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• **Original Paper** •

Time-lagged Effects of the Spring Atmospheric Heat Source over the Tibetan Plateau on Summer Precipitation in Northeast China during 1961–2020: Role of Soil Moisture※

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ABSTRACT

The spring atmospheric heat source (AHS) over the Tibetan Plateau (TP) has been suggested to affect the Asian summer monsoon and summer precipitation over South China. However, its influence on the summer precipitation in Northeast China (NEC) remains unknown. The connection between spring TP AHS and subsequent summer precipitation over NEC from 1961 to 2020 is analyzed in this study. Results illustrate that stronger spring TP AHS can enhance subsequent summer NEC precipitation, and higher soil moisture in the Yellow River Valley–North China region (YRVNC) acts as a bridge. During spring, the strong TP AHS could strengthen the transportation of water vapor to East China and lead to excessive rainfall in the YRVNC. Thus, soil moisture increases, which regulates local thermal conditions by decreasing local surface skin temperature and sensible heat. Owing to the memory of soil moisture, the lower spring sensible heat over the YRVNC can last until mid-summer, decrease the land–sea thermal contrast, and weaken the southerly winds over the East Asia–western Pacific region and convective activities over the South China Sea and tropical western Pacific. This modulates the East Asia–Pacific teleconnection pattern, which leads to a cyclonic anomaly and excessive summer precipitation over NEC.

Key words: Tibetan Plateau, atmospheric heat source, Northeast China, summer precipitation, soil moisture

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Article Highlights:

- The spring atmospheric heat source of the Tibetan Plateau has a lagged effect on summer precipitation over Northeast China (NEC).
- Spring soil moisture in the Yellow River Valley–North China (YRVNC) region acts as a bridge.
- The memory of spring soil moisture in the YRVNC prolongs the surface thermal state into mid-summer, and affects summer NEC precipitation.

1. Introduction

The spring thermal forcing of the Tibetan Plateau (TP) can not only significantly affect the Asian summer monsoon system, but also influence the summer atmospheric circula-

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tion in East Asia (Zhao and Chen, 2001; Xu et al., 2013; Wu et al., 2015). Some studies have investigated the impact of the spring thermal effect of the TP on East Asian summer precipitation (Duan et al., 2013; Xu et al., 2013; Ge et al., 2019). For instance, the spring atmospheric heat source (AHS) over the TP can influence summer precipitation over East China through local convection (Zhao et al., 2016), water vapor transportation (Xu et al., 2013), low-frequency oscillations of atmospheric circulation systems (Liu et al., 2007), the western North Pacific subtropical high (Zhang et al., 2018), and the South Asian high (Ge et al., 2019). Besides, the impacts of the spring TP AHS on East China summer precipitation are found on both interannual (Zhao and Chen, 2001) and interdecadal (Si and Ding, 2013) time scales. However, in contrast to existing studies that have focused on the impact of the spring TP AHS on the following precipitation in downstream areas (Southeast China and the Yangtze River Valley), its influence on summer Northeast China (NEC) precipitation has received little attention.

NEC is an important grain production area in China. Weather and climate disasters that arise from summer precipitation affect local grain production (Shen et al., 2011; Han et al., 2015). Due to the importance of summer NEC precipitation, many studies have investigated its potential mechanisms. The summer NEC precipitation has been found to be influenced by atmospheric circulation anomalies, such as the East Asian summer monsoon (EASM) (Sun et al., 2017), the Northeast Cold Vortex (He et al., 2007), blockings in the northern high latitudes (He et al., 2013), and the western North Pacific subtropical high (Shen et al., 2011). The soil moisture over East China (Zuo and Zhang, 2016) and the sea surface temperature anomaly (SSTA) in the Kuroshio region (Fang et al., 2018) also play a significant role. Besides, some studies have analyzed the influences of the TP's surface elements on summer NEC precipitation, such as snow cover (Wang et al., 2017), soil moisture (Yang and Wang, 2019), and surface temperature (Zhuo et al., 2016), while the response of summer NEC precipitation to the spring TP AHS remains unknown. Since the surface elements over the TP could affect the local AHS through land–atmosphere interaction, and then regulate the surrounding atmospheric circulation and weather and climate (Liu et al., 2020), the spring TP AHS is likely to affect summer NEC precipitation. Earlier studies emphasized the importance of the spring TP AHS to the EASM, which is also one of the main factors affecting summer NEC precipitation (Sun et al., 2007). For these reasons, it is essential to examine the potential effects of the spring TP AHS on summer NEC precipitation.

Compared with the interannual variation of summer NEC precipitation (Han et al., 2017), few studies have examined its interdecadal variation (Han et al., 2020). Since the 1980s, both the spring TP AHS and summer NEC precipitation have shown relatively consistent interdecadal variation characteristics, with downward trends during 1980– 2000 and upward trends after 2000 (Xu et al., 2013, 2015). These findings raise the question of whether summer NEC precipitation is physically linked to the spring TP AHS on the interdecadal scale. Accordingly, in the present study, we investigate the influence of the spring TP AHS on summer NEC precipitation on the interdecadal time scale and the associated physical mechanism.

The remainder of the paper is organized as follows. The data and methods employed in our study are introduced in section 2. The relationship and potential physical mechanisms between the spring TP AHS and summer NEC precipitation on the interdecadal time scale are examined in section 3. A summary of our findings is provided in section 4.

2. Data and methods

We use the monthly mean ERA5 reanalysis dataset, with a horizontal resolution of 1.0° × 1.0°, for the period 1961–2020 (Hersbach et al., 2019). The variables include surface skin temperature, 2-m air temperature, sea surface temperature, surface sensible heat flux, soil moisture, precipitation, vertically integrated moisture flux, and 500-hPa geopotential height. Only the surface-layer (0–7 cm) soil moisture data are used because it is more sensitive to external forcing (Dirmeyer, 2011). The spring Normalized Difference Vegetation Index (NDVI) data derived from the AVHRR sensor onboard NOAA's polar-orbiting satellite series from 1982 to 2020, with a horizontal resolution of 0.5° × 0.5°, are used to represent the vegetation condition (Vermote, 2019). The China Gridded Monthly Precipitation Dataset, with a horizontal resolution of 1.0° × 1.0° (CN05.1), which is interpolated from 2416 meteorological stations, is applied as the observational data (Wu and Gao, 2013). In addition, air temperature, vertical velocity, and the zonal and meridional wind of ERA5 pressure level data (horizontal resolution: 1.0° × 1.0°) are used to calculate the spring AHS according to the following equations (Luo and Yanai, 1984):

$$Q_1 = C_\mathrm{p}\left[\frac{\partial T}{\partial t} + \mathbf{V}\cdot\nabla T + \left(\frac{P}{P_\mathrm{s}}\right)^K \omega\frac{\partial \theta}{\partial p}\right], \quad (1)$$

$$\langle Q_1\rangle = \frac{1}{g}\int_{100}^{P_\mathrm{s}} Q_1 \mathrm{d}p, \quad (2)$$

where Q_1 is the AHS; T and θ are the air temperature and potential temperature, respectively; $\mathbf{V}$ and ω are the horizontal wind velocity and vertical velocity, respectively; P and P_s are the pressure and surface pressure, respectively; C_p is the specific heat at a constant pressure of dry air; g is the gravitational acceleration; and $K \approx 0.286$.

Simulation data from sensitivity modeling experiments of sensible heat over the TP by the Community Earth System Model (CESM1.2.0) (1979–2014) are used. The data include two groups of sensitivity runs: the TP spring sensible heating is set to be 150% of the normal value in the first run (referred to as strong heating), while the second is set to be 50% (referred to as weak heating) (Sun et al., 2019; Duan, 2022). Detailed information on those experiments is introduced by Duan (2022). Since the spring TP AHS is mainly dominated by local sensible heat (Wu et al., 2017), those sensible heating experimental data are taken to analyze the physical mechanism of the spring TP AHS affecting summer NEC precipitation.

The Niño-3.4 index (SSTA averaged within 5°N–5°S and 120°–170°W) is employed to denote El Niño–Southern Oscillation (ENSO) events. A 9-year running mean is applied to obtain the interdecadal signal. In addition, linear regression, Pearson correlation, composite analysis, and singular value decomposition (SVD) (Prohaska, 1976) are applied to investigate how the spring TP AHS affects summer NEC precipitation. SVD is a matrix decomposition, which can obtain the spatial mode and temporal variation information of the correlation field between the paired variable fields (Prohaska, 1976). Before applying SVD, it is necessary to conduct covariance analysis on the variable fields (**X** and **Y**) to obtain the covariance matrix **C**. Based on the SVD principle, the matrix **C** can be expressed as the following formula:

$$\mathbf{C} = \frac{1}{n}\mathbf{X}\mathbf{Y}^{\mathrm{T}} = \mathbf{U}\cdot\mathbf{\Lambda}\cdot\mathbf{V}^{\mathrm{T}}, \quad (3)$$

where n is the number of time points, $\mathbf{Y}^{\mathrm{T}}$ is the transpose of matrix **Y**, the vectors in **U** and **V** are singular vectors of **C**, $\mathbf{\Lambda}$ is a diagonal matrix whose diagonal elements are singular values, and $\mathbf{V}^{\mathrm{T}}$ is the transpose of matrix **V**. According to the singular value, the variance contribution rates of the spatial modes can be calculated, and the time series of the corresponding spatial modes and their correlations could be obtained. The larger the correlation coefficient of the time series of two variables, the more consistent the corresponding spatial mode changes (Wang et al., 1997). This study uses the first SVD mode (SVD1) to investigate the relationship between the spring TP AHS and summer NEC precipitation.

In addition, partial correlation analysis is used to calculate the correlation between two variables (A and B) and exclude the impact of the third independent variable (C) (Behera and Yamagata, 2003). The detailed formula is as follows:

$$r_{\mathrm{AB\cdot C}} = \frac{(r_{\mathrm{AB}} - r_{\mathrm{AC}}r_{\mathrm{BC}})}{\sqrt{1-r_{\mathrm{AC}}^2}\sqrt{1-r_{\mathrm{BC}}^2}}, \quad (4)$$

where r_{AB}, r_{AC} and r_{BC} are the correlations between A and B, A and C, and B and C, respectively. This method is commonly used in meteorological analysis (Yuan and Yang, 2012; Chen et al., 2014; Liu et al., 2017; Gao et al., 2019). The data are normalized using *Z*-score normalization. For a variable X, its normalized value X' is calculated as follows:

$$X' = (X - \bar{X})/\sigma_X, \quad (5)$$

where $\bar{X}$ and σ_X are the mean and standard deviation of X, respectively. We also use Student's t-test to quantify the significance of the correlation coefficient and regression coefficient, and the degree of freedom is determined by the sample size after the 9-year running mean.

3. Results

3.1. *Relationship between the spring TP AHS and summer NEC precipitation*

Figure 1 shows various characteristics of the spring TP AHS and summer NEC precipitation. The former varies in phase with the latter; both of them show a notable negative–positive–negative variation, with negative phases in 1965–1980 and 2001–2012 and a positive phase in 1981–2000 (Figs. 1a and b). Their correlation coefficients on the interannual and interdecadal time scales are 0.29 and 0.75, significant at the 0.95 and 0.99 confidence levels, respectively. The SVD method is used to capture the coupled mode between them. Figures 1c and d display their standardized time series of SVD1, accounting for 41.5% and 77.2% of the total squared covariance on interannual and interdecadal time scales, respectively. The correlation coefficients between the two SVD1 time series reach 0.57 on the interannual timescale and 0.88 on the interdecadal time scale, both significant at the 0.99 confidence level and demonstrating a close relationship between each other.

Overall, the spring TP AHS and summer NEC precipitation evolve consistently on the interdecadal scale. This phenomenon is found in both their correlation and SVD analyses, indicating that the spring TP AHS may have a lagged effect on summer NEC precipitation.

3.2. *Physical mechanism of the spring TP AHS affecting summer NEC precipitation*

3.2.1. *Effects of the TP AHS on atmospheric circulation and precipitation in spring*

To study the potential impacts of the spring TP AHS on subsequent summer NEC precipitation, we analyze the regression of the atmospheric circulation system to the TP AHS in spring (Figs. 2a and b). A substantial negative geopotential height anomaly exists in the TP–West China region, while a strong southwesterly wind is apparent in Southeast China. The low-level southwesterly winds extend to approximately 30°N and then turns northwestward, transporting moisture from the oceans to East China. Two water vapor convergence zones appear in Southeast China (22°–30°N, 110°–120°E) and the Hetao area (33°–38°N, 105°–114°E), leading to substantial spring precipitation over there. Those patterns can be captured by the reanalysis and observational datasets (Figs. 2c and d).

Since ENSO has a significant impact on East Asian spring precipitation (Huang and Wu, 1989), we apply partial correlation analysis to exclude the impact of spring ENSO events. The partial correlation between the TP AHS and precipitation in China in spring is shown in Fig. 3. After removing the impacts of spring ENSO, the correlation between the TP AHS and precipitation decreases significantly in Southeast

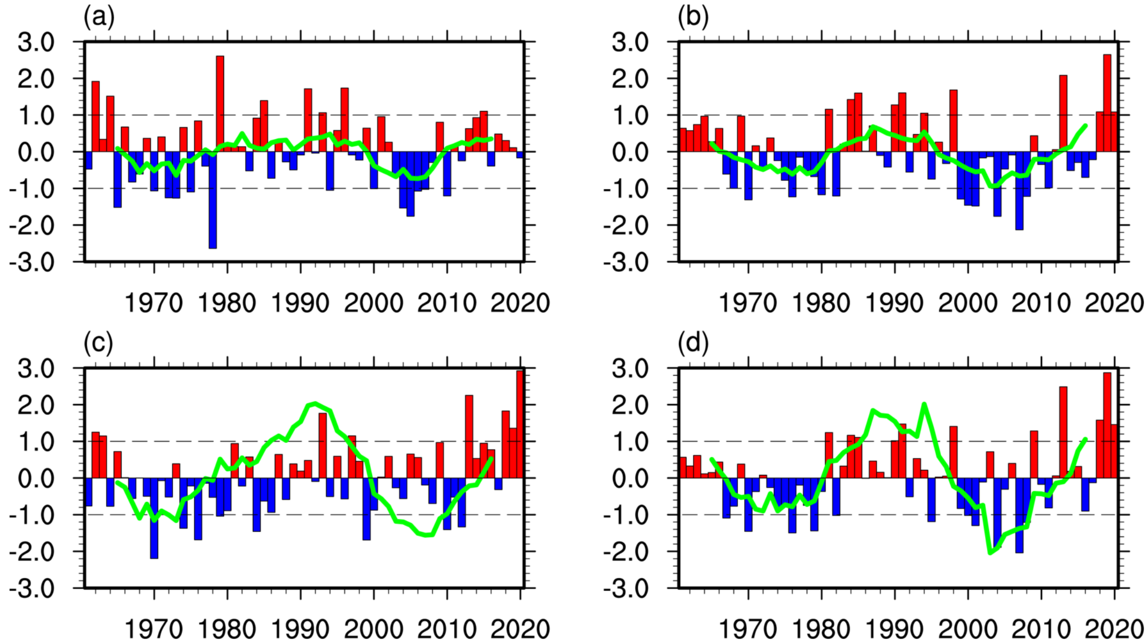

Fig. 1. (a) Normalized time series of the detrended spring AHS of the TP. (b) As in (a) but for summer precipitation in NEC. (c) Time series corresponding to the SVD1 of the spring TP AHS. (d) As in (c) but for summer NEC precipitation. All time series are for the period 1961–2020. The bar charts denote their annual variation and the green lines indicate their 9-year running mean.

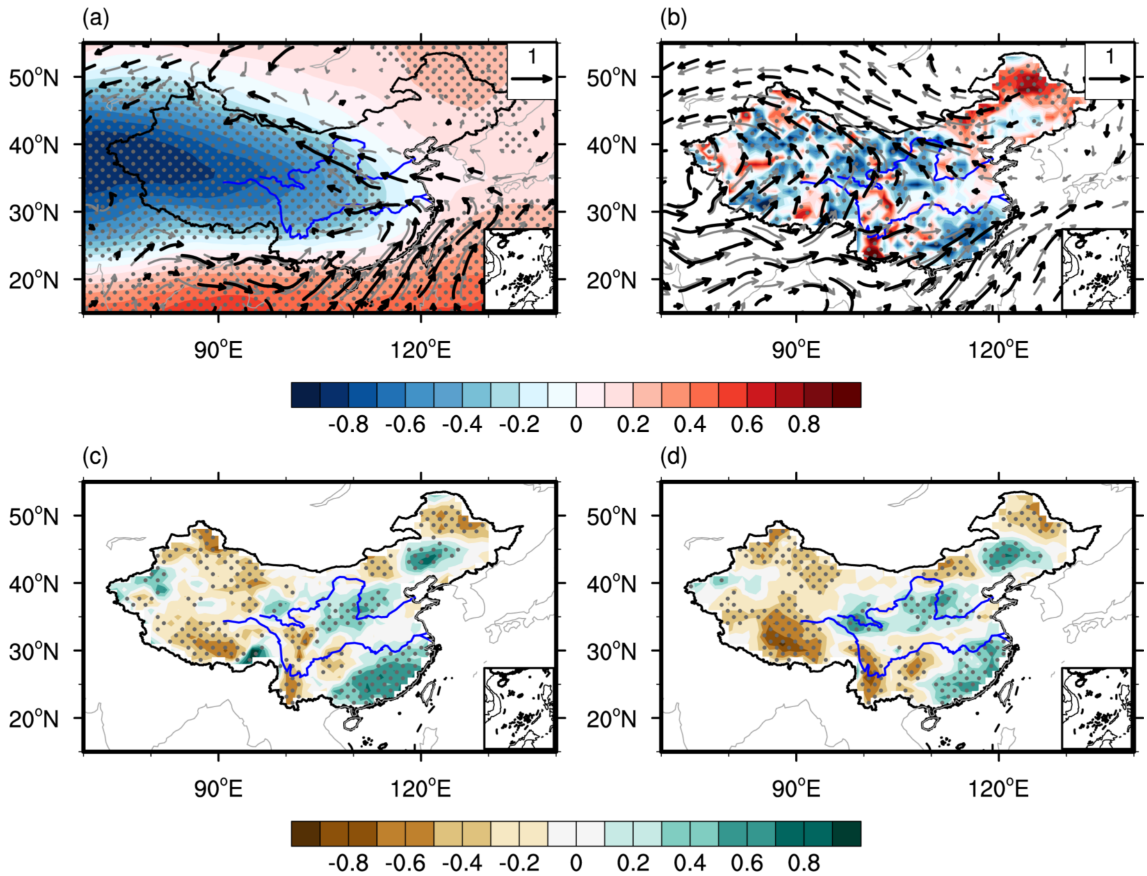

Fig. 2. Regression of the (a) normalized spring 850-hPa wind (vectors; units: m s^{-1}) and 500-hPa geopotential height (shading; units: gpm), (b) vertically integrated moisture flux (vectors; units: kg m^{-1} s^{-1}) and its divergence (shading; units: 10^5 kg m^{-2} s^{-1}) from the surface to 300 hPa, (c) ERA5 precipitation, and (d) CN05.1 precipitation, upon the 9-year running mean spring TP AHS during 1961–2020. The black vectors and grey dotted regions represent statistically significant results at the 0.90 and 0.95 confidence levels, respectively.

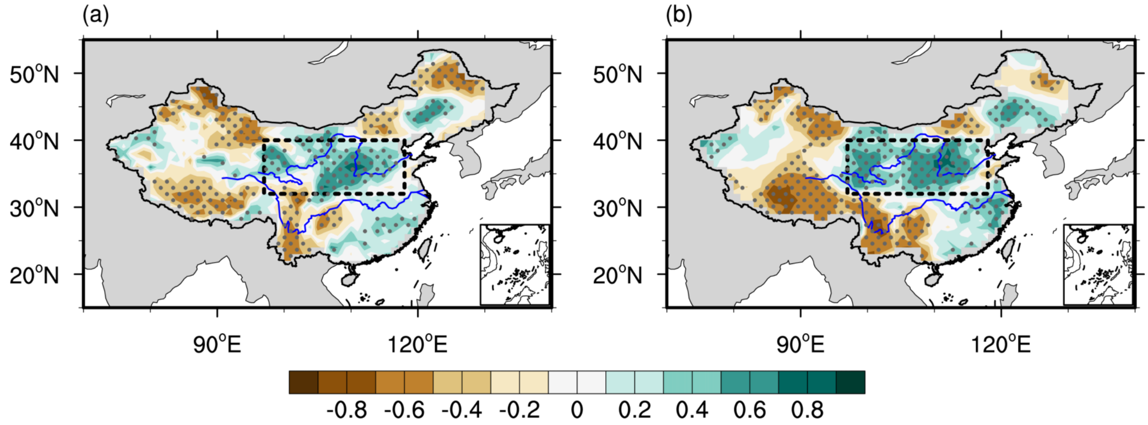

Fig. 3. The partial correlation between the 9-year running mean spring TP AHS and (a) ERA5 precipitation and (b) CN05.1 precipitation during 1961–2020. The black box (32°–40°N, 97°–118°E) represents the YRVNC region. The grey dotted regions represent statistically significant results at the 0.95 confidence level. The influence of ENSO events has been removed.

China but increases along the Yellow River valley. This indicates that spring precipitation in Southeast China is mainly influenced by ENSO events (Feng and Li, 2011), while the spring precipitation in the Yellow River Valley– North China (YRVNC) region is highly correlated with the spring TP AHS. Since the observational and reanalysis precipitation datasets show similar distribution patterns in East China, we employ the CN05.1 precipitation data for subsequent analysis because it is built on observational data (Wu and Gao, 2013).

3.2.2. *Local thermal effect of soil moisture over the YRVNC region*

Considering soil moisture exerts prominent prolonged effects on subsequent atmospheric circulation and precipitation due to its memory effect (Koster and Suarez, 2001; Zuo and Zhang, 2007; Gao et al., 2019), we introduce the YRVNC spring soil moisture as a bridge to examine how the spring TP AHS affects summer NEC precipitation. Figure 4a indicates the partial correlation between the TP AHS and soil moisture in China in spring, with the influence of ENSO events having been removed. They are strongly negatively correlated over West China but positively correlated over East China, especially in the YRVNC region. This pattern is similar to Fig. 3, illustrating that precipitation could determine the local soil moisture.

Figure 4b illustrates the change in the TP AHS and the YRVNC soil moisture and precipitation during spring and summer NEC precipitation. An in-phase relationship exists among them, with correlation coefficients of at least 0.80 and passing the 0.99 confidence level. Since both the spring TP AHS and summer NEC precipitation are significantly correlated with spring soil moisture in the YRVNC region, we focus on the role of local soil moisture in the process of the spring TP AHS affecting summer NEC precipitation.

In addition to the direct impact of precipitation on soil moisture in the YRVNC region, local vegetation changes may also affect soil moisture. Previous studies have shown

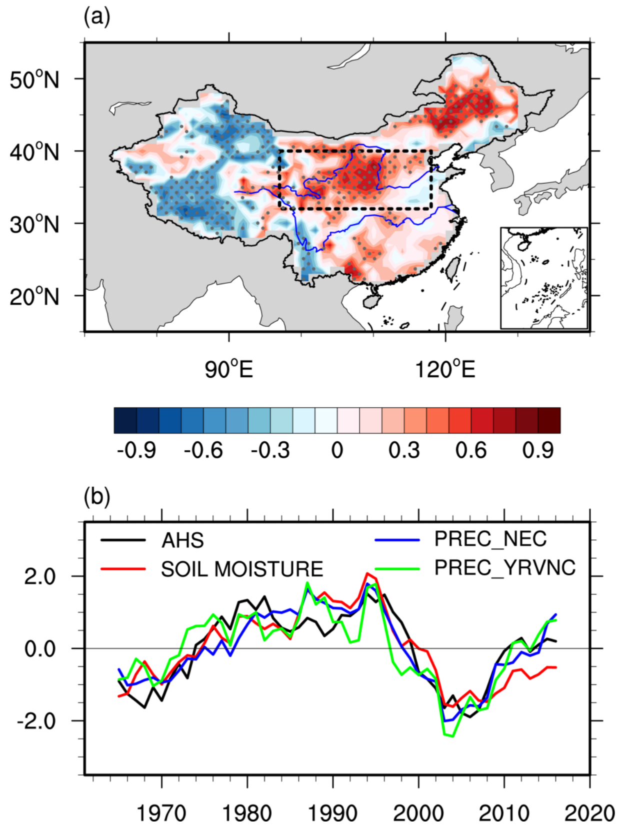

Fig. 4. (a) The partial correlation between the 9-year running mean spring TP AHS and soil moisture in China during 1961–2020, with the influence of ENSO events having been removed. The grey dotted regions represent statistically significant results at the 0.95 confidence level. (b) The normalized 9-year running mean TP AHS (black line), precipitation (green line), and soil moisture (red line) in the YRVNC region during spring and summer NEC precipitation (blue line) in the period 1961–2020, with the influence of ENSO events having been removed.

that vegetation is mainly influenced by precipitation and temperature (Zhao and Running, 2010). Meanwhile, vegetation coverage has been proven to be one of the dominant factors for soil moisture change (Feng, 2016). To examine whether vegetation coverage impacts soil moisture in the YRVNC, the relationships between the TP AHS, vegetation and soil moisture in the YRVNC region in spring are investigated (Fig. 5). During 1982–2020, the TP AHS is highly positively correlated with NDVI over East China, especially over the YRVNC region (Fig. 5a). However, the significance of this relationship greatly reduces with the effect of the YRVNC spring precipitation removed (Fig. 5b). This indicates that the TP AHS can affect the vegetation in North China through precipitation. Moreover, the spring TP AHS, precipitation, NDVI and soil moisture in the YRVNC region during 1982–2020 show similar variation characteristics, with correlation coefficients all being greater than 0.45 and passing the 0.99 confidence level. On the whole, the TP AHS can not only directly affect soil moisture through precipitation, but also indirectly influence soil moisture through vegetation. The strong TP AHS can enhance the precipitation in the YRVNC region, which improves local vegetation and results in higher soil moisture.

Given that soil moisture anomalies can regulate atmospheric circulation through local thermal conditions (Liu et al., 2017; Gao et al., 2020), we further investigate the relationships between YRVNC soil moisture and local surface thermal parameters (surface skin temperature, 2-m air temperature, and sensible heat flux) in spring. The YRVNC soil moisture has significant negative correlations with local thermal parameters after removing the effect of ENSO. The coefficients among soil moisture and surface skin temperature, 2-m air temperature, and sensible heat over the YRVNC are −0.74, −0.70, and −0.93, respectively, all passing the 0.99 significance level. This means wet soil in spring could decrease the synchronous YRVNC sensible heat.

In addition to synchronously affecting climate, soil moisture can also exert lagged impacts on atmospheric circulation and climate elements due to its memory (Beljaars et al., 1996; Ruosteenoja et al., 2018). To verify the sustainability of spring soil moisture, the correlation between the monthly soil moisture and spring soil moisture on the interdecadal scale is investigated (Fig. 6). The spring YRVNC soil moisture is significantly correlated with local soil moisture in March, April and May, with correlation coefficients of at least 0.75. The correlation coefficients gradually decrease in June, July and August, but spring YRVNC soil moisture is still significantly positively correlated with local soil moisture. This indicates that anomalous YRVNC soil moisture in spring can sustain through the following summer.

To further identify the role of the memory effect of spring YRVNC soil moisture, we first investigate the relationships between the spring TP AHS and the three-month mean sensible heat from March to July (Figs. 7a–c). During spring, a stronger TP AHS would lead to increased YRVNC precipitation and soil moisture, resulting in lower local sensi-

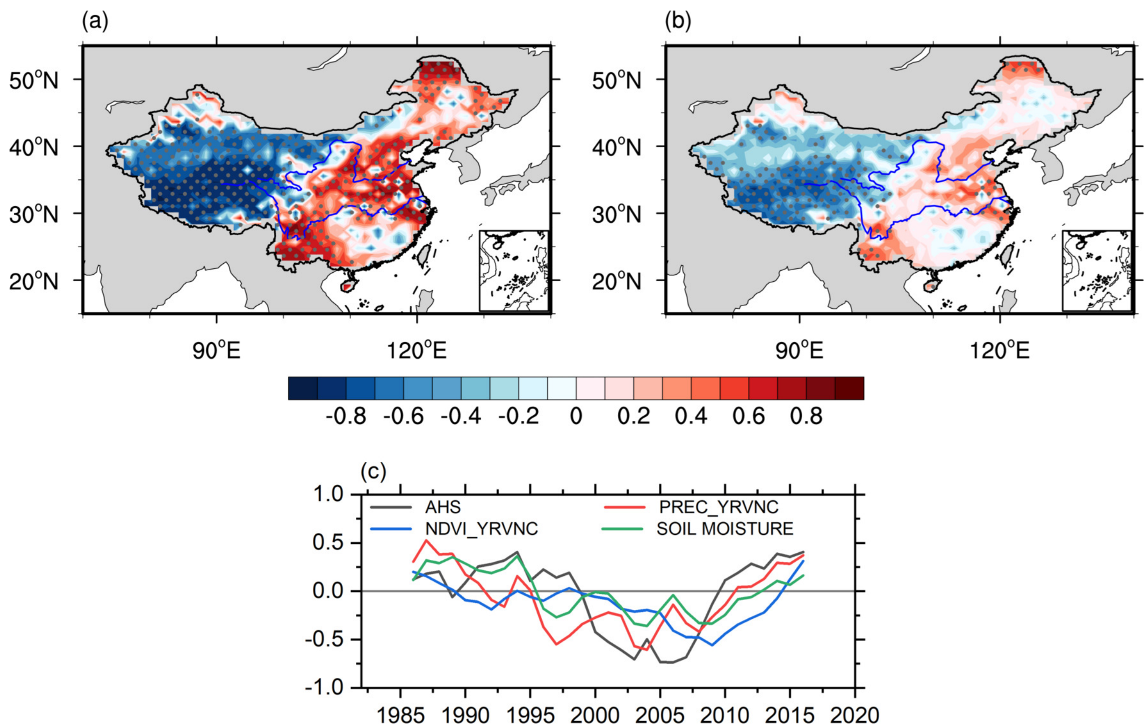

Fig. 5. (a) The partial correlation between the 9-year running mean spring TP AHS and NDVI in China during 1982–2020, with the influence of ENSO events having been removed. The grey dotted regions represent statistically significant results at the 0.95 confidence level. (b) As in (a) but with the influence of the spring YRVNC precipitation removed. (c) The normalized 9-year running mean TP AHS (black line), precipitation (red line), NDVI (blue line), and soil moisture (green line) in the YRVNC region during spring in the period 1982–2020, with the influence of ENSO events having been removed.

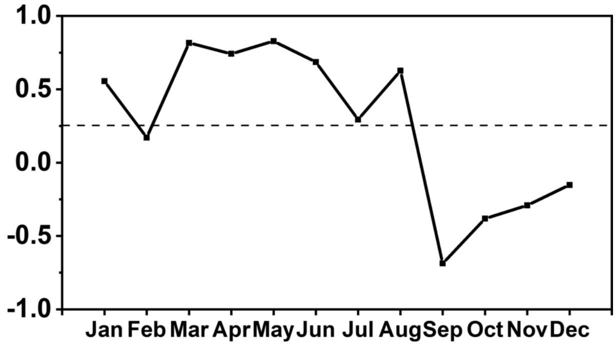

Fig. 6. Correlation coefficients between the 9-year running mean spring soil moisture and monthly soil moisture over the YRVNC during 1961–2020. The black dashed line represents statistical significance at the 0.95 confidence level. The influence of spring ENSO events has been removed.

ble heat (Fig. 7a). The lower sensible heat over the YRVNC sustains through the following summer (Figs. 7b and c). Using partial correlation, we remove the impact of YRVNC soil moisture in spring (Figs. 7d–f). The negative correlation between the sensible heat and TP AHS is weakened, and the significantly correlated area over the YRVNC is dramatically reduced except for the Hetao region. This indicates that the relationship between the TP AHS and YRVNC sensible heat during spring cannot be sustained without the influence of soil moisture.

Overall, the spring YRVNC thermal condition could maintain until summer and influence the land–sea thermal difference due to the memory effect of local soil moisture. We conclude that the TP AHS alters the YRVNC surface heat condition by modulating local soil moisture in spring. Meanwhile, the memory of soil moisture leads to a sustained sensi-

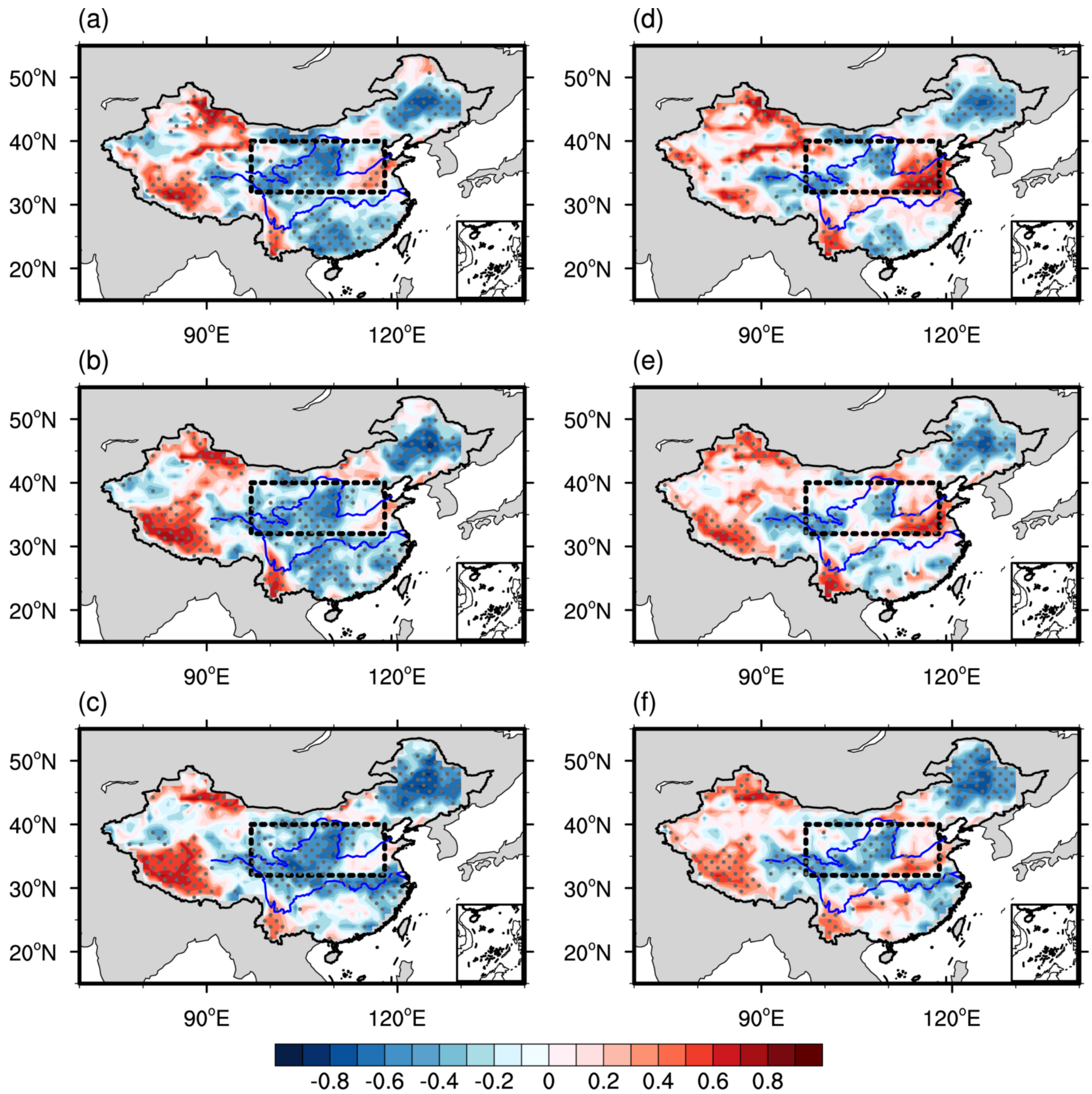

Fig. 7. Correlation coefficients of the 9-year running mean spring TP AHS with the sensible heat over China in (a) March–April–May, (b) April–May–June, and (c) May–June–July during 1961–2020. (d–f) As in (a–c) but with the influences of spring YRVNC soil moisture having been removed. The black box represents the YRVNC region. The grey dotted regions represent statistically significant results at the 0.95 confidence level.

ble heat anomaly and influences the weather and climate in summer.

3.2.3. *Atmospheric circulation and precipitation responses to soil moisture anomalies*

Figure 8 indicates the regression of the summer 850-hPa wind against the spring TP AHS, spring soil moisture, and sensible heat averaged over the YRVNC region. A strong TP AHS corresponds to high soil moisture over the YRVNC region, which leads to a weak land–sea thermal contrast and anomalous southerly winds over the East Asia–western Pacific region. Eventually, an anticyclonic circulation anomaly and weak convective activities occur in the South China Sea and tropical western Pacific (Zuo and Zhang, 2016). The weak convective activities further excite a cyclonic anomaly over NEC and an anticyclonic anomaly over Southeast China through the East Asia–Pacific teleconnection pattern (Huang and Li, 1988). The anomalous cyclone over NEC favors water vapor convergence and, in turn, local summer precipitation. In contrast, the anticyclonic anomaly in Southeast China leads to the divergence of water vapor and decreases local precipitation in summer. Meanwhile, northerly flows produced by the anticyclone converge with southerly flows related to the cyclone in the Hetao region, ultimately leading to excessive precipitation over those regions (Figs. 8a and b). A similar distribution characteristic exists in Fig. 8a and b, while the pattern in Fig. 8c contrasts with that in Fig. 8a, confirming the key role of spring YRVNC soil moisture and the local thermal condition in activating the abnormal summer circulations in East Asia. This result further implies that a strong TP AHS and wet YRVNC soil moisture in spring contribute to excessive summer NEC precipitation.

We also compare the summer precipitation and circulation in positive and negative soil moisture years and their difference to analyze the impacts of soil moisture (Fig. 9). The years in which the time sequences of normalized YRVNC soil moisture (Fig. 4b) are below 0 and above 0 are set as the negative and positive years of soil moisture, respectively. During positive years, a meridional wave train extends from the South China Sea to NEC. An anomalous anticyclone and an anomalous cyclone dominate the South China Sea and NEC respectively, which favor abundant summer precipitation in NEC and the Yellow River Valley (Fig. 9a). These features indicate a weak East Asia–western Pacific thermal contrast (Sun et al., 2002). During negative years, the low-

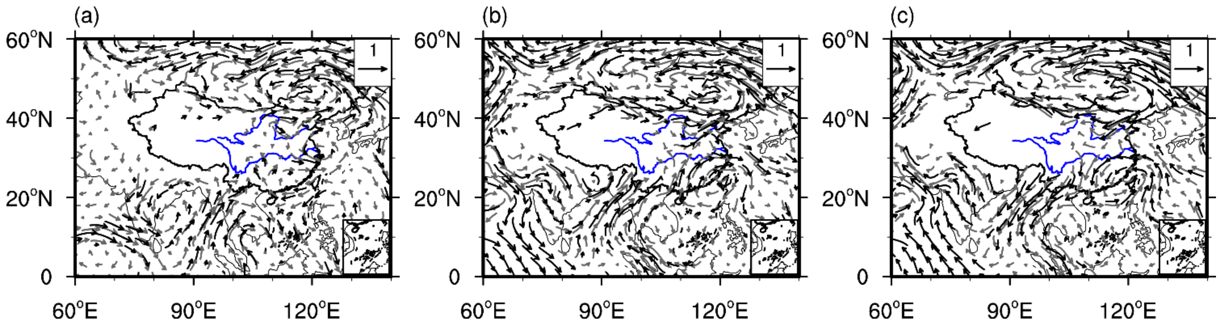

Fig. 8. Regressions of summer 850-hPa wind against the 9-year running mean spring (a) TP AHS, (b) soil moisture, and (c) sensible heat averaged over the YRVNC region during 1961–2020. The black vectors represent statistically significant results at the 0.90 confidence level.

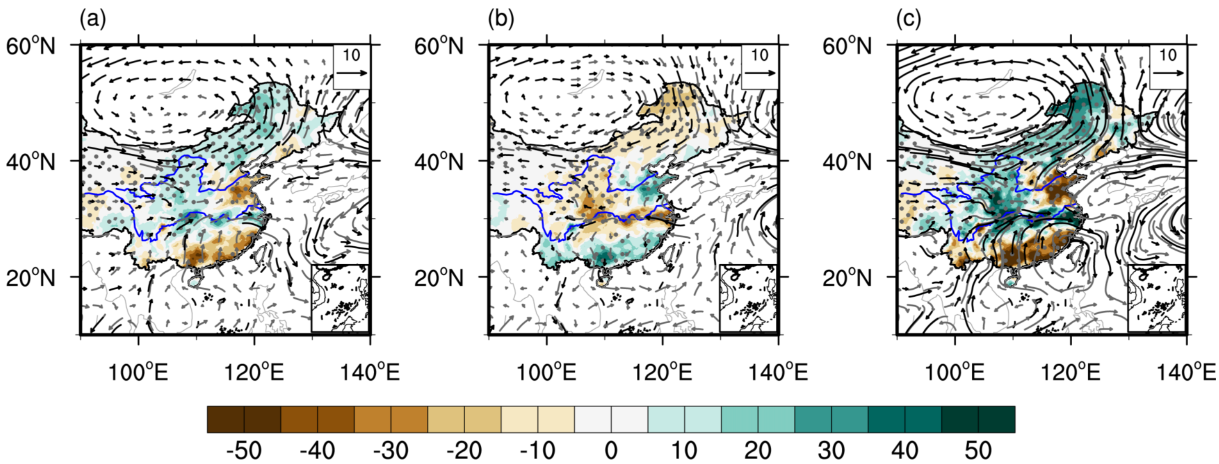

Fig. 9. The summer vertically integrated water vapor anomaly (arrows; units: kg m^{-1} s^{-1}) and precipitation anomaly (shading; units: mm d^{-1}) in (a) positive YRVNC soil moisture years, (b) negative YRVNC soil moisture years, and (c) their difference (positive minus negative). The black vectors and grey dotted regions represent statistically significant results at the 0.90 and 0.95 confidence levels, respectively.

level atmospheric circulation and precipitation anomalies are mirror images of the positive years with opposite signs, indicating that the YRVNC soil moisture is the primary cause of these anomalies (Fig. 9b). Their differences (Fig. 9c) confirm the impacts of the YRVNC soil moisture on summer circulation and NEC precipitation.

3.2.4. *Simulation results*

To verify the above physical mechanism, the results of sensitivity modeling experiments of sensible heat over the TP by CESM1.2.0 are analyzed. We first calculate the differences in the spring TP AHS between the two sensitivity experiments and find that a more robust spring TP sensible heat corresponds to a stronger local AHS (figure not shown). This also confirms that the spring TP sensible heat has a significant impact on the TP AHS. As such, the differences between the two sensitivity runs are used to examine the effects of the spring TP AHS. Figure 10 shows the 9-year running mean precipitation differences between the two sensitivity runs in spring and summer. A north–south dipole pattern of the spring precipitation anomaly exists in East China, with more in the YRVNC region and less in South China (Fig. 10a). This indicates that a stronger TP AHS leads to abundant precipitation over the YRVNC region in spring. In summer, the precipitation anomalies show a tripole-type pattern, with enhanced precipitation in NEC (Fig. 10b). Generally, CESM reproduces the time-lagged effects of the spring TP AHS on summer NEC precipitation.

Altogether, in spring, a strong TP AHS leads to excessive precipitation and wet soil in the YRVNC, which reduces the local surface skin temperature and sensible heat. Owing to the prolonged memory of soil moisture, the weak spring heat condition over the YRVNC region lasts until summer, resulting in a weak land–sea thermal difference and above-normal summer precipitation in NEC.

4. Summary and discussion

We investigate the time-lagged effects of the spring TP AHS on summer NEC precipitation and the associated physical processes. The results indicate that their long-term changes are significantly positively correlated, while spring YRVNC soil moisture serves as a bridge connecting the spring TP AHS and following summer NEC precipitation.

Further analysis indicates that, during spring, a strong TP AHS enhances the moisture transport to East China and leads to excessive precipitation in the YRVNC region. The latter results in vegetation restoration and wetter local soil, which in turn causes stronger land–atmosphere coupling and regulates the local surface thermal condition by decreasing the local surface skin temperature and sensible heat. Due to the memory effect of the soil moisture, the YRVNC anomalous heat condition in spring can last until mid-summer, weakening the land–sea thermal contrast. This leads to anomalous southerly winds over the East Asia–western North Pacific region and weak convective activities over the South China Sea and tropical western Pacific. The weak convective activities excite a cyclonic atmospheric circulation over NEC and the surrounding region through the East Asia–Pacific pattern. This anomalous cyclone brings abun-

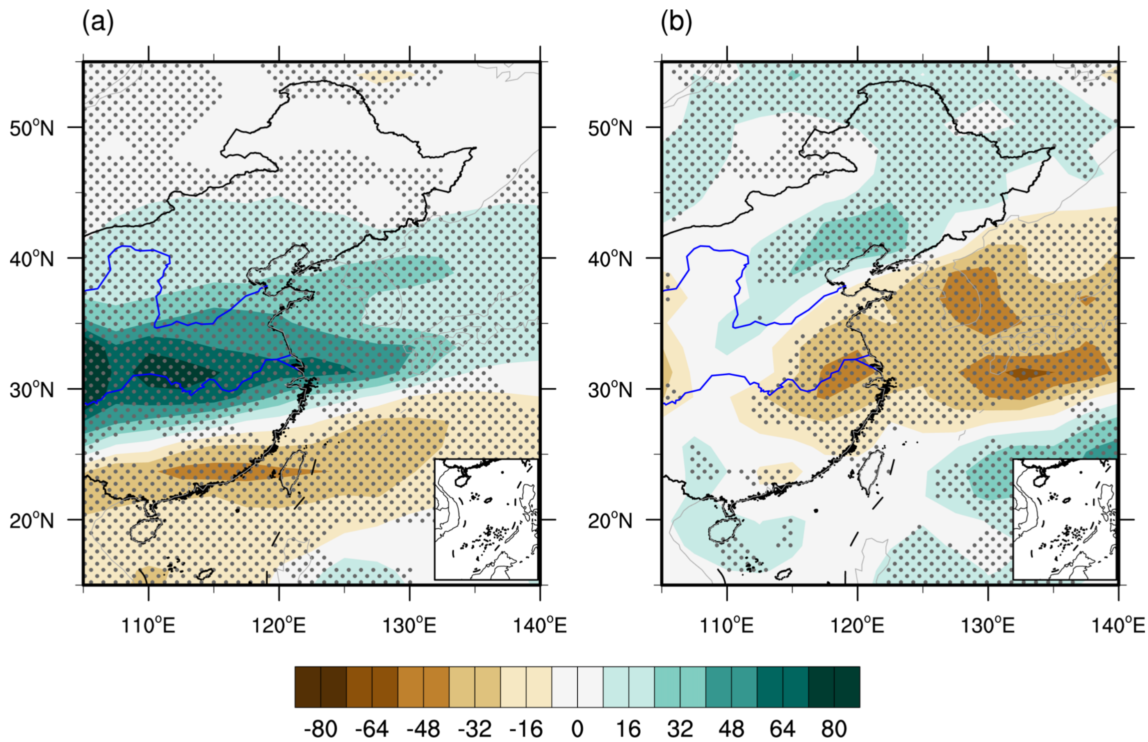

Fig. 10. Differences of the 9-year running mean precipitation (color shading; units: mm $month^{-1}$) in (a) spring and (b) summer between two sensitivity runs (strong minus weak) during 1979–2014. The grey dotted regions represent statistical significance at the 0.95 confidence level.

dant moisture from the Hetao–North China region, Northwest Pacific, and Japan Sea, ultimately increasing the summer NEC precipitation. CESM reproduces the climate response to the observed spring TP AHS forcing. Hence, the key role of the spring TP AHS in generating the subsequent summer NEC precipitation anomaly is further verified by model results.

It should be noted that our study indicates an obvious positive correlation between the TP AHS and precipitation over Southeast China during spring (Figs. 2c and d). Meanwhile, ENSO has also been suggested to be able to affect the spring precipitation over there (Feng and Li, 2011; Zhang et al., 2016). By removing the influence of ENSO events, we find that the correlation between the spring TP AHS and precipitation in Southeast China is substantially reduced, while the significant correlation in the Hetao region increases remarkably, expanding to the entire YRVNC region. This indicates that spring precipitation in Southeast China is mainly influenced by ENSO, and the influence of the spring TP AHS is not significant.

Although our study indicates that the spring TP AHS can significantly affect the soil moisture and surface heat flux in the YRVNC region, the influence of spring NEC soil moisture on local summer precipitation cannot be ignored. The correlation coefficients between summer NEC precipitation and local soil moisture in spring and summer are 0.65 and 0.90, respectively, indicating a statistically significant relationship between them. In fact, NEC has been proven to be a key soil moisture–precipitation feedback area, and the feedback process is achieved through local evapotranspiration. Evapotranspiration in NEC can modulate the local water vapor and surface energy, which influences summer NEC precipitation (Chen et al., 2023). In contrast, the spring YRVNC soil moisture affects the atmospheric circulation and water vapor transport through the land–sea thermal difference, and then affects summer NEC precipitation.

Notably, our study emphasizes the impact of vegetation changes on soil moisture over the YRVNC region. Although most previous studies have demonstrated that positive feedback exists between soil moisture and local vegetation dynamics (D'Odorico et al., 2007; Wu et al., 2014), it has also been shown that increased vegetation can cause more evapotranspiration and, in turn, reduce local soil moisture (Jackson et al., 2005; Chen et al., 2008). Li et al. (2018) focused on this issue and investigated the hydrological response to vegetation changes in China. Their results indicate that the increase in precipitation caused by vegetation may cancel out the enhanced evapotranspiration and offset its negative impact on soil moisture in North China. This suggests that vegetation enhancement in North China can increase local soil moisture in spring.

This study indicates the physical mechanism by which the spring TP AHS affects summer NEC precipitation on the interdecadal scale, and highlights the important bridging role that soil moisture in the YRVNC region plays. Besides, the effect of vegetation on spring YRVNC soil moisture and the influence of spring NEC soil moisture are also important. The relationship between the spring TP AHS and summer NEC precipitation addressed here is important not only in understanding the summer climate in NEC, but also in improving its predictability.

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