

Wind profiles from a Sodar system under hilly terrain

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ABSTRACT: This paper focuses on an investigation of hilly effects on vertical distributions of both mean wind speed and turbulence components within the surface layer. Profiles of wind speed and turbulence intensity under conditions with both upwind hills and downwind hills are presented and discussed. Phenomena of forced convection due to hill obstructions are observed and discussed through comparison with the log law models which correspond to the case with open flat terrain. Relationships between the vertical wind speed and longitudinal wind speed are highlighted. A stability parameter is introduced to help depict wind speed profiles using the log-linear model. Specific estimating operators for a number of key parameters involved in the log-linear model are proposed.

KEYWORDS: hill, wind profile, forced convection, wind speed, turbulence intensity, Sodar.

1 INTRODUCTION

Hilly terrain may bring in different wind characteristics from those under open flat terrain conditions. For example, speed-up effect near mountain crest has been recognized long time ago, and has been stipulated in wind load code of several countries and regions ^[1-4]. It has been reported that geometry and coverage (or roughness) of hills, as well as spatial distances away from hill crests have significant effects on the distributions of both mean wind speed and fluctuation components ^[5,6]. According to reference [7], studies on wind characteristics under hilly conditions began from the 1930s with simply phenomenological observations. Theoretical analysis of non-viscous flows over hills came out in the 1950s, and developed into a more matured research topic since the 1970s ^[8]. As the fast development of CFD techniques and wind tunnel tests in recent years, more specific studies on air motions under complicated hilly terrains have been conducted by numerical and wind tunnel investigations ^[9-11]. More detailed reviews on this topic are summarized by References [7, 12].

Hong Kong is sited on the southeast coastal line of mainland China, and is featured by complicated hilly/mountainous terrains. It is one of the most typhoon-prone areas in the world. The potential danger for aircrafts and dense distributions of high-rise buildings against strong winds makes it of great importance to clarify the hilly effects on near surface boundary layer wind characteristics. Up to now, Hong Kong Observatory (HKO) has established about 50 surface weather stations which are equipped with traditional meteorological instruments and 6 stations with remote sensing devices to serve for weather forecast for both daily life and civil aviation of Hong Kong International Airport (HKIA). Most of these stations are located among hills or mountains terrains and have been put into use for decades or years. This paper focuses on an investigation of wind profiles based on the wind data recorded from a Sodar profiler system during windstorms at a weather station around HKIA.

2 WEATHER STATION AND DATA QUALITY CONTROL

2.1 Local terrain of the weather station

Sui Ho Wan (SHW) meteorological station is located at the foot of hills on the northeast coast of Lantau Island, and is in front of the runway of HKIA. Except for the north-west azimuth range where there is a stretch of open water, this station is basically surrounded by hills or mountains whose body heights extend from ~100m (east) to several hundred meters, as shown in Figure 1.

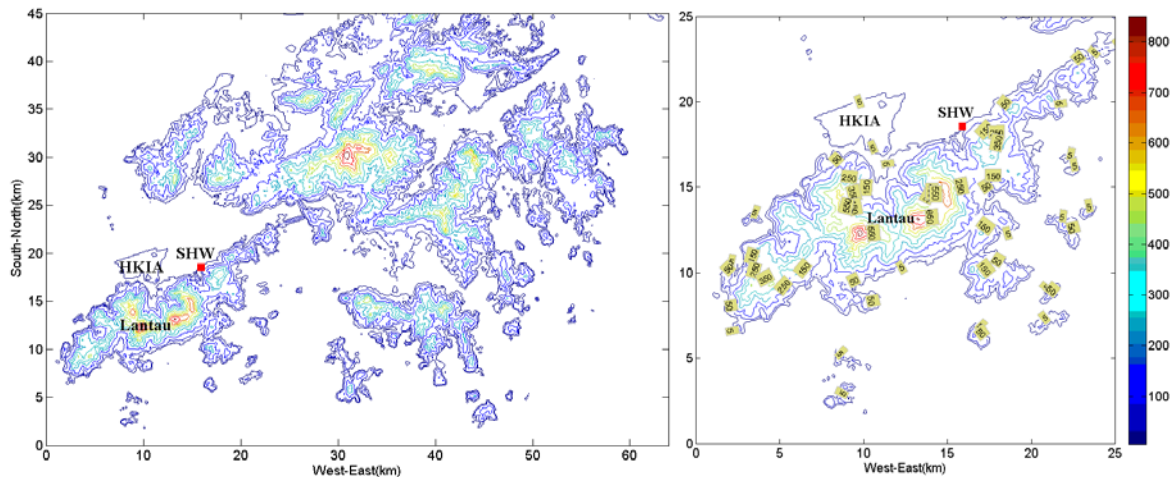


Figure 1. Location of the SHW meteorological station and surrounding terrain conditions.

2.2 Data quality control

SHW has been equipped with a Sodar profiler system by HKO for years. The profiler system can provide 5min-to-5min updated non-overlapping average wind profile records. The detecting range extends from 5m to 100m above the local ground (4.7m above the mean sea level) with a height resolution of 5m. But due to nearby obstructions, records below 25m (i.e., levels at 5, 10, 15, and 20m) are found to be contaminated severely by surrounding clutter interferences, and are discarded in this study. Consequently, there are totally 16 height levels where the recorded data are considered herein. For each of these levels, the recorded wind information includes the mean horizontal wind speeds and directions in a pair of orthogonal directions, a couple of standard deviation values of the corresponding horizontal wind speeds within the average duration, the vertical wind speed and corresponding standard deviation value, as well as the index numbers of signal-to-noise-ratio (SNR) in these 3 directions for data quality control. In this study, records with SNR index number no smaller than 8 are regarded as credible, and a profile with at least 13 credible records (totally 16) is regarded as acceptable. All the following analysis is based on the acceptable profiles during strong windstorms including tropical cyclones and severe monsoons from 2008 to 2010 (http://www.weather.gov.hk/cis/warndb_e.htm).

It is noteworthy that the Sodar profiler system may lose efficiency in case of heavy rains. Data collected under these conditions may be unaccepted through the quality control process. However, since strong winds are usually accompanied with heavy rains, a considerable amount of dataset recorded during high wind speeds is probably excluded. Another point to be noted is that the Sodar system can only detect components of wind velocity vector along the vertical direction (w), and a couple of horizontal directions (x , y) which are orthogonally distributed with each other and have been fixed during the installation of the Sodar system. The longitudinal mean wind speed U and the effective standard deviation σ_u , as well as the effective turbulence intensity (the effective value is adopted to distinguish it from the traditional form) are calculated:

$$U = \sqrt{U_x^2 + U_y^2}; \sigma_U = \sqrt{\sigma_x^2 + \sigma_y^2}; TI_i = \sigma_i / U, i = U, W. \quad (1)$$

3 RESULTS OF THE MEASUREMENTS

3.1 Reference wind speed and direction

Under thermally neutral stratification conditions, wind characteristics are generally dominated by wind strength and upwind terrain setups. Thus, it is necessary to categorize the records into different groups according to the reference wind speed and direction. We use the mean boundary layer (MBL) values which are defined as the arithmetic average wind speed V and the vector average direction θ of all height level records within 25-100m. Wind direction is defined as positive along clockwise from north, which is in consistence with the meteorological convention.

In consideration of both the local upwind terrains and the amount of selected datasets, the upwind azimuth of the weather station is uniformly divided into 6 sections sequentially from the north (or 0°) along clockwise, which are denoted as θ_i ($i=1, 2, 3, 4, 5, 6$). This study only considers θ_2 ($60-120^\circ$) and θ_6 ($300-360^\circ$) sections which correspond to the upwind hilly terrain and downwind hilly terrain, respectively. The reference wind speeds are divided into groups starting from 0 with an incremental step of 3m/s, which are denoted as V_i ($i=1, 2, 3 \dots$).

3.2 Results with upwind hills

Wind flows from the θ_2 azimuth section blow through the hilly obstruction before arriving to the SHW station. Figure 2 shows the profiles of the normalized longitudinal wind speed (U_{Norm}), the effective turbulence intensity (TI) and the vertical wind speed (W). It is found that both the longitudinal and vertical mean wind speed profiles demonstrate evidently different features from those under open flat terrain conditions. The ensemble mean longitudinal speed deviates gradually from the log-law predictions with height. The ensemble mean vertical wind speed increases in absolute value with height consistently, while the negative values of the vertical wind speed denote downward direction. On the other hand, the profiles of the horizontal TI show an exponentially decreasing trend with height.

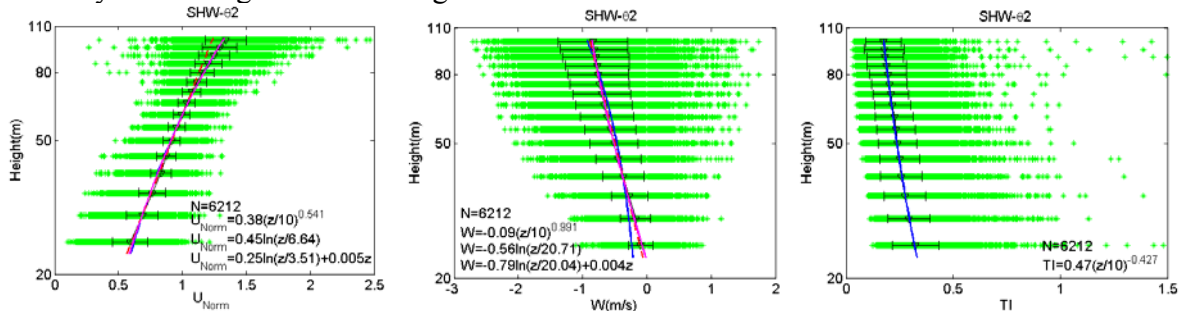


Figure 2. Profiles of normalized longitudinal speed (left), vertical speed (middle) and effective horizontal turbulence intensity (right), fitted by the power law (green line), log law (red dash line), and log-linear law (magenta line), with upwind hills (datasets with $V > 5\text{m/s}$).

The log-law is generally used to model the vertical distributions of mean wind speed in the surface layer. Here and throughout this paper, a form of the log-law with no zero-displacement term is adopted due to the reasons: (1) by comparison, an introduction of a zero-displacement parameter is not very helpful to improve final fitting results; (2) according to ESDU-82026^[13], zero-displacement for rugged hilly terrain (roughness length scale is 3-5m) is about $d=12z_0$, or 36-60m. This value is too large compared to the detecting range of 25-100m in this study.

Figure 3 shows the results in consideration of the wind strength effect. Profiles of the longitudinal mean wind speed follow both the power law and log-law quite well below certain heights. Beyond these heights, wind speed begins to speed up and sways to the right side of the log-law predictions. But, the power-law is still able to provide acceptable estimations. It is observed that the height where the log-law begins to depart from the ensemble measurement profiles decreases with wind strength. This is quite similar to the case of vertical speed profiles. The profiles of σ_U and σ_W have the same tendency with each other. The values basically increase with the reference speed. But, as wind speed strengthens, the profiles ascend monotonously along height first, then level off, and finally decrease vertically. The effective TI basically decreases with the increase of both the reference wind speed and height. But, in case of weak winds, thermal effect may dominate air motion, and TI shows much more fluctuations with distinctly large values.

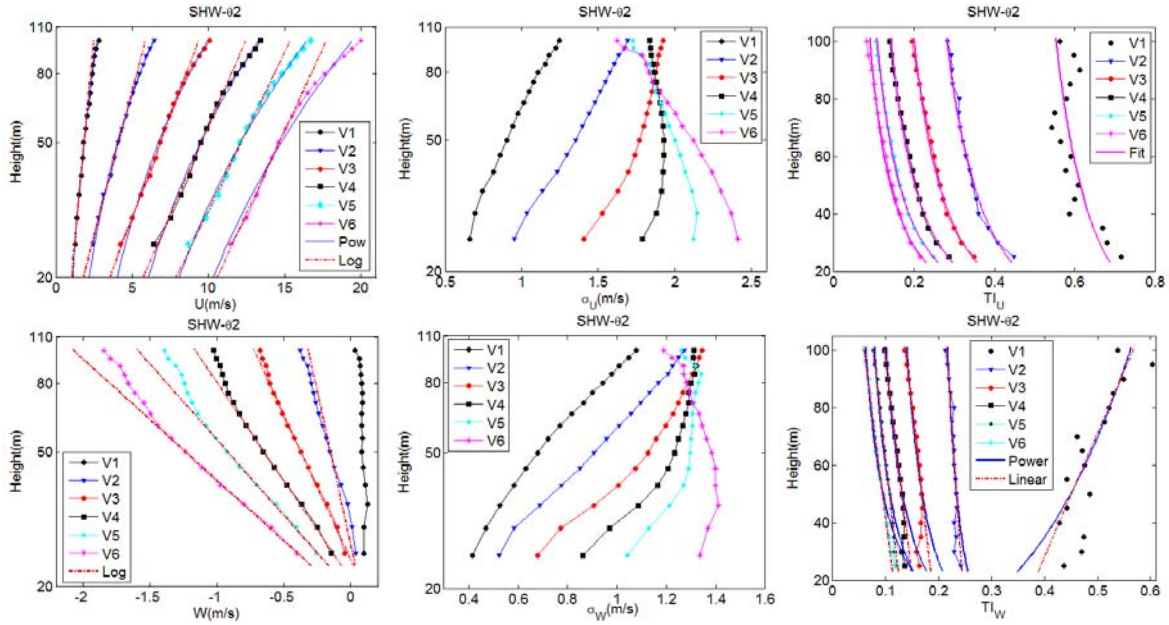


Figure 3. Profiles of ensemble mean wind speed (left) fitted by the log law and/or the power law, effective standard deviation of wind speed (middle), and effective turbulence intensity (right) fitted by the power law and/or the linear law in the 06 azimuth section with upwind hills (Except for the case of TI_W fitted by 5th-16th height levels, all other fitting lines are based on the lowest 8 levels within the range of 25-60m); the y-axis with range of 20-110m is in a log format, while the one with a range of 20-100 is in the linear format, hereafter.

It is evident that there are correlations between the longitudinal wind speed and vertical wind speed components. Air flows overcoming the upwind hill obstructions go downwards as they move ahead. This forced downward convection process accompanies with energy transmission from the upper upwind flows to the beneath atmosphere. The larger the downward speed is, the stronger the longitudinal wind speed becomes. But more energy is expected to join air flows at the upper part of the beneath atmosphere during this superincumbent process, which leads to the deviation of the observed profiles from the log-law predictions. Similarly, more turbulent downward flows also correspond to more fluctuating longitudinal wind speeds.

Hence, the longitudinal mean wind speed values are dependent upon both local terrain setups and upwind flows. Analogue to the Monin-Obukhov (M-O) similarity theory^[14], this study assumes that turbulence characteristic quantities within the forced convection surface layer can be described by using a stability parameter ξ . $\xi=0, \xi>0$, and $\xi<0$ correspond to conditions of the unforced convection, downward forced convection and upward forced convection, respectively.

Using the log-linear model, wind speed profile under thermally neutral conditions with the forced convection can be expressed as:

$$U(z) = (u_{*0} / k) \ln(z / z_0) + \xi z. \quad (2)$$

where $k \approx 0.4$ is the von Karman constant, u_{*0} is the surface friction velocity, z_0 is the roughness length scale and z is the height.

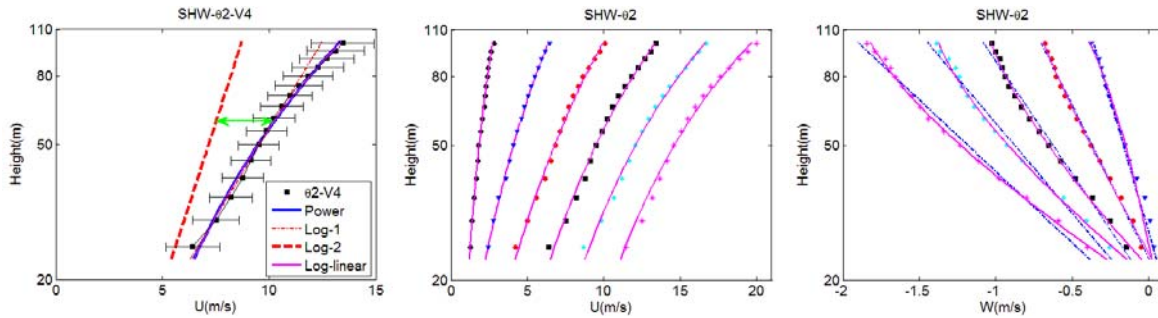


Figure 4. Comparison of fitting lines by the log law and log-linear law (left picture: Log-1 is the log-law fitting line using the lowest 10 levels data. Log-linear is the log-linear law fitting line. Log-2 is drawn from the log-linear line by setting $\xi=0$. Green line with arrows is the difference between the measurements and Log-2 line), profiles of longitudinal speed (middle) fitted by the log-linear model (in magenta), and profiles of vertical speed (right) fitted by both the log law (in blue) and log-linear model (in magenta) for the 02 section.

The left picture in Figure 4 presents a comparison between the log-law model (Log-1) and the log-linear model (Log-linear) for the case of 02 & V4. Another log-power line, denoted as Log-2, is also plotted, which is deduced from Equation 2 by setting $\xi=0$. As discussed above, Log-2 is governed by the local terrain roughness. It forms the asymptotic line that the mean wind profile should approach to downward the height. The deviation between the profile and the asymptotic line, indicated by the green arrowed line, stands for the wind component related to the downward flows. It is evident that a direct fitting of the longitudinal mean wind speed using the log-law (Log-1) would overestimate both the dynamic roughness length scale and the friction velocity.

Table 1. Fitting parameters for profiles of longitudinal wind speed for 02 section with respect to different reference speeds (N: specimen number; R^2 : fitting goodness).

V_i	N	U_{MBL}	σ_{MBL}	Power Law			Log Law		Log-linear Law			
				U_{10}	α	R^2	$2.5 u_*$	z_0	$2.5 u_*$	z_0	ξ	R^2
V2	2752	4.61	1.41	1.39	.665	.997	2.54	9.85	1.48	7.35	.025	.998
V3	2573	7.50	1.78	2.72	.564	.993	3.61	7.50	2.16	4.66	.033	.994
V4	1944	10.4	1.88	4.32	.488	.993	4.17	5.07	2.23	2.02	.046	.994
V5	633	13.1	1.93	5.96	.442	.993	4.65	3.68	2.17	0.77	.060	.995
V6	90	15.9	2.01	7.84	.394	.984	4.45	1.86	2.02	0.22	.072	.991

The other two pictures in Figure 4 show the ensemble mean profiles fitted by the log-linear model for both longitudinal (the middle picture) and vertical (the right picture) wind speeds. Table 1 and Table 2 list the key parameters involved in the fitting models. It can be seen that both the power law and log-linear law are able to provide favorite estimations for the longitudinal mean wind speed. But, the performance of the log-linear model is a little better. The power exponent decreases with the reference wind speed; while the stability parameter increases with it. For the vertical speed profiles, since both the log law and log-linear law agree with the measurements (nearly all $R^2 > 0.995$) well, the log-law with the simpler form is adopted. The results

for the V1 group are excluded herein, as which show remarkable deviations from those for other groups. This may be attributed to thermal effects under weak wind conditions.

Table 2. Fitting parameters for profiles of vertical speed for $\theta 2$ section with respect to different mean boundary layer speeds.

V_i	N	W_{MBL}	σ_{MBL}	Log Law			Log-linear Law			
				$2.5 u'_*$	z'_0	R^2	$2.5 u'_*$	z'_0	ξ	R^2
V2	2752	-0.198	0.981	-0.237	26.50	0.9154	-0.119	48.44	-0.0029	0.9769
V3	2573	-0.436	1.141	-0.502	23.85	0.9960	-0.585	22.28	0.0019	0.9966
V4	1944	-0.718	1.215	-0.743	20.98	0.9983	-1.008	19.00	0.0065	0.9976
V5	633	-0.992	1.268	-0.968	19.41	0.9964	-1.323	17.62	0.0093	0.9973
V6	90	-1.328	1.322	-1.206	18.03	0.9954	-1.594	16.74	0.0103	0.9984

3.3 Results with downwind hills

Results for the section $\theta 6$ with downwind hills are shown in Figure 5. Compared to the case of section $\theta 2$ with upwind hill obstructions, the longitudinal speed profiles for this section deviate from the log-law predictions to the left-hand-side. The vertical ensemble mean wind speed is positive and increases logarithmically along height. The effective turbulence intensity does not decrease monotonously with altitude. But, its variation follows three consecutive parts: the decreasing part, the leveling off part, and the increasing part. This is attributed to the less increase of U and a relatively faster increase of σ_U along height, which will be shown in Figure 6.

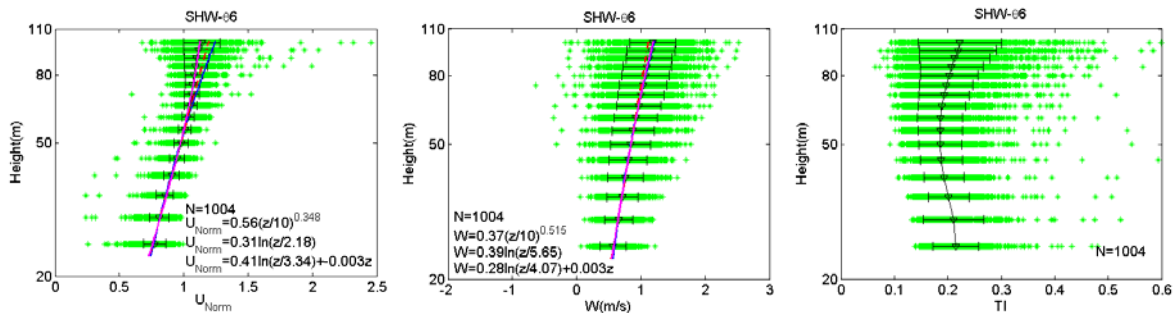


Figure 5. Profiles of normalized longitudinal speed (left), vertical speed (middle) and horizontal effective turbulence intensity (right), fitted by the power law (green line), log law (red dash line), and log-linear law (magenta line), for the $\theta 6$ azimuth section with downwind hills (datasets with $V > 5 \text{ m/s}$).

Figure 6 shows the profiles of mean and standard deviation of wind speed as well as the effective turbulence intensity, with respect to different reference speeds. As the reference speed increases, the longitudinal speed deviates from the log-law predictions more evidently and the height where the log-law begins to fail to predict the measurements decreases consistently. Standard deviations, σ_U and σ_W , of wind speed increase with both the reference speed and height. σ_W is distributed in a linear form along height, compared to a more complicated nonlinear form of σ_U .

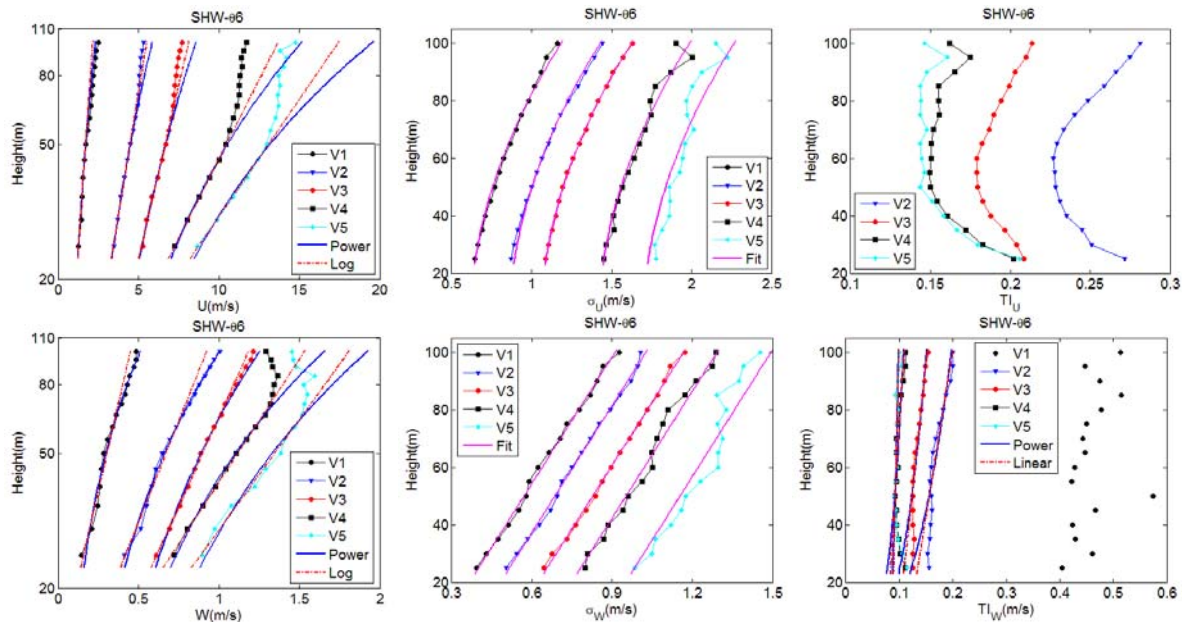


Figure 6. Profiles of mean (left) and standard deviation (middle) of wind speed, and effective turbulence intensity (right) in both longitudinal and vertical directions, for $\theta 6$ azimuth section with down-hills (fitting lines for U profiles are based on the lowest 6 levels data, W profiles are based on the lowest 10 levels data, TI_w profiles are determined by the top 12 levels data, others are based on the total 16 levels data).

Following the analysis method for the $\theta 2$ section, the log-linear law is adopted to model both the longitudinal and vertical wind speed profiles. Selected results are shown in Figure 7 and Tables 3-4. All of the fitting results agree well with the measurements, with the minimum R^2 of 0.968 for the vertical speed profile for the case of V5 where there are only 10 specimens. Opposite to the results of the $\theta 2$ section, direct usage of the log-law herein would underestimate both the roughness scales and the surface friction velocities. Meanwhile, the calculated z_0 increases with the reference speed, compared to the decreasing trend for the $\theta 2$ section. This may lie in that stronger wind, while disturbed by the downwind hills, will generate more turbulent air flows. This may also account for the continuous increase of σ_U and σ_W along altitude with respect to different reference wind speeds, compared to the situations of increasing first, then leveling off and finally decreasing along height with respect to different reference speeds for the $\theta 2$ section.

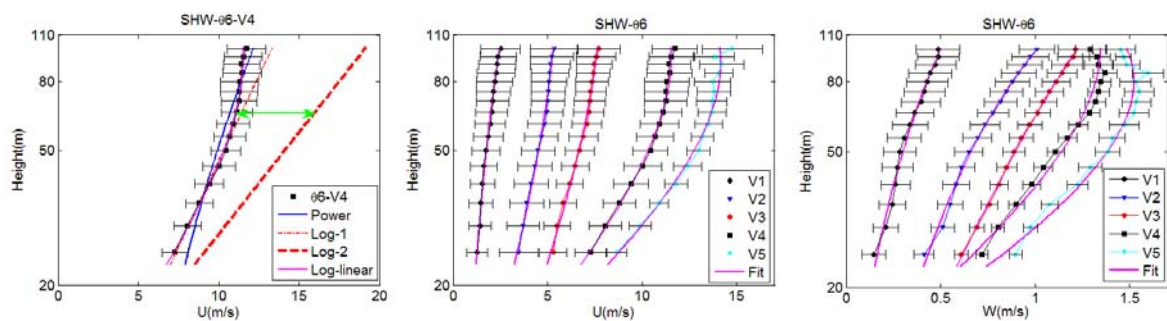


Figure 7. Comparison of fitting lines by the log law and log-linear law (left picture: Log-1 is the log-law fitting line using the lowest 10 levels data. Log-linear is the log-linear law fitting line. Log-2 is drawn from the log-linear line by setting $\xi=0$. Green line with arrows is the difference between the measurements and Log-2 line). Profiles of longitudinal speed (middle) fitted by the log-linear model (in magenta), and profiles of vertical speed (right) fitted by the log-linear model (in magenta) for the $\theta 6$ section.

Table 3. Parameters of the log-linear models for profiles of longitudinal speed in 06 section with downwind hills.

V_i	N	U_{MBL}	σ_{MBL}	Power Law		Log Law		Log-linear Law			
				U_{10}	α	$2.5u_*$	z_0	$2.5u_*$	z_0	ξ	R^2
V1	396	1.934	0.867	0.800	0.495	0.811	5.474	0.415	1.941	0.0084	0.994
V2	1164	4.652	1.112	2.474	0.369	1.570	2.829	2.110	4.252	-0.014	0.993
V3	491	6.815	1.308	3.918	0.325	2.053	1.973	2.900	3.515	-0.021	0.992
V4	46	10.41	1.670	5.238	0.409	3.977	3.854	7.218	7.091	-0.076	0.996
V5	10	12.81	1.949	6.405	0.414	5.008	4.062	9.460	7.536	-0.103	0.982

Table 4. Parameters for profiles of vertical speed using the power, log and log-linear laws in 06 section

V_i	N	W_{MBL}	σ_{MBL}	Power Law		Log Law		Log-linear Law			
				W_{10}	α	$2.5u'_*$	z'_0	$2.5u'_*$	z'_0	ξ	R^2
V1	396	1.934	0.655	0.084	0.785	0.211	11.84	0.104	9.485	0.0026	0.988
V2	1164	4.652	0.771	0.251	0.601	0.364	7.935	0.160	3.330	0.0048	0.996
V3	491	6.815	0.912	0.401	0.494	0.412	5.646	0.327	4.401	0.0020	0.999
V4	46	10.41	1.037	0.430	0.584	0.596	7.690	1.040	10.24	-0.010	0.978
V5	10	12.81	1.239	0.567	0.530	0.664	6.601	1.114	10.33	-0.018	0.968

3.4 Empirical models of key parameters

From the above analysis, all the parameters involved in the fitting models are of wind speed dependence. This part will model these key parameters as a function of the reference wind speed, based on the fitting results as listed in Tables 1-4. The following criteria are adopted herein: (1) predictions should make sense under limiting conditions (e.g., $z_0 > 0$ for $U \rightarrow \infty, 0$); (2) predictions are able to reflect the varying trend of modeled parameters; (3) models should be robust.

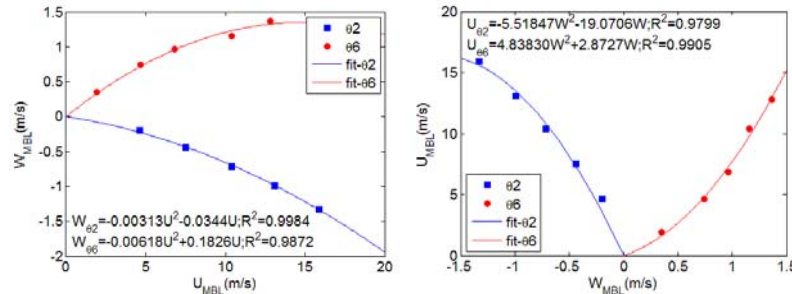


Figure 8. Correlations between the ensemble-mean boundary layer (MBL) values of longitudinal speed and vertical speed in both 02 and 06 sections using quadratic models.

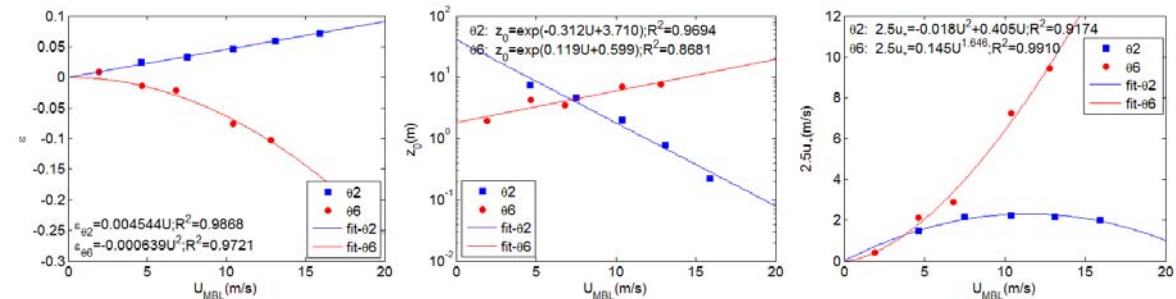


Figure 9. Correlations between the mean boundary layer (MBL) value of longitudinal speed and the stability parameter (ξ), effective dynamic roughness length scale (z_0), and the friction velocity (u_*).

Figure 8 shows the correlations between the mean boundary layer values (MBL) of the ensemble-mean longitudinal speed profile and the ensemble-mean vertical speed profile for both 02

and $\theta 6$ sections, using quadratic models. In the left picture, U_{MBL} is the independent variable, while in the right picture, the independent variable is W_{MBL} . It can be seen that the modeled W_{MBL} for the $\theta 6$ section with respect to U_{MBL} in the left picture and the modeled U_{MBL} for the $\theta 2$ section with respect to W_{MBL} in the right picture are capped with peak values. But, there is no evidence for the existence of these upper limits. Therefore, the following two un-capped fitting equations are adopted, through which, U_{MBL} and W_{MBL} can be estimated from each other.

$$W_{MBL} = -3.13 \times 10^{-3} U_{MBL}^2 - 3.44 \times 10^{-2} U_{MBL}, \text{ for } \theta 2; \quad (3)$$

$$U_{MBL} = 4.84 W_{MBL}^2 + 2.87 W_{MBL}, \text{ for } \theta 6.$$

(4)

Figure 9 shows the results for the three parameters involved in the log-linear law (see Equation 2). The empirical fitting equations are given by:

$$\xi = 4.54 \times 10^{-3} U_{MBL}, \text{ for } \theta 2; \quad (5)$$

$$\xi = -6.39 \times 10^{-4} U_{MBL}^2, \text{ for } \theta 6. \quad (6)$$

$$z_0 = \exp(-0.312 U_{MBL} + 3.71), \text{ for } \theta 2;$$

(7)

$$z_0 = \exp(0.119 U_{MBL} + 0.599), \text{ for } \theta 6. \quad (8)$$

$$2.5u_* = -0.018 U_{MBL}^2 + 0.405 U_{MBL}, \text{ for } \theta 2; \quad (9)$$

$$2.5u_* = 0.145 U_{MBL}^{1.646}, \text{ for } \theta 6. \quad (10)$$

Using Equations 2-10, the longitudinal mean wind profiles within the considered height range (25-100m) can be predicted, in case of giving the value of either U_{MBL} or W_{MBL} .

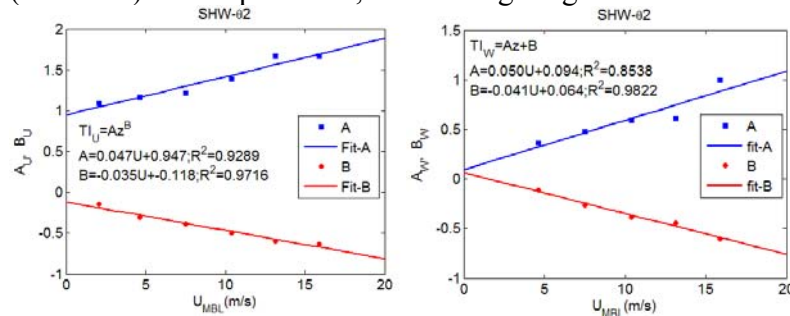


Figure 10. Empirical models for the effective turbulence intensity of both horizontal speed (left) and vertical speed (right) for the $\theta 2$ azimuth section.

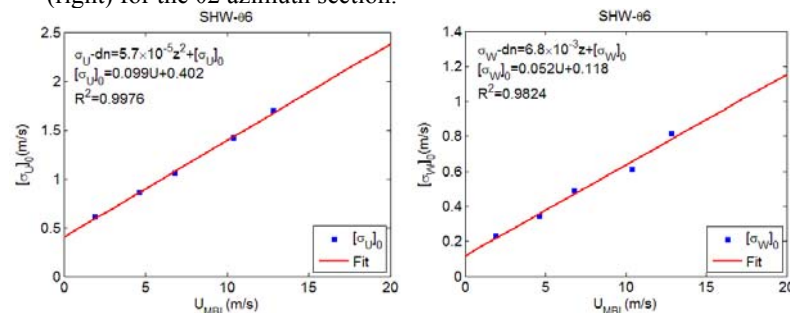


Figure 11. Empirical models for the effective standard deviation of both horizontal speed (left) and vertical speed (right) for the $\theta 6$ azimuth section.

The standard deviation of wind speed and the turbulence intensity (TI) can be inferred from each other through Equation 1. From Figure 3 and Figure 6, for the $\theta 2$ section, it is more feasible to model the effective TI first, and then formulate σ . But, for the $\theta 6$ section, the procedure is op-

posite, i.e., determining σ first and then computing the effective TI is more appropriate. The associated results are shown in Figure 10 (for $\theta 2$) and Figure 11 (for $\theta 6$):

$$TI_U = (0.047U_{MBL} + 0.947)z^{(-0.035U_{MBL}-0.118)}, \text{ for } \theta 2; \quad (11)$$

$$TI_W = (1.97 \times 10^{-3} / U_{MBL} - 8.24 \times 10^{-4})z + 0.568U_{MBL}^{-0.533} \quad (U_{MBL} < 40), \text{ for } \theta 2; \quad (12)$$

$$\sigma_U = 5.7 \times 10^{-5} z^2 + (0.099U_{MBL} + 0.402), \text{ for } \theta 6; \quad (13)$$

$$\sigma_W = 6.8 \times 10^{-3} z + (0.052U_{MBL} + 0.118), \text{ for } \theta 6. \quad (14)$$

Using Equation 1 and Equations 11-14, the effective standard deviation and the effective turbulence intensity of both horizontal speed and vertical speed can be determined.

From the previous analysis it can be seen that the effective standard deviation of horizontal wind speed and the vertical speed for both $\theta 2$ (Figure 3) and $\theta 6$ (Figure 6) sections are positively correlated with each other. Under open flat neutral conditions, the relationship between σ_w and σ_u can be depicted by the following equation as recommended in ESDU^[15]:

$$\sigma_w / \sigma_u = 1 - 0.45 \cos^4[\pi z / (2h)], \quad h = u_* / (6f).$$

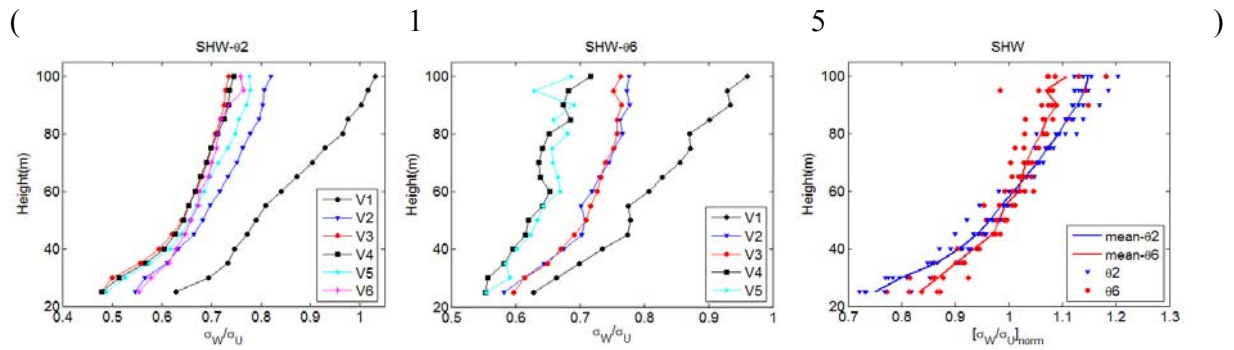


Figure 12. Correlations between the standard deviations of both vertical speed and horizontal speed with respect to different reference speeds in both $\theta 2$ (left) and $\theta 6$ sections (middle), and the correlations regardless of wind strength (right, the values are normalized by the MBL values).

In the above equation, h is the depth of the atmospheric boundary layer with the order of 1000m. But, the results under hilly terrains obtained in this study show significant differences. Figure 12 shows the variations of the ratio of σ_w/σ_u with respect to both height and reference wind speed. A best fit for the measurements using Equation 15 (other coefficients are still kept, and z and h are regarded as variables) finds the estimated $h \approx 100m$ which is in the order of the characteristic height of upstream hills. Another point is that, according to ESDU^[15], under neutral conditions all open flat terrains correspond to almost the same ratio of σ_w/σ_u irrespective of the nature of the terrain surfaces. But under hilly terrains, it is clear from the right picture in Figure 12 that the topographic effect can not be neglected. This is a feature of wind characteristics under hilly terrains as distinguished from those with open flat terrains.

4 CONCLUSIONS

This paper has analyzed the hill effects on near surface wind characteristics based on the field measurements from a Sodar profiler system. The longitudinal wind speed is found to be closely correlated to the forced convective flows. The $\theta 2$ azimuth section with upwind hills corresponds to downward flows (or negative vertical speed). The longitudinal mean wind speed in this section speeds up at higher altitudes and gradually departs from the log-law predictions. The $\theta 6$ section with downwind hills corresponds to upward flows. The longitudinal mean wind speed in this section also deviates from the log-law predictions and levels off along height at the upper alti-

tude range. The height where the log-law begins to fail to model the mean wind speed in both the sections decreases as the reference speed increases. The log-linear law is adopted to model the mean wind speed profiles. Results from the model agree well with the measurements. The effective standard deviations of wind speed in horizontal and vertical directions are also found to be closely correlated with each other in both sections. But the profiles in one section vary remarkably to those in the other section. The ratios of σ_w/σ_u in these two sections are different from those stipulated in the ESDU model for open flat terrains. A number of empirical estimators for both the mean wind speed profiles and the standard deviation of wind speed profiles are presented. The findings of this study can be used as reference for the determination of wind profiles under hilly terrain conditions.

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