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ATMOSPHERIC TURBULENCE STRUCTURE AND SPECTRAL CHARACTERISTICS AT NEAR SURFACE LAYER ON TROPICAL COASTS

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ABSTRACT

By use of an observational experiment at the village of Tianwei, Haikou, Hainan province in 1990, characteristic turbulence values such as velocity component spectra and turbulence intensity are studied. The data were mostly obtained in cloudy condition, so that the stability parameter (L) and thermal flux (wt) did not vary diurnally while the turbulent energy and mean-temperature did. The basic characteristics of turbulence spectra are similar to those with fine weather, being close to local isotropy in the inertial subrange. The velocity spectra agree with the law of "$-2/3$ th power" in Kolmogrov's similarity theory. The relationship between turbulent intensity of components δ_i/U_* ($i = u, v, w$) and stability Z/L is studied following the Monim-Obukhov(M-O) similarity theory. It is shown that the two observe the law of "1/3 th power", though the turbulent intensity and energy are generally larger than those on the flat underlying topography.

Key words: atmospheric turbulence, turbulence, turbulent intensity, velocity spectra, similarity theory

Ⅰ. INTRODUCTION

Much research has been done at home or abroad over the past few decades on the structure of atmospheric turbulence and that with homogeneous, flat underlying surface has been studied in a large number of experimental and theoretic analyses, the latter being specially clear. It is generally held that the spectra of vertical velocity component usually observes the M-O similarity theory, although it may be subject to weak effect of the inversion layer height Zi at the lowest portion of frequency, while the energy-included zone of horizontal velocity spectra are much more influenced by Zi, with adjustment to the pattern of M-O scale only at the high frequency sections (Kaimal, Wyngaard and Isumi et al., 1972; Kaimal, Wyngaard and Hangen et al., 1976). Having different features with the change of topographical conditions, the turbulent structure above complicated surface has also been deeply studied with main conclusions as follows (Kaimal, Evarsole and Lenschow et al., 1982; Panofsky, Larko and Lipschutz et al., 1982). Turbulent vortexes with high frequency can make rapid adaptation to local conditions to arrive at equilibrium; low-frequency disturbance of turbulence spectra due to topography dislocates the peak value and relevant results derived for the inertial subrange of spectra in homogeneous topography are still applicable here; the principal energy of the vertical velocity spectra concentrates on the high-frequency part with no significant alternation to the basic shape while the horizontal velocity spectra are more influenced by topography upstream and retain corresponding spectral features in the lower part of frequency and downstream planetary conditions are more quickly adapted in the higher part of the frequency for a new equilibrium; with stable stratification, there is a remarkable increase in the energy taken up by low-frequency vortex due to additional effects like gravitational waves. Studies on the features of planetary boundary condition for urban and coastal regions have been done for the past few years, of which a study by the Atmospheric Physics Institute of Chinese Academy of Science on the fluctuations of wind and temperature with data of a meteorological tower in the suburbs of Beijing (Ye, Zhu and Li et al., 1983; Wang, Zhang and Wang et al., 1985), one by Wang (1992) on the turbulence characteristics at the near-surface layer for valley-located cities, one by Zhu, Zhu and Li (1994) on the spectral features of individual synoptic processes with unstable condition, are some of them. Specially, the work by Zhang (1991) on the structure of atmospheric turbulence for the outskirts and its outlaying regions of Beijing concluded that a weak relationship existed between turbulence characteristic quantities and stability in neutral condition, and the one by Xu and Li (1993) in a paper entitled " the microstructure of turbulence and spectral features of near-surface layer atmosphere in Guangzhou" pointed out a larger increase of atmospheric turbulence energy at the near-surface layer than at the layer over flat and homogeneous underlying surface for coastal cities.

In this paper, an observational experiment conducted at the Tianwei Village, Haikou City, Hainan Province, in 1990, is used to discuss the turbulence features of near-surface layer in tropical coastal areas and the applicability of the similarity theory.

Ⅱ. OBSERVATIONAL DATA AND METHOD OF TREATMENT

A field observation was carried out 14 through 24 July, 1990, at the Tianwei Village using Gill U. V. W-components properler anemograph (Model 27005) made by R. M. Yong Company, U. S. A., to measure speed components and directional fluctuations. The device was fixed on an 6-m-high iron frame on top of a two-storey building at the seaside in an area about 19 m above the sea level (15 m above the ground). The three axises had been designated against the standard set by the manufacturer in terms of the rate of rotation. The sampling was rated at 4 records per second, or, at an interval of 0.25 second, recording in turn the component U, V, W speed and temperature value. Each of the measurements was 1 hr in continuity and written on IBM—PC disks in six data files. The observation was generally 6 times a day to go in phase with low-level sounding and anemometry. Continuous 24-hr observation was done in specific types of weather if needs arise.

The data set from 20 to 24 July, 1990 was a complete one, based on which the analysis was done. The cloud amount was usually larger than 8 and in more times equal to 10. The data is mostly of Type D in neutral condition in accordance with the criterion of Pasquill stability (National Standard) and another criterion of M-O Stability, Z/L, also classifies it as occurrences in weak instable, neutral and weak stable condition. Relevant papers up to now have reported wide-spread, significant diurnal variations in turbulent characteristics with fine-sky background, leaving the cloudy-sky one largely untackled. Clouds act in a mechanism that is multi-aspect. In summary, feedbacks in clouds, however, can be affecting the thermodynamics of turbulence, probably more indicative of the role of the dynamic factor by the turbulent spectrum of cloudy condition. Among the complex underlying surface on the coast, the intersection between sea and land is the most fundamental geographic nature. Should the particularity of the sea-land planetary boundary layer as reflected by the site of Tianwei have light to shed on the turbulence structure? It is what is sought to understand and discuss in this paper. The raw data were first processed by the steps that followed.

(1) The data were pre-processed to delete noise disturbance and perform low pass filter;

(2) Then, they were derived for transient modulus of velocity and transient direction and with quadratic curve their mean tendency of temporal evolution is fitted using corresponding series of temporal variation series. Afterwards, readings at various time on the quadratic curve were compared with transient values observed for horizontal velocity and directional fluctuations;

(3) Then, the coordinated system was oriented in the direction of the modulus of the horizontal velocity to derive U' and V' while the fluctuation W' of the vertical was directly available from the series of readings, and temperature fluctuations T' were obtained in a similar way for U' ;

(4) From U', $V'$and W' and T', the frictional velocity U_*, characteristic temperature T_*, turbulence intensity for each of the components and the length of M-O and other typical turbulence quantities, are derived;

(5) And fast Fourier transformation (FFT) was used to compute energy spectrum of each of the fluctuated turbulence.

Ⅲ. CHARACTERISTIC TURBULENCE QUANTITIES AND ANALYSIS OF ENERGY SPECTRUM

The characteristic turbulence quantities are macro-statistics averaged every 30 minutes. Table 1 gives part of the list of computed data starting the statistic treatment at the shown time each lasting 30 minutes.

1. *Analysis of characteristic turbulence*

In fine weather generally, the thermal flux is in the order of magnitude varying between $+10^{-1}$ and -10^{-2} for daytime and nighttime, respectively, showing regular change in the pattern of positive day value (with maximum after midday) and negative night one. An obvious feature as shown in Table 1, Figs. 1a and 1b is that no diurnal variability is found in the stability parameter L and thermal flux wt, and the flux is in the order of 10^{-3}, the absolute values are all present in the form of minor quantity, and the upward and downward thermal fluxes are within a small scale. They are consistent with the feature typical of condition of quasi-neutral stability. Examination of the data for 14-24, July 1990 reveals that all of them concentrate around Type D of the National Standard Stability and 90% in it. The reference to the stability criteria Z/L also indicates the company of weak instability, neutrality and weak stability in the period the set of data covers. They all point to a dynamic rather than thermal role for the turbulence. That the insignificant diurnal change in Z/L and wt is generally found may be the indirect indication of the factors of cloud feedback, complicated nature of land-sea-bordered underlying surface and velocity shear. The effect of clouds, particularly, acts substantially in coastal regions where they are quite active at low levels and in movements difficult to locate exactly. The lack of changes in Z/L and wt in the pattern usually observed for either complex thermal effects arisen from alternative appearence of cloud cover and glaring sun at the site of observation, or by possible failure of response to such effects by insufficient precision on the part of the observing equipment.

Another obvious feature seen in Table 1 is the extent to which the wind velocity varies over periods of day and night. It is generally higher in the daytime than in the nighttime. The values of $\delta_{u,v,w}$ and U_* are larger than those for flat underlying surface but the diurnal change of turbulence intensity is small. The greater the velocity, the larger the fluctuation of δ_u, δ_v, δ_w will be, suggesting a close link between turbulence diffusion and velocity shear and emphasizing on the dependence of turbulence intensity on mechanical instead of thermodynamical process.

Table 1. General list of the part of characteristic turbulence values.

DD.Hr:Min	U	δ_u	δ_v	δ_w	U_*	T_*	Z/L	wt	Cloudaga (Total/Low)
21.04:45	2.53	0.3830	0.4145	0.3938	0.1527	$-0.65e^{-03}$	$0.693e^{-02}$	−0.0001	1/1
21.05:05	2.35	0.4133	0.4473	0.4093	0.1511	$-0.10e^{-02}$	$0.113e^{-01}$	−0.0002	1/1
21.08:00	4.25	0.7426	0.9153	0.6674	0.2595	$0.21e^{-01}$	$-0.774e^{-01}$	0.0055	9/7
21.08:30	4.72	0.7471	0.9848	0.8150	0.3378	$0.57e^{-03}$	$-0.123e^{-02}$	0.0002	9/7
21.11:55	5.98	1.1528	1.2389	0.9052	0.5108	$0.31e^{-03}$	$-0.290e^{-03}$	0.0002	9/8
21.15:30	7.06	1.4026	1.4340	1.0531	0.4680	$0.98e^{-02}$	$-0.111e^{-01}$	0.0046	10/9
21.16:00	7.40	1.4899	1.5264	1.1449	0.5665	$-0.37e^{-02}$	$0.285e^{-02}$	−0.0021	10/9
21.19:40	4.61	0.6982	0.8934	0.7545	0.2881	$0.64e^{-02}$	$-0.191e^{-01}$	0.0018	10/9
21.20:10	4.23	0.8526	0.9202	0.8183	0.4141	$-0.48e^{-02}$	$0.694e^{-02}$	−0.0020	10/9
22.04:00	5.40	0.9132	0.9197	0.7905	0.3105	$0.90e^{-02}$	$-0.231e^{-01}$	0.0028	8/5
22.04:30	4.29	0.6857	1.0073	0.7375	0.3586	$-0.44e^{-02}$	$0.847e^{-02}$	−0.0016	8/5
22.07:30	2.79	0.7299	1.2074	0.6354	0.2797	$-0.25e^{-02}$	$0.784e^{-02}$	−0.0007	10/10
22.15:30	6.54	1.2263	1.1405	0.9477	0.4180	$-0.92e^{-03}$	$0.130e^{-02}$	−0.0004	10/10
22.16:00	5.78	1.1341	1.0100	0.8387	0.4063	$-0.19e^{-01}$	$0.279e^{-01}$	−0.0075	10/10
23.04:10	3.36	0.6370	0.6604	0.5260	0.2200	$-0.25e^{-01}$	$0.127e^{+00}$	−0.0054	3/3
23.04:40	2.57	0.4720	0.5351	0.4118	0.1657	$0.12e^{-02}$	$-0.109e^{-01}$	0.0002	3/3
23.07:40	4.13	0.7049	0.6802	0.6095	0.3316	$-0.94e^{-05}$	$0.213e^{-04}$	0.0000	10/5
23.08:10	4.92	0.9264	0.7686	0.6624	0.3934	$-0.10e^{-01}$	$0.161e^{-01}$	−0.0040	10/5
23.08:40	4.78	0.7904	0.9012	0.6572	0.2521	$-0.26e^{-02}$	$0.102e^{-01}$	−0.0007	10/3
23.09:10	5.60	1.2456	0.9059	0.7158	0.4003	$0.15e^{-01}$	$-0.238e^{-01}$	0.0062	10/3
23.11:45	5.99	1.1051	1.1628	0.7512	0.3688	$-0.21e^{-01}$	$0.374e^{-01}$	−0.0076	10/7
23.12:15	4.16	0.8002	0.7261	0.5886	0.3681	$-0.38e^{-02}$	$0.694e^{-02}$	−0.0014	10/7
23.13:30	4.24	0.9064	0.8527	0.6264	0.2761	$0.34e^{-01}$	$-0.110e^{+00}$	0.0094	10/6
23.14:00	5.06	1.1296	0.8594	0.6321	0.1276	$-0.54e^{-02}$	$0.811e^{-01}$	−0.0007	10/6
23.17:30	6.82	1.1073	1.0294	0.8117	0.3703	$-0.21e^{-01}$	$0.381e^{-01}$	−0.0079	10/5
23.18:00	4.72	1.0343	0.7827	0.6574	0.3625	$-0.13e^{-01}$	$0.233e^{-01}$	−0.0045	10/5
23.18:35	3.42	0.7696	0.7343	0.5076	0.2514	$0.61e^{-02}$	$-0.237e^{-01}$	0.0015	10/4
23.19:15	3.89	0.8787	0.7263	0.6672	0.3641	$-0.11e^{-01}$	$0.200e^{-01}$	−0.0039	10/4
23.19:35	3.55	0.7092	0.6562	0.6263	0.3302	$-0.81e^{-02}$	$0.183e^{-01}$	−0.0027	10/3
23.20:05	3.28	0.6343	0.6546	0.6350	0.2234	$-0.50e^{-01}$	$0.246e^{+00}$	−0.0111	10/3
23.21:42	3.33	0.6724	0.6769	0.5231	0.2208	$0.38e^{-02}$	$-0.193e^{-01}$	0.0008	10/5
23.22:12	3.48	0.7066	0.5541	0.5357	0.2656	$-0.81e^{-02}$	$0.283e^{-01}$	−0.0021	10/5
23.23:15	2.81	0.4991	0.4436	0.4121	0.2062	$-0.41e^{-02}$	$0.240e^{-01}$	−0.0008	10/5
24.05:35	1.98	0.3956	0.3353	0.3578	0.1305	$0.49e^{-02}$	$-0.720e^{-01}$	0.0006	3/2
24.05:56	2.18	0.3647	0.3365	0.3687	0.1080	$0.59e^{-02}$	$-0.125e^{+00}$	0.0006	9/1
24.06:26	1.93	0.3986	0.3900	0.3826	0.1335	$-0.22e^{-01}$	$0.312e^{+00}$	−0.0030	9/1
24.06:58	2.27	0.4871	0.4426	0.3579	0.1498	$-0.27e^{-02}$	$0.296e^{-01}$	−0.0004	9/5
24.07:28	3.67	0.5743	0.5135	0.4857	0.2364	$0.46e^{-02}$	$-0.206e^{-01}$	0.0011	10/5
24.09:35	2.11	0.5293	0.4620	0.3594	0.1890	$0.54e^{-02}$	$-0.369e^{-01}$	0.0010	10/3
24.10:05	1.50	0.4348	0.3143	0.3250	0.1050	$0.59e^{-01}$	$-0.131e^{+01}$	0.0062	10/3
24.14:00	4.29	1.0840	0.8812	0.7046	0.4274	$-0.48e^{-01}$	$0.638e^{-01}$	−0.0203	10/4
24.14:30	6.10	1.2165	1.3187	0.9295	0.5306	$0.17e^{-01}$	$-0.146e^{-01}$	0.0089	8/4
24.15:03	5.18	1.0385	1.1683	0.7732	0.3981	$-0.60e^{-02}$	$0.922e^{-02}$	−0.0024	8/6
24.15:33	9.79	0.9043	1.0895	0.7116	0.2837	$0.52e^{-02}$	$-0.158e^{-01}$	0.0015	8/6
24.16:06	4.74	1.2081	1.2749	0.7167	0.4154	$-0.33e^{-01}$	$0.475e^{-01}$	−0.0139	8/3
24.16:36	4.88	0.9840	0.9133	0.7438	0.4183	$1.00e^{-02}$	$-0.140e^{-01}$	0.0042	8/3
24.17:08	5.03	0.7497	0.9589	0.6841	0.3308	$0.15e^{-01}$	$-0.338e^{-01}$	0.0050	8/6

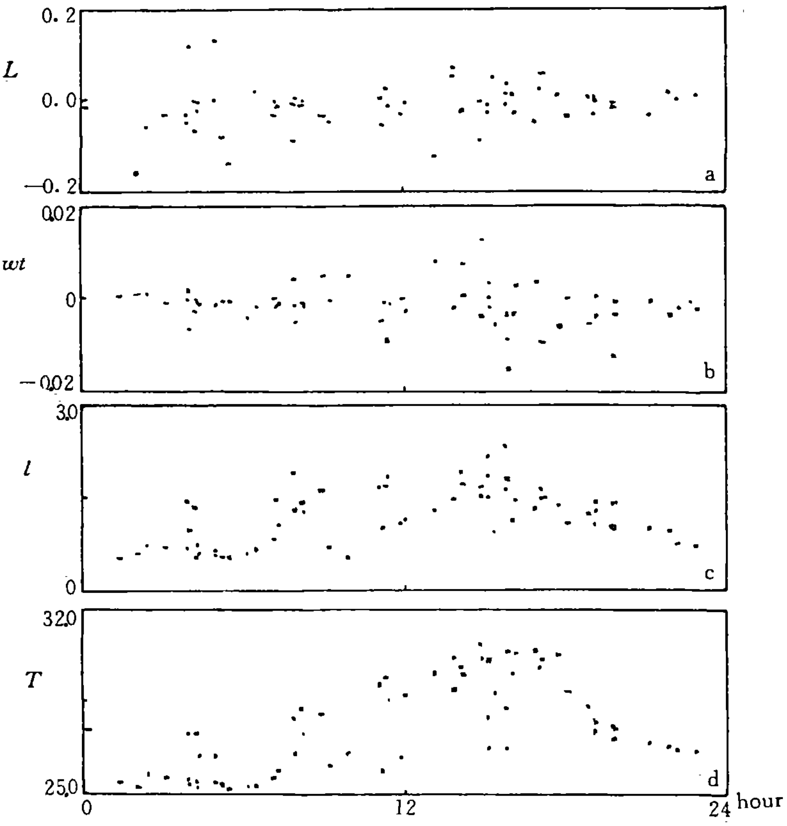

Fig. 1. Variation with time of M-O length (a), heat flux (b), turbulence energy (c) and mean temperature (d).

Fig. 1c describes the diurnal variation of turbulence energy $e = 1/2(\delta u^2 + \delta v^2 + \delta w^2)$. It is understood that the energy has remarkable diurnal variability by displaying smaller values at night than during the day in which the maximum is reached after midday, a pattern that differs from that for Z/L and thermal flux.

Fig. 1d tells the diurnal variation of mean temperature that consistently follows the variability, i. e. it responds to that for thermal effects. Fig. 1 illustrates that thermal variability is covered up by the dynamic effect for characteristic quantities with superposition of thermal and dynamic effects.

2. *Relationship between turbulence intensity and stability*

$\delta_{u,v,w}/U_*$ is the function of Z/L in the Monim-Obukhov's theory of similarity. Their relationship is fitted into

$$\frac{\delta_u}{U_*} = 3.268(1 - 0.487Z/L)^{1/3} \tag{1}$$

$$\frac{\delta_v}{U_*} = 3.037(1 - 0.646Z/L)^{1/3} \tag{2}$$

$$\frac{\delta_w}{U_*} = 2.24(1 - 0.311Z/L)^{1/3} \qquad Z/L \leqslant 0 \tag{3}$$

$$\frac{\delta_w}{U_*} = 2.45\,(1 + 0.582Z/L)^{1/3} \qquad Z/L > 0. \qquad (4)$$

Similarly, Merry and Panofsky (1976) obtained the relationship of $\delta_{u,v,w}/U_*$ with Z/L and recommended the use of it, and Xu and Li (1993) also worked it out, in their "Micro-scale turbulence structure and spectral features of near-surface atmosphere in Guangzhou", for coastal cities. The relationship of δ_i/U_* to Z/L obtained here by the formula agrees with the "1/3th power" law that is derived by the similarity theory. From the table, one sees that it is largely the same with that by Merry et al., though with our coefficient being, on the one hand, higher and indicative of larger intensity of turbulence in all directions, and on the other, closer to that by Xu et al. (1993) that great intensity in both the vertical and horizontal exist in coastal regions where the near-surface turbulence comes more strongly than that over flat, homogeneous underlying surface.

Table 2. The comparison of relationship of several $\delta_{u,v,w}/U_*$ and Z/L.

	Z/L	−1.0	−0.1	0.1	1.0
Merry (1976)	δ_u/U_*	2.46	2.32	2.28	2.12
	δ_w/U_*	1.98	1.36	1.40	1.97
Xu Yumao (1993)	δ_u/U_*	2.56	2.37	2.33	2.09
	δ_w/U_*	2.02	1.49	1.56	2.35
Current text	δ_u/U_*	3.73	3.32	3.21	2.62
	δ_w/U_*	2.45	2.26	2.50	2.85

3. *Analysis of turbulence spectrum*

The specturm is computed based on the temporal series of turbulent amount and by use of FFT and results of each of the velocity components are seen in Fig. 2 that is in logarithmic coordinates consisting of spectrum frequency of $f = nz/u$ on the abscissa and spectrum of $n \cdot s(n)/(\psi_e^{2/3} \cdot U_*^2)$ on the ordinate, both of which being dimensionless. Specifically,

$$\psi_e^{2/3} = \begin{cases} 1 + 0.5|Z/L|^{2/3} & -2 < Z/L < 0 \\ 1 + 0.25|Z/L|^{3/5} & 0 < Z/L < +2 \end{cases} \qquad (5)$$

Fig. 2 compares the spectra of U, V and W for a given stability Z/L. As revealed by the shape in three successive days (being 22, 23 and 24 July in the top, middle and bottom panels, respectively), the spectra are marked by the following features. (1) The mean spectrum at the higher section of frequency is basically conformable to the "−2/3 th power" law in the inertial subrange. (2) At the lower section of frequency, greater dissociation appears with decreasing tendency for U, V and W, respectively, in terms of spectral value. The value is much smaller for the W spectrum than the other two. (3) Over the transitional area between the inertial subrange and energy-included zone, the spectrum shows a multipeak pattern and does not decrease monotonously with f for a certain narrow amplitude of dimensional frequency (about 0.3 s^{-1}). Instead, it gradually increases and then sharply decreases for a small range of frequency, constituting an obvious unimodal distribution. It suggests that some wave forcing over a segment of high frequency has complicated the shape of spectra in atmospheric motion. The complex shape is a particular case, though how the wave effect is triggered off at specific frequency re-

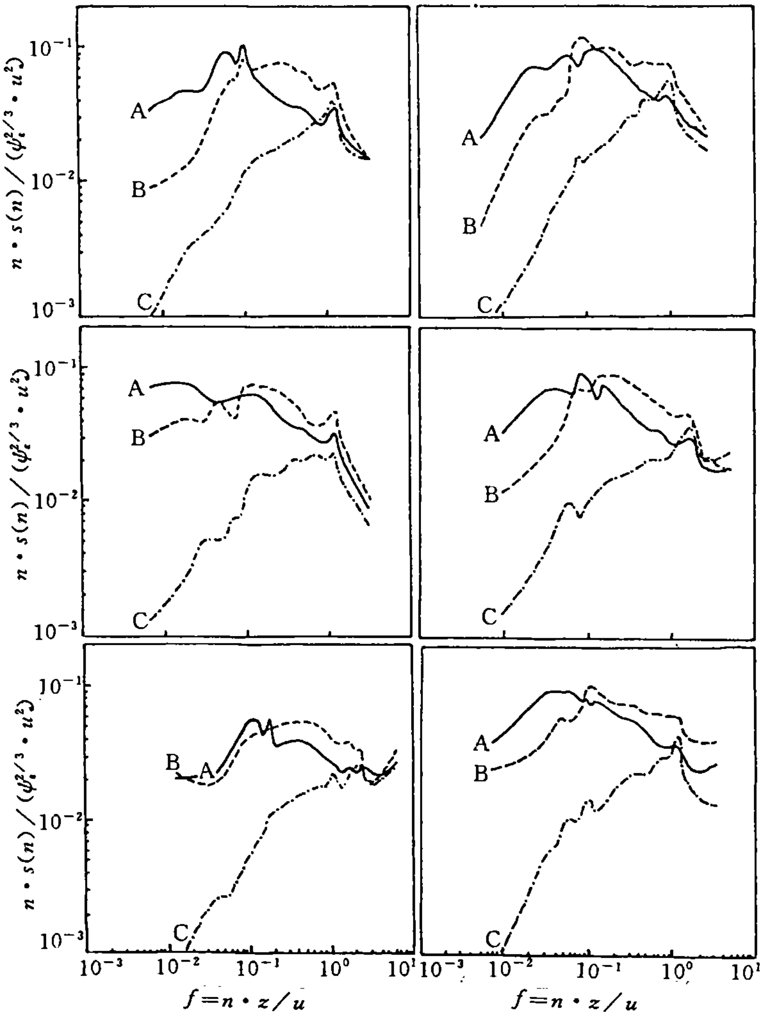

Fig. 2. The comparison of U, V, W spectra, the lines of A, B, C stand for U, V, W spectra respectively. Top left: $Z/L = -2.9 \times 10^{-3}$, right: $Z/L = 2.8 \times 10^{-3}$. Middle left: $Z/L = -5.8 \times 10^{-3}$, right: $Z/L = 1.5 \times 10^{-2}$. Bottom left: $Z/L = -4.4 \times 10^{-2}$, right: $Z/L = 3.6 \times 10^{-3}$.

mains to further understand and discuss.

Under the condition of cloudy weather, the study got spectral shape and characteristics which are generally similar to those with fine weather. Specifically, the inertial subrange, the mean spectrum observes a pattern similar to the "$-2/3$ th power" law over the high frequency section and the tendency is for $U > V > W$ in terms of corresponding spectrum for a given frequency within the lower section. The difference is that the spectrum does not vary systematically with Z/L which in our study is changing for only a small range and weakly associated with individual velocity spectra. It may be attributable to cloud effects so that turbulence is resulted from superpositioned dynamic and thermal forcing, which is possibly overshadowed by the irregular forcing of former to have any apparent effects.

Ⅳ. CONCLUSIONS

a. Analyses in this work have indicated that considerable diurnal variability, i.e. it is low at night and high during the day with the maximum just after midday, is still true of turbulence energy with cloudy weather condition, despite the absence of the pattern usually accompanied with fine weather condition, like the regualr decrease of turbulence thermodynamics and the variation of the M-O length and thermal flux in a diurnal manner. The diurnal pattern shows as strongly in the mean temperature.

b. The turbulence intensity, $\delta_{u,v,w}/U_*$ and Z/L, are shown to observe the similarity law of "1/3 th power", though with higher value than with flat underlying surface, a phenomenon suggests very active turbulence for tropical coasts. The less obvious thermal effects in condition of near-neutral stability as shown in this paper may be attributed to greater contribution to turbulence by dynamic effects and corresponding underlying surface.

c. The spectrum is dissociatively distributed at the lower end of frequency while observing the "—2/3 th power " law in the inertial subrange at the higher one. It does not vary systematically with Z/L, due to the existence of cloud effects that have weakened the relationship between the spectrum and the stability Z/L.

REFERENCES

Kaimal J C, Wyngaard J C, Isumi Y, et al., Spectral characteristics of surface layer turbulence, *Quart. J. Roy. Meteor. Soc.*, 1972, **98**: 563-589.

Kaimal J C, Wyngaard J C, Haugen D A, et al. 1976. Turbulence structure in the convective boundary layer, *J. Atmos. Sci.*, **33**: 2152-2169.

Kaimal J C, Evarsole R A, Lenschow D H, 1982. Spectral characteristic of the convective boundary layer over uneven terrain, *J. Atmos. Sci.*, **39**: 1098-1114.

Merry M, Panofsdy H A., 1976. Statistic of vertical motion over land and water, *Quart. J. R., Meteor. Soc.*, **102 (431)**: 255-263.

Panofsky H A, Larko D, Lipschutz R, et al., 1982. Spectra of velocity components over complex terrain, *Quart. J. Roy. Meteor. Soc.*, **108**: 215-230.

Wang Jiemin, 1992. Turbulence characteristics at the near-surface layer for valley-located cities, *Scientia Atmospherica Sinica*, **16** (1): 11-17. (in Chinese)

Wang Lizhi, Zhang Xiaoping, Wang Xiaoxi, et al., 1985. Preliminary study of turbulence characteristics of near surface atmospheric layer in suburbs, *Scientia Atmospherica Sinica*, **9** (1): 11-18. (in Chinese)

Xu Yumao, Li Zongkai, 1993. The micro-structure of turbulence and spectral features of near-surface layer of atmosphere in Guangzhou, *Scientia Atmospherica Sinica*, **17** (3): 338-348. (in Chinese)

Ye Zhuojia, Zhu Cuijuan, Li Xingsheng, et al., 1983. Micro-structures and spectral features of severe thundery clouds at the boundary layer. *Scientia Atmospherica Sinica*, **7** (2): 162-169.

Zhang Aicheng, 1991. Structure of atmospheric turbulence for the outskirts and its outlaying regions of Beijing, *Scientia Atmospherica Sinica*, **15** (4): 87-96. (in Chinese)

Zhu Wenqin, Zhu Cuijuan, Li Xingsheng, 1994. Characteristics of turbulence spectra in different weather processes under unstable conditions. *Acta Meteorologica Sinica*, **8**: 296-304. (in Chinese)