Turbulent exchange of heat, water vapor, and momentum over a Tibetan prairie by eddy covariance and flux variance measurements

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[1] Land-atmosphere interactions on the Tibetan Plateau are important because of their influence on energy and water cycles on both regional and global scales. Flux variance and eddy covariance methods were used to measure turbulent fluxes of heat, water vapor, and momentum over a Tibetan shortgrass prairie during the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME) in 1998. Under unstable conditions during the monsoon period (July–September), the observed standard deviations of temperature and specific humidity (normalized by appropriate scaling parameters) followed the Monin-Obukhov theory. The similarity constants for heat \( C_T \) and water vapor \( C_q \) in their dimensionless functions of stability under a free convection limit were both 1.1, unlike the differences (i.e., \( C_T \leq C_q \)) reported in other studies. While the transfer efficiency of heat and water vapor exchange generally agreed with the prediction from the Monin-Obukhov theory, momentum exchange was less efficient than predicted. In comparison with the eddy covariance data, the flux variance method (with \( C_T = C_q = 1.1 \)) underestimated both heat and water vapor fluxes by <5%. When the eddy covariance data were absent, the flux variance method was used for gap filling the seasonal flux database. To estimate latent heat flux during the premonsoon period in June, \( C_T/C_q \) was approximated as \( r_{Tq} \) (where \( r_{Tq} \) is a correlation coefficient for the fluctuations of temperature and water vapor) because of the sensitivity of \( C_q \) to changes in soil moisture conditions. The dramatic changes in the Bowen ratio from 9.0 to 0.4 indicate the shift of energy sources for atmospheric heating over the plateau, which, in turn, resulted in the shift of turbulent exchange mechanisms for heat and water vapor.

INDEX TERMS:
1878 Hydrology: Water/energy interactions; 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3379 Meteorology and Atmospheric Dynamics: Turbulence; KEYWORDS: Tibetan Plateau, eddy covariance, flux variance, Monin-Obukhov theory


1. Introduction

[2] The Tibetan Plateau is characterized by high elevation (>4000 m) and vast area (~10° in latitude and ~25° in longitude). The plateau has been the subject of climate research for several decades because of its topographic characteristics and its influence on energy and water cycles on both regional (e.g., Asian 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].

[3] Much effort has been made to evaluate the strength and distribution of atmospheric heat and moisture sources over the plateau and its vicinity. Researchers have found that: (1) the plateau is the major energy source by providing sensible heat flux to the atmosphere before the onset of monsoon [e.g., Li and Yanai, 1996]; (2) during the rainy season, the latent heat released to the atmosphere is the dominant heat source over the eastern plateau, whereas...
sensible heat flux is comparable to latent heat flux over the western plateau [e.g., Chen et al., 1985]; (3) local recycling through evaporation is important in the water budget over the western plateau, whereas water vapor transport from outside is significant over the eastern plateau [e.g., Luo and Yanai, 1983]; and (4) there is a consensus on the distribution of heat/moisture sources and the heating mechanism over the plateau, but the magnitudes are conflicting. For instance, Yeh and Gao [1979] obtained a vertically integrated mean heat source of 138 Wm$^{-2}$ over the western plateau in June, whereas Chen et al. [1985] estimated it as 37 Wm$^{-2}$. This large discrepancy was caused by the different drag coefficients used in the bulk method, resulting in different sensible heat fluxes by a factor of 2–3.

2.1.1. Eddy Covariance Method

2.1.1.1. Eddy Covariance Method

[6] Vertical flux $F$ of any scalar is based on the conservation equation. If the site is homogeneous and flat, and assuming stationarity and no sink/source for the scalar, then $F$ can be obtained from the covariance between the fluctuations of vertical wind velocity $w$ and a mixing ratio of scalar $\chi$ as below [e.g., Swinbank, 1951].

$$F = \rho_w w \overline{\chi}.$$

where $\rho_w$ is the air density ($\sim0.71$ kg m$^{-3}$ at the study site), and the overbar and primes denote time averaging and fluctuations from the mean, respectively.

2.1.2. Flux Variance Method

[7] On the basis of the Monin-Obukhov similarity theory, standard deviations of any quantity, $x$ such as $w$, longitudinal wind speed $u$, temperature $T$ and specific humidity $q$ normalized by scaling parameters become universal functions of $z/L$ as [e.g., Tillman, 1972]:

$$\sigma_x/z = \phi_x(z/L) = C_x(1 - C_x z/L)^{3/2},$$

where $\sigma_x$ is the standard deviation of $x$, $z$ is the scaling parameter ($=w_L^2/u_*$), where $w_L^2$ is the flux at the surface and $u_*$ is the friction velocity, $\phi_x$ is the normalized function, $z$ is the measurement height, $L$ is the Obukhov length, and $C_1$ and $C_2$ are empirical constants. Positive (negative) sign corresponds to wind components (scalars). As $-z/L$ approaches infinity (i.e., local free convection), equation (2) can be simplified as [e.g., Wyngaard et al., 1971]:

$$\sigma_x/z = \phi_x(z/L) = C_x(-z/L)^{3/2},$$

where $C_x = C_1(-C_2/2)$ is a similarity constant. Taking $T$ as $x$ and rearranging equation (3), sensible heat flux $H$ is expressed as [e.g., Katul et al., 1995].

$$H = c_p \rho_w \left( \frac{\sigma_T}{\sigma_x} \right)^{3/2} \left( \frac{k w_T}{T} \right)^{1/2},$$

where $c_p$ is the specific heat capacity of dry air at constant pressure (1005 Jkg$^{-1}$ K$^{-1}$). $C_T$ is a similarity constant for heat, $k$ is the von Kármán constant (0.4), and $g$ is the acceleration due to gravity.

[8] Water vapor flux is better estimated using a site-specific similarity constant for water vapor $C_q$ determined under free convection limit than using values in the literature [Asanuma and Brutsaert, 1999];

$$\lambda E = \lambda_0 \frac{C_T}{C_q} \frac{\sigma_T}{\sigma_T} \frac{w_T}{w_T} = \lambda_0 \frac{r_{wq}}{\sigma_T} \frac{w_T}{q_T} \frac{w_T}{w_T},$$

where $r_{wT}$ and $r_{wq}$ are the correlation coefficients for $w'$ and $T$, and $w'$ and $q'$, respectively.

[9] The value of $C_T$ seems universal and independent on surface conditions, unlike that of $C_q$ [e.g., Weaver, 1990; De Bruin et al., 1993; Andreas et al., 1998]. The latter increases pronouncedly as $r_{Tq}$ decreases [Asanuma and Brutsaert, 1999]. The surface moisture condition at our study site changed dramatically as the summer monsoon progressed. We therefore assume that $C_T$ does not change through the season, whereas $C_q$ changes with soil water availability.

[10] The term, $r_{wq} r_{wq}$ in equation (5) could be approximated by $r_{Tq}$ when $r_{wT} r_{wq} < 1$ (or $1/r_{Tq}$ when $r_{wT} r_{wq} > 1$)
We can rewrite equation (5) as

\[ \lambda E = \lambda v T q \frac{\sigma_u}{\sigma_T} \frac{w}{T'} \text{ if } r_{u'T} < r_{uTq} \]  

(6a)

\[ \lambda E = \lambda v T q \frac{\sigma_u}{\sigma_T} \frac{w}{T'} \text{ if } r_{u'T} > r_{uTq}. \]  

(6b)

Figure 1a shows the relationship between \( r_{Tq} \) (or \( 1/r_{Tq} \)) and \( r_{w'T}/r_{wTq} \) at the study site (BJ site), indicating that equations (6a) and (6b) hold. When quadrant analysis is applied to remove the likely effect of entrainment from the ABL top on \( r_{Tq} \), better relationship is obtained (Figure 1b).

### 2.1.3. Correlation Coefficients

The vertical transfer efficiencies for heat and water vapor can be evaluated by their correlation coefficients, \( r_{u'T} \) and \( r_{w'T} \), respectively. The ratio of \( r_{u'T} \) to \( r_{w'T} \) represents the relative transfer efficiency. On the basis of the Monin-Obukhov similarity theory, \( r_{w'T} \) can be predicted using the corresponding integral turbulence characteristics (ITC) [e.g., De Bruin et al., 1993]:

\[ r_{w'r} = \frac{w'}{\sigma_w} \frac{x}{x} = \left( 1 - C_\alpha \frac{z}{L} \right)^{1/3} / C_{x'} C_{x'1} \left( 1 - C_a \frac{z}{L} \right)^{1/3}. \]  

(7)

If \( x \) is scalar, the numerator is \( [1 - C_\alpha (z/L)]^{1/3} \). Otherwise, \( [1 - C_\alpha (z/L)]^{-1/3} \) is used.

### 2.1.4. Drag Coefficients

Drag coefficients \( C_D \) at the reference height (i.e., 10 m) and under neutral stability (\( C_{DN10} \)), can be evaluated through the relation [e.g., Andreas et al., 1998],

\[ C_{DN10} = \frac{k^2}{\ln(10/z_0)^2}. \]  

(8)

where \( z_0 \) is the roughness length for momentum.

### 2.2. Site and Measurements

#### 2.2.1. Study Site

The field experiment was conducted at a shortgrass prairie (BJ site) near Naqu (92.04°E, 31.29°N, 4580 m above m.s.l.), Tibet in China. Soil was predominantly sandy silt loam at the site, which was homogeneous and flat with a fetch of >1 km for the prevailing wind directions. The flux measurement was made from late May to mid-September in 1998. The rainy season started in late June. During the premonsoon period the surface was dry and sparsely covered with short grasses. With the onset of the monsoon, the volumetric soil water content remained >15% and the average grass height was about 0.05 m with grazing.

#### 2.2.2. Flux Measurement

The eddy covariance measurement system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc.), a krypton hygrometer (KH20, Campbell Scientific, Inc.), and a fine-wire thermocouple. Measurements were taken 2.85 m above the ground, and the separation between the sonic anemometer and the hygrometer was 0.15 m. The prevailing wind direction was from 135° to 225°. The sampling rate was 20 Hz and the raw data were saved on a laptop computer connected to a data logger (CR9000, Campbell Scientific, Inc.) for postprocessing. Half-hourly averaged turbulence statistics were calculated and recorded on the data logger.

Because of long and rough transportation to the experimental site, the sonic anemometer was broken and was not replaced until 14 July. During this period standard deviations of temperature and humidity were measured with fine wire thermocouples and a krypton hygrometer, respectively. Because of a wide range of humidity, the path length of krypton hygrometer was adjusted, and the instrument was calibrated again in a low-pressure chamber after the experiment.
3. Results and Discussion

3.1. Turbulence Characteristics

[19] The measured $\sigma_{u}/u*$ is plotted with $-z/L$ in Figure 3a. A normalized function of $\sigma_{u}/u* = (C_w1(1 + C_w2)z/L)^{1/3}$ was determined, resulting in $C_w1 = 1.12$ and $C_w2 = 2.8$. Also presented is the formulation of Kaimal and Finnigan [1994] (i.e., $\sigma_{u}/u* = 1.25(1 + 3[z/L])^{1/3}$), which predicts consistently greater $\sigma_{u}/u*$. Similar results were obtained from data collected 20 m above ground using taller towers: one at the BJ site in 2002 and the other at Anni site in 2003 [Hong et al., 2004]. The $\sigma_{u}/u*$ value of ~1.12 under near-neutral conditions is within the range reported in the literature [i.e., Kaimal and Finnigan, 1994; Pahlow et al., 2001]. Pattey et al. [2002] show that $\sigma_{u}/u*$ can vary depending on the types of sonic anemometers, particularly with one with longer path length due to loss of covariance between $u$ and $w$.

[20] The measured $\sigma_{u}/u*$ is plotted with $-z/L$ in Figure 3b. Its normalized function is $3.13(1 + 8[z/L])^{1/3}$. In comparison with $\sigma_{u}/u*$, more scatters are evident with $\sigma_{u}/u*$. The latter may not totally follow the Monin-Obukhov theory and be better scaled with boundary layer depth $h_b$ [Pitawsky and Dutton, 1984; Van Den Hurk and De Bruin, 1995]. However, $\sigma_{u}/u*$ in Figure 3b did not scale with $h_b$, where $h_b$ was given as constant. The normalized function ($\sigma_{u}/u* = 2.2(1 + 3[z/L])^{1/3}$ of De Bruin et al. [1993] underestimates the observed $\sigma_{u}/u*$. Other supporting micrometeorological measurements made at the site included radiation components, soil heat flux, soil temperature, soil water content, air temperature and humidity, wind speed, and direction. All these slow-response signals were sampled every 30 s. Average values for 30-min periods were stored on the same data logger. Electrical power was not available, and thus all the instruments and the data-logging system were operated through 12 VDC batteries that were recharged by solar panels [Kim et al., 2001].

2.2.3. Flux Corrections

[17] The effect of coordinate rotation on fluxes was less than 1%. To further evaluate the contribution of low-frequency eddies [e.g., Finnigan et al., 2003], half-hourly averaged fluxes were compared against 2-hour averages and the agreement was within 1%. Following Moore [1986], fluxes were adjusted for the effects of path length averaging and sensor separation, resulting in 5% increase in latent heat flux. Further correction for the density variation was applied to latent heat flux [Webb et al., 1980].

2.2.4. Stationarity Test

[18] To satisfy the stationarity assumption, the statistical properties of the measured time series should not change with time. To evaluate the degree to which turbulent statistics may violate this assumption, the nonstationarity ratio (NR) is defined as [Mahrht, 1998]

$$\text{NR} \equiv \sigma_{\text{bys}}/\text{RE},$$

where $\sigma_{\text{bys}}$ is the between-record standard deviation of statistics (for this analysis, half-hourly raw data were divided into four records), and RE ($=\sigma_{\text{wi}}/\sqrt{J}$) is the random error estimate, where $\sigma_{\text{wi}}$ is the averaged within-record standard deviation over all of the records, and $J$ is the number of subrecord segments (six segments per record were used for this study). While RE has the effect of random variability on turbulence statistics only, $\sigma_{\text{bys}}$ may be affected by both nonstationarity and random variability. Ideally, NR = 1 if the turbulence statistics are stationary. In practice, data are considered nonstationary when NR $\geq$ 2 [Mahrht, 1998]. The NR values for daytime averaged $\overline{wT}$ and $\overline{\sigma T}$ in Figure 2 show that the stationarity requirement is generally met.
selected when \( r_{T_q} > 0.9 \). For comparison, the normalized functions for heat of Kaimal and Finnigan [1994] and Andreas et al. [1998] are also presented in Figure 5. The normalized function for \( \sigma_{T^*} \) in our study is almost identical to that of Andreas et al. [1998] over a terrain with patchy vegetation with height of <0.6 m. However, the magnitudes of \( \sigma_{T^*} \) in our study are greater than those from the Kansas data [Kaimal and Finnigan, 1994].

[24] Surprisingly, the behavior of \( \sigma_{\theta^*}/q^* \) is markedly similar to that of heat (Figure 5b). Unlike \( \sigma_{T^*}/T^*_w \), the normalized function for \( \sigma_{\theta^*}/q^* \) of Andreas et al. [1998] overestimates \( \sigma_{\theta^*}/q^* \). A normalized function for \( \sigma_{\theta^*}/q^* \) is not given by Kaimal and Finnigan [1994] but is suggested to have a functional form similar to that for \( \sigma_{T^*}/T^*_w \) (also shown in Figure 5b for comparison).

[25] Figure 6 shows the behavior of \( \sigma_{T^*}/T^*_w \) and \( \sigma_{\theta^*}/q^* \) within the free convection limit (\(-z/L > 0.2\)). The similarity constant in a simplified function (i.e., \( C_{\sigma} \) in equation (3)) is 1.1 for both \( C_T \) and \( C_{\theta} \). In the literature, \( C_T \) ranges from 0.91

Figure 3. Integral turbulence characteristics of (a) vertical and (b) streamwise wind component with \(-z/L\) during the monsoon period. Solid lines are the normalized functions from this study, the dash-dotted line is that by Kaimal and Finnigan [1994], and the dotted line is that by De Bruin et al. [1993].

Figure 4. Variation of correlation coefficients for \( w \) and \( u \) during the monsoon period. The solid line is predicted by the corresponding ITCs in this study, and the dashed line is provided by De Bruin et al. [1993].
to 1.12 whereas $C_q$ is greater, with a range of 1.1–1.5 [e.g., Asanuma and Brutsaert, 1999; Katul and Hsieh, 1999]. On the basis of the analysis of covariance budget equations for $w_0T_0$ and $w_0q_0$, Katul and Hsieh [1999] showed that $CT < Cq$, suggesting a dissimilarity between heat and water vapor.

In Figure 7, the transfer efficiency of heat to water vapor (i.e., $r_{wT}/r_{wq}$) is plotted against $-z/L$. Except the scatters toward near-neutral conditions, the data converge to unity under unstable conditions, suggesting a similarity of source/sink between heat and water vapor near the ground surface.

The measured $r_{wT}$ and $r_{wq}$ are shown in Figure 8 with equation (7) (with the predetermined constants: $C_{x1} = 3.7$, $C_{x2} = 34.5$, $C_{w1} = 1.12$, and $C_{w2} = 2.8$). Both $r_{wT}$ and $r_{wq}$ increase as the stability becomes more unstable. For comparison, the formulation of De Bruin et al. [1993] is also included. Both $r_{wT}$ and $r_{wq}$ show that each scalar follows the Monin-Obukhov theory with similar transfer efficiency.

Figure 9 shows the transfer efficiencies of heat and water vapor as compared to momentum. Heat and water vapor are transferred more efficiently than momentum over a range of different stabilities. While the momentum exchange is systematically less efficient, heat and water vapor exchange shows a similar efficiency in magnitude, following the Monin-Obukhov theory.

3.2. Drag Coefficients

First, $z_0$ is estimated on the basis of logarithmic wind profiles under neutral conditions ($-0.05 < z/L < 0.05$). By substituting the estimated $z_o(=0.009 \pm 0.009 \text{ m})$ in equation (8), $CDN$ is estimated to be $3.1 (\pm 0.7) \times 10^{-3}$. On the basis of wind profile measurements at the same site, Gao et al. [2000] reported $z_o$ of 0.0113 m and $CDN$ of $3.5 \times 10^{-3}$. Li et al. [2001] estimated the drag coefficients at four stations on the plateau using wind profile measurements over 6 years and obtained $4.4–4.7 \times 10^{-3}$. Bian et al.
[2002] obtained $C_{DN}$ of $5.5 \times 10^{-3}$ through turbulence measurements at Qamdo site with sparse weeds of 0.35 m height in the southeastern Tibetan Plateau. Overall, these recent estimates of drag coefficients are only half of those ($6 \sim 8 \times 10^{-3}$) reported by earlier studies [e.g., Yeh and Gao, 1979].

3.3. Flux Comparison Between Eddy Covariance and Flux Variance Methods

[30] Sensible heat $H_{VAR}$ and latent heat fluxes $\lambda E_{VAR}$ from the flux variance method were calculated using equations (4) and (5), respectively (with $C_T = C_q = 1.1$) and compared against the available eddy covariance fluxes ($H_{EC}$ and $\lambda E_{EC}$) for the same period. The fluxes from the two methods agree within 5% (SEE = 12 Wm$^{-2}$ and $r^2 = 0.88$ for $H$; SEE = 37 Wm$^{-2}$ and $r^2 = 0.78$ for $\lambda E$).

[31] Because of changes in $C_q$ with varying soil water conditions, $\lambda E_{VAR}$ was also computed with equations (6a) and (6b) using $r_{Tq}$ and $1/r_{Tq}$. Again, the flux comparison between the two methods is similar to that with a constant

Figure 6. Integral turbulence characteristics of (a) $T$ and (b) $q$ under free convection ($-z/L > 0.2$) during the monsoon period. Solid lines are the regression lines fitted to the measurements from this study.

Figure 7. Variation of $r_{wT}/r_{wq}$ with $-z/L$ under near-neutral and unstable conditions during the monsoon period. The dotted line shows $r_{wT}/r_{wq} = 1$. 

$C_p$, except for larger values of $\text{SEE} (=74 \text{ Wm}^{-2})$ and lower $r^2 (=0.34)$ (Figure 10b). This is mainly due to small $r_{Tq}$, resulting in $1/r_{Tq}$ of much larger than 1.1. It is encouraging, however, that $\lambda E_{VAR}$ using $r_{Tq}$ is comparable to the measured $\lambda E_{EC}$. This result provides good grounds for applying the flux variance method when eddy covariance measurement is not available.

3.4. Seasonal Variations of Energy Partitioning and Turbulent Exchange Mechanism

As the summer monsoon advanced, there were significant changes in meteorological conditions, surface energy partitioning and turbulent exchange characteristics.

3.4.1. Precipitation and Land Cover

Figure 11 shows the seasonal variations of precipitation and soil water content (0.1 m layer). Frequency and magnitude of precipitation increased particularly in late June, resulting in a rapid increase in soil water content. From the green-up stage in late June to peak growth in July–August, the approximate leaf area index (LAI) increased up to 0.45, with a mean canopy height of 0.05 m [Gao et al., 2004]. Following the change in vegetation cover, color and soil water conditions at the site, the radiation balance changed dramatically.

3.4.2. Radiation Balance

Figure 12 shows the diurnal variation of radiation components on two fairly clear days (12 June and 9 August 1998). Prior to monsoon (12 June), the daytime outgoing longwave radiation $R_{oup}$ and incoming longwave radiation $R_{ldn}$ reached up to 600 Wm$^{-2}$ and 300 Wm$^{-2}$, respectively. The $R_{oup}$ is significantly larger than those at low altitudes in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Variation of correlation coefficients for (a) $w$ and $T$ and (b) $w$ and $q$ during the monsoon period. Solid lines are predicted by the corresponding ITCs in this study, and dashed lines for each correlation are provided by De Bruin et al. [1993].}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Transfer efficiencies of heat and water vapor to momentum under near-neutral and unstable conditions during the monsoon period. The solid line is the formulation from De Bruin et al. [1993].}
\end{figure}
similar latitudes. Smith and Shi [1992] also reported large values of $R_{\text{lup}}$ over the Tibetan Plateau. During the monsoon (9 August), $R_{\text{rup}}$ decreased by 30% but $R_{\text{ldn}}$ increased by 20%, resulting in 60% increase in net longwave radiation. While downward shortwave radiation $R_{\text{sdn}}$ remained almost the same, the albedo ($=R_{\text{lup}}/R_{\text{sdn}}$) decreased by 30% from premonsoon (0.2) to monsoon (0.15). Consequently, the net radiation ($R_{n}$) increased by 20%. During midday, about 25% of $R_{n}$ was dissipated into soil heat flux.

### 3.4.3. Surface Energy Partitioning

Figure 13 shows the seasonal variation of the energy partitioning in terms of the Bowen ratio ($\beta = H/LE$). With the onset of the summer monsoon, $\beta$ decreased rapidly from 9 in early June to 0.4 in July and remained low until mid-September. Then, $\beta$ began to increase with the withdrawal of the monsoon. Prior to the monsoon, sensible heat flux from the surface was the major source of heating over the plateau, whereas the latent heat released by condensation became the primary source with the onset of the monsoon.

#### 3.4.4. Shift in Turbulent Exchange Mechanism

The seasonal variation of daytime averaged $r_{Tq}$ increases from near zero during the premonsoon to 0.8 during the monsoon period (Figure 14). Such a change in $r_{Tq}$ implies a shift in the similarity between heat and water vapor with the seasonal march of summer monsoon. Changes in skewness of $T$ ($Sk_T$), $q$ ($Sk_q$) and $w$ ($Sk_w$) provide further insights. Normally, positive skewness values are expected because of narrow, warm and moist updrafts, compared to wider, cool and dry downdrafts [Mahrt, 1991]. Throughout the season, $Sk_T$ and $Sk_q$ are consistently

![Figure 10](image1.png)

**Figure 10.** Comparison of measured fluxes of (a) sensible heat and (b) latent heat with estimated ones. The open circles represent latent heat flux $\lambda E_{Cq}$ from the flux variance method using $C_q$ of 1.1, and the pluses represent latent heat flux $\lambda E_{Tq}$ from flux variance method using $r_{Tq}$ (or $1/r_{Tq}$).
positive (0.2 ~ 1.5). However, as $\beta$ rapidly decreases with enhanced $\lambda E$, Skq shifts from negative to near-zero values in June to positive values comparable to $Sk_T$ during the monsoon period. Mahrt [1991] reported that $r_{Tq}$ and $Sk_q$ (measured at 100–150 m above ground) increased with decreasing boundary layer height because of strong surface evaporation. During our study, $h_i$ over Amdo site (~100 km north of BJ site) also decreased from ~2.5 km during premonsoon to about 1 km during monsoon period in 1998 (http://monsoon.t.u-tokyo.ac.jp/tibet/data/iop/pbltower/). As

Figure 11. Seasonal variations of precipitation and soil water content (SWC).

Figure 12. Diurnal variations of radiation budget components on 12 June (Figures 12a and 12c, premonsoon) and 9 August 1998 (Figures 12b and 12d, monsoon). $R_{ldn}$ is the downward longwave radiation, $R_{up}$ is the outgoing longwave radiation, $R_n$ is the net radiation, $R_{sup}$ is the reflected shortwave radiation, and $R_{s dn}$ is the incoming shortwave radiation.

Figure 13. Seasonal variation of the Bowen ratio.
pointed out by De Bruin et al. [1999], the relative contributions of entrainment of warm and dry air from the boundary layer top probably have influenced the similarity near the surface. Local advection or the heterogeneity of sink/source distributions of heat and water vapor also could result in dissimilarity between the two scalars [e.g., Katul et al., 1995; De Bruin et al., 1999]. Analysis of skewness under such influences would be helpful to better understand the turbulent exchange mechanisms over the Tibetan Plateau.

4. Concluding Remarks

[17] Turbulent exchange characteristics in a Tibetan shortgrass prairie were investigated in terms of flux variance relation, and the changes in environmental conditions, surface energy partitioning, and the similarity between heat and water vapor were presented with the seasonal march of the summer monsoon. Main results are summarized as follows.

[18] 1. Normalized standard deviations of heat and water vapor follow the Monin-Obukhov similarity theory. Heat and water vapor are similar in terms of the similarity constant, and the flux variance method produces comparable \( H \) and \( \lambda E \) to those of eddy covariance method.

[19] 2. Unlike the similar magnitudes of transfer efficiency of heat and water vapor, momentum exchange is underestimated compared to the Monin-Obukhov similarity prediction.

[20] 3. As the summer monsoon progresses, significant changes in surface energy partitioning occur toward the enhancement of \( \lambda E \). The entrainment from boundary layer top or inversion layer aloft probably affects the dissimilarity between heat and water vapor during the premonsoon, whereas its effect during the monsoon seems relatively weak as evidenced by low \( \beta \). More information is needed on the likely role of inactive eddies associated with turbulent exchange mechanisms over the plateau [Hong et al., 2004].

[21] 4. Further direct measurements on turbulence statistics, evaluation of local advection and heterogeneity of source/sink distribution through remote sensing analysis, and profile measurements of heat and water vapor in the boundary layer are needed, particularly for premonsoon periods. Such measurements are currently in progress on the plateau through ongoing CEOP field campaigns.

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