Assessment of the impact of soil moisture on spring surface air temperature over the low-latitude highlands of China

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Abstract
The low-latitude highlands (LLH) of China are situated in the subtropical southwest China. The spring climatic characteristics of the LLH were previously regarded as being governed by remote sea surface temperature forcing and large-scale atmospheric circulations. Recent studies qualitatively demonstrated that the LLH is a relatively strong soil moisture (SM)-surface air temperature (SAT) coupling region in China during spring. In this study, the quantitative spring SM-SAT coupling (mean of March and April before wet season) is further statistically analysed using two different SM data sources (one reanalysis data set and one land surface assimilation product). The results show that significant negative SM-SAT feedbacks mainly occur in the western and middle part of the LLH. Over these areas, 10–50% of the total SAT variance could be explained by the SM-induced negative feedbacks with a feedback parameter of $-0.2°C$ (standardized SM)$^{-1}$ to $-0.8°C$ (standardized SM)$^{-1}$. Further analyses show that SM negatively impacts Bowen ratio in the western and middle part of the LLH where Bowen ratio positively affects SAT, therefore significant negative SM-SAT feedbacks occur therein. The potential impact of India–Burma Trough (IBT) on the SM-SAT coupling is also investigated in this study, the results of which suggest that SM-SAT coupling and the effects of SM on land surface energy balance may be immune to the influence of the IBT. Furthermore, SM and IBT may comparably affect SAT in the western and middle part of the LLH. This highlights that SM might have prominent effects on the subseasonal predictability of spring SAT over these areas.

KEYWORDS
low-latitude highlands of China, spring soil moisture, surface air temperature

1 | INTRODUCTION

As a crucial land surface variable, soil moisture (SM) exerts prominent impact on land surface processes and land-atmosphere interactions (Seneviratne et al., 2010; Legates et al., 2011). Owing to its relatively long persistence (Koster and Suarez, 2001; Orth and Seneviratne, 2012; Liu et al., 2014a, 2014b), SM can...
significantly regulate soil thermal parameters, land surface albedo, vegetation, and partitioning of net surface radiation which is further divided into surface sensible and latent heat fluxes (Shukla and Mintz, 1982; Dirrmeier et al., 2000; D’Odorico et al., 2007; Guan et al., 2009; Ford et al., 2014; Crow et al., 2015; Schwinghaschki et al., 2017; Haghighi et al., 2018). Thus, it substantially influences land surface energy budget and water balance, and to a large extent, has a direct impact on local weather and climate, especially in the regions where evapotranspiration is strongly controlled by SM. It can also modify the land surface diabatic heating and land-sea thermal contrast, thus SM potentially affects large-scale atmospheric circulation and monsoon systems and has a remote impact on regional-scale weather and climate (Douville, 2002; Collini et al., 2008; Zhang and Zuo, 2011; Asharaf et al., 2012; Koster et al., 2014; Liu et al., 2017; Zhong et al., 2018; Gao et al., 2019).

The effect of SM on surface air temperature (SAT), which is commonly referred to as SM-SAT coupling, is one of the central topics of land-atmosphere interaction studies and has drawn extensive attention from researchers. Quantifying the SM-SAT coupling and revealing its possible mechanism is important as it strongly influences climate research, human health and ecosystem functions (Bomblies and Eltahir, 2009; Falloon et al., 2011). On a global scale, strong SM-SAT coupling generally occurs in the dry-wet transitional regions where evapotranspiration is significantly constrained by SM and is also large enough to have a noticeable impact on local land surface energy budget and atmosphere dynamics, such as the North American Great Plains, India, Australia and southern Africa (Miralles et al., 2012; Gevaert et al., 2018; Chen et al., 2019). Regionally, North China (NC) is a typical dry-wet transition zone in East Asia (Li and Ma, 2013) where the summer SM anomaly and spring SM anomaly persisting to summer strongly contribute to summer hot days and heat waves (Zhang and Dong, 2010; Wu and Zhang, 2015). Feedback of local SM on diurnal temperature range is also noticeable in NC (Wu and Zhang, 2013). Meanwhile, SM-SAT coupling in NC has been enhanced after the 1990s under the background of significant warming therein (Xu et al., 2019). Furthermore, Li et al. (2019) suggested that feedback of summer SM on daily minimum air temperature in NC would be intensified in the future. In other wet and/or monsoon dominated regions, the antecedent SM anomaly plays a crucial role in the formation and maintenance of summer heat wave in Europe (Fischer et al., 2007; Hirschi et al., 2011) and short-term hot weather in East China (Zeng et al., 2014).

The low-latitude highlands (LLH) of China (21–29°N, 97–108°N, Cao et al., 2014) is situated in the subtropical southwest China with an average altitude of over 1,500 m above sea level, including four provinces (municipality, autonomous region), namely, Yunnan, southern Sichuan, western Guizhou, and western Guangxi. As a stretch of terrain belonging to the southeastern Tibetan Plateau, the LLH is featured by a pronounced northwest-southeast elevation gradient. Owing to local terrain complexity, and as a conjunction of Asian Monsoon systems, the climatic characteristics in the LLH exhibit strong spatiotemporal variations (Wang, 2002; Cao et al., 2012; Zhang et al., 2014a, 2014b; Liu et al., 2016).

Previously, spring climatic characteristics in the LLH were regarded as being governed by remote sea surface temperature (SST) forcing and large-scale atmospheric circulations. For example, Li et al. (2018) demonstrated that abnormal warming of spring North Atlantic SST can excite a teleconnection wave train extended from North Atlantic to the LLH with an anomalous cyclone over Bay of Bengal in the lower troposphere, which favours moisture transport to the LLH. The relatively strong negative phase of Arctic Oscillation is considered to be a major potential factor leading to extreme spring droughts in the LLH (Huang et al., 2012; Yang et al., 2012). Sun et al. (2017) pointed out that rainfall in late spring over the LLH has been closely related to Somali Jet intensity since 1980.

Recently, Gao et al. (2018) found that the LLH is a hot spot of land-atmosphere coupling over eastern China in spring. Additionally, the LLH is also a relatively strong SM-SAT coupling region in China during spring (Yuan et al., 2020). However, to what extent SM affects SAT in the LLH during spring and its possible mechanisms are yet to be studied, which are the main purpose of this research.

This paper is arranged as follows: data and methods are described in Section 2. Section 3.1 describes the quantitative assessment of SM-SAT coupling in the LLH during spring. Section 3.2 discusses the possible mechanisms from the perspective of land surface energy balance. Potential impact of India–Burma Trough on SM-SAT coupling is further discussed in Section 3.3. The conclusions and discussion are presented in Section 4.

## 2 | DATA AND METHOD

### 2.1 | Data

Due to the lack of long-term and continuous observed SM data in the LLH (Li et al., 2005; Liu et al., 2014a, 2014b), two different modelled SM data sets produced by the European Center for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim,
Dee et al., 2011) and the Global Land Data Assimilation System Noah model (GLDAS-Noah, Rodell et al., 2004) are used to cross-validate the quantitative SM-SAT coupling as well as its possible mechanisms. ERA-Interim provides several land surface variables by the Tiled ECMWF Scheme for Surface Exchanges over Land surface model (Van den Hurk et al., 2000) and a 4-D assimilation method. Liu et al. (2014a, 2014b) demonstrated that ERA-Interim can well reproduce the spatiotemporal features of SM over eastern China in spring. Thus, the monthly ERA-Interim SM data at 0.75° × 0.75° resolution and three layers of 0–7, 7–28, 28–100 cm depth are selected for this study. GLDAS-Noah is forced by a combination of atmospheric analysis, satellite-based precipitation, and observation-based radiation fields. Using state-of-the-art land surface modelling and data assimilation techniques, the GLDAS-Noah SM data set has been widely used in investigating land-atmosphere interactions (e.g., Wu and Zhang, 2013; Gao et al., 2019; Xu et al., 2019). Considering the terrain complexity in LLH, we use monthly GLDAS-Noah SM data at 0.25° × 0.25° resolution and three layers of 0–10, 10–40, 40–100 cm depth in the present study, including GLDAS-Noah V1.0 from 1979 to 1999 and GLDAS-Noah V2.0 from 2000 to 2016. The net surface radiation, sensible and latent heat fluxes produced by ERA-Interim and GLDAS-Noah are also applied to explore the relevant mechanisms.

Other datasets used in this study include: (a) the monthly mean atmospheric circulation and SAT data from ERA-Interim with a horizontal resolution of 0.75° × 0.75°; (b) the gridded observational monthly SAT, precipitation and total cloud cover data from the Climatic Research Unit of the University of East Anglia version 4.01 (CRU TS4.01, Harris et al., 2014), with a horizontal resolution of 0.5° × 0.5°.

2.2 Method

A variance method is adopted to quantitatively evaluate the effect of SM on SAT (i.e., SM-SAT coupling) in the LLH during spring. This method is described as follows:

In general, SAT can be divided into two parts:

\[ T(t + dt_a) = \lambda_T S(t) + N(t + dt_a) \]  \hspace{1cm} (1)

where \( T(t) \) and \( S(t) \) are SAT and SM at time \( t \), respectively. \( dt_a \) is the atmospheric response time, which is typically less than 1 week. \( N(t + dt_a) \) represents the internal variability of atmosphere (or white noise), and \( \lambda_T S(t) \) is regarded as the SM-induced feedback on SAT. Thus, the parameter \( \lambda_T \) can be used to quantitatively evaluate SM-SAT coupling and will be referred to as the SM feedback parameter.

To eliminate the white noise term, we first multiply both sides of Equation (1) by \( S(t - \tau) \). Taking the covariance, the result is as follows:

\[ \text{Cov}(T(t + dt_a), S(t - \tau)) = \lambda_T \text{Cov}(S(t), S(t - \tau)) + \text{Cov}(N(t + dt_a), S(t - \tau)) \]  \hspace{1cm} (2)

where \( \tau \) is the time that SM leads the SAT (\( \tau = 1 \) month in this research). Since \( \tau \) (1 month) is much longer than the atmospheric response time \( dt_a \) (1 week), and we assume that antecedent SM does not affect later atmospheric internal variability. Consequently, \( dt_a \) and the covariance between \( N(t + dt_a) \) and \( S(t - \tau) \) are both approximated to be 0.

Finally, the SM feedback parameter \( \lambda_T \) can be expressed as follows:

\[ \lambda_T = \frac{\text{Cov}(S(t - \tau), T(t))}{\text{Cov}(S(t - \tau), S(t))} \]  \hspace{1cm} (3)

where \( \text{Cov}(S(t - \tau), T(t)) \) is the lagged covariance between SM in the previous month and SAT in the present month and \( \text{Cov}(S(t - \tau), S(t)) \) is the auto-covariance of the SM. Physically, \( \lambda_T \) measures the instantaneous feedback of SM on SAT at time \( t \).

This variance method was initially proposed by Frankignoul and Hasselmann (1977) to quantitatively assess the impacts of the ocean on the atmosphere, recently it has been widely applied in the studies of SM-atmosphere interactions (e.g., Notaro, 2008; Zhang et al., 2008; Orlowsky and Seneviratne, 2010; Sun and Wang, 2012; Spennemann and Saulo, 2015; Xu et al., 2019). More details about this variance method can be obtained from Liu et al. (2006). A Monte Carlo bootstrap technique is utilized to assess the statistical significance of \( \lambda_T \). At each grid cell, firstly \( \lambda_T \) is repeatedly computed 10,000 times using the original SM time series and SAT time series derived from a random permutation of the original SAT time series. The bootstrapped 95% confidence interval is then determined at the lower and upper bounds of 0.025 and 0.975 quantiles. Furthermore, \( \sigma^2(\lambda_T S)/\sigma^2(T) \) is used to quantify the variance percentage of monthly anomalies of SAT that are attributed to SM feedbacks, where \( \sigma^2(\lambda_T S) \) and \( \sigma^2(T) \) represent the variance of monthly SAT anomalies owing to SM feedbacks and the total variance of monthly SAT anomalies, respectively.

When \( \lambda_T \) is calculated using SM and SAT data derived from ERA-Interim, firstly the average SM between 0 and 1 m is summed up and weighted by the thickness of each
layer. Then, the annual cycle and long-term trends are removed. Finally, the SM anomalies are further standarized by the standard deviation in order to cross-validate the quantitative SM-SAT coupling between the two different SM datasets (ERA-Interim and GLDAS-Noah).

For GLDAS-Noah, λ3 is calculated using SAT data provided by the CRU. First, the 0.5° × 0.5° CRU SAT data are bilinearly interpolated to the same spatial resolution as that of the GLDAS-Noah SM data (0.25° × 0.25°). Given the terrain complexity in the LLH, topographic correction is then applied to the interpolated SAT data by a lapse rate assumed to be −6.5°C·km−1 (Zhao et al., 2008). Second, to ensure consistency with ERA-Interim, the GLDAS-Noah SM is rescaled into volumetric SM (units: m³ m⁻³). The rest of procedure is identical to the procedure described for ERA-Interim.

Additionally, commonly used methods such as (partial) correlation and regression analyses are also employed. The linear trend of each variable is removed before regression and correlation analyses. The significance of the 95% confidence level (α = 0.05 level) of the results is evaluated with the two-tailed Student’s t test.

The study period is from 1979 to 2016. Monthly regional averaged precipitation of the LLH in spring is shown in Figure 1. Evidently, the LLH experiences a rapid precipitation increase in May, which demonstrates a dry-to-wet climate regime transition from March and April to May and suggests a potentially substantial impact of Asian summer monsoon system on the SM-SAT coupling in May. Zhang et al. (2014a, 2014b) stated that the LLH is distinguished by dry (October–April) and wet (May–September) seasons, and approximately 70% to 80% of the annual total rainfall in the LLH is from the wet season. Zhou et al. (2019) pointed out that summer SAT over central India is strongly modulated by the onset of Indian summer monsoon, even though strong summer SM-SAT coupling occurs in the area. Thus, to mitigate the potentially substantial influence of Asian summer monsoon on the SM-SAT coupling in the LLH, our study focuses on the SM-SAT coupling in the LLH during early spring (mean of March and April) before wet season.

3 | RESULTS

3.1 | Estimation of SM feedbacks

The spring mean SM feedback parameters on SAT are presented in Figure 2a,b for ERA-Interim and GLDAS-Noah, respectively. The spatial patterns and magnitudes of the SM feedback parameters in the two data sets are generally consistent. Significant negative feedbacks mostly exist in the western and middle part of the LLH, with a magnitude of approximately −0.2°C·(standardized SM)⁻¹ to −0.8°C·(standardized SM)⁻¹. Weak and/or positive feedbacks appear over some regions in the eastern part of the LLH, but generally cannot achieve the 95% confidence level compared to those for the negative feedbacks. To further quantify SM-SAT coupling, we select a typical region in the western and middle part of the LLH with significant SM-SAT coupling (23–25°N, 97–101°E). In this typical region, the area-averaged SM feedback parameters are −0.50°C·(standardized SM)⁻¹ and −0.24°C·(standardized SM)⁻¹ for ERA-Interim and GLDAS-Noah, respectively. Some differences also exist in terms of the spatial distribution of the SM feedback parameters as well as its magnitudes between ERA-Interim and GLDAS-Noah, which might have resulted from the different physical processes in land surface models and forcing data for the two SM data sets. For example, for ERA-Interim, significant negative and positive feedbacks exhibit in the conjunction of Yuanan, Guizhou, Guangxi and northeastern part of the LLH, with a magnitude of −0.3°C·(standardized SM)⁻¹ to −0.6°C·(standardized SM)⁻¹ and 0.2°C·(standardized SM)⁻¹ to 0.4°C·(standardized SM)⁻¹, respectively. In contrast, weak feedbacks exhibit therein for GLDAS-Noah.

Figure 3a,b demonstrates the spring mean percentage of the SAT variances owing to the SM feedbacks for ERA-Interim and GLDAS-Noah, respectively. Generally, 10–50% of the total SAT variances could be explained by the SM-induced negative feedbacks in the western and middle part of the LLH, where significant SM feedbacks
occur (Figure 2a,b). Moreover, in the typical region, the area-averaged contributions of SM to the SAT variation are 32% and 18% for ERA-Interim and GLDAS-Noah, respectively. In comparison, this percentage is mostly less than 5% in the eastern part of the LLH.

3.2 Possible mechanisms

SM does not influence SAT directly. The ability of SM to affect SAT is further split into two contributions, namely the ability that SM affects the latent heat flux (evapotranspiration) and the ability that the latent heat flux (evapotranspiration) affects SAT (Seneviratne et al., 2010; Schwingshackl et al., 2017). Therefore, for the possible mechanisms, we mainly investigate the impact of SM on land surface energy balance. Correlation coefficients between SM and Bowen ratio, Bowen ratio and SAT, SM and total cloud cover, SM and net surface radiation flux over the LLH in spring are presented in Figure 4a,b,c,d, respectively, for ERA-Interim. The Bowen ratio is defined by the ratio of sensible heat flux to latent heat flux and is often considered to be a reflection of upward thermal transfer on the land surface (Xu et al., 2019). Generally, the larger its value, the more (less) net surface radiation is allocated into sensible (latent) heat flux, which favours the increase in SAT. SM has significant negative correlation with Bowen ratio over most of the LLH (Figure 4a),
that is, higher SM may result in stronger (weaker) evapotranspiration (upward thermal transfer), indicating that evapotranspiration (upward thermal transfer) is greatly constrained by SM over the LLH in spring. However, the negative correlation between SM and Bowen ratio is only a necessary but not a sufficient condition of strong SM-SAT coupling (Seneviratne et al., 2010; Schwingshackl et al., 2017; Gao et al., 2019). Therefore, the correlation between SAT and Bowen ratio is further shown in Figure 4b. It is noticeable that SAT is significantly positive correlated with Bowen ratio only in the western and middle part of the LLH (i.e., enhanced upward thermal transfer leads to increased SAT), where significant negative SM feedbacks are also present (Figure 2a). These suggest that local upward thermal transfer on the land surface might have a direct and significant impact on the SAT therein. In comparison, although SM is negatively correlated with Bowen ratio in the eastern part of the LLH, SAT has a weak and/or negative correlation with Bowen ratio. This indicates that atmospheric dynamics may play a relatively more important role on SAT in the eastern part of the LLH compared with that of local upward thermal transfer on the land surface (i.e., weak SM-SAT coupling). Additionally, the relationships between SM and total cloud cover as well as net surface radiation flux are also investigated. It is shown that by enhanced evapotranspiration, the wet condition of soil moisture may result in an increased total cloud cover in
FIGURE 4  Correlation coefficients between spring (a) SM and Bowen ratio, (b) Bowen ratio and SAT, (c) SM and total cloud cover, and (d) SM and net surface radiation flux for the period of 1979–2016 derived from ERA-interim. The black lines indicate grid cells with values significant at the 95% confidence level. (e), (f), (g), and (h) are the same as (a), (b), (c), and (d), but derived from GLDAS-Noah. All data are linearly detrended.
the western and middle part of the LLH (Figure 4c), which may lead to a decrease in net surface radiation flux (Figure 4d) and may further cool the land surface and reduce the SAT. Similar results are also obtained in the western and middle part of the LLH from GLDAS-Noah (Figure 4e–h), but there are little discrepancies in the eastern part of the LLH.

To further quantitatively assess the effects of SM on land surface energy balance, the spring mean feedback parameters of SM on net surface radiation flux

![Figure 5](image)

**FIGURE 5** Spring mean SM feedback parameters [units: W m$^{-2}$ (standardized SM)$^{-1}$] on net surface radiation flux for the period of 1979–2016 for (a) ERA-interim and (b) GLDAS-Noah. The black lines indicate grid cells with values that achieve the 95% significance level. The black box indicates the significant SM-SAT coupling region used to quantify the SM feedbacks. (c) and (d) are the same as (a) and (b), but for the SM feedback parameters on sensible heat flux. (e) and (f) are the same as (a) and (b), but for the SM feedback parameters on latent heat flux.
(Figure 5a,b), sensible heat flux (Figure 5c,d) and latent heat flux (Figure 5e,f) are obtained following a similar procedure to that for the feedback parameters of SM on SAT for ERA-Interim and GLDAS-Noah. The SM feedbacks on the net surface radiation flux and sensible heat flux are mainly negative, whereas the SM feedbacks on latent heat flux are mainly positive. In addition, the area with significance at a 95% confidence level is slightly different between the SM feedbacks and SM correlations (e.g., the SM feedback parameters on net surface radiation flux and the correlation coefficients between SM and net surface radiation flux). This might have been caused by the sampling error of Monte Carlo bootstrap technique which is adopted to assess the statistical significance of SM feedbacks. In the typical region, the area-averaged SM feedback parameters on net surface radiation flux are $-4.8$ W m$^{-2}$ (standardized SM)$^{-1}$ and $-4.0$ W m$^{-2}$ (standardized SM)$^{-1}$ for ERA-Interim and GLDAS-Noah, respectively. The area-averaged SM feedback parameters on sensible heat flux are $-3.9$ W m$^{-2}$ (standardized SM)$^{-1}$ and $-6.0$ W m$^{-2}$ (standardized SM)$^{-1}$ for ERA-Interim and GLDAS-Noah, respectively. The area-averaged SM feedback parameters on latent heat flux are $5.7$ W m$^{-2}$ (standardized SM)$^{-1}$ and $6.6$ W m$^{-2}$ (standardized SM)$^{-1}$ for ERA-Interim and GLDAS-Noah, respectively. These suggest that from the perspective of land surface energy balance, SM may exert a more significant effect on latent heat flux than on sensible heat flux and net surface radiation flux in the western and middle part of the LLH.

### 3.3 Potential impact of India–Burma Trough on the SM-SAT coupling

As mentioned in Section 1 (Introduction), remote SST forcing and large-scale atmospheric circulations greatly impact the climatic characteristics of the LLH in spring. This implies that spring LLH SM-SAT coupling may be potentially regulated by remote SST forcing and large-scale atmospheric circulations in some extent. Furthermore, Orlowsky and Seneviratne (2010) as well as Sun and Wang (2012) demonstrated that SM-precipitation coupling strength is strongly affected by remote SST forcing; Ford et al. (2017) also pointed out that SM-SAT coupling in the United States is greatly related to the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation. These results suggest that the assessment of spring LLH SM-SAT coupling in this study should be evaluated carefully. Otherwise, the accuracy and reliability of the quantitative SM-SAT coupling evaluation will also be influenced by the essential impacts of remote SST forcing and large-scale atmospheric circulations on SM and SAT over the LLH in spring.

To investigate the potential impact of large-scale atmospheric circulations on spring LLH SM-SAT coupling, firstly the LLH SAT index (SATI) is defined as the area-averaged SAT anomalies over the LLH during spring (Figure 6a). The regressed wind anomalies at 700 hPa height against SATI are then analysed (Figure 6b). Noticeable anticyclonic (cyclonic) wind anomalies are observed over Bay of Bengal (BOB), which are associated with the higher (lower) SAT in the LLH.

In the Asian subtropics, the tropospheric prevailing westerlies are dynamically blocked by the Tibetan Plateau (TP) during the boreal winter half year (October to May), and the circulation patterns are further split into two branches. One is an anticyclonically curved flow to

**Figure 6** (a) Time series of the LLH SAT index (SATI, units: $^\circ$C) for the period of 1979–2016. (b) Regression patterns of spring wind anomalies (units: m s$^{-1}$) at 700 hPa onto the SATI for the period of 1979–2016. The black box indicates the LLH. The grey shading areas are statistically significant at the 95% confidence level. All data are linearly detrended before regression.
the north side of the TP, and the other is a cyclonically curved flow to the south side of the TP. The southern branch forms a large-scale trough over the BOB, which is often noted as the India–Burma Trough (IBT).

The IBT is a semi-permanent trough anchored over the BOB. It is an important factor that has substantial effects on weather and climate over East Asia during the boreal winter half year. For example, Gao and Yang (2009) stated that the shallower and less active IBT was closely related to the severe drought event of northern China in the winter 2008–2009. Wang et al. (2011) demonstrated that the relationships between the IBT and SAT as well as precipitation over southern and eastern Asia in winter were enhanced after 1978. For the LLH, the southwesterly wind in front of the IBT transports water vapour from the BOB to the LLH, and the water vapour transportation of the IBT is the primary moisture source for the LLH during the boreal winter half year, hence the IBT is considered as one of the major factors that has significant effects on weather and climate in the LLH (Qin et al., 1991; Duan et al., 2012; Li and Zhou, 2016; Liu et al., 2018). Figure 6b suggests that higher (lower) spring SAT in the LLH is corresponding to a weakened (intensified) IBT, which may be caused by the surface cooling (warming) effect of increased (decreased) precipitation in the LLH. Additionally, correlation coefficient between SATI and spring precipitation in East Asia is displayed in Figure 7. A significant negative relationship between SATI and precipitation dominates the LLH, while a significant positive relationship exists over the middle and lower reaches of the Yangtze River valley, which is similar to the result of Liu et al. (2018). Correlation coefficient between SATI and the IBT index (standardized area-mean vertical velocity defined by Liu et al. (2018)) is −0.38 (exceeding the 95% confidence level based on the Student’s t test), thereby indicating that the IBT may have a potential impact on SAT and precipitation in the LLH. Therefore, SM-SAT coupling might be potentially modulated by the IBT.

Spring mean SM feedback parameters on SAT are recalculated (Figure 2c,d) after statistically removing the IBT-related parts in SM as well as in SAT by linear regression upon the IBT index defined by Liu et al. (2018) during spring for ERA-Interim and GLDAS-Noah, respectively. As portrayed in Figure 2, there are no significant differences in the sign and/or the pattern of the SM-SAT coupling strength before and after removing the effects of the IBT. Significant negative feedbacks mostly exist in the western and middle part of the LLH, whereas weak and/or positive feedbacks are present in the eastern part of the LLH. In the typical region, the area-averaged SM feedback parameters are −0.48°C/(standardized SM)−1 and −0.27°C/(standardized SM)−1 for ERA-Interim and GLDAS-Noah, respectively. The modified spring mean percentage of the SAT variances owing to the SM feedbacks (Figure 3c,d) also demonstrate similar results compared to those calculated using the original SM and SAT data (Figure 3a,b). In the typical region, the area-averaged contributions of SM to the SAT variation are 40% and 27% for ERA-Interim and GLDAS-Noah, respectively. In addition, the partial correlation coefficients between SM and Bowen ratio, Bowen ratio and SAT, SM and total cloud cover, and SM and net surface radiation flux over the LLH in spring are also very similar before and after removing the effects of the IBT (Figure 8), as are the feedback parameters of SM on net surface radiation flux, sensible heat flux and latent heat flux (Figure 9). All of these results suggest that SM-SAT coupling and the effects of SM on land surface energy balance may be immune to the influence of the IBT.

Accordingly, a natural question is what the quantitative effects of SM and the IBT on SAT are in the LLH during spring. To answer this question, the regression coefficients of spring LLH SAT on the IBT index and spring mean SM feedback parameters on SAT with only the removal of IBT-related part from SM by linear regression upon the IBT index are calculated (Figure 10). The spring mean percentage of the variances of SAT owing to the SM feedbacks and variation of IBT are also calculated (Figure 11). As shown in Figure 10a,b, the spatial patterns and magnitudes of the SM feedback parameters are generally consistent compared with those calculated using the original SM and SAT data. The IBT also has significant cooling effects on SAT in the western and middle part of the LLH, but with a relatively larger area

**FIGURE 7** Correlation coefficient between spring precipitation and the SATI for the period of 1979–2016. The black lines indicate grid cells with values significant at the 95% confidence level. The black box indicates the LLH. All data are linearly detrended.
FIGURE 8  Partial correlation coefficients between spring (a) SM and Bowen ratio, (b) Bowen ratio and SAT, (c) SM and total cloud cover, and (d) SM and net surface radiation flux for the period of 1979–2016 derived from ERA-interim after excluding the effects of the IBT index. The black lines indicate grid cells with values significant at the 95% confidence level. (e), (f), (g), and (h) are the same as (a), (b), (c), and (d), but derived from GLDAS-Noah. All data are linearly detrended.
compared to that of SM feedback parameters (Figure 10c), as well as the percentage of variances of SAT explained by variation of IBT (Figure 11). In the typical region, the area-averaged SM feedback parameters are \(-0.42\,\text{C/(standardized SM)}\) and \(-0.22\,\text{C/(standardized SM)}\) for ERA-Interim and GLDAS-Noah, respectively. The area-averaged regression coefficient of spring LLH SAT on the IBT index is \(-0.51\,\text{C/(standardized IBT)}\).
The area-averaged contributions of SM to the SAT variation are 26% and 22% for ERA-Interim and GLDAS-Noah, respectively. The area-averaged contribution of IBT to the variation in SAT is 26%. These results suggest that the local SM may have a comparable effect on SAT to that of the IBT in the western and middle part of the LLH.

### 4 CONCLUSIONS AND DISCUSSIONS

Recent studies demonstrated that the LLH is a relatively strong SM-SAT coupling region in China during spring, this study further quantitatively explored the SM-SAT coupling over the LLH during spring (mean of March and April before wet season) using reanalysis data set, land surface assimilation product and observational temperature. The results show that significant negative SM-SAT feedbacks mainly occur in the western and middle part of the LLH, with a magnitude of $-0.2^\circ\text{C}(\text{standardized SM})^{-1}$ to $-0.8^\circ\text{C}(\text{standardized SM})^{-1}$, and 10–50% of the total SAT variance could be explained by the SM-induced negative feedbacks therein. By contrast, weak feedbacks appear over some regions in the eastern part of the LLH, and the variances of SAT owing to the SM feedbacks is mostly less than 5% in that area.

The possible physical mechanisms are also investigated from the perspective of land surface energy balance. In the western and middle part of the LLH, upward thermal transfer on the land surface is greatly constrained by SM. Meanwhile, SAT has a significantly positive correlation with upward thermal transfer. Therefore, significant negative SM-SAT feedbacks occur therein. In comparison, although upward thermal transfer is negatively impacted by SM over some regions
in the eastern part of the LLH, SAT has a negative and/or weak correlation with upward thermal transfer in that area, which implies that atmospheric dynamics rather than local upward thermal transfer may play a more important role in SAT in the eastern part of the LLH. Therefore, weak SM-SAT feedbacks occur in that area. Moreover, the wet condition of soil moisture may lead to increased total cloud cover in the western and middle part of the LLH, which may result in a decrease in the net surface radiation flux and further cool the land surface and reduce the SAT therein. Quantitatively, SM may exert a more significant effect on latent heat flux than on sensible heat flux and net surface radiation flux in the western and middle part of the LLH.

Many studies have revealed that large-scale atmospheric circulations greatly impact the climatic characteristics of the LLH in spring, hence the potential impact of IBT, which is the primary moisture source for the LLH during spring, on the SM-SAT coupling is also investigated. The results of this study suggest that SM-SAT coupling and the effects of SM on land surface energy balance may be immune to the influence of IBT. Furthermore, local SM may have a comparable effect on SAT to that of the IBT in the western and middle part of the LLH. Therefore, local SM might also have prominent effects on subseasonal predictability of spring SAT therein.

However, there are still some drawbacks in this study. Firstly, owing to the lack of observed SM data in the LLH, the results are based on reanalysis SM data set and land surface assimilation SM product. Thus, the uncertainties of ERA-Interim SM and GLDAS-Noah SM must be noted, especially in this complex terrain area, and the results need to be further examined when more reliable observed SM data are available. Secondly, the feedback parameter method applied in this research has some limitations that may lead to misestimation of the real SM-
induced feedbacks to some extent (e.g., ignoring the nonlinear feedbacks between SM and SAT). Statistically removing the IBT-related parts in SM as well as in SAT by linear regression upon the IBT index also ignores the nonlinear IBT impacts. Furthermore, besides the IBT, remote SST forcing and other large-scale atmospheric circulations (e.g., tropical and North Atlantic SST forcing and Arctic Oscillation) may also potentially modulate the SM-SAT coupling, which are not considered in this study. Therefore, the current results need to be verified by model simulations in the future.

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