Influences of Spring Land Surface Thermal Anomalies over West Asia on Indian Early Summer Monsoon Activity and Its Pathway

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ABSTRACT: Exploring the premonsoonal land thermal predictor of the Indian summer monsoon is a hot topic under the background of global warming, and West Asia is one of the regions with the most significant warming in spring. In this study, we investigated the impact of anomalous spring land surface warming over West Asia on early summer (June) Indian monsoon precipitation as well as its possible mechanisms based on statistical analysis and numerical simulations. It has been found that spring land surface anomalous warming over West Asia corresponds to the enhancement of the leading mode of early summer precipitation in the Indian subcontinent, especially in its northern part. Further analysis indicates that an anomalously warm land surface over West Asia can advance the transition of atmospheric conditions toward the warm season by heating the atmosphere above. The increased land–sea meridional thermal contrast favors the intensification of the low-level jet and monsoon trough, further inducing anomalous moisture convergence and ascending motion over northern India. Additionally, the heat-driven anomalous upper-tropospheric anticyclone over West Asia favors the intensification of the tropical easterly jet and the northwestward development of the South Asian high (SAH). The enhanced SAH dynamically couples with the lower- to middle-level cyclonic circulation over northern India, resulting in a stronger monsoon and increased precipitation. These findings are helpful for better understanding and prediction of Indian early summer monsoon.

SIGNIFICANCE STATEMENT: The land surface thermal condition is critical to the monsoon activity and exploring the premonsoonal land thermal predictor of Indian summer monsoon remains a hot topic. The purpose of this study is to explore how spring land surface thermal anomalies over West Asia impact Indian monsoon activity in early summer (June). The anomalous land surface warming over West Asia can lead to a stronger Indian monsoon in early summer by heating and driving the atmosphere, which benefits the precipitation increase over northern India. Our results provide a further scientific basis for the prediction of early summer Indian precipitation.

KEYWORDS: Atmosphere-land interaction; Land surface; Surface temperature; Forcing; Dynamics; Monsoons

1. Introduction

The Indian summer monsoon (ISM) is crucial for the human life and agriculture of the densely populated Indian subcontinent (Rosenzweig and Binswanger 1993; Gadgil and Gadgil 2006; Subash and Gangwar 2014; Mishra et al. 2019). The onset of the ISM exhibits significant interannual variability (Joseph et al. 1994; Raju et al. 2007; Pai and Nair 2009; Shukla and Huang 2016). A slight deviation of the monsoon onset timing manifested as monsoon delay usually leads to below-normal precipitation, and even severe droughts in early summer (Liu and Xie 2017). In view of a considerable gap between the prediction skill and predictability of the Indian summer monsoon precipitation (ISMP) (Wang et al. 2015; Saha et al. 2019, 2021), further investigation of the antecedent signals associated with ISM activity and precipitation remains necessary for their accurate prediction.

Since land–sea thermal contrast is the main driving force of the ISM (Yang et al. 1992; Li and Yanai 1996; Yang and Lau 1998; Liu and Yanai 2001), many studies emphasized the oceanic role in modulating the land–sea thermal contrast and the ISM (Wang et al. 2003; Roxy et al. 2015; Prodhomme et al. 2015; Borah et al. 2020; Rajesh and Goswami 2020). However, the contributions of the Eurasian thermal conditions are also crucial to the ISM activity (Robock et al. 2003; Bollasina et al. 2011; Yang et al. 2011; Zhao et al. 2016; Roxy 2017). Studies highlighted that the direct heating of the Tibetan Plateau plays a key role in intensifying the ISMP since its elevated land surface is crucial to the reversing of the meridional temperature gradient that can lead to the monsoon onset (Yanai et al. 1992; Yang et al. 2004; Yanai and Wu 2006). Nevertheless, Boos and Kuang (2010) proposed that the ISM is more sensitive to the surface heating at the southern slopes of the Himalaya and the northern Indian subcontinent. Also, the influences of premonsoonal soil moisture over the Indian subcontinent on ISMP have been explored by recent studies (Ashraf et al. 2012; Saha et al. 2012; Ashraf and Ahrens 2013; Halder et al. 2015). Meanwhile, existing research showed that increased Eurasian snow cover anomalies in winter and spring usually cause an anomalous deficit of ISMP via decreasing the land–sea thermal contrast (Blanford 1884; Dong and Valdes 1998; Bamzai and Shukla 1999; Saha et al. 2013; Senan et al. 2016), and other studies emphasized the “bridge” role of the soil moisture in the snow–monsoon.
teleconnection (Matsuyama and Masuda 1998; Halder and Dirmeyer 2017). But recently, Zhang et al. (2019) found that the inverse relationship between the central Eurasian spring snow cover and ISMP has disappeared since 1990.

Generally, the ISM starts in Kerala at the end of May. Then the rainy belt advances from the southern to the northern part of the Indian peninsula in June. ISMP usually peaks in July and August, and gradually withdraws southward in September (Tao 1987; Tanaka 1992; Soman and Kumar 1993; Lau and Yang 1997; Wang and LinHo 2002; Fasullo and Webster 2003; Stolbova et al. 2016). The intraseasonal evolution of ISM tends to produce month-to-month variation of ISMP. Recent studies proposed that the ISMP in early summer may be influenced by premonsoonal land thermal conditions more significantly than that in late summer. Rajagopalan and Molnar (2013) reported that the heating of the Tibetan Plateau correlates significantly with ISMP in the early monsoon season (20 May–15 June) whereas the correlations during the main monsoon season (15 June–31 August) are weak and insignificant. Saha et al. (2011) showed that dry local land surface condition in May increases June rainfall whereas the remaining months of the season do not show much rainfall change, which in turn leads to an anomalous increase in seasonal ISMP. Rai et al. (2015) discovered that colder and wetter land atmospheric conditions (negative 2-m temperature anomaly and positive rainfall anomaly) over northwest India, Pakistan, Afghanistan, and Iran in April–May are associated with ISMP decrease primarily in June and July, which further affects the seasonal mean. In fact, the land thermal conditions may change with the coming of monsoon, so the indicative effect displayed by the premonsoonal land thermal conditions may be reduced subsequently. Therefore, it is imperative to take the Indian monsoon precipitation in early summer as a research object when exploring the premonsoonal Eurasian predictors.

Several observational studies suggested that spring land surface thermal anomalies over West Asia may affect the Indian monsoon activity in early summer (Rai et al. 2015; Moon and Ha 2019). Rai et al. (2015) reported that the coupled land–atmosphere interactions may enhance the persistence of anomalous low pressure system over West Asia and further affect the early ISMP. However, the potential roles of land surface heat flux with regard to the anomalous low over West Asia and the early ISMP need further investigation. Moon and Ha (2019) declared that lower soil moisture over the Iranian desert region during March and April can induce weakened latent heat but intensified sensible heat, which generate relatively warm air temperature above land and advance ISM onset. In fact, the surface sensible heat is a direct land surface thermal forcing of the atmosphere, whereas the latent heat plays an indirect role by regulating the sensible heat. Therefore, the variability of the sensible heat has the potential to exert anomalous heating/cooling to the atmosphere above the land surface, and the current study is focused on this direct thermal forcing of the land surface, which can be effectively characterized by the year-to-year variations in the land surface temperature. With this in mind, the relationship between spring land surface temperature over West Asia and early summer Indian monsoon precipitation, as well as its possible mechanisms, was investigated based on statistical analysis and numerical simulations in this study to provide a further scientific basis for the prediction of early summer Indian precipitation.

On the other hand, Yang et al. (2021) pointed out that the anomalous spring land surface warming over West Asia can be an external forcing to the formation of the atmospheric circum-global teleconnection (CGT), and it can further affect northern China climate in early summer. Also, some studies illustrated the CGT is, in part, a response to the ISMP heating source (Ding and Wang 2005, 2007). It is possible that the Indian early summer monsoon heating plays a role of bridge in the West Asia–northern China teleconnection. Further explorations of the linkage between spring land surface temperature and early summer Indian monsoon precipitation are also essential for a comprehensive understanding of the West Asia–northern China teleconnection.

The article is organized as follows: section 2 introduces the datasets, methods, model description, and numerical experiments. Section 3 explores the relationship between spring land surface temperature over West Asia and early summer Indian monsoon precipitation, and possible mechanisms are discussed in section 4. To further support the findings in sections 3 and 4, section 5 presents results of numerical experiments. Finally, conclusions and discussion are given in section 6.

2. Datasets and methods

a. Datasets

Three precipitation monthly datasets were used for our analyses: the National Oceanic and Atmospheric Administration precipitation reconstruction data over land (NOAA-PRECL) (Chen et al. 2002) with a horizontal resolution of $0.5^\circ \times 0.5^\circ$; the Global Precipitation Climatology Centre (GPCC) precipitation dataset (Schneider et al. 2015) with a horizontal resolution of $0.5^\circ \times 0.5^\circ$; University of Delaware Precipitation, version 5.01 (UDel-v5.01), with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ (Legates and Willmott 1990).

The land surface monthly datasets used include the skin temperature, soil temperature level 1 (layer between 0 and 7 cm below land surface), soil temperature level 2 (layer between 7 and 28 cm below land surface), and soil temperature level 3 (layer between 28 and 100 cm below land surface) from ERA-20C (Poli et al. 2016) with a horizontal resolution of $1^\circ \times 1^\circ$; the near-surface temperature from the Climatic Research Unit high-resolution gridded datasets, version 4.02 (CRU-Ts4.02) (Harris et al. 2020) on a horizontal resolution of $0.5^\circ \times 0.5^\circ$; the surface temperature anomalies (1951–80 base period) from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) (Hansen et al. 1999) on a horizontal resolution of $2^\circ \times 2^\circ$; the skin temperature data from the National Centers for Environmental Prediction and National Center for Atmosphere Research (NCEP–NCAR) (Kalnay et al. 1996) on a horizontal resolution of $2.5^\circ \times 2.5^\circ$.

The monthly sea surface temperature (SST) was from the Japanese Meteorological Agency’s Centennial Observation-Based Estimates of SSTs (COBE SST) (Ishi et al. 2005), with a horizontal resolution of $1^\circ \times 1^\circ$. The oceanic Niño index (ONI) from the NOAA Climate Prediction Center is based on the 3-month running mean of ERSST.v5 SST anomalies in the
Niño-3.4 region (5°N–5°S, 120°–170°W), which can indicate the ENSO signal (available at https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt). The NOAA Earth System Research Laboratory provided the Atlantic multidecadal oscillation (AMO) index (available at https://www.daculawether.com/4_amo_index.php).

The atmospheric monthly variables were also derived from not only ERA-20C but also NCEP–NCAR. NCEP–NCAR provided the air temperature, geopotential height, $u$ wind, and $v$ wind, while the vertical integral of water vapor flux as well as the divergence of moisture flux were from ERA-20C. The daily atmospheric variables from NCEP–NCAR were also used to calculate the apparent moisture sink (Q2), including the specific humidity, omega, $u$ wind, and $v$ wind. Also, the outgoing longwave radiation (OLR) was provided by NOAA and NCAR (Liebmann and Smith 1996), with a horizontal resolution of $2.5° \times 2.5°$. In this study, the periods for all datasets are 1951–2010 except for OLR, which has a period of 1974–2010.

### b. Methods

The EOF analysis was carried out to acquire the leading mode of early summer precipitation over the Indian peninsula, and the Pearson correlation analysis, linear regression analysis, and composite analysis were employed to explore the relationship between spring land thermal anomalies and Indian early summer monsoon precipitation.

To examine the independence of this relationship from the spring sea surface temperature, the partial correlation coefficients were calculated as follows:

$$PR_{ab,c} = \frac{R_{ab} - R_{ac} \times R_{bc}}{\sqrt{(1 - R_{ac}^2)} \times (1 - R_{bc}^2)},$$

in which $PR_{ab,c}$ is the partial correlation coefficient of $a$ and $b$ independent of $c$, while $R_{ab}$, $R_{ac}$, and $R_{bc}$ refer to the correlation coefficient of $a$ and $b$, $a$ and $c$, and $b$ and $c$, respectively.

A multiple linear regression approach was also employed to separate the influence of West Asian land surface temperature in spring [the spring West Asian land surface thermal index (WALTI)] on the northern Indian precipitation in early summer [the early summer northern Indian precipitation index (NPII)] from the impacts of seven SST target indices, namely the northeast Pacific ($40°$–$55°N, 170°$–$140°W$) SST index (NEPSI), the northwest Pacific ($10°$–$35°N, 120°E$–$140°W$) SST index (NWPSI), the equatorial Pacific ($5°$–$10°N, 170°E$–$80°W$) SST index (EPSI), the southwest Pacific ($30°$–$55°S, 130°$–$180°E$) SST index (SWPSI), the North Atlantic ($20°$–$35°N, 70°$–$30°W$) SST index (NASI), the tropical south Indian ($0°$–$20°S, 40°$–$100°E$) SST index (TSISI), and the subtropical south Indian ($25°$–$40°S, 55°$–$95°E$) SST index (SSISI):

$$NIPI(t) = C_0 + C_{NEPSI} \times NEPSI(t) + C_{NWPSI} \times NWPSI(t) + C_{EPSI} \times EPSI(t) + C_{SWPSI} \times SWPSI(t) + C_{NASI} \times NASI(t) + C_{TSISI} \times TSISI(t) + C_{SSISI} \times SSISI(t) + \varepsilon(t),$$

in which $C_0, C_{NEPSI}, C_{NWPSI}, C_{EPSI}, C_{SWPSI}, C_{NASI}, C_{TSISI}$, and $C_{SSISI}$ represent the regression coefficients, and $\varepsilon$ denotes the regression residuals.

The apparent moisture sink (Q2) introduced by Yanai et al. (1973) was used to represent the latent heating due to condensation or evaporation processes and subgrid-scale moisture flux convergences. The vertical integral of Q2 was calculated as follows:

$$(Q2) \equiv \frac{1}{g} \int_{300\text{hPa}}^{1000\text{hPa}} - L \left( \frac{\partial q}{\partial t} + \mathbf{V} \cdot \nabla q + \alpha \frac{\partial q}{\partial p} \right) dp,$$

in which $g$ is the gravitational acceleration, $L$ is the latent heat of condensation, $q$ is the specific humidity, $\mathbf{V}$ is the horizontal velocity, $\alpha$ is the vertical $p$ velocity, and $p$ is the pressure.

### c. Model description and numerical experiments

Numerical simulations were performed with the Community Earth System Model version 1.2.2 (CESM1.2; for more details refer to http://www.cesm.ucar.edu/models/cesm1.2). The Community Atmosphere Model version 5 (CAM5) (Neale et al. 2010) and the Community Land Model version 4.5 (CLM4.5) (Oleson et al. 2010) were used in the coupling (F.2000_CAM5), with a horizontal resolution of $0.9° \times 1.25°$.

We conducted control (CTL) and sensitivity (SEN) experiments to validate the effects of spring land surface warming over West Asia on the Indian monsoon activity in early summer. In CTL, the model was driven by cyclic present-day (circa year 2000) forcing with climatological SST from the Hadley Centre (Rayner et al. 2003), and other external forcing data were also provided by the model developer (Hurrell et al. 2013; https://svn-cesm-inputdata.cgd.ucar.edu/trunk/inputdata/). The model ran for 100 years, and results were saved at monthly intervals. Then, based on the CTL, 100-member ensemble runs in the SEN got conducted. In each subset run, the model was integrated from 1 March to 30 June, and the initial field was obtained from the output data on each 1 March of CTL. To represent anomalous surface heating relevant to the land surface warming, the land surface sensible heat forcing of $30$ W m$^{-2}$ was added over West Asia at each time step of spring in the SEN (according to Fig. 13), and the qconv in the SEN was designed based on figures shown below (see Figs. 7a and 7c). The SST and other external forcing data in the SEN were the same as those used by the CTL.

### 3. Features of Indian early summer monsoon precipitation and their linkage with spring land thermal anomalies over West Asia

To explore the dominant mode of early summer precipitation over the Indian peninsula ($8°$–$30°N, 70°$–$90°E$), the EOF analysis was carried out with three reanalysis datasets. Figure 1 shows that the spatial patterns and normalized principal components (PC1) of the first EOF modes (EOF1) based on different precipitation datasets are generally consistent, with the EOF1 accounting for about 25.0%, 23.5%, and 22.5% of the total variance for the NOAA, UDel, and GPCC data, respectively. The EOF1 is significantly separated from the other modes according to the criterion defined by North.
et al. (1982). The spatial pattern of EOF1 displays positive loads over the northern part (Figs. 1a–c), which is in good agreement with the result of KanthaRao and Rakesh (2018). The corresponding PC1 exhibits obvious interannual variations (Fig. 1e). To avoid the uncertainty of the single-source dataset, Fig. 1d also presents the EOF1 based on the average of NOAA, UDel, and GPCC (referred to as DATAAVE), whose distribution is similar to those in Figs. 1a–c. Hence, PC1 based on DATAAVE (red line in Fig. 1e) was used for the following analysis.

To explore the possible precursor related to the leading mode of Indian monsoon precipitation in early summer, Fig. 2 shows the correlations between PC1 and Eurasian surface temperature in spring based on multiple datasets (ERA-20C, CRU, and GISS). There are significant positive correlations over West Asia, illustrating that the spring land surface thermal condition over West Asia is closely linked with the leading mode of early summer Indian precipitation. To confirm this relationship, we further selected West Asia (45°–70°E, 30°–40°N) shown in Fig. 2 as the target region and defined the spring West Asian land surface thermal index (WALTI) as the regionally averaged standardized skin temperature. Figure 3 further presents the regression early summer precipitation onto the WALTI. As seen in Figs. 3a–d, the regressed distributions over the Indian peninsula are generally consistent with the spatial pattern of EOF1 (Figs. 1a–d). The most significant response occurs over northern India, which is manifested as precipitation increase when the land surface is anomalously warm over West Asia in spring (hereafter West Asia–northern India connection). Comparing Figs. 3a–d with Figs. 3e–h, it can be seen that after removing the long-term trends, this connection remains, and the precipitation anomalies over northern India further strengthen. Therefore, the target region of northern India (76°–88°E, 20°–28°N) shown in Fig. 3 was chosen to calculate the regional-averaged standardized precipitation index in early summer based on DATAAVE [the early summer northern Indian precipitation index (NIPI)], which could be used to directly measure the variations of Indian early summer monsoon precipitation relevant to the spring land thermal anomalies over West Asia.

To further characterize the temporal features of the West Asia–northern India connection, the time series of WALTI, PC1, and NIPI are depicted in Fig. 4a. It is shown there are coherent variations between WALTI and PC1/NIPI, with the correlation coefficient being 0.40 and 0.45, respectively, at the 1% significance level according to Student’s t test. It is thus proved once again that the anomalous increase of early summer precipitation over northern India highly depends on the anomalous spring land thermal warming over West Asia. Furthermore, Goswami et al. (1999) pointed out that the monsoon Hadley circulation index (MHI) represents the regional character of the ISM and correlates well with monsoon precipitation. To characterize early summer monsoon activity, we calculated the standardized MHI, which was defined as the meridional wind shear anomaly between 850 and 200 hPa averaged over 70°–110°E, 10°–30°N. As seen in Fig. 4a, the variation of WALTI is also similar to that of MHI, and their correlation coefficient is 0.33, exceeding the 1% significance level according to Student’s t test. It is concluded that the spring land surface thermal condition is significantly linked with
the early summer Indian monsoon activity and the associated precipitation. Furthermore, considering the possible influences of the long-term trends, Fig. 4b shows the time series after removing the long-term trends. It is noteworthy that the correlation coefficient between the WALTI and PC1 (NIPI) increases to 0.43 (0.47), while that between the WALTI and MHI decreases to 0.27 at the 5% significance level. The differences between Figs. 4a and 4b suggest that...
the long-term trends have little effect on West Asia–northern India connection. Therefore, we would remove the long-term trends when discussing the relevant mechanisms.

Additionally, in light of the possible influences of oceanic thermal forcing on the monsoon, the correlation distribution between the NIPI and spring SST has been given to examine the independence of the West Asia–northern India connection from the SST. As seen in Fig. 5, the spring SSTs of the northwest Pacific, southwest Pacific, subtropical south Indian Ocean, and North Atlantic positively correlate to the NIPI, while those of the northeast Pacific, equatorial Pacific, and tropical south Indian Ocean negatively correlate to the NIPI.

Fig. 4. The spring West Asian land surface thermal index (WALTI), PC1 of early summer precipitation over the Indian peninsula, early summer northern Indian precipitation index (NIPI), and the monsoon Hadley circulation index (MHI), using (a) the original data and (b) the data with long-term trends removed. One asterisk (*) indicates statistically significance at the 5% level and two asterisks (**) imply statistically significance at the 1% level based on Student’s t test.

Fig. 5. The correlation distribution between the early summer NIPI based on DATAAVE and spring SST based on COBESSST. The quadrilaterals represent the selected SST target regions. Dotted areas are statistically significant at the 5% level based on Student’s t test.
Table 1. Partial correlation coefficients of spring West Asian land surface thermal index (WALTI) and early summer northern India precipitation index (NIPI) independent of the seven regionally averaged standardized indices of spring SST target regions (SSTIs): the northeast Pacific (40°–55°N, 170°–140°W) SST index (NEPSI), the northwest Pacific (10°–35°N, 120°E–140°W) SST index (NWPSI), the equatorial Pacific (5°S–10°N, 170°E–80°W) SST index (EPSI), the southwest Pacific (10°–35°S, 130°–180°E) SST index (SWPSI), the North Atlantic (20°–35°N, 70°–30°W) SST index (NASI), the tropical south Indian (0°–20°S, 40°–100°E) SST index (TSISI), and the subtropical south Indian (25°–40°S, 55°–95°E) SST index (SSISI). One asterisk (*) indicates statistically significant at the 5% level, and two asterisks (**) statistically significant at the 1% level based on Student’s t test.

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<tr>
<th>NEPSI</th>
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<td>0.39**</td>
<td>0.27*</td>
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Therefore, as shown in Fig. 5, we selected seven regionally averaged standardized indices of spring SST target regions: the northeast Pacific (40°–55°N, 170°–140°W) SST index (NEPSI), the northwest Pacific (10°–35°N, 120°E–140°W) SST index (NWPSI), the equatorial Pacific (5°S–10°N, 170°E–80°W) SST index (EPSI), the southwest Pacific (30°–55°S, 130°–180°E) SST index (SWPSI), the North Atlantic (20°–35°N, 70°–30°W) SST index (NASI), the tropical south Indian (0°–20°S, 40°–100°E) SST index (TSISI), and the subtropical south Indian (25°–40°S, 55°–85°E) SST index (SSISI). One asterisk (*) indicates statistically significant at the 5% level, and two asterisks (**) statistically significant at the 1% level based on Student’s t test.

Next, Table 1 shows the partial correlation coefficients of WALTI and NIPI independent of the seven indices of SST target regions. Based on Student’s t test, the partial correlation coefficient of WALTI and NIPI independent of NWPSI is significant at the 5% level, and other partial correlation coefficients are all significant at the 1% level. Considering the different effects of SST from these seven regions on Indian precipitation, we also performed the multiple linear regression of the seven SST indices onto NIPI, and calculated the correlation coefficient between the regression residual and WALTI, which is 0.21 and reaches statistical significance at the 10% level. Therefore, the relationship between the spring land temperature over West Asia and northern Indian precipitation in early summer remains significant when the SST signals are removed, suggesting that the potential of spring land temperature over West Asia to further enhance the ISM predictability should not be ignored.

It is noted that the correlation pattern (Fig. 5) is similar to the interdecadal ENSO-like mode (Zhang et al. 1997). The impacts of slowly varying SST drivers of ISM like ENSO (Joseph et al. 2011) and AMO (Krishnamurthy and Krishnamurthy 2016; Rajesh and Goswami 2020) are reported by several previous studies. Although Rai et al. (2015) have pointed out that ENSO does not have substantial influence on the starting phase (June) of ISM, establishing the independence of the land thermal driver of ISM variability from the typically slowly varying predictable drivers remains necessary. Figure 6 depicts the early summer Indian precipitation before and after removing ENSO, interdecadal ENSO, and AMO signals onto WALTI. The spatial patterns of the regressions are similar with and without slowly varying SST signals, indicating that the relationship between spring land thermal conditions over West Asia and the dominant mode of Indian early summer precipitation is not driven by ENSO and AMO, which further demonstrates the potential importance of land surface thermal forcing.

4. Possible mechanisms

The aforementioned results imply that the spring land surface thermal anomalies over West Asia are closely linked with the first leading mode of early summer monsoon precipitation over the Indian peninsula, especially over the northern part; that is, when land surface anomalous warming (cooling) occurs over West Asia, the northern Indian precipitation significantly increases (decreases). In this section, the related atmospheric general circulations will be examined to explore the possible mechanisms behind such a relationship, focusing on the physical processes of the land surface anomalous warming promoting the monsoon activity.

First, the simultaneous responses of the atmosphere to land surface thermal anomalies are analyzed. Some anomalous fields in spring regressed onto WALTI are illustrated in Figs. 7a–9. According to Figs. 7a and 7c, the spring land surface warms (cools) significantly over West Asia when WALTI abnormally increases (decreases), and the spatial distributions of regressed

![Fig. 6. Early summer precipitation (mm day⁻¹) regressed onto WALTI (a) in the original data, and after removal of the (b) ENSO, (c) interdecadal ENSO [6-yr low-pass filtered based on Zhang et al. (1997)], and (d) AMO signals. Dotted areas are statistically significant at the 10% level based on Student’s t test.](image-url)
land skin temperature based on different datasets (ERA-20C and NCEP–NCAR) are consistent, indicating the robustness of WALTI used here. Yang et al. (2021) proposed that when the land surface warms anomalously over West Asia, the sensible heating and longwave radiation from land are enhanced, and the troposphere above West Asia exhibits anomalous warming that gradually weakens from the lower to upper level. To adapt to the anomalous tropospheric thermal distribution, an anomalous vertical ascending motion (Fig. 8a) and an anomalous cyclonic (anticyclonic) circulation of the lower (middle to upper) troposphere (Figs. 9a,c,e) occur above West Asia, which has also been thoroughly analyzed by Yang et al. (2021). Due to the anomalous ascending motion and meridional thermal gradient especially in the lower level above West Asia, enhanced southwesterly (northeasterly) flows appear in the lower (upper) troposphere over the oceanic regions (Figs. 9a,e). In the lower troposphere (Fig. 9e), the low-level jet extending across the equator and the Somali coast into the equatorial Arabian Sea is established, which is considered as a critical element of ISM circulation (Findlater 1969; Krishnamurti and Bhalme 1976; Murakami et al. 1984; Sandeep and Ajayamohan 2015; Rai et al. 2018). Accordingly, a monsoon trough is also generated over the southwest part of the Bay of Bengal. The surface of the oceanic regions and the Indian peninsula is dominated by an anomalous low pressure belt (Fig. 9e). In the upper troposphere (Fig. 9a), an easterly jet stream appears in the tropics due to the anomalous anticyclone over West Asia, which is another essential part of monsoon

![Figure 7](image-url)

**Fig. 7.** Anomalies of (a),(c) spring and (b),(d) early summer land skin temperature (K) from (top) ERA-20C and (bottom) NCEP–NCAR regressed onto the spring West Asian land surface thermal index (WALTI). All data have removed the long-term trends. Dotted areas are statistically significant at the 5% level based on Student’s t test.
The above analysis indicates that the simultaneous atmospheric dynamic and thermal anomalies associated with anomalous spring land surface warming over West Asia bring forward the transition from a cold to warm seasonal condition and favor the earlier onset of southwesterly monsoon.

To further explore the anomalous atmospheric features in early summer, Figs. 7–9 also give the regressions of the same variables in early summer. By comparing Figs. 7a,c and Figs. 7b,d, the anomalous land surface warming over West Asia decreases from spring to early summer. However, the anomalous spring tropospheric warming above West Asia lasts into early summer (Fig. 8b). Unlike the anomaly distribution in spring (Fig. 8a), the tropospheric warming of the upper level in early summer is higher than that of the lower level (Fig. 8b), which is probably due to the feedback of ISM. With the northward progress of monsoon, the surface low pressure belt in early summer not only controls the northern Indian peninsula, but also covers West Asia (Fig. 9). Consequently, it benefits the water vapor transport from the Arabian Sea to West Asia (Fig. 10a) and further favors the convection formation over West Asia (Fig. 8b), resulting in precipitation increase there (Figs. 3d,h). Yang et al. (2021) have...
FIG. 9. Anomalies of (a)–(d) geopotential height (colors; m) and (e),(f) sea level pressure (colors; hPa) and wind (black and gray vectors; m s$^{-1}$) at (top) 200, (middle) 500, and (bottom) 700 hPa in spring in (a), (c), and (e) and early summer in (b), (d), and (f) regressed onto the spring West Asian land surface thermal index (WALTI). The 850-hPa wind anomalies (purple vectors) over and around the oceanic regions (10$^\circ$S–25$^\circ$N, 40$^\circ$–95$^\circ$E) are also shown in (e) and (f). All data have been removed the long-term trends. Dotted areas (black and purple vectors) are statistically significant at the 5% (10%) level based on Student’s $t$ test.
pointed out that the thermal forcing of spring land surface warming over West Asia on the atmosphere above is not affected by negative feedback of the precipitation, which is primarily due to lack of water vapor supply. Thus, the increased early summer precipitation over West Asia weakens the anomalous warming in the lower troposphere and at the land surface (Figs. 7b,d and 8b). Meanwhile, the enhanced latent heating release from the precipitation makes for the strengthening (maintaining) of the anomalous warming in the upper (middle) troposphere. Consequently, the anomalous tropospheric meridional thermal gradient persisting from spring to early summer further promotes the development of the summer monsoon. In Fig. 9f, as the intensified cross-equatorial low-level jet in early summer passes the Somali coast into the northern Arabian Sea, the monsoon trough also shifts northward, extending from the northern part of Bay of Bengal to northern India. As illustrated by Fig. 10a, the enhanced monsoon trough guides the water vapor transport from the Arabian Sea and the Bay of Bengal to northern India, leading to moisture divergence over the ocean and moisture convergence over northern India. Accordingly, there exists intensive convection accompanied by convergence circulation, which can be seen from the OLR anomalies (Fig. 10b). As a result, the early summer monsoon precipitation increases over northern India.

On the other hand, Dai et al. (2013) have discovered a bigger role of the upper troposphere in driving the ISM because the summer thermal structure and winds over South Asia show larger land–sea thermal contrast in the upper troposphere than in the lower troposphere, which is consistent with Figs. 8b, 9b, and 9f. Therefore, we further analyzed the possible effects of anomalous circulation in the upper troposphere on the Indian monsoon precipitation in early summer. Comparison between Figs. 9a and 9b suggests that the anomalous anticyclone in the
upper troposphere narrows northwardly from spring to early summer, perhaps due to the transition of westerly jet stream (Yang et al. 2021) and the northward progress of the monsoon, while the intensity of anticyclone remains stable, suggesting the persistence of the low-frequency circulations forced by land thermal anomalies. Additionally, the monsoon heating has a vital effect on generating the Gill-type Rossby wave pattern to its northwest, and this pattern features a surface low pressure and an upper-tropospheric high pressure (Gill 1980; Rodwell and Hoskins 1996; Joseph and Srinivasan 1999; Enomoto et al. 2003; Ding and Wang 2005, 2007). To investigate the possible impact of enhanced northern Indian precipitation on maintaining strong upper-level positive height anomalies over West Asia, Fig. 10c gives the regressed vertical integral of apparent moisture sink $\langle Q^2 \rangle$ in early summer onto the NIPI. It is obvious that the precipitation over northern India increases the latent heat release there. On this basis, $\langle Q^2 \rangle$ averaged over 23°–35°N, 76°–95°E (the rectangle region shown in Fig. 10c) was standardized as index QI, and Fig. 10d further shows the regression of 200-hPa geopotential height from QI. The enhanced monsoon heating corresponds to the positive anomalies over West Asia, which favors the maintenance of upper-tropospheric anticyclonic circulation in early summer. Meanwhile, the tropical easterly jet also intensifies (Fig. 9b), indicating the strengthening of monsoon. Furthermore, the South Asian high (SAH) is a large-scale anticyclone system in the upper troposphere over South Asia, whose intensity variations and location shifts are usually described at 100 hPa since the SAH is the strongest and the steadiest circulation system at the 100-hPa level besides the polar vortex (Mason and Anderson 1963; Zhang et al. 2002). To explore the possible response of the SAH in late spring and early summer to the anomalous upper-tropospheric anticyclone caused by land surface thermal forcing, Fig. 11 depicts the composites of May and June 100-hPa geopotential height from the eight warmest years (1977, 2000, 2001, 2002, 2004, 2006, 2008, 2010) and eight coolest years (1957, 1960, 1967, 1968, 1969, 1972, 1976, 1992) during 1951–2010 based on WALTI, and Student’s $t$ test was performed on the differences (composites minus climatologies). It is noteworthy that the original data of geopotential height were used here to capture the SAH. When the land surface in springtime anomalously warms over West Asia, the SAH in late spring (Figs. 11a, c) and early summer (Figs. 11b, d) relatively strengthens and moves toward West Asia due to the anticyclonic anomalies there (figures not shown for brevity). Zhang et al. (2002) raised that the SAH is a warm high and its center has the property of the heat preference (i.e., it usually propagates to the area with relatively larger heating rates). Based on the thermotaxis of SAH, summer SAH usually exhibits two dominant modes, with its main body located over the Tibetan Plateau (the Tibetan mode) and the Iranian Plateau (the Iranian mode), respectively (Qian et al. 2002; Zhang et al. 2002; Yan et al. 2011; Wei et al. 2014). The Iranian mode always corresponds to above-normal Indian monsoon precipitation (Wei et al. 2014, 2015). Therefore, anomalous spring land surface warming favors early summer precipitation over northern India by driving the SAH to shift northwestward and

![Fig. 11. Composites of (a),(c) May and (b),(d) June 100-hPa geopotential height (m) from the (top) eight coolest years and (bottom) eight warmest years during 1951–2010 based on the spring WALTI. Dotted areas are the statistically significant areas for the differences (composites minus climatologies) at the 5% level based on Student’s $t$ test.](image-url)
inducing the occurrence of the SAH’s Iranian mode in early summer (Figs. 11b,d).

It has been thus concluded that there are two possible pathways via which spring land surface thermal anomalies affect the northern Indian precipitation in early summer. On the one hand, anomalous spring land surface warming over West Asia encourages earlier onset of the southwesterly monsoon circulation by heating the atmosphere above and increasing meridional thermal contrast, resulting in above-normal precipitation over northern India in early summer. On the other hand, spring land surface warming over West Asia favors the enhancement of tropical easterly jet and the northwestward development of SAH through the thermal-driven anticyclone lasting from spring to early summer above West Asia (Yang et al. 2021). The intensified easterly jet and SAH dynamically couples with the lower-middle-level monsoon systems, further affecting the precipitation.

5. Numerical simulations

Based on the observational results above, the tropospheric warming induced by land surface heating over West Asia is an important driver to promote the monsoon onset. Nevertheless, the eastward propagating stationary Rossby wave may also generate the tropospheric warming (Rai et al. 2015; Hong et al. 2017). To verify the local processes related to the land surface thermal forcing, several numerical experiments were conducted. A series of sensitivity experiments (SEN) were designed to characterize the anomalous land surface warming over West Asia, and the differences between CTL and SEN (SEN minus CTL) are given to further explore the responses of early summer Indian monsoon to West Asia land surface heating in spring and investigate the associated mechanism.

First, Fig. 12 illustrates the spatial patterns of the climatologies for typical variables from the CTL and observations, respectively. As seen in Figs. 12a1–a5 and 12b1–b5, the simulated land surface thermal conditions in spring and the atmospheric dynamic/thermal conditions in early summer are generally consistent with the observations. The main features of the spatial pattern of early summer precipitation are also well reproduced by the model although there are systematic differences over the location and intensity (Figs. 12a6,b6). In general, the CTL can capture the basic states of both land surface and the atmosphere in the study area.

The numerical experiments of Yang et al. (2021) demonstrated an additional land surface sensible heat (hereafter SH) forcing of 30 W m\(^{-2}\) can effectively and rationally represent the anomalous land surface warming over West Asia in spring. To verify such a hypothesis, Fig. 13 shows composites of observed spring precipitation and land surface SH between anomalous warming and land surface SH of 30 W m\(^{-2}\) as shown in Fig. 13a. That further proves the rationality of 30 W m\(^{-2}\) SH forcing. Therefore, the SH forcing of 30 W m\(^{-2}\) was added in the elliptic region, which includes the target region of West Asia (45°–70°E, 30°–40°N) from March to May (Figs. 14a1–a3). As illustrated by Figs. 14b1–b3, the ground temperature anomalously increases with the positive SH forcing, indicating the feasibility of experimental design in this study. In addition, the land surface thermal anomalies disappear with the arrival of early summer (Figs. 14a4,b4), suggesting that the land surface warming over West Asia decreases from spring to early summer, which corroborates the foregoing.

To figure out whether or not the land surface thermal anomalies can affect the atmosphere, Figs. 14c1–c3 and 14d1–d3 further illustrate the latitude–height cross section of anomalous spring air temperature and vertical velocity (omega) averaged along 45°–70°E. Along with the surface heating from March to May, the atmosphere above gradually warms and generates ascending motion from the lower to upper level. Consequently, the spring-averaged tropospheric thermal distribution shows significant warming in the whole layer, and the warming in the lower layer is stronger than that in the upper layer. Meanwhile, the spring-averaged vertical velocity (omega) exhibits negative anomalies above West Asia but positive anomalies over the Arabian Sea (figures not shown for brevity). These results indicate that the land surface warming could not only heat the atmosphere directly, but also stimulate the convection, which is consistent with the observational result in Fig. 8a. Moreover, cyclonic (anticyclonic) circulation anomalies emerge in the lower (middle-upper) troposphere due to the thermal adaptation process. The anomalous vortexes are gradually enhanced as the thermal forcing persists, in which the anticyclone of the upper troposphere further favors the enhancement of the tropical easterly jet (Figs. 15a1–a3,b1–b3,c1–c3). Figure 15 also shows the simulated horizontal wind in spring. Corresponding to the anomalous vertical field and the land–sea meridional thermal gradient, the southwesterly (northeasterly) wind appears in the lower (upper) troposphere above the Arabian Sea due to the compensation effect, which is in turn beneficial to the development of the low-level jet and monsoon trough. As described above, the atmospheric thermal and dynamic conditions respond to the anomalous land surface heating from March to May, advancing the atmospheric transition from cold to warm season and benefiting the onset of southwesterly monsoon.

From late spring to early summer, with the monsoon advancing northward, the warm anomalies in the middle-upper troposphere above West Asia persist, while cold anomalies appear in the lower level (Fig. 14c4), which proves that the increased precipitation over West Asia in early summer (Fig. 17c) produces negative feedback to the land thermal forcing. Notably, the cooling anomalies in lower troposphere indicate stronger feedback in simulation than in observation. Moreover, the ascending motion anomalies over West Asia in early summer weaken compared to that in spring (Fig. 14d4), which is also different from the observation (Figs. 8a,b). It is indicated that the stronger negative feedback of precipitation to surface heating over West Asia in model simulations leads to the conversion of vertical thermal gradient.
The weakening of ascending motion anomalies from spring to early summer. We also noted that, with the land surface heating in spring, the descending motion over the Arabian Sea occurring in March and strengthening in April turns into an ascending motion in May, which continues until June (Figs. 14d1–d4). The conversion of vertical motion above the Arabian Sea during spring and early summer is perhaps due to the ocean–atmosphere interaction, and the interaction intensity in the model may impact on the simulated monsoon circulations. By comparing Fig. 9e and Figs. 15c1–c3, we found that the simulated lower-level jet in spring locates more northwesterly than the observed, leading to stronger moisture transportation to...
West Asia and stronger negative feedback of increased precipitation to surface heating there, which is not conducive to further monsoonal development. As a result, in simulations, a lower-level jet crossing the equator and the Somali coast into the Arabian Sea is gradually established in spring (Figs. 15c1–c3), but it weakens in early summer. The significant jet is mainly located along the southeast coast of the Arabian Peninsula (Fig. 15c4). Correspondingly, a monsoon trough embedded in an anomalous cyclone is generated over the northern Bay of Bengal and northern India (Fig. 15c4). This accords with the distribution of reanalysis results (Fig. 9f). In addition, the intensified monsoon trough and cyclone over northern India tend to induce moisture convergence and intensive convection there (Figs. 17a,b), which is also consistent with observation (Figs. 10a,b).

On the other hand, the anomalous anticyclone and tropical easterly jet in the upper level persist into early summer. The anticyclone narrows northwardly due to the guidance of westerly jet stream and monsoon, making the tropical easterly jet shift northwardly as well (Fig. 15a4), which is basically consistent with observations. Moreover, Fig. 16 depicts the composites of 100-hPa geopotential height in May and June from CTL and SEN, respectively. As shown in the comparison of Fig. 16a with Fig. 16c, corresponding to the upper-level anticyclonic warm circulation in late spring, the center of SAH in May moves from the east to the middle of the north Indian Peninsula, and the western edge of SAH extends from the northeast Arabian Sea to the southeast Arabian Peninsula, illustrating the extension of SAH to the warming area. With the arrival of early summer, the SAH further expands northwestward (Figs. 16a,b), and this propagation also anomalously strengthens with the occurrence of anticyclonic warm circulation at the northwest side of SAH (Figs. 16b,d). It is thus demonstrated that the spring land heating forcing over West Asia could favor the anomalous intensification and northwestward shifting of SAH via the anomalous heat-driven circulation above West Asia. Furthermore, the SAH in early summer mainly controls the northern Indian peninsula (Fig. 16d), benefiting the wet instability and convective activity there (Figs. 17a,b).

The simulated early summer precipitation associated with anomalous spring land surface warming is shown by Fig. 17c. As a result of the land surface thermal forcing over West Asia in spring, positive precipitation anomalies occur over northern India. Compared with observational results (Fig. 3), the location of positive anomalies is slightly southward, perhaps due to the inaccurate simulation of the monsoon trough. Despite slight deviations of the anomalous center between the model and observational results, the main features of precipitation responses are well simulated by the model.

Generally, numerical simulations can reproduce the observational results and corroborate the possible physical pathways. The anomalous spring land surface warming can cause anomalous summer monsoon activity, and further contribute to increase of early summer precipitation over northern India. In addition, sensitivity experiments with 30 W m$^{-2}$ SH forcing (NSEN) were also conducted. For brevity, only the simulated variables that are the same as those in Fig. 15 are shown. As seen in Fig. 18, the land surface anomalous cooling over West Asia in spring can lead to the significant weakening of Indian monsoon circulation in early summer, and the order of magnitude of anomalous circulations from NSEN is consistent.
FIG. 14. Differences (SEN minus CTL) in (a) sensible heat (W m$^{-2}$) and (b) ground temperature (K) and latitude–height cross section of (c) air temperature (K) and (d) vertical velocity (omega) (Pa s$^{-1}$) averaged along 45$^\circ$–70$^\circ$E, where numbers 1, 2, 3, and 4 represent March, April, May, and June, respectively. Dotted areas are statistically significant at the 5% level based on Student’s $t$ test.
with that from SEN, which further verifies the mechanisms proposed.

6. Conclusions and discussion

Based on statistical analysis and numerical simulations, the possible impacts of spring land surface thermal anomalies over West Asia on the Indian early summer monsoon have been explored. Results show that the spring land surface thermal condition over West Asia is closely associated with the first leading EOF mode of Indian early summer monsoon precipitation; that is, the land surface warming of West Asia corresponds to evidently increased precipitation over northern India. Further analysis suggested two possible pathways by which spring land surface warming over West Asia affects early summer Indian monsoon precipitation. On the one hand, the underlying surface abnormal warming heats the atmosphere above by enhancing sensible heat and longwave radiation (Yang et al. 2021), leading to increased meridional land–sea thermal contrast that persists from spring to early summer, and bringing forward a transition from cold-season to warm-season atmospheric conditions. As a result, a southerly monsoon flow is induced in the lower troposphere, which is characterized as the intensified cross-equatorial low-level jet extending from Somalia to the Indian

FIG. 15. Differences (SEN minus CTL) in (a),(b) geopotential height (colors; m) and (c) sea level pressure (colors; hPa) and wind (black and gray vectors; m s\(^{-1}\)) at 200 hPa in (a), 500 hPa in (b), and 700 hPa in (c), in which numbers 1, 2, 3, and 4 represent March, April, May, and June, respectively. The 850-hPa wind differences (purple vectors) over and around the oceanic regions (10°S–25°N, 40°–95°E) are also shown in (c1)–(c4). Dotted areas (black and purple vectors) are statistically significant at the 5% (10%) level based on Student’s t test.
peninsula and the monsoon trough stretching from the northern Bay of Bengal to northern India in early summer. Consequently, an anomalous cyclonic circulation and convection appear over northern India, bringing the necessary moisture for monsoon precipitation there. On the other hand, as Yang et al. (2021) suggested, the spring land surface thermal forcing could induce anomalous anticyclonic circulation in the upper troposphere via the thermal adaptation process, which benefits the strengthening of tropical easterly jet and favors the enhancement and northwestward shift of the early summer South Asian high (SAH).

![FIG. 16. Composites of (a),(c) May and (b),(d) June 100-hPa geopotential height (m) from (top) CTL and (bottom) SEN, respectively. Dotted areas in (c) and (d) are the statistically significant areas for the differences between CTL and SEN at the 1% level based on Student’s t test.](image)

![FIG. 17. Differences (SEN minus CTL) in (a) relative humidity (%) at 1000–500 hPa, (b) vertical velocity (omega; Pa s⁻¹) at 500 hPa, and (c) precipitation (mm day⁻¹) in early summer. Dotted areas are statistically significant at the 5% level based on Student’s t test.](image)
The dynamic coupling of anomalous circulations in upper and lower levels results in stronger monsoon and above-normal precipitation over northern India.

The sensitivity experiments were further designed to verify the observational results. Under the background of climatological sea surface temperature, we conducted ensemble runs in which the single positive forcing of land surface sensible heat was added over West Asia during spring, changing the land surface thermal fields and land–atmosphere thermal difference. Consequently, the simulated atmosphere above West Asia warms anomalously from the lower to upper level, which promotes the increase of meridional land–sea thermal contrast and provides the necessary thermal conditions for the early onset of monsoon. Additionally, with the continuous thermal forcing from land surface, the anticyclonic (cyclonic) anomalies are gradually generated and strengthened in the middle to upper (lower) troposphere, leading to the intensification of tropical easterly jet and favoring the monsoon onset. Meanwhile, the upper-level SAH in late spring and early summer exhibits a northwestward shift due to the anomalous anticyclonic circulations above West Asia and the thermotaxis of the SAH, providing a favorable condition for the Indian monsoon as well. The anomalous water vapor convergence and ascending motion corresponding to the monsoon circulations are responsible for the increase of Indian precipitation in early summer. The simulated results further confirmed the influence pathways derived from the observation.

In this study, we investigated the possible causes of Indian early summer monsoon precipitation from the perspective of spring land surface thermal anomalies over West Asia based

FIG. 18. As in Fig. 15, but the differences are the results of NSEN minus CTL.
on statistical methods and numerical simulations. The relevant physical mechanism illustrated by Fig. 19 has been proposed. The anomalous land surface warming can drive an early onset of Indian monsoon by increasing land–sea thermal contrast (Meehl 1994; Xavier et al. 2007; Zuo et al. 2012; Rai et al. 2015; Moon and Ha 2019) and adjusting dynamic circulations, which brings about increased precipitation in northern India. At the same time, with the establishment of monsoon in early summer, the latent heat released by enhanced precipitation over West Asia and the Gill-type Rossby wave excited by monsoon heating over northern India are conductive to the continuation of anomalous upper-level anticyclone over West Asia from spring to early summer, thus forming positive feedback for the development of monsoon. Notably, Yang et al. (2021) discovered that the land surface warming anomalies over West Asia in spring can cause a baroclinic disturbance in the atmosphere above and further excite Rossby waves, which benefits the enhancement of circumglobal teleconnection (CGT) and further affects the climate over northern China. The relative contributions of premonsoon land surface heating over West Asia and monsoon heating to early summer CGT deserve further exploration for improving the physical framework of the West Asia–northern China teleconnection.

It is noted that the middle–upper tropospheric warming above West Asia can persist from spring to early summer, while the warming of the lower-level atmosphere disappears due to the negative feedback of the monsoon precipitation. However, this feedback in the model simulations is linked with both the distribution of land surface thermal forcing and the ocean–atmosphere interaction. For the former, the location and shape of forcing decide the position and direction of lower-level jet, and then further affect the water vapor transportation. It has been found that the signals of spring land surface heating anomalies in our simulations mainly appear in the target region of West Asia that we defined. The range of those signals is relatively smaller compared with that of the anomalous positive skin temperature in the observation. Therefore, a more rational forcing is required to characterize the heating from the land to the atmosphere in further exploration. As for the role of ocean–atmosphere interaction in simulated results, it is indicated that the land surface heating over West Asia can drive meridional circulations that influence the surface conditions of the Arabian Sea, and the oceanic adaption processes then react on the atmosphere above, which could further affect the development of monsoon. As the climatological sea surface temperature was used in our simulations, there are certain differences between the simulated Indian monsoon and that from the reanalysis results. Taking the ocean–atmosphere coupling into consideration in the follow-up work may help capture the processes resulting in land–sea thermal contrast anomalies. Moreover, it is noticed that the spatial pattern of the simulated precipitation is not exactly the same as the observation. Apart from the possible sources of the deviation discussed above, another source may come from the model uncertainty related to the model-dependent land–atmosphere coupling. Therefore, similar experiments with other climate models may increase the confidence in this finding.

Our study highlighted the role of antecedent land surface thermal conditions over West Asia in Indian early summer...
monsoon precipitation anomalies. Meanwhile, previous studies have investigated the effects of other factors, such as the Tibetan Plateau heating (Rajagopalan and Molnar 2013) and local dry/wet conditions (Saha et al. 2011). Taking the synergistic effect of multiple factors into consideration may advance the understanding of Indian monsoon precipitation in early summer, which deserves further investigation. Besides, dust loading has increased considerably during past decades over West Asia (Hsu et al. 2012), and studies suggested that there is also a close connection between the aerosols over West Asia and the Indian summer monsoon (Jin et al. 2014; Vinoj et al. 2014; Jin et al. 2016). Jin et al. (2014) highlighted that the dust-induced atmospheric heating centered over West Asia can enhance the meridional thermal contrast and strengthen the Indian summer monsoon circulation and precipitation. Hence, the possible role of aerosols in the process by which the land thermal condition over West Asia drives the Indian summer monsoon is also worthy of further exploration.

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Data availability statement. The ERA-20C reanalysis can be acquired at https://apps.ecmwf.int/datasets/data/era20c-moda/levtype=sfc/type=an; the CRU-Ts4.02 is available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.02; the ISMIS surface global temperature anomaly product can be downloaded from https://psl.noaa.gov/data/gridded/data. The COBESSST is from https://psl.noaa.gov/data/gridded/data.cobe.html. The NOAA precipitation data are available at https://www.esrl.noaa.gov/psd/data/gridded/data.precl.html; the GPCC rainfall is available at https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html; the UDel-v5.01 data can be downloaded from https://psl.noaa.gov/data/gridded/data.udel-AirT_Precip.html. The NCEP–NCAR reanalysis dataset can be acquired from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html, and the outgoing longwave radiation dataset is available at https://psl.noaa.gov/data/gridded/data.olrder.interp.html.

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