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Unified Non-stationary Mathematical Model for Near-ground Surface Strong Winds

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ABSTRACT

This paper attempts to establish a unified non-stationary wind speed model to represent near-ground surface strong winds, such as strong monsoon, typhoon, tornado and downburst, as a summation of a time-varying mean wind speed and an amplitude-modulated stationary random process. The suggested model is adopted to analyze various types of field-measured wind records including downburst (Andrew downburst and Shangqiu downburst), tornado (Fujita tornado), typhoon and monsoon winds. The feasibility and applicability of the suggested model is demonstrated by checking the skewness and kurtosis of the resulting fluctuating component. Cases studies show that the proposed model was capable of describing different kinds of strong winds.

1. INTRODUCTION

Almost all atmospheric motions are non-stationary or inhomogeneous to some degree (Mahrt, 1998). However in current practice the boundary layer wind speed time history is generally assumed to be a stationary process consisting of a constant mean and a fluctuating wind speed component. This model is generally referred as stationary wind speed model (SWSM). The SWSM, however, has been proved by many field measurements to be not tenable for strong winds such as typhoon, downburst and tornado etc. (Schroeder 1998; Xu 2004; Kwon 2009). Therefore, different models for characterizing the non-stationarity of strong winds have been proposed by researchers in the past decades. In 1990's, Schroeder *et al.* (1998) suggested to model the wind speed process by an Auto Regressive model (AR model). Gurley and Kareem (1999) adopted the Wavelet transform (WT) to explore the instance energy varying characteristics of hurricane. Chen and Xu (2004) proposed a non-stationary wind speed

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model to represent the typhoon record as a summation of a time-varying mean wind speed (TVM) and a stationary fluctuating wind speed component. Chen and Letechford (2004) have proposed a nonparametric deterministic-stochastic hybrid model (NDESH), in which the wind speed of a downburst at any height is assumed to be the summations of a moving average mean wind speed and a non-stationary fluctuating wind speed process.

All the above mentioned models are proposed to treat certain types of wind data, e.g. typhoon, monsoon, downburst. To the author's experience, in field measurements especially on-line long-term wind property measurement system, it is not an easy task to classify the wind type and extract the required data from a continuous measurement records. Therefore, a unified non-stationary wind speed model for near-ground strong winds is desired and will benefit wind data process. In this connection, this paper attempts to build such a unified model based on the previous work.

2. UNIFIED WIND SPEED MODEL

Inspired by all the above mentioned wind models, we suggest the following mathematical model to represent the near ground strong wind (downburst, typhoon, monsoon) as a summation of a time-varying mean wind speed and a amplitude-modulated stationary random process, that is

$$U(z,t) = \overline{U}(z,t) + u(z,t) \tag{1}$$

$$u(z,t) = f(z,t)\tilde{u}(z,t) \tag{2}$$

where $\bar{U}(z,t)$ is the time–varying mean wind speed, $u(z,t)$ is the fluctuating wind speed, $f(z,t)$ is a deterministic envelope function and $\tilde{u}(z,t)$ represents the normalized fluctuating component, and it is assumed to be a stationary stochastic process. The suggest model is actually a combination of so-called 'time-varying mean model' and 'time-varying standard deviation model' for treating non-stationary random process (Bandat and Persol 1986).

Note that in the proposed model deterministic function $\bar{U}(z,t)$ reflects the slow-varying characteristics of wind speed, and $\tilde{u}(z,t)$ shows the stochastic disturbance of the fluctuating wind in small scale. The new model has the same form as the traditional wind speed model, which is

$$U(z,t) = \overline{U}(z) + u(z,t) \tag{3}$$

Where $U(z)$ is the constant mean wind speed and $u(z,t)$ is the fluctuating wind speed which is assumed to be a stationary random process.

To determine the time-varying mean wind speed $\bar{U}(z,t)$ in Eq.(1), some researches have been carried out. Xu and Chen (2004) recommend to use the empirical mode decomposition (EMD) method to caculate the mean wind speed, which is typically the temporal trend of a signal. Holmes proposed an empirical downburst model with physical meaning to simulate the mean wind speed of downburst (Holmes and Oliver 2000). For field measured downburst, Chen and Letechford (2004) suggested to obtain the time-varying mean by moving average.

As for the envelope function, Chen and Letechford (2004) suggests that $f(z,t) = 0.25\bar{U}(z,t)$, and $u(z,t)$ is a stationary Gaussian stochastic process with standard deviation of unit. The calculation of the fluctuating wind speed and the envelope function are based on a determined time-varying mean wind speed. The time-varying mean at a designated frequency level is closely related to the traditional time-averaged mean wind speed over the corresponding time interval. In other word, the averaging period (frequency level) used for non-stationary wind sample is crucial for the definition of time-varying mean wind speed. Obviously, a small averaging period is desired for analysis of downburst or other non-stationary events in order to reveal the non-turbulent component and/or the local turbulence intensity

Applicability of the proposed unified model is verified by applying to field measurements of several different types of winds. The time-varying mean wind speed is extracted from the field records by EMD (Wu and Chen 2009), and the envelope function is determined by try-and-error process .

3. CASE STUDIES

Three types of strong winds have been adopted in this section to verify the proposed unified wind model. They are downburst, tornado and typhoon.

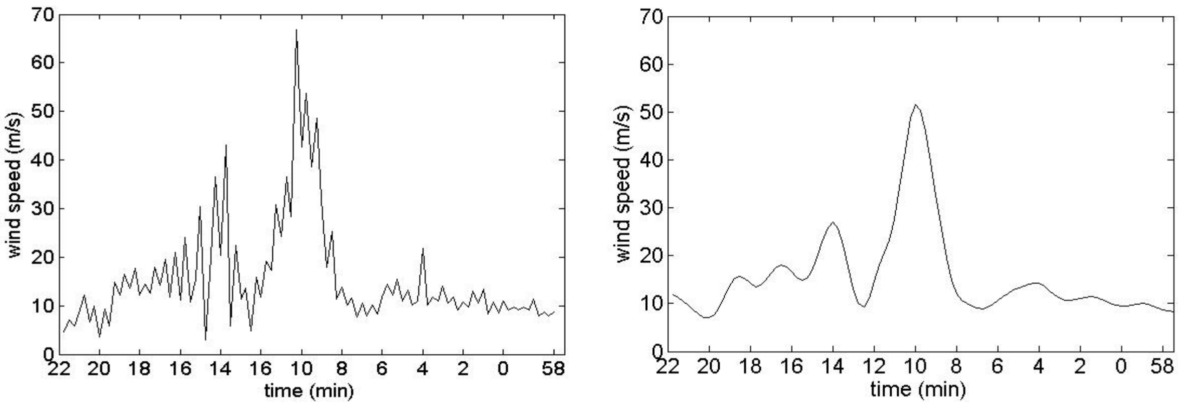
3.1. Downburst

Fig 1a shows a field measured downburst time history (Fujita, 1985). Fig.1b is the mean wind speed obtained by EMD. The fluctuating wind speed $u(z,t)$ and the amplitude envelope function is presented in Fig.1c. Fig.1d shows the stochastic process derived from the fluctuating wind speed $u(z,t)$ divided by the amplitude envelope function. Obviously, the mean wind speed of downburst is not a constant and the amplitude of the fluctuating wind speed is also non-stationary.

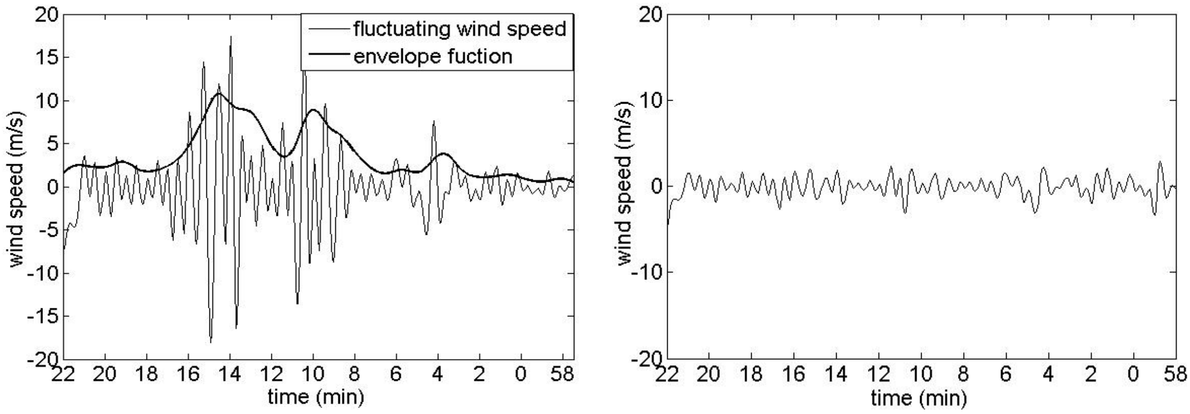
The numerical characteristics of downburst wind speed data in every stage are listed in Table 1. The first row to the fourth row are values of, respectively, the original wind speed, the flunctuating wind speed obtained by SWSM (a constant mean is subtracted), the flunctuating wind speed obtained by NWSM, the normalized fluctuating wind speed. It is seen that the kurtosis value of the fluctuating component reduces from 7.22 to 3.15, which is close to 3.0. All the analysis results indicate that the normalized fluctuating component $\tilde{u}(z,t)$ can be reasonably assumed as a Gaussian random process.

Table 1 Comparison of numerical characteristics of downburst

Stage	Mean(m/s)	Standard Deviation(m/s)	Skewness	Kurtosis
Field measured wind speed $U(z,t)$	11.05	0.64	2.25	8.58
Fluctuating wind speed $\bar{u}(z,t)$	0.00	3.03	2.12	7.40
Fluctuating wind speed $u(z,t)$	-0.09	4.37	4.37	7.22
Normalized fluctuating component $\tilde{u}(z,t)$	-0.03	1.08	0	3.15



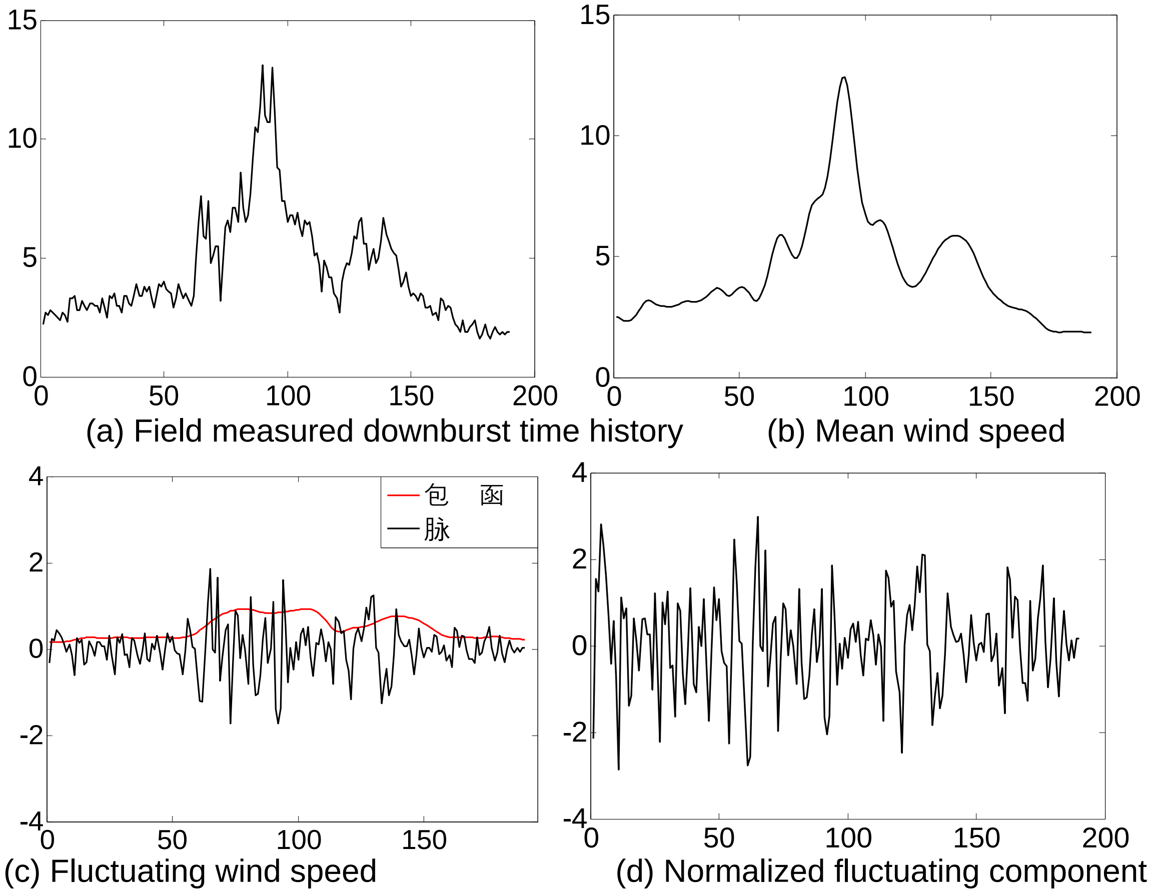
(a) Field measured downburst time history (b) Mean wind speed



(c) Fluctuating wind speed (d) Normalized fluctuating component

Fig. 1 Application of proposed wind model to Andrew downburst

The model is also applied to another downburst record which is called Shangqiu downburst. All the analysis results all demonstrated in Fig. 2. Using the new model, the Kurtosis of the turbulence component reduces from the original 4.90 to 3.19, which is much closer to 3.0 of a standard Gaussian process.



(a) Field measured downburst time history　(b) Mean wind speed

(c) Fluctuating wind speed　(d) Normalized fluctuating component

Fig. 2　Application of proposed wind model to Shangqiu downburst

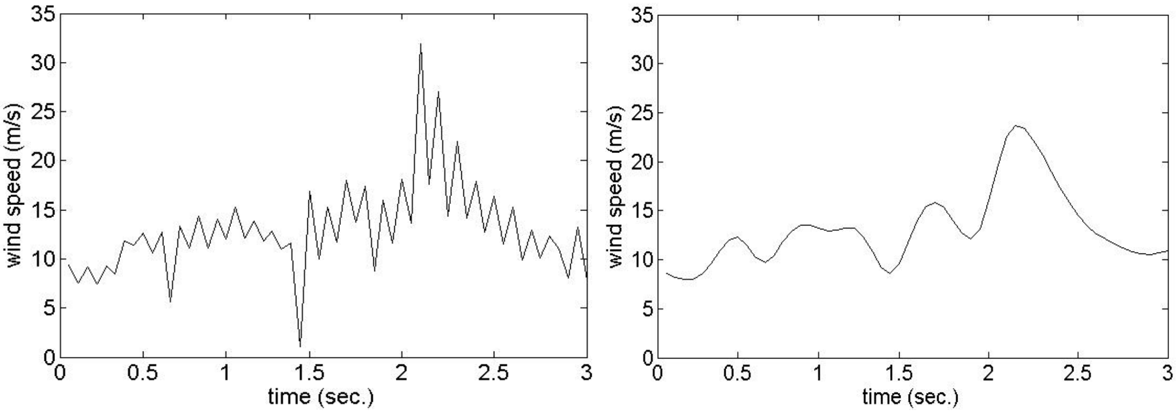
3.2 Tornado

Fig. 3a shows a field measured tornado time history (Fujita 1973; Dutta 2002). Fig. 3b is the time-varying mean wind speed obtained by EMD. Fluctuating wind speed $u(z,t)$ and the amplitude envelope function is presented in Fig.3c and Fig. 3d shows the stochastic process derived from the fluctuating wind speed divided by the amplitude envelope function.

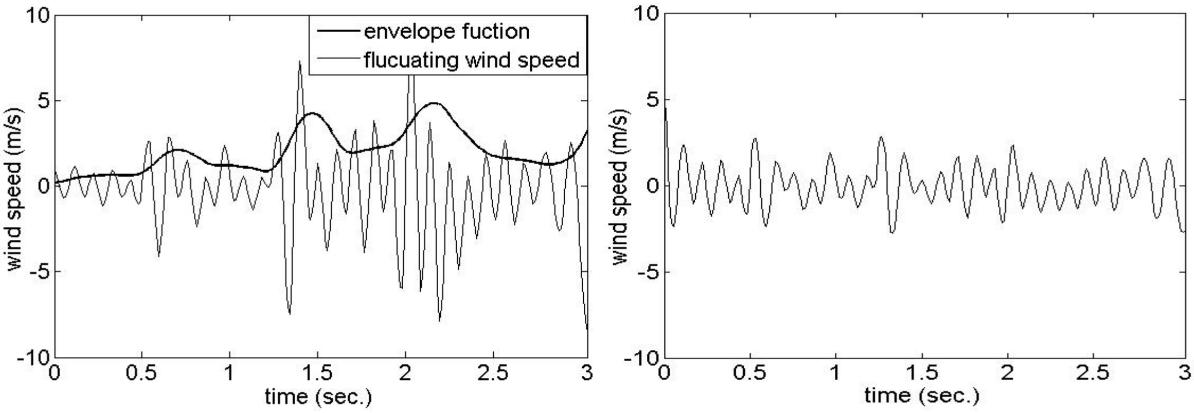
The numerical characteristics of tornado wind speed data in every stage are listed in Table 2. Divided by the envelope function, the kurtosis value of the fluctuating component reduces from 5.23 to 3.20.

Table 2 Comparison of numerical characteristics of tornado

Stage	Mean(m/s)	Standard Deviation(m/s)	Skewness	Kurtosis
Field measured wind speed $U(z,t)$	12.98	4.75	1.34	7.34
Fluctuating wind speed $\bar{u}(z,t)$	0.00	4.34	1.09	6.51
Fluctuating wind speed $u(z,t)$	-0.92	9.00	-0.21	5.23
Normalized fluct. component $\tilde{u}(z,t)$	-0.05	1.19	0.21	3.20



(a) Field measured tornado time history (b) Mean wind speed



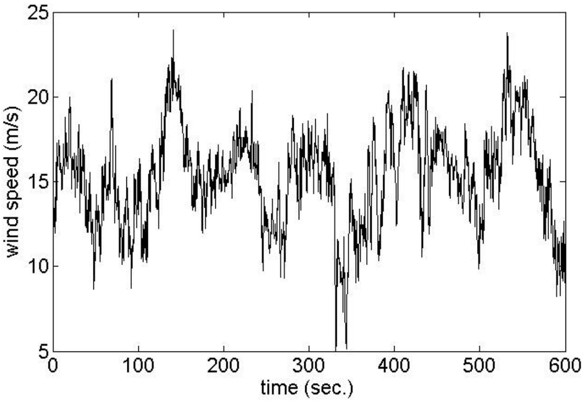
(c) Fluctuating wind speed (d) Normalized fluctuating component

Fig. 3 Application of proposed wind model to tornado

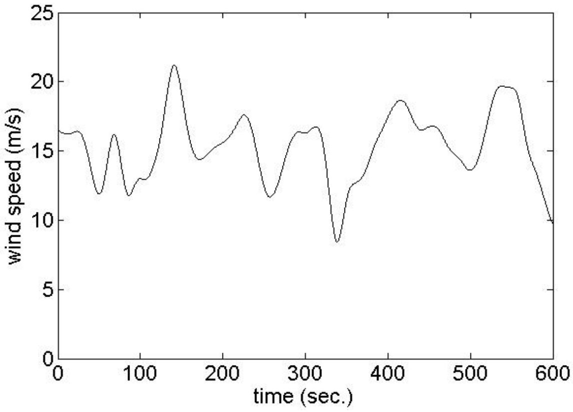
3.2 Typhoon

The data are collected in a typhoon-prone region using an ultrasonic anemometer installed on a 50m high mast. Details of the data can be found in Chen *et al.* (2007). Fig 4a shows a field measured typhoon time history and Fig. 4b is the time-varying mean wind speed which was determined by EMD. Fluctuating wind speed $u(z,t)$ and the amplitude envelope function is presented in Fig 4c, and Fig 4d shows the stochastic process derived from the fluctuating wind speed $u(z,t)$ divided by the amplitude envelope function.

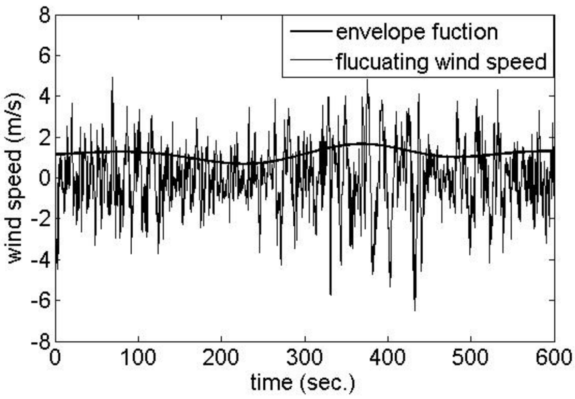
The numerical characteristics of typhoon wind speed data in every stage are listed in Table 3. Divided by the envelope function, the kurtosis value of the fluctuating component reduces from the original 3.65 to 3.38. The change of the kurtosis value is not that significant compared with the change of the downburst and tornado. For more typhoon data, Fig 5 shows the kurtosis values of the fluctuating wind speed before and after it divided by the amplitude envelope function. Divided by the amplitude envelope function, the kurtosis value of the fluctuating wind speed is closer to that of the stationary Gauss stochastic process.



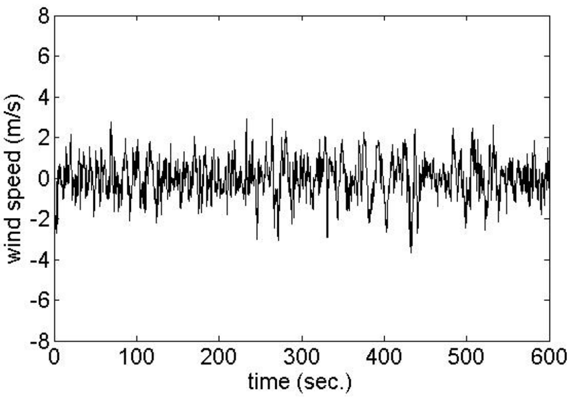
(a) Field measured typhoon time history



(b) Mean wind speed



(c) Fluctuating wind speed



(d) Normalized fluctuating component

Fig. 4 Application of proposed wind model to typhoon

Table 3 Comparison of numerical characteristics of typhoon

Stage	Mean(m/s)	Standard Deviation(m/s)	Skewness	Kurtosis
Field measured wind speed $U(z,t)$	12.77	3.63	0.51	2.79
Fluctuating wind speed $\bar{u}(z,t)$	0.00	2.93	-0.14	3.04
Fluctuating wind speed $u(z,t)$	0.00	1.62	-0.22	3.65
Normalized fluctuating component $\tilde{u}(z,t)$	0.00	0.95	-0.19	3.38

4. CONCLUDING REMARKS

A unified non-stationary wind speed model is suggested in this paper to represent non-stationary near-ground strong wind as summation of a time-varying mean wind speed and an amplitude-modulated stationary random process following Gaussian distribution.

The model is characterized by a distinctive feature that it is adaptive to various types of strong winds including strong monsoon, typhoon, downburst and tornado. The results indicate that the proposed model is applicable to represent different types of near-ground strong winds

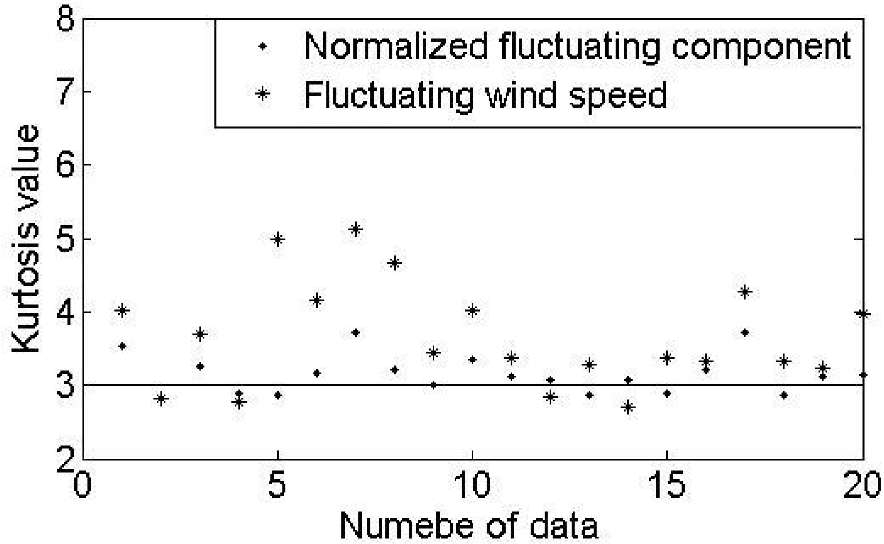


Fig. 5 Comparison of kurtosis value of typhoon

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