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ABSTRACT

The impacts of the thermal forcing over the Tibetan Plateau (TP) in spring on changes in summer rainfall in China are investigated using historical records from the period between 1980 and 2008. The spring sensible heat (SH) flux and snow depth over the TP both decreased over this time period, although the trend in SH was more significant than that in snow depth. The similarity between patterns of precipitation trends over China and corresponding patterns of regression coefficients on the leading mode of spring SH change over the TP demonstrates the distinct contribution of changes in TP SH during spring. Enhanced precipitation in southern China was accompanied by increases in heavy rainfall, precipitation intensity, and the frequency of precipitation events, while reduced precipitation in northern China and northeastern China was primarily associated with decreases in the frequency of precipitation events. Further analysis using observational data and numerical simulations reveals that the reductions in SH over the TP have weakened the monsoon circulation and postponed the seasonal reversal of the land–sea thermal contrast in East Asia. In addition, the positive spring SH anomaly may generate a stronger summer atmospheric heat source over the TP due to the positive feedback between diabatic heating and local circulation.

1. Introduction

The atmospheric heat source/sink over the Tibetan Plateau (TP) has experienced significant changes during recent decades, particularly in the spring sensible heat (SH) source (Duan and Wu 2008). Previous studies have indicated that the thermal forcing over the TP during winter and spring, which includes both snow cover/depth and SH, plays a considerable role in regulating the East Asian summer monsoon (EASM) and corresponding precipitation patterns (Wu et al. 1997; Chen and Wu 2000; Zhang and Tao 2001; Zhao and Chen 2001; Wu and Qian 2003; Duan et al. 2003; Zhao and Qian 2007; Zhao et al. 2007).

Most previous studies on this topic have focused on climatological means or interannual variability. Zhang et al. (2004) investigated decadal changes in snow depth over the TP during spring and their impacts on the
EASM during the period of 1962–93. Their studies revealed a close relationship between interdecadal increases of snow depth over the TP during March–April and interdecadal changes of summer rainfall over the Yangtze River valley (wetter), along the southeastern coast of China (drier), and over the Indochina peninsula (drier). Similar results were shown by Zhu et al. (2007), who found close linkages among decadal changes in the TP atmospheric heat source, in TP snow depth during spring, and in summer rainfall over eastern China. Zhao et al. (2010) also suggest that winter and spring snow cover over the TP tended to increase between 1960 and 2001, which increased the local soil moisture content, and cooled the overlying atmosphere during spring and summer. This further weakened the EASM circulation and resulted in an increase in the mei-yu front rainfall over the Yangtze River valley.

This work addresses the following questions. What dominates changes in the thermal forcing over the TP in spring over the past three decades? Are these changes responsible for changes in precipitation over China? What is the mechanism by which the spring thermal forcing over the TP influences precipitation patterns over China? This text is organized as follows. Section 2 provides brief descriptions of the data, model, and numerical experiments. Section 3 investigates the relationship between the trend in summer rainfall over China and the weakened SH sources over the TP during spring. In Section 4, an atmospheric general circulation model (AGCM) is used in conjunction with observational and reanalysis data to illustrate how spring SH over the TP influences the EASM. Section 5 provides a discussion and summary of the major results.

2. Data, model, and design of numerical experiments

a. Data

The data employed in this study include historical 6-hourly observations of surface temperature, air temperature 2 m above land surface, 10-m wind speed, and daily snow depth at 71 stations over the central and eastern TP (CE-TP) and two stations over the western TP. The two stations over the western TP are located at Shiquanhe (32.50°N, 80.08°E; 4278 m) and Gaize (32.15°N, 84.42°E; 4415 m). Records of daily precipitation at 602 stations in China during the period 1980–2008 provided by the China Meteorological Administration are also used. Monthly-mean air temperature, relative humidity, geopotential height, and zonal and meridional wind fields that cover the same period are taken from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis 2 [hereafter NCEP–Department of Energy (DOE); Kanamitsu et al. 2002]. These data are used to diagnose changes in circulation and moisture transport. Different reanalysis datasets may provide different characterizations of meteorological fields, especially on the interdecadal scale over China (Liu et al. 2012); therefore, the Japanese 25-yr Reanalysis (JRA-25; Onogi et al. 2007) conducted by the Japan Meteorological Agency (JMA) is analyzed simultaneously. The NCEP–DOE reanalysis is provided at a horizontal resolution of 2.5° × 2.5° with 17 standard pressure levels, while the JRA-25 is provided at a horizontal resolution of 1.25° × 1.25° with 23 standard pressure levels.

Following Duan et al. (2011), SH was calculated using in situ observations at all 73 stations over the TP using the bulk aerodynamic method. Statistical significance was evaluated using the $t$ test, and a partial regression analysis was employed to detect possible relationships between the spring TP thermal forcing and summer precipitation over China.

b. Model

The model used in this study is the current version of the Spectral Atmospheric Model developed by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics (LASG/IAP). This model (SAMIL2.4.7) uses a horizontal resolution of R42 (2.81° longitude × 1.66° latitude) with 26 sigma–pressure ($\sigma$–$p$) hybrid vertical layers that extend from the surface up to 2.19 hPa. The model dynamical framework employs a standard atmosphere subtraction scheme (Wu et al. 1996) to accurately calculate pressure gradient forces. The effects of gravity wave drag are included (Palmer et al. 1986).

Convective precipitation is calculated according to the mass flux cumulus parameterization developed by Tiedtke (1989) with a modified closure assumption and organized entrainment and detrainment (Nordeng 1994; Song 2005). The cloud scheme is diagnostic and is parameterized according to low-layer static stability and relative humidity (Slingo 1980, 1989). A statistical stratocumulus cloud scheme is also employed (Dai et al. 2004).

The model includes a nonlocal scheme that calculates the profile of eddy diffusivity, the scale of turbulent velocity, and the effects of nonlocal transport on heat and moisture (Holtslag and Boville 1993). The Sun–Edwards–Slingo (SES2) radiation scheme is used to model radiative transfer (Edwards and Slingo 1996; Sun 2005). The AGCM successfully reproduces the monsoon circulation and precipitation in the EASM region (Wang et al. 2012).
c. Numerical experiments

Three sets of AGCM ensemble runs are carried out under different SH conditions over the TP during spring (March–May average). The control run, in which spring SH intensity over the TP is maintained at 100%, is referred to as SH100. Two sensitivity ensembles are run in which the intensity of spring SH at grids higher than 2000 m MSL within the TP area (20°–40°N, 70°–110°E) is specified to be 50% (SH50) or 150% (SH150) of normal.

Each ensemble includes 10 cases integrated from 1 January to 31 December with different initial conditions. The forcing fields are identical in all three ensembles. In particular, monthly sea surface temperature (SST) and sea ice extent are prescribed according to the 20-yr climatology used by the Atmospheric Model Intercomparison Project (AMIP) II (see http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS_OBS/amip2_bcs.htm for details). These monthly-mean conditions are linearly interpolated to each integration step. Differences between the ensembles are evaluated using the average results from each 10-member ensemble.

3. Trends in summer rainfall over China and spring SH over the TP

SH is the dominant component of the atmospheric heat source over the TP prior to summer monsoon onset (Yeh and Gao 1979; Zhao and Chen 2001; Duan et al. 2003). This heat source acts as an effective air pump, not only driving convergence of the surrounding air onto the plateau, especially along the steep southern and eastern slopes (Wu et al. 1997), but also modulating the timing of monsoon onset over South Asia (Wu and Zhang 1998).

Figure 1 shows the first two leading modes of decadal changes in SH and snow depth at 71 stations in the CE-TP during spring and their corresponding temporal evolutions according to empirical orthogonal function (EOF) analysis of low-pass filtered observational data. EOF1 of spring SH indicates a uniform change over most parts of the CE-TP except the northern periphery, with a variance contribution of 67%. The temporal evolution of the first principal component (PC1) shows an accelerated decline in spring SH over the TP during the late 1980s and 1990s. The second leading mode (EOF2) of spring SH is characterized by an opposite signal over the central TP relative to its northern and southern sides, and contributes only 18% of the total variance. The corresponding principal component (PC2) indicates a strong decadal oscillation with a positive phase during 1988–98 and negative phases during the beginning and end of the analysis period.

EOF1 of the spring snow depth, which explains 40.5% of the variance, shows a seesaw pattern between the eastern TP and the western TP. PC1 suggests the snow depth over the eastern TP is relatively deep during the period 1986–2000 and relatively shallow during the first decade of the twenty-first century. An opposite transition (from shallow to deep) is observed over the western TP. The long-term trend of spring snow depth over most parts of the TP is described by EOF2, which explains 35% of the variance. The time series of PC2 shows a decreasing trend in spring snow depth accompanied by large interannual variability. The changes in spring SH and snow depth at two stations on the western plateau were nearly identical, with average rates of $-0.5 \text{ W m}^{-2} \text{ yr}^{-1}$ and $-0.001 \text{ cm yr}^{-1}$, respectively. Clearly, the decadal changes in SH are more obvious than those in snow depth. Considering the sparse distribution of stations within the western TP and the overall similarity of these trends with those observed in the CE-TP, the changes in thermal forcing over the TP will be represented by PC1 of spring SH at the 71 CE-TP stations (Fig. 1) throughout the remainder of this paper.

Summer rainfall over China has experienced substantial variability on longer time scales during recent decades (e.g., Zhai et al. 2005; Ding et al. 2008). Two dominant patterns of decadal variability make contributions to the recent prevalence of flooding in the south and drought in the north. Increases in the intensity of rainfall and decreases in the frequency of light rainfall have been observed throughout the country, and may indicate significant anthropogenic influences on the regional climate (Lei et al. 2011).

The left panels of Fig. 2 exhibit the spatial patterns of linear trends in total rainfall amount, heavy rainfall amount (>27.5 mm day$^{-1}$), rainfall intensity, and rain event frequency in the summer season (June–August average) during 1980–2008. Partial regression coefficients of these characteristics of summer rainfall on the PC1 of spring SH with PC2 of spring snow depth on the TP excluded are shown in the middle panels of Fig. 2. These partial regressions are performed to identify the degree to which weakened SH over the TP has influenced summer precipitation changes over China. During the past three decades, the linear trends are characterized by increases in precipitation over southern China and between the Huanghe and Huaihe Rivers and by decreases in precipitation over northern China and northeastern China and along the middle and lower reaches of the Yangtze River. Similar changes have been identified in gridded data compiled by the Global Precipitation Climatology Centre (Fig. 6 of Duan et al. 2011). The increase in precipitation over southern China corresponds to enhancements of heavy rainfall, precipitation intensity, and...
FIG. 1. The first two leading EOF modes of low-pass filtered spring (March–May mean) sensible heat (W m$^{-2}$) and snow depth (cm) over the central and eastern Tibetan Plateau between 1980 and 2008 based on station data, showing (left) the spatial patterns and (right) the corresponding principal components (black lines). The variance explained by each mode is marked at the upper right of the panel. The original time series are shown as red lines in the right panels. Open circles, solid circles, and stars denote stations at altitudes of 2000–3000, 3000–4000, and 4000–5000 m MSL, respectively.
frequency of precipitation events. By contrast, the decrease in precipitation along the middle and lower reaches of the Yangtze River is coherent with weakened heavy rainfall, precipitation intensity, and frequency of precipitation events. Over northern and northeastern China, however, the decreases in precipitation may be attributed primarily to reductions in the frequency of precipitation events. The changes in heavy rainfall and precipitation intensity in these regions are complicated and are oriented contrary to trends in total rainfall amount in some places.

The precipitation trends along the Yangtze River and in regions between the Huanghe and Huaihe Rivers are different from those reported in some previous studies (Chang et al. 2000; Ding et al. 2008; Huang et al. 2006; Lei et al. 2011). These differences are due to differences in time period and in the number of stations used. Nevertheless, the increases in precipitation over southern China from the mid-1970s to the present are consistent with previous results.

FIG. 2. (left) Linear trends in (top) total summer (June–August mean) rainfall amount (mm yr$^{-1}$), (top middle) heavy rainfall amount (mm yr$^{-1}$), (bottom middle) average rainfall intensity (mm day$^{-1}$ yr$^{-1}$), and (bottom) rainfall frequency (day yr$^{-1}$) over China between 1980 and 2008. (middle) Partial regression coefficients of the precipitation characteristics in the left panels on PC1 of spring sensible heating (SH) over the Tibetan Plateau (TP) with PC2 of snow depth excluded. (right) Partial regression coefficients on PC2 of spring snow depth over the TP with PC1 of SH excluded. Dark dots indicate trends and partial regression coefficients that are significant at the 90% confidence level.

The partial regression coefficients of precipitation characteristics on PC1 of spring SH over the TP when PC2 of spring snow depth is excluded are similar to the trends in precipitation characteristics. This resemblance is true not only for total rainfall amount, but also for heavy rainfall, precipitation intensity, and frequency of precipitation events.
Unlike over the TP and regions downstream of the TP, the linear trends and regression coefficients for heavy rainfall, precipitation intensity, and frequency of precipitation events are obviously different over northwestern China, to the north of the TP. This difference implies that other factors may be responsible for these changes.

The pattern of partial regression coefficients of summer rainfall characteristics on PC2 of spring snow depth over the TP with PC1 of spring SH excluded (Fig. 2, right panels) is clearly different from the pattern of linear trends in most regions, particularly in eastern and southern China. This result verifies that trends in summer precipitation over China are directly
related to reductions in TP SH rather than reductions in snow depth.

The climatological mean, long-term trend, and partial regression coefficients of the atmospheric circulation and moisture flux divergence at 850 hPa are shown in Fig. 3. A vigorous low-level southwesterly jet is apparent to the east of the TP. This southwesterly jet extends northward to 40°N, providing a plentiful supply of moisture to the EASM from the South China Sea and Bay of Bengal. The western Pacific subtropical anticyclone also supplies moisture to the southern and eastern coasts of China. During recent decades, the trend in the low-level flow is counter to the climatological mean, with particularly significant changes in northern China and South Asia. A belt of anomalous moisture convergence stretches from the northern Indochina peninsula to southern China and the coastal areas of southeastern China. Another zone of anomalous moisture convergence can be identified over the Sichuan Basin and Loess Plateau to the east and northeast of the TP. Anomalous moisture divergence occurs mainly in northern China, northeastern China, and along the middle and lower reaches of the Yangtze River. The corresponding partial regression coefficients on PC1 of spring SH over the TP with PC2 of snow depth excluded presents a very similar pattern to the linear trends, not only over eastern China,
but also over southern India and Southeast Asia. This similarity suggests that these changes in the low-level circulation and moisture transport may be closely related to weakening of spring SH over the TP.

Figure 4 shows the climatological mean, long-term trend, and partial regression coefficients of the atmospheric circulation at 500 hPa. The long-term trend in the midtropospheric circulation indicates a deceleration of the subtropical westerly jet and a cyclonic circulation anomaly over the western Pacific relative to the climatology. These changes suggest a weakening trend in the western Pacific subtropical high. Consequently, moisture transport into northern China from the southwestern flank of the high is reduced. The pattern of the partial regression coefficient is similar, with a significant signal surrounding the northern and eastern TP. The trend and partial regression coefficients of the upper-level atmospheric circulation indicate a clear weakening of the South Asian high (not shown).

In addition to modifying the monsoon circulation, the weakened spring thermal forcing over the TP has delayed the winter-to-summer reversal of the meridional land–sea thermal contrast in the troposphere over the EASM region with a linear trend of 0.05 pentad yr\(^{-1}\). A later seasonal transition from winter to summer and a delayed EASM are both associated with enhanced rainfall in southern China and reduced rainfall in northern China.

These results suggest a considerable relationship between the weakening spring SH source over the TP and the weakening summer monsoon circulation and southward retreat of the EASM rainfall belt.

4. Results of numerical simulations

Two possible mechanisms by which spring SH over the TP might affect EASM circulation and rainfall have been proposed by previous studies (e.g., Wu et al. 1997;
Zhang and Tao 2001; Duan et al. 2003, 2008). The first possible mechanism is as follows. Strong (weak) SH anomalies over the TP during spring are usually followed by strong (weak) atmospheric heat source anomalies over the TP during summer, which in turn induce an abnormally strong (weak) shallow surface cyclone, an abnormally strong (weak) upper-layer anticyclone, and anomalous convergence (divergence) of air over the TP (Blake et al. 1983; Krishnamurti 1985). The low-level southwesterly jet located to the south and east of the TP, which provides moisture to East Asia, is then stronger (weaker) than normal, and the northern edge of the monsoon rainfall belt is located farther northward (southward). These conditions correspond to a so-called strong (weak) EASM. The second possible mechanism is that a strong (weak) thermal forcing over the TP during spring promotes a warm (cold) troposphere over surrounding areas, leading to an earlier (later) seasonal reversal of the land–sea thermal contrast. These conditions correspond to an early (late) monsoon onset.

A series of numerical experiments using the SAMIL2.4.7 AGCM has been carried out to further evaluate and illustrate these two possible methods (see section 2 for details). Figure 5 shows the annual cycle of SH averaged over the TP for all three experiments. The simulated annual cycle of SH in the control run of the model (SH100) is comparable to the observed annual cycle as documented by previous studies (e.g., Zhao and Chen 2001; Duan and Wu 2008), with a typical peak value of about 60 W m$^{-2}$ in May and June. Following the onset of the summer monsoon, the intensity of SH decreases gradually to an annual minimum of less than 10 W m$^{-2}$ in December and January. The differences in SH among the various numerical experiments were significant during spring, but less so at other times.

Figure 6 presents the observed and simulated annual cycles of the pentad-mean EASM index. This index is defined by the vertical shear of zonal and meridional wind between 200 and 850 hPa within the area bounded by 20°–40°N and 110°–130°E (Webster and Yang 1992). Both the NCEP–DOE reanalysis and JRA-25 datasets indicate that the transition from winter to summer occurs during pentad 32 (early May) in zonal wind shear and during pentad 21 (mid-April) in meridional wind shear. The opposite transition (from summer to winter) occurs during pentad 51 (mid-September) in zonal wind shear and during pentad 57 (mid-October) in meridional wind shear. The AGCM is able to reproduce the
seasonal evolution of wind shear, although the onset of the EASM in the SH100 simulations is approximately five pentads earlier in zonal wind shear and three pentads earlier in meridional wind shear. Comparison of the SH150 and SH50 ensembles shows that the more intense spring SH (SH150) is associated with an earlier seasonal transition (by two pentads in the zonal wind shear and by four pentads in the meridional wind shear). The quantitative results are not conclusive given the uncertainties and errors in current models; however, the evident difference between the SH150 and SH50 ensembles indicates that stronger spring SH over the TP is favorable to an earlier EASM onset.

In addition to the seasonal transition in the atmospheric circulation, a plentiful supply of moisture is a necessary prerequisite for EASM precipitation. Figure 7 shows the direction and intensity of the vertically integrated water vapor flux generated by the SH100 run during spring and summer, along with corresponding differences between the SH150 and SH50 ensembles. Moisture transport simulated by the AGCM is similar to that observed (cf. Fig. 3). In spring, the moisture supply over the EASM region originates mainly from the Bay of Bengal and South China Sea. In summer, the Arabian Sea and the northwestern Pacific also supply significant moisture to the region. This vigorous moisture “conveyor belt” can even extend northward to northeastern China and the Korean Peninsula. The differences between SH150 and SH50 indicate that stronger spring SH over the TP substantially enhances this moisture conveyor belt during spring and summer. The vertically integrated water vapor flux primarily reflects low-level winds and moisture; therefore, these results confirm that spring SH over the TP intensifies the low-level southwesterly jet located to the south and east of the TP and shifts its northern edge farther to the north.

The patterns and seasonal evolution of the general circulation in the middle and upper troposphere are also well reproduced by the model (Figs. 8a,b and 9a,b). In spring, the subtropical and midlatitude troposphere over the Eurasian continent is dominated by westerly winds at 500 hPa and an orography-induced ridge over the northern TP. Positive vorticity is confined mainly to the southeastern TP and around the southern periphery of the TP. At 200 hPa, strong westerly winds and positive vorticity are dominant over the Eurasian continent. In summer, the 500-hPa westerly jet shifts northward to the midlatitudes. A cyclone dominates the TP and surrounding areas, with strong positive vorticity over the southern TP. In the upper troposphere, the massive South

![Fig. 8](https://example.com/fig8.png)
Asian high and strong negative vorticity dominate the tropics and subtropics. The center of the South Asian high is located to the southwest of the TP.

The differences between the SH150 and SH50 ensembles visibly demonstrate the role of spring SH over the TP in modulating the large-scale circulation pattern in the middle and upper troposphere (Figs. 8c,d and 9c,d). In spring, stronger SH induces a cyclonic circulation anomaly and positive vorticity anomaly over the TP. These anomalies are accompanied by an anticyclonic circulation anomaly to the north and east TP at 500 hPa, and substantially stronger westerly winds along the southern periphery of the TP, while an easterly wind anomaly over southern China and eastern China decelerates the climatological westerly winds. A positive anomaly in SH over the TP establishes a robust anticyclonic circulation anomaly and negative vorticity over the entire subtropics at 200 hPa. This anticyclonic anomaly intensifies the westerlies in midlatitudes and weakens the westerlies in the tropics.

The impacts of anomalous spring SH over the TP persist at least until the summer. A 500-hPa cyclonic anomaly around the TP enhances not only the positive vorticity over the plateau but also southerly winds to the east of the TP and westerly winds to the south of the TP, intensifying the background circulation over the EASM region. The circulation difference at 200 hPa is similar to that at 500 hPa. A dipole circulation anomaly develops over the EASM region and northwestern Pacific, featuring an anticyclonic anomaly in midlatitudes and a cyclonic anomaly to the south. Strong negative vorticity in the anomalous anticyclone implies an intensification of divergence from the climatological mean. Furthermore, an easterly anomaly in midlatitudes suggests that the westerly jet is decelerated, possibly resulting in more active trough and ridge development, more cold air intrusions, and frontal precipitation over the EASM region.

Duan et al. (2003) found that there is a reliable “memory” in SH over the TP—that is, that stronger (weaker) spring SH is usually followed by a stronger (weaker) atmospheric heat source in summer. To further illustrate that the signal of spring SH over the TP can persist until to summer, in Fig. 10 we plot the temporal evolution of the 2-station-averaged SH in the western TP and the 71-station-averaged SH in the CE-TP in both spring and summer during 1980–2008. The correlation coefficient between the spring SH and summer SH is 0.43 for the western TP and 0.74 for the CE-TP, with the significance above the 95% confidence level.

However, at present, the mechanism of the persistence in spring SH over the TP remains unclear. Based
on the results of the numerical experiments, we propose a possible mechanism involving positive feedback between diabatic heating and local atmospheric circulation. Hoskins and Karoly (1981) used a PV-θ (i.e., isentropic potential vorticity) perspective to show that the atmosphere responds to positive thermal forcing by forming a lower-layer cyclonic circulation, and an upper-layer anticyclonic circulation. The large-scale steady barotropic vorticity equation indicates that to the east of the diabatic heating area airflows must converge at low levels and diverge at upper levels, with the reverse being true to the west (i.e., divergence at low levels and convergence at upper levels). When a positive SH anomaly is prescribed over the TP, pumping and draining processes promote upward motion on the eastern side of the TP, and downward motion to the west of the TP (Duan and Wu 2005). Dry and cold northerlies favor enhanced SH over the western TP, while wet and warm southerlies favor enhanced LH by latent heating over the eastern TP.

This mechanism is confirmed by our numerical experiments. Figure 11 shows that the positive spring SH anomaly over the TP results in an anomaly of more than 10 W m\(^{-2}\) LH on the eastern TP (east of 85°E), while the contribution to the net radiation anomaly is rather small, ranging from -2 to +2 W m\(^{-2}\), and the TP domain average is close to zero. Consequently, a positive total diabatic heating anomaly appears over and around the TP. It is noteworthy that the convective heating over the eastern TP will in turn strengthen the local ascending motion through “diabatic enhancement” (Rodwell and Hoskins 2001). Furthermore, as the seasons progress from spring to summer, this anomalous circulation coincides with the climate mean background circulation and consequently reinforces it (Figs. 8 and 9), which further enhances the convective precipitation in the southern and eastern TP.

In summer, a 2.5–5 W m\(^{-2}\) positive SH anomaly still remains in most of the northwestern TP, and a 2.5–5 W m\(^{-2}\) negative SH develops in the southeastern corner (Fig. 12). Meanwhile, a positive LH anomaly of more than 10 W m\(^{-2}\) is seen in the southern and eastern TP, with a 5 W m\(^{-2}\) negative LH anomaly in the northern TP. Again, net radiation forcing of these anomalies is weak. The combined effect of all diabatic inputs produces a positive summer atmospheric heat source anomaly over the TP, although the intensity of this anomaly is much lower than that in spring (about 15 W m\(^{-2}\) for the domain average). Consequently, the spring SH anomaly over the TP is able to retain its “memory” until summer, mainly by enhancing the LH over the eastern side.

In addition to their effects on the local thermal forcing, spring SH anomalies over the TP may also affect the summer circulation through “soil memory.” Using the results of numerical simulations, Zhu et al. (2009) suggested that a weaker TP heat source could persist from spring until summer via long-term interactions between moist soil and the atmosphere. Zhu et al. (2009) further indicated that these soil–atmosphere interactions could act to weaken the EASM and the South Asian summer monsoon.

5. Concluding remarks

Historical records at 73 meteorological stations over the TP and precipitation observations at 602 stations in China during the period 1980–2008 have been used to investigate the impacts of changes in the spring thermal forcing over the TP on changes in precipitation over China. Numerical sensitivity experiments using the SAMIL2.4.7 AGCM have been performed to illustrate possible mechanisms. The main results of this study are summarized below.

1) During the last three decades, both spring SH and snow depth over the TP have decreased. The former represents the primary and most significant change in the TP thermal forcing.

2) Precipitation, heavy rainfall, average rainfall intensity, and the frequency of precipitation events all increased substantially in southern China over the
same time period, while a nearly opposite change occurred in the middle and lower reaches of the Yangtze River. Precipitation also decreased in northern China and northeastern China; however, this decrease was induced primarily by a decrease in the frequency of precipitation events.

3) Partial regression coefficients of precipitation characteristics on PC1 of spring SH over the TP with PC2 of spring snow depth excluded are similar to the corresponding trends. This similarity suggests that the reduction in SH over the TP was an important factor in determining the pattern of precipitation changes over China.

4) The reduction of SH over the TP leads to a weakening of the EASM circulation system. This weakening includes the low-level southwesterly jet, the western Pacific subtropical high, the midtropospheric subtropical westerly jet, and the upper-tropospheric South Asian high. These changes are consistent with the southward retreat of the monsoon rainfall belt and weakening of the EASM. The weakening of spring SH over the TP also postponed the winter-to-summer reversal of the land-sea thermal and led to a later onset of the EASM.

5) The distinctive impact of spring SH over the TP on the EASM has been demonstrated using numerical simulations. According to the AGCM, a positive anomaly in SH over the TP brings about not only an earlier EASM onset but also a stronger EASM circulation and a more northward extension of the monsoon rainfall belt. Conversely, a negative anomaly in SH over the TP delays monsoon onset and weakens the EASM circulations. These results qualitatively verify the role of spring SH over the TP in regulating summer rainfall over eastern China at the time scales of long-term trends. In addition, the positive spring SH anomaly may generate a stronger summer atmospheric heat source over the TP due to the positive feedback between diabatic heating and local circulation.

**Fig. 11.** Difference fields (W m$^{-2}$) between SH150 and SH50 runs in (a) spring sensible heat flux, (b) latent heat of condensation, (c) air column net radiation cooling, and (d) the total diabatic heating [i.e., sum of (a)–(c)]. Hatched area in each panel denotes the TP.
Climate variations represent the superposition of many factors over a wide range of spatial and temporal scales, and their complexity is well known. The changes in the EASM that are examined in this study may also be related to factors that are not explored here, such as warming in the tropical oceans (Zhou et al. 2008) or changes in atmospheric aerosols (Xu 2001). Additional work will be required to distinguish the impacts of changes in the TP thermal forcing from other factors.

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