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Estimation of Turbulent Fluxes Using the Flux-Variance Method over an Alpine Meadow Surface in the Eastern Tibetan Plateau

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ABSTRACT

The flux-variance similarity relation and the vertical transfer of scalars exhibit dissimilarity over different types of surfaces, resulting in different parameterization approaches of relative transport efficiency among scalars to estimate turbulent fluxes using the flux-variance method. We investigated these issues using eddy-covariance measurements over an open, homogeneous and flat grassland in the eastern Tibetan Plateau in summer under intermediate hydrological conditions during rainy season. In unstable conditions, the temperature, water vapor, and CO_2 followed the flux-variance similarity relation, but did not show in precisely the same way due to different roles (active or passive) of these scalars. Similarity constants of temperature, water vapor and CO_2 were found to be 1.12, 1.19 and 1.17, respectively. Heat transportation was more efficient than water vapor and CO_2. Based on the estimated sensible heat flux, five parameterization methods of relative transport efficiency of heat to water vapor and CO_2 were examined to estimate latent heat and CO_2 fluxes. The strategy of local determination of flux-variance similarity relation is recommended for the estimation of latent heat and CO_2 fluxes. This approach is better for representing the averaged relative transport efficiency, and technically easier to apply, compared to other more complex ones.

Key words: flux-variance method, relative transfer efficiency, eddy-covariance method, homogeneous land surface, turbulent flux

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1. Introduction

The flux-variance (FV) method, which is based on Monin–Obukhov similarity theory (MOST) and was first introduced by Tillman (1972), has received long-term attention and wide application in surface micrometeorology (e.g. Wesely, 1988; Lloyd et al., 1991; De Bruin et al., 1993; Katul et al., 1995; Castellvi and Martínez-Cob, 2005; Gao et al., 2006; Hsieh et al., 2008; Guo et al., 2009). In previous studies, the FV similarity relation has been widely used to investigate the similarities in sources/sinks of scalars at the land surface (e.g. Hill, 1989; Padro, 1993; Katul et al., 1995), or to quantify similarities in turbulent transport efficiencies of various scalars (e.g. McBean and Miyake, 1972; De Bruin et al., 1993; Katul and Hsieh, 1997; Asanuma and Brutsaert, 1999; Lamaud and Irvine, 2006; Detto et al., 2008). More recently, FV similarity relation has been proposed as a tool for the quality assessment of eddy-covariance (EC) flux measurements (e.g. Foken and Wichura, 1996; Foken et al., 2004), as well as a viable tool for gap-filling long-term flux data when high frequency wind velocity measurements of the EC system are not available

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(e.g. Choi et al., 2004; Guo et al., 2009).

Over the past two decades, comparisons between FV- and EC-based estimations of latent heat fluxes (LE) over a wide range of climates, land surface types and atmospheric stability conditions have produced mixed results (e.g. Weaver, 1990; De Bruin et al., 1993; Andreas et al., 1998; Asanuma and Brutsaert, 1999; Castellvi and Martínez-Cob, 2005; Hsieh et al., 2008; Guo et al., 2009). For the estimation of LE using the FV method, Hill (1989) proposed that the correlation coefficients of vertical velocity (w) with temperature (T) and water vapor (q) must be equal, i.e. $R_{wT} = R_{wq}$. In practice, there are numerous case studies in the literatures where the method worked quite well, albeit the inequality between the two scalars' correlation with the turbulent vertical velocity (e.g. Katul et al., 1995; Castellvi and Martínez-Cob, 2005; Lamaud and Irvine, 2006; Guo et al., 2009). This dissimilarity among the scalars is generally attributed to the following reasons (e.g. Cava et al., 2008; Katul et al., 2008): (1) the active or passive roles of scalars in the turbulent kinetic energy budget equation; (2) advection of heat or water vapor (both vertically and longitudinally); (3) non-stationarity in the outer-layer flow that can influence the atmospheric surface layer; (4) source heterogeneity at the ground surface; and (5) local entrainment processes from the top of the atmospheric boundary layer.

Such a variety of factors has led many authors to propose different parameterization approaches of the relative efficiency of sensible heat flux to latent heat flux ($\lambda_{Tq} = R_{wT}/R_{wq}$) to improve estimations of LE using the FV method. Hill (1989) pointed out that surface layer similarity theory assumes a perfect scalar correlation and adopted unity as the relative transport efficiency (λ_{Tq}), but this approach is generally unfeasible, owing to heterogeneity in sources/sinks of scalars at the biosphere–atmosphere interface. Katul et al. (1995) demonstrated that λ_{Tq} is equivalent to the temperature–humidity correlation coefficient (R_{Tq}), but results showed that reproduced LE was systematically overestimated compared to direct measurements in dry surface conditions. Bink and Meesters (1997) argued that λ_{Tq} could be expressed with either R_{Tq} when water vapor is transported more efficiently than sensible heat, i.e. $\lambda_{Tq}<1$, which corresponds to wet conditions, or R_{Tq}^{-1} when heat transport is more efficient than water vapor, i.e. $\lambda_{Tq}>1$, which corresponds to dry conditions. They proved their conclusions using data from a dry area in the south of France. Lamaud and Irvine (2006) investigated the relationship between λ_{Tq} and R_{Tq} using data measured at a pine forest site, and parameterized the λ_{Tq} as a function of R_{Tq} and the Bowen ratio B_O in intermediate hydrological conditions.

Recently, some scientists have been interested in exploring FV similarity relationships for CO_2, in addition to T and q (e.g. Ohtaki, 1985; Cava et al., 2008; Detto et al., 2008; Hsieh et al., 2008; Guo et al., 2009). Ohtaki (1985) pointed out that the stability dependence of normalized standard deviation of CO_2 is very similar to those of T and q over two wheat fields in Japan. However, in other studies, the ecosystem respiration was an additional source, which introduced significant dissimilarity in CO_2 sources and sinks when compared to water vapor (e.g. Cava et al., 2008). Furthermore, surface physiology changes with season, which can cause an impermanent production of inhomogeneity in the scalar sources/sinks field, and result in dissimilarity, especially for CO_2 (e.g. Williams et al., 2007). Hsieh et al. (2008) demonstrated that CO_2 did not satisfy the MOST, and the estimations of CO_2 flux ($F_{\rm c}$) using the FV method were found to switch from poor to fair among the three sites (grassland, rice paddy field and forest). They attributed this to the complexity of CO_2 sources/sinks on the surface and their seasonal variation. However, Guo et al. (2009) found that CO_2 follows the FV relation over a farmland, and relative transport efficiency ($\lambda_{T{\rm c}} = R_{wT}/R_{w{\rm c}}$) can be described as a function of the correlation coefficient (R_{Tq}) by introducing a new non-dimensional variable (α).

Although the MOST is based on the assumption of steadiness and horizontal homogeneity, it is practically only a conceptual framework in the realm of surface-layer meteorology (Andreas et al., 1998). Even when the terrain is uniform, some factors such as the active roles of temperature, modulations from the outer layer, and cloud effects on radiation can influence the FV relationships and the expressions of relative transport efficiency between different scalars, and result in some uncertainties in calculations of turbulent flux (e.g. Katul et al., 1995; Roth and Oke, 1995; Bink and Meesters, 1997; Katul and Hsieh, 1997; Katul and Hsieh, 1999; Lamaud and Irvine, 2006; Katul et al., 2008; Guo et al., 2009). The EC system can be used continuously for long-term measurements of energy and mass exchanges in land surface processes. However, data coverage is severely influenced by environmental and anthropogenic factors, especially in the Tibetan Plateau, such as instrument problems, power supply, extreme weather and instrument maintenance. As a feasible tool, the FV method can be used for gap-filling long-term flux data when high frequency wind velocity measurements are not available under the extreme environmental conditions on the Tibetan Plateau. However, there is no agreement yet in the literature about parameterization approaches of relative transport efficiency. It is the importance of investigating the FV relationship to the determination of turbulent fluxes that motivated this study over a homogeneous short grass surface in the eastern Tibetan Plateau. The objectives of the work reported in this paper were to examine turbulent transportation characteristics over an alpine meadow surface in the eastern Tibetan Plateau in terms of the FV relationship, and to examine different parameterization approaches of relative transport efficiency for estimating LE and F_c.

2. Materials

2.1 *Site*

Measurements were carried out at a grassland site (33°53′N, 102°08′E, 3423 m a.s.l.) in a typical alpine meadow, in the eastern part of the Tibetan Plateau, Gansu, China. This site is a long-term flux monitoring station in the Yellow River source region. The meadow is dominated by Cyperaceae and Gramineae, with an average height of about 0.2 m. The soil is silt clay loam, which is composed of 29.8% sand, 66.7% silt and 3.5% clay in the top 40 cm based on the classification of the United States Department of Agriculture. The annual mean air temperature is 1.2°C, and mean air temperatures in January and July are −10°C and 11.7°C, respectively. The annual mean precipitation is 620 mm, which has mainly fallen in the short, cool summers over the last 35 years (Niu et al., 2009). The terrain is flat, homogeneous, and about 3 km from the nearest herder's community. A picture of the field site is shown in Fig. 1.

2.2 *Micrometeorological measurements*

A 3-D sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) was used to measure high frequency wind velocity components (i.e. u, v and w) and sonic temperature (T). An open-path infrared gas analyzer (LI-7500, LI-COR, Lincoln, NE, USA) was used to measure high frequency signals of water vapor density (q) and CO_2 concentration. The lateral separation between the two sensors was fixed at about 15 cm. As recommended in the LI-COR LI-7500 manual, this instrument was tipped about 15° from the vertical to facilitate drainage of condensation and rain from the optical windows. A periodic (1 yr) calibration of the gas analyzer was performed by technicians. Those sensors were installed at a height of 3.15 m above the ground. Sampling rate was adjusted to 10 Hz. Other slow response measurements set at the site included wind speed and direction, air temperature and humidity, radiation components, soil water content, soil temperature and soil heat flux. All these slow response signals were sampled every 30 s. Data were recorded by a data logger CR3000 (Campbell Scientific Inc., Logan, UT, USA).

2.3 *Data selection and preliminary data-processing*

With the aforementioned measurements, data from 18 fair weather days were selected during the summer from 1 July to 30 September 2010. Half-hourly mean values of the turbulence statistics were calculated on the basis of the two-rotation method (McMillen, 1988) to nullify the average cross-stream and vertical wind components. The planar fit method (Wilczak et al., 2001) was also used for tilt correction, but no obvi-

Fig. 1. Setup of the measurement station over the alpine meadow.

ous difference was found. Sonic temperature was converted into actual temperature according to Schotanus et al. (1983). The effects introduced by path length averaging of the sonic anemometer and the gas analyzer, and for the spatial separation of sensors, were corrected following Moore (1986). The influences of air density variation induced by air temperature and water vapor concentration fluctuations were corrected following Webb et al. (1980). The non-stationarity test was performed according to Foken et al. (2004) to minimize the effect of diurnal trends or weather patterns on flux computations. Data were collected under unstable and stationarity conditions during the daytime (i.e. between 1000 and 1600 LST) were used for analyzing the FV relationship and estimating turbulent flux.

3. Theory

3.1 *FV similarity relation*

On the basis of the MOST, any normalized turbulence statistic depends on the non-dimensional atmospheric stability,

$$\zeta = \frac{z-d}{L} , \tag{1}$$

where $z = 3.15$ m is the measurement height above the ground, $d = 0.13$ m is the zero-plane displacement ($\approx 0.65h$; $h = 0.2$ m is the canopy height) (Campbell and Norman, 1998), and L is the Obukhov length given by

$$L = -\frac{u_*^3 \overline{T}}{kg\overline{w'T'}} , \tag{2}$$

where $\overline{w'T'}$ is the covariance between vertical velocity and air temperature, $\overline{T}$ is mean air temperature, $k = 0.4$ is von Karman's constant, g (9.81 m s^{-2}) is gravitational acceleration, and u_* (m s^{-1}) is friction velocity given by

$$u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4} , \tag{3}$$

where u', v', and w' are turbulent fluctuations in longitudinal, latitudinal and vertical velocity (m s^{-1}), respectively. The normalized standard deviation of scalar, s [s represents a scalar; namely, T for temperature (°C), q for water vapor density (g m^{-3}) and c for CO_2 concentration (mg m^{-3})], normalized standard deviation σ_s/s_*, can be described as (e.g. Tillman, 1972; Businger, 1973):

$$\frac{\sigma_s}{|s_*|} = \Psi_s(\zeta) , \tag{4}$$

where $s_* = \overline{w's'}/u_*$ is a scale parameter. The expression of $\Psi_s(\zeta)$ must satisfy two limits: (1) in neutral conditions, $-\zeta \to 0$ and $\Psi_s(\zeta)$ converge to a constant; (2) in free convective conditions, $-\zeta \to \infty$, and $\Psi_s(\zeta)$ should become independent of u_* (e.g. De Bruin, 1982; De Bruin et al., 1993; De Bruin, 1994; Albertson et al., 1995; Katul et al., 1995; Wesson et al., 2001; Cava et al., 2008). Based on those two limits, the form of $\Psi_s(\zeta)$ can be reduced to:

$$\Psi_s(\zeta) = C_{s1}(C_{s2} - \zeta)^{-1/3} , \tag{5}$$

where C_{s1} and C_{s2} are empirical constants. In neutral conditions ($-\zeta = 0$), $\Psi_s(\zeta)$ approaches constant value $C_{s1}C_{s2}^{-1/3}$. For free convection conditions, Eq. (5) is given by

$$\Psi_s(\zeta) = C_{s3}(-\zeta)^{-1/3} , \tag{6}$$

where C_{s3} is a similarity constant of scalar s.

3.2 *Flux estimations using the FV method*

Based on the definitions of Obukhov length (L) and temperature scale (T_*), sensible heat flux (H) leads to (e.g. Padro, 1993; Katul et al., 1995; Choi et al., 2004; Hsieh et al., 2008)

$$H = \rho c_p \overline{w'T'} = \rho c_p \left(\frac{\sigma_T}{C_{T3}}\right)^{3/2} \left[\frac{kg(z-d)}{\overline{T}}\right]^{1/2} , \tag{7}$$

where ρ is the air density (kg m^{-3}), c_p is the specific heat capacity of dry air at constant pressure (=1005 J kg^{-1} K^{-1}). Furthermore, based on the estimated H using the FV method, LE and F_c can be estimated from Eq. (7) by

$$\overline{w's'} = \frac{R_{ws}\sigma_s}{R_{wT}\sigma_T} \times \overline{w'T'} , \tag{8}$$

where $R_{ws} = \overline{w's'}/\sigma_w\sigma_s$ are the correlation coefficients between w' and s'. McBean and Miyake (1972) defined the ratio R_{wT}/R_{ws} as the relative transport efficiency of heat to scalar transport (denoted by λ_{Ts}). Thus, Eq. (8) can be expressed as the following:

$$\overline{w's'} = \lambda_{Ts}^{-1} \times \frac{\sigma_s}{\sigma_T} \times \overline{w'T'} . \tag{9}$$

Hence, to estimate LE and F_c using Eq. (9), the relative efficiencies λ_{Tq} and λ_{Tc} need to be determined a priori. There have been five strategies proposed to represent λ_{Tq} and λ_{Tc} in previous studies, as summarized by Guo et al. (2009; see their Table 1). The strategies are, respectively: (1) for perfect scalar similarity conditions, i.e. $R_{wT} = R_{wq}$ and $R_{wT} = -R_{wc}$ (Hill, 1989); (2) for conditions where sensible heat is transported more efficiently than water vapor and CO_2, i.e. $\lambda_{Tq}<1$ and $\lambda_{Tc}<1$, $\lambda_{Tq} = R_{Tq}$ and $\lambda_{Tc} = R_{Tc}$ (e.g. Katul et al., 1995); (3) for conditions where sensible heat is transported less efficiently than water vapor and CO_2, i.e. $\lambda_{Tq}>1$ and

Table 1. Flux-variance similarity constants for temperature (C_{T3}), humidity (C_{q3}), and CO_2 (C_{c3}) from the literature.

Author(s)	C_{T3}	C_{q3}	C_{c3}	Ecosystem
This work	1.12	1.19	1.17	grassland
Tillman (1972)	0.95			grassland
Weaver (Weaver, 1990)	1.00			grassland
Lloyd (1991)				grassland
Katul et al. (1995)	0.95	1.30		grassland
Choi et al. (2004)	1.1	1.10		grassland
Detto and Katul (2007)		0.99	0.99	grassland
Hsieh et al. (2008)	1.10	1.10	0.95	grassland
Högström and Smedman-Högström (1974)	0.92	1.04		farmland
Ohtaki (1985)	0.95	1.10	1.10	farmland
Lloyd (1991)	0.95			farmland
Gao et al. (2006)	1.09	1.49		farmland
Hsieh et al. (2008)	1.00	1.00	1.00	farmland
Guo et al. (2009)	1.16	0.92	1.10	farmland
Padro (1993)	0.95	0.95		forest
Hsieh et al.(1996)	1.36			forest
Lamaud and Irvine (2006)	0.95	1.30		forest
Cava et al. (2008)	1.09	1.61	1.32	forest
Hsieh et al. (2008)	1.25	1.50	1.70	forest

$\lambda_{Tc}>1$, $\lambda_{Tq} = R_{Tq}^{-1}$ and $\lambda_{Tc} = R_{Tc}^{-1}$ (e.g. Bink and Meesters, 1997); (4) based on the FV similarity relation $\lambda_{Tq} = C_{q3}/C_{T3}$ and $\lambda_{Tc} = -C_{c3}/C_{T3}$ (e.g. Hsieh et al., 2008); (5) Lamaud and Irvine (2006) proposed that $\lambda_{Tq} = R_{Tq}^{K}$ for all kinds hydrological conditions, where $K = 1$ for $B_O \leqslant 0.1$, $K = -1 - 2\log(B_O)$ for $0.1<B_O \leqslant 1$, and $K = -1$ for $B_O \geqslant 1$, where B_O is the Bowen ration (H/LE). Furthermore, for CO_2, Guo et al. (2009) proposed that $\lambda_{Tc} = -(-R_{Tc})^M$, where $M = 1.16 - 1.33\log(-\alpha)$, $\alpha = H/\overline{w'c'}$, $\varepsilon = 1.0886\times10^6$ (J kg^{-1}), and $\varepsilon\overline{w'c'}$ is the energy consumption in chemical processes related to CO_2 exchange, with the same dimension as H (Laubach and Teichmann, 1999), and α can be regarded as a "logical equivalent" to B_O (Moene and Schüttemeyer, 2008).

4. Results and Discussion

4.1 *Analysis of FV similarity relation*

4.1.1 *Normalized standard deviation of scalars*

The normalized standard deviations of temperature (σ_T/T_*), water vapor density (σ_q/q_*) and CO_2 concentration (σ_c/c_*) are plotted against the stability parameter ζ in Fig. 2. The $-1/3$ power law was evident for three scalars in unstable conditions. The similarity constants C_{T3}, C_{q3} and C_{c3} were determined to be 1.12, 1.19 and 1.17, respectively. Lloyd et al. (1991) and Hsieh et al. (1996) found that the FV relation was the same for the surfaces considered. However, in previous studies, as summarized in Table 1, even for the same ecosystem, different authors have reported different values of C_{T3}, C_{q3} or C_{c3}, with larger differences

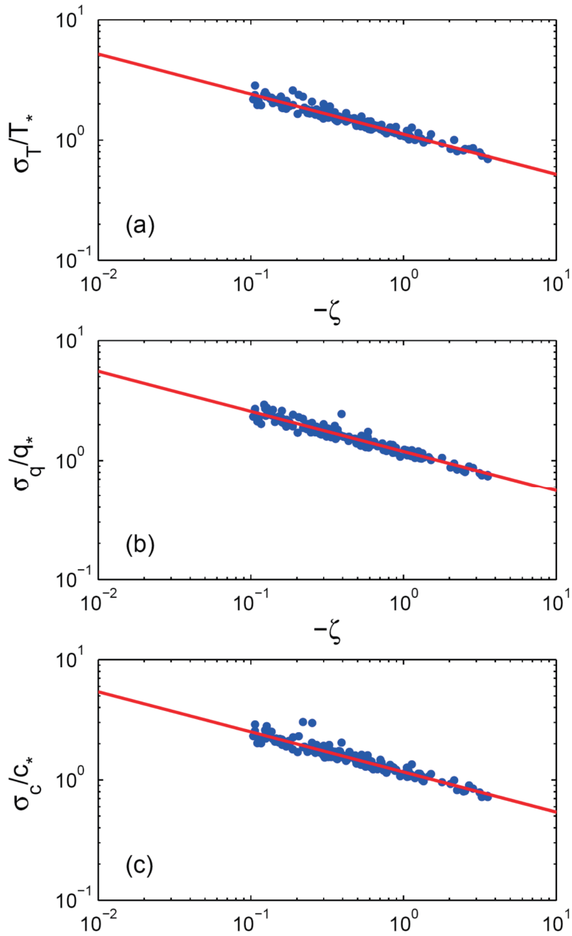

Fig. 2. Normalized standard deviation of (a) temperature, (b) water vapor density and (c) CO_2 concentration as a function of the stability parameter (ζ). The solid lines represent the similarity functions for Eq. (6).

Table 2. Coefficients of regression analyses between measured and estimated sensible heat (H), water vapor (LE), and CO_2 (F_c) fluxes.

Flux	Slope (A)	Intercept (B)	R^2	SEE
H	0.92	11.64	0.92	10.22 (W m^{-2})
LE ($\lambda_{Tq}=1$)	0.96	31.52	0.88	28.05 (W m^{-2})
LE ($\lambda_{Tq}=R_{Tq}$)	0.98	68.56	0.49	78.62 (W m^{-2})
LE ($\lambda_{Tq}=R_{Tq}^{-1}$)	0.88	12.51	0.88	25.33 (W m^{-2})
LE ($\lambda_{Tq}=C_{q3}/C_{T3}$)	0.90	29.21	0.88	26.27 (W m^{-2})
LE ($\lambda_{Tq}=R_{Tq}^{K}$)	0.92	33.37	0.79	39.88 (W m^{-2})
F_c ($\lambda_{Tc}=1$)	0.98	−0.06	0.80	0.11 (mg m^{-2} s^{-1})
F_c ($\lambda_{Tc}=R_{Tc}$)	0.99	−0.16	0.62	0.16 (mg m^{-2} s^{-1})
F_c ($\lambda_{Tc}=R_{Tc}^{-1}$)	0.88	−0.03	0.82	0.08 (mg m^{-2} s^{-1})
F_c ($\lambda_{Tc}=-C_{c3}/C_{T3}$)	0.95	−0.05	0.85	0.09 (mg m^{-2} s^{-1})
F_c [$\lambda_{Tc}=-(-R_{Tc})^{M}$]	0.88	−0.13	0.81	0.12 (mg m^{-2} s^{-1})

usually among C_{T3}, C_{q3} and C_{c3} for forest ecosystems, while smaller differences for grassland/farmland. The values of C_{T3}, C_{q3} and C_{c3} at our site were within these ranges, and the values of C_{q3} and C_{c3} were both slightly higher than the value of C_{T3}. This feature is in agreement with results of several other studies conducted over various surfaces (Table 2), which points to the fact that standard deviations of T, q and CO_2 do not behave precisely in the same way (e.g. Lamaud and Irvine, 2006), and suggests dissimilarity among T, q and CO_2 (e.g. Gao et al., 2006). A possible cause for the imperfect similarity is associated with different levels of scalar passivity (e.g. Guo et al., 2009).

4.1.2 *Correlation coefficient between vertical velocity and scalars*

The correlation coefficient between vertical velocity and scalars can be regarded as a measure of overall efficiency, which changes between 0 (no correlation) to ±1 (optimal efficient transfer) (Roth and Oke, 1995). In Fig. 3, they are plotted against the stability parameter ζ. The mean values (and standard deviations) of R_{wT}, R_{wq} and R_{wc} were 0.52 (0.05), 0.49 (0.05) and −0.50 (0.06), respectively. In Fig. 3a, R_{wT} is dependent upon ζ, increasing from about 0.35 at $\zeta=-0.1$ to about 0.57 at $\zeta=-1$, and R_{wT} tends to approach a constant with higher instabilities. This feature has been noted by some other authors (e.g. De Bruin et al., 1993; Roth and Oke, 1995; Lamaud and Irvine, 2006; Moriwaki and Kanda, 2006). The reason for this increased heat transport with ζ over flat surfaces is attributed to relatively low σ_w/u_* compared to the data presented by Panofsky et al. (1977) (e.g. Roth and Oke, 1995; Moriwaki and Kanda, 2006). The dependencies of R_{wq} and R_{wc} (Figs. 3b, c) upon $-\zeta$ are similar to that of R_{wT}, but with smaller magnitudes.

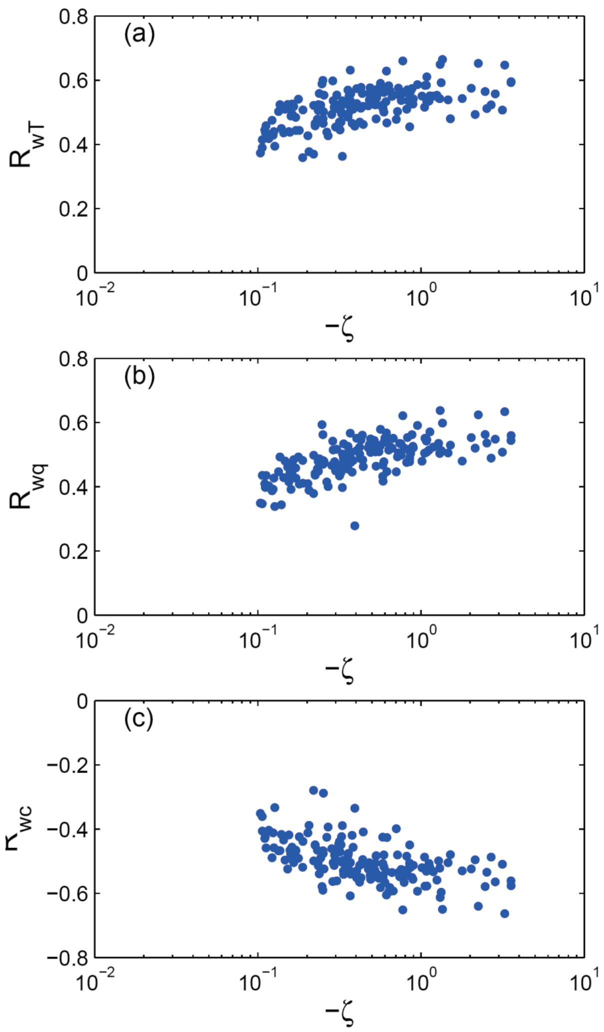

Fig. 3. Correlation coefficient of (a) R_{wT}, (b) R_{wq} and (c) R_{wc} against the non-dimensional stability (ζ).

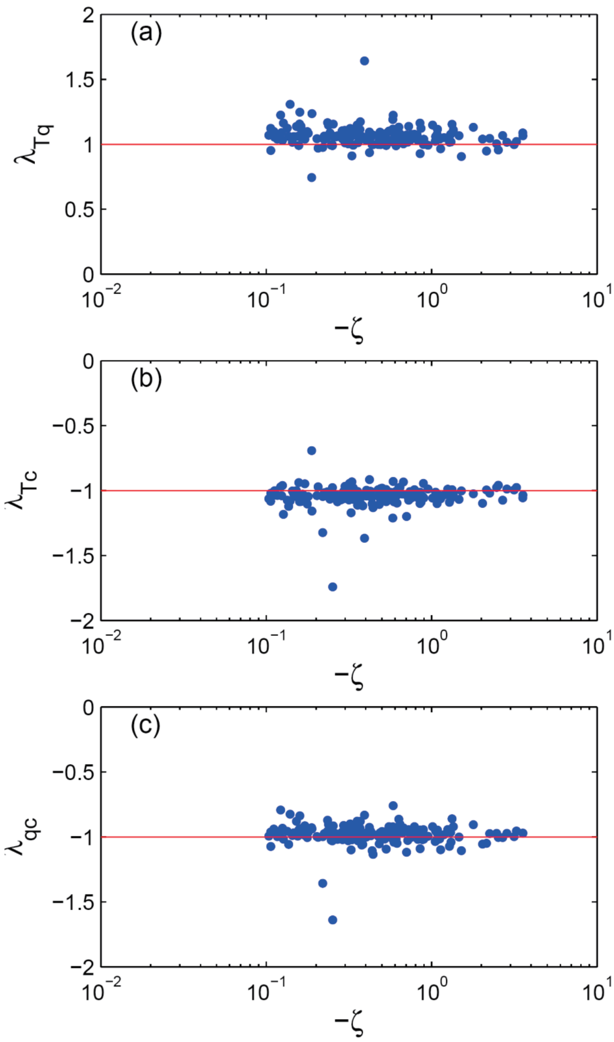

Fig. 4. Relative transfer efficiency of (a) λ_{Tq}, (b) λ_{Tc}, and (c) λ_{qc} against the non-dimensional stability (ζ).

4.1.3 *Relative transport efficiency of heat to water vapor and* CO_2

Figures 4a, b and c show plots of the relative transfer efficiency of heat to water vapor (λ_{Tq}), heat to CO_2 (λ_{Tc}), and water vapor to CO_2 (λ_{qc}), respectively. In unstable conditions, heat transportation was more efficient than water vapor and CO_2, which is in agreement with results from several other studies (e.g. Katul et al., 1995; Roth and Oke, 1995; Katul and Hsieh, 1999; Lamaud and Irvine, 2006; Moriwaki and Kanda, 2006; Cava et al., 2008). Deviation from unity of relative transfer efficiency was in contrast to the MOST prediction of unity indicating that scalars should be transported by the same mechanism in a homogeneous surface layer (Roth and Oke, 1995). Hill (1989) suggested that the reason for relative transfer efficiency deviated from unity results from different active or passive roles of scalars. Katul et al. (1995) pointed out that statistics for T and q could be different, because T is an active scalar but q is generally not. Furthermore, CO_2 might be regarded as a passive scalar (e.g. Moriwaki and Kanda, 2006). Also, some authors have suggested that relative transfer efficiency deviating from unity results from the heterogeneity of the surface structure (e.g. Roth and Oke, 1995), cloud effects on radiation (e.g. Roth and Oke, 1995), modulations from the outer layer (e.g. McNaughton and Laubach, 1998; Moriwaki and Kanda, 2006; Asanuma et al., 2007), hydrologic conditions of the site (e.g. Lamaud and Irvine, 2006; Guo et al., 2009), and the complexity of CO_2 sources/sinks on the surface (e.g. Williams et al., 2007; Hsieh et al., 2008).

At our site, however, the land surface is homogeneous short grassland, and data used for analysis were from fair weather days and satisfied the stationarity test. So, heterogeneity of the surface structure can be

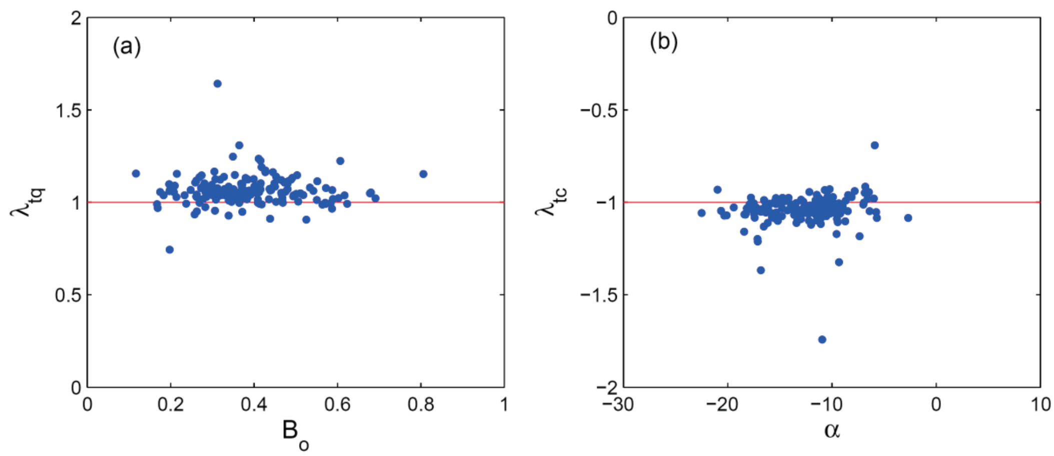

Fig. 5. Relative transfer efficiency of (a) λ_{Tq} and (b) λ_{Tc} against the non-dimensional quantities B_O and α.

disregarded as a potential factor. Plus, cloud effects on radiation and modulations from the outer layer can also be minimized by data selection to a certain degree. Lamaud and Irvine (2006) described wet and dry conditions as $B_O \leqslant 0.1$ and $B_O \geqslant 1$, and found that a quick rise of λ_{Tq} with B_O when the latter was lower than 0.5. However, at our site, λ_{Tq} and λ_{Tc} were independent of B_O and α, as illustrated in Fig. 5. Although, following the data selection criteria, the complexity of CO_2 sources/sinks on the surface cannot be disregarded, because the photosynthesis and respiration of an ecosystem are influenced by multiple environmental factors, such as air temperature, soil water content, vapor pressure deficit, and precipitation (e.g. Xu and Baldocchi, 2004; Zhao et al., 2006, 2010). Thus, through the above analysis, different roles (active or passive) of these scalars and the complexity of CO_2 sources/sinks on the surface may be the main reason for the deviation from unity of the relative transfer efficiency.

4.2 *Estimation of turbulent fluxes using the FV method*

4.2.1 *Sensible heat flux*

Using Eq. (7) and measured standard deviations of temperature, sensible heat flux can be calculated by the FV method. Figure 6 shows the comparison of sensible heat flux between FV estimations ($H_{\rm FV}$) and EC measurements ($H_{\rm EC}$). A regression model ($H_{\rm EC} = A \times H_{\rm FV} + B$) was used to evaluate the FV method estimated sensible heat flux. The coefficient of determination (R^2) and standard errors of estimation

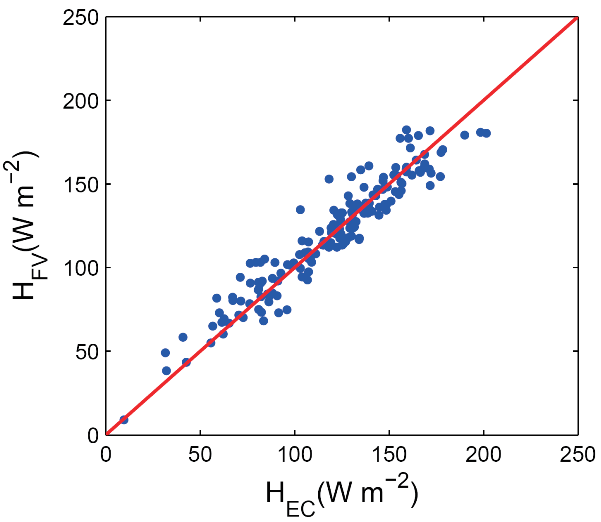

Fig. 6. Comparison of sensible heat fluxes between flux-variance estimations ($H_{\rm FV}$) and eddy-covariance measurements ($H_{\rm EC}$).

(SEE) were 0.92 and 10.22 W m^{-2}, respectively. In the past, SEE for sensible heat flux estimation has ranged from 8.9 W m^{-2} to 49.4 W m^{-2} (e.g. Katul et al., 1995; Sugita and Kawakubo, 2003; Hsieh et al., 2008). It is clear that, from Eq. (9), the accuracy of LE and $F_{\rm c}$ estimations depends upon $H_{\rm FV}$. Thus, reasonable agreement between $H_{\rm FV}$ and $H_{\rm EC}$ implies that temperature is suitable to be used as a reference scalar for LE and $F_{\rm c}$ estimation.

4.2.2 *Latent heat flux*

The suitable expression of λ_{Tq} is important to latent heat flux estimation, as described in Section 3.2. Figure 7 plots the comparisons of latent heat flux between EC measurements (LE$_{\rm EC}$) and FV estimations (LE$_{\rm FV}$) using the five representations of λ_{Tq} as described in section 3.2. Figure 8a shows the relationships between λ_{Tq} and R_{Tq}. Coefficients of regression analyses are shown in Table 2. Obviously, the FV method systematically overestimated the latent heat flux by about 6% (Fig. 7a) with the strategy proposed by Hill (1989); R^2 and SEE were 0.88 and 28.05 W m^{-2}, respectively. The primary reason is attributed to simplification of $\lambda_{Tq} = 1$, which means that water vapor and heat are transported by the same mechanism in a homogeneous surface layer (e.g. Roth and Oke, 1995). In contrast, at the present site, heat transportation was more efficient than water vapor (Fig. 8a), and the averaged λ_{Tq} was 1.06.

As implied in Fig. 8a, the R_{Tq} is not a proper expression for λ_{Tq}; the strategy $\lambda_{Tq} = R_{Tq}$ might only be valid when $\lambda_{Tq}<1$, such as in Guo et al. (2009). However, at our site, only very few of measured λ_{Tq} satisfied this limit; the averaged R_{Tq} was 0.87, quite different from the averaged λ_{Tq}, which resulted in the FV method systematically overestimating the EC-measured LE by about 23% with the strategy proposed by Katul et al. (1995) (Fig. 7b); R^2 and SEE were 0.49 and 78.62 W m^{-2}, respectively.

Although most values of λ_{Tq} were higher than unity and the strategy proposed by Bink and Meesters (1997) can potentially be applied to our site, they were systematically less than R_{Tq}^{-1} (Fig. 8a), and the averaged value of R_{Tq}^{-1} was 1.18. Bink and Meesters (1997) demonstrated that λ_{Tq} is expressed by R_{Tq}^{-1} when relative transfer efficiency of heat to water vapor is about twice the average, but this ratio is higher than the value of averaged λ_{Tq} in this study. Thus, the FV method systematically underestimated the EC-measured LE by about 8% with this strategy (Fig. 7c); R^2 and SEE were 0.88 and 25.33 W m^{-2}, respectively.

Reasonable agreement between measured and predicted LE are shown in Fig. 7d; R^2 and SEE were 0.88 and 26.27 W m^{-2}, respectively. The ratio

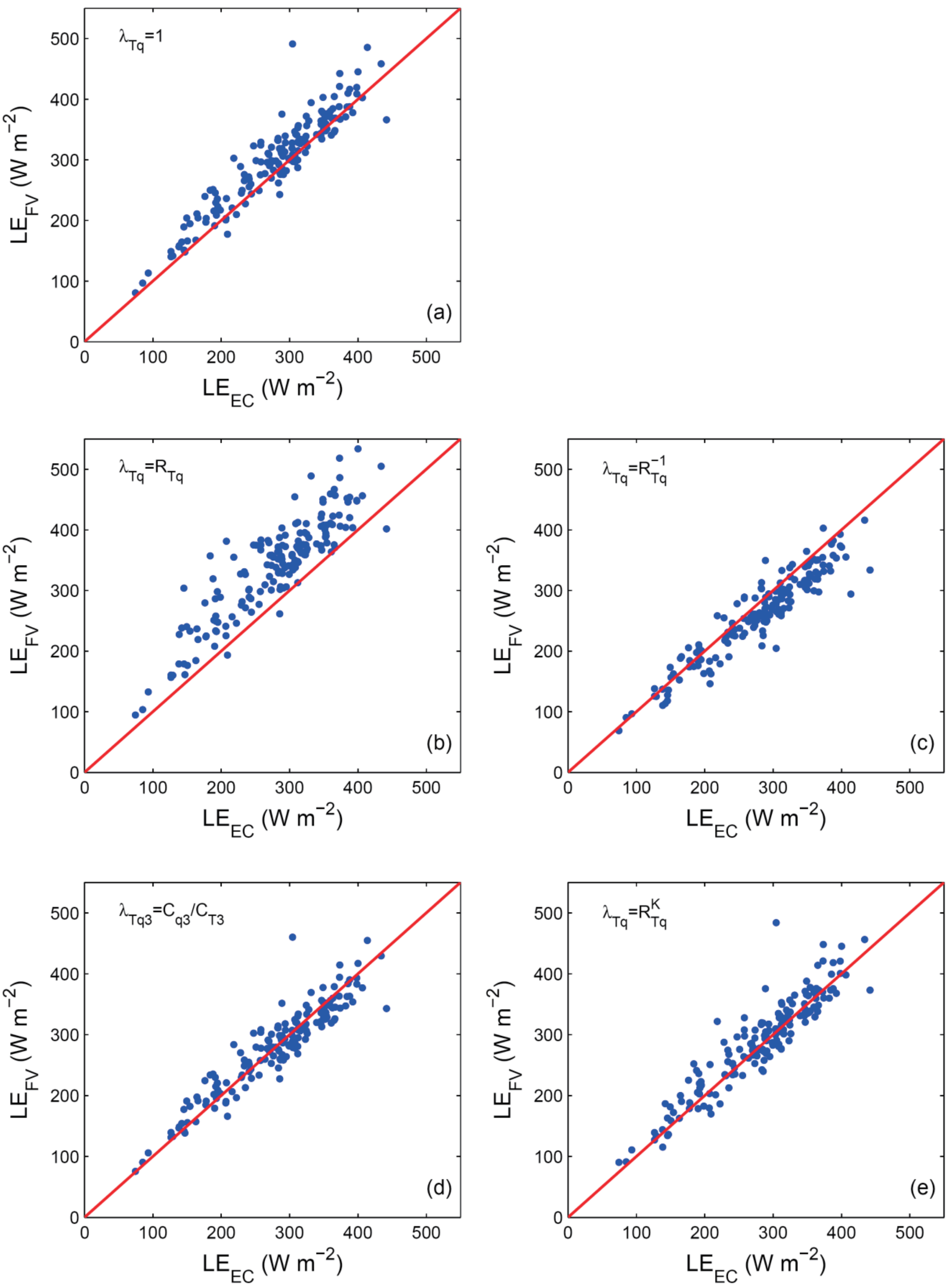

Fig. 7. Comparison of latent heat fluxes between flux-variance estimations (LE_{FV}) and eddy-covariance measurements (LE_{EC}).

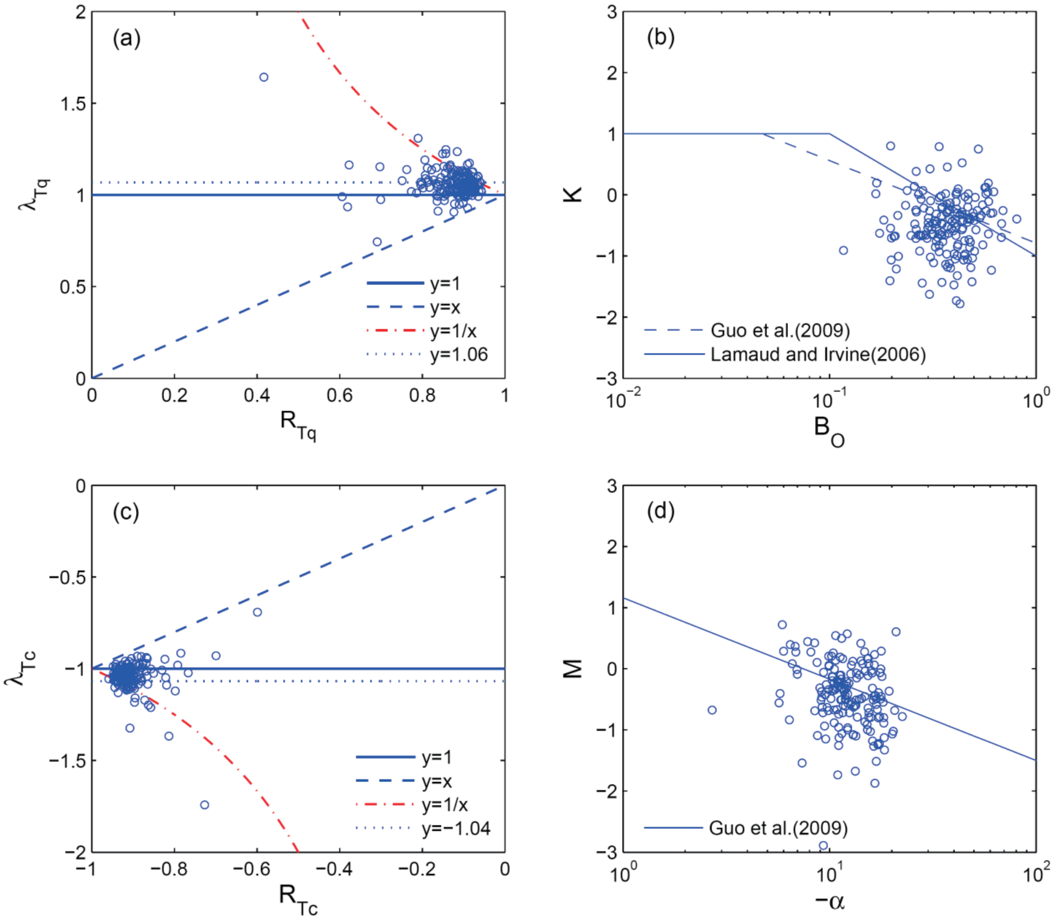

Fig. 8. Different parameterization strategies of the relationship (a) $\lambda_{Tq} - R_{Tq}$, (b) $\lambda_{Tc} - R_{Tc}$, (c) $K - B_O$, and (d) $M - \alpha$.

$C_{q3}/C_{T3} = 1.06$ equaled the value of averaged λ_{Tq}. As shown in Fig. 7e, the LE estimated with the strategy proposed by Lamaud and Irvine (2006) was in agreement with measured results. However, this is somewhat misleading. As implied in Fig. 8b, all of the data fell under intermediate hydrological conditions, but the relationship between K and the B_O as described by Lamaud and Irvine (2006) or Guo et al. (2009) could not be found. Lamaud and Irvine (2006) pointed out that the λ_{Tq} is dependent on the B_O from measurements performed in a large range of hydrological conditions, although they did not exclude the possibility of other factors. One of the consequences of this relationship between K and B_O is that $\lambda_{Tq} = 1$, for $B_O = 0.316$, regardless of the correlation between T and q. As Moene and Schüttemeyer (2008) pointed out, Lamaud and Irvine (2006) did not explain the origin of B_O dependence on K. Thus, strategy $\lambda_{Tq} = C_{q3}/C_{T3}$ is only recommended for latent heat flux estimation by the FV method.

4.2.3 CO_2 *flux*

Figure 9 plots the comparisons of CO_2 flux between EC measurements ($F_{\rm cEC}$) and FV calculations ($F_{\rm cFV}$) using the five representations of λ_{Tc} as described in Section 3.2. Figure 8c shows the relationships between λ_{Tc} and R_{Tc}. Coefficients of regression analyses are shown in Table 2. As shown in Fig. 9a, there was a systematic overestimation of carbon uptake by strategy $\lambda_{Tc} = -1$, while R^2 and SEE were 0.8 and 0.11 mg m^{-2} s^{-1}, respectively. The main reason is that the heat is transported more efficiently than CO_2 at our site; the averaged $\lambda_{Tc} = -1.04$. Also, neither $\lambda_{Tc} = R_{Tc}$ nor $\lambda_{Tc} = R_{Tc}^{-1}$ estimated CO_2 flux feasibly, overestimating (17%) and underestimating (10%) carbon uptake, owing to improper representations of λ_{Tc} (Fig. 8c). The averaged R_{Tc} and R_{Tc}^{-1} were -0.9 and -1.11, respectively. Obviously, the strategy based on the FV similarity relation provided a reasonable agreement between measured and predicted CO_2 flux (Fig. 9d). The R^2 and SEE were 0.85 and 0.09 mg

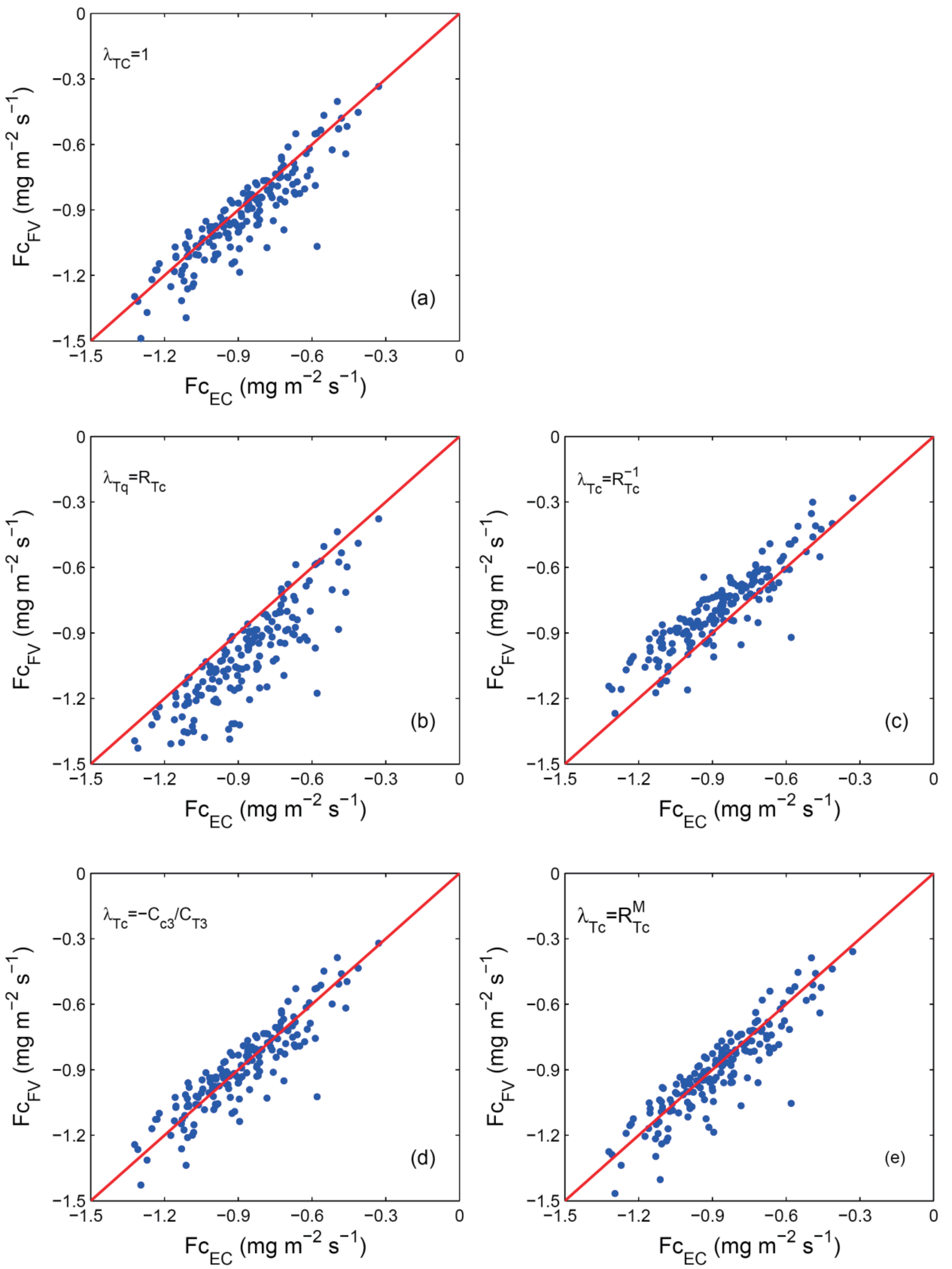

Fig. 9. Comparison of CO_2 fluxes between flux-variance estimations ($F_{\rm cFV}$) and eddy-covariance measurements ($F_{\rm cEC}$).

m^{-2} s^{-1}, respectively. The ratio $-C_{c3}/C_{T3} = -1.04$ was equivalent to the averaged λ_{Tc}.

As shown in Fig. 9e, the CO_2 flux estimated with the strategy proposed by Guo et al. (2008) was in agreement with measured results. However, as shown in Fig. 8d, the relationship between power M and α could not be reproduced by our data. The averaged λ_{Tc} of Guo et al. (2009) was -0.92 at the farmland station, whereas in our study it was -1.04. Moreover, R_{Tc} values for our site were also higher than values found by Guo et al. (2009). These differences might imply different transfer mechanisms for these variables between the two sites. As Guo et al. (2009) pointed out, the $M-\alpha$ relationship is likely to vary from site to site, and has to be further examined. Thus, based on our study, the strategy $\lambda_{Tq} = -C_{c3}/C_{T3}$ is recommended for CO_2 flux estimation.

5. Conclusions

From measurements performed over a homogeneous short grass surface in the eastern Tibetan Plateau, we examined the FV relationship of temperature, water vapor density and CO_2 concentration. Based on these relationships, five representations of relative transport efficiency were applied to calculate latent heat and CO_2 fluxes using the FV method. Our results suggested the following:

In unstable conditions, the normalized standard deviation of temperature, water vapor density, and CO_2 concentration followed the FV similarity relation, but did not behave in exactly the same way due to different roles (active or passive) of these scalars in the production/destruction of turbulent kinetic energy. Similarity constants for temperature (C_{T3}), water vapor (C_{q3}) and CO_2 (C_{c3}) were found to be 1.12, 1.19 and 1.17, respectively. Heat was transported more efficiently than water vapor and CO_2.

On the basis of the similarity constant C_{T3} determined locally, sensible heat flux estimated by the FV method was in agreement with results measured by the EC system.

On the basis of estimated sensible heat flux, five strategies were applied to calculate latent heat and CO_2 fluxes. The strategy of local determination of the FV similarity relation had the practical applicability for the estimation of latent heat and CO_2 fluxes. Compared to other more complex ones, this approach was better at representing the averaged relative transport efficiency, and technically easier to apply. The relationships of $K-B_O$ and $M-\alpha$ have to be examined before using the FV method for estimating latent heat and CO_2 fluxes.

A final important point to make is that the data used in this paper were from summers under intermediate hydrological conditions, during rainy season. The results may not represent other drier seasons.

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