SURFACE FLUX PARAMETERIZATION IN THE TIBETAN PLATEAU

KUN YANG*
Core Research for Evolutional Science and Technology (CREST), the University of Tokyo, Tokyo, Japan

TOSHIO KOIKE and DAWEN YANG
The University of Tokyo, Tokyo, Japan

(Received in final form 29 January 2002)

Abstract. This study investigates some basic aspects related to surface-flux parameterization in the Tibetan Plateau, based on the measurement at three sites. These sites are essentially flat and covered by very sparse and short grasses in the monsoon season. The main contributions include: (1) an optimization technique is proposed to estimate aerodynamic roughness length based on wind and temperature profiles. The approach is not sensitive to random measurement errors if the number of data samples is large enough. The optimized values reasonably vary with surface characteristics. (2) At the three sites, kB^{-1} (the logarithm of the ratio of aerodynamic roughness length to thermal roughness length) experiences seasonal and diurnal variations in addition to a dependence on surface types. The mean values for the individual sites vary over a range of 2.7 to 6.4 with large standard deviations. (3) A formula for estimating the value of kB^{-1} is proposed to account for the effect of seasonal variation of aerodynamic roughness length and diurnal variation of surface temperature. With the formula, the flux parameterization with surface temperature estimates sensible heat flux better than profile parameterization for all the sites.

Keywords: GAME-Tibet, Roughness length, Surface-flux parameterization, Surface temperature, Tibetan Plateau.

1. Introduction

As the largest and highest plateau in the world, the Tibetan Plateau affects the atmospheric circulation through land surface processes in addition to direct topographic influences. On the plateau, the temperature and energy partition experience not only a strong diurnal variation due to intensive solar radiation but also dramatic seasonal variations due to frequent rainfall during the Asian summer monsoon period (Ye and Gao, 1979; Zhou et al., 2000). Because the heat and water vapour from the surface are directly transported vertically to warm and moisten the middle troposphere over the Plateau, the land-atmosphere interactions not only affect the development of the local boundary layer but also change the horizontal gradient of temperature and moisture at a continent scale. Therefore, the energy and water

* Corresponding author and address: Dr. Kun Yang, River Lab., Dept. of Civil Engineering, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan.
E-mail: yangk@hydra.t.u-tokyo.ac.jp

Boundary-Layer Meteorology **116:** 245–262, 2003.

cycles over the plateau are believed to play an important role in the evolution of the Asian summer monsoon system (see e.g., Yanai et al., 1992; Yanai and Li, 1994; Wu and Zhang, 1998). To clarify the land-atmosphere interactions over the Tibetan Plateau in the context of the Asian monsoon system, an observation project was initiated in 1998: GAME-Tibet, i.e., the GEWEX (Global Energy and Water Cycle Experiment) Asian Monsoon Experiment (GAME) in the Tibetan Plateau (Koike et al., 1999). Based on the observations, several studies have reported a surface energy imbalance problem (Ishikawa et al., 1999; Tanaka et al., 2001; Yang and Koike, 2001), and our numerical experiments with a simple biosphere model also show the difficulties in reproducing the high surface temperature in the dry season. In order to clarify these problems and to model the hydrological processes and climate variability, it is important to investigate the surface-flux parameterization for the Tibetan Plateau. Unfortunately, systematic studies on flux parameterization in the plateau are scarce (Li et al., 2000; Gao et al., 2000), because of the lack of observations. The GAME-Tibet project provides unique opportunity to study diurnal and seasonal variations of surface energy partition, because the data obtained through the project cover a long period, from pre-monsoon to post-monsoon during 1998.

Heat flux parameterization with surface temperature introduces a parameter kB^{-1}, i.e., the logarithm of the ratio of aerodynamic roughness length z_{m0} to thermal roughness length z_{h0}. The length z_{h0} is the height at which the temperature extrapolated from its profile in the inertial layer equates to the surface temperature; some researchers (e.g., Malhi, 1996; Verhoef et al., 1997) suggested that z_{h0} is simply a mathematically fitting parameter with little physical basis. Unfortunately, it is difficult to determine z_{h0} or kB^{-1}, because they vary with both surface type and meteorological conditions. For homogenous vegetation, the value $kB^{-1} = 2$ recommended by Garratt and Francey (1978) and Garratt (1992) is widely used, although Brutsaert (1982) found lower values for high and dense vegetation and Sun (1999) found a diurnal variation of kB^{-1} for a homogenous grass surface. For a bare soil surface, Verhoef et al. (1997) suggested a small and negative value of kB^{-1} for one smooth surface, but Stewart et al. (1994) found a value 4.5 for another rough surface. For sparse vegetation, heat transfer is essentially from both the ground surface and the vegetation. Kohsiek et al. (1993) found a single value of kB^{-1} for a semi-arid area with sparse vegetation of grasses and herbs. Sun and Mahrt (1995) also derived a simple expression of z_{h0} for their specific sites, but its generality is not known and they did not recommend using it in modelling studies. More researchers (Blyth and Dolman, 1995; Blümel, 1999; Massman, 1999) use dual-source models to derive a thermal roughness length for a single-source model; so kB^{-1} may be determined by many input quantities in dual-source models. For example, using 'localized near-field' Lagrangian theory, Massman (1999) showed that kB^{-1} can be influenced by foliage density, leaf size, sheltering effects, wind speed, and other meteorological conditions. Blümel (1999) pointed out that the concept of kB^{-1} may become senseless for a snow surface with sparse vegetation.

Therefore, the determination of kB^{-1} for partly vegetation-covered surfaces is particularly complex. Blyth and Dolman (1995) commented that 'any meteorological model using a fixed value of z_{h0} to represent the heat transfer properties of a sparse surface is introducing errors. A dual-source model is the ideal method of representing sparse terrain'.

In the experimental area of GAME-Tibet, the land surface is essentially flat. Before the onset of the summer monsoon, the surface is very dry and characterized by bare soil; after the onset of the summer monsoon, the surface becomes very wet and partially covered with grasses; these are very short (tens of millimetres only) and leaves are slender. To quantitatively understand the vegetation effect on heat transfer, we calculated the energy partition on the surface by a dual-source model, which shows that the ground surface contributes more than 80% of the total sensible heat flux while the vegetation shares less than 20%, therefore, the surface can be approximately deemed as a single-source one from the viewpoint of heat transfer, and thus the concept of kB^{-1} is applicable on the plateau. However, this does not mean that vegetation is not important for the surface flux parameterization, because it can affect the roughness length and thus the value of kB^{-1}. This paper, using the GAME-Tibet data at three sites, will study the magnitude of roughness lengths and their determination, and clarify the effect of the sparse vegetation on both momentum and heat transfer in the Tibetan Plateau.

2. Data

In the mesoscale region shown in Figure 1, a GAME-Tibet intensive observing period (IOP) was implemented during May–September 1998, during which a large number of observational data were obtained (see web site: http://monsoon.t.u-tokyo.ac.jp/tibet/). At Anduo PBL, Naqu FX and MS3478 PAM, both turbulence quantities and temperature profiles were measured, and the quantities and sensors are shown in Table I for the individual sites. The measurement system included a fast response system for measuring turbulent quantities and a slow response system for measuring wind, temperature and moisture profiles. The surface temperature was measured using an infrared thermometer (at MS3478) or two infrared radiometers (at Anduo and Nagu); because the vegetation is so short the observed temperature is not sensitive to the view angle. Turbulent fluxes were computed as 30-min averages using the eddy-correlation technique, but most of the momentum flux data were missed at Anduo and Naqu. Data quality was controlled through spectrum analyses (for fast response measurements), manual inspection of all the time series, and consistency checks among overlapping or related measurements.

The obtained data at Anduo PBL, Naqu FX and MS3478 PAM are used in this study. To avoid anomalous results, data are rejected when (i) a data set (surface temperature, air temperature profile, wind speed profile, sensible heat flux) is incomplete, (ii) sensible heat flux is less than 10 W m^{-2}, or (iii) the temperature

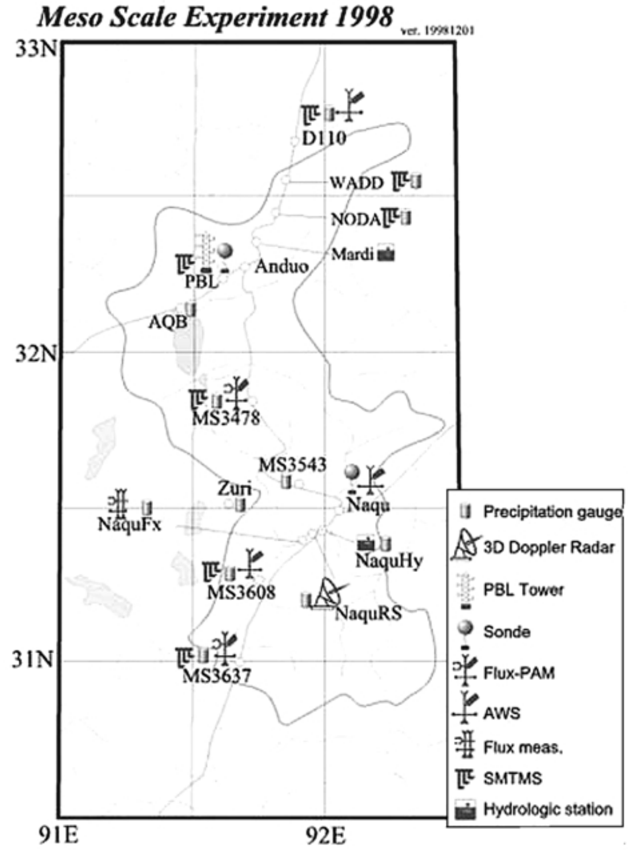

Figure 1. The observing network in the mesoscale region of GAME-Tibet.

difference between two levels is less than 0.1 K, or the wind speed difference between two levels is less than 0.1 m s^{-1}. After the data filtering, we retain 1755 data sets during May 21 to September 10 for Anduo PBL, 1180 during June 6 to September 14 for Naqu FX, and 946 during May 8 to July 2 for Ms3478.

3. Data Analysis

3.1. Profile Flux Parameterization

Flux-gradient relationships in the surface layer can be described with Monin–Obukhov similarity theory. Given air potential temperature θ_1, θ_2 at levels z_{h1} and z_{h2}, and wind speed U_1, U_2 at levels z_{m1} and z_{m2}, the following equations can be derived from the similarity theory:

$$\frac{U_2 - U_1}{u_*} = \frac{1}{k}\left[\ln\frac{z_{m2}}{z_{m1}} - \psi_m(z_{m1}/L, z_{m2}/L)\right], \tag{1a}$$

TABLE I
The measurement system of meteorological quantities at Anduo, Naqu and MS3478 sites.

Site	Items	Level (m)	Sensor
Anduo	Wind speed and direction	1.9, 6.0, 14.1	Ogasawara FF-11 aerobane
PBL	Air temperature	1.55, 5.65, 13.75	Vaisala HMP35D Pt-100
	Humidity	1.55, 5.65, 13.75	Electric capacitance (ibid)
	Surface temperature		Eppley PIR radiometer
	Wind fluctuation	2.85	Kanjo DAT-300 sonic anemometer
	Temperature fluctuation	2.85	Kanjo DAT-300 sonic anemometer
	Humidity fluctuation	2.85	Kanjo AH-300 infrared hygrometer
Naqu	Wind speed and direction	0.7, 1.3, 2.2, 3.5	03100 wind sentry set
FX	Air temperature	1.3, 3.5	HMP35C temperature probe
	Humidity	1.3, 3.5	HMP35C humidity probe
	Surface temperature		CNR1 radiometer
	Wind fluctuation	2.9	CSAT3 3-D sonic anemometer
	Temperature fluctuation	2.9	FW05 fine thermocouple
	Humidity fluctuation	2.9	KH20 krypton hygrometer
Ms3478	Wind speed and direction	5.6	Propeller-vane Anemometer
PAM			Model-09101
	Air temperature	2.3, 7.8	Vaisala 50Y
	Humidity	2.3, 7.8	Vaisala 50Y
	Surface temperature		Everest 400.4G- IR thermometer
	Friction velocity	2.85	Gill SAT-R3A
	Sensible heat flux	2.85	Gill SAT-R3A
	Latent heat flux	2.85	Gill SAT-R3A + Bandpass
			TRH (Vaisala 50Y)

$$\frac{(\theta_2 - \theta_1)}{\theta_*} = \frac{Pr_0}{k}\left[\ln\frac{z_{h2}}{z_{h1}} - \psi_h(z_{h1}/L, z_{h2}/L)\right], \tag{1b}$$

where

$$\psi_m(z_{m1}/L, z_{m2}/L) = \int_{z_{m1}/L}^{z_{m2}/L} \frac{(1-\phi_m(z/L))}{z/L} d(z/L), \tag{2a}$$

$$\psi_h(z_{h1}/L, z_{h2}/L) = \int_{z_{h1}/L}^{z_{h2}/L} \frac{(1-\phi_h(z/L)/Pr_0)}{z/L} d(z/L), \tag{2b}$$

$$\phi_m = \begin{cases} 1 + 5.3z/L & z/L \geq 0 \\ (1-19z/L)^{-1/4} & z/L < 0, \end{cases} \tag{3a}$$

$$\phi_h = \begin{cases} Pr_0(1 + 8.0z/L) & z/L \geq 0 \\ Pr_0(1 - 11.6z/L)^{-1/2} & z/L < 0. \end{cases} \tag{3b}$$

Here, all the symbols in Equations (1)–(3) have their common meaning. The coefficients in Equation (3) are suggested by Högström (1996), the von Karman constant $k = 0.4$, the Prandtl number $Pr_0 = 1$ if $z/L \geq 0$ and $Pr_0 = 0.95$ if $z/L < 0$. The buoyancy length L is solved by an analytical method (Yang et al., 2001) to improve computational efficiency. The turbulent fluxes in the surface layer can then be calculated using

$$\tau = \rho u_*^2, \tag{4a}$$

$$H = -\rho c_p u_* \theta_*, \tag{4b}$$

where τ is the surface stress, H is the sensible heat flux, ρ is the air density and c_p is the air specific heat.

The above parameterization is based on wind and temperature at two levels, so it is referred to as the profile flux parameterization. For the three GAME-Tibet sites, the comparison between the observations and parameterized heat fluxes is shown in Figures 2a–c, which indicate that the similarity theory is applicable in the Tibetan Plateau, especially at Anduo.

3.2. THE DETERMINATION OF z_{m0}

Aerodynamic roughness length z_{m0} can be derived from wind and temperature profiles. Using the wind profile under neutral conditions to determine z_{m0} is a common approach (e.g., Kohsiek et al., 1993; Grimmond et al., 1998; Zhou et al., 2000), but it is sensitive to measurement errors. Moreover, this approach rejects a large number of valuable datasets under non-neutral conditions and does not work well in some cases. Schaudt (1998) proposed a new method to select a high quality dataset for estimating z_{m0}, and a robust application of his method requires more than four observation heights be taken, but the observation at the three sites does not meet this condition (note: there are three heights at Anduo, four at Naqu and two at MS3478, see Table I). Here, we propose a new approach to derive the value of z_{m0}, when such conditions are not met.

Since z_{m0} is physically related to the underlying surface and not sensitive to the diurnal variation of atmospheric stability (Sun, 1999), we can assume z_{m0} is constant over short periods of time (for example, 10 days). Therefore, z_{m0} can be obtained by minimizing the cost function below:

$$J = \sum_t \sum_{i=1}^{n} \left\{ u_*^t - kU_i^t \Big/ \left[\ln \frac{z_{mi}}{z_{m0}} - \psi_m(z_{m0}/L^t, z_{mi}/L^t) \right] \right\}^2 \tag{5}$$

where n is the number of measurement levels and t represents time serials of data.

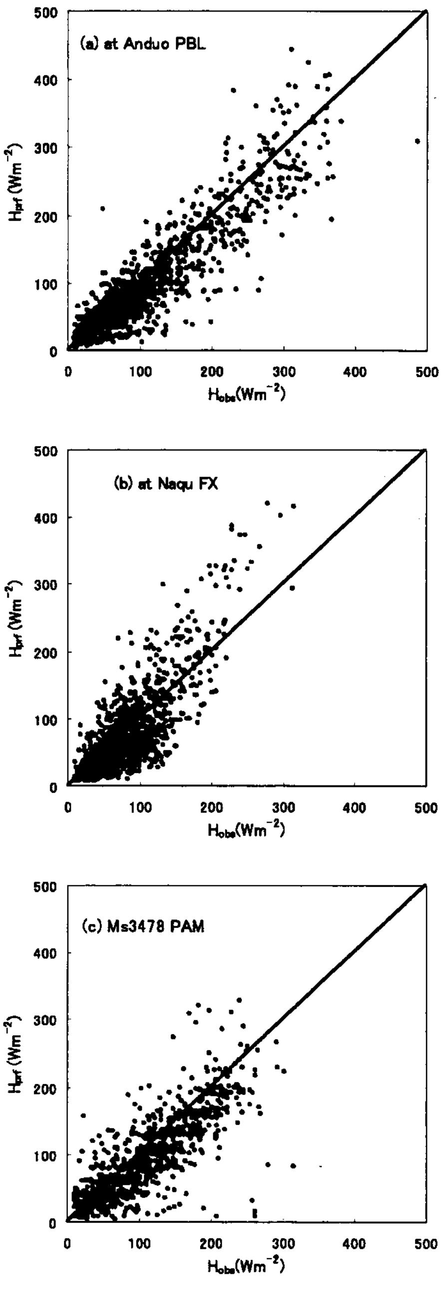

Figure 2. Sensible heat flux comparison between observed (H_{obs}) and profile parameterization (H_{prf}), (a) at Anduo PBL, (b) at Naqu FX, (c) at MS3478 PAM.

Since u_* and L can be obtained from observations or derived from profile parameterization with Equations (1)–(4), the value of the cost function varies only with z_{m0}. If the number of data sets is large enough, the effect of random measurement errors can be removed.

Figure 3a shows the variation of z_{m0} obtained through the method for the individual sites. The figure shows (i) the order of the magnitude of z_{m0} is from 0.001 to 0.01 m; (ii) z_{m0} for Anduo and Naqu is smaller than that for MS3478 before the monsoon season, because the surfaces at Anduo and Naqu are relatively smooth, compared to that at MS3478, which is rough earth hammock; (iii) z_{m0} increases from the pre-monsoon season to the monsoon season for all sites, which reflects the vegetation effect on momentum transfer at individual sites. As shown in Figure 3b, the vegetation biomass (represented by the NDVI) at Anduo is obviously smaller than at Naqu, which results in a smaller value of z_{m0} at Anduo.

3.3. THE DETERMINATION OF kB^{-1} OR z_{h0}

The values of kB^{-1} or z_{h0} can be derived from the surface temperature, and wind speed and temperature profiles. The thermal roughness length z_{h0} is defined through

$$\frac{(\theta - \theta_{\mathrm{sfc}})}{\theta_*} = \frac{PR_0}{k}\left[\ln\frac{z_h}{z_{h0}} - \psi_h(z_{h0}/L, z_h/L)\right] \tag{6}$$

where θ_{sfc} is the surface temperature and θ is air temperature in the surface layer.

With u_*, θ_* and L derived from the profile flux parameterization, kB^{-1} can be easily determined through Equation (6). Considering that the value of kB^{-1} may vary with the growth phase of vegetation, we classify the observing period into three phases: before June 20, the surfaces are nearly bare soil; June 20 to July 31, the surfaces are partially covered by growing grasses; after July 31, the surfaces are partially covered by mature grasses.

The derived mean values and standard deviations of kB^{-1} are shown in Table II for each phase and individual sites. The mean values depend on both sites and periods, and vary over a range of 2.7 to 6.4. In Table II, the value of kB^{-1} for a rough surface (MS3478) is larger than that for a relatively flat surface (Anduo and Naqu); a similar tendency is found in some previous studies (Stewart et al., 1994; Verhoef et al., 1997). It is suggested that the roughness length may play an important role in the estimation of kB^{-1}.

On the other hand, the large standard deviations of kB^{-1} shown in Table II imply that it is not reliable to use a mean value for surface flux parameterization. As shown in Figure 4, kB^{-1} also experiences diurnal variations, with small values in the morning and in the later afternoon, and large values at noon and in the early afternoon. A similar diurnal variation was found by Verhoef et al. (1997) for a bare soil surface. Brutsaert and Sugita (1996) and Kustas (1989) argued that the variation of kB^{-1} for a sparse vegetation surface might depend on the solar angle or

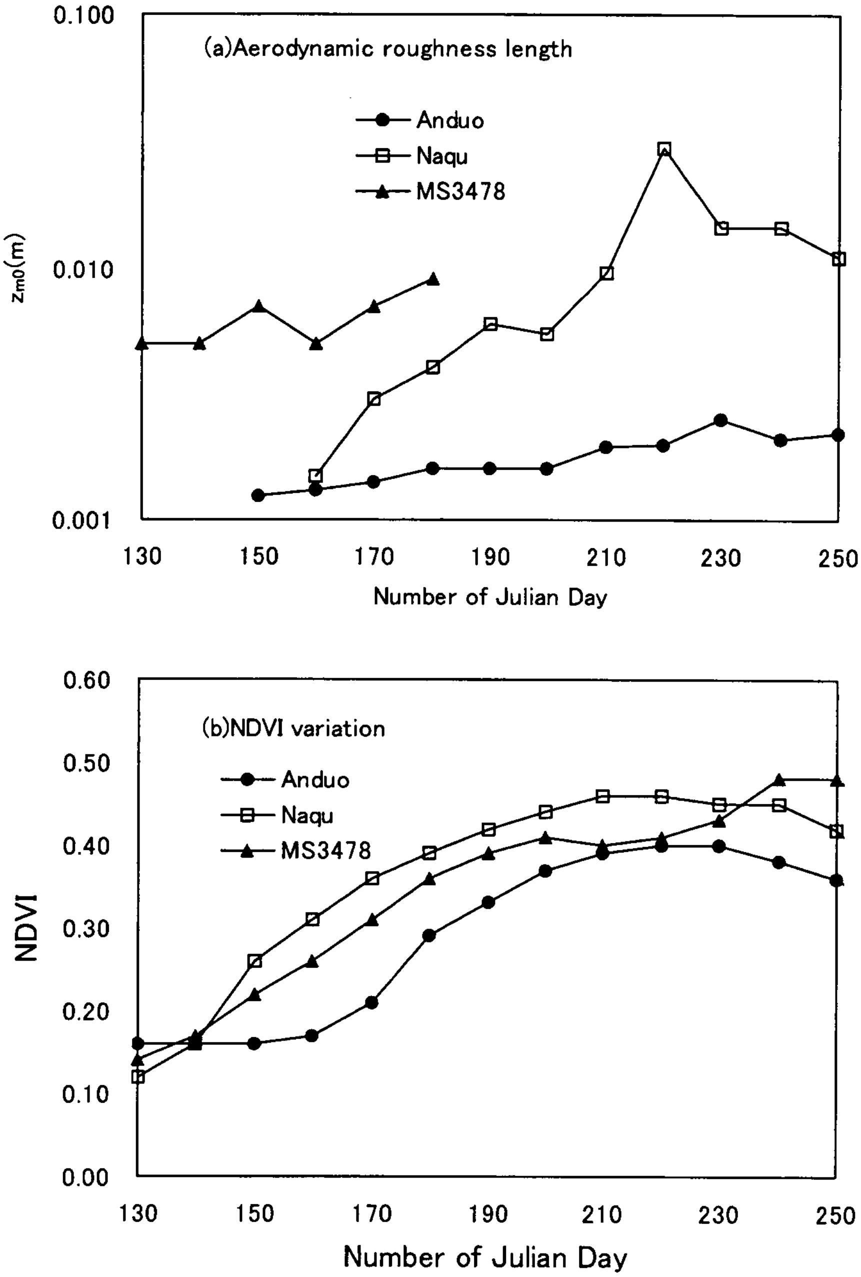

Figure 3. (a) Aerodynamic roughness length derived through an optimization method, (b) seasonal variation of NDVI at Anduo, Naqu and MS3478.

TABLE II

Mean values and standard deviation of kB^{-1} at Anduo, Naqu and MS3478.

Site	June 20		June 21–July 31		August 1	
	kB^{-1}	σ	kB^{-1}	σ	kB^{-1}	σ
Anduo	5.07	1.45	3.73	1.77	2.74	1.23
Naqu	3.75	1.44	4.62	2.41	5.28	2.99
MS3478	6.35	2.37	6.30	3.34	–	–

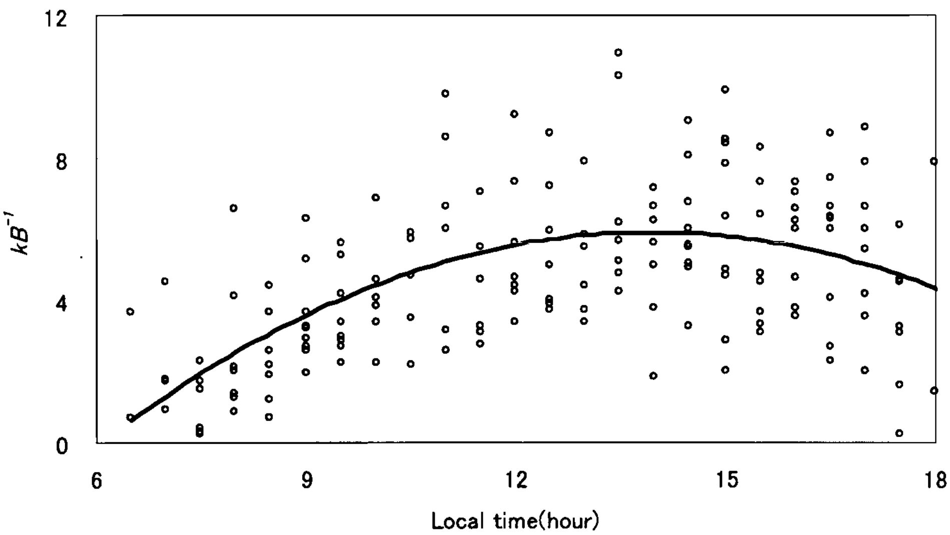

Figure 4. The diurnal variation of kB^{-1} at Anduo PBL during the first 10 observing days,

the zenith angle of infrared radiometers, although the similar variation of kB^{-1} for bare soil surfaces cannot be explained with this argument. Instead, kB^{-1} perhaps depends on the surface-air temperature difference.

The authors tested several previous formulae (Owen and Thomson, 1963; Thom, 1972; Brutsaert, 1982), but none reasonably estimated the diurnal and seasonal variations of kB^{-1} (not shown). Kustas et al. (1989) assumed

$$kB^{-1} = cU(\theta_{\text{sfc}} - \theta), \tag{7}$$

where the coefficient $c = 0.17$ was found for their specific surface, and it is likely that each surface type would require its own coefficient.

We calibrate the coefficient in Equation (7) for each site of interest by minimizing the mean bias error of sensible heat flux, and find that the coefficient is site

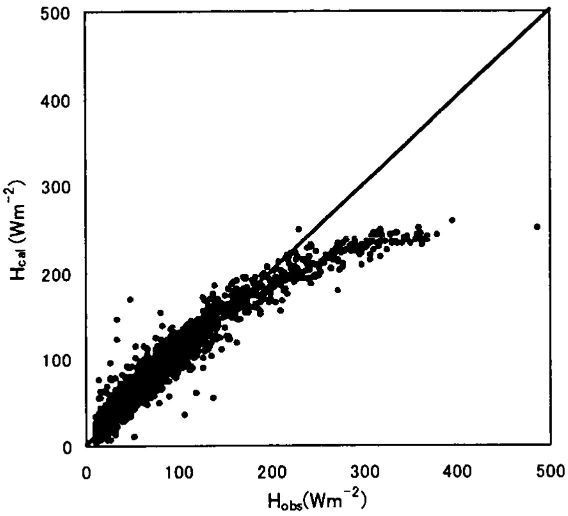

Figure 5. Sensible heat flux comparison between surface parameterization (H_{cal}) and observations (H_{obs}) at Anduo PBL.

dependent, $c = 0.032$ for Anduo, 0.095 for Naqu and 0.06 for MS3478. With Equation (7) and the coefficient for Anduo, the estimated heat flux is compared with the observed flux in Figure 5. Clearly, a lower heat flux is slightly overestimated while a higher heat flux is obviously underestimated. A similar problem is found for Naqu and MS3478, and their errors are shown in Table III. Therefore, although Equation (7) can give diurnal and seasonal variations of kB^{-1}, its magnitude is overestimated when $(\theta_{\text{sfc}} - \theta) \gg 1$ K.

The above data analysis suggests that kB^{-1} may depend on the wind speed, surface-air temperature difference and aerodynamic roughness length, so we propose the following formula to estimate the value of kB^{-1}:

$$kB^{-1} = 23.5 \frac{[kU/\ln(z_m/z_{m0})]^{1/2} |\theta_{\text{sfc}} - \theta_{\text{ref}}|^{1/4}}{\ln(z_{\text{ref}}/z_{m0})}, \tag{8}$$

where U is the wind speed at level z_m and θ_{ref} is the aerodynamic temperature at a reference level $z_{\text{ref}} = 1$ m. The power of 1/4 for $(\theta_{\text{sfc}} - \theta_{\text{ref}})$ is used to constrain the amplitude of the diurnal and seasonal variations. The constant 23.5 is calibrated at Naqu site, because the aerodynamic roughness length at this site covers a wide range. The performance of Equation (8) will be demonstrated in Section 3.4 and compared with Equation (7) in Section 4.

3.4. Flux Parameterization with Surface Temperature

Using z_{m0} shown in Figure 3a and kB^{-1} calculated from Equation (8), the flux can be parameterized with the surface temperature (the method is hereafter referred to

TABLE III

The mean bias errors (MBE), root mean square errors (RMSE) and correlation coefficients (R) of heat flux estimated by surface parameterization and profile parameterization at Anduo, Naqu and MS3478 sites.

Site	Method	MBE (Wm^{-2})	RMSE (Wm^{-2})	R
Anduo	Profile parameterization	10.8	32.2	0.918
PBL	Surface par. with Equation (7)	0.0	26.9	0.953
	Surface par. with Equation (8)	−2.8	19.0	0.971
Naqu	Profile parameterization	5.6	38.2	0.809
FX	Surface par. with Equation (7)	0.0	32.2	0.742
	Surface par. with Equation (8)	0.0	21.5	0.912
MS3478	Profile parameterization	18.2	42.1	0.810
PAM	Surface par. with Equation (7)	0	35.1	0.830
	Surface par. with Equation (8)	1.2	32.5	0.873

as surface parameterization). The parameterization requires setting in Equation (1) $U_1 = 0$, $\theta_1 = \theta_{sfc}$, $z_{m1} = z_{m0}$, and $z_{h1} = z_{h0}$.

Figure 6a shows the comparison of u_* between profile parameterization and surface parameterization at Anduo, while Figure 6b shows the comparison between observations and the surface parameterization at MS3478. Most of the observed u_* were missed at Anduo and Naqu. As indicated in these figures, the surface parameterization of u_* agrees well with that observed or parameterized with profiles. In turn, it indicates that the aerodynamic roughness length is reasonable.

The comparisons of sensible heat flux determined from surface parameterization and observations are shown in Figures 7a, b, respectively, for Anduo and MS3478. Again, the observed flux was derived by the eddy-correlation technique. These figures show a reasonable agreement between observation and parameterization. Table III shows the mean bias errors (MBE), root mean square errors (RMSE) and correlation coefficients (R) of profile parameterization, surface parameterization with Equation (7) and with Equation (8) at the three sites. It is shown that surface parameterization using Equation (8) gives lower MBE and RMSE and higher correlation coefficients than the other methods at all the sites. Sugita and Kubota (1994) reasoned that the surface-air temperature difference is usually much higher than the vertical air temperature differences within the surface layer, and thus the relative measurement error in the surface-air temperature difference may be less than that in the air temperature difference between two levels. As a result, it is possible that parameterization with surface temperature may give a better and more robust estimate of sensible heat flux than profile parameterization.

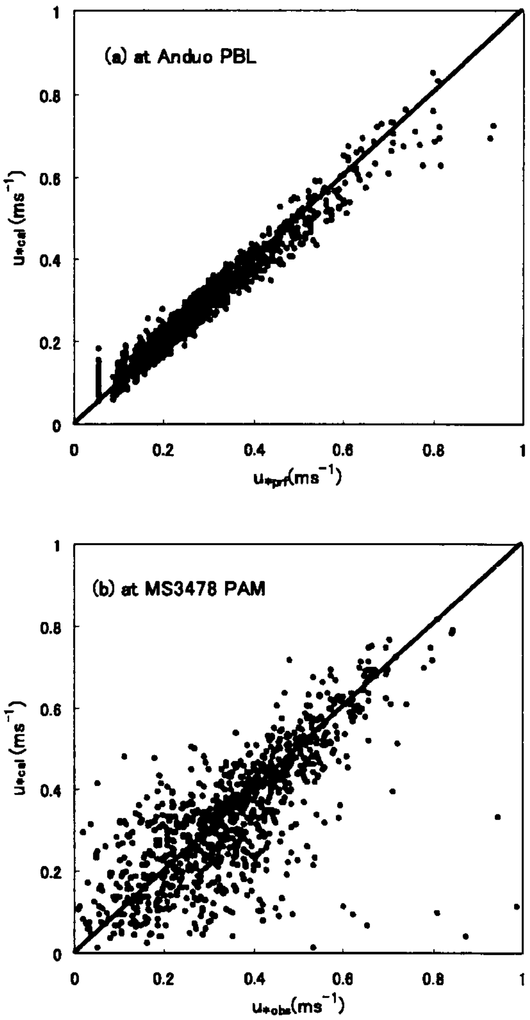

Figure 6. Frictional velocity comparison between surface parameterization ($u_{*\mathrm{cal}}$) and observations ($u_{*\mathrm{obs}}$) or profile parameterization ($u_{*\mathrm{prf}}$), (a) at Anduo PBL, (b) at MS3478 PAM.

Their presumption is demonstrated by our results, given that the value of kB^{-1} is estimated by Equation (8).

Note that Equation (8) can be applied to stable conditions for estimating kB^{-1} for the plateau surface although the above only shows the application for unstable conditions.

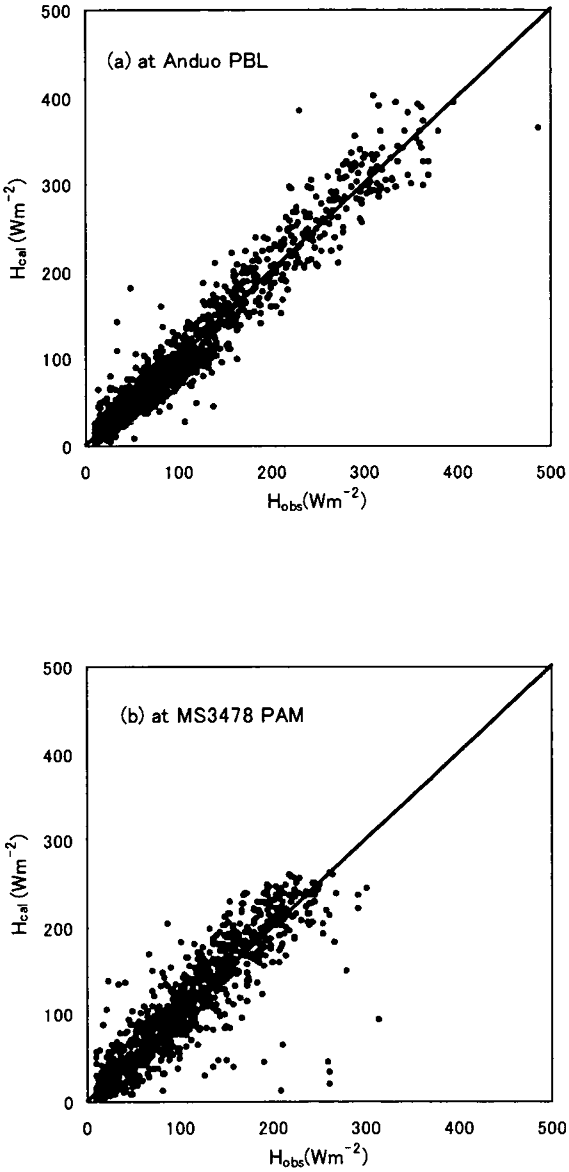

Figure 7. Sensible heat flux comparison between surface parameterization (H_{cal}) and observation (H_{obs}), (a) at Anduo PBL, (b) at MS3478 PAM.

4. Discussion: The Role of z_{m0} in Surface Flux Parameterization

The essential difference between Equation (7) and Equation (8) lies in the relationship between z_{h0} and z_{m0}. The value of z_{h0} increases with z_{m0} in Equation (7) while it decreases with z_{m0} in Equation (8). The difference can lead to very different estimates of the vegetation effect on heat transfer on the plateau. To explain it, we compare the performance of Equations (7) and (8) under ideal conditions: reference height $z = 5$ m, wind speed $U = 5$ m s^{-1}, surface-air temperature difference $\Delta T = 20$ K, air density $\rho = 0.69$ kg m^{-3}, and $z_{m0} = 0.001$ to 0.03 m (the range of z_{m0} at Naqu). Figure 8 shows the comparison of the parameterized fluxes, (a) for momentum and (b) for sensible heat. It shows that the formula of kB^{-1} does not much affect the parameterized momentum flux, but its effect on heat flux is great. When z_{m0} increases from 0.001 m to 0.03 m, the heat flux given by Equation (7) is almost doubled while that given by Equation (8) only has a small increase. The reason is that the simultaneous increase of z_{m0} and z_{0h} in Equation (7) results in a too quick increase of the heat exchange coefficient, whereas the exchange coefficient enhanced by the increase of z_{m0} can be limited by the decrease of z_{h0} in Equation (8). The latter case is consistent with the well-known knowledge that individual roughness elements at a surface may contribute greatly to momentum transfer through form drag, but little to the area-averaged heat transfer (Mahrt, 1996). Therefore, Equation (8) gives a more reliable estimate of kB^{-1} for a single-source model. The result also indicates that the increase of z_{m0} caused by vegetation mainly affects the momentum flux, but only slightly changes heat flux, on the plateau.

5. Summary

Surface flux parameterization is one of the crucial factors for modelling the energy and water cycles in the Tibetan Plateau. This study investigates the determination of the aerodynamic roughness length and thermal roughness length for the flux parameterization in the Tibetan Plateau, based on observations at three sites of GAME-Tibet project.

The land surface at the plateau can be deemed as a single-source surface from the viewpoint of heat transfer, so the concept of kB^{-1} is applicable. The determination of kB^{-1} depends on both surface characteristics and meteorological conditions. In the Tibetan Plateau, the mean values for different periods and for the individual sites vary in a wide range of 2.7 to 6.4, with large standard deviations because the value of kB^{-1} undergoes diurnal and seasonal variations. The authors propose a formula for estimating the value of kB^{-1}, which introduces the surface-air temperature difference, wind speed and aerodynamic roughness length to account for its temporal variations and the effect of z_{m0}. The essential point differing from other simple formulae is that kB^{-1} increases with the increase of z_{m0}, which is critical for correct heat flux parameterization. Using the new formula, flux parameterization with the surface temperature gives momentum and sensible heat fluxes in agreement with observations for all the sites. Since our study sites possess the typical surface characteristics of the Tibetan Plateau, and the study period lasts

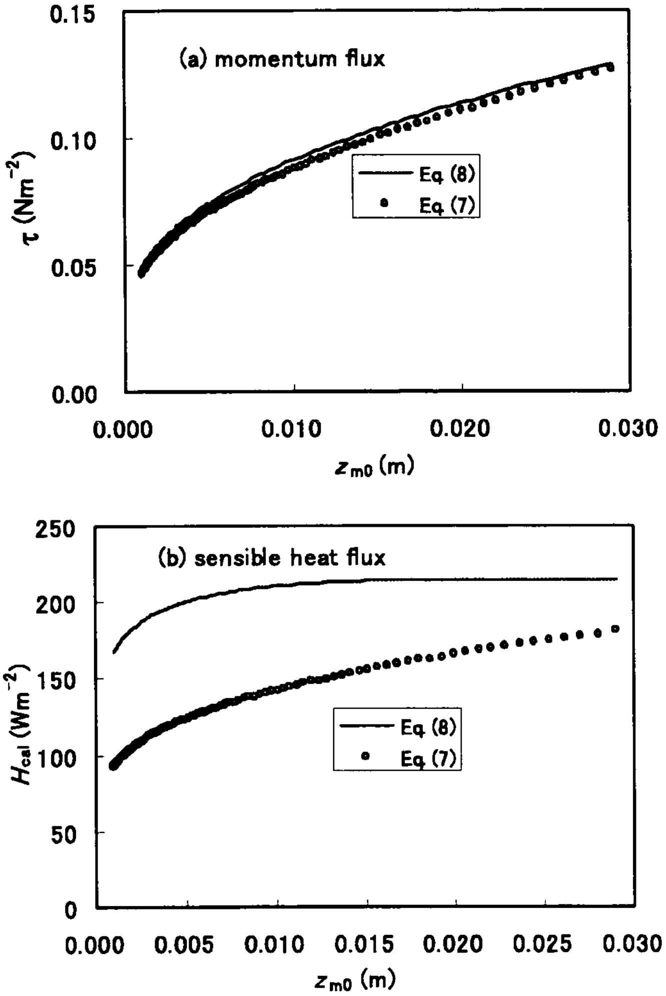

Figure 8. The variation of fluxes with aerodynamic roughness length under ideal conditions (see text for details). Fluxes are calculated with Equation (7) and with Equation (8), respectively; $c = 0.095$ in Equation (7).

from pre-monsoon to post-monsoon, the empirical formula for estimating kB^{-1} may represent a general relationship for the Tibetan Plateau.

Acknowledgements

The GAME-Tibet data used in this paper were obtained through the GAME-Tibet project supported by the Ministry of Education, Science, Sport and Culture of Japan, Science and Technology Agency of Japan, Chinese Academy of Science, Frontier Research System for Global Change, National Space Development

Agency, and Asian Pacific Network. The authors would like to express their acknowledgement to all the scientists involved in the tough fieldwork at Anduo PBL, Naqu FX and MS3478 PAM site. The authors also thank the anonymous reviewers for their valuable suggestions.

References

Blümel, K.: 1999, 'A Simple Formula for Estimation of the Roughness Length for Heat Transfer over Partly Vegetated Surfaces', *J. Appl. Meteorol.* **38**, 814–829.

Blyth E. M. and Dolman, A. J.: 1995, 'The Roughness Length for Heat of Sparse Vegetation', *J. Appl. Meteorol.* **34**, 583–585.

Brutsaert, W.: 1982, *Evaporation into the Atmosphere*, D. Reidel Publishing Company, Dordrecht, 299 pp.

Brutsaert, W. and Sugita, M.: 1996, 'Sensible Heat Transfer Parameterization for Surfaces with Anisothermal Dense Vegetation', *J. Atmos. Sci.* **53**, 209–216.

Gao, Z., Wang, J., Ma, Y., Kim, J., Choi, T., Lee., H., Asanuma, J., and Su., Z.: 2000, 'Study of Roughness Lengths and Drag Coefficients over Nansha Sea Region, Gobi, Desert, Oasis and Tibetan Plateau', *Phys. Chem. Earth (B)* **25**, 141–145.

Garratt, J. R.: 1992, *The Atmosphere Boundary Layer*, Cambridge University Press, Cambridge, 316 pp.

Garratt, J. R. and Francey, R. J.: 1978, 'Bulk Characteristics of Heat Transfer in the Unstable, Baroclinic Atmospheric Boundary Layer', *Boundary-Layer Meteorol.* **15**, 399–421.

Grimmond, C. S. B., King, T. S., Roth M., and Oke, T. R.: 1998, 'Aerodynamic Roughness of Urban Areas Derived from Wind Observations', *Boundary-Layer Meteorol.* **89**, 1–24.

Högström, U. L. F.: 1996, 'Review of Some Basic Characteristics of the Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **78**, 215–246.

Ishikawa, H., Hayashi, T., Tanaka, K., Tsukamoto, O., Fedeyasu, H., Tamagawa, I., Asanuma, J., and Qi, Y.: 1999, 'Summary and the Preminary Results of PBL Observation', in *Proceeding of the 1st International Workshop on GAME-Tibet*, January 11–13, 1999, Xi'an, China, pp. 73–76.

Kohsiek, W., Bruin, H. A. R., The, H., and Van Den Hurk, B.: 1993, 'Estimation of the Sensible Heat Flux of a Semi-Arid Area Using Surface Radiative Temperature Measurements', *Boundary-Layer Meteorol.* **63**, 213–230.

Koike, T., Yasunari, T., Wang, J., and Yao, T.: 1999, 'GAME-Tibet IOP Summary Report', in *Proceeding of the 1st International Workshop on GAME-Tibet*, January 11–13, 1999, Xi'an, China, pp. 1–2.

Kustas, W. P., Choudhury, B. J., Moran, M. S., Reginato, R. J., Jackson, R. D., Gay, L. W., and Weaver, H. L.: 1989, 'Determination of Sensible Heat Flux over Sparse Canopy Using Thermal Infrared Data', *Agric. For. Meteorol.* **44**, 197–216.

Li, G., Duan T., and Gong, Y.: 2000, 'The Bulk Transfer Coefficients and Surface Fluxes on the Western Tibetan Plateau', *Chinese Sci. Bull.* **45**, 1221–1226.

Mahrt, L.: 1996, 'The Bulk Aerodynamic Formulation over Heterogeneous Surfaces', *Boundary-Layer Meteorol.* **78**, 87–119.

Malhi, Y.: 1996, 'The Behavior of the Roughness Length for Temperature over Heterogeneous Surfaces', *Quart. J. Roy. Meteorol. Soc.* **122**, 1095–1125.

Massman, W. J.: 1999, 'A Model Study of for Vegetated Surfaces Using "Localized Near-Field" Lagrangian Theory', *J. Hydrol.* **223**, 27–43.

Owen, P. R. and Thomson, W. R.: 1963, 'Heat Transfer across Rough Surfaces', *J. Fluid. Mech.* **15**, 321–334.

Schaudt, K. J.: 1998, 'A New Method for Estimating Roughness Parameters and Evaluating the Quality of Observations', *J. Appl. Meteorol.* **37**, 470–476.

Stewart, J. B., Kustas, W. P., Humes, K. S., Nichols, W. D., Moran, M. S., and De Bruin, H. A. R.: 1994, 'Sensible Heat Flux-Radiometric Surface Temperature Relationship for Eight Semiarid Areas', *J. Appl. Meteorol.* **33**, 1110–1117.

Sugita, M. and Kubota, A.: 1994, 'Radiaometrically Determined Skin Temperature and Scalar Roughness to Estimate Surface Heat Flux, Part II: Performance of Parameterized Scalar Roughness for the Determination of Sensible Heat', *Boundary-Layer Meteorol.* **70**, 1–12.

Sun, J.: 1999, 'Diurnal Variations of Thermal Roughness Height over a Grassland', *Boundary-Layer Meteorol.* **92**, 404–427.

Sun, J. and Mahrt L.: 1995, 'Determination of Surface Fluxes from the Surface Radiative Temperature', *J. Atmos. Sci.* **52**, 1096–1106.

Tanaka, K., Ishikawa, H., Hayashi, T., Tamagawa, I., and Ma, Y: 2001, 'Surface Energy Budget at Amdo on the Tibetan Plateau Using GAME/Tibet IOP98 Data', *J. Meteorol. Soc. Japan* **79**(1B), 505–517.

Thom, A. S.: 1972, 'Momentum, Mass, and Heat Exchange of Vegetation', *Quart. J. Roy. Meteorol. Soc.* **98**, 124–134.

Verhoef, A., De Bruin, H. A. R., and Van Den Hurk, B. J. J. M.: 1997, 'Some Practical Notes on the Parameter kB-1 for Sparse Vegetation', *J. Appl. Meteorol.* **36**, 560–572.

Wu, G. X. and Zhang, Y. S.: 1998, 'Tibetan Plateau Forcing and Timing of the Monsoon Onset over South Asia and South China Sea', *Mon. Wea. Rev*. **126**, 913–927.

Yanai, M. and Li, C.: 1994, 'Mechanism of Heating and the Boundary Layer over the Tibetan Plateau', *Mon. Wea. Rev.* **122**, 305–323.

Yanai, M., Li, C., and Song, Z.: 1992, 'Seasonal Heating of the Tibetan Plateau and its Effects on the Evolution of the Asian Summer Monsoon', *J. Meteorol. Soc. Japan* **70**, 319–351.

Yang, K. and Koike, T.: 2001, 'Modeling Analysis to Energy Closure Problem at a GAME/Tibet Site', in *Proceedings of the Fifth International Study Conference on GEWEX in Asia and GAME 1*, October 3–5, 2001, Nagoya, Japan, pp. 36–41.

Yang, K., Tamai, N., and Koike, T.: 2001, ''Analytical Solution of Surface Layer Similarity Equations', *J. Appl. Meteorol.* **40**, 1647–1653.

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

Zhou, M., and Staff Members of Chinese Academy of Meteorological Science: 2000, *Observational Analysis and Dynamic Study of Atmospheric Boundary Layer on Tibetan Plateau*, Meteorology Press, Beijing, 125 pp (in Chinese).