Different Turbulent Regimes and Vertical Turbulence Structures of the Urban Nocturnal Stable Boundary Layer

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Introduction

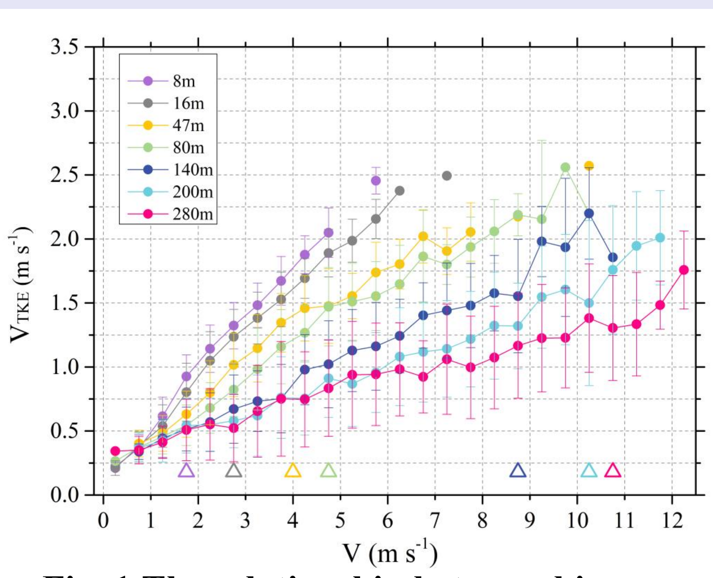
◆Sun et al. (2012) proposed the famous "HOckey stick transition" (HOST) theory available for flat areas according to the relationship between turbulence strength V_{TKE} and mean horizontal wind speed V. However, most previous studies have focused on the flat area. Whether the relationship in the urban boundary layer (UBL) conforms to the HOST theory has still not been verified.

Observation instruments and data

◆The meteorological tower of the Institute of Atmospheric Physics, Chinese Academy Sciences, is 49m above sea level, 325m high. There are 15 observation platforms (at 8, 15, 32, 47, 65, 80, 103, 120, 140, 160, 180, 200, 240, 280 and 320 m) equipped on the tower, and each platform is mounted with measurement instruments of wind speed, wind direction, temperature and humidity. A total of 7 levels (8, 15, 47, 80, 140, 200 and 280 m) of three-dimensional ultrasonic anemometers (Wind Master, Gill, UK) is measured on the tower;

◆Hourly averaged concentrations of surface $PM_{2.5}$ can be found on the official website of the Beijing Environmental Protection Agency (http://beijingair.sinaapp.com/)

Turbulence regime analysis: division method and deciding factors



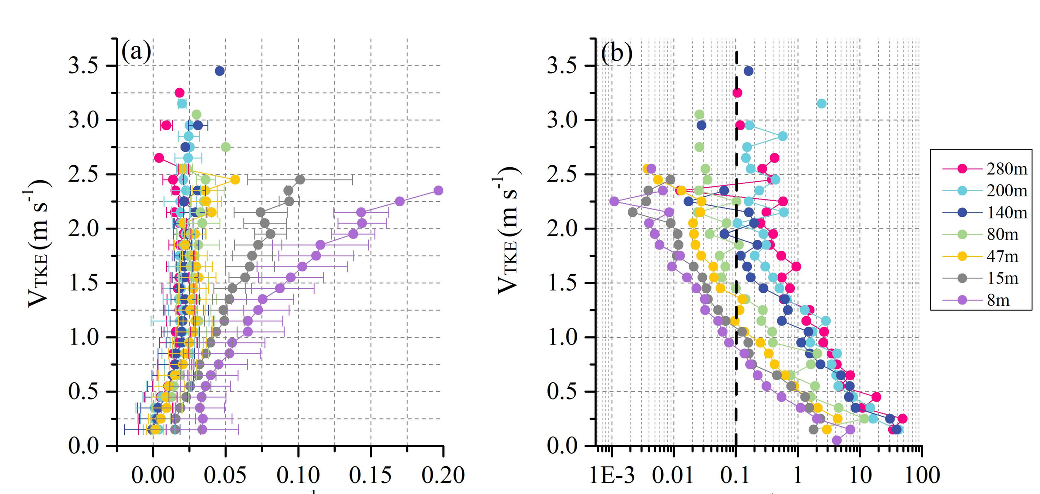


Fig. 1 The relationship between bin-averaged turbulence strength V_{TKE} and wind speed V at seven observation levels on the Beijing 325-m meteorological tower. The threshold wind speed V_T at each level is marked with a triangle in the color of the height. Fig. 2 The relationship between V_{TKE} and local shear (a) and the relationship between V_{TKE} and stability parameter z/Λ at the seven observation levels of the 325-m meteorological tower.

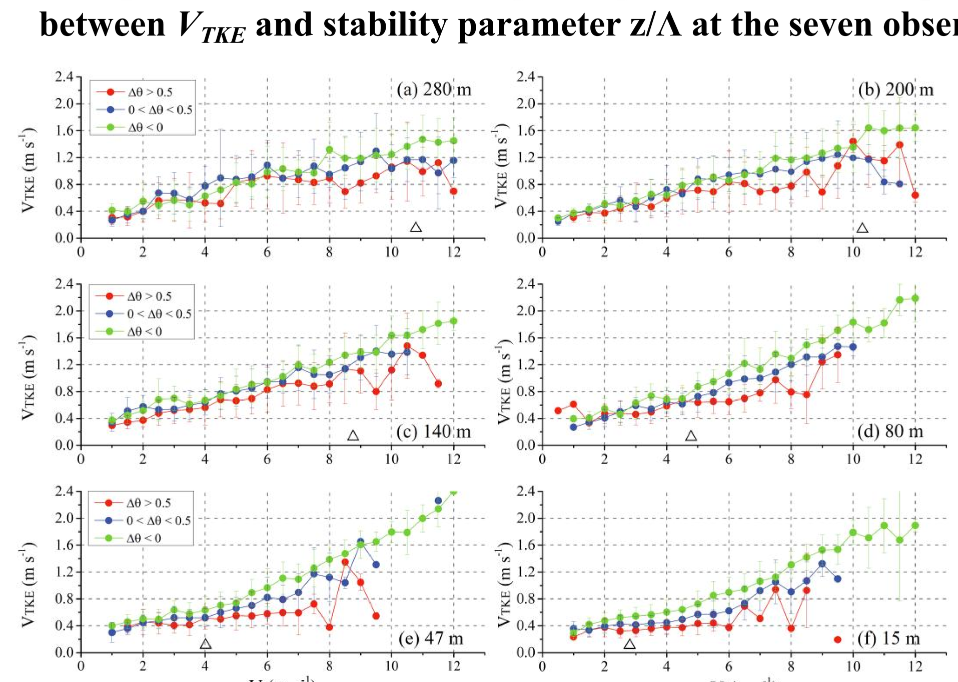


Fig. 3 The relationship between the bin-averaged turbulence strength V_{TKE} and the wind speed V at the seven observation levels as a function of potential temperature difference intervals, defined as $\Delta\theta=\theta(z)-\theta_{z0}$, where θ_{z0} is the potential temperature of reference at 8 m, and $\theta(z)$ is the potential temperature at each height z: (a) 280 m, (b) 200 m, (c) 140 m, (d) 80 m, (e) 47 m, and (f) 15 m. The wind speed threshold V_T is marked using a black triangle for each height.

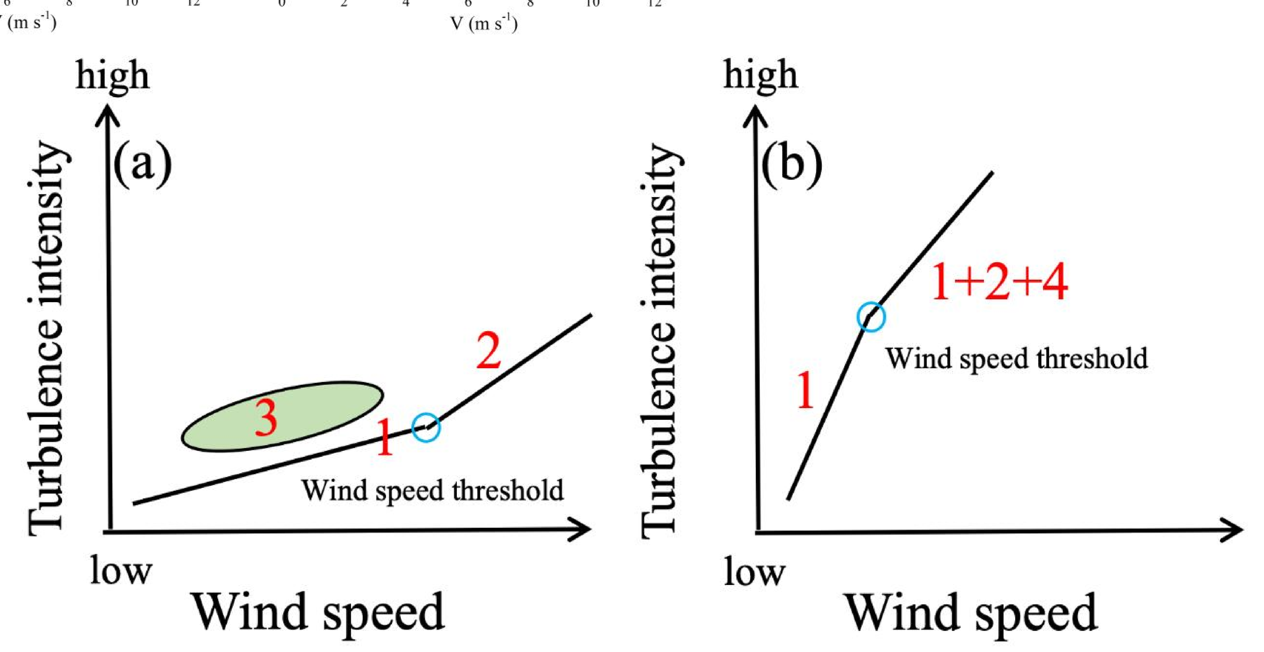


Fig. 4 Schematic representation of the relationship between the turbulence strength V_{TKE} and the wind speed V with the four turbulence regimes (regimes 1, 2, 3, and 4) for the Beijing 325-m meteorological tower, located at a typical city underlying surface. (a) 140 m, 200 m, and 280 m; and (b) 8 m, 15 m, 47 m, and 80 m. The urban canopy height of the observation site is estimated to be approximately 80 m. Turbulence in regime 1 is mainly generated by local instability. Turbulence in regime 2 is mainly generated by bulk shear. Turbulence in regime 3 is mainly generated by upside-down turbulence flows. Turbulence in regime 4 is generated by buoyancy turbulence flows.

Vertical distribution of the stability parameters of different SBLs

Table 1: The distribution of the frequency (%) for stable (S, z/Λ>0.1), near-neutral (N, <0.1) and unstable (U, z/Λ<-0.1) cases of the downside-up, upside-down, weak-transport cases from November 2017 to January 2018 observed by the 325-m tower.

	downside-up			weak transport			upside-down		
Height	S	N	U	S	N	U	S	N	U
8 m	35.6	62.2	2.2	72.4	16.1	11.5	62.1	31.8	6.1
15 m	39.8	57.0	3.2	70.7	14.2	15.1	62.2	27.5	10.3
47 m	29.0	57.6	13.4	51.7	8.1	40.2	47.9	30.2	21.9
80 m	29.0	52.1	18.9	44.0	8.5	47.5	50.1	26.6	23.3
140 m	38.4	30.1	31.5	46.2	3.2	50.6	56.0	15.7	28.3
200 m	61.4	14.2	24.4	53.5	2.0	44.5	70.0	7.0	23.0
280 m	63.7	10.3	26.0	52.4	1.7	45.9	67.3	7.3	25.4

Categories and examples of different SBLs

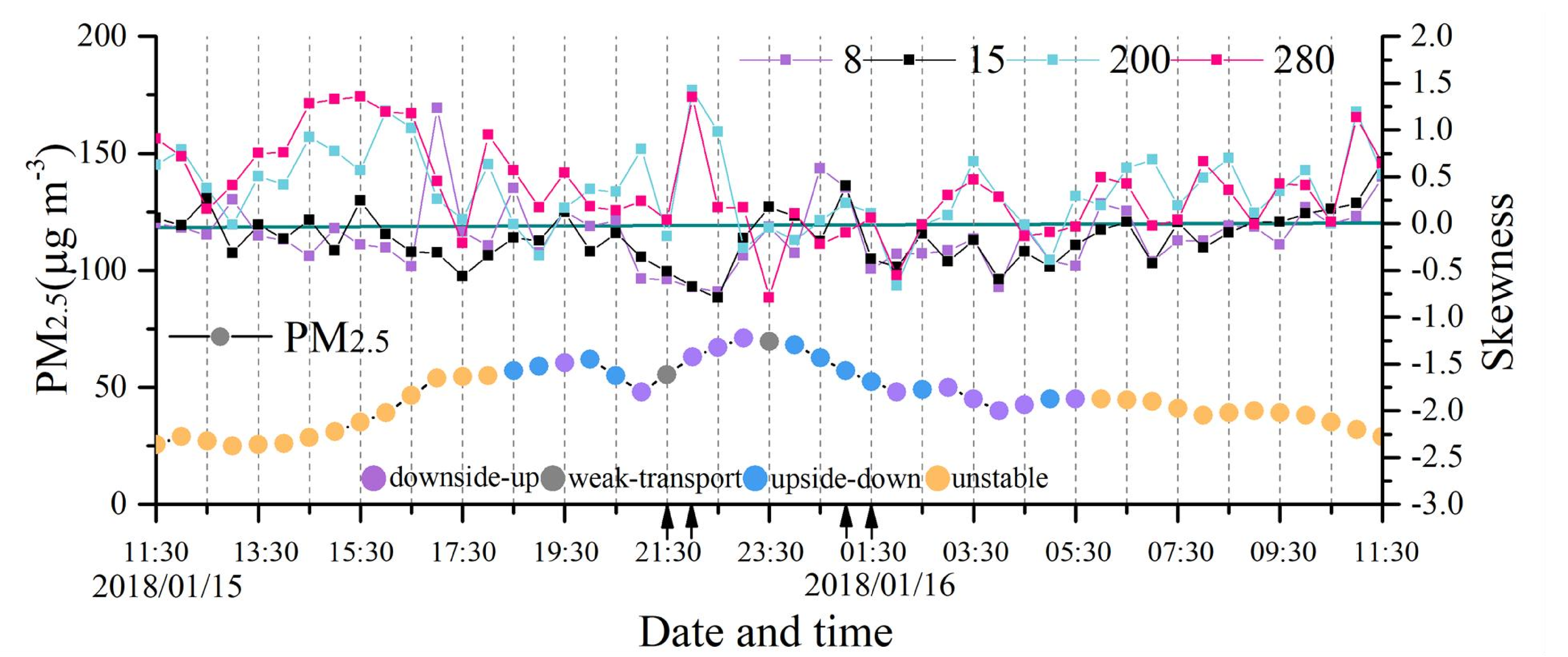


Fig. 5 The time series of the skewness of the vertical velocity at 8 m, 15 m, 200 m and 280 m and the concentration of $PM_{2.5}$ from 11:30 on 15 January 2018 to 11:30 on 16 January 2018. The variation process is marked by different circle colors, representing the different boundary layer structures.

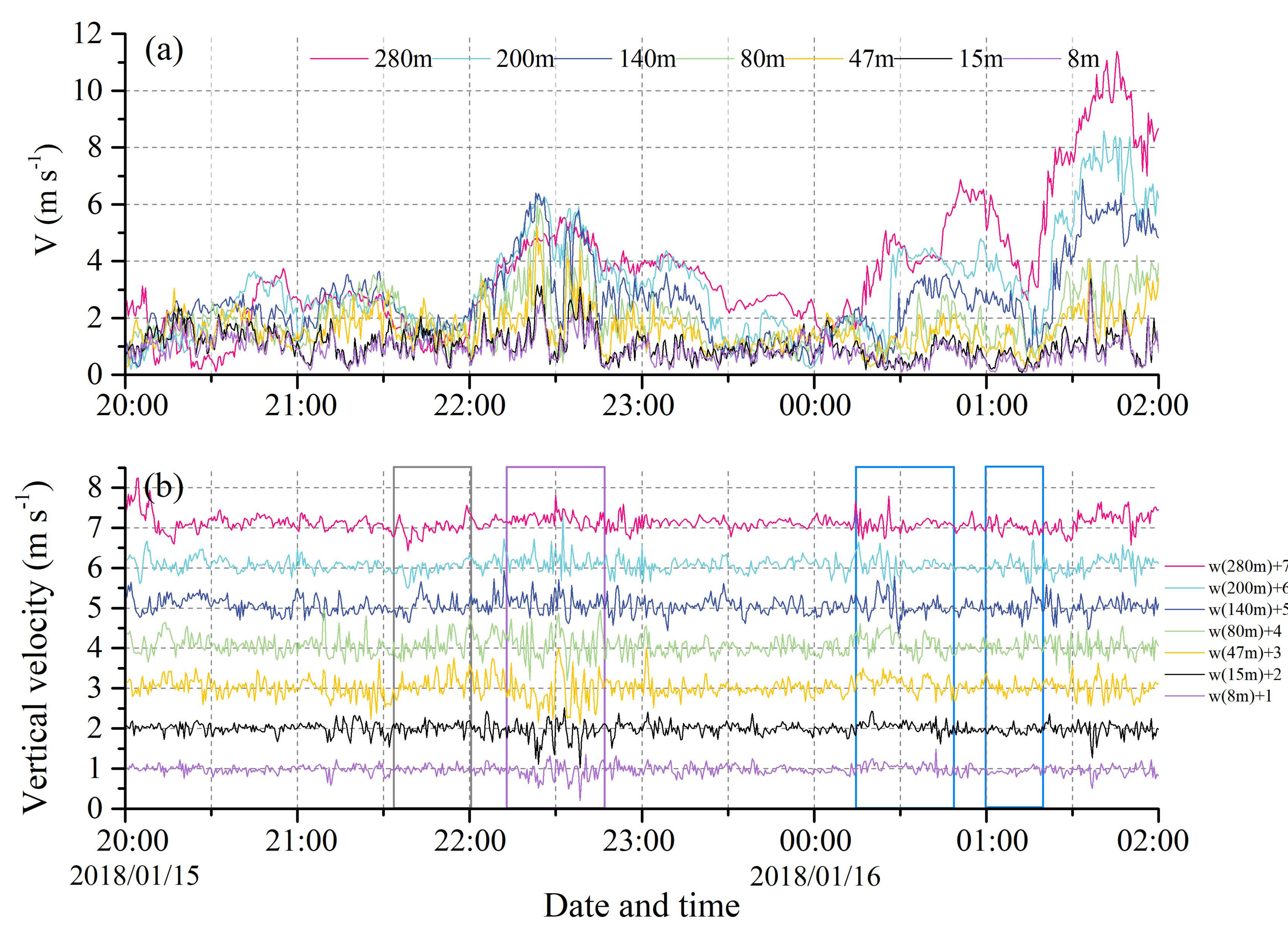


Fig. 6 Time series of the wind speed V and the vertical velocity w for the seven observation levels from 20:00 on 15 January 2018 to 02:00 on 16 January 2018. For vertical velocity w starting from 15 m, the value is shifted by the amount shown to the right of each time series. The data shown are the 30 s temporal average from sonic anemometers with a frequency of 10 Hz.

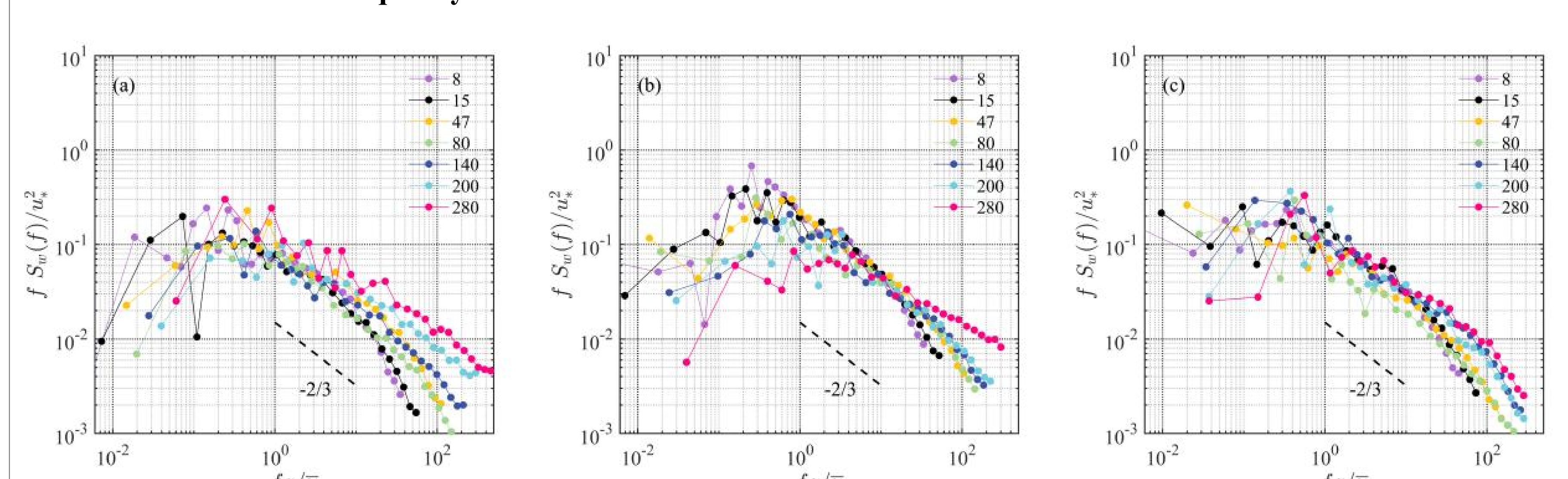


Fig. 7 Power spectra of the w wind component at weak transport at 21:00 on 15 January 2018 (a), downside-up at 22:00 on 15 January 2018 (b), and upside-down at 00:00 on 16 January 2018 (c). A 1-h data segment is used at each observation height in both panels.

Conclusions

- For heights above the UCL (140, 200 and 280 m), the pattern of V_{TKE} vs. V is consistent with the HOST theory proposed according to the flat area; For the height inside the canopy (8, 15, 47 and 80 m), these layers were strongly affected by the thermal-dynamic properties of the UCL. Weak turbulence in the UCL was strongly affected by local wind shear (regime 1) when $V<V_T$, and the local wind shear was the most important determining factor for the variation in V_{TKE}. When $V>V_T$, the generation of strong turbulence is a result of a combination of local wind shear (regime 1), bulk shear (regime 2), and buoyancy turbulence (regime 4);
- Strong turbulence activities within the UCL were usually accompanied by this thermally unstable stratification; The buoyancy turbulence also constituted the generation of strong turbulence within the UCL (regime 4). The turbulence generated by bulk shear was more likely to be affected by thermal stratification. Turbulence was partially suppressed with the stratification $\Delta\theta$>0.5;
- The stable stratification at 140-280 m mostly corresponded to the upside-down structure.

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