Comparison of sensible and latent heat fluxes during the transition season over the western Tibetan Plateau from reanalysis datasets

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Abstract

The sensible and latent heat fluxes during the transition season over the western Tibetan Plateau from the NCEP-1 (NCEP/NCAR Reanalysis 1), AR-II (NCEP-DOE Reanalysis 2) and ERA40 reanalysis datasets were compared and analyzed. The results show that the phase change in soil moisture has a significant effect on the sensible and latent heat fluxes over the western Tibetan Plateau (TP) due to the freezing–thawing processes during the transition from the dry to the wet period. The uncertainties in the sensible and latent heat fluxes over the western TP are quite high in the reanalysis data, and depend largely on the success of the soil moisture simulations in the models. Improving the hydrological process simulations in the land-surface models in seasonally frozen ground and in the active frozen soil layer may be an effective way of enhancing the reliability of the surface heat fluxes from the reanalysis data over the Tibetan Plateau.

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Keywords: Western Tibetan Plateau; Surface heat fluxes; Reanalysis data; Transition season; Freezing–thawing process

1. Introduction

The thermal effects of the Tibetan Plateau (TP), the world’s largest and highest plateau with varied terrains and heterogeneous surface, on the atmosphere has been the subject of extensive scientific investigations since the last several decades. Ye et al. [1] and Flohn [2] studied the thermal effects of the TP on atmospheric circulation, and showed that TP is a source of heat in summer. Flohn [3,4] analyzed the evolution of the South Asia High (SAH) and suggested that the thermal effects of the TP are responsible for the formation of the SAH. Other studies also show that the TP thermal forcing not only plays an important role in producing the East Asia summer general circulation [5–8], but also has significant effects on the development of weather systems in East China [9] and the climate patterns over the Northern Hemisphere [10–13]. However, these results were based on limited observations. Recently, the sensible and latent heat fluxes from improved reanalysis datasets (i.e., NCEP-I, NCEP-II (AR-II) and ERA) have been used widely to study the TP thermal forcing as it relates to global general circulation and climate change [14–18]. The main concerns are the reliability and quality of the reanalysis data over the TP. Su et al. [19] showed that the sensible and latent heat fluxes from the NCEP reanalysis data obviously display a large positive shift over the TP, and Song et al. [20] reported that the reanalysis data are able to reproduce the intensity and inter-annual changes in the ground heat fluxes over the TP. Moreover, the monthly mean temperature from the NCEP reanalysis data is lower than the observations [21,22], while the precipitation is higher [23] than the observations.
Simulations from the numerical models are largely uncertain over the TP, due to its heterogeneous surface and much more complicated physical processes, especially during the transition season when the interaction between the earth and atmosphere becomes more complicated than usual. Due to snowmelt and thawing–freezing processes, there are also large differences between the sensible and latent heat fluxes in different regions over the TP [24]. Wang and Shi [25] investigated the soil temperature and moisture changes over the TP during the transition season and showed that the latent heat flux contributed more to the process of surface thermal balance after the beginning of the ground thawing-freezing process, which means that the reanalysis data will have larger biases in the transition period. Therefore, spring (the transition season) was chosen as the main study period in their study.

In this study, we focus on a comparison of the sensible and latent heat fluxes of the reanalysis data, including NCEP-I, NCEP-II and ERA, with observations during the transition season over the western TP. Our aim is to find representations of the analysis data during the transition season over the western TP and to try to understand the possible reasons for the large discrepancies observed in the area’s reanalysis data.

2. Data and methodology

The daily mean sensible and latent heat flux data of Reanalysis-I, Reanalysis-II (from May 1998 to October 1998) of NCEP/NCAR and ECMWF(ERA) were used in order to compare and analyze the differences between the reanalysis data. Observational data from the intensive period of the Global Energy and Water Cycle Experiment (GEWEX) and the Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet) were also used. Two AWS stations over the western TP were chosen, which provide observations 24 times daily: Shiquanhe (80.05°E, 32.30°N, 4378 m) from 1 May to 17 September 1998, Gaize (84.25°E, 32.09°N, 4416 m) from 1 May to 30 July 1998. The main observations included upward/downward long-wave radiation, upward/downward short-wave radiation, ground fluxes (2.5 cm, 7.5 cm), wind speed, wind direction, air temperature and relative humidity at 1.0 m, 2.0 m and 4.0 m, soil temperature (0.0 m, 0.05 m, 0.10 m, 0.20 m, 0.40 m, 0.80 m), precipitation, and pressure. The dataset contains short periods of missing data for the equipment failure.

The daily mean values in the AWS data were calculated using 60 min interval observations. The daily mean sensible and latent heat fluxes were computed using the Bowen scheme (BR) as follows:

\[ \begin{align*}
R_n &= SH + LE + G \\
\beta &= \frac{SH}{LE} = \frac{C_p}{L_e} \frac{\Delta T}{\Delta z} \\
SH &= (R_n - G)/(1 + \beta^{-1}) \\
LE &= (R_n - G)/(1 + \beta)
\end{align*} \]  

(1)

Here, \( R_n \) is the net radiation, \( G \) the soil heat flux, \( C_p \) the specific heat at constant pressure, \( \beta \) the Bowen ratio, \( \varepsilon \) the weight ratio of water vapor to the dry air molecule (\( \varepsilon = 0.622 \)), \( P \) the pressure, \( \Delta T \) and \( \Delta \varepsilon \) are the temperature and vapor pressure difference at different altitude levels, respectively. \( SH \) is the sensible heat flux, and \( LE \) is the latent heat flux.

The aerodynamic scheme (AD) was also used to calculate the surface heat fluxes in order to obtain more realistic ground heat fluxes over the western TP and to improve the comparison with the reanalysis data. This is given by the following:

\[ \begin{align*}
SH &= -\rho C_p u_*, T_* \\
LE &= -\rho L u_*, q_* \\
\frac{k_z}{u_*} \frac{\partial u}{\partial z} &= \phi_u \\
\frac{k_z}{T_*} \frac{\partial T}{\partial z} &= \phi_T \\
\frac{k_z}{q_*} \frac{\partial q}{\partial z} &= \phi_q
\end{align*} \]  

(4)

Here, \( u_* \) is the friction velocity, \( T_* \) the turbulent temperature scale, \( q_* \) the turbulent humidity scale, \( \kappa \) the Karman constant, \( z \) the height, which is a simple function of the wind, temperature and humidity, according to Dyer [26] and Hicks [27].

The reanalysis data from NCEP-I, NCEP-II, ERA40 were interpolated to the observational sites by a bilinear interpolation method to ensure consistent comparisons.

3. Results

The transition season (spring) corresponds to a period of dramatic changes in surface conditions over the plateau. The phases of temperature and humidity change frequently during spring (Fig. 1). This not only corresponds to the early stage of the onset of the East Asian monsoon, but also to the sensitive period of the changing surface hydro-thermal state. Some studies have suggested that the ground freezing–thawing processes of the Tibetan Plateau significantly delayed the onset of the monsoon and the global climate progress [28–30]. Hence, spring was chosen as the study period for our study. Previous studies have shown that the time of the onset of the South China Sea monsoon is 1–23 May 1998, which leads to the onset of the Indian monsoon in early June [31,32]. Therefore, the second pentad of June was used as the date of onset of the Asian monsoon, which also corresponds to the onset of the wet season over the western TP.

3.1. Variability in the ground temperature and moisture

Firstly the BR was used to estimate the sensible and latent heat fluxes. However, when the net radiation remains unchanged, it is mostly dependent on the changes in the surface heat fluxes, so it can indirectly reflect the variations in the soil temperature and moisture. Note that when the soil moisture or temperature change becomes larger, the
Bowen scheme frequently loses its reliability. Therefore, it can be used to judge the changes in the ground temperature and moisture in the plateau region.

Fig. 1. The daily evolution of air temperature ($T_a$), surface temperature ($T_s$), air humidity ($q_a$) and soil moisture ($q_s$) over the western Tibetan Plateau from May 1 to June 13. (a) Curve 1 is for $T_a$; curve 2 is for $q_a$. (b) Curve 1 is for $T_s$; curve 2 is for $q_s$. (c) Same as (a). (d) Same as (b). Shiquanhe (a and b); Gaize (c and d).

Fig. 2. The daily variations in the Bowen-ratio (a), the minimum and the average surface temperature ($T_s$) over the western TP from May 1 to June 13. In (b) and (d), curve 1 is for average $T_s$; curve 2 is for minimum $T_s$. Shiquanhe (a and b); Gaize (c and d).

Fig. 2 presents the daily estimation of the BR. The results show that, during May to June in 1998, the change range in $\beta$ is small and ranges from 0.0 to 1.5 in the Shiqu-
anhe area (Fig. 2(a)), but in Gaize it is obviously larger and fluctuates between 2.0 and 4.0 (Fig. 2(c)). These indicate that, during the transition season, the soil temperature and moisture in Shiquanhe are more stable than those in Gaize where there are significant variations. Although the daily mean air temperature is above 0 °C the minimum daily ground temperature is always below 0 °C (Fig. 2(b) and (d)). In other words, despite the high temperature during the daytime which leads to the melting of the surface soil, the temperature during the nighttime is still lower than 0 °C and the ground is also in the freezing state. This results in the diurnal cycle of the freezing–thawing processes and leads to phase changes in the surface soil moisture between ice and water.

For the long-term average of the climate, the daily mean downward short-wave radiation was found to be 344.3 W/m² for the Shiquanhe area and 340.4 W/m² for the Gaize area from May to June. These are very similar results. However, the rainfall is obviously different. The annual temperature range in Shiquanhe is larger, and the annual precipitation is 80 mm less than that in the Gaize region. The former is located at the western TP and belongs to the arid–monsoon region of the plateau’s sub-frigid zone. Due to its inland location within the TP, Gaize is a semiarid–monsoon region of the plateau’s sub-frigid zone, experiencing low temperatures, drought, great temperature ranges, and an annual mean precipitation of about 189 mm. In the study period, the maximum and minimum daily temperatures were 17.2 °C and −1.9 °C, respectively in Shiquanhe, but 16.5 °C and −3.1 °C in Gaize. On the other hand, as the soil thawed in the former area, the soil remained frozen in Gaize. This implies that the amount of unfrozen water in the soil is small. The variation in the Bowen ratio also confirms this process. The daily cycle of the freezing–thawing, which is caused by the large day-night temperature range, leads to the frequently changing ground and soil moisture and the thermal property changes in the soil. Most significant is that there was no snowfall in the period over these two sites. This suggests that the change in the Bowen ratio is mainly influenced by the daily cycle of the freezing–thawing processes. That is to say, with the cycle of the freezing–thawing process and the increasing ground temperature, the unfreezing moisture in the soil changes significantly and the range of the Bowen ratio is small.

### 3.2. Differences in the results between BR and AD

The results of the two schemes (Fig. 3(a)) show that during the transition season, the maximum and minimum sensible heat fluxes are 120 W/m² and 7 W/m², respectively. The amplitude range is 113 W/m², smaller than the results of Zhang et al. [33], which found a maximum range of 139 W/m². From May to June in 1998, a distinct jump occurred in the sensible and latent heat fluxes calculated by the aerodynamic scheme (Fig. 3(b)), in which its values became positive from the negative. This is consistent with Yu et al.’s [34] results, and confirms that the sensible heat

![Fig. 3](https://example.com/f3.png)
flux becomes the main component of the surface energy balance.

In the Gaize region, due to the effect of the diurnal cycle in the soil freezing–thawing processes, the sensible heat flux computed by the BR has a positive deviation. The daily mean in the transition season is 49.3 W/m². This value is greater than Zhang et al.’s [33] value, but smaller than those of Li et al. [35] and Yu et al. [34]. Meanwhile, the mean sensible flux calculated by AR is about 140 W/m² in May, similar to the results obtained by Li et al. [35], and the latent heat flux changes are small during the transition season.

During the transition season, the surface heat fluxes calculated by the BR and AR showed large differences in both direction and value. During the spring, there were frequent freezing and thawing episodes, and the moisture content and humidity near the ground changed frequently, leading to obvious changes in the thermal properties. Furthermore, it explains a significant component of the observational error in the soil moisture and ground heat flux. The results also showed that the different freezing and thawing states at the two sites result in significant differences in the sensible and latent heat fluxes, and explain the complexity in the TP’s thermal effect.

3.3. Comparison and analysis of the heat flux between the reanalysis data and that computed based on observations

Fig. 4 shows the evolution of the heat flux from the three reanalysis data sets, i.e., BR and AD. There are large differences in the surface heat fluxes which come from different reanalysis data sets and observational data by different methods. The relationships between the three reanalysis data sets and the computed results with the two methods are analyzed. The correlation coefficients of the heat flux between each reanalysis dataset (NCEP-I, AR-II and ERA) and the estimations with the two sets of observational data (BR, AR) are presented in Table 1. The results presented in the table show that all the correlations between each reanalysis and estimations in the two regions (Gaize and Shiquanhe) are poor. The maximum coefficient reaches only 0.339 and does not pass the level of significance according to a t-test. The results indicate that, during the transition season, there exist large differences between the reanalysis and computational schemes with observations. Both the sensible and latent flux estimates from the reanalysis data of the ERA are better than those of NCEP-I and AR-II in terms of correlation. Most of the correlation coefficients between ERA and the computed results by AR are over the significance level $p < 0.01$, but the latent heat flux computed using BR and Eq. (3) resulted in a negative correlation. According to the previous study, when the surface heat fluxes changed significantly, especially during the period when the temperature and moisture changed rapidly, the Bowen ratio tended to lose its accuracy. Therefore, the results imply that the fast changes in the soil temperature and moisture lead to distortions in the BR. The diurnal cycle of the freezing–thawing process is a notable feature of the TP’s surface processes during
3.4. Possible reasons for the reanalysis data’s bias error during the transition season

There are two explanations for the bias in the heat flux in the reanalysis data. One is the unreasonable computational schemes of the sensible and latent heat fluxes which represent information from the soil temperature and moisture, and the other might exist due to a temperature and moisture bias between reanalysis and observation.

3.4.1. Estimation of the soil temperature and moisture in the surface heat flux reanalysis data

The surface sensible heat flux depends mainly on the difference between the ground and air temperature, while the latent heat flux is mostly determined by the ground-air temperature difference and the soil moisture. In order to evaluate how much of the information of air temperature ($T_a$), ground temperature ($T_s$), air humidity ($q_a$), and soil moisture ($q_s$) are represented in the surface heat fluxes, the correlation coefficients between the surface heat fluxes and the above elements of the reanalysis data from May 1 to June 13 were calculated. Table 2 demonstrates that the relationships between the three reanalyses have uncertainties, implying that their computational schemes about the surface heat fluxes have some flaws. In the western TP, the correlation coefficients between the sensible heat flux and the air and ground temperatures of NCEP-I are 0.013 and 0.241, respectively. The latent heat flux results in better correlations with the ground-air temperature difference ($T_s - T_a$) in the two areas. AR-II has a poor correlation in Gaize where the surface processes are evidently influenced by the diurnal cycle of the freezing–thawing process. Similarly, the latent heat fluxes of NCEP-I and AR-II also have a better correlation with the ground-air moisture difference ($q_s - q_a$) in the Shiquanhe region, but it becomes poor in the Gaize region. It is consistent with the results we described in Section 2. All the above provide the evidence that the sensible and latent heat flux data of NCEP-I cannot reflect the contribution of the temperature and moisture. As for AR-II, both $SH$ and $LH$ show poor correlations with air temperature, ground temperature and air humidity, especially for the sensible heat flux. The data of AR-II have largely lost their information on temperature and moisture, indicating that AR-II is not suitable for diagnosing the ground heating effect and thermal properties of the western TP during the transition season.

When comparing NCEP-I and AR-II, the surface heat fluxes of ERA display distinctly better correlations with the air and ground temperature, with all the correlations passing the significance test of $p < 0.01$. However, the Gaize data are clearly of poorer quality than that of Shiquanhe. This shows that, during the transition season and the process of ground freezing and thawing, the surface heat

<table>
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<tr>
<th>Table 1</th>
<th>Correlation coefficients between the sensible and latent heat fluxes calculated with the observation data and those coming from reanalysis data.</th>
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<tr>
<td></td>
<td>NCEP-I</td>
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<tr>
<td>Shiquanhe</td>
<td>Bowen $SH$</td>
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<td>Bowen $LH$</td>
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<td>Dynamics $LH$</td>
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<td>Gaize</td>
<td>Bowen $SH$</td>
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<td>Dynamics $SH$</td>
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<td>Dynamics $LH$</td>
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* Over the significance level $p < 0.01$. 

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<tr>
<th>Table 2</th>
<th>Correlation coefficients between the surface heat fluxes reanalysis data and the air temperature ($T_a$), ground temperature ($T_s$), air humidity ($q_a$), and soil moisture ($q_s$) of those data from May 1 to June 13.</th>
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<tbody>
<tr>
<td></td>
<td>NCEP-I $SH$</td>
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<td>Shiquanhe</td>
<td>$T_a$</td>
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<td>$T_s$</td>
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<td>$q_s - q_a$</td>
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Gaize: $T_a$ | 0.203  | 0.569*  | 0.174  | -0.002 | 0.469* | 0.572* |
|          | $T_s$ | -0.044 | 0.525*  | 0.208  | -0.013 | 0.642* | 0.507* |
|          | $T_s - T_a$ | 0.550* | -0.302 | 0.146  | -0.125 | 0.521* | -0.139 |
|          | $q_a$ | 0.562*  | 0.229  | 0.229  | 0.229  | 0.229  |
|          | $q_s$ | -0.253 | 0.341  | -0.139 | -0.139 | -0.139 |
|          | $q_s - q_a$ | -0.400 | 0.047  | -0.094 | -0.094 | -0.094 |

* Over the significance level $p < 0.01$. 

flux scheme of ERA is better than that of the other two reanalysis datasets. However, some problems in its surface
process scheme remain. The correlation of the sensible heat
flux with the air and soil moisture of ERA is not very good.
This implies that the scheme of surface heat fluxes cannot
fully reflect the effect of the hydrological cycle between
the land and the atmosphere during the ground freezing–
thawing processes.

All the above analyses show that, during the transition
season and the freezing–thawing processes, all the sensible
and latent heat flux computational schemes of the NCEP-I,
AR-II and ERA contain some flaws/bugs over the western
TP. In particular, the correlations are all quite poor
between the sensible/latent heat fluxes and the air and soil
moisture.

3.4.2. Correlation of the reanalysis data with the soil
temperature and moisture

To investigate the possible causes for the bias in the sur-
face heat fluxes of the reanalysis data, the correlation coef-
ficients between the reanalysis and observational data, such
as air temperature, ground temperature, air humidity and
soil moisture are calculated. Fig. 5 shows that the correla-
tions of the air temperature, soil temperature and air mois-
ture are very high between the reanalysis and observation;
most of the correlation coefficients are distributed around
the reference line, with the values lying above 0.70 and
passing the 99% confidence level. It shows that the air
and ground temperature simulations of all three kinds of
reanalysis data are closest to the observation data. The cor-
relation coefficients of the air moisture are distributed
between 0.5 and 0.8, and all pass the significance test of
$p < 0.01$. This implies that all the air moisture reanalysis
data are also reasonable.

The correlation coefficients of the soil moisture between
reanalysis (NCEP-I, AR-II, ERA) and observations cannot
pass the significance test. It suggests that the quality of the
soil moisture in the reanalysis data is poorly simulated over
the western TP. Although the correlation coefficient of the
soil moisture of the ERA is high (0.941), its variance is
extraordinarily large and beyond the plot border. Therefore,
all three reanalysis datasets are poor at explaining
the soil hydrological status. However, the soil hydrological
processes, especially soil heat conduction and content, are
dominated by the phase change process of the soil mois-
ture. This deficiency leads to a bias error in the ground
energy balance calculation.

All the above results show that, during the transition
season, the soil phase changes frequently. There exist large
bias errors in the soil moisture of the reanalysis data
(NCEP-I, AR-II, ERA). This is the main reason why the
sensible and latent heat fluxes of the reanalysis data over
the western TP have poor reliability. Meanwhile, the com-
putational schemes of the reanalysis data also have some
deficiencies.

4. Conclusions and discussion

The major findings of this investigation can be summa-
rized as follows:

(1) During the transition season, the reanalysis data
(NCEP-I, AR-II, ERA) are not reliable over the wes-
tern TP and large differences exist between three
kinds of reanalysis datasets. So care needs to be taken
when using reanalysis data to diagnose the thermal
effects of the TP.

(2) The soil freezing–thawing processes in the TP have a
significant influence on the change in sensible and
latent heat fluxes. During the spring, the phase
change processes in the soil moisture which are
caused by freezing–thawing processes also have sig-
nificant effects on the change in the sensible and latent
heat fluxes.

(3) Differences in ground moisture between the reanalysis
data and observation have remarkable impacts on the
quality of surface heat fluxes.

(4) The diurnal cycle in the freezing–thawing processes in
the TP has a critical impact on the sensible and latent
heat fluxes. Particularly during the transition season,

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Fig. 5. The Taylor diagram between the reanalysis and observational data. (a) Shiquanhe and (b) Gaize.
the change in soil moisture caused by these processes has a significant influence on the change in the sensible and latent heat fluxes over the plateau.

Due to the high complexity and uncertainty in the TP’s land processes, the integrity of the land processes needs to be further improved in the numerical model. On the one hand, the simulative ability of the reanalysis data for land processes over the TP needs to be sufficiently considered and enhanced. On the other hand, the sensible and latent heat flux scheme of the reanalysis data, especially for the hydrological process description of seasonal frozen ground and the permafrost active-layer needs to be improved.

Acknowledgments

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