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Analysis of Turbulence Characteristics over the Northern Tibetan Plateau Area

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ABSTRACT

Based on CAMP/Tibet [Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau] turbulent data collected at the Bujiao (BJ) site of the Nagqu area, the turbulent structure and transportation characteristics in the near surface layer during summer are analyzed. The main results show that the relationship between the normalized standard deviation of 3D wind speed and stability satisfies the similarity law under both unstable and stable stratifications. The relations of normalized standard deviation of temperature and specific humidity to stability only obey the “$-1/3$ power law” under unstable conditions. In the case of stable stratifications, their relations to stability are dispersing. The sensible heat dominates in the dry period, while in the wet period, the latent heat is larger than the sensible heat.

Key words: normalized standard deviation, eddy correlation method, turbulent flux

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1. Introduction

The mass and energy exchange between the land surface and atmosphere plays a key role in the land-surface processes. Through various thermal and dynamical processes, the Tibetan Plateau affects the atmospheric circulation through the atmospheric boundary layer. The plateau has been the subject of climate research for several decades because of its topographic characteristics and its influence on the energy and water cycles on both regional (e.g., Asia monsoon) and global (e.g., El Niño) scales (e.g., Flohn, 1957; Yeh et al., 1957; Liu et al., 2003). The onset of the Asian Summer monsoon coincides with the reversal of the meridional temperature gradient in the upper troposphere south of the Tibetan Plateau, resulting from the large temperature increases in May to June over Eurasia and centered on the plateau (Li and Yanai, 1996). At the same time, the mass and energy exchange between the land surface and atmosphere mainly depends on the turbulent processes. Before the onset of the monsoon, the plateau is the major energy source by providing sensible heat flux to the atmosphere (e.g., Li and Yanai, 1996). During the rainy season, the latent heat released to the atmosphere is the dominant heat source over the eastern plateau, whereas the sensible heat flux is comparable to the latent heat flux over the western plateau (e.g., Chen et al., 1985). Therefore, measurements of the land-atmosphere physical processes and the determination

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of the variation of turbulence parameters help us to obtain better parameterization schemes of the atmospheric boundary layer over the Tibetan Plateau. Over the past 50 years, scientists have paid much attention to this kind of research over the Tibetan Plateau. The first Qinghai-Xizang Plateau Meteorological Experiment held in 1979 obtained some important results: during the dry period, the sensible heat flux is the major energy source to provide heat to the atmosphere, whereas the latent heat flux is larger than the sensible heat flux in the wet period (Zhang et al., 1988). Many observations (Ji et al., 1986) on the Tibetan Plateau ground surface have improved our understanding of the land-atmosphere interaction. In summer, the plateau surface is a heat source, and in the dry period the sensible heat flux is the major heat source; during the rainy season, the latent heat flux becomes as important as the sensible heat flux (Qian et al., 1997). Several studies about turbulent structure have been conducted for different regions of the Tibetan Plateau (Qi et al., 1996; Ma et al., 2002). For instance, Yeh and Gao (1979) obtained a vertically integrated mean heat source of 138 W m^{-2} over the western plateau in June, whereas Chen et al. (1985) estimated it as 37 W m^{-2}. This large discrepancy was caused by the different drag coefficients used in the bulk method, resulting in the sensible heat fluxes differing by a factor of 2–3. Li et al. (2001) reported a wide range of drag coefficients (i.e., 2.5×10^{-3} to 12×10^{-3}) over the plateau despite the use of the same data. Latent heat flux can be estimated as a residual of the surface energy budget. However, this approach is prone to error because a significant imbalance (10%–40%) in the energy budget on the plateau has been reported (e.g., Kim et al., 2001; Bian et al., 2002). The flux-variance method was probably first introduced by Tillman (1972). Over the past decades, this method has been extensively tested. However, this extension has caused debates and its correctness is still in question (e.g., Bink and Meesters, 1997; Katul and Hsieh, 1997). When sensible heat H_{VAR} and latent heat fluxes λE_{VAR} from the flux-variance method are compared to the eddy covariance fluxes (H_{EC} and λE_{EC}) for the same period, they agree within 5% (Choi et al., 2004). In this paper, using the sonic data collected during the period from 18 April to 12 June 2004 in CAMP/Tibet [Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau], we analyzed the relationship between the Monin-Obukhov similarity parameter z/L and the normalized standard deviation of three-dimensional wind speed, temperature and humidity, and we also obtained the variance of turbulent flux with changes of different averaging periods by the eddy correlation method. The aim of this study is to better understand the land-atmosphere interaction on the Tibetan Plateau.

2. Field observation and instruments

CAMP/Tibet has been conducted successfully in the Nagquarea located in the central Tibetan Plateau (31.37°N, 91.9°E, 4534 m above m. s. l.). Its surface is essentially flat and open. Prior to the Asian summer monsoon period, the surface is very dry and covered by dry grass; and the surface becomes wet, and the grass starts to grow at the onset of the Asian summer monsoon. A turbulent flux measurement [sonic anemo-thermometer (KAIJO-DA600)] was set up at 20 m above the ground at the Bujiao (BJ) site. The precision of the horizontal wind speed is better than 0.04 m s^{-1}, while that of the vertical wind speed is better than 0.02 m s^{-1}. The density of water vapor and concentration of carbon dioxide was obtained by an LI-7500 device. The instruments respond quickly to the information, and have also been used stably for a long time in the field. The data logging system is the CR5000 control system. The measurement frequency of the eddy system is 10 Hz, and the flux data are output every 30 minutes.

3. Data analysis and methodology

The field turbulence data, after removing noise and bad records caused by instrument failures, are given every 30 minutes. The momentum flux (τ), sensible heat flux (Q_{H}), latent heat flux (Q_{E}) and other parameters were calculated by the eddy correlation technique. Their expressions are as follows:

$$\text{Friction velocity} \quad u_* = \sqrt{|\overline{-u'w'}|}\ , \tag{1}$$

$$\text{Characteristic temperature} \quad T_* = -\frac{\overline{w'T'}}{u_*}\ , \tag{2}$$

$$\text{Characteristic specific humidity} \quad q_* = -\frac{\overline{w'q'}}{u_*}\ , \tag{3}$$

$$\text{Stability parameter} \quad \zeta = -\frac{zTu_*^3}{kg\overline{w'T'}}\ , \tag{4}$$

$$\text{Momentum flux} \quad \tau = -\rho\overline{u'w'}\ , \tag{5}$$

$$\text{Sensible heat flux} \quad Q_{\mathrm{H}} = \rho c_p\overline{w'T'}\ , \tag{6}$$

$$\text{Latent heat flux} \quad Q_{\mathrm{E}} = L\rho\overline{w'q'}\ , \tag{7}$$

where L is the Monin-Obukhov length, θ and ρ are potential temperature and air density respectively, κ is Von Karman's constant ($\kappa = 0.4$), g is the acceleration of gravity, c_p is the air specific heat, and λ is the vaporization heat. $\zeta = z/L$ is the atmospheric stability parameter. z is the observational height (here, $z = 20$

m).

4. Results

4.1 *Turbulent structure*

According to the Monin-Obukhov hypothesis, standard deviations of 3D wind speed, temperature and specific humidity, normalized by the scaling parameters (u_*, T_*, q_*) should be universal functions of z/L. The relevant non-dimensional forms are mainly

$$\sigma_a/u_* = \Phi_a(z/L),\ \ a = u, v, w\ , \tag{8}$$

$$\sigma_T/|T_*| = \Phi_T(z/L)\ , \tag{9}$$

$$\sigma_q/|q_*| = \Phi_q(z/L)\ , \tag{10}$$

where Φ_a, Φ_T, and Φ_q are the universal functions of 3D wind speed, temperature and specific humidity respectively. A free convection asymptotic analysis shows that $\sigma_w/u_* \propto (-z/L)^{1/3}$ and, $\sigma_\theta/|T_*| \propto (-z/L)^{1/3}$ and based on observational data, the proportional constants are 1.90 and 0.95 respectively (Wyngaard, 1971). At neutral stratification, the standard deviations of 3D wind speed, temperature and specific humidity, when normalized by appropriate powers of the scaling parameter u_*, should become constant, that is, $\sigma_w = Au_*$, $\sigma_v = Bu_*$, $\sigma_w = Cu_*$. Panofsky and Dutton (1984) summarized some observations in uniform terrain and presented a mean value of $\sigma_w/u_* = 1.25$. They also recommended an empirical form for the unstable situation:

$$\sigma_w/u_* = 1.25(1 - 3z/L)^{1/3} \quad (z/L \leqslant 0)\ . \tag{11}$$

This is commonly referred to in the literature. In stable air, considering the low accuracy in determining σ_w, u_*, and other factors, Panofsky and Dutton still recommend setting σ_w/u_* to a constant value of 1.25, i.e. its neutral state value.

Figure 1 shows the variations of σ_u/u_*, σ_v/u_*, and σ_w/u_* versus stability obtained from the CAMP/Tibet observations at the BJ site of the Nagquarea. Compared to σ_w/u_*, both σ_u/u_* and σ_v/u_* are more scattered. Because they are influenced by the large horizontal wind field, in the strongly unstable situation ($z/L \leqslant 0.3$), the normalized standard deviations between the 3D wind speeds obey the 1/3 law proportion, for which the similarity formulas are:

$$\sigma_u/u_* = 2.803(1 - 3z/L)^{1/3}\ \ z/L \leqslant -0.3\ , \tag{12}$$

$$\sigma_v/u_* = 2.799(1 - 3z/L)^{1/3}\ \ z/L \leqslant -0.3\ , \tag{13}$$

$$\sigma_w/u_* = 1.214(1 - 3z/L)^{1/3}\ \ z/L \leqslant -0.3\ . \tag{14}$$

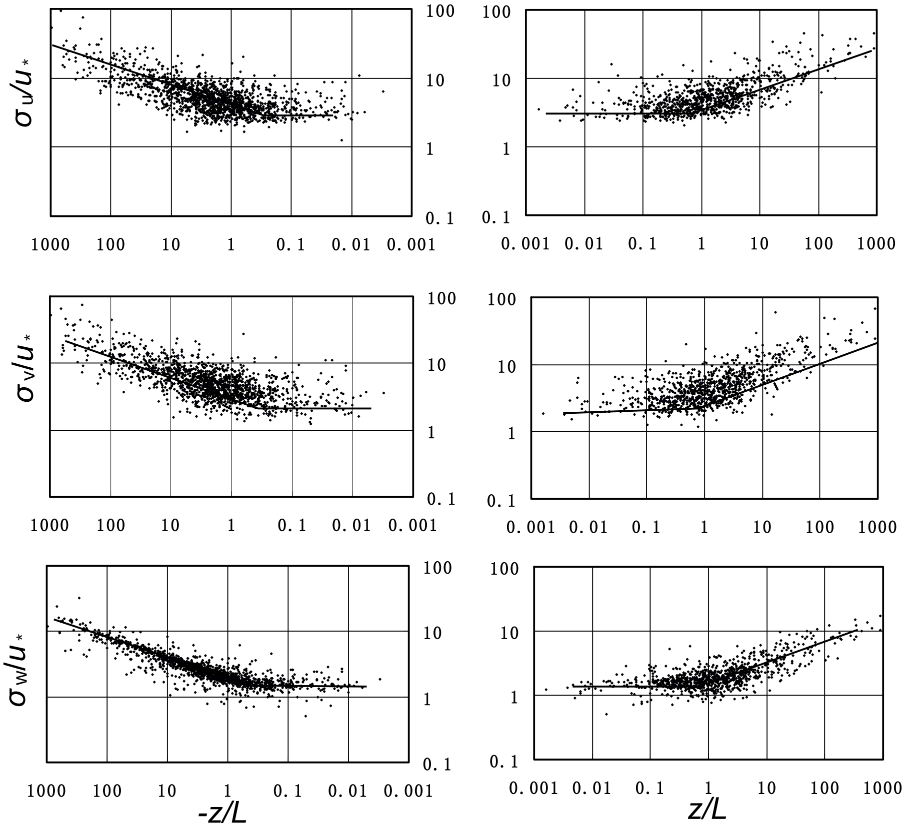

Fig. 1. The relationship between the normalized standard deviation of the three-dimensional wind speed fluctuation and stability.

Table 1. Non-dimensional covariance values under neutral stratification.

Site	$\sigma_u/u_* = A$	$\sigma_v/u_* = B$	$\sigma_w/u_* = C$	
Nagqu BJ site (20 m)	2.803	2.799	1.214	This study
Nagqu BJ site (2.85 m)	3.13	–	1.12	(Choi et al., 2004)
Wudaoliang	2.98	2.91	1.35	(Qi et al., 1995)
Changdu	3.45	3.15	1.30	(Bian et al., 2001)
Erie, Colombia (gurgitation terrain)	2.65	2.00	1.20	(Panofsky et al., 1977)
Rock Springs, Pennsylvania (same as above)	3.20	2.90	1.24	(Panofsky et al., 1977)
Rock Springs, Pennsylvania (mountainous area)	4.50	3.80	1.24	(Panofsky et al., 1977)

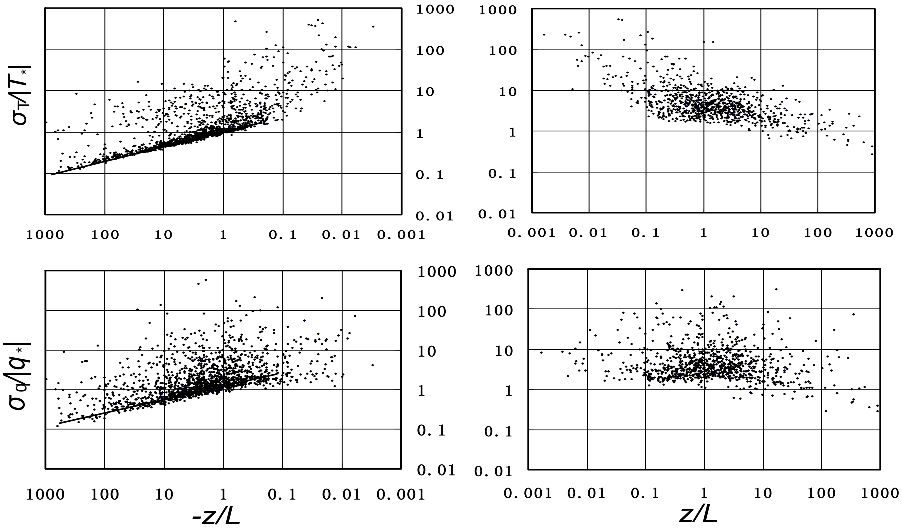

Fig. 2. The relationship between the normalized standard deviation of the temperature fluctuation (and the specific humidity fluctuation) and stability.

For neutral stratification, the universal functions become constant, that is:

$$\sigma_u/u_* = A,\ \sigma_v/u_* = B,\ \sigma_w/u_* = C. \quad (15)$$

Here, the above similarity functions hold the values $A = 2.803$, $B = 2.799$, $C = 1.214$.

Table 1 lists the constants in neutral stratification at the Nagquarea and other places. It shows that the values at the BJ site are consistent with those of the Wudaoliang area (Qi et al, 1995). The values for C are almost the same at all locations, which indicates that the influence of horizontal wind is more than that of vertical wind. Yet the value C increases with height at the BJ site. The data used in this study were observed at 20 m, and the data of Choi et al. (2004) were observed at 2.85 m above the ground.

Normalized covariance of temperature and specific humidity in the unstable situation are:

$$\sigma_T/|T_*| = \beta(-z/L)^{-1/3}\ , \quad (16)$$

$$\sigma_q/|q_*| = \beta(-z/L)^{-1/3}\ , \quad (17)$$

where β is a constant. Figure 2 shows the relation of the normalized covariances of temperature with specific humidity with stability. In unstable stratification, the relation of $\sigma_T/|T_*|$ and z/L is nearly satisfied with the $-1/3$ power law. The formula is:

$$\sigma_T/|T_*| = 1.544(1 - 3z/L)^{1/3} \quad z/L \leqslant -0.3\ . \quad (18)$$

In the stable situation, $\sigma_T/|T_*|$ decreases with the increase of stability, but its universal relation is not clear.

Based on the mixing length concept, Panofsky and Dutton (1984) introduced a formula for unstable and neutral stratification,

$$\sigma_T/|T_*| = 5(1 - 16z/L)^{-1/2} \quad (z/L \leqslant 0)\ . \quad (19)$$

By using turbulent data from HEIFE observations, Wang et al. (1993) obtained a formula for strongly unstable conditions:

$$\sigma_T/|T_*| = 0.96(z/L)^{-1/3} \quad (z/L \leqslant -0.35)\ . \quad (20)$$

Bian et al. (2001) gave the following functional form for $\sigma_T/|T_*|$ in their study at the Changdu site :

$$\sigma_T/|T_*| = 1.0(1 - 3z/L)^{-1/3} \quad z/L < 0\ . \quad (21)$$

Compared to the above results, the relation between $\sigma_T/|T_*|$ and z/L at the BJ site of the Nagqu

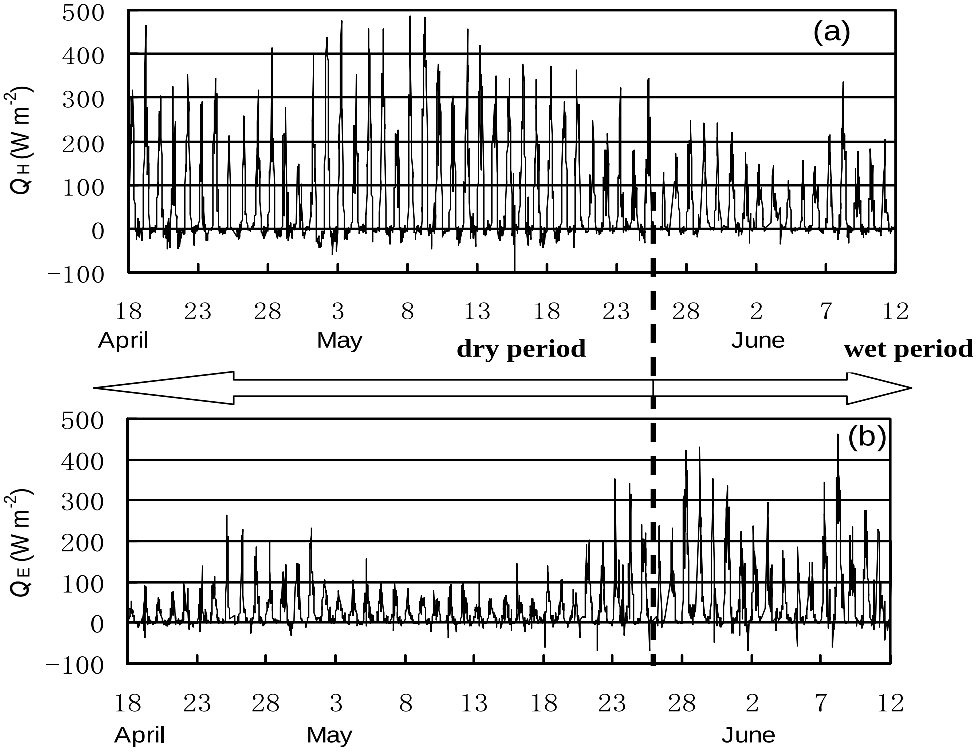

Fig. 3. The hourly variation of (a) sensible heat flux ($Q_{\rm H}$) and (b) latent flux ($Q_{\rm E}$) from 18 April to 12 June. The date of 26 May separates the period from the wet period.

area agrees with the result of Bian et al. (2001), and it is clearly different from the result of Panofsky and Dutton. The relation between $\sigma_T/|T_*|$ and z/L can be seen in Fig. 2. The data points are highly scattered under neutral stratification. The reason for this may be the low turbulent thermals in the weak convection; therefore it is difficult to make a precise observation and the result shows the absence of order.

Though the scattering of $\sigma_q/|q_*|$ is higher than that of $\sigma/|T_*|$, the formula of $\sigma_q/|q_*|$ and stability obeys the power law of $-1/3$ in the unstable situation:

$$\sigma_q/|q_*| = 3.35(-z/L)^{-1/3} \quad z/L \leqslant -0.3 \,. \tag{22}$$

There is much scattering in the stable situation. Hogstrom smedman-Hogstrom (1974) found that the constant β has a value of 1.04. Therefore, the value of β is bigger than that in the plains, and smaller than the result $\beta = 5.3$ by Bian et al. (2001).

4.2 *Transfer characteristics of turbulent flux*

Li et al. (1999) studied the variance of turbulent flux in the Gaize area of the western Tibetan Plateau by using the eddy correlation technique. The daily averaged sensible heat flux is 53 W m^{-2}, while the daily averaged latent heat flux is 28 W m^{-2} by using 13 days of data in June. Li et al. (1997) showed that the sensible heat flux was above 80 W m^{-2} in June. The sensible heat flux and latent heat flux calculated by the eddy correlation technique obtained in this study from 18 April to 12 June 2004 are shown in Fig. 3. The time of the experiment is separated into two periods: dry and wet. During the dry period, the sensible heat flux is bigger than the latent heat flux, with a daily maximum over 400 W m^{-2}, which is larger than the result of Bian et al. (2001), 300 W m^{-2}, while the latent heat does not exceed 100 W m^{-2}, it is also bigger than that from the southeastern Tibetan Plateau, 40 W m^{-2}, (Bian et al., 2001). During the wet period, the daytime latent heat flux is larger than the sensible heat flux, increasing to a daily maximum over 400 W m^{-2}, which is due to the increased precipitation which is a result of the water vapor content in the wet period.

Figure 4 shows the average diurnal variation of sensible heat flux and latent heat flux during the dry period and wet period respectively. In both periods, the diurnal variations are very obvious: from 0800 LST, with the sun increasing in altitude both fluxes increase to their maximums at 1400 LST in the afternoon, followed by their decrease. During the dry period, the range of increase in sensible heat flux is bigger than during the wet period. The maximum value reaches 243 W m^{-2}, close to the result calculated in the western Tibetan Plateau of 200–240 W m^{-2} (Li et al., 1999), where as the maximum value of the latent heat flux is 90 W m^{-2}. In the wet period, the reverse is true, i.e. the latent heat flux is larger than the sensible flux,

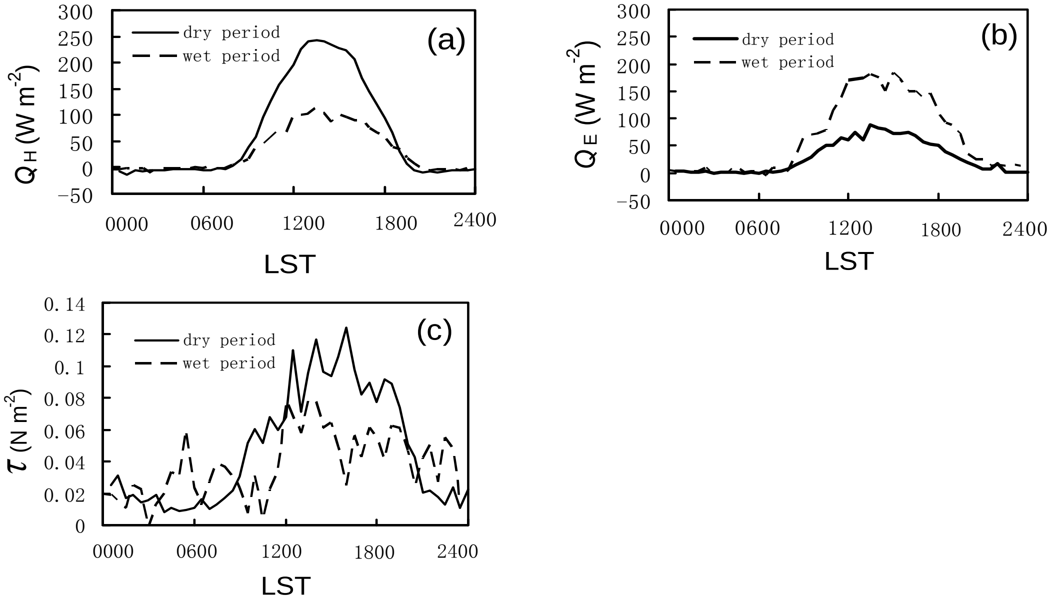

Fig. 4. The average diurnal variation of the turbulence flux over the Nagqu area of the northern of Tibetan Plateau. (a) the diurnal variation of sensible heat flux during the dry and wet periods, (b) the diurnal variation of latent heat flux, and (c) the diurnal variation of momentum flux. Note: The local time is 2 hours later than Beijing Standard Time.

and the maximum value of the latent heat flux is 181 W m^{-2} and that of the sensible heat flux is 133 W m^{-2}.

The diurnal variation of momentum flux is shown in Fig. 4c; it is also very obvious during the dry period. From 0800 LST, the momentum flux increases as the sun increases in altitude; at 1600 LST, it reaches its maximum and then decreases towards evening. During the wet period, the diurnal variation of momentum flux is complex; the momentum flux in the daytime is distinctly lower than that during the dry period, caused by a manifold increase of water vapor during the wet period. At night, the momentum flux increases due to the release of energy absorbed by the plateau grassland in the daytime.

5. Discussion and conclusions

In this paper, the relationship between normalized covariance and stability is studied. The normalized covariance of the vertical wind was in better agreement with the law of similarity theory than the horizontal wind. The normalized covariance of 3D wind speed obeys the power law of 1/3. The normalized covariance of temperature and specific humidity satisfies the power law of $-1/3$ only in unstable conditions, it shows a very big discrepancy under neutral stratification, but this is reduced with the increase of stability under stable conditions.

The variation of turbulent flux is different during the dry and wet periods. During dry period, the daytime sensible heat flux is larger than the latent heat flux, while during the wet period, the latent heat flux is larger than the sensible heat flux. The diurnal variation of turbulent flux is very obvious. During the dry period, the daily average of sensible heat flux reaches a maximum of 243 W m^{-2}, and the daily average of latent heat flux reaches a maximum of 90 W m^{-2}. During the wet period, the latent heat flux is larger than the sensible heat flux; the daily average latent heat flux reaches a maximum of 181 W m^{-2}, and the daily average sensible heat flux reaches a maximum of 133 W m^{-2}. The diurnal variation of momentum flux is also very obvious, increasing in the morning to its maximum in the afternoon, and then decreasing. During the wet period, it is complex; the daytime momentum flux is lower than that during the dry period, yet it still increases at night.

This is only a preliminary analysis of similarity and turbulent flux in the northern Tibetan Plateau. Further systematic research is necessary in the near future.

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REFERENCES

Bian Lingen, Lu Longhua, Cheng Yanjie, Lu Changgui, Yao Zhanyu, Xu Qiangde, and Chen Lianshou, 2001: Turbulent measurement over the southeastern Tibetan Plateau. *Quarterly Journal of Applied Meteorology*, **12**(1), 1–13. (in Chinese)

Bian, L., Z. Gao, Q. Xu, L. Lu, and Y. Cheng, 2002: Measurements of turbulence transfer in the near-surface layer over the southeastern Tibetan Plateau. *Bound. Layer Meteor.*, **102**, 281–300.

Bink, N. J., and A. G. C. A. Meesters, 1997: Comment on "Estimation of surface heat and momentum fluxes using the flux-variance method above uniform and non-uniform terrain" by Katul et al. (1995). *Bound.-Layer Meteor.*, **84**, 497–502.

Chen, L., E. R. Reiter, and Z. Feng, 1985: The atmosphere heat source over the Tibetan Plateau: May-August 1979. *Mon. Weather. Rev.*, **113**, 1771–1790.

Choi, T., and Coauthors, 2004: Turbulent exchange of heat, water vapor, and momentum over a Tibetan prairie by eddy covariance and flux variance measurements. *J. Geophys. Res.*, **109**, D21106, 10.1029/2004JD004767.

Flohn, H., 1957: Large-scale aspects of the "summer monsoon" in South and East Asia. *J. Meteorology. Soc. Japan*, the 75th Anniversary Volume, 180–186.

Hogstrom, U., and A. S. Smedman-Hogstrom, 1974: Turbulence mechanics at an agricultural site. *Bound.-Layer Meteor.*, **7**, 374–388.

Ji Guoliang, Yao Lanchang, Yuan Fumao, and Yang Huayi, 1986: Characteristics of surface and atmosphere heating field over the Tibetan Plateau in winter in 1982. *Science in China*(*B*), **31**(8) 876–888. (in Chinese)

Katul, G., and C. L. Hsieh, 1997: Reply to the comment by Bink and Meesters. *Bound.-Layer Meteor.*, **84**, 503–509.

Kim, J., and Coauthors, 2001: On measuring and modeling surface energy partitioning in a Tibetan prairie during GAME-IOP 1998. *Proceedings of the Fifth International Study Conference on GEWEX in Asia and GAME*, World Climate Research Programme(WCRP), Nagoya University, Nagoya, Japan, 18–25.

Li, C., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast. *J. Climate*, **9**, 358–375.

Li, C., T. Duan, S. Haginoya, and L. Chen, 2001: Estimates of the bulk transfer coefficients and surface fluxes over the Tibetan Plateau using AWS data. *J. Meteor. Soc. Japan.*, **79**(2), 625–635.

Li Dongliang, Zhang Jijia, and Wu Hongbao, 1997: Diagnosis study of sensible heat flux unnormal on the Tibetan Plateau. *Plateau Meteorology*, **16**(4), 367–375. (in Chinese)

Li Jialun, Hong Zhongxiang, Luo Weidong, Li Aiguo, and Zhao Yijun, 1999: A study of surface fluxes in Gerze Area, Qinghai-Xizang Plateau. *Chinese Journal of Atmospheric Sciences*, **23**(2), 142–151. (in Chinese)

Liu, Xiaodong, J. E. Kutzbach, Z. Liu, Z. An, and L. Li, 2003: The Tibetan Plateau as amplifier of orbital-scale variability of the East Asian monsoon. *Geophys. Res. Lett.*, **30**(16), 1839, doi:10.1029/2003GL017510.

Ma Yaoming, Ma Weiqiang, Hu Zeyong, Li Maoshan, Wang Jiemin, H. Ishikawa, and O. Tsukamoto, 2002: Similarity Analysis of Atmospheric Turbulent intensity over Grassland Surface of Qinghai-Xizang Plateau. *Plateau Meteorology*, **21**(5), 514–517. (in Chinese)

Panofsky, H. A., and J. A. Dutton, 1984: *Atmospheric Turbulence*. John Wiley and Sons, New York, 397pp.

Qian Zhengan, and Jiao Yanjun, 1997: Advances and problems on Qinghai-Xizang Plateau meteorology research. *Advances in Earth Sciences*, **12**(3), 207–216. (in Chinese)

Qi Yongqiang, Wang Jiemin, Jia Li, Liu Wei, Ma Yaoming, and Ren Yanxia, 1996: A study of turbulent transfer characteristics in Wudaoliang area of Qinghai-Xizang Plateau. *Plateau Meteorology*, **15**(2), 172–174. (in Chinese)

Tillman, J. E., 1972: The indirect determination of stability, heat and momentum fluxes in the atmospheric boundary layer from simple scalar variables during unstable conditions. *J. Appl. Meteorol.*, **11**, 783–792.

Wang Jiemin, Liu Xiaohu, and Ma Yaoming, 1993: Atmospheric turbulent structure and transfer characteristics in HEIFE Gobi area. *Acta Meteorologica Sinica*, **51**(3), 343–349.

Wyngaard, J. C., O. R. Cote, and Y. Izumi, 1971: Local free convection, similarity, and the budgets of shear stress and heat flux. *J. Atmos. Sci.*, **28**, 1171–1182.

Yeh Duzheng, and Gao Youxi, 1979: *The Meteorology of the Qinghai-Xizang* (*Tibet*) *Plateau*. Science Press, Beijing, 278pp. (in Chinese)

Yeh, T.-C., S. -Y. Dao, and M. -T. Li, 1957: The abrupt change of circulation over the Northern Hemisphere during June and October. The *Atmosphere and the Sea in Motion, Rossby Memorial Volume*, Rockefeller Institute Press, Albany, New York, 249-267.

Zhang Jijia, Zhu Baozhen, Zhu Fukang, Weng Duming, Sun Guowu, Lu Junning, Peng Yongqing, and Wang Yuanzhong, 1988: *Advances in the Qinghai-Xizang Plateau Meteorology*. Sciences Press, Beijing, 268pp. (in Chinese)