Method Development for Estimating Sensible Heat Flux over the Tibetan Plateau from CMA Data

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ABSTRACT

To clarify the thermal forcing of the Tibetan Plateau, long-term coarse-temporal-resolution data from the China Meteorological Administration have been widely used to estimate surface sensible heat flux by bulk methods in many previous studies; however, these estimates have seldom been evaluated against observations. This study at first evaluates three widely used bulk schemes against Tibet instrumental flux data. The evaluation shows that large uncertainties exist in the heat flux estimated by these schemes; in particular, upward heat fluxes in winter may be significantly underestimated, because diurnal variations of atmospheric stability were not taken into account. To improve the estimate, a new method is developed to disaggregate coarse-resolution meteorological data to hourly according to statistical relationships derived from high-resolution experimental data, and then sensible heat flux is estimated from the hourly data by a well-validated flux scheme. Evaluations against heat flux observations in summer and against net radiation observations in winter indicate that the new method performs much better than previous schemes, and therefore it provides a robust basis for quantifying the Tibetan surface energy budget.

1. Introduction

It is well recognized that the Tibetan Plateau (TP) provides an elevated heat source for the North Hemisphere (Flohn 1957; Ye and Gao 1979), and this elevated heating drives the TP monsoon, enhances the Asian monsoon circulation, and significantly influences precipitation in China (He et al. 1987; Yanai et al. 1992; Wu and Zhang 1998; Qian et al. 2004; Liu et al. 2007). The sensible heat flux is a major component of the TP heat source and has been addressed for several decades, but it is still difficult to estimate the flux from routine observations.

The sensible heat fluxes over TP surfaces have been estimated from the China Meteorological Administration (CMA) data in tens of studies during the past three decades (e.g., Ye and Gao 1979; Chen et al. 1985; Feng et al. 1985; Zhao and Chen 2000; Duan and Wu 2008). All these studies use the bulk transfer equation below:

\[ H = \rho c_p C_H u (T_g - T_a), \]  

where \( \rho \) is the air density, \( c_p \) is the specific heat capacity at a constant pressure, \( u \) is the wind speed at level \( z_m \), \( T_g \) is the ground temperature, \( T_a \) is the air temperature at level \( z_h \), and \( C_H \) is the bulk transfer coefficient for heat.

Equation (1) is straightforward and possibly the most important application of Monin–Obukhov similarity theory (MOST; Monin and Obukhov 1954), as the sensible heat flux can be conveniently estimated with this equation if \( C_H \) is known. It is worth noting that a fundamental hypothesis of MOST is that “the flow is horizontally homogeneous and quasi-stationary” (Arya 1988), which can hopefully be met only for a very short time interval, normally within 1 h or so. Such a strict prerequisite poses practical concerns for the applicability of the bulk formulation with CMA data, which have a coarse temporal resolution of typically 6 h.

Nevertheless, CMA data make up the only observational dataset in China for quantifying the climatology and long-term trend of the TP energy budget. In reality, most studies used daily averaged values of CMA data to calculate the heat flux with Eq. (1) for TP surface heat flux. As the coarse resolution of CMA data does not meet the prerequisite to apply Eq. (1), the bulk transfer coefficient \( C_H \) in Eq. (1) cannot be strictly derived within the framework of MOST, but represents an “equivalent...
value” that has to be empirically determined. Such an empirical value may cause significant errors and uncertainties, as will be presented in this study.

By contrast, Tibetan field experiments have been implemented since 1998 and remarkable progress in the heat transfer processes and parameterizations has been made. For example, Ma et al. (2002) and Yang et al. (2003) determined that the thermal roughness length, a key parameter for estimating heat flux from the ground–air temperature gradient, exhibits significant diurnal variations in the plateau. Such diurnal changes were also found in lowland surfaces (e.g., Verhoef et al. 1997; Sun 1999) but not so significant as in the plateau. Yang et al. (2008) evaluated several parameterization schemes and indicated that a scheme that can account for the diurnal variations of the thermal roughness length shows the best performance in the heat flux estimation. These schemes rely on hourly or subhourly data, which are not available from CMA stations. Therefore, there is a gap between recent experimental studies and CMA database studies on the sensible heat flux estimation.

Based on the above analysis, several questions naturally arise from the uncertainties in Eq. (1): (i) How effective is Eq. (1) in estimating the sensible heat flux from daily averaged data? (ii) Is it possible to parameterize the daily-mean equivalent transfer coefficient over TP? (iii) In which occasion is Eq. (1) most biased or even not applicable? (iv) How can one utilize recent experimental data and achievements to develop a better method for estimating sensible heat flux from coarse-resolution data?

This study attempts to clarify these crucial issues. First, three widely used schemes for the equivalent heat transfer coefficient in Eq. (1) are evaluated against two datasets from field experiments. Then, the causes of their biases are analyzed and the possibility of parameterizing the equivalent heat transfer coefficient is discussed. Last, a new method is developed to improve the estimates of sensible heat flux from coarse-resolution datasets.

2. Data

The Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment – Tibet (GAME-Tibet) in 1998 and follow-up experiments between 1999 and 2003 (Koike et al. 1999) provide automatic weather station (AWS) data for this study, which include hourly or subhourly averages of pressure, wind speed, ground temperature, and air temperature at seven sites. They have a relatively broad geographical distribution over the plateau (see Fig. 1). Basic site information is given in Table 1. Among the experiments, Naqu, MS3608, D66, and Gerze provide data for a full year, while Amdo, NPAM, and Shiquanhe are for summer only. For an evaluation against direct flux measurements, eddy covariance data are available at Amdo and NPAM, provided by GAME-Tibet 1998. The details of the sites and data have been introduced in several studies (Ueno et al. 2001; Haginoya 2001; Xu and Haginoya 2001; Tanaka et al. 2003; Ma et al. 2004).

Figure 2 shows the monthly average wind speed and ground–air temperature difference at these sites. The two parameters are the input of Eq. (1). High wind speed is typically found in spring, which decreases with the progress of the plateau monsoon. The temperature differences are larger in dry areas (D66, Gerze, and Shiquanhe) than in relatively wet areas (the other sites). The differences span from about −6 K in winter to +10 K in summer,
indicating the cooling and heating effects of the surface on the atmosphere in an annual cycle.

The procedure of the evaluation is illustrated in Fig. 3. First, the high-resolution AWS data are aggregated to generate a dataset of daily average meteorological parameters. The so-called daily schemes are three parameterizations for the equivalent heat transfer coefficient that will be evaluated using two datasets. The first dataset is eddy covariance flux data, which are available at Amdo and NPAM sites for summer. To extend the spatiotemporal coverage of this evaluation, a second flux dataset, called reference flux, is generated by a “reference scheme” from AWS measurements at high temporal resolution (e.g., 10, 30, and 60 min). The reference scheme will be introduced and validated below.

3. Theoretical basis

a. Reference scheme

In the reference scheme, the sensible heat flux is first calculated with the bulk formulation [Eq. (1)] for each measurement interval (10, 30, or 60 min). Then, the daily average value is derived from the arithmetic mean of the fluxes in a specific day:

$$H = \rho c_p C_H u (T_g - T_a).$$

When there are data gaps during a day, that day is excluded from the calculation. The bulk transfer coefficient for heat $C_H$ is calculated with the following equation that differentiates between the thermal roughness length $z_{0h}$ and the aerodynamic $z_{0m}$ roughness length:

$$C_H = \frac{k^2}{Pr_0} \left[ \ln \left( \frac{z_m}{z_{0m}} \right) - \psi_m \left( \frac{z_m}{L}, \frac{z_{0m}}{L} \right) \right]^{-1} \left[ \ln \left( \frac{z_h}{z_{0h}} \right) - \psi_h \left( \frac{z_h}{L}, \frac{z_{0h}}{L} \right) \right],$$

where $k$ is the von Kármán constant (0.4); $Pr_0$ is the Prandtl number (=1 if $z/L \geq 0$ and 0.95 if $z/L < 0$); $L = -u_a^2/[k(g/T_a)(H/\rho c_p)]$ is the Obukhov length with $g = 9.81 \text{ m s}^{-2}$; $z_m$ and $z_h$ are the measurement levels for...
This algorithm is stable and efficient. In general, \( H \) is converged after three iterations.

3) Calculate \( C_p \) by Eq. (3) and then \( H \) by Eq. (1).
4) Calculate \( u_\infty \) by \( L = \frac{-1}{u_\infty}[k(T_a/(H/\rho c_p))] \) and \( T_a \) by \( T_a = \frac{-H}{\rho c_p u_\infty} \).
5) Calculate \( z_{0h} \) by Eq. (6).
6) Go to step 2 until \( H \) is converged.

This algorithm is stable and efficient. In general, \( H \) is converged after three iterations.

where \( x = [1 - (19z_m/L)]^{1/4} \), \( y = [1 - (11.6z_h/L)]^{1/2} \), and \( y_0 = [1 - (11.6z_{0h}/L)]^{1/2} \).

Both \( z_{0m} \) and \( z_{0h} \) are not physically based parameters and thus cannot be measured directly. The quantity \( z_{0m} \) is a relatively stable parameter and can be empirically estimated according to the geometry of surface roughness elements, whereas \( z_{0h} \) exhibits typical diurnal variations over TP. We use a scheme recommended in Yang et al. (2008) to calculate \( z_{0h} \) for bare-soil surfaces and sparsely vegetated surfaces:

\[
z_{0h} = \frac{70 \nu}{u_\infty} \exp(-7.2u_\infty^{0.5}/|T_u|^{0.25}),
\]

where the fluid kinematical viscosity \( \nu \) is equal to 1.328 \( \times 10^{-5} \) \((p_0/p)(T/T_0)^{1.754} \) with \( p_0 = 1.013 \times 10^3 \) Pa and \( T_0 = 273.15 \) K, where \( p \) (Pa) is the surface pressure and \( T \) (K) is the air temperature; \( u_\infty \) is the frictional velocity; and \( T_u \) is the temperature scale defined by \( T_u = -H/(\rho c_p u_\infty) \).

The calculation of \( z_{0h} \) in Eq. (6) uses \( T_u \), which in turn depends on \( H \); therefore, the solution of sensible heat flux is found by the following iterative algorithm:

1) Assume \( z_{0h} = z_{0m} \).
2) Given \( z_m, z_h, z_{0m}, z_{0h}, T_a, T_g, \) and \( u \), the Obukhov length \( L \) can be derived from the following equation, with \( \psi_m \) and \( \psi_h \) given by Eq. (4) for stable boundary layers or Eq. (5) for unstable boundary layers:

\[
\frac{(z_m - z_{0m})}{L} \ln \left( \frac{z_h}{z_{0h}} - \frac{\psi_h(z_{0h}/L, z_h)}{\psi_m(z_{0m}/L, z_m)} \right) = \frac{g(z_m - z_{0m})(T_a - T_g)}{u^2 T_g \pi \rho c_p},
\]

\( b. \) Daily schemes

In almost all previous studies, daily schemes were used to estimate TP sensible heat flux from CMA data. According to daily schemes, the daily average sensible heat flux \( \overline{H} \) is estimated as

\[
\overline{H} = \rho c_p C_p \overline{w} \overline{(T_g - T_a)},
\]

where \( \overline{w}, \overline{T_g}, \) and \( \overline{T_a} \) denote the daily average of respective meteorological parameters. In this study, we select three different parameterizations for the equivalent
transfer coefficient $C_H$ in Eq. (8). The first was proposed by Ye and Gao (1979) who assumed that this coefficient is identical to the drag coefficient and equal to a constant (Ye scheme):

$$C_H = 0.008. \quad (9)$$

The second was proposed by Chen et al. (1985) who regarded 0.008 as too high and suggested (Chen scheme)

$$C_H = 0.004. \quad (10)$$

In the third one, Feng et al. (1985) empirically expressed $C_H$ as a function of the mean wind speed (Feng scheme):

$$C_H = 0.0012 + \frac{0.01}{u}. \quad (11)$$

Since then, there essentially has been no progress in this aspect, and therefore, these parameterizations are still widely used (e.g., Duan and Wu 2008). Their validity will be quantitatively examined in our study.

4. Evaluation of reference scheme

Before the reference scheme can be used for an extended evaluation, it needs to be validated to guarantee its reliability. Figure 4 compares the sensible heat fluxes by the reference scheme against the eddy covariance measurements at two sites. A good agreement is observed at both sites, with small mean bias error (MBE), small root-mean-square error (RMSE), and high $R^2$ (coefficient of determination). Therefore, the reference scheme could produce reliable 30-min sensible heat fluxes and thus provide the daily averages for the extended evaluation in this study. A wide validation of this scheme was presented in an earlier study (Yang et al. 2008).

Note that the above reference fluxes at Amdo and NPAM sites are calculated with the locally determined aerodynamic roughness lengths, which varied over 1–3 mm at Amdo and over 5–9 mm at NPAM (Yang et al. 2003). However, without high-quality wind profile measurements, it is difficult to accurately determine the length solely using the AWS data. Recent studies have shown that $z_{om}$ ranges between 1 and 10 mm at the plateau experimental sites. Though much higher values estimated from AWS data are also reported (Li et al. 2001), those values are not yet justified by direct measurements of momentum flux. To properly apply the reference scheme, we first explore the sensitivity of the reference values of daily mean heat fluxes to the choice of $z_{om}$. This is shown in Fig. 5. Relative to the results with $z_{om} = 3$ mm, slightly underestimated and overestimated fluxes result from $z_{om} = 1$ mm and $z_{om} = 10$ mm, respectively. As the linear regressions in Fig. 5 indicate that their relative differences are around 10%, the logarithmic average of 3 mm is adopted in calculations hereafter.

5. Evaluation of daily schemes

a. Compare with observations

In Fig. 6, the daily mean sensible heat fluxes by the three daily schemes are compared with the eddy covariance observations at Amdo and NPAM sites. Obviously, the Ye scheme yields significant overestimates. Its daily mean values could occasionally exceed 200 W m$^{-2}$, even much higher than the observed daily mean net radiation. As a component in the equation of surface energy budget, the sensible heat flux should not exceed the net radiation. In comparison, two relative new parameterizations (Chen and Feng schemes) make better estimations with lower equivalent heat transfer coefficients.
Almost no mean bias is observed for the two schemes, but the data scatter remains notable.

b. Compare with reference values

As the eddy covariance flux data are only available at two sites during a summer, the evaluation in section 5a is limited. Therefore, a reference dataset was produced from high-resolution experimental data by the reference scheme so that the evaluation could be extended to all sites and seasons. As the Ye scheme produces high biases in the heat flux, it is not evaluated further.

Figure 7 compares the reference values against the daily scheme estimates of daily/monthly mean heat fluxes at all sites, and Table 2 shows the mean reference values, MBE, RMSE, and $R^2$ for the daily mean flux. Figure 7 shows that both schemes underestimated heat fluxes for certain sites and months. A further screen to all the sites and months shows that this phenomenon mainly takes place in winter of MS3608, Naqu, and Gerze, when daily mean ground–air temperature differences become small or even negative. As shown in Table 2, MBE averaged over the three sites is about $-17 \, \text{W m}^{-2}$, that is, half of the mean reference values ($34 \, \text{W m}^{-2}$). This issue will be discussed in section 6.

6. Discussion

a. Diurnal variations of bulk heat transfer coefficient

In fact, the bulk transfer coefficients exhibit diurnal variability, but do not remain constant in a diurnal cycle. First, the turbulent motion is enhanced and weakened during the daytime and nighttime, respectively. Accordingly, stronger turbulent transport, related to higher transfer coefficients, occurs during the daytime. Moreover, thermal and aerodynamic roughness lengths also play an important role in the turbulent exchange, because individual roughness elements may enhance momentum transfer through form drag but contribute less to the heat transfer (Yang et al. 2008). Simultaneously, the thermal roughness length depends on the flow state, which is lower in the daytime than the nocturnal counterpart. Figure 8 shows multiday composite diurnal variation of

![Fig. 5. Sensitivity of the reference values of daily mean sensible heat fluxes to aerodynamic roughness length ($z_{0m}$). Values on x axis (Reference) and y axis (Estimation) are derived from the assumption of $z_{0m} = 0.003 \, \text{m}$ and $z_{0m} = 0.001$–$0.01 \, \text{m}$, respectively. $R^2$ is the coefficient of determination.](image1)

![Fig. 6. Comparison of the daily average sensible heat flux between observations (x) and estimations by the daily scheme (y): (a) Ye scheme, (b) Chen scheme, and (c) Feng scheme; $R^2$ is the coefficient of determination.](image2)
$C_D$ and $C_H$ at the Amdo site using different parameterizations for the thermal roughness length. The values of $C_D$ and $C_H$ have been converted to 2-m height from their observing heights.

As can be seen in Fig. 8, the simplification of $z_0 = z_0m$ leads to $C_H > C_D$ [a similar result was also found in Li et al. (2001)]. Consequently, estimated heat fluxes would become unrealistically large. By adopting an updated parameterization of $z_0$ [Eq. (6)], the relationship between $C_D$ and $C_H$ is reversed, namely $C_H < C_D$, leading to much lower estimations of heat fluxes. The over-estimations of the heat fluxes by assuming $z_0 = z_0m$ can even exceed the net radiation fluxes, going against the surface energy budget. Therefore, it is crucial to properly introduce the parameterization of the thermal roughness length into the estimation of sensible heat flux.

A heuristic analysis could explain the large uncertainties of the daily schemes for winter, as mentioned

### Table 2. Statistical differences of daily-mean heat fluxes estimated between two daily schemes (Chen and Feng) and the reference scheme (Reference). Mean: mean value.

<table>
<thead>
<tr>
<th>Station</th>
<th>Amdo</th>
<th>NPAM</th>
<th>Naqu</th>
<th>D66</th>
<th>MS3608</th>
<th>Gerze</th>
<th>Shiquanhe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (W m$^{-2}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>44.9</td>
<td>29.5</td>
<td>33.2</td>
<td>57.9</td>
<td>28.2</td>
<td>41.9</td>
<td>83.3</td>
</tr>
<tr>
<td>MBE (W m$^{-2}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen</td>
<td>3.0</td>
<td>2.5</td>
<td>17.2</td>
<td>12.6</td>
<td>14.5</td>
<td>26.0</td>
<td>28.3</td>
</tr>
<tr>
<td>Feng</td>
<td>4.4</td>
<td>2.2</td>
<td>15.0</td>
<td>1.0</td>
<td>13.8</td>
<td>22.5</td>
<td>3.6</td>
</tr>
<tr>
<td>RMSE (W m$^{-2}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen</td>
<td>12.2</td>
<td>9.1</td>
<td>25.4</td>
<td>21.9</td>
<td>25.6</td>
<td>31.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Feng</td>
<td>12.5</td>
<td>8.6</td>
<td>26.2</td>
<td>7.8</td>
<td>23.4</td>
<td>29.2</td>
<td>6.8</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen</td>
<td>0.834</td>
<td>0.635</td>
<td>0.662</td>
<td>0.774</td>
<td>0.268</td>
<td>0.659</td>
<td>0.705</td>
</tr>
<tr>
<td>Feng</td>
<td>0.842</td>
<td>0.646</td>
<td>0.612</td>
<td>0.813</td>
<td>0.264</td>
<td>0.677</td>
<td>0.904</td>
</tr>
</tbody>
</table>
in section 5b. In winter, the daily ground temperature is often lower than the air temperature; according to Eq. (8), the daily schemes produce downward heat fluxes. However, due to the diurnal variation of $C_H$, the heat transfer amount can be much higher in the daytime than in the nighttime; accordingly, the daily mean heat flux can be positive (upward). Therefore, the daily schemes are unreliable for winter when the daily mean ground–air temperature difference is small or even negative.

b. Possibility of parameterizing daily heat transfer coefficient

The equivalent heat transfer coefficient $C_H$ cannot be deduced from MOST, which is empirically parameterized with daily mean wind speed in Feng et al. (1985). With our dataset, we examine the possibility of parameterizing $C_H$ values.

Figure 9 shows the variation of $C_H$ with the daily average wind speed at the Amdo and MS3608 sites. At the Amdo site, $C_H$ roughly decreases with the increase of wind speed, which qualitatively agrees with the Feng scheme; however, a similar relationship cannot be observed for MS3608. We have also investigated the relationship between $C_H$ and $(\bar{T}_g - \bar{T}_a)$ or $\bar{u}(\bar{T}_g - \bar{T}_a)$, but a reliable parameterization cannot be constructed. In other words, it is very difficult, if not impossible, to parameterize the equivalent coefficient for a daily scheme.

7. New method to utilize CMA data for flux estimation

CMA data relevant to heat flux calculation consist of (i) 6-hourly (02, 08, 14, 20 BST; BST is Beijing standard time and = UTC + 8) ground temperature, air temperature, wind speed, and pressure, (ii) daily minimum, maximum, and mean air temperature, and (iii) 10-min maximum wind speed.

Because of the diurnal variations of the bulk heat transfer coefficient, it is crucial to obtain high-resolution input (ground temperature, air temperature, wind speed) from CMA data to calculate the heat flux. This section develops such a downscaling method based on statistical relationships derived from the Tibet experimental data, and then uses the reference scheme and the disaggregated data to calculate the sensible heat flux. The difference between the reference scheme and the new method lies in the input (i.e., the former uses observed high-resolution data, while the latter uses disaggregated high-resolution data).

The flowchart of the method development is as follows: first, high-resolution AWS data are aggregated to coarse-resolution data to mimic CMA data; this aggregation will lose detailed information contained in the observed high-resolution time series. Second, the coarse-resolution data are disaggregated to hourly data according to statistical relationships, and the new method uses the hourly data to calculate sensible heat flux. Third, the estimated fluxes are evaluated against measured energy fluxes.
a. Downscaling CMA data

To produce the diurnal variation of a meteorological variable, it is necessary to find its maximum and minimum values as well as their occurrence times in a day. The occurrence times are obtained through a statistical analysis based on the Tibet high-resolution experimental data. Figure 10 shows the composite diurnal variations of meteorological variables at all sites (note that we use local time throughout this study, which varies from site to site). Though these sites were distributed widely, the diurnal patterns of each variable are very similar. Such similarities are the basis of data downscaling.

1) DISAGGREGATING AIR TEMPERATURE DATA

Minimum air temperature ($T_{a,\text{min}}$) usually occurs in the early morning and maximum air temperature ($T_{a,\text{max}}$) in the midafternoon. Figure 11a shows the relationship between sunrise ($t_{\text{rise}}$) and the time when minimum air temperature most frequently occurs ($t_{a,\text{min}}$). Clearly, $t_{a,\text{min}}$ linearly depends on $t_{\text{rise}}$, while the times for the occurrence of the maximum air temperature ($t_{a,\text{max}}$) and the daily mean temperature in the morning ($t_{a,\text{am}}$) and in the afternoon ($t_{a,\text{pm}}$) are much more stable. These characteristic times are estimated below (unit: local solar hours):

\[ t_{a,\text{min}} = 0.842t_{\text{rise}} + 0.71, \]  
\[ t_{a,\text{max}} = 14.59, \]
\[ t_{a,\text{am}} = 8.4 \quad \text{and} \]
\[ t_{a,\text{pm}} = 19.7. \]
According to Fig. 10a, the diurnal variation of air temperature does not follow a cosine (or sine) curve. In this study, its diurnal variation is separated into the ascending phase (from $T_{a,\text{min}}$ to $T_{a,\text{max}}$) and the descending phase (from $T_{a,\text{max}}$ to $T_{a,\text{min}}$).

During the ascending phase, the statistical curve of air temperature in Fig. 10a can be fitted well by

$$T_{a,i} = a_0 + a_1 t_i + a_2 t_i^2 + a_3 t_i^3,$$  \hspace{1cm} (13)

where $a_0$–$a_3$ are coefficients to be determined, $t_i$ is the $i$th local solar hour, and $T_{a,i}$ is the air temperature at $t_i$.

The coefficients $a_0$–$a_3$ are determined by Eqs. (12a)–(12c) and the following condition for the derivative of Eq. (13) at $t_{a,\text{max}}$:

$$a_1 + 2a_2 t_{a,\text{max}} + 3a_3 t_{a,\text{max}}^2 = 0.$$  \hspace{1cm} (14)

During the descending phase, we assume $T_{a,i}$ follows

$$T_{a,i} = b_0 + \frac{b_1}{[1 + b_2(t_i - t_{a,\text{max}})^2]},$$  \hspace{1cm} (15)

where coefficients $b_0$–$b_2$ are determined by Eqs. (12a), (12b), and (12d). Note, Eq. (15) automatically satisfies the derivative condition at $t_{a,\text{max}}$ being zero.

Figure 12a shows the comparison of monthly mean hourly air temperature between the interpolation and the observation for all experimental sites. The high accuracy indicates that the proposed downscaling method works well.

2) DISAGGREGATING GROUND TEMPERATURE DATA

Minimum ground temperature $T_{g,\text{min}}$ usually occurs in the early morning and maximum ground temperature $T_{g,\text{max}}$ occurs near noon. Figure 11b shows that the time for minimum ground temperature ($t_{g,\text{min}}$) linearly depends on sunrise time $t_{\text{rise}}$, while the statistic time for maximum ground temperature ($t_{g,\text{max}}$) is stable. They are formulated by

$$t_{g,\text{min}} = 0.885 t_{\text{rise}} + 0.35$$  \hspace{1cm} (16a)

$$t_{g,\text{max}} = 12.2.$$  \hspace{1cm} (16b)

Though minimum and maximum ground temperatures ($T_{g,\text{min}}$ and $T_{g,\text{max}}$) are not available in CMA data, their corresponding times $t_{g,\text{min}}$ and $t_{g,\text{max}}$ in Tibet are accidentally close to observing times (0800 and 1400 BST or 0600 and 1200 LST). Therefore, interpolating $T_{g,\text{min}}$ and $T_{g,\text{max}}$ from nearby data would not cause big errors. In this study, $T_{g,\text{min}}$ is linearly interpolated from observations at 0800 and 1400 BST: $T_{g,\text{max}}$ is interpolated by a quadratic equation, which passes data at 0800 and 1400 BST and satisfies the derivative at $t_{g,\text{max}}$ being zero.

The diurnal variation of ground temperature is interpolated by a cubic-spline curve passing six points: four 6-hourly values, maximum value, and minimum value. Figure 12b shows that the interpolated values are agreeable with observations at all experimental sites.

3) DISAGGREGATING WIND SPEED DATA

Wind speed is more variable than air temperature and ground temperature. Similarly, we obtain the statistical time when maximum wind speed occurs ($t_{w,\text{max}}$):
Diurnal variation of wind speed is directly interpolated by a cubic-spline curve that passes five points: four 6-hourly values and 10-min mean maximum data. We do not formulate minimum wind speed, because it occurs around the morning observing time (0800 BST), as shown in Fig. 10c. Figure 12c shows the downsampled monthly mean hourly wind speed and observed one for all experimental sites. The downsampled wind speed is acceptable though its accuracy is not as high as the interpolation of air temperature and ground temperature.

b. Evaluation of present method

Heat flux is estimated from the disaggregated data by the reference scheme. Figures 13a–c show comparisons of estimated heat flux with the direct observations, with the daily mean reference flux data, and with monthly mean reference flux data, respectively. Compared with Figs. 6 and 7, a much better performance of the new method can be observed. The notable negative biases from the two daily schemes (see Fig. 7) are no longer existent in the new method. To compare their performance in winter, Fig. 14 compares sensible heat fluxes between the new method and the daily schemes at Naqu and Gerze. In winter, daily mean ground temperatures are often lower than air temperatures, so the daily schemes yield downward (or negative) heat fluxes. By contrast, the new method usually produces upward (or positive) sensible heat flux. Their difference indicates that the effects of diurnal variations are significant. In the plateau winter, both air temperature and ground temperature are very low. Therefore, latent heat flux (or surface evaporation) is negligible. Meanwhile, soil heat flux is usually small at the daily scale. According to the surface energy budget, daily mean sensible heat fluxes must be comparable to daily mean net radiation. As shown in Fig. 14, the heat flux estimates by the new method are accordant with this reasoning, while the estimates by the daily schemes deviate far.

In a word, the new method shows good accuracy in estimating sensible heat flux from coarse-resolution data, when compared with previous daily schemes. The improvements for winter are particularly remarkable.

8. Concluding remarks

Bulk schemes are widely used to estimate surface heat fluxes over TP from CMA daily data. Based on Tibet high-resolution experimental data, this study analyzed major problems of previous daily schemes and developed a new method to improve the estimates.

This study indicates that there are some conceptual difficulties in the daily bulk schemes. First, these daily schemes do not satisfy the prerequisite of applying the similarity theory, and therefore, the heat transfer coefficient in these schemes is an empirical parameter but there is no robust basis for its parameterization. Second, neglecting diurnal variation of meteorological variables brings large uncertainties in heat fluxes estimated by
a daily scheme. At the least, two diurnal variations should be introduced in estimating sensible heat fluxes. One is the diurnal variation of the surface layer stability, which causes evident diurnal variation of \( C_H \). The other is the diurnal variation of the thermal roughness length, which causes a heat transfer coefficient different from momentum transfer coefficient. Neglecting their diurnal variations would result in large biases and uncertainties.

Then, we developed a physical method to estimate surface heat flux from CMA routine data. The new method relies on two advances. One is the statistical relationships for meteorological variables. They were derived from high–temporal resolution data and are used to disaggregate coarse-resolution data to hourly data so that the bulk method can be applied. The other is a flux parameterization scheme that has been widely validated. The new method is validated with observed heat fluxes in summer and observed net radiation in winter, and shows significant improvements compared to previous schemes. Nevertheless, it should be noticed that both CMA surface temperature data and the thermal roughness length parameterization are for bare-soil surfaces; therefore, the heat flux estimated by the new method only represents that from the bare-soil part rather than from the composite surfaces. Caution must be exercised when interpreting the estimated fluxes at some eastern plateau sites that are partially covered by vegetation.

In summary, previous studies on TP heating would have large uncertainties and should be revisited if a daily scheme had been used to provide sensible heat fluxes. In particular, the heat source would have been underestimated (or heat sink overestimated) in winter. Hopefully, the new method in this study will contribute to better quantifying the surface energy budget and thermal forcing over TP, as well as its role in the Asian monsoon system.

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