# Discussion on Calculation Methods of Sensible Heat Flux during GAME/Tibet in 1998

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**ABSTRACT**

Based on previous research on sensible heat flux, we investigate it from different aspects using GAME/Tibet data measured during 6 June–13 September, 1998. This work consists of the derivation of the surface heat flux equation, analysis on counter-gradient heat transference, comparison between two different methods to compute the sensible heat flux, and investigation on the calculation scheme of sensible heat flux in the Simple Biosphere model 2 (SiB2) with relevant simulation. By improving two previous formulations, an integrated formulation for calculating surface heat flux is given. Secondly, using the measured data, the counter-gradient heat flux is clarified, leading to the fact that buoyancy plays an important role in the sensible heat transfer process. It is concluded that (1) energy imbalance is a common phenomenon resulting from the use of the traditional closure scheme on the heterogeneous underlying surface because the measured ensemble heat fluxes by eddy correlation contain the effect of nonlocal parcel movements; and (2) nonlocal parcel movement deserves more attention in any future heat flux study.

**Key words:** sensible heat flux, heat conduction, adverse gradient transference, SiB2, energy imbalance

## 1. Introduction

In 1998, as a part of the GEWEX Asian Monsoon Experiment (GAME), surface turbulent fluxes and other meteorological measurements were made at several sites in the central Tibetan Plateau during the Intensive Observation Period (IOP) from May to September. One of the interesting results from this field campaign was the apparent energy imbalance observed over the Plateau at many stations (e.g., Kim et al., 2000; Wang et al., 1999; Wang, 2000), namely, about 20% of the net radiation, $R_n$, is missing.

Energy budget closure $\varepsilon$, defined as the ratio of the sum of sensible and latent heat fluxes $(H + \lambda E)$ to available energy (the difference of net radiation and the soil heat flux: $R_n - G_0$), has been examined by using the measured energy components. Ideally $\varepsilon$ should be 1.0, however, energy imbalance has been found in the literature related to the eddy method on measured data in field experiments. For instance, after the First International Satellite Land Surface Climatology Projects (ISLSCP) Field Experiment (FIFE), it was concluded by various participants (e.g., Strebel et al., 1990; Smith et al., 1992; Nie et al., 1992) that the uncertainty in sensible and latent surface heat fluxes measured locally was at least ~10% and up to 20%, or up to around 20–30 W m$^{-2}$, even on a daily basis (see also, e.g., Brutsaert and Sugita, 1992a, b; Qualls and Brutsaert, 1996a, b; Sugita and Brutsaert, 1990, 1996). Brutsaert (1998) indicated that current technology is still incapable of measuring turbulent heat fluxes with an accuracy needed to detect likely climate change signals. In a well-watered broad-leaved forest of Nothofagus trees, $(R_n - J - G)$ tended to exceed $(H + \lambda E)$ by 50 150 W m$^{-2}$ during periods of intermittent cloudiness (Kelliher et al., 1992); here, $J$ is the heat storage in the canopy. Kustas et al. (1999) pointed out that the measured $H + LE$ by the eddy correlation method is generally less than $R_n - G_0$: $\varepsilon = (H + LE)/(R_n - G_0) \approx 0.7$–$0.9$ (daytime average 0.77) during the Washita 1994 Experiment conducted in the Little Washita Experimental Watershed near Chickasha, Oklahoma. Gu et al. (1999) used GOES satellite-retrieved surface net radiation and the *in situ*

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estimates of surface sensible-latent heat fluxes from eddy correlation measurements to test the energy balance closure at the top of boreal forest. The tests were carried out at five tower flux (TF) sites within the Boreal Ecosystem-Atmosphere Study (BOREAS) experimental area for June–September 1996. Their main result was that the measured eddy correlation fluxes showed a negative bias. Their results of the closure analysis are in near agreement to results from a set of seven independent energy balance closure studies conducted at individual BOREAS tower flux sites in 1994, which are based on *in situ* tower measurements of the surface flux terms. This led them to conclude that combined sensible-latent heat flux estimates from TF eddy correlation measurements were approximately 15% too low. They did not, however, examine the true reason for the energy imbalance. Therefore, it is worthwhile to examine the energy transfer in the near surface layer, together with the eddy correlation principle and observations. After examining the literature about thermal transfer, sensible heat flux, and surface heat flux, we attempt to investigate the methods for computing sensible heat flux and surface heat flux from four different aspects. These four aspects are the derivation of the sensible heat flux formula, analysis on counter-gradient heat flux, comparison between two different methods for calculating sensible heat flux, and investigation on the calculation scheme of sensible heat flux in SiB2 with a relevant simulation. Our objectives are to advance previous research on energy balance, and to better understand sensible heat flux and surface heat flux. To achieve these objectives, we will proceed as follows: Sun et al.'s (1995) Eq. (48) of thermal conduction $Q_H$ and Lee's (1998) equation of net ecosystem exchange (NEE) are examined and integrated respectively in section 2, while the counter-gradient heat flux is clarified in section 3. Sun et al.'s (1995) Eq. (48) and Stull's (1988) Eq. (10.7c) are compared in section 4. Sensible heat flux calculated in SiB2 is presented in section 5. The energy imbalance is discussed in section 6, followed by the main conclusions in section 7.

## 2. A new formulation for sensible heat transfer

Sun et al. (1995) used a scale analysis to derive and approximate the thermal conduction $Q_H$ formulation as (their Eq. 48)

$$Q_H \approx (\overline{\rho_\mathrm{d}} c_\mathrm{pd} + \overline{\rho_\mathrm{v}} c_\mathrm{pv}) \overline{w'T'} + \overline{\rho} c_\mathrm{pv} \overline{w'q'} \left(\overline{T} - \overline{T_0}\right) - Q_R, \tag{1}$$

where $\overline{\rho}$, $\overline{\rho_\mathrm{d}}$, $\overline{\rho_\mathrm{v}}$, $c_\mathrm{pd}$ and $c_\mathrm{pv}$ are the mean air density, the mean density for dry air and water vapor respectively, and the specific heat at constant pressure for dry air and water vapor, (Stull, 1988; Sun et al., 1995). The radiation term $Q_R$ is approximately 3 W m$^{-2}$. Sun et al.'s study is based on the concept that the thermal conduction between the ground surface and the observation level can be approximated by the net enthalpy flux between the two levels. Sun et al. contends that Eq. (1), which is based on their five assumptions, can be applied to the thin layer of moist air adjacent to a flat surface where the vertical thickness of the layer is sufficiently small. Under this condition, the time-averaged heat, the mass storage, and the advection of time-averaged heat and mass can be neglected within the layer, and there is no horizontal flow convergence/divergence nor any non-zero mean vertical velocity. Eq. (1) is propitious to a thin layer of moist air adjacent to ideal underlying surfaces such as an ocean, sea, or big lake surface, wheat or rice field, desert, Gobi, and lush prairie. In their conclusions, Sun et al. (1995) argue that Eq. (1) permits the evaluation of $Q_H$ with the use of conventional fast-response aircraft, tower, or shipboard measurements of wind, temperature, and humidity in the atmospheric boundary layer. However, there are two unexplained difficulties in their work. First, they did not clarify the scope of the vertical thickness of this layer. Therefore, it is difficult to install sonic instruments at the top of the layer. Second, their argument in the conclusion seems incompatible with their first assumption.

Lee (1998) derived a new formulation to calculate the net ecosystem exchange (NEE) of a scalar constituent with atmosphere from the mass couservation and the continuity equations as,

$$\mathrm{NEE} = \int_0^{z_\mathrm{r}} \frac{\partial \overline{c}}{\partial t} dz + \left(\overline{w'c'}\right)_\mathrm{r} + \overline{w_\mathrm{r}} \left(\overline{c_\mathrm{r}} - \frac{1}{z_\mathrm{r}} \int_0^{z_\mathrm{r}} \overline{c} dz\right), \tag{2}$$

where the first term on the RHS is the storage below the height of observation ($z_\mathrm{r}$), the second term is the eddy flux, and the third term is a mass flow component arising from horizontal flow convergence/divergence or a non-zero mean vertical velocity ($\overline{w_\mathrm{r}}$) at height $z_\mathrm{r}$. The last term is a major challenge facing the micrometeorological community. In his paper, however, Lee did not consider the thin layer adjacent to the ground surface. In this paper, we divide the layer from the ground surface to the sonic measurement height into two layers. As a result, the lower layer satisfies Sun et al.'s (1995) five assumptions, and the upper layer satisfies Lee's (1998) equation at the same time. Under this condition, the term of $\overline{w'T'}$ in Eq. (1) is equal to NEE in Eq. (2). Therefore, the following formulation is derived:

$$Q_H \approx (\overline{\rho_{\rm d}} c_{\rm pd} + \overline{\rho_{\rm v}} c_{\rm pv}) \overline{w'T'} + \bar{\rho} c_{\rm pv} \overline{w'q'} \left(\overline{T_1} - \overline{T_0}\right) - Q_R + (\overline{\rho_{\rm d}} c_{\rm pd} + \overline{\rho_{\rm v}} c_{\rm pv}) \left[ \int_0^{z_{\rm r}} \frac{\partial \overline{T}}{\partial t} dz + \overline{w_{\rm r}} \left( \overline{T} - \frac{1}{z_{\rm r}} \int_0^{z_{\rm r}} \overline{T} dz \right) \right]. \quad (3)$$

Eq.(3) eliminates the five restrictive assumptions of Eq.(1), and at the same time, has more transparent physical meaning than Eq.(2).

## 3. Counter-gradient heat flux

The zero gradient or counter-gradient thermal transportation has been observed in the neutral and stable atmospheric boundary layer. Lettau and Davidson (1957) observed counter-gradient heat flux at the height 100 m of a great plain during their turbulence experiment period. Webb (1958) observed a severe thermal convection at the height of 25 m above the ground surface, where the temperature gradient was equal to zero and the wind speed was quite small. Bunker (1956) measured counter-gradient heat flux at the height of 150–550 m above the West Atlantic Ocean by aircraft. Telford and Warner (1964) detected counter-gradient heat flux at several heights of 150 m, 350 m, and 1250 m above the ground surface by aircraft. Wong and Brundidge (1966) observed the vertical and temporal distributions of the heat conductivity and flux at the Cedar Hill tower site in Texas and indicated that counter-gradient heat transfer appeared between 0300 to 0700 LST. Thmoas and Townsend (1957) examined the air turbulent convection between two metal panels with different temperatures, and their result was that 50% of the air having the same isobaric temperature and heat was, nonetheless transferred through this isobaric temperature layer. Deardorff (1966) repeated this experiment and reached the same conclusion. All of this research shows that heat transfer in atmosphere with gravity differs from gradient heat transfer in molecular conduction theory, to a considerable degree.

It is difficult to explain counter-gradient heat flux by using classical mixed length theory. Considering that an air parcel might rise or sink when its temperature differs from the surrounding environment, Priestley and Swinbank (1947) used a buoyancy term to revise the mixed length equation. They, however, failed to obtain the expected result. In order to solve this problem, Deardorff (1966) added a parameter $r_{\rm c}$ to the gradient transfer theory, to create a new empirical formula:

$$\overline{w'\theta'} = -K'_H \left( \frac{\partial \bar{\theta}}{\partial z} - r_{\rm c} \right). \quad (4)$$

There is, however, another problem; using this formulation, it is impossible to calculate sensible heat flux since the value for $K'_H$ is unknown. On the other hand, Yang et al. (1983) derived an equation of sensible heat flux from the turbulent transfer formulation ($Q = \rho \overline{w's'}$):

$$Q_H = \rho c_{\rm p} K_T (\gamma - \gamma_{\rm d}) + \rho c_{\rm p} \overline{w'T'_0}, \quad (5)$$

because the last term on the RHS (i.e., buoyancy) is always greater than zero. Under the stable condition, if this buoyancy term is greater than the absolute value of the first term on the RHS, and if the first term on the RHS is less than zero, the result should be $Q_H > 0$. This is to say that a counter-gradient heat flux is attained. However, we cannot calculate the value of sensible heat flux with Eq. (5). Sorbjan (1989) integrated a new formula through the following procedure. The vertical transfer of sensible heat flux is expressed as:

$$\frac{\partial \overline{w'\theta'}}{\partial t} = -\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z} - \frac{\partial \overline{w'^2\theta'}}{\partial z} + \frac{g}{\bar{\theta}} \overline{\theta'^2} - \frac{1}{\rho_0} \overline{\theta' \frac{\partial p'}{\partial z}}. \quad (6)$$

Since it is possible to neglect the higher-order terms $\left(\frac{\partial \overline{w'^2\theta'}}{\partial z}\right)$ and to parameterize $\frac{1}{\rho_0} \overline{\theta' \frac{\partial p'}{\partial z}}$ with $\frac{\overline{w'\theta'}}{\tau}$, under the steady condition, the following is obtained from Eq.(6):

$$\overline{w'\theta'} = -\tau \left( \overline{w'^2} \frac{\partial \bar{\theta}}{\partial z} - \frac{g}{\bar{\theta}} \overline{\theta'^2} \right), \quad (7)$$

where $\tau$ is a time scale parameter. Xu (1992) set up a system of Reynolds equations of the multi-scale atmospheric motions by decomposing the meteorological elements into multi-scale disturbances. Then, he demonstrated that the Reynolds exchange term in the averaged motion was equal to the sum of the averaged nonlinear terms in all the sub-averaged motions. The Langevin form of individual particle motion was used to describe sub-scale motion. The sensible heat flux was derived as:

$$\overline{w'\theta'} = \sigma_w^2 T_H \left( \frac{g}{\bar{\theta}} \frac{\sigma_\theta^2}{\sigma_w^2} - \frac{\partial \bar{\theta}}{\partial z} \right), \quad (8)$$

where $T_H = \left( \frac{1}{T_{wws}} + \frac{1}{T_{\theta\theta s}} \right)^{-1}$ is the Lagrangian turbulence time scale, and $T_{wws}$ and $T_{\theta\theta s}$ are the time scales of $w'$ and $\theta'$, respectively. Comparing Eq. (8) with Eq. (4), we see that the term, $\frac{g}{\bar{\theta}} \frac{\sigma_\theta^2}{\sigma_w^2}$, is equivalent to $\gamma_{\rm c}$ in Eq. (4). $\gamma_{\rm c}$ is the adiabatic lapse rate, which, in dry air, equals 0.98°C/100 m. It follows that $\gamma_{\rm c}$ depends on the environment temperature, gravititational acceleration, the mean-square deviation of fluctuating potential temperature, and vertical speed. $\sigma_w^2$ should be small and $\gamma_c$ should be large on a flat underlying surface.

In order to validate the counter-gradient heat transfer, in Fig. 1 we plot the sensible heat flux obtained by the eddy correlation method versus the temperature gradient in Tibetan shortgrass prairie from 6 June to 15 September 1998. From the figure it is obvious that the trend line of distribution does not cross the origin, which means that the parameter $r_c$ is not zero. Evidently, some data (72% of total points) located in the first and third quadrants illustrate the mean gradient heat transfer, while the others (28%) indicate the existence of a counter-gradient phenomenon. Furthermore, the sample distributions of the mean gradient heat flux are given in Figs. 2 and 3.

According to these two figures, the mean sample number is about 30 during the nighttime; the sample number increases gradually with time after 0830 LST reaches a maximum (97) at 1330 LST, then decreases gradually with time. The sample distribution of counter-gradient heat flux is given in Fig. 4, where the mean sample number is about 17 during the nighttime, increases gradually in the early morning, reaches a maximum (52) at 0830 LST, and then decreases gradually. The distribution of samples is well-proportioned during the daytime, the sample number increases gradually at nightfall and reaches a maximum (56) again at 2000 LST, then decreases gradually. The instrument error should be considered in this analysis, but since there were more than three thousand samples taken, the error can be neglected. All four figures show the existence of counter-gradient heat flux. Furthermore, the probability of counter-gradient heat flux occurring is bigger in both early morning and at nightfall than at any other time.

## 4. Comparison of Sun et al.'s (1995) Eq. (48) and Stull's (1988) Eq. (10.7.1c)

Panofsky and Dutton (1984) derived an equation which is useful for calculating the turbulent energy at the level close to the ground surface,

$$\frac{d\bar{e}}{dt} = -\overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \overline{v'w'}\frac{\partial \bar{v}}{\partial z} + g\frac{\overline{w'T'}}{\bar{T}}\left(1+\frac{0.07}{B}\right) - \frac{1}{\bar{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \frac{\partial \overline{ew'}}{\partial z} - \varepsilon, \qquad (9)$$

where the factor $(1+0.07/B)$ has been added to allow for the possibility of convective energy production when rising air is more humid than its surroundings;

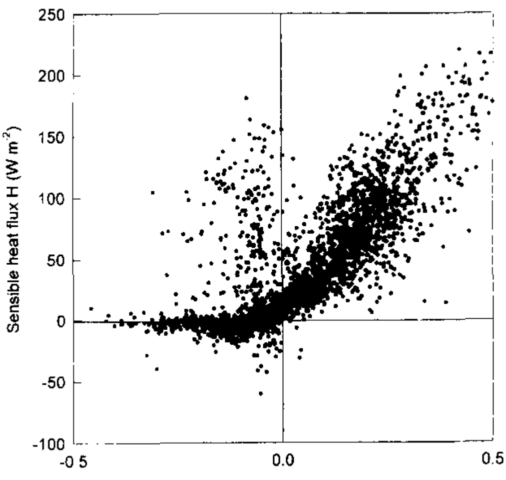


**Fig. 1.** Comparison of sensible heat flux by eddy correlation and by temperature gradient in Tibetan shortgrass prairie from 6 June to 15 September, 1998.

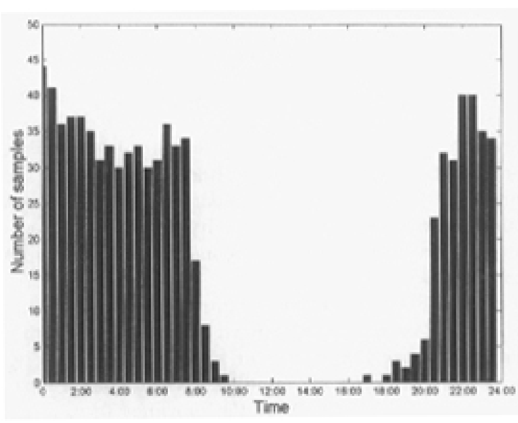


**Fig. 2.** The sample distribution of gradient heat flux on the condition that air temperature at 1.3 m height is less than that at 3.5 m height and that sensible heat flux $H > 0$.

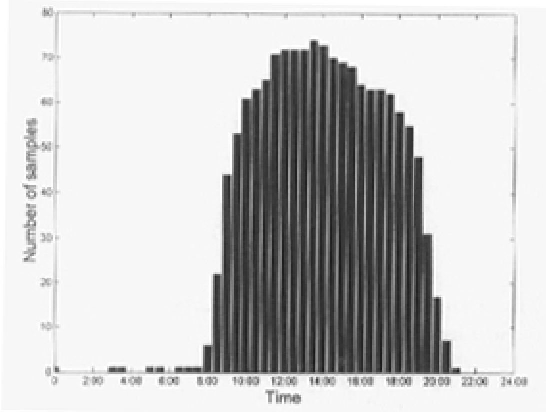


**Fig. 3.** The sample distribution of gradient heat flux on the condition that air temperature at 1.3 m is greater than that at 3.5 m height and that sensible heat flux $H > 0$.

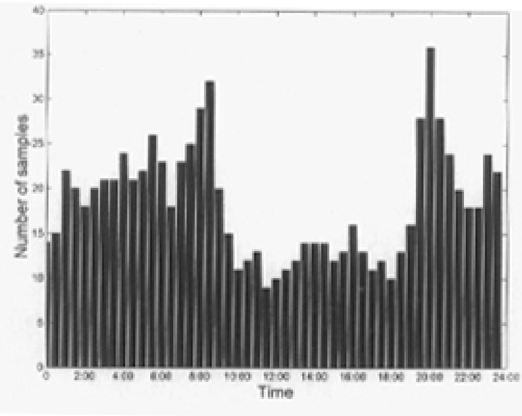


**Fig. 4.** The sample distribution of counter-gradient heat flux on the condition that air temperature at 1.3 m height is less than that at 3.5 m and sensible heat flux $H > 0$, or air temperature at 1.3 m is greater than that at 3.5 m height and sensible heat flux $H < 0$.

and $B$ is the Bowen Ratio, the ratio of sensible to latent heat flux at the surface. Stull (1988), recognizing this important process, combined the precise relationships in Eq. (10) and Eq. (11), but neglected the higher-order terms to arrive at Eq. (12). This equation is often used in the eddy correlation method of *in situ* measurements.

$$H = \overline{\rho w' (c_{\mathrm{p}} T)'}, \tag{10}$$

$$c_{\mathrm{p}} = c_{\mathrm{pd}} (1 + 0.84 q), \tag{11}$$

$$H \approx \overline{\rho} c_{\mathrm{pd}} \left( \overline{w'T'} + 0.84 \overline{T w'q'} \right). \tag{12}$$

Both of $g\frac{\overline{w'T'}}{\overline{T}} \times \frac{0.07}{B}$ in Eq. (9) and $0.84\overline{\rho}c_{\mathrm{pd}}\overline{Tw'q'}$ in Eq. (12) suggest that latent heat flux contributes energy to sensible heat flux. Calculations show that $0.84\overline{\rho}c_{\mathrm{pd}}\overline{Tw'q'}$ is about 10% of latent heat flux.

Eq. (1) emphasizes the following two aspects: (1) surface temperature $T_0$ is used, and (2) the radiation term $Q_R$ is reserved although it is approximately 3 W m$^{-2}$ close to the earth's surface, and the value of $Q_R$ is so small relative to the instrument error that it can be neglected. According to their derivation process, it was known that the surface temperature $T_0$ is the air temperature at the interface of air and the ground surface rather than the ground surface temperature. To better understand Eq. (1) and to conveniently compare it with Eq.(12), it is necessary to reexamine Eq. (12) by integrating the neglected parts. In Eq. (11), $\left(\overline{c_{\mathrm{pv}}} - \overline{c_{\mathrm{pd}}}\right)/\overline{c_{\mathrm{pd}}} = 0.84$, and inserting Eq. (11) into (10), we get

$$\begin{aligned} H &= \overline{\rho w'(c_p T)'} = \overline{\rho w' \{ c_{\mathrm{pd}} [1 + 0.84 (\overline{q} + q')] (\overline{T} + T') \}'} \\ &= \overline{\rho} c_{\mathrm{pd}} \overline{w'\overline{T} + w'T' + 0.84 w'\overline{q}\overline{T} + 0.84 w'\overline{q}T' + 0.84 w'q'\overline{T} + 0.84 w'q'T'} \\ &= \overline{\rho} c_{\mathrm{pd}} \left( \overline{w'\overline{T}} + \overline{w'T'} + 0.84 \overline{w'\overline{q}\overline{T}} + 0.84 \overline{w'\overline{q}T'} + 0.84 \overline{w'q'\overline{T}} + 0.84 \overline{w'q'T'} \right). \end{aligned} \tag{13}$$

Considering that $0.84\overline{w'q'T'}$ is a higher order term, and applying Reynolds averaging, we obtain:

$$H = \overline{\rho}c_{\rm pd}\left(0 + \overline{w'T'} + 0 + 0.84\overline{w'\overline{q}T'} + 0.84\overline{w'q'\overline{T}} + 0\right)$$
$$= \overline{\rho}c_{\rm pd}\left(\overline{w'T'} + 0.84\overline{q}\overline{w'T'} + 0.84\overline{T}\overline{w'q'}\right). \quad (14)$$

If the term $0.84\overline{q}\overline{w'T'}$ is neglected in Eq. (14) since $\overline{q}$ is $O\left(10^{-2}\right)$, we obtain Eq. (12) as a result. We can replace 0.84 with $\left(\overline{c_{\rm pv}} - \overline{c_{\rm pd}}\right)/\overline{c_{\rm pd}}$ and consequently, Eq. (14) is changed into:

$$H = \overline{\rho}c_{\rm pd}(1+0.84q)\overline{w'T'} + (c_{\rm pv} - c_{\rm pd})\overline{\rho}\overline{w'q'}T$$
$$= \overline{\rho}c_{\rm pd}\left[1 + (c_{\rm pv} - c_{pd})q/c_{\rm pd}\right]\overline{w'T'} + (c_{\rm pv} - c_{\rm pd})\overline{\rho}\overline{w'q'T}$$
$$= \overline{\rho}\left[(1-q)c_{\rm pd} + qc_{\rm pv}\right]\overline{w'T'} + (c_{\rm pv} - c_{\rm pd})\overline{\rho}\overline{w'q'}T$$
$$= (\overline{\rho_{\rm d}}c_{\rm pd} + \overline{\rho_v}c_{\rm pv})\overline{w'T'} + (c_{\rm pv} - c_{\rm pd})\overline{\rho}\overline{w'q'}T. \quad (15)$$

When the neglected $0.84\overline{w'q'T'}$ is integrated into Eq. (15), it becomes:

$$H = \left(\overline{\rho_{\rm d}}c_{\rm pd} + \overline{\rho_{\rm v}}c_{\rm pv}\right)\overline{w'T'} + c_{\rm pv}\overline{\rho}\overline{w'q'}T$$
$$- c_{\rm pd}\overline{\rho}\overline{w'q'}T + \left(c_{\rm pv} - c_{\rm pd}\right)\overline{\rho}\overline{w'q'T'}, \quad (16)$$

which is similar to Frank and Emmitt's (1981) expression for their total turbulent flux, which is given as:

$$\overline{\rho w h_{\rm m}}\,|_{z=\delta z} = \overline{\rho}c_{\rm pm}\overline{w'T'}$$
$$+ \overline{\rho}\overline{w'q'}\left[\left(c_{\rm pv} - c_{\rm pd}\right)\overline{T} + \overline{L}\right). \quad (17)$$

Physically, the LHSs of Eqs. (16) and (17) represent the sensible heat flux at a certain level above the surface within the turbulent boundary layer. Although the term $\left(\overline{\rho_{\rm d}}c_{\rm pd} + \overline{\rho_{\rm v}}c_{\rm pv}\right)\overline{w'T'} + c_{\rm pv}\overline{\rho}\overline{w'q'}T$ on the RHS of Eq. (16) is the same as a part of Eq. (1), the LHS of Eq. (1) represents the thermal conduction between the ground surface and a thin layer of air as mentioned above. The similarity between Eq. (16), Eq. (17), and Eq. (1), however, suggests that Eq. (1) can be replaced with Eq. (16) and that it may be possible to get an approximate estimate of the surface heat flux. To validate and quantify our understanding, we examine the data collected from 15 to 21 July 1998 at the Nagqu site of GAME/Tibet, taking the single-level datasets from one sonic anemometer into Eqs. (16) and (1) respectively. In doing so, we find that the relative error between $Q_H$ of Eq.(1) and $H$ of Eq.(16) is just 2.2%, which shows that Eq. (16) and Eq. (1) are equivalent.

## 5. Sensible heat flux calculated with SiB2

The ensuing formula (Sellers et al., 1996) is used in SiB2, in order to calculate sensible heat flux $H$:

$$H = H_{\rm g} + H_{\rm c}, \quad (18)$$

where

$$H_{\rm g} = \frac{(T_{\rm g} - T_{\rm a})\,\rho c_{\rm p}}{r_{\rm d}}, \quad (19)$$

and

$$H_{\rm c} = \frac{(T_{\rm c} - T_{\rm a})\,\rho c_{\rm p}}{r_{\rm b}}. \quad (20)$$

The ground to canopy air space (CAS) resistance $r_{\rm d}$ is defined as follows, as in SiB:

$$r_{\rm d} = \frac{C_2}{u_2} = \int_{z_s}^{h_a}\frac{1}{K_{\rm s}}dz, \quad (21)$$

where $C_2 =$ ground to CAS resistance coefficient $((\rm m\ s^{-1})^{-1/2})$; $u_2 =$ wind speed at canopy to height $z_2$ $(\rm ms^{-1})$; $K_{\rm s} =$ heat-water vapor transfer coefficient, which is assumed to be equal to $K_{\rm m}$ $(\rm m^2\ s^{-1})$; $h_{\rm a} =$ canopy source height (m); $z_{\rm s} =$ ground surface height $(\approx 0)$. The bulk canopy boundary-layer resistance (under neutral conditions) is given by:

$$r_{\rm b} = \frac{C_1}{(u_2)^{1/2}} = \left[\int_{z_1}^{z_2}\frac{L_{\rm d}\,(u_2)^{1/2}}{p_{\rm s}C_{\rm s}}dz\right]^{-1}, \quad (22)$$

where $C_1 =$ bulk canopy boundary-layer resistance coefficient $((\rm m\ s^{-1})^{-1/2})$; $C_{\rm s} =$ heat-mass transfer coefficient $= 90(l_{\rm w})^{-1/2}$, $l_{\rm w} =$ leaf width (m); $p_{\rm s} =$ leaf shelter factor; $L_{\rm d} =$ leaf area density. These formulae point out that the method to calculate sensible heat flux in SiB2 is based on the basic principle of the thermal conduction between the two different materials. There is a subtle but extremely important difference between the method used to calculate the sensible heat flux in SiB2, and the one using the traditional K-theory, since the latter is an effective method to calculate heat fluxes in a unitary fluid where a constant flux layer exists. Sellers et al.. (1996) took the ground temperature ($T_{\rm g}$) into Eq. (19) and the canopy temperature ($T_{\rm c}$) into Eq. (20) in SiB2. In order to clarify the difference between these formulae and traditional K-theory, we review the popular formula of K-theory as Eq. (23), which does not involve ground and canopy temperature:

$$\overline{w'\theta'} = -K_H\Delta\overline{\theta}/\Delta z, \quad (23)$$

where $\Delta\bar{\theta}$ means the difference of the mean air potential temperatures at two layers. In fact, the temperature of the ground surface is higher than the air temperature even though the air layer is very near to the skin of the ground in the daytime, which is especially true at noon.

In SiB2, the measured sensible heat flux ($H$) was calculated by Eq. (16) while the higher-order term $(c_{pv}-c_{pd})\,\bar{\rho}\overline{w'q'T'}$ was neglected, and latent heat flux ($\lambda E$) was obtained by using the eddy correlation while the measured soil heat flux ($G_0$) was calculated by the second law of thermodynamics (i.e., $\frac{\partial T}{\partial t}=-\left(\frac{1}{C_g}\right)\frac{\partial G_g}{\partial z}$, where $C_g$ is the soil heat capacity) based on field measurements. SiB2 was adopted as an offline mode with six atmospheric forcing variables (i.e., downward long and short wave radiation, air temperature, horizontal wind speed, vapor pressure and precipitation) and various input parameters (e.g., canopy morphological, optical, physiological properties, and soil physical properties based on soil and plant measurements at the site). A simulation was conducted by using SiB2 from 15 to 21 July during the Monsoon period. Modeled surface energy fluxes were compared against the measured values at the Nagqu site in a shortgrass prairie in the central Tibetan Plateau. The soil surface temperature was modeled fairly well with an agreement within 1%, and the modeled soil wetness agreed well within 1% of the *in situ* measurement, which showed that the parameters set were pertinent and the simulation was successful (Gao et al., 2000). The following results were obtained: (1) the ratio of the modeled net radiation ($R_n$) to the measured net radiation ($R_n$) was 1.0, (2) the ratio of the modeled latent heat flux ($\lambda E$) to the measured latent heat flux ($\lambda E$) was 0.96, (3) the ratio of the modeled soil heat flux ($G_0$) to the measured soil heat flux was 1.08, and (4) the ratio of the modeled sensible heat flux to the measured heat flux was 1.44 on average. The comparison between the modeled and the measured results are shown in Fig.5a and Fig.5b. Figure 5a gives the diurnal variation of the modeled and measured energy components with corresponding precipitation, and Fig.5b gives the relationship between the modeled and measured energy components, surface radiation temperature, and soil wetness. Both figures support the idea that we should focus on the examination of sensible heat flux in future research. The model performance shows a tendency to overestimate sensible heat flux and surface temperature, and to underestimate latent heat flux in reference to *in situ* measurements. This tendency coincides with similar simulation research using SiB2 or SiB, (Zhang et al., 1996; Schelde et al., 1997; Doran et al., 1998).

## 6. Discussion on energy imbalance

In the last section, the modeled results by SiB2 sound like a labyrinth. It should be noted that in SiB2, the concept of "sensible heat flux" is a thermal conduction between the ground surface and the atmosphere near the ground surface. This thermal conduction depends mainly on the difference between ground surface temperature and the air temperature at the measurement height. On the other hand, the measured sensible heat flux by Eq. (16) presents sensible heat flux at the measurement height in the turbulent layer. Heat flux measured by eddy correlation is affected by heat sources on the ground, air moisture, air heat storage (mainly in the lowest millimeters of the air), and the vertical movement of air parcels with different space scales. The values of the measured heat flux should be less than the modeled values by SiB2. According to Stull (1988), the forcings from the ground generate much of the boundary layer turbulence. Solar heating of the ground during sunny days causes thermals of warm air to rise. These thermals are just large eddies. The transfer by large eddies reduces the value of $\theta'$ measured at a certain level above the surface within the turbulent boundary layer. Prandtl's mixing length theory implies that the lifecycle of a physical quantity transferred by $w'$ should be larger than the timescale of $w'$, but sometimes this hypothesis is not judicious because the transferred quantity may change in transfer process. Large scale eddies can leap across a certain distance and transfer physical quantities before small scale eddies mix. To deal with the excessive result of nonlocal thermal movements, counter-gradient heat transfer was measured in the Tibetan shortgrass prairie. Care should be taken not to confuse or substitute the concept "counter-gradient heat transfer" for the concept "nonlocal thermal movement" Actually, nonlocal thermal movements should reduce measured sensible heat flux at some layer in turbulent boundary layer. Hence, we suppose that the counter-gradient heat flux is caused mainly by the penetration of a buoyancy turbulence eddy and that the flux is nearly independent of the temperature, under the condition above. The classical gradient transfer formula has turned out to be an inappropriate tool to solve our problem.

Here, we focus on the difference between K-theory (first-order closure) and the eddy correlation method. Panofsky and Dutton (1984) indicated that one of the factors that has led to the failure in the application of K-theory is that in reality, the property transported has sources or sinks in the mixing region. The water tank analogy was based on the assumption that the particles kept their properties unchanged in the mixing process during the travel from their initial to their final location (Panofsky and Dutton, 1984). If the hot water cooled on the way, it could not warm the cool region and there would be no heat flux. Stull (1993) suggested that some of the large eddies in a turbulent region could be coherent structures that turbulently advected air parcels across large vertical distances before smaller eddies mix the parcels with the environment. Such a process is nonlocal rather diffusive.

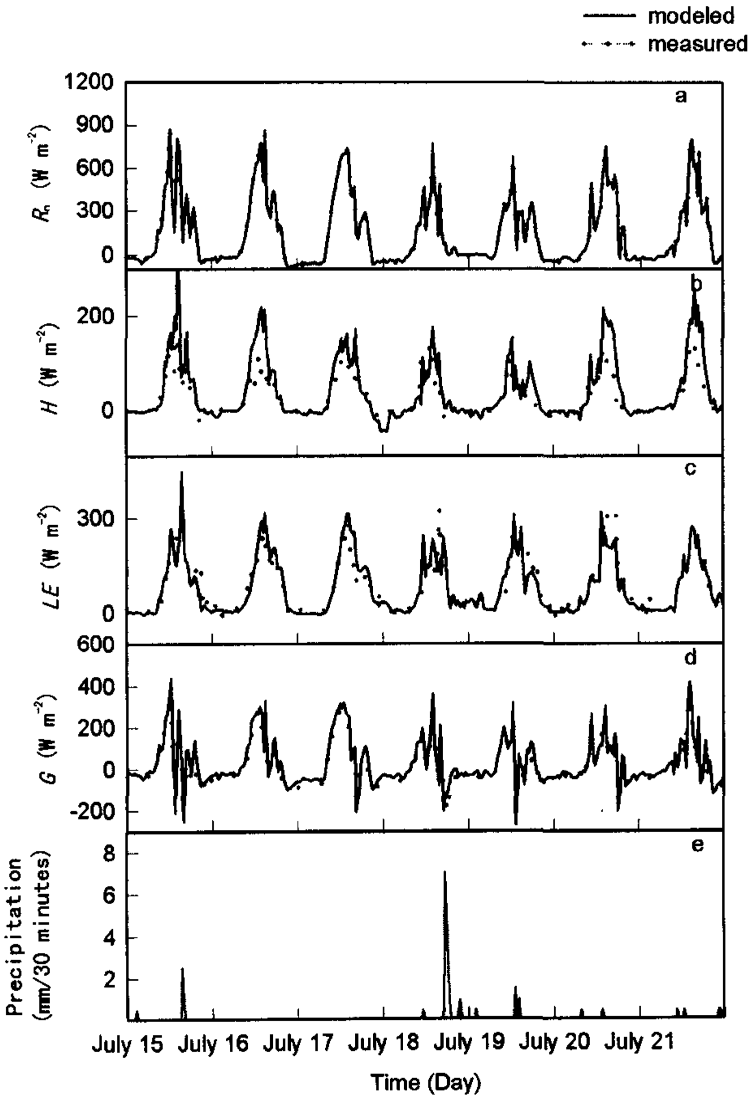


**Fig. 5a.** Diurnal variation of the modeled and measured energy components with corresponding precipitation.

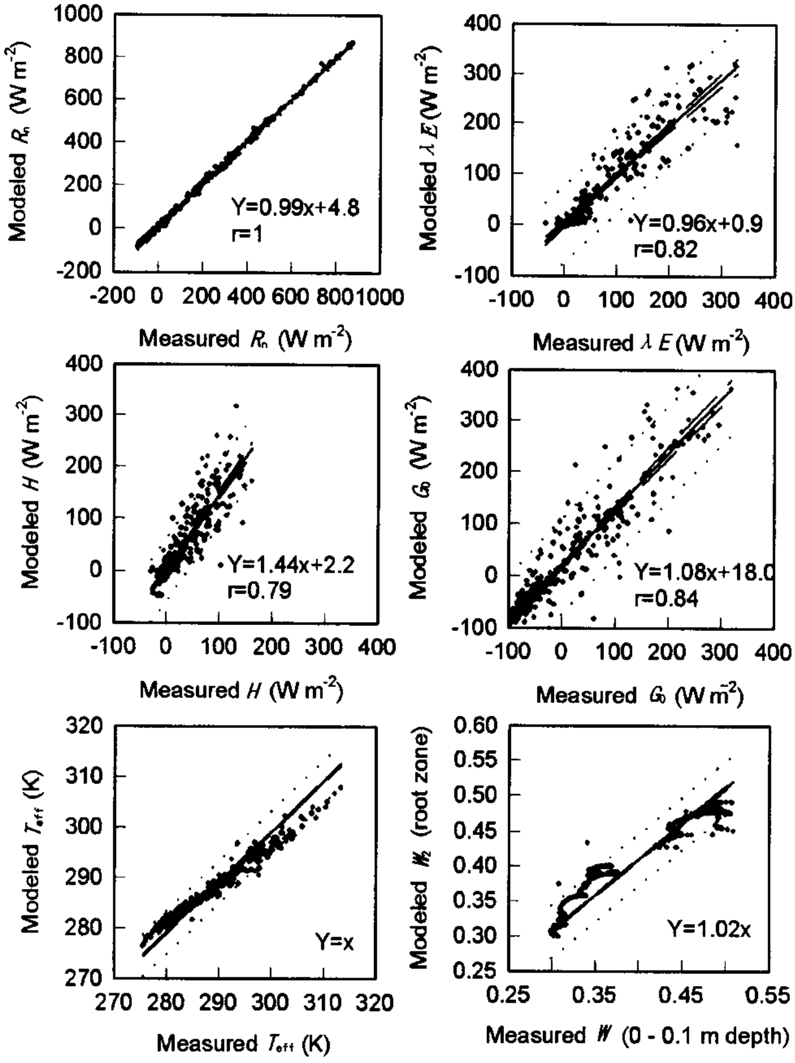


**Fig. 5b.** Fitting relations between the modeled and the measured energy components in Tibetan shortgrass prairie from 15 to 21, July 1998.

Stull (1993) contended that static stability indicates whether flow will become or remain turbulent when there is no mean wind shear. Once becoming turbulent, the large coherent structures in the flow advectively communicate this turbulent state across large distances. The resulting turbulent state at any point may thus depend on nonlocal influences. Local lapse rate is a poor indicator of static stability. Figures 1.4 and 1.5 of Stull (1993) are schematics of nonlocal parcel movement. One may find that a turbulent state may be determined by nonlocal parcel movement and not by the local lapse rate. For this reason, one should not use a stability quantifier such as "unstable" or "neutral" to specify the lapse rate. Instead, one should use the words "superadiabatic", "diabatic" or "subadiabatic" for lapse rates of $\partial\theta/\partial z$ that are negative, zero, or positive, respectively, as in Fig. 1.4 and Fig. 1.5 of Stull (1993).

Lee (1998, 1999) and Finnigan (1999) gave interesting and meaningful arguments. Lee (1998) presented a new concept, "mass flow" and discussed three mechanisms causing the non-zero mean vertical velocity. Finnigan (1999) adopted Lee's one-dimensional framework, and commented on 3D mean velocity fields and the proper choice of coordinate frames for analysis. Unfortunately, both of them just discussed an isolated, perfect, and local system, such that nonlocal thermal (parcel) movements were arbitrarily neglected. Use of their equations to calculate sensible heat flux at the Nagqu site would have unavoidably encouraged. Care should be taken in the comparison of Lee's (1998) mass flow term $\overline{w}_{\mathrm{r}}\left(\overline{c}_{\mathrm{r}}-\frac{1}{z_{\mathrm{r}}}\int_{0}^{z_{\mathrm{r}}}\overline{c}dz\right)$ and the second term on the RHS of Stull's (1988) equation (ordered as 6.8.4b there):

$$\overline{w'\xi'}(k)=\overline{w'\xi'}(k-1)+\left(\frac{\Delta z}{\Delta t}\right)\sum_{j=1}^{N}c_{kj}\left(\overline{\xi}_{k}-\overline{\xi}_{j}\right), \quad (24)$$

Since they are similar to each other in form, but the former is generated by the same vortex array or a pair of spanwise vortices (see Figs.1, 2, and 3 in Finnigan (1999)) and happens inside an air parcel, while the latter (i.e., $\left(\frac{\Delta z}{\Delta t}\right)\sum_{j=1}^{n}c_{kj}\left(\overline{\xi}_{k}-\overline{\xi}_{j}\right)$) indicates movements of exotic air parcels. The analysis above implicitly shows that the large eddy transfer process should be considered in any study of energy budget closure, leading to nonlocal closure theory.

## 7. Conclusions

By improving Sun et al.'s (1995) and Lee's (1998) formulations, an integrated formulation (namely, Eq. (3)) for calculating surface heat flux is given in this paper. Secondly, in the context of observations from 6 June to 15 September at the Nagqu site of GAME/Tibet in 1998, the counter-gradient heat flux is clarified, leading to the fact that buoyancy plays an important role in the sensible heat transfer process. Thirdly, Sun et al.'s (1995) Eq. (48) and Stull's (1988) Eq. (10.7.1c) are comparatively examined, and the result shows that the relative error between the thermal conduction $Q_H$ of Sun et al.'s (1995) Eq. (48) and the sensible heat flux $H$ of Stull's (1988) Eq. (10.7c) is just 2.2%. Fourthly, sensible heat flux calculated in SiB2 is also examined. Fifthly, the energy imbalance is discussed. Our final conclusions are as follows. (1) Energy imbalance is a common phenomenon by resulting from the use of the traditional closure scheme on the heterogeneous underlying surface because the measured ensemble heat fluxes by eddy correlation contain the effect of nonlocal parcel movements; a heterogeneous underlying surface is crucial for energy imbalance. (2) Nonlocal parcel movement deserves more attention in any heat flux study in the future. The application of land surface models is strongly recommended for further investigations on energy balance.

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# GAME/Tibet实验中感热通量计算方法的讨论

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## 摘 要

P4 A

回顾了前人对感热通量的分析研究，详细分析了计算感热通量公式的推导过程。结合GAME/Tibet那曲近地面通量观测站1998年6月6日到9月13日的观测资料验证了近地面层逆梯度热输送现象的存在；并比较了两种不同计算感热通量的方法。同时，对简化生物圈模式(SiB2)计算感热通量方案进行了分析。主要结论有：(1) 由于用涡旋相关法测量得到的总体感热通量本身已经包含了非局地热(冷)泡运动的影响，所以在非均匀下垫面上，传统的闭合方案必然会“遭遇”能量不平衡。这里，非均匀下垫面可能是导致能量不平衡的关键所在。(2) 在今后的有关热通量研究中，有必要仔细研究非局地热(冷)泡运动对热通量的贡献，而为了更好地理解这种贡献，应用陆面过程模式研究能量平衡是必需的。

关键词: 感热通量, 热传导, 逆梯度输送, SiB2, 不平衡现象