Atmospheric Circumglobal Teleconnection Triggered by Spring Land Thermal Anomalies over West Asia and Its Possible Impacts on Early Summer Climate over Northern China

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ABSTRACT: The Eurasian continent experienced significant warming during the past decades. West Asia is located in an arid/semiarid zone, and its warming amplification has drawn considerable attention. However, the climatic effect of such a warming is not clear yet. In this study, we explored the possible impacts of recent land surface warming over West Asia on the atmospheric general circulation and climate. Results show that abnormal spring land surface warming over West Asia tends to increase precipitation over North China and decrease (increase) precipitation (air temperature) over Northeast China in early summer (June). It is noted that the precipitation anomalies are much stronger over the eastern region of North/Northeast China. Further analysis suggests that abnormal spring land surface warming can trigger eastward-propagating disturbances via diabatic heating, which intensifies the atmospheric circumglobal teleconnection (CGT) pattern, causing anomalous circulation and climate in early summer over northern China. Sensitivity experiments demonstrate that abnormal spring land surface warming can increase the atmospheric baroclinic instability and trigger Rossby waves that propagate along the westerly jet stream (WJS), resulting in the formation of CGT. Due to persistent land surface thermal forcing and the interaction between the basic flow (especially the WJS) and CGT, the CGT tends to be intensified. The anomalous wave center over East Asia in early summer is responsible for the precipitation increases (decreases) over North (Northeast) China and the evident warming in Northeast China. Our results suggest that the spring land surface thermal anomalies over West Asia can be a potential signal for short-term prediction of early summer climate over northern China.

KEYWORDS: Land surface; Atmosphere-land interaction; Teleconnections; Dynamics; Climate variability

1. Introduction

The land thermal conditions are crucial to control the energy transfers between the ground and the atmosphere (Cohen and Rind 1991; Matsui et al. 2003; Amenu et al. 2005; Orlowsky and Seneviratne 2010; Gao et al. 2010; Williams et al. 2012). As an essential thermal parameter (Santanello et al. 2018), the land surface temperature is closely linked to both regional climate (Zhu et al. 2008; Wu et al. 2009; Liu et al. 2012; Zhu et al. 2012; Xue et al. 2016; Roxy 2017; Chen et al. 2017; Xue et al. 2018; Chen et al. 2019, 2020) and many atmospheric teleconnection phenomena (Zhou et al. 2002; Wang and He 2015; Zhao et al. 2016; Zhang et al. 2018, 2019). Under the background of global warming (IPCC 2013), the land surface warming over the Eurasian continent has aroused widespread concern, in which West Asia is one of areas with most significant warming (Hansen et al. 2010; Cohen et al. 2012; Hong et al. 2017). West Asia (35°–75°E, 12°–45°N, Fig. 1a), which mainly consists of mountains and deserts (Pal and Eltahir 2015), belongs to the arid/semiarid climate zone (Agrawala et al. 2001; Barlow et al.

2002; Mishra and Singh 2010; Golian et al. 2015; Barlow et al. 2016). Zhou et al. (2015) and Zhou et al. (2016) detected that the land warming rate over the drier ecoregions is stronger, suggesting warming amplification over arid/semiarid zones. Meanwhile, Marcella and Eltahir (2012) highlighted the contribution of land surface processes to reshape the climate over West Asia. These results indicated that the possible climatic effects of land surface anomalous warming over West Asia deserve further exploration.

Previous studies pointed out that land surface thermal conditions over West Asia have crucial impacts on the local climate. Zaitchik et al. (2007) found that the heat-driven circulation triggered by the Zagros Plateau benefits the rainfall increase and warming over the Middle East Plain to its west. Liu et al. (2017) discovered that the summer sensible heating over the Iranian Plateau can heat the atmosphere over this region and favor the water vapor transport from the Arabian Sea, resulting in more (less) precipitation over the Iranian Plateau (the Arabian Sea). Located at the climatological position of the South Asian high (Zhang et al. 2002; Shi and Qian 2016), the Iranian Plateau can evidently influence the Indian and East Asian summer monsoons via its thermal effect (Wu et al. 2012; Wei et al. 2015). However, most of the previous studies emphasized the role of summer land surface thermal over West Asia. In fact, spring is the strongest warming season over West Asia (Fig. S1 in the online supplemental material; Cohen et al. 2012), and the spring land surface temperature shows large variability (Figs. 1b,c) relative to other seasons (Fig. S2). Moreover, Wang et al. (2018) found that there was a significant negative correlation between the spring land thermal anomalies over West Asia and the early summer cold

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FIG. 1. Geographic distribution of (a) topography (m) from NOAA, (b) standard deviation of spring land skin temperature (K), and (c) standard deviation of spring soil temperature (level 1–3 averaged; K) over West Asia (35° – 75° E, 12° – 45° N) based on the ERA-20C.

vortex over Northeast China. Further analysis indicated that anomalous land surface thermal forcing may result in abnormal atmospheric circulation and further affect the cold vortex activity via the circumglobal teleconnection (CGT) pattern in early summer, but the specific physical processes are not well understood. On the other hand, both the general circulation and climate over northern China exhibit evident differences between early and late summer (Wang et al. 2009; Shen et al. 2011; Zhao et al. 2018). Affected by the intraseasonal activity of the East Asia summer monsoon (EASM), the rain belt in June is mainly located in the middle and lower reaches of the Yangtze River basin, and the rainy season of northern China begins in July together with the northward advancement of EASM (Wang and Ho 2002; Ding and Johnny 2005; Yu and Zhou 2007). As a result, the early summer climate over northern China is affected by not only the EASM but also middle- to high-latitude systems, such as cold vortex activity (Shen et al. 2011; Zhao et al. 2018; Fang et al. 2018). With this in mind, here we aim to explore the possible teleconnection between the spring land surface thermal condition and early summer climate over northern China as well as its relevant mechanisms.

Based on Wang et al. (2018), the CGT pattern may play an important role in the teleconnection between the spring land surface thermal condition and early summer climate over northern China. Ding and Wang (2005) defined the CGT as the one-point correlation map of 200-hPa summer geopotential height anomalies around the Northern Hemisphere with reference to the geopotential height over parts of West Asia (60° – 70° E, 35° – 40° N), which tends to be composed of zonal wavenumber-5 structure, with six prominent “centers of action” located over West Asia, East Asia, the North Pacific, North America, western Europe, and European Russia. Previous studies have pointed out that the CGT anomalies are accompanied by abnormal rainfall and air temperature in the continental regions of centers of action (Ding and Wang 2005, 2007; Chen and Huang 2012) and associated with the occurrence of extreme events (Trenberth and Fasullo 2012; Petoukhov et al. 2013; Teng et al. 2013; Screen and Simmonds 2014; Wang and He 2015; Lee et al. 2017). Therefore, seeking the forcing sources of the CGT

appears to be crucial for the weather and climate prediction in relevant regions (Beverley et al. 2019). Based on the definition, the CGT is closely related to the atmospheric low-frequency circulation over West Asia. Many studies have demonstrated that this wave packet starts in West Asia and then propagates eastward (Enomoto et al. 2003; Enomoto 2004; Sato and Takahashi 2006; Chen and Huang 2012), so that the diabatic heating (Enomoto et al. 2003; Saeed et al. 2011) over West Asia contributes to the formation of CGT. Moreover, the Indian summer monsoon (ISM) heating generates the Gill-type Rossby wave pattern over West Asia, which is also a potential wave source of CGT (Ding and Wang 2005, 2007; Lin 2009; Wang et al. 2012; Chen and Huang 2012). However, Yasui and Watanabe (2010) designed numerical experiments and indicated that the key region where the simultaneous diabatic heating contributes most to the CGT is West Asia instead of India. Considering the contributions of external forcing, ENSO (Ding et al. 2011; Lee and Ha 2015) and the North Atlantic (Stephan et al. 2019) and Indian (Yang et al. 2009) sea surface temperature anomalies can induce CGT indirectly, by modulating the ISM to trigger the wave source over West Asia. However, there are wave phase differences in CGT anomalies caused by different forcing sources, so the effects of forcing sources on the CGT remain as important research topics (Yasui and Watanabe 2010; Kosaka et al. 2012). Starting from the possible influence of the underlying surface, Wang et al. (2018) suggested a new idea, namely that the previous land surface thermal condition over West Asia may be an external forcing to form the CGT and further affect the climate over northern China. Based on the results given by Wang et al. (2018), we propose the following questions: 1) Do the spring land surface thermal anomalies over West Asia connect with the early summer (June) climate (precipitation and air temperature) over northern China? 2) If the connection exists, what is its possible physical mechanism? And what role does the early summer CGT play in it?

The remaining sections of this paper are structured as follows. Section 2 introduces the datasets, methods, model description, and numerical experiments. Section 3 explores the relationship between spring land surface thermal anomalies over West Asia

TABLE 1. Statistics of various IMFs of WALTl (calculated with the land skin temperature from ERA-20C), NCPI, NECPI, and NECTI (calculated based on NCC station data) given by the EEMD. One asterisk (*) means statistically significant at the 5% level and two asterisks (**) statistically significant at the 1% level.

EEMD modes	Effective degrees of freedom/ covariance/correlation between WALTl and NCPI	Effective degrees of freedom/ covariance/correlation between WALTl and NECPI	Effective degrees of freedom/ covariance/correlation between WALTl and NECTI
IMF1 (2–3 yr)	32/0.184/0.351*	39/−0.104/−0.193	34/0.170/0.348*
IMF2 (5–6 yr)	26/0.005/0.051	30/−0.048/−0.512**	29/0.025/0.307
IMF3 (10–12 yr)	5/0.032/0.401	5/−0.023/−0.308	6/0.019/0.576
IMF4 (19–35 yr)	2/0.001/0.054	1/−0.010/−0.201	1/0.015/0.845
IMF5 (long-term trend)	0/−0.038/−0.879	0/−0.053/−0.561	0/0.285/0.97

and early summer climate over northern China, and the possible mechanisms are further discussed in section 4. To further support the findings in sections 3 and 4, section 5 presents the results of numerical experiments and the relevant analysis. Finally, conclusions and discussion are given in section 6.

2. Datasets and methods

a. Datasets

In this study, both observational data and reanalysis data are obtained to analyze precipitation and temperature over northern China: 1) observational precipitation and temperature data at 160 stations, provided by the National Meteorological Information Center of China (NCC; https://cmdp.ncc-cma.net/nccdownload/data_160.php); 2) the National Oceanic and Atmospheric Administration precipitation reconstruction data over land (NOAA-PREC/L) (Chen et al. 2002), and the Global Precipitation Climatology Centre (GPCC) rainfall dataset derived from global station data (Schneider et al. 2015), with a horizontal resolution of $1^\circ \times 1^\circ$; 3) the near-surface temperature at 2 m from the European Centre for Medium-Range Weather Forecasts Atmospheric reanalysis of the twentieth century (ERA-20C) (Poli et al. 2016) on a horizontal resolution of $1^\circ \times 1^\circ$ and 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 land datasets used include 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), soil temperature level 3 (layer between 28 and 100 cm below land surface), surface upward sensible heat flux and surface net upward longwave flux from ERA-20C on a horizontal resolution of $1^\circ \times 1^\circ$, and surface net shortwave radiation flux from the National Centers for Environmental Prediction–National Center for Atmosphere Research (NCEP–NCAR) dataset (Kalnay et al. 1996) with a horizontal resolution of $2.5^\circ \times 2.5^\circ$. The atmospheric datasets are provided by the NCEP–NCAR and ERA-20C, in which the air temperature, geopotential height, u wind, v wind, omega, and total cloud cover data are from NCEP–NCAR and the vertical integral of water vapor flux as well as divergence of moisture flux are from the ERA-20C. All the data used in this paper are monthly mean data chosen from the period of 1951–2010. Moreover, the ETOPO orography height data are provided

by NOAA (Amante and Eakins 2009) with a horizontal resolution of $0.16^\circ \times 0.16^\circ$.

b. Methods

The main statistic tools used in this study include singular value decomposition (SVD) analysis, Pearson correlation analysis, linear regression analysis, composite analysis, and Student's t test.

Using the ensemble empirical mode decomposition (EEMD) methods (Wu and Huang 2009), the multiscale variations of the teleconnection between spring land surface temperature over West Asia and early summer precipitation/air temperature over northern China are investigated. To avoid the autocorrelation of intrinsic mode functions (IMFs) in the EEMD analysis, the effective sample sizes (N^*) of IMF $_i$ ($i = 1, 5$) between the spring West Asia land surface thermal index (WALTl-IMFi) and the early summer North China precipitation index (NCPI-IMFi), the early summer Northeast China precipitation index (NECPI-IMFi), and the early summer Northeast China temperature index (NECTI-IMFi) were computed following Bretherton et al. (1999): $N^* = N(1 - r_1r_2)/(1 + r_1r_2)$, respectively, where N is the number of available time steps, r_1 is the lag-one-step autocorrelation of WALTl-IMFi ($i = 1, 5$), and r_2 is the lag-one-step autocorrelation of NCPI-IMFi/NECPI-IMFi/NECTI-IMFi ($i = 1, 5$). The corrected sample sizes (the effective degrees of freedom) are shown in Table 1.

The wave activity flux (WAF) is a useful diagnostic tool to illustrate stationary or migratory quasigeostrophic wave disturbances and reveal where anomalous waves are emitted, absorbed and transferred (Plumb 1985). It was defined as

$$\text{WAF} = \begin{cases} F_\lambda = \frac{P}{2000a^2 \cos \varphi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \\ F_\varphi = \frac{P}{2000a^2} \left(\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right) \end{cases},$$

where F_λ is the zonal component of WAF, F_φ is the meridional component of WAF, ψ' is the disturbance streamfunction, P is the pressure, φ is the latitude, λ is the longitude, and a is the radius of Earth.

c. Model description and numerical experiments

Numerical simulations presented in this study were performed using the Community Earth System Model version 1.2.2 (readers

are referred to <http://www.cesm.ucar.edu/models/cesm1.2/> for more details). The component was set to F_2000_CAM5, which includes 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), applied with a horizontal resolution of f09_g16 ($0.9^\circ \times 1.25^\circ$).

The numerical simulations were climatological, which consist of the control (CTL) and sensitivity experiments. First, the CTL experiments were driven by cyclic present-day (circa year 2000) forcing with identical prescribed sea surface temperature (SST) from the Hadley Center (Rayner et al. 2003), and other external forcing data were also provided by the model developer (Hurrell et al. 2013; <https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/>). In CTL, the model ran for 100 years, and results were saved at monthly intervals.

Because the focus of this study is the local and nonlocal atmospheric response caused by the spring land surface anomalous warming over West Asia, 100-member ensemble runs were conducted in the sensitivity experiments based on CTL. In each subset run, the model was integrated from 1 March to 30 June, whose initial field was obtained from each 1 March in CTL. Meanwhile, the land surface upward sensible heat (SH) forcing of 30 W m^{-2} was added in the target region of West Asia ($45^\circ\text{--}70^\circ\text{E}$, $30^\circ\text{--}40^\circ\text{N}$) at each time step of spring to represent the surface heating from land over there. The SST and other external forcing data were all consistent with the CTL.

3. Teleconnection between early summer climate anomalies over northern China and spring land surface thermal anomalies over West Asia

In this study, northern China refers to the region to the east of 108°E and north of 34°N . Taking 40°N as the boundary, the northern part of northern China is referred to as Northeast China, while the southern part of northern China is called North China. To investigate the coupling relationship between early summer climate anomalies over northern China and spring land surface thermal anomalies over West Asia, we performed the SVD analysis on them, and removed the long-term trend of the data before the SVD analysis. Figure 2 presents the standardized time series and heterogeneous correlation maps of the first leading SVD mode between spring land surface temperature over West Asia and early summer (June) precipitation/air temperature over northern China, in which the spring land surface temperature are from ERA-20C and CRU while the early summer precipitation and air temperature are from the NCC station. The first mode can generally represent the relationships between the spring land surface temperature over West Asia and the early summer precipitation and air temperature over northern China, as it accounts for 44.52% and 82.88% (57.00% and 88.07%) of the total variance for ERA-20C (CRU) data, respectively. As seen in Figs. 2a(1) and 2a(2), there are significant positive correlations between the time series of the leading SVD modes of the spring land surface temperature over West Asia and the early summer precipitation and air temperature over northern China, with correlation coefficients of 0.49 and 0.51 (0.54 and 0.50) at the 1% level according to Student's *t* test for ERA-20C

(CRU) data respectively. Furthermore, the heterogeneous correlations are given in Figs. 2b–e. In Figs. 2b(1)–2e(1), positive (negative) correlations between the spring land surface temperature over West Asia and the rainfall over North (Northeast) China are found, with significant correlation coefficients primarily over the northern part of West Asia and the eastern part of North (Northeast) China. Revealed by Figs. 2b(2)–2e(2), the air temperature over Northeast China significantly and positively correlates to the spring land surface temperature over West Asia. It could be concluded that, in both the temporal variation and spatial distribution, there is a close relationship between the spring land surface temperature over West Asia and the early summer climate over northern China, so we defined it as the West Asia–northern China teleconnection.

To characterize the West Asia–northern China teleconnection more directly, the rectangles in Fig. 2 were selected as the target regions to calculate four regional-average standardized indexes with the ERA-20C data and NCC station data: the spring West Asia ($45^\circ\text{--}70^\circ\text{E}$, $30^\circ\text{--}40^\circ\text{N}$) land thermal index (WALTI); the early summer North China ($110^\circ\text{--}118^\circ\text{E}$, $35^\circ\text{--}39^\circ\text{N}$) precipitation index (NCPI), and the early summer precipitation index and temperature index over Northeast China ($120^\circ\text{--}135^\circ\text{E}$, $40^\circ\text{--}54^\circ\text{N}$) (NECPI and NECTI). Using EEMD analysis, the multiscale variations of the four indexes were discussed. As seen in Fig. 3, each index was decomposed into five intrinsic mode functions (WALTI-IMFi, NCPI-IMFi, NECPI-IMFi, NECTI-IMFi, $i = 1, 5$), and periods of WALTI-IMFi, NCPI-IMFi, NECPI-IMFi and NECTI-IMFi ($i = 1, 5$) are very similar. From IMF1 to IMF4 (Figs. 3a–d), their periods are generally 2–3, 5–6, 10–12, and 19–35 years, respectively, implying the variations of the four indexes on the interannual, interdecadal, and multidecadal scales, while IMF5 (Fig. 3e) represents the long-term trend. To quantify the relationship between WALTI and NCPI/NECPI/NECTI on different time scales, Table 1 shows the covariances and correlation coefficients between WALTI-IMFi and NCPI-IMFi/NECPI-IMFi/NECTI-IMFi ($i = 1, 5$), which were tested based on their effective degrees of freedom. It is noted that the best relationship of WALTI and NCPI/NECPI/NECTI is on the interannual scale, since WALTI and NCPI/NECTI are significantly correlated for a 2–3-yr period, whereas WALTI and NECPI are significantly correlated for a 5–6-yr period, illustrating that the interannual component is the main component of the West Asia–northern China teleconnection. In addition, although the effective degrees of freedom of IMF5 is 0, the covariances of WALTI-IMF5 and NCPI-IMF5/NECPI-IMF5/NECTI-IMF5 are all large. Particularly, WALTI-IMF5 and NCPI-IMF5 are negatively correlated, which indicates that the long-term trend may affect the teleconnection.

To further confirm the teleconnection, the regressions of early summer precipitation (based on NOAA-PREC/L and GPCC) and air temperature (based on ERA-20C and CRU) in relation to WALTI are shown in Fig. 4. As seen in Fig. 4, the results from different data are consistent. When there is an abnormal land surface warming over West Asia in spring, the early summer precipitation tends to be increased over North China and decreased over Northeast China, in both of which the precipitation anomalies are mainly concentrated over the

FIG. 2. (a1),(a2) Standardized time series, and heterogeneous correlation maps of the leading SVD coupled modes for spring land surface temperature over West Asia (SWALT) with early summer station (b1)–(e1) precipitation (JNCP) and (b2)–(e2) air temperature (JNCT) over northern China, respectively. SWALT in (b) and (d) are from the ERA-20C; (c) and (e) are from the CRU. All data have had the long-term trend removed before the SVD. Dotted areas are statistically significant at the 10% level; two asterisks (**) indicate statistically significance at the 1% level. The rectangles represent the selected target regions.

eastern part. Meanwhile, the air temperature over Northeast China warms significantly. These results verify the results from SVD. In addition, comparing Figs. 4a, 4b, 4e, and 4f with Figs. 4c, 4d, 4g, and 4h, it can be found that after removing the long-term trend from original data, the anomalous positive (negative) precipitation in North (Northeast) China strengthens, while the anomalous positive air temperature weakens, thus revealing the impact of the long-term trend on the teleconnection. To avoid this impact, the long-term trend of data is removed in the following exploration.

4. Possible mechanism for the thermal forcing–triggered teleconnection

Given the above relationship between spring land surface temperature over West Asia and early summer precipitation/air temperature over northern China, one is led to consider whether the corresponding atmospheric circulation anomalies as well as

their seasonal transitions play the role of a “bridge” in the formation of the teleconnection. Therefore, the following section attempts to investigate the possible mechanisms for the thermal forcing–triggered teleconnection from the perspective of abnormal atmospheric circulations.

a. Atmospheric circulation anomalies associated with spring land surface thermal anomalies over West Asia

First, the interactions between spring land surface thermal anomalies and simultaneous atmospheric circulation anomalies were investigated. Previous studies have pointed out that regional land surface warming benefits the increase of average precipitation rate in the next 10–30 days, which is a negative feedback for the land surface warming (Wang 1991). Therefore, the “memory” of land surface temperature generally lasts no more than a season (Liu and Avissar 1999; Hu and Feng 2004a,b; Amenu et al. 2005). However, Fig. 5 shows the time-lagged autocorrelations of land surface temperatures over West Asia. It is

FIG. 3. The intrinsic mode functions 1–5 of WALTl (calculated with the land skin temperature from ERA-20C), NCPI, NECPI, and NECTI (calculated based on NCC station data) during 1951–2010 given by the EEMD, which are marked as WALTl-IMFi, NCPI-IMFi, NECPI-IMFi, and NECTI-IMFi ($i = 1, 5$), respectively.

noteworthy that the land surface thermal anomalies over West Asia persist from March to May (Figs. 5a,b,d,e), which may induce a seasonal-scale land thermal forcing to the atmosphere above. To explore this phenomenon, Figs. 6–9 illustrate some anomalous fields of land surface and atmosphere in spring based on WALTl.

Figures 6a and 6b depict the composite difference of spring land surface sensible heat flux anomalies and upward longwave radiation anomalies over West Asia between the 10 warmest years (1955, 1958, 1970, 1971, 1977, 2000, 2001, 2006, 2008, 2010) and 10 coolest years (1957, 1968, 1972, 1976, 1983, 1986, 1991, 1992, 1993, 1996) during 1951–2010 based on WALTl. With abnormal warming of land surface in spring over West Asia, the upward sensible heat flux and longwave radiation there are significantly increased, indicating enhanced diabatic heating of the land surface to the atmosphere above. In fact, the sensible heat forcing, which is the heat exchange directly caused by land–air temperature difference, primarily heats the lower atmosphere, while the upward longwave radiation is mainly absorbed by the middle to upper atmosphere. It can be seen from the tropospheric temperature anomalies over West Asia (Fig. 6c) that the intensity of abnormal warming in the lower troposphere is higher than that in the middle-upper troposphere, showing that the sensible heat forcing may be the

dominant way via which spring land surface warming over West Asia heats the atmosphere above. Based on the equilibrium thermodynamic equation $\mathbf{V} \cdot \nabla \theta = Q$, in which $\mathbf{V}$ is the wind, θ is the potential temperature, and Q is the diabatic heating, the diabatic heating ($Q > 0$) can drive the airflow to move upward through the isentropic surface, which reveals that stronger land surface sensible heat over West Asia may promote convective instability by increasing the specific enthalpy of the lower troposphere, resulting in an abnormal vertical ascending motion in the lower and middle troposphere (Fig. 6c), as well as an anomalous cyclonic (anticyclonic) circulation in the lower (middle) troposphere [Figs. 8c(1) and 8b(1)]. Besides, on account of the overshooting caused by the thermal adaptation process (Wu and Liu 2000), the abnormal anticyclonic circulation occurs in the upper troposphere [Fig. 8a(1)] as well. At the same time, due to the anomalous cyclonic circulation near the land surface, the atmosphere reacts to the anticyclonic vorticity forcing resulting from the land surface friction. In accordance with the theory of thermal adaptation (Wu and Liu 2000; Wu et al. 2009), in the quasi-equilibrium state of thermal adaptation, the negative vorticity that is caused by land surface friction and applied to the atmospheric column through the underlying boundary not only compensates for the positive vorticity triggered by diabatic heating in the lower troposphere, but also can be transported to the middle to upper troposphere. For this reason, the anomalous anticyclonic circulation in the middle to upper troposphere is stronger than that in the lower layer [Figs. 8a(1)–c(1)].

Furthermore, Fig. 7a shows the regression of vertical integral of water vapor flux and its divergence in spring onto WALTl. Guided by the anomalous anticyclone circulation obtained with the vertical average of anomalous tropospheric circulation, the water vapor flux anomalies over West Asia are mainly westerly and northerly, following the abnormal moisture divergence there. Hence, even though the dynamic circulation triggered by land warming are conducive to rainfall increase (Fig. 6c), the spring rainfall over West Asia shows an abnormal decrease (Fig. 7b) owing to the extreme lack of water vapor supply, which indicates that the forcing of land surface warming over West Asia in spring on the atmosphere above is not affected by the negative feedback of precipitation. This is the main reason why the land surface thermal anomalies over West Asia persist throughout the spring, and also helps to maintain and strengthen the anomalous atmospheric circulation shown in Figs. 8a(1)–8c(1).

Meanwhile, along with the abnormal warming of land surface over West Asia in spring, there is an anomalous wave train featuring the circumglobal teleconnection (CGT) in the Northern Hemisphere [Figs. 8a(1)–8c(1)], and it is more evident in the upper troposphere. As seen in Fig. 8a(1), the 200-hPa CGT has a zonal wavenumber-5 structure, with prominent anomalous centers of action over West Asia (around 34°N, 59°E), East Asia (around 25°N, 113°E), the North Pacific (around 38°N, 153°W), North America (around 28°N, 105°W), the North Atlantic (around 68°N, 65°W), and western Europe (around 60°N, 15°E) respectively. Hoskins and Karoly (1981) pointed out that the atmospheric teleconnection patterns generated by the energy dispersion of quasi-stationary planetary

FIG. 4. Regressed early summer precipitation (mm day^{-1}) based on (a),(c) NOAA-PREC/L (b),(d) GPCC, and near-surface air temperature (K) based on (e),(g) ERA-20C and (f),(h) CRU onto the spring West Asia land surface thermal index (WALTI). The original data are used in (a), (b), (e), and (f); in (c), (d), (g), and (h) the long-term trend is removed. Dotted areas are statistically significant at the 10% level.

waves are the responses of spherical atmosphere to localized forcing. As an external forcing source, do the land surface thermal anomalies over West Asia contribute to the CGT shown in Figs. 8a(1)–c(1)? Based on the theory of stationary external Rossby waves (Held et al. 1985), the typical responses of the upper troposphere to a localized stationary midlatitude source propagate farther than those of the lower troposphere; thus, Fig. 9a illustrates the regressed 200-hPa relative vorticity anomalies and abnormal wave activity flux in spring onto WALTI. It can be found that there is a steady negative vorticity source over West Asia, indicating that the abnormal land surface warming over West Asia in spring can trigger a source for Rossby waves (Sardeshmukh and Hoskins 1988). Previous studies exhibited that the kinetic energy obtained from the basic (climatological) flow by baroclinic energy conversion (conversion of available potential energy from the mean flow, which is denoted by CP) is beneficial to the formation of abnormal wave trains (Sato and Takahashi 2006; Kosaka and Nakamura 2006; Kosaka et al. 2009; Yasui and Watanabe 2010; Chen et al. 2013; Li et al. 2020), while the enhancement of atmospheric baroclinicity caused by land heating can lead to increased CP (Zhang et al. 2019). Therefore, the abnormal land surface warming over West Asia in spring may trigger the wave source by exciting the atmospheric baroclinic disturbance and increasing CP [Figs. 8a(1)–8c(1)].

Moreover, according to the Rossby wave ray theory (Hoskins and Ambrizzi 1993; Ambrizzi et al. 1995), the westerly jet stream (WJS) acts as a waveguide in the propagation of atmospheric disturbance. The anomalous wave train can propagate along WJS, resulting in new disturbances downstream. In Fig. 9a, the spring WJS over the Northern Hemisphere is mainly composed

of three parts: the North African jet, which extends from North Africa to West Asia with its center located about 28°N ; the East Asian jet, which extends from East Asia to the North Pacific with its center located about 32°N ; and the North American jet, which extends from the tropical Pacific to the North Atlantic with its center located about 36°N . Among them the strongest is the East Asian jet, which has a maximum of about 48 m s^{-1} . It is worth noting that, accompanied by anomalous wave activity flux that starts from West Asia and propagates downstream along the WJS, zonally elongated anomalous negative vortices ($|u'^2| \gg |v'^2|$, where u' and v' are the anomalous zonal and meridional wind velocity, respectively) are established over East Asia, the North Pacific, North America, and the North Atlantic, which correspond to the anomalous anticyclonic centers of action in Figs. 8a(1)–8c(1). Further analysis concludes that the anticyclonic vortices over West Asia, the North Pacific, and the North Atlantic are all located in the jet exit regions, and their wave amplitudes are stronger than those of the others. Hoskins et al. (1983) and Simmons et al. (1983) held that the barotropic energy conversion (conversion of kinetic energy from the mean flow, which denoted by CK) is critical for the propagation characteristics of forced waves, and the increase of CK can help to strengthen the anomalous forced waves. According to the definition of CK, its expression is given as follows:

$$\text{CK} = \frac{v'^2 - u'^2}{2} \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) - v' u' \left(\frac{\partial \bar{u}}{\partial y} - \frac{\partial \bar{v}}{\partial x} \right),$$

where $\bar{u}$ (u') and $\bar{v}$ (v') are the mean (anomalous) zonal and meridional wind velocity, respectively. In the exit of WJS ($\partial \bar{u} / \partial x < 0$), the item of $[(v'^2 - u'^2) / 2] (\partial \bar{u} / \partial x)$ is the largest and

FIG. 5. Geographic distribution of the autocorrelations of land surface temperatures over West Asia from March with a lag time of (a),(d) 1 month, (b),(e) 2 months, and (c),(f) 3 months for (top) skin temperature and (bottom) soil temperature (level 1–3 averaged) based on the ERA-20C. All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level.

$[(v^2 - u^2)/2] (\partial \bar{u} / \partial x) > 0$, corresponding to increased CK and intensified wave amplitude. Furthermore, because the East Asian jet is stronger, $|\partial \bar{u} / \partial x|$ is larger in the exit of the East Asian jet than in the North American jet, resulting in a stronger

anticyclonic vortex in the North Pacific than in the North Atlantic. Consequently, in spring, the abnormal land surface warming over West Asia acts as an external forcing source that contributes to the formation of CGT, and the characteristics of

FIG. 6. Composites of spring (a) surface sensible heat flux anomalies (the vertical upward direction means positive; W m^{-2}), and (b) upward longwave radiation (W m^{-2}) over West Asia between the 10 warmest years and 10 coolest years during 1951–2010 based on the spring West Asia land surface thermal index (WALTI). (c) Longitude–height cross section along 35°N of regressed spring air temperature (shaded; K) and zonal circulation (vector arrows; vertical velocity in $10^{-3} \text{ Pa s}^{-1}$ and zonal wind in m s^{-1}) onto the WALTI. All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level. The gray mask in (c) indicates the topography.

FIG. 7. Regressed (a) vertical integral of water vapor flux ($\text{kg m}^{-1} \text{s}^{-1}$) as well as its divergence ($\text{kg m}^{-2} \text{s}^{-1}$) and (b) precipitation (from NOAA-PREC/L; mm day^{-1}) in spring onto the spring West Asia land surface thermal index (WALTI). All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level.

basic flow and the interactions between basic flow and CGT play a crucial role in the propagation of CGT.

As seen in Figs. 8a(2)–8c(2), the CGT anomalies persist from spring to early summer, but their shape, intensity, and location change. Previous studies showed that the shape of WJS determines the structure of the Rossby waves that are trapped (Hoskins and Ambrizzi 1993; Ambrizzi et al. 1995; Naoe and Matsuda 1998; Newman and Sardeshmukh 1998).

The WJS weakens and shifts northward from the cold to warm season, leading to increased zonal wavenumber as well as the northward shift of trapped wave train (Namias and Clapp 1949; Lau and Peng 1992; Lu et al. 2002; Kosaka et al. 2009; Woollings et al. 2010; Manola et al. 2013), and thus resulting in the transition of the action centers of CGT (Hong and Lu 2016). For this reason, Figs. 8a(2) and 9b give the regressed early summer 200-hPa abnormal geopotential height, relatively vorticity and

FIG. 8. Regressed (a1)–(c1) spring and (a2)–(c2) early summer geopotential heights (m) and (a3)–(c3) early summer wind anomalies (m s^{-1}) at (top) 200, (middle) 500, and (bottom) 850 hPa onto the spring West Asia land surface thermal index (WALTI), where plus (minus) signs indicate the main anticyclonic (cyclonic) action centers of the CGT. All data have had the long-term trend removed. Dotted areas in (a1)–(c1) and (a2)–(c2) and colored areas in (a3)–(c3) are statistically significant at the 10% level.

FIG. 9. Regressed (a) spring and (b) early summer 200-hPa relative vorticity anomalies (color; 10^{-5} s^{-1}) and abnormal wave activity flux (arrows; $\text{m}^2 \text{ s}^{-2}$) with magnitudes larger than $0.01 \text{ m}^2 \text{ s}^{-2}$ onto the spring West Asia land surface thermal index (WALTI). Contours represent the climatology of the zonal wind (unit: m s^{-1}) with an interval of 10 m s^{-1} . All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level.

wave activity flux onto WALTI. Comparing Fig. 9a with Fig. 9b, it is found that while the maximum of WJS decreases from about 48 to about 37 m s^{-1} , the zonal wavenumber-5 structure of early summer CGT is enhanced. Besides, as the centers of North African and East Asian jets move northward to about 40°N while that of the North American jet shifts northward to about 45°N , the WJS turns into a midlatitude quasi-zonal distribution, causing the trapped CGT to transform. As seen in Fig. 8a(2), the five anomalous anticyclonic centers move to West Asia (around 36°N , 41°E), East Asia (around 54°N , 115°E), the North Pacific (around 47°N , 182°E), North America (around 38°N , 111°W), the North Atlantic (around 65°N , 43°W), and western Europe (around 60°N , 10°E), respectively. Moreover, the CGT anomaly shown in Fig. 8a(2) is similar to the early summer CGT pattern defined by Ding and Wang (2005); the correlation coefficient between the WALTI and the CGT index defined by Ding and Wang (2005) is 0.41, which reaches statistical significance at the 0.01 level. In fact, previous studies have focused on the relationships between summer CGT pattern and the basic flow. For instance, Ding and Wang (2005, 2007) considered that the CGT patterns in each summer month are established along the location of the climatological WJS, and the linear barotropic mechanisms, including energy propagation and barotropic instability of the basic-state flow, act to shape and maintain the CGT. Kosaka et al. (2009) pointed out that the Silk Road pattern, which can be viewed as the Eurasian part of the CGT (Zhou et al. 2019), is maintained and intensified by its interaction with the WJS. Lin et al. (2017a) emphasized that the main reason for the decadal variation of early summer CGT pattern is the change of basic flow. Therefore, it is suggested that the change of basic flow

(especially the WJS) and its interaction with CGT could play an important role in the transition of CGT from spring to early summer as well.

b. Impacts of early summer CGT on rainfall and temperature over northern China

A series of studies have shown that the CGT patterns are critical atmospheric patterns affecting the climate over northern China in summer (Ding and Wang 2005; Wang et al. 2009; Wang and He 2015; Orsolini et al. 2015; Zhang et al. 2018, 2019). As seen in Figs. 8a(2)–8c(2), the northern China region is affected by the anomalous anticyclonic center of the early summer CGT over East Asia. It is obvious that there is an equivalent barotropic anomalous anticyclonic vortex over Northeast China and an anomalous cyclonic (anticyclonic) vortex in the lower (upper) troposphere over North China. Further, the anomalies of vertical integral of water vapor flux and divergence over eastern China are shown in Fig. 10a. Guided by the abnormal southerly wind, water vapor from the northwest Pacific is transported to North China, resulting in convergence of water vapor there. However, as the southerly wind progresses to Northeast China, the water vapor diverges due to the blocking effect of the Inner Mongolian Plateau. Meanwhile, the vertical velocity fields indicate an anomalous ascending motion over North China (Fig. 10b) and an anomalous descending motion over Northeast China (Fig. 10c), which are caused by the compensation effect. Overall, affected by the abnormal water vapor transport and vertical motion, the precipitation in North (Northeast) China increases (decreases) abnormally. Moreover, differences are seen in the divergence

FIG. 10. Regressed (a) vertical integral of water vapor flux ($\text{kg m}^{-1} \text{s}^{-1}$) as well as its divergence ($\text{kg m}^{-2} \text{s}^{-1}$) over eastern China and vertical velocity (ω ; Pa s^{-1}) over (b) North China (averaged over 35° – 39°N) and (c) Northeast China (averaged over 40° – 54°N) in early summer onto the spring West Asia land surface thermal index (WALTl). All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level.

of moisture flux between the eastern and western part of North/Northeast China (Fig. 10a), which are similar to the precipitation anomalies shown in Figs. 4a–d. In North China, the southerly water vapor transportation mainly reaches the eastern part of North China due to the blocking effect of the Loess Plateau, resulting in stronger water vapor convergence over the eastern part than over the western. In Northeast China, affected by the dry northerly wind, the divergence of water vapor over the eastern part is stronger than that over the western as well. Thus, the distribution of abnormal water vapor transport is the main reason for the difference between the eastern and western part of precipitation anomalies in North/Northeast China.

Thermodynamic diagnostics were carried out further to give more detailed explanations for the temperature anomalies over Northeast China. The thermodynamic equation is given as follows:

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \frac{RT}{gp}(\gamma_d - \gamma)\omega + \frac{1}{C_p} \frac{dQ}{dt},$$

where T is the air temperature, $\mathbf{V}$ is the horizontal wind, R is the gas constant, g is the acceleration of gravity, p is the air pressure, γ_d is the dry adiabatic lapse rate, γ is the wet adiabatic lapse rate, ω is the omega, C_p is the specific heat capacity at constant pressure, and dQ/dt is the diabatic heating. The local temperature change is governed by the horizontal temperature advection $-\mathbf{V} \cdot \nabla T$, the vertical motion $(RT/gp)(\gamma_d - \gamma)\omega$ and the diabatic heating $(1/C_p)(dQ/dt)$, which represent the effect of heat transfer caused by horizontal advection motion, vertical motion, and radiation, respectively. The horizontal temperature advection $-\mathbf{V} \cdot \nabla T$ is composed of zonal temperature advection $-u(\partial T/\partial x)$ and meridional temperature advection $-v(\partial T/\partial y)$.

For the horizontal temperature advection term, because the abnormal wind over Northeast China is quasi-longitudinal [Fig. 8c(3)], the regression of 1000–500-hPa averaged meridional temperature advection in early summer from WALTl is given in Fig. 11c. It can be found that a significant warm temperature advection occurs over the western part of Northeast China, contributing to the air warming there. For the vertical motion term, the abnormal descending motion ($\omega > 0$) illustrated in Fig. 10c is beneficial to the increase of temperature in Northeast China since the term of $(RT/gp)(\gamma_d - \gamma)$ is always positive. In addition, Figs. 11a and 11b depict the regressed total cloud cover and land surface net shortwave radiation flux in early summer onto WALTl. Due to the abnormal water vapor divergence and descending motion, the cloud cover over the eastern part of Northeast China decreases evidently (Fig. 11a), leading to significantly increased land surface net shortwave radiation ($dQ/dt > 0$) (Fig. 11b) that is beneficial to higher air temperature. It is concluded that the descending motion contributes to the abnormal warming over Northeast China, while the horizontal warm advection and radiation warming are also important for the abnormal warming over the western and eastern part of Northeast China, respectively.

The above analysis shows that intensified early summer CGT results in precipitation increasing over North China, whereas over Northeast China precipitation decreases and air temperature rises. These findings are consistent with those of Ding and Wang (2005). Besides, intensified early summer CGT corresponds to weakened cold vortex over Northeast China (Wang et al. 2018), while the cold vortex activity is closely related to local precipitation and temperature (Shen et al. 2011; Xie and Bueh 2015). Hence, the weakened cold vortex over Northeast China caused by intensified early summer CGT may

FIG. 11. Regressed early summer (a) total cloud cover (%), (b) land surface net shortwave radiation (the vertical downward direction means positive; W m^{-2}) and (c) 1000–500-hPa averaged meridional temperature advection ($^{\circ}\text{C s}^{-1}$) over Northeast China onto the spring West Asia land surface thermal index (WALTl). All data have had the long-term trend removed, and dotted areas are statistically significant at the 10% level.

be another reason for the decrease (increase) of local precipitation (temperature).

The analysis presented above reveals that the abnormal land surface warming over West Asia in spring can trigger anomalous Rossby waves by diabatic heating to the atmosphere above, thus benefiting the intensification of early summer CGT, and consequently causing anomalous circulation over northern China and further affecting local precipitation and air temperature.

5. Numerical simulation results

In this section, the numerical simulations, whose details are shown in section 2c, are designed to further explore the West Asia–northern China teleconnection and the evolution characteristics of related atmospheric circulations.

After adding the thermal forcing of 30 W m^{-2} (the magnitude of forcing is based on Fig. 6a) over the target region of West Asia in spring (Fig. 12a), the differences of spring ground temperature between the sensitivity experiments and CTL are presented in Fig. 12b to confirm the plausibility of the forcing value. With an increase of SH forcing, simulated ground temperature anomalies over West Asia increase significantly, and their order of magnitude is consistent with that of the composites of spring skin temperature over West Asia between the 10 warmest years and the climatology during 1951–2010 based on WALTl (Fig. 12c), which indicates that increased SH forcing in the sensitivity runs can effectively and rationally represent the abnormal land surface warming over the target region.

At the same time, there are abnormal ascending motions in the troposphere over the target region (Fig. 13a) due to the dynamic adjustment caused by the thermal forcing. However,

FIG. 12. Simulated spring (a) sensible heat and (b) ground temperature anomalies given by sensitivity runs with the thermal forcing of 30 W m^{-2} over the target region of West Asia. (c) Composites of spring skin temperature (K) between 10 warmest years and the climatology during 1951–2010 based on the spring West Asia land surface thermal index (WALTl; calculated with the land skin temperature from ERA-20C) with the long-term trend removed. Dotted areas are statistically significant at the 10% level.

FIG. 13. Simulated spring vertical mean (a) omega, (b) horizontal wind velocity (vector; m s^{-1}) and relative humidity (color; %) at 1000–200 hPa, and (c) precipitation anomalies given by sensitivity runs with the thermal forcing of 30 W m^{-2} over the target region of West Asia. Dotted areas are statistically significant at the 10% level.

under the guidance of abnormal anticyclonic circulation, the relative humidity there abnormally decreases (Fig. 13b) due to the lack of water vapor supply, resulting in weak response in precipitation (Fig. 13c). These results verify the previous analysis that the forcing effect of the land surface anomalous warming over West Asia on the atmosphere above is unaffected by the negative feedback of precipitation.

a. Simulated rainfall and temperature anomalies

To explore whether the model can simulate the West Asia–northern China teleconnection, the anomalous precipitation (the sum of convective precipitation and large-scale precipitation) and surface air temperature over northern China in early summer were obtained by composing the differences between CTL and sensitivity experiments (the latter minus the former). As seen in Fig. 14a, with the upward land surface sensible heat (SH) forcing over West Asia in spring, the early summer precipitation over North (Northeast) China increases (decreases). The negative anomalies of precipitation over Northeast China are concentrated in the eastern part, which is consistent with the observed results (Figs. 4a–d). Surface air temperature over Northeast China increases abnormally with the positive SH forcing over West Asia in spring (Fig. 14b), which agrees with the results of Figs. 4c–f. Moreover, there are significant negative temperature anomalies over North China, forming a dipole distribution whose phase is opposite to the anomalous precipitation field.

b. Simulated atmospheric general circulation anomalies

To investigate the mechanism of the West Asia–northern China teleconnection in the model, simulated atmospheric general circulation anomalies were obtained by composing the differences between the results of CTL and sensitivity experiments (the latter minus the former). First, the atmospheric temperature, vertical velocity (omega), and geopotential height anomalies over West Asia in spring are displayed in Figs. 15–17 to characterize the thermal and dynamic adaptation of local atmospheric circulation to the land surface heating. From March to

May, driven by increased SH forcing, the atmosphere over West Asia gradually warms from lower to upper levels [Figs. 15a(1)–15a(3)], which is accompanied by developing convective ascending motion [Figs. 15b(1)–15b(3)]. This results in the increase of abnormal cyclonic circulation in the lower troposphere [Figs. 16c(1), c(2) and 17c(1)] and abnormal anticyclonic circulation in the middle to upper troposphere [Figs. 16a(1), a(2), b(1), b(2) and 17a(1), b(1)]. These results are consistent with the conclusions of Figs. 6c and 8a(1)–c(1), proving that abnormal land surface warming over West Asia in spring can lead to the baroclinic instability of the atmosphere above by stimulating local heat-driven circulation. Furthermore, in order to verify whether the baroclinic disturbance can trigger CGT, Figs. 16 and 17 depict the geopotential height anomalies at 200, 500, and 850 hPa from March to May, in which contours represent the climatology of zonal wind from CTL to discuss the role of basic flow. It can be seen that the model can reproduce the three jet streams of the Northern Hemisphere in spring, but in simulation the North African jet is integrated with the East Asian jet, so they can be referred to together as the African–Asian jet. To quantify the WJS, here we define the maximum value of WJS and the meridional length value of WJS at 90°E as its strength and width, respectively. From March to May, the troposphere responds to the anomalous circumglobal teleconnection (CGT) wave train along the African–Asian jet and the North American jet. It is seen that the vortex of the CGT over West Asia is baroclinic, whereas the vortices outside West Asia are quasi-barotropic. According to the analytical solution of the quasigeostrophic thermodynamic equation considering diabatic heating, the response waves outside the specific heating region are dominated by the equivalent barotropic Rossby waves. Overall, the baroclinic disturbance over West Asia can effectively trigger anomalous Rossby waves that propagate eastward along the WJS and excite barotropic wave train downstream.

Further analysis shows that there are obvious subseasonal evolutions of WJS and CGT in spring. In March [Figs. 16a(1)–c(1)], the WJS is strong (the maximum is about 66 m s^{-1}) but the CGT

FIG. 14. Differences (sensitivity runs minus CTL run) in early summer (a) precipitation (mm day^{-1}) and (b) surface air temperature (K) over northern China. Dotted areas are statistically significant at the 10% level.

is weak, indicating that increased SH forcing over West Asia in March cannot trigger significant CGT although there is a strong waveguide in the upper troposphere. In April [Figs. 16a(2)–c(2)] the WJS weakens (the maximum is about 45 m s^{-1}), but it is still a strong waveguide. With continuous SH forcing over West Asia, the CGT enhances and becomes a significant anomalous wave train with a zonal wavenumber-3 structure.

The two anticyclonic centers outside West Asia are located over the North Pacific and North Atlantic, with the North Pacific center being stronger. Similar to the results of Fig. 9a, these two action centers are located at the exit of the African-Asian jet and the North American jet, respectively, and $|\partial \bar{u} / \partial x|$ in the exit of the African-Asian jet is larger than that in the exit of the North American jet, which demonstrates the

FIG. 15. Longitude–height cross sections along 35°N of differences (sensitivity runs minus CTL run) in (a) air temperature (K) and (b) vertical velocity (omega; Pa s^{-1}), in which 1, 2, 3, and 4 represent March, April, May, and June, respectively. Dotted areas are statistically significant at the 10% level, and the gray mask means the topography.

FIG. 16. Differences (sensitivity runs minus CTL run) in (a) 200-, (b) 500- and (c) 850-hPa geopotential heights (m) in (left) March and (right) April. Contours represent the climatology of the zonal wind (m s^{-1}) with an interval of 10 m s^{-1} , and dotted areas are statistically significant at the 10% level.

phenomenon and mechanism of wave amplification in the exit of WJS. In May [Figs. 17a(1)–c(1)], the SH forcing over West Asia persists and the WJS further weakens (the maximum is about 40 m s^{-1}), resulting in the transformation of CGT from zonal wavenumber-3 distribution to zonal wavenumber-5 distribution. The new anticyclonic centers appear over East Asia and North America. At the same time, from April to May, the WJS narrows meridionally and shifts northward, leading the positions of action centers over West Asia, the North Pacific, and the North Atlantic to adjust accordingly. The above analysis confirms that persistent land surface thermal forcing is a necessary condition for the excitation of CGT, while the basic flow (especially WJS) determines the propagation and distribution characteristics of CGT.

To explore the transition of CGT from spring to early summer, Figs. 15a(4) and 15b(4) illustrate the local atmospheric temperature and omega anomalies in early summer, corresponding to the spring SH forcing over West Asia. Although the anomalous land surface thermal forcing ends in May, there are delayed positive temperature anomalies [Fig. 15a(4)] and negative omega anomalies [Fig. 15b(4)] in the middle to upper atmosphere in June, indicating that part of the heat-driven circulation lasts from last spring to early summer, thus resulting in the atmospheric baroclinic instability over West Asia in early summer [Figs. 17a(2)–c(2)], which is beneficial to the maintenance of CGT. At the same time, as seen in Figs. 17a(1) and 17a(2), the WJS further weakens (the maximum is reduced from about 40 m s^{-1} to about 36 m s^{-1}), narrows (the width is reduced

from about 33° to about 19°) and shifts northward from May to June. Manola et al. (2013) studied the ability of idealized jets to trap Rossby wave energy (“waveguidability”) and suggested that stronger and narrower jets lead to higher forced wave density. However, the variation rate of the waveguidability with jet width is greater than that with jet strength (Wirth 2020). It is conceivable that the waveguidability of WJS in June could be stronger than that in May. Therefore, from May to June, due to strengthened waveguidability and the northward shift of WJS, the CGT is also strengthened and northward shifted, resulting in a quasi-zonal distribution. The five anticyclonic centers respectively move to West Asia (around 39°N , 66°E), East Asia (around 38°N , 129°E), the North Pacific (around 48°N , 196°W), North America (around 46°N , 90°W), and North Atlantic–western Europe (around 55°N , 20°W), corresponding to the main action centers of the early summer CGT pattern defined by Ding and Wang (2005). These results prove that the spring land surface warming over West Asia helps to excite early summer CGT, and the basic flow (especially the WJS) plays a critical role in the transition of CGT from late spring to early summer.

Furthermore, the 200-hPa anomalies of relative vorticity and wave activity flux in the Northern Hemisphere from March to June are shown in Fig. 18. In March (Fig. 18a), accompanied by the land surface anomalous warming, there are positive vorticity responses at 200 hPa over West Asia, revealing the high-level divergence induced by the ground heating. Meanwhile, the triggered Rossby wave originates from West Asia and is trapped

FIG. 17. As in Fig. 16, but for (left) May and (right) June.

by the Asian jet at entrance, then propagates quasi-zonally along the WJS, forming the circumglobal distribution. It is noted that the CGT strengthens over the North Pacific and North Atlantic, which are located in the exit of the African-Asian and the North American jet, respectively. These results are consistent with the characteristics of the excitation and propagation of forced waves in the foregoing analysis. As seen in Figs. 18a–c, from March to May the CGT gradually enhances due to the ground heating over West Asia. Moreover, the interactions between the forced wave and the basic flow contribute to maintaining the CGT as well, in which WJS plays an important role in shaping the feature and location of CGT. As a result, the CGT in the late spring (Fig. 18c) has a zonal wavenumber-5 structure. From late spring to early summer (Figs. 18c,d), similar to Fig. 17, the waveguidability of WJS strengthens due to the sudden narrowing of WJS during the seasonal transition period, which leads the forced waves to further evolve into that similar to the early summer CGT pattern proposed by Ding and Wang (2005). Obviously, the transition of abnormal Rossby waves in Fig. 18 also proves the conclusions from the observation.

Figures 19a and 19b display the early summer wind field, relative humidity, and vertical velocity anomalies at 500 hPa to explore the simulated relationship between early summer CGT and precipitation over northern China. With the abnormal intensification of early summer CGT, the relative humidity increases (decreases) and the ascending (descending) motion strengthens over North (Northeast) China, leading to the increase (decrease) of precipitation in North (Northeast) China. In addition, the negative anomalies of relative humidity over

the eastern part of Northeast China are stronger than that over the western part, resulting in stronger negative precipitation anomalies over the eastern part of Northeast China (Fig. 14a), which is consistent with the previous analysis.

To investigate the causes of early summer temperature anomalies over Northeast China in model simulations, Figs. 20a–c give the related abnormal fields of model output variables. Figures 20a and 20b are the anomalies of vertically integrated total cloud and surface net solar flux in early summer. It can be seen that there are negative cloud cover anomalies (Fig. 20a) and positive surface net solar radiation flux (Fig. 20b) over the eastern part of Northeast China. Meanwhile, southerly heat transport anomalies occur over the western part of Northeast China according to the abnormal field of vertical mean meridional heat transport at 1000–500 hPa in early summer (Fig. 20c). It is consistent with the observed results (Figs. 10c and 11) that the anomalous descending motion (Fig. 19b), horizontal warm advection (Fig. 20c), and radiation warming (Fig. 20b) contribute to the abnormal warming over Northeast China. What is more, sensitivity runs with other forcings (10, 15, 20, and 25 W m^{-2}) were also conducted; the results were similar to the 30 W m^{-2} forcing and not shown.

6. Conclusions and discussion

By using the SVD analysis, the teleconnection between spring land surface thermal anomalies over West Asia and early summer (June) precipitation/air temperature over northern China are revealed based on station data and reanalysis datasets. When

FIG. 18. Differences (sensitivity runs minus CTL run) in 200-hPa relative vorticity (color; 10^{-5} s^{-1}) and wave activity flux with magnitudes larger than $0.01 \text{ m}^2 \text{ s}^{-2}$ (arrows; $\text{m}^2 \text{ s}^{-2}$) in the Northern Hemisphere for (a) March, (b) April, (c) May, and (d) June. Contours represent the climatology of the zonal wind (m s^{-1}) with an interval of 10 m s^{-1} , and dotted areas are statistically significant at the 10% level.

the land surface warms abnormally in spring over West Asia (45° – 70°E , 30° – 40°N), the early summer precipitation tends to be increased over North China (110° – 118°E , 35° – 39°N) and decreased over Northeast China (120° – 135°E , 40° – 54°N). The latter is also accompanied by higher air temperature. Besides, the precipitation anomalies over the eastern part of northern China are stronger than those over the western part, which is confirmed by the conclusions from regression analysis. Results of the EEMD analysis further indicate that the best relationship between spring land surface thermal anomalies over West Asia and early summer precipitation/air temperature over northern China is on the interannual scale.

Atmospheric circulations related to the spring land surface thermal anomalies over West Asia are further examined. Affected by the abnormal land surface warming over West Asia in spring, the upward sensible heat flux and longwave radiation from the land surface increase, leading to abnormal atmospheric vertical upward motion in the troposphere and thus providing the dynamic condition for precipitation. However, precipitation fails to be formed due to a lack of the water vapor condition. This is caused by the abnormal divergence of water vapor over West Asia, which favors the persistence of land surface warming, and the formation, maintenance, and strengthening of anomalous cyclonic (anticyclonic) circulation in the

FIG. 19. Differences (sensitivity runs minus CTL run) in early summer of (a) wind velocity (m s^{-1}) and relative humidity (unit: %), and (b) vertical velocity (omega) at 500 hPa (Pa s^{-1}) over eastern China. Dotted areas are statistically significant at the 10% level.

lower (middle to upper) troposphere in the region. Meanwhile, the baroclinic disturbance over West Asia can stimulate eastward-propagating Rossby waves via local heat-driven circulation, which contributes to the formation of anomalous circumglobal teleconnection (CGT) wave train in the troposphere of the Northern Hemisphere. From spring to early summer, with the weakening and northward shift of the westerly jet stream (WJS) in the Northern Hemisphere, the CGT transforms into a distribution similar to the early summer CGT pattern raised by [Ding and Wang \(2005\)](#). Because of the anomalous action

center of CGT over East Asia, the strengthening (weakening) of water vapor supply and upward (downward) motion result in increased (decreased) precipitation over North (Northeast) China. Moreover, the effect of topographic barrier is a key reason for the concentration of abnormal precipitation over the eastern part of North China, while intensified northerly wind plays an essential role in generating stronger precipitation anomalies over the eastern part of Northeast China. At the same time, the early summer temperature over Northeast China increases because of the enhancement of abnormal

FIG. 20. Differences (sensitivity runs minus CTL run) in early summer of (a) vertically integrated total cloud (fraction), (b) surface net solar flux (W m^{-2}), and (c) vertical mean meridional heat transport at 1000–500 hPa (K m s^{-1}) over Northeast China. Dotted areas are statistically significant at the 10% level.

FIG. 21. Schematic diagram on mechanisms in which spring land surface warming over West Asia affects early summer climate over northern China. WA, NC, and NEC represent the locations of West Asia, North China, and Northeast China. Letters A and C in the circle represent the anticyclonic and cyclonic circulation anomalies, respectively. The thick arrows represent the wind directions and the thin arrows in 200 hPa show the directions of Rossby wave propagation. The filled contour areas at 200 hPa show westerly jet streams (WJS; dark and light colors correspond to strong and weak WJS, respectively).

descending motion; besides, intensified warm temperature advection caused by the strengthening of southerly wind is an important factor for the abnormal warming over the western part of Northeast China, while enhanced surface net shortwave radiation due to cloud cover reduction makes for the abnormal warming over the eastern part.

To determine the effects of the land surface anomalous warming over the West Asia on the precipitation/air temperature anomalies over northern China, the control experiment (CTL) and the sensitivity experiments with positive (upward) land surface sensible heat forcing added over the target region of West Asia (45° – 70° E, 30° – 40° N) in spring are conducted by using CESM1.2.2. In the set of sensitivity experiments, there are 100 ensemble runs from 1 March to 30 June with different initial fields obtained from CTL. Through analyzing the differences between CTL and the sensitivity experiments (the latter minus the former), it is found that the early summer precipitation increases over North China and decreases over Northeast China accompanied by higher air temperature when the positive SH forcing added over West Asia in spring, which generally agrees with the observational results. Furthermore, the analysis of atmospheric circulations supports the above mechanisms. It is noteworthy that the abnormal land surface warming over West Asia in spring can cause anomalous CGT in the Northern Hemispheric troposphere. Affected by the persistent thermal forcing of land surface and the interaction between the basic flow (especially WJS) and CGT, the CGT generally enhances. From late spring to early summer, accompanied by the weakened, narrowed and northward-shifted WJS, the enhanced CGT captures a zonal wavenumber-5 structure, which is similar to the early summer CGT pattern raised by Ding and Wang (2005).

Further analysis of model results indicates that the abnormal circulation over northern China caused by the early summer CGT leads to evident local precipitation and temperature anomalies, which are consistent with the observations.

Our study emphasizes that the unique geographical location of West Asia is an important reason why its land thermal anomalies in spring are significantly related to the early summer climate of northern China. First of all, all boundaries of West Asia penetrate into Eurasia except for its southern part. Therefore, with anomalous land surface warming over West Asia in spring, there is no effective water vapor transported to the target region of West Asia under the guidance of anomalous tropospheric anticyclonic circulation. As a result, the forcing of spring land surface warming over West Asia on the atmosphere above is not affected by the negative feedback of precipitation, which also verified by the numerical simulations. Second, the target region of West Asia is located between the exit of North African jet and the entrance of East Asian jet in spring, so that the atmospheric disturbance caused by abnormal land surface warming over West Asia can be magnified by the barotropic energy conversion at the exit of North African jet. It is then effectively trapped and propagates downstream along the East Asian jet (Sato and Takahashi 2006).

In summary, this study discovers that the abnormal land surface warming over West Asia in spring can cause a baroclinic disturbance in the atmosphere above and further excite Rossby waves, which is beneficial to the enhancement of early summer CGT and further affects the climate over northern China (Fig. 21). It is shown that the spring land surface thermal conditions over West Asia are of great significance to the prediction of early summer climate over northern China.

However, there are remaining questions about the physical processes of the teleconnection that need to be further explored. One of them is that the interaction between the basic flow (especially WJS) and CGT plays an important role in the propagation, maintenance, and transition of CGT. However, we have noted that, as an external forcing source, the abnormal spring land surface warming over West Asia weakens significantly with the coming of early summer (Figs. 5c,f). Thus, the early summer CGT may also be influenced by the interactions between the abnormal action centers outside West Asia and its underlying surface (Wang et al. 2012; Lin et al. 2017b; Teng et al. 2019). In addition, simulation results show that the characteristics of the WJS (the jet strength/width/location) have different effects on the transition of CGT in different months. For example, the weakening of the WJS may be the main reason for the zonal number increase of CGT from April to May, while the narrowing of the WJS may stimulate the enhancement of CGT from May to June. Therefore, the internal dynamic evolution of CGT needs to be further investigated.

Furthermore, the land surface thermal forcing in the experimental design is the ideal forcing, which is effective for the exploration of the climate response to the external forcing (Kang et al. 2009; Zhang et al. 2020), but still preliminary and conceptual. It is suggested that considering the spatiotemporal variations of the land thermal forcing in the model may make more sense, so a more reasonable experimental design is needed for further study. Moreover, Yasui and Watanabe (2010) discussed the contributions of thermal forcing in different regions to the summer CGT. With that in mind, we would quantify the contribution of abnormal spring land surface warming over West Asia to early summer CGT with the numerical simulations in the follow-up work.

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