

# 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.

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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:

$$\begin{cases} R_n = SH + LE + G \\ \beta = \frac{SH}{LE} = \frac{C_p}{L_v(\varepsilon/P)} \frac{\Delta T}{\Delta e} \end{cases} \quad (1)$$

$$\begin{cases} SH = (R_n - G)/(1 + \beta^{-1}) \\ LE = (R_n - G)/(1 + \beta) \end{cases} \quad (2)$$

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  $\Delta e$  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:

$$\begin{cases} SH = -\rho C_p u_* T_* \\ LE = -\rho L u_* q_* \end{cases} \quad (3)$$

$$\begin{cases} \frac{\kappa z}{u_*} \cdot \frac{\partial u}{\partial z} = \phi_m \\ \frac{\kappa z}{T_*} \cdot \frac{\partial T}{\partial z} = \phi_h \\ \frac{\kappa z}{q_*} \cdot \frac{\partial q}{\partial z} = \phi_w \end{cases} \quad (4)$$

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

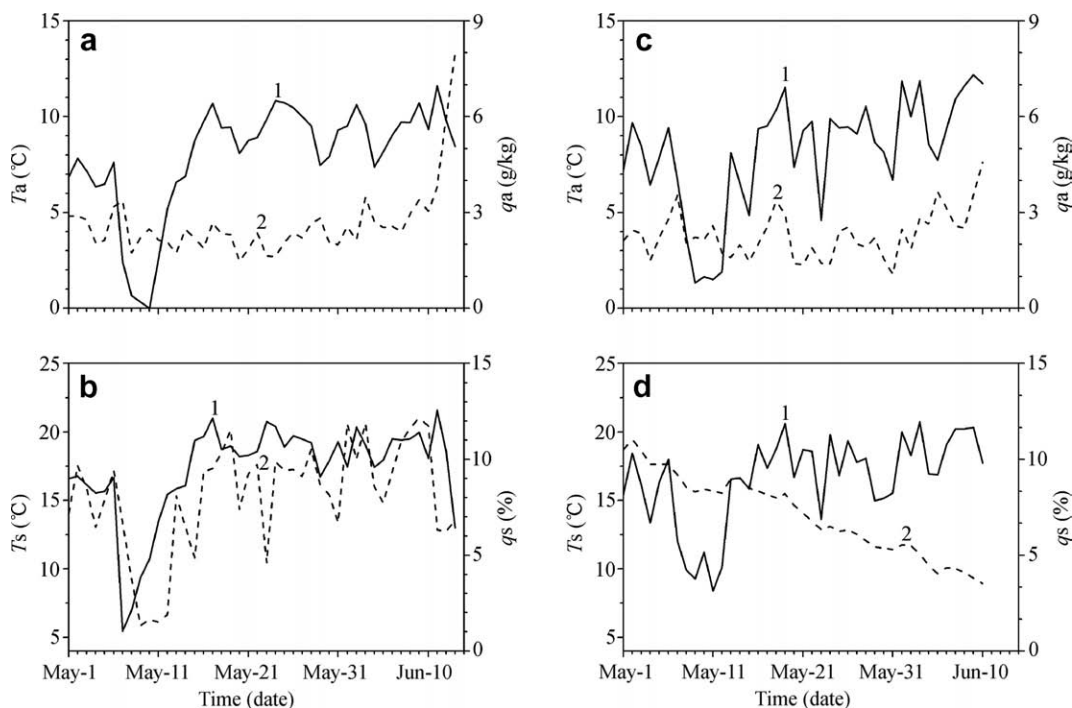


Fig. 1. The daily evolution of air temperature ( $T_a$ ), surface temperature ( $T_s$ ), air humidity ( $q_a$ ) and soil moisture ( $q_s$ ) over the western Tibetan Plateau from May 1 to June 13. (a) Curve 1 is for  $T_a$ ; curve 2 is for  $q_a$ . (b) Curve 1 is for  $T_s$ ; curve 2 is for  $q_s$ . (c)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

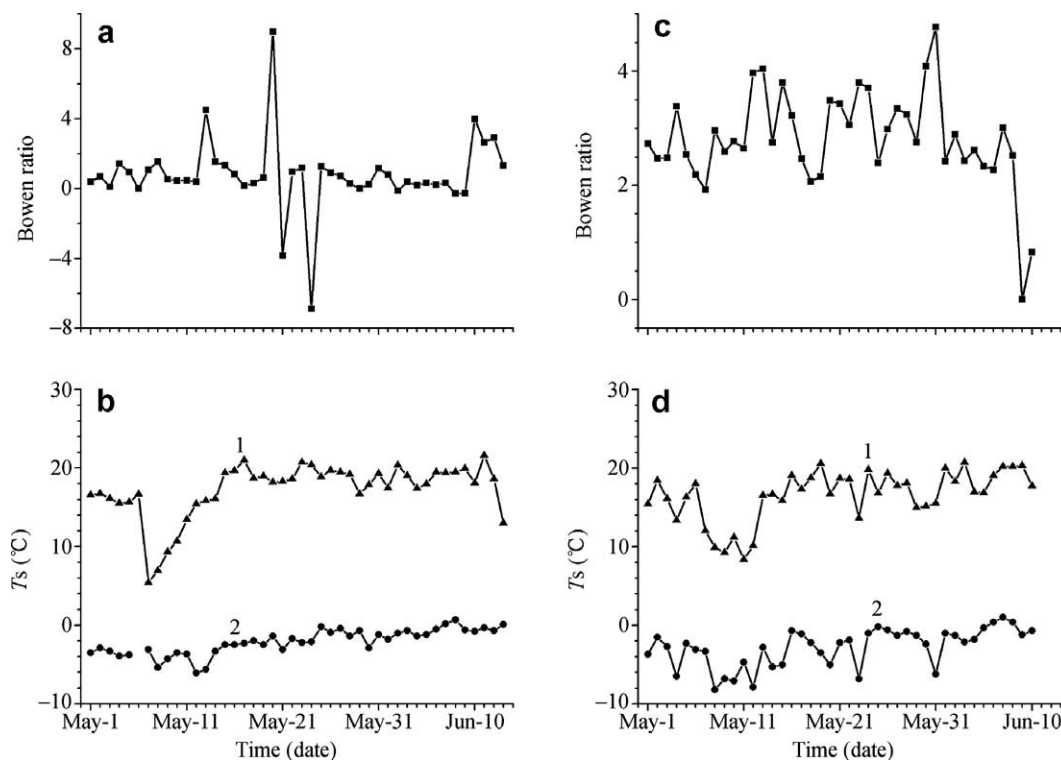


Fig. 2. The daily variations in the Bowen-ratio (a), the minimum and the average surface temperature ( $T_s$ ) over the western TP from May 1 to June 13. In (b) and (d), curve 1 is for average  $T_s$ ; curve 2 is for minimum  $T_s$ . Shiquanhe (a and b); Gaize (c and d).

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. 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/m<sup>2</sup> for the Shiquanhe area and 340.4 W/m<sup>2</sup> 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 TP 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/m<sup>2</sup> and 7 W/m<sup>2</sup>, respectively. The amplitude range is 113 W/m<sup>2</sup>, smaller than the results of Zhang et al. [33], which found a maximum range of 139 W/m<sup>2</sup>. 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

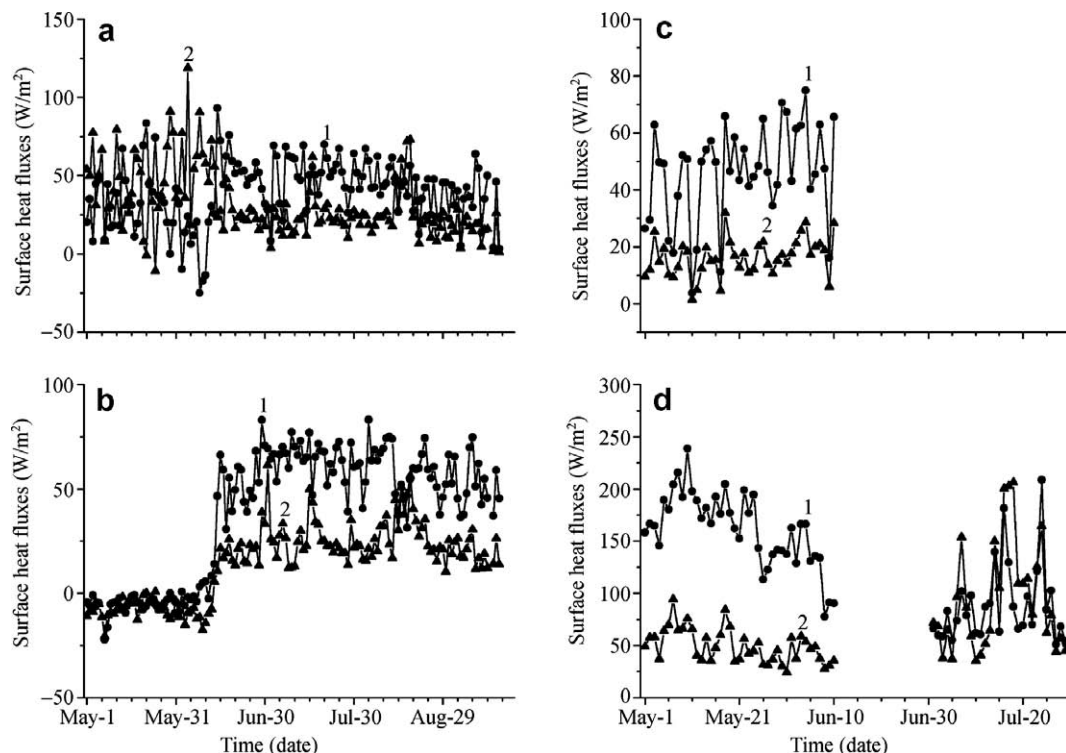


Fig. 3. The daily variations in the sensible and latent heat fluxes over the western TP. (a) Curve 1 is for SH; curve 2 is for LH; (b)–(d) same as (a); Shiquanhe (a and b); Gaize (c and d). BR (a and c); AD (b and d).

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  $49.3 \text{ W/m}^2$ . 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  $140 \text{ W/m}^2$  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 differ-

ences 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

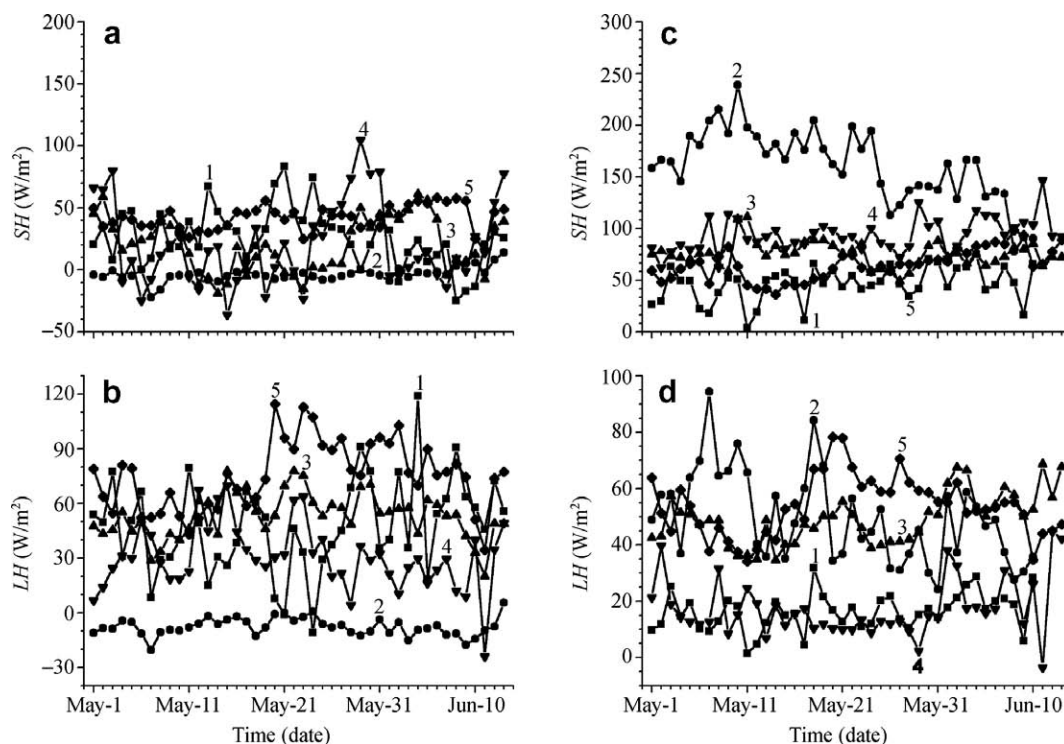


Fig. 4. The daily variations in the sensible and latent heat fluxes over the western TP from May 1 to June 13. (a) Curve 1 is for the Bowen ratio; curve 2 is for dynamics; curve 3 is for NCEP-I; curve 4 is for AR-II; curve 5 is for ERA; (b)–(d) same as (a). Shiquanhe (a and b); Gaize (c and d).

Table 1

Correlation coefficients between the sensible and latent heat fluxes calculated with the observation data and those coming from reanalysis data.

		NCEP-I	AR-II	ERA
Shiquanhe	Bowen_SH	-0.293	-0.060	-0.269
	Bowen_LH	-0.088	-0.233	-0.242
	Dynamics_SH	0.081	0.265	0.155
	Dynamics_LH	0.339	0.335	0.399*
Gaize	Bowen_SH	-0.163	0.194	0.228
	Bowen_LH	0.273	0.046	0.131
	Dynamics_SH	0.292	-0.110	0.501*
	Dynamics_LH	-0.150	0.017	0.349*

\* Over the significance level  $p < 0.01$ .

the transition season. The computational instability is most likely caused by that cycle and is an important issue in the numerical simulation of hydrological processes. As seen in the above analysis, the ERA scheme might be deficient in terms of the soil freezing–thawing process, and the NCEP schemes might have some bias error in the description of the whole soil hydrological process.

### 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 tem-

perature 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 2

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.

		NCEP-I_SH	NCEP-I_LH	AR-II_SH	AR-II_LH	ERA_SH	ERA_LH
Shiquanhe	$T_a$	0.229	0.083	0.267	0.007	0.301	0.651*
	$T_s$	0.527*	0.021	0.518*	-0.124	0.521*	0.629*
	$T_s - T_a$	0.545*	-0.113	0.686*	-0.283	0.302	-0.011
	$q_a$		-0.373		-0.436*		-0.217
	$q_s$		-0.462*		-0.163		-0.701*
	$q_s - q_a$		-0.417*		-0.128		-0.676*
Gaize	$T_a$	-0.203	0.569*	0.174	-0.002	0.468*	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
	$q_s$		-0.253		0.341		-0.139
	$q_s - q_a$		-0.400		0.047		-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 surface heat fluxes of the reanalysis data, the correlation coefficients between the reanalysis and observational data, such as air temperature, ground temperature, air humidity and soil moisture are calculated. Fig. 5 shows that the correlations of the air temperature, soil temperature and air moisture 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 correlation 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 moisture. 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 computational schemes of the reanalysis data also have some deficiencies.

## 4. Conclusions and discussion

The major findings of this investigation can be summarized as follows:

- (1) During the transition season, the reanalysis data (NCEP-I, AR-II, ERA) are not reliable over the western 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 significant 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,

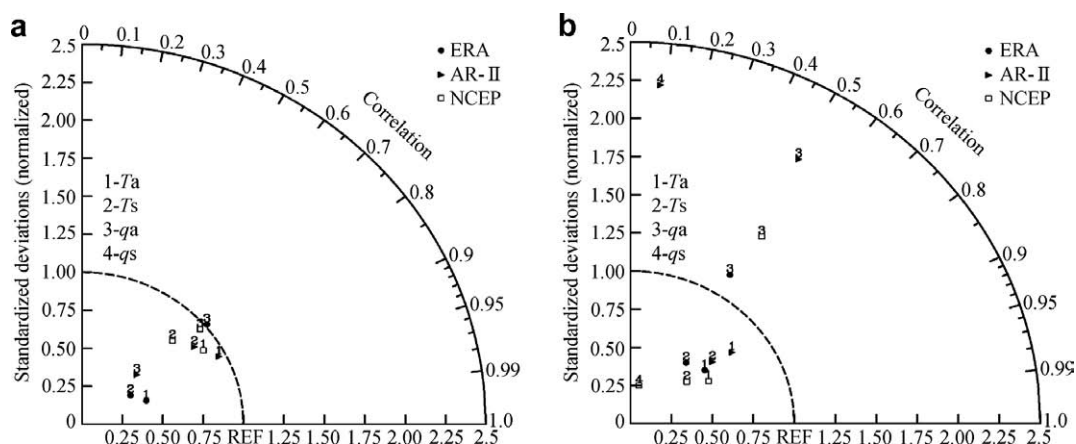


Fig. 5. The Taylor diagram between the reanalysis and observational data. (a) Shiquanhe and (b) Gaize.

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.

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