most substantial at the high levels, displaying a sudden increase and decrease in wind speed, as shown in Figs. 5p and the bottom-center-right panel of Fig. 5.

In summary, during the ST gale period, the fluctuation and increase of speed are relatively flat and regular across four levels, while the \( \overline{U} \) increases with height. Contrastingly, the \( \overline{U} \) of the SCG gale time is much smaller than that of the ST because of the short lifetime of the gale. For SCG, prior to the MHP, horizontal wind speeds were relatively calm at all levels. However, during the MHP, particularly at 320 m, wind speed changed abruptly and peaked rapidly. This drastic
speed change in gales poses a significant challenge to the safety of high-rise buildings in urban areas.

c. Wind profile

During ST and SCG events, it was indicated that the source of building damage may come from not only high wind speeds, but also fluctuating energy (Dai et al. 2021; Li et al. 2017; Zhu et al. 2018). Therefore, the evolutionary pattern of 1-min maximum wind speed in height can provide some support for the wind resistance design of high-rise buildings. The wind profile contains vital information of horizontal wind speed at different altitudes, which is of great importance in both the meteorological and construction industries. Therefore, the wind profiles of \( U \) and \( U_{\text{max}} \) (maximum wind speed per minute) during the STs and SCGs were compared in this study. According to previous studies, the log wind profile

\[
\begin{align*}
    f_\mu(z) &= \frac{u_*}{\kappa} \ln \left( \frac{z - z_o}{z_0} \right), \\
    \ln \text{(4a)}
\end{align*}
\]

satisfies the lowest boundary conditions, which adequately describes the vertical distribution of wind speed below 100 m (Cook 1997; Thrulier and Lappe 1964; Tielman 2008). In the equation, \( f_\mu(z) \) is the mean wind speed at height \( z \); \( u_* \) is the surface friction velocity, calculated directly from a least squares fitting of the wind profile; \( \kappa \) is the von Kármán constant \((k \approx 0.4)\); \( z_0 \) (0.8–1.5 m) is the surface roughness length; and \( z_o \) (7–15 m) is the zero-plane displacement (Grimmond and Oke 1999; Wiernga 1993). Recent studies have shown that wind profiles of tropical cyclones follow similar logarithmic (or at least near logarithmic) distributions (Alford et al. 2020; Ming et al. 2014; Powell et al. 2003; Zhang et al. 2011).

Because of its simplicity, the power-law distribution has been widely used to assess wind loads on structures (Davenport 1960):

\[
\begin{align*}
    f_\mu(z) &= a(z/z_{\text{ref}})\alpha, \\
    \ln \text{(4b)}
\end{align*}
\]

where \( a \) is the average wind speed at the reference height \( z_{\text{ref}} \) \((z_{\text{ref}} = 10 \text{ m})\) and the ground roughness index \( \alpha \) was determined from least squares fitting of the average wind speed at the four heights. In general, it has been applied to heights ranging from 30 to 300 m (Cook 1997).

The goodness of fit of the mixture model with different components to the measured wind profile was tested by the coefficient of determination \( R^2 \):

\[
R^2 = \frac{SS_{\text{reg}}}{SS_{\text{tot}}} = 1 - \frac{\sum (y_i - f_i)^2}{\sum (y_i - \bar{y})^2}. \tag{5}
\]

Figures 6 and 7 delineate the mean winds before, during, and after maximum wind of \( U \) and \( U_{\text{max}} \), respectively, at the four measurement levels and compare the measurements and the goodness of fit of the two models. The red circles represent the average values of the data, the black vertical line represents the median, and the box-and-whisker plot represents the upper and lower quartiles and outliers, respectively. The coefficient of determination \( R^2 \) is calculated in Table 3 to test the models. The results show that the logarithmic (“1-law”) profile and power-law (“p-law”) model are both generally more consistent with the observed profiles of STs (Figs. 6a–f) than those of SCGs (Figs. 6g–i). Although the performance of the two models is generally similar, the p-law model still performs slightly better. In the events of the current study, the average value of the \( R^2 \) obtained by the p-law model is 0.84, whereas that obtained by the logarithmic-profile model is only 0.82. Actually, the logarithmic-profile model typically works under neutral stability (Powell et al. 2003). It is certainly commonly used in hurricanes as stability profiles typically fit such an assumption. While under strong convection environments, its capability may be worse, for under strong convection environments, the atmospheric stratification tends to be unstable instead of neutral. It can be also found from Table 3 that both models have a worse result in fitting the SCG gusts profiles in P-MHP and L-MHP. The power law has a slightly better performance under both conditions. It also appears that in some cases, both models are inconsistent with the observed wind profile of SCGs, such as in Fig. 6 and Figs. 7g and 7j.

From Figs. 7b, 7e, 7h, and 7k, it can be observed that the variance of STs during the MHP is much smaller than that of SCGs. The presence of turbulent pulsations complicates the variations of wind speed. When the maximum wind speed exceeds the average value to a higher extent, the wind pulsations have a larger amplitude and correspondingly a higher energy, resulting in a higher risk of damage relative to a scenario where only the average wind is considered. The results of the analysis showed that the average value of \( U_{\text{max}} \) for both types of events was much higher than the average value of \( U \) during the MHP; therefore, the risk of damage to the building was higher during this period. Meanwhile, through the average wind speed of SCG is smaller than that of ST, it may also cause more serious disasters because of its strong pulsation fluctuation. As the mean value of \( U_{\text{max}} \) is much larger than the mean value of \( U \) for both types of events, it is evident that damage is not only caused by high winds but also by large pulsation fluctuations during the MHP. These results further suggest that the vertical wind speed structure under convective weather systems may be more complex, and further research is required.

d. Statistical characteristics of raw data and gusts

Owing to the highly heterogeneous nature of the wind direction and the thermodynamic and kinetic evolution, gust characteristics contain various uncertainties. On the one hand, the comparison of statistical methods helps us to better understand the distribution characteristics of different types of gales. Meanwhile, the differences in the statistical methods in characterizing various types of gales provide us with a certain reference basis for distinguishing between various types of gale events. On the other hand, comparison of the performance of existing statistical methods in characterizing the distribution of different types of gales also offers a theoretical foundation for the selection of suitable statistical models for
the analysis of potential effects of various types of gales on buildings. Table 4 demonstrates the statistical information of raw wind speed and gust at the four measured heights by calculating the skewness $S$ and kurtosis $K$:

\[
K = \frac{1}{\left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^4 \right]^2} \quad \text{and} \quad S = \frac{1}{\left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^3 \right]^2}.
\]

The standardized 3rd-order ($S$) and 4th-order ($K$) central moments in Eqs. (6a) and (6b) are used to determine the non-Gaussian distribution of finite and random datasets. Most of the $S$ is positive and decreases gradually with

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**Fig. 6.** Mean wind speed profiles of the raw wind speed and results of the goodness of fit of l-law and p-law models; the numbers are the p-law and l-law exponents, and the observation height was set in logarithmic increments.
increasing height above 40 m. This leads to a right-skewed or right-tailed distribution with a decreasingly strong trend in height. Additionally, the $K$ values of SCG (10 May 2010) are greater than 3.0 below 320 m, suggesting that the distributions ($K > 3.0$) are leptokurtic and thick tailed. Further, Table 3 shows that the $S$ and $K$ values of $U$ are all larger than $U_g$, which implies a more peaked distribution with longer tails.

Considering the homogeneity and extremality of finite sequences, the Gaussian distribution

$$f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left[\frac{-(x - \mu)^2}{2\sigma^2}\right]$$

and the generalized extreme value (GEV) distribution

$$f(x; \mu, \sigma, \gamma) = \frac{1}{\sigma} \exp\left[-\left(1 + \gamma \frac{x - \mu}{\sigma}\right)^{-\frac{1}{\gamma}}\right] \times \left(1 + \gamma \frac{x - \mu}{\sigma}\right)^{-\frac{1}{\gamma}}^{-\frac{1}{\gamma}}, \quad \gamma \neq 0,$$
were used to model the distribution where $\mu$, $\sigma$, and $\gamma$ are the location, scale, and shape parameter, respectively. The parameters in Eqs. (7) and (8) were estimated using the maximum likelihood estimation (McLachlan and Basford 1988). Figure 8 shows the distribution of $U$ and $U_g$ fitted with the GEV distribution at different heights (for simplicity, the results of the Gaussian distribution are not given superfluously).

The discrepancy between the estimated values and the measured data were assessed, with a larger $R^2$ value suggesting a better model. Table 5 presents the results of the $R^2$ values of the Gaussian distributions against the GEV distributions. Overall, the stronger and more extreme the wind, the worse the simulation of $U_g$. Further, the differences in the distribution may exist even in the same type of windy event. Both statistical models perform better in fitting the distribution of $U$ than that of $U_g$ to STs. Meanwhile, almost all results reveal that GEV provides a better model for distribution than Gaussian distributions, especially in SCGs. Even so, GEV distributions are not suitable for all conditions and cannot accurately capture all characteristics of $U_g$ (McLachlan and Basford 1988).

d. Spectrum

In the ABL, eddies can overlap and interact with the basic flow, which can transport kinetic energy between different heights. Studies suggest that the largest eddies contain the most energy and transfer energy to smaller eddies via fluid inertia (Zhang 2010). To understand the cascade process of the turbulent kinetic energy (TKE) of the mean flow in the production range, the energy cascade in the inertial subrange of the turbulence power spectrum was analyzed, thus improving the understanding of the energy transportation process of turbulent flow. In addition, the turbulence power spectrum is a vital parameter for estimating wind-induced fluctuating loads and dynamic responses of high-rise buildings or long-span bridges (Dai et al. 2021). As spectra provide essential information, it is important to clearly understand the general properties of the ST and SCG spectra.

The $-5/3$ law can describe the characteristics of the inertial subrange of the turbulence spectrum based on the local isotropy (Kolmogorov 1941). The following considers the $U$ (alongside) component,

$$E_u(k) = \alpha e^{-2/3} k^{-5/3},$$  \hspace{1cm} (9)

$e$ and $k$ are the TKE dissipation rates and $\alpha \approx 0.5$ (Sreenivasan 1995). The $-5/3$ law was also considered an indicator of good datasets; however, in recent years, an increasing number of studies have found that deviations from the traditional $-5/3$ law in gales, where processes such as typhoons may follow a von Kármán–type spectrum instead (von Kármán 1948). Based on the 10-Hz wind data at the four levels, the power spectra of STs and SCGs were analyzed and compared with Kolmogorov’s hypotheses by computing the estimated spectra of P-MHP, MHP, and L-MHP, each with 36,000 samples.

Figure 9 compares the turbulence spectra of STs and SCGs at the gale time at the four levels, respectively. To protect the low-frequency information in the results from interference and to facilitate the observation and comparison of the results, we only smoothed the data corresponding to the points on the $x$ axis, excluding the first 21 points. (Larsén et al. 2018).

### Table 3. The $l$-law and $p$-law results vs the observed profile $R^2$.

<table>
<thead>
<tr>
<th>Test</th>
<th>Date</th>
<th>$U$</th>
<th>$U_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-MHP</td>
<td>MHP</td>
<td>L-MHP</td>
<td>P-MHP</td>
</tr>
<tr>
<td>1-law</td>
<td>23 Aug 2017</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>p-law</td>
<td>0.98</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>1-law</td>
<td>16 Sep 2018</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>p-law</td>
<td>0.99</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>1-law</td>
<td>3 Mar 2019</td>
<td>0.70</td>
<td>0.77</td>
</tr>
<tr>
<td>p-law</td>
<td>0.77</td>
<td>0.74</td>
<td>0.95</td>
</tr>
<tr>
<td>1-law</td>
<td>10 May 2020</td>
<td>0.09</td>
<td>0.83</td>
</tr>
<tr>
<td>p-law</td>
<td>0.09</td>
<td>0.87</td>
<td>0.89</td>
</tr>
</tbody>
</table>

### Table 4. Statistical characteristics of wind and gusts at different heights.

<table>
<thead>
<tr>
<th>Test</th>
<th>10 m</th>
<th>40 m</th>
<th>160 m</th>
<th>320 m</th>
<th>Date</th>
<th>10 m</th>
<th>40 m</th>
<th>160 m</th>
<th>320 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0.29</td>
<td>0.58</td>
<td>0.33</td>
<td>0.10</td>
<td>23 Aug 2017</td>
<td>-0.12</td>
<td>0.29</td>
<td>0.18</td>
<td>0.06</td>
</tr>
<tr>
<td>K</td>
<td>3.30</td>
<td>3.20</td>
<td>2.82</td>
<td>2.79</td>
<td></td>
<td>2.81</td>
<td>2.66</td>
<td>2.59</td>
<td>2.26</td>
</tr>
<tr>
<td>S</td>
<td>0.57</td>
<td>0.43</td>
<td>0.13</td>
<td>-0.09</td>
<td>16 Sep 2018</td>
<td>0.15</td>
<td>0.14</td>
<td>0.01</td>
<td>-0.08</td>
</tr>
<tr>
<td>K</td>
<td>3.13</td>
<td>2.51</td>
<td>2.08</td>
<td>2.09</td>
<td></td>
<td>2.22</td>
<td>1.68</td>
<td>1.64</td>
<td>1.68</td>
</tr>
<tr>
<td>S</td>
<td>0.94</td>
<td>0.96</td>
<td>0.74</td>
<td>1.23</td>
<td>3 Mar 2019</td>
<td>0.69</td>
<td>0.82</td>
<td>0.67</td>
<td>1.19</td>
</tr>
<tr>
<td>K</td>
<td>2.62</td>
<td>2.51</td>
<td>1.82</td>
<td>2.78</td>
<td></td>
<td>2.89</td>
<td>2.13</td>
<td>1.65</td>
<td>2.62</td>
</tr>
<tr>
<td>S</td>
<td>1.97</td>
<td>1.88</td>
<td>1.77</td>
<td>0.84</td>
<td>10 May 2020</td>
<td>1.55</td>
<td>1.65</td>
<td>1.64</td>
<td>0.75</td>
</tr>
<tr>
<td>K</td>
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<td>4.86</td>
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<td></td>
<td>3.98</td>
<td>4.32</td>
<td>4.17</td>
<td>1.83</td>
</tr>
</tbody>
</table>
All spectra possess microscale turbulent fluctuation behavior. For $f > 1$ Hz, all spectra show positive deviation from Kolmogorov’s law, which may imply that the presence of more energy in smaller eddies, a special feature for gales, or high-frequency noise, and needs to be verified further (Tao and Wang 2019). The spectra observed at 10 m were in general agreement with the $-5/3$ energy cascade law. They performed better at SCG and showed deviations at higher altitudes with a calculated p-law exponent of around $-1.2$ (obtained by least squares fitting). This may be related to the increased wind speed with height. Considering these differences, spectral models require updating (He et al. 2022; Yim and Chou 2001). In addition, in terms of energy in different time periods, the fluctuation of energy during ST gales is smaller than that of SCG gales at all the four levels, while the wind spectra are coincident at high levels during different periods. This may be connected to the slow variation of the wind speed. For SCGs, the energy in MHP is much higher than that in the other two periods, which may be related to the short lifetime of the gales. It can also be seen in all four events that after the gales, a lower height corresponds to a larger reduction in energy, which may be due to the higher near-surface roughness. Owing to the lack of continuous energy replenishment, this change is more pronounced in SCGs events. It is also necessary to mention that, to ensure the validity of the original data, excessive consecutively missing measurements and random unstable pulsations are shown as null and left without correction in the data quality-control process. The sequences with nulls were not involved in the calculation, which led to missing graphs in Figs. 9a, 9k, and 9o (specific missing measurements can be found in Fig. 4).

In general, large-scale turbulent vortices obtain energy from the mean motion and transfer it to small-scale turbulent vortices by stepwise transfer. Rolling vortices are often observed in the boundary layer as a potential means of energy transfer (Morrison et al. 2005), capable of transferring high-momentum fluxes downward (Foster 2005). Flux refers to the

<table>
<thead>
<tr>
<th>Test</th>
<th>$U_{10m}$</th>
<th>$U_{40m}$</th>
<th>$U_{160m}$</th>
<th>$U_{320m}$</th>
<th>Date</th>
<th>$U_{10m}$</th>
<th>$U_{40m}$</th>
<th>$U_{160m}$</th>
<th>$U_{320m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized</td>
<td>0.95</td>
<td>0.87</td>
<td>0.94</td>
<td>0.97</td>
<td>23 Aug 2017</td>
<td>0.84</td>
<td>0.58</td>
<td>0.69</td>
<td>0.70</td>
</tr>
<tr>
<td>GEV</td>
<td>0.98</td>
<td>0.95</td>
<td>0.97</td>
<td>0.98</td>
<td></td>
<td>0.82</td>
<td>0.60</td>
<td>0.73</td>
<td>0.71</td>
</tr>
<tr>
<td>Normalized</td>
<td>0.88</td>
<td>0.73</td>
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<td>0.75</td>
<td>16 Sep 2018</td>
<td>0.61</td>
<td>0.05</td>
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<td>0.96</td>
<td>0.48</td>
<td>0.71</td>
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<td>0.61</td>
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<tr>
<td>Normalized</td>
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<td>0.07</td>
<td>0.003</td>
<td>0.02</td>
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<tr>
<td>GEV</td>
<td>0.54</td>
<td>0.66</td>
<td>0.55</td>
<td>0.71</td>
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<td>0.59</td>
<td>0.64</td>
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</tr>
<tr>
<td>Normalized</td>
<td>0.21</td>
<td>0.23</td>
<td>0.20</td>
<td>0.06</td>
<td>10 May 2020</td>
<td>0.08</td>
<td>0.11</td>
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<td>0.01</td>
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<tr>
<td>GEV</td>
<td>0.81</td>
<td>0.87</td>
<td>0.84</td>
<td>0.68</td>
<td></td>
<td>0.58</td>
<td>0.52</td>
<td>0.57</td>
<td>0.51</td>
</tr>
</tbody>
</table>
amount of material transported across a unit area per unit time. As such, the turbulent flux is the covariance of the atmospheric parameter; therefore, the momentum flux of transport can be expressed as

\[ \tau_i = -\rho_a \langle s'w' \rangle, \quad (10) \]

where \( \rho_a \) is the air density and \( s \) can be taken as \( u \), temperature \( t \), humidity, and so on.

Here, we mainly consider the momentum transport per minute. As shown in Fig. 10, during an ST, downward transfer of momentum exists at almost every level, with more transfer at upper levels than at lower levels. Contrastingly, during an
SCG, downward transfer of momentum exists only during strong convective periods with much less intensity than in STs. This phenomenon is likely caused by the lifetime of an ST being longer than that of an SCG, which makes continuous energy transfer possible during STs. In general, the larger the amplitude of the wind fluctuations, the larger the impact will be, so it is especially important to consider the extreme pulsation of the wind, where extreme pulsation is defined as the $U_{\text{max}} - U_{\text{min}}$ in one minute. Across the duration of the 3-h period at 320 m, it was the pulsation rather than the average wind speed that was more significantly associated with the downward transfer of turbulent momentum flux, whose correlation coefficient passed the 95% significance test. The above results show that a more turbulent downward energy may be related to the extreme pulsation of the gusts rather than to the large-scale base flow during the gale time.

After a typhoon makes landfall, the increase in horizontal drag may reduce near-surface wind speeds as the near-surface topography changes from smooth to rough. Morrison and Zhang pointed out that the boundary layer roll vortices, which are often observed in the typhoon boundary layer (Morrison et al. 2005; Zhang et al. 2008) could transport high momentum downward from the upper boundary layer of a typhoon (or low momentum upward from lower altitudes; Foster 2005; X. Li et al. 2021). According to the results of this study, we also observed a downward transfer of momentum. It was speculated that this downward transfer of the high-level momentum flux had two major effects on the horizontal wind speeds. It maintained the high wind speeds at lower levels, while potentially enhancing horizontal wind shear at lower levels, thus, making turbulent motion more intense and potentially increasing the risk of damage to near-surface buildings. However, changes in horizontal flux may be the result of coupling of multiple factors, which may be subjected to the influence of not only downward and upward fluxes but also horizontal roughness. This study primarily aimed to identify the key factors influencing the downward transmission of momentum during strong winds. The effect of the downward transmission of momentum on the horizontal flux will be further investigated and discussed in future work.

4. Conclusions

Based on records from the SZMGT, this paper presents an observational study of raw wind and gust structures of two STs (Mangkhut and Hato) and two SCG events over land. The gales from each event were compared to contribute to the understanding of typhoons and convective wind structures, facilitate the wind-resistant design of high-rise constructions in gale-prone regions, and provide references for the simulations and forecasts of typhoons and convection. The main conclusions are as follows:

1) The evolution of the gale speed in each event is quite different from each other; the wind speed gradually increases with height at the four height levels for ST, but an intense growth of wind speed was witnessed in SCGs, especially at higher levels (320 m).

2) Vertical profiles of different types of gales were inspected, with most of the results showing that both types of gale profiles can adequately be described using the power law and logarithmic distributions during MHP. The fitting results of STs are significantly better than those of SCGs.

3) The statistical characteristics of each gale event were analyzed. Calculations of skewness, kurtosis, and the $R^2$ indicate that the Gaussian distribution is only suitable for typhoon simulations. Although the GEV distribution also has some shortcomings in characterizing SCGs, it is better than the Gaussian distribution for both types of wind simulations.

4) The wind spectra density at 10 and 40 m close to the $-5/3$ law was observed between the inertial subrange, and a higher spectral law around $-1.2$ was observed at higher levels. In addition, during STs, the wind spectra of each high-level measurement at different periods generally coincided with each other; however, a higher spectral density was only observed during the strongest wind period for SCGs.

5) Based on the calculation of turbulent momentum fluxes, the results show that most of the downward transfer of momentum exists during periods of gales, where a higher gust pulsation transfer may correspond to a higher turbulent pulsation transfer. In most cases, SCGs can only exhibit turbulent downward momentum transfer during brief gale periods. It is noteworthy that both have a high downward transfer of turbulent momentum flux at a height of 320 m, and this downward transfer of energy is dependent more on the pulsation of the gusts than the large-scale base flow.

These conclusions should help to enhance the knowledge of STs and SCGs, allowing for better discrimination between different types of gales over land. Further, these outcomes should help the design of high-rise constructions, facilitate the assessment of aviation safety, and improve simulation results.

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Data availability statement. The data that support the finding of this study are available from the corresponding author upon reasonable request. The data are not publicly available because of privacy or ethical restrictions.

REFERENCES


