Impacts of Sensible Heat Anomalies over the Iranian Plateau and North Africa on Summer Precipitation in the Tarim Basin Postprint

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Abstract

Based on JRA-55 surface sensible heat and atmospheric circulation reanalysis data from the Japan Meteorological Agency for 1971–2019, together with monthly gridded precipitation data over China' s land surface from the National Meteorological Information Center, this study investigates the potential influence of summer sensible heat anomalies over the Iranian Plateau and North Africa on concurrent precipitation in the Tarim Basin. The results indicate that: (1) Both summer sensible heat over the Iranian Plateau and North Africa exhibit close relationships with summer precipitation in the Tarim Basin, and when heating from the two regions is considered jointly, its relationship with Tarim Basin precipitation is closer than when considering single-region heating alone. (2) When sensible heat over the Iranian Plateau is anomalously strong overall, and sensible heat over North Africa displays a north-weak-south-strong anomalous pattern, the Central Asian subtropical westerly jet is correspondingly displaced southward, with anomalous cyclonic and anticyclonic circulations dominating over Central Asia and the Mongolian Plateau, respectively, and southerly winds strengthening over the Tarim Basin; moisture from the tropical Indian Ocean, facilitated by anomalous circulation over the Arabian Sea and Central Asia, advances northward into the Tarim Basin; these combined conditions lead to increased concurrent precipitation in the Tarim Basin, and vice versa. (3) Heating over both North Africa and the Iranian Plateau can independently affect summer precipitation in the Tarim Basin, wherein sensible heat over the Iranian Plateau significantly influences both large-scale circulation and moisture transport, thus exhibiting a closer relationship with precipitation. The impact of sensible heat heating over North Africa is primarily manifested in large-scale circulation, with its effect on moisture transport differing from that of the Iranian Plateau, mainly reflected in the anomalous anticyclone over the Indian Peninsula being positioned further south, which prevents Arabian Sea moisture from entering the Tarim Basin.

Full Text

Effects of Sensible Heat Anomalies in the Iranian Plateau and North Africa on Summer Precipitation in the Tarim Basin

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Abstract: Based on monthly gridded precipitation data over China' s land surface, surface sensible heat flux, and atmospheric circulation reanalysis data from JRA-55 (provided by the Japan Meteorological Agency) spanning 1971–2019, this study investigates the potential effects of sensible heat anomalies over the Iranian Plateau and North Africa on concurrent summer precipitation in the Tarim Basin. The results indicate that: (1) Summer sensible heat flux over both the Iranian Plateau and North Africa is closely associated with summer precipitation in the Tarim Basin, and the combined heating from these two regions shows a stronger relationship with precipitation than heating from either region alone. (2) When sensible heat over the Iranian Plateau is abnormally strong while North Africa exhibits a north-weak, south-strong pattern, the subtropical westerly jet over Central Asia shifts southward, with an anomalous cyclone and anticyclone dominating the central Asian and Mongolian Plateau regions, respectively. This configuration strengthens southerly winds over the Tarim Basin. Meanwhile, water vapor from the tropical Indian Ocean, facilitated by anomalous circulation over the Arabian Sea and Central Asia, moves northward into the Tarim Basin. These combined conditions lead to increased precipitation in the Tarim Basin during the same period, and vice versa. (3) Thermal anomalies in both North Africa and the Iranian Plateau can individually influence summer precipitation in the Tarim Basin. However, the Iranian Plateau' s sensible heating significantly affects both large-scale circulation and water vapor transport, resulting in a closer relationship with precipitation. In contrast, the impact of North Africa' s sensible heating is primarily manifested in large-scale circulation, with its effect on water vapor transport differing from that of the Iranian Plateau—mainly reflected in the more southerly position of the anomalous anticyclone over the Indian Peninsula, which prevents Arabian Sea moisture from entering the Tarim Basin.

Keywords: sensible heat anomaly; combined heating; North Africa; Iranian Plateau; summer precipitation in the Tarim Basin

Introduction

Surface heating is one of the driving factors for the evolution of atmospheric circulation and exerts important influences on regional weather and climate. Many meteorologists have analyzed the effects of surface thermal conditions on summer precipitation in China from the perspective of underlying surface heating. As the most extensive underlying surface, the ocean can store large amounts of water vapor and energy, and changes in its surface thermal conditions have significant impacts on atmospheric circulation and precipitation across China and the entire Northern Hemisphere. For example, anomalous warming of tropical Indian Ocean sea surface temperature can enhance northward water vapor transport from the Arabian Sea, favoring summer precipitation in Northwest China. Although oceanic thermal conditions substantially influence summer precipitation in China, land surface thermal forcing cannot be ignored. The Tibetan Plateau, as the region with the most significant thermal effects in the Eurasian land surface process, exhibits heat source variations that serve as good indicators for summer drought-flood distributions in China. Currently, most studies on surface thermal effects focus on the Tibetan Plateau, though some have examined the connections between thermal forcing over the Iranian Plateau and North Africa and summer precipitation in China. Sensible heating over the Iranian Plateau can excite anomalous cyclonic circulation in the mid-lower troposphere, enhancing the transport of South Asian water vapor inland and playing an important role in monsoon precipitation over East Asia. Spring sensible heat anomalies in North Africa can force zonal circulation wave trains in the westerlies that propagate eastward, exerting a lagged effect on summer precipitation in eastern China. The sensible heat over North Africa and the northwestern Tibetan Plateau shows a significant negative correlation, with the former mainly affecting precipitation in North China and the Jianghuai region, while the latter primarily influences precipitation in North China and South China. When the underlying surfaces of the northwestern Indian Ocean and central North Africa are colder in summer, the low-pressure trough in northern Central Asia deepens and the western Pacific subtropical high strengthens in autumn, forming favorable circulation conditions and moisture conditions for continuous autumn rain in Huaibei. Zhao et al. studied the relationship between land-sea thermal differences in North Africa and summer precipitation in the Jianghuai region, finding that when the North African continent is colder while sea temperatures to its northwest are warmer in early winter, precipitation in the Jianghuai River basin increases the following summer.

Against the background of global warming, the extent of semi-arid regions in China has expanded, with significant climate changes in arid and semi-arid areas. Since the 1980s, Northwest China has transitioned from warm-dry to warm-wet conditions, with significant increases in summer precipitation in the Tarim Basin. Many meteorologists have conducted multifaceted research on the causes of anomalous summer precipitation changes in Xinjiang, and some scholars have explored the connections between Iranian Plateau and North Africa land surface thermal forcing and summer precipitation in Xinjiang from the perspective of land surface thermal forcing. Abnormal enhancement of spring sensible heat over the Iranian Plateau favors increased precipitation in northern Xinjiang. Sensible heat forcing over the Iranian Plateau significantly influences large-scale circulation systems such as the Central Asian vortex, which are key factors for summer precipitation in Xinjiang. Land surface heating in North Africa can affect the development of the North African high, which is related to summer precipitation anomalies in Xinjiang. In summary, surface sensible heat over both North Africa and the Iranian Plateau is connected to summer precipitation in Xinjiang, but few studies have considered both regions together from a regional synergy perspective to analyze their combined effects on Xinjiang summer precipitation. This paper first presents the relationship between sensible heat anomalies over the Iranian Plateau and North Africa and precipitation in the Tarim Basin, then investigates the influence processes of the two regional heatings on Tarim Basin summer precipitation by analyzing their effects on large-scale circulation and water vapor transport, thereby deepening our understanding of climate change mechanisms in arid regions.

1 Study Area Overview

The Tarim Basin is located in southern Xinjiang, China, surrounded by high mountains on three sides. Blocked by the Tibetan Plateau to the south, moisture from tropical oceans has difficulty reaching the basin. The desert and oasis within the basin constitute a unique and fragile ecological environment, making it a sensitive region to climate change. These special geographical conditions result in poor moisture conditions, high dependence on natural precipitation, and the lowest precipitation at the same latitude in China. In the process of climate transition in Xinjiang, summer precipitation has shown an increasing trend, with particularly significant increases in the Ili River Valley, Tianshan Mountains, and western Tarim Basin.

2.1 Data Sources

Due to the scarcity of meteorological observation data in North Africa and the Iranian Plateau, reanalysis data are commonly used. Previous studies comparing multiple reanalysis datasets have concluded that JRA-55 reanalysis data can accurately reflect the spatiotemporal variation characteristics of surface sensible heat over the Iranian Plateau with high reliability. Therefore, this study selects monthly mean surface sensible heat flux data from JRA-55 (available at https://climatedataguide.ucar.edu/climate-data/jra-55). To analyze the effects of sensible heat anomalies on circulation patterns and water vapor transport, monthly mean isobaric wind fields, relative humidity, and surface pressure fields from JRA-55 are also selected, with a horizontal resolution of 1.25°$×1.25°.*MonthlyprecipitationdatafortheTarimBasinareprovidedbytheNationalMeteorologicalInform*
The climatological mean state is based on data from 1971–2019.

2.2 Research Methods

The main methods employed in this study include singular value decomposition (SVD) analysis, multiple linear regression analysis, and linear and partial correlation analysis.

(1) Singular Value Decomposition Analysis: To analyze the relationship between sensible heat over the Iranian Plateau and North Africa and summer precipitation in the Tarim Basin, standardized surface sensible heat flux over the Iranian Plateau (25°–40°N, 50°–70°E) and North Africa (0°–35°N, 0°–50°E) are selected as left fields (X), and summer precipitation in the Tarim Basin is selected as the right field (Y) for SVD analysis to investigate the spatial patterns of temporal correlation between the two fields.

The cross-covariance matrix between X and Y is S = XY^T. Through SVD, left and right singular vector matrices L and R can be obtained such that S = LΛR^T, where Λ is a diagonal matrix of singular values satisfying $\Lambda_1 \geq \Lambda_2 \geq \cdots \geq \Lambda > 0$. Significance is tested using the Monte Carlo method. The SVD expansion yields time coefficient matrices for left and right fields that maximize covariance between U and V.

(2) Multiple Linear Regression Analysis: To analyze the effect of combined heating from the two regions on summer precipitation in the Tarim Basin, summer precipitation in the Tarim Basin is selected as the response variable Y, and summer sensible heat over the Iranian Plateau and North Africa are selected as predictor variables X to establish a multiple linear regression model:

$Y = X\beta +$

where Y is the vector of observed precipitation, X is the matrix of predictor variables, β is the coefficient vector, and is the random error term. The least squares estimate of the coefficient vector is β = (X^T X)^(-1) X^T Y. Model fit is evaluated using the multiple correlation coefficient R, and regression coefficients are tested for significance using t-tests.

(3) Partial Correlation Analysis: To investigate the individual effects of sensible heat from the two regions on precipitation in the Tarim Basin, Iranian Plateau sensible heat is selected as variable X, North Africa sensible heat as variable Z, and Tarim Basin summer precipitation as variable Y for partial correlation analysis. The partial correlation coefficient between X and Y after removing the linear influence of Z is:

r_{XY·Z} = (r_{XY} - r_{XZ} r_{YZ}) / √[(1 - r_{XZ}²)(1 - r_{YZ}²)]

where r_{XY}, r_{XZ}, and r_{YZ} are correlation coefficients. Significance is tested using the t-statistic.

3.1 Relationship Between Surface Sensible Heat Over the Iranian Plateau and North Africa and Summer Precipitation in the Tarim Basin

To investigate the relationship between sensible heat anomalies over the Iranian Plateau and North Africa and summer precipitation in the Tarim Basin, standardized surface sensible heat flux over the Iranian Plateau (25°-40°N, 50°-70°E) and North Africa (0°-35°N, 0°-50°E) are selected as left fields, and Tarim Basin summer precipitation as the right field for SVD analysis. The left field uses homogeneous correlation coefficients while the right field uses heterogeneous correlation coefficients. Since the first SVD mode between the Iranian Plateau and Tarim Basin precipitation accounts for 56.2% of the covariance contribution and passes the 95% significance test, this study focuses on the first mode. When sensible heat over the Iranian Plateau shows a positive anomaly [Figure 2a: see original paper], precipitation distribution in the Tarim Basin also exhibits a positive anomaly pattern [Figure 2b: see original paper]. The correlation coefficient between their time coefficients is 0.56 (exceeding the 99% confidence level), indicating that enhanced sensible heat over the Iranian Plateau corresponds to increased rainfall throughout the Tarim Basin, particularly in the western basin. A similar relationship exists between summer sensible heat over North Africa and precipitation in the Tarim Basin [FIGURE:2c, d], with the first mode explaining 52.4% of the covariance. When North Africa shows a north-weak, south-strong sensible heat pattern, precipitation in the Tarim Basin is uniformly above normal, with the most significant increases again in the western basin. In summary, summer sensible heat anomalies over both the Iranian Plateau and North Africa are closely linked to precipitation in the western Tarim Basin—the region where summer precipitation has increased most significantly in Xinjiang in recent years.

To analyze the influence processes of the two regional heatings on Tarim Basin precipitation, thermal indices for the Iranian Plateau and North Africa and a summer precipitation index for the Tarim Basin are defined based on [Figure 2: see original paper].

Iranian Plateau Thermal Index (IPTI) = Nor(27°-40°N, 57°-67°E)
North Africa Thermal Index (NATI) = Nor(0°-15°N, 10°-40°E) - Nor(20°-30°N, 20°-45°E)
Summer Precipitation Index (SPI) = standardized sequence of regional average precipitation (36°-42°N, 73.5°-84°E)

where Nor represents standardized average surface sensible heat anomalies in the key regions, and standardized processing is applied to all variables.

Correlation analysis reveals that the correlation coefficient between IPTI and SPI is 0.45, and between NATI and SPI is 0.38, both exceeding the 99% confidence level. Although both thermal indices are closely related to precipitation, the relationship between combined heating from the two regions and Tarim Basin summer precipitation is stronger than when considering only a single region’ s heating.

3.2 Individual Effects of Summer Thermal Anomalies Over the Iranian Plateau and North Africa on Tarim Basin Precipitation

Using multiple linear regression with IPNATI (Iranian Plateau & North Africa Thermal Index) as the independent variable and Tarim Basin summer precipitation as the dependent variable yields the regression distribution [Figure 7: see original paper]. The two show a significant positive correlation, with precipitation uniformly above normal across the Tarim Basin when Iranian Plateau and North Africa heating is strong. Composite analysis confirms this: when IPNATI > 0.5 (strong heating years), summer precipitation in the Tarim Basin increases significantly [Figure 7a: see original paper]; when IPNATI < -0.5 (weak heating years), precipitation shows the opposite pattern with uniformly less rainfall [Figure 7b: see original paper].

Partial correlation analysis is used to examine the individual effects of sensible heat from the two regions. After removing the influence of North African heating, the partial correlation between Iranian Plateau thermal index and Tarim Basin precipitation [Figure 4a: see original paper] shows a significant positive relationship. When Iranian Plateau summer sensible heat is strong, precipitation across the Tarim Basin increases, particularly in the western region. After removing Iranian Plateau heating and considering only North African heating [Figure 4b: see original paper], strong North African thermal index corresponds to uniformly above-normal precipitation, though the significant area is slightly smaller than in [Figure 4a: see original paper].

The circulation mechanisms are further analyzed. Under the sole influence of Iranian Plateau sensible heat anomalies [Figure 5a: see original paper], the Iranian Plateau thermal index is closely associated with 500 hPa wind fields, with cyclonic and anticyclonic circulations controlling Central Asia and Mongolia, respectively. Southerly winds strengthen over the Tarim Basin, forming a circulation pattern favorable for increased precipitation. After removing Iranian Plateau heating, the effect of North African heating on 500 hPa circulation [Figure 5b: see original paper] is similar, with an anticyclonic circulation over the Iranian Plateau cooperating with a cyclonic circulation over Central Asia.

Analysis of water vapor transport shows that under Iranian Plateau sensible heat anomalies alone (after removing North African heating), an anomalous anticyclone over the Arabian Sea cooperates with a cyclonic circulation over Central Asia to transport Arabian Sea water vapor northward to the Tarim Basin through a two-step process [Figure 6a: see original paper]. However, after removing Iranian Plateau heating and considering only North African heating [Figure 6b: see original paper], this two-step transport cannot form. Although the upper-level cyclonic circulation over Central Asia still exists (forming the second step), the anticyclonic circulation over the Arabian Sea-Indian Peninsula is positioned too far south, preventing tropical Indian Ocean moisture from moving northward into the Tarim Basin. This explains why the correlation between the North African heating index and Tarim Basin summer precipitation is slightly weaker.

3.3 Combined Effects of Summer Thermal Anomalies Over the Iranian Plateau and North Africa on Tarim Basin Precipitation

Precipitation generation requires both favorable circulation dynamics and water vapor transport. The regression distribution between IPNATI and 200 hPa zonal wind [Figure 8: see original paper] shows that when Iranian Plateau and North African heating is strong, the 200 hPa zonal wind exhibits a "negative north, positive south" pattern, with enhanced westerlies on the southern side and weakened westerlies on the northern side of the Central Asian subtropical westerly jet, causing the jet axis to shift southward—corresponding to above-normal precipitation in the Tarim Basin. In weak heating years, the pattern reverses to "positive north, negative south," shifting the jet axis northward and reducing precipitation.

The regression distribution between IPNATI and 500 hPa wind [Figure 9: see original paper] shows that combined heating from the two regions is closely related to the wind field over Central Asia. In strong heating years [Figure 9a: see original paper], under the combined influence of cyclonic circulation over Central Asia and anticyclonic circulation over the Mongolian Plateau, southerly winds strengthen over the Tarim Basin, facilitating the northward movement of warm, moist air from low latitudes and providing favorable circulation conditions for precipitation. In weak heating years [Figure 9b: see original paper], the wind field distribution is opposite, with anticyclonic and cyclonic circulations at mid-tropospheric levels over Central Asia and the Mongolian Plateau, respectively, strengthening northerly winds over the Tarim Basin and guiding dry, cold air southward, resulting in reduced precipitation.

Water vapor transport analysis [Figure 10: see original paper] reveals that combined heating from the two regions primarily affects the wind field over the Arabian Sea. In strong heating years [Figure 10a: see original paper], Arabian Sea water vapor is transported northward to mid-latitudes by the anomalous anticyclone aloft, then continues moving northward into the Tarim Basin under the influence of the anomalous cyclonic circulation over Central Asia. In weak heating years [Figure 10b: see original paper], the spatial distribution of water vapor transport is essentially opposite, with both the tropical Indian Ocean and Central Asia controlled by anomalous cyclonic and anticyclonic circulations that are unfavorable for northward water vapor transport.

4 Discussion

This study analyzed the effects of sensible heat heating over the Iranian Plateau and North Africa on summer precipitation in the Tarim Basin and revealed possible influence mechanisms, but several limitations remain: (1) The research focused on the interannual scale of the relationship between heating and Tarim Basin summer precipitation without considering decadal effects. However, [Figure 3: see original paper] shows that Iranian Plateau sensible heat and Tarim Basin precipitation exhibited opposite signals during 1997–2002, as did North African sensible heat and Tarim Basin precipitation during 1980–1985. Whether these opposite signals are caused by decadal variations in sensible heat requires further investigation. (2) Both Iranian Plateau and North African sensible heating can individually affect Tarim Basin summer precipitation, but with differences. When only Iranian Plateau sensible heating is considered, both circulation patterns and water vapor transport favor precipitation occurrence in the Tarim Basin. However, when only North African sensible heating is considered, only the large-scale circulation conditions for precipitation can form. Therefore, in the process of combined influence from both regions, Iranian Plateau sensible heating plays a dominant role, cooperating with North African heating to jointly affect Central Asian circulation and water vapor transport, thereby modulating summer drought-flood distributions in the Tarim Basin. (3) Previous studies have indicated that the thermal effects of the Tibetan Plateau are closely related to thermal changes in North Africa, and that a coupled system of mutual influence exists between the surface thermal effects of the Tibetan Plateau and Iranian Plateau and Indian Ocean water vapor transport. Additionally, latent heat changes over the Tibetan Plateau significantly affect drought-flood distributions in the Tarim Basin. The contribution of Tibetan Plateau thermal effects to the influence process of Iranian Plateau and North African heating on Tarim Basin precipitation requires further analysis through numerical experiments.

5 Conclusions

Against the background of climate transition in Xinjiang, summer precipitation has shown an increasing trend, with significant increases in the Ili River Valley, Tianshan Mountains, and western Tarim Basin. What has caused this significant increase in summer precipitation in the Tarim Basin? From a regional synergy perspective, this paper analyzed the main physical processes through which heating over the Iranian Plateau and North Africa affects summer precipitation in the Tarim Basin. The main conclusions are as follows:

(1) SVD analysis reveals that summer surface sensible heat anomalies over both the Iranian Plateau and North Africa are closely related to precipitation in the Tarim Basin. Correlation analysis shows that the relationship between combined heating from both regions and summer precipitation in the Tarim Basin is stronger than when considering heating from only a single region.

(2) When sensible heat over the Iranian Plateau is abnormally strong (weak) while North Africa shows a north-weak, south-strong (north-strong, south-weak) pattern, the Central Asian subtropical westerly jet shifts southward (northward). Central Asia and the Mongolian Plateau are controlled by anomalous cyclonic (anticyclonic) and anticyclonic (cyclonic) circulations,

respectively. Under the combined influence of these two systems, southerly (northerly) winds strengthen over the Tarim Basin, forming favorable (unfavorable) circulation conditions. Simultaneously, water vapor from the Arabian Sea is transported northward to the Tarim Basin by the anomalous anticyclone (cyclone) aloft, and with the cooperation of the anomalous cyclone (anticyclone) over Central Asia, mid-latitude water vapor is delivered to (prevented from reaching) the Tarim Basin, resulting in above-normal (below-normal) precipitation.

(3) Both Iranian Plateau and North African sensible heating can individually affect summer precipitation in the Tarim Basin, but with differences. When only Iranian Plateau sensible heating is strong, both circulation patterns and water vapor transport favor precipitation occurrence. When only North African sensible heating is strong, only the large-scale circulation conditions for precipitation can form. Therefore, in the process of combined influence on summer precipitation in the Tarim Basin, Iranian Plateau sensible heating plays a dominant role, cooperating with North African heating to jointly influence Central Asian circulation and water vapor transport, thereby modulating summer drought-flood distributions in the Tarim Basin.

References

[1] Duan Anmin, Liu Yimin, Wu Guoxiong. Thermal state of Tibetan Plateau in April to June and association with East Asian summer precipitation and atmospheric circulation anomalies [J]. Scientia Sinica (Terrae), 2003, 33(10): 997-1004.

[2] Wu Guoxiong, Mao Jiangyu, Duan Anmin, et al. Recent progress in the study on the impacts of Tibetan Plateau on Asian summer climate[J]. Acta Meteorologica Sinica, 2004, 62(5): 528-540.

[3] Zhao Ping, Chen Longxun. Climatic features of atmospheric heat source/sink over the Qinghai Xizang Plateau in 35 years and its relation to rainfall in China[J]. Scientia Sinica (Terrae), 2001, 31(4): 327-332.

[4] Huang R H, Wu Y F. The influence of ENSO on the summer climate change in China and its mechanism[J]. Advances in Atmospheric Sciences, 1989, 6: 21-32.

[5] Huang Ronghui, Xu Yuhong, Zhou Liantong. The interdecadal variation of summer precipitations in China and the drought trend in north China[J]. Plateau Meteorology, 1999, 18(4): 465-476.

[6] Li Qifen, Wu Zhehong, Wang Xingju, et al. The characteristics of summer precipitation in China since 1981 and its relationship with SST and pre circulation[J]. Plateau Meteorology, 2020, 39(1): 58-67.

[7] Li Chao, Wei Jiansu, Sun Hongchuan, et al. Correlation analysis between the

decadal character of sensible heat in north Africa and rainfall in east China[J]. Scientia Meteorologica Sicica, 2012, 32(4): 443-450.

[8] Yang Jianling, Hu Haibo, Mu Jianhua, et al. Study of numerical model stimulation of the tropical Indian Ocean basin mode impacts on May precipitation anomaly in east of northwest China[J]. Plateau Meteorology, 2017, 36(2): 510-516.

[9] Zhou Y, Huang A N, Zhao Y, et al. Influence of the sea surface temperature anomaly over the Indian Ocean in March on the summer rainfall in Xinjiang[J]. Theoretical and Applied Climatology, 2015, 119(3-4): 781-789.

[10] Luo Huibang, Chen Rong. The impact of the anomalous heat sources over the eastern Tibetan Plateau on the circulation over East Asia in summer half year[J]. Scientia Meteorologica Sicica, 1995, 15(4): 94-102.

[11] Ning Liang, Qian Yongfu. Oscillation characteristics of sensible heat in north Africa and Qinghai Xizang Plateau and their impacts on the rainfall in east China[J]. Plateau Meteorology, 2006, 25(3): 357-365.

[12] Li Dongliang, Liu Miao, Wang Hui. Latent heat series over the east part of QXP in rainy season and its impact on 500 hPa height fields of northern hemisphere and precipitation in China flood season[J]. Plateau Meteorology, 2008, 27(4): 713-718.

[13] He Dongyan, Wu Rong, Tian Hong, et al. Analysis on the feature and formation mechanism of the continuous rain in autumn in Anhui since 1971[J]. Plateau Meteorology, 2019, 38(4): 829-844.

[14] Zhao Yong, Qian Yongfu. Relationships between the anomalies of sea land thermal contrast in the northern Africa areas and the flood and drought in the Changjiang and Huaihe River areas in summer[J]. Acta Meteorologica Sinica, 2008, 66(2): 203-212.

[15] Wu G X, Zhuo H F, Wang Z Q, et al. Two types of summertime heating over the Asian large scale orography and excitation of potential vorticity forcing I. over Tibetan Plateau[J]. Science China Earth Sciences, 2016, 59(10): 1996-2008.

[16] Zhang Y N, Wu G X, Liu Y M, et al. The effects of asymmetric potential vorticity forcing on the instability of South Asia High and Indian summer monsoon onset[J]. Science China Earth Sciences, 2014, 57(2): 337-350.

[17] Yang Lianmei, Zhang Qingyun. Wave sources, energy propagation and conversion for anomalous Rossby wave activities along West Asian jet stream[J]. Acta Meteorologica Sinica, 2008, 66(4): 555-565.

[18] Wang Xiurong, Xu Xiangde, Wang Weiguo. Characteristic of spatial transportation of water vapor for northwest China' s rainfall in spring and summer[J]. Plateau Meteorology, 2007, 26(4): 749-758.

[19] Zhang Q, Wu G, Qian Y. The bimodality of the 100 hPa South Asia High and its relationship to the climate anomaly over East Asia in summer[J]. Journal

of the Meteorological Society of Japan, 2015, 93(6): 581-595.

[20] Xie S P, Yu K, Yan D U, et al. Indo western Pacific Ocean capacitor and coherent climate anomalies in Post ENSO summer: A review[J]. Advances in Atmospheric Sciences, 2016, 33(4): 411-432.

[21] Liu Chao, Liu Yimin, Liu Boqi. Comparison of six sensible heat flux datasets over the Iranian Tibetan Plateaus[J]. Scientia Meteorologica Sicica, 2015, 35(4): 398-404.

[22] Yang Y X, Liu Y M, Li M S, et al. Assessment of reanalysis flux products based on eddy covariance observations over the Tibetan Plateau[J]. Theoretical and Applied Climatology, 2019, 138(1/2): 519-532.

[23] Kobayashi C, Iwasaki T. Brewer Dobson circulation diagnosed from JRA-55[J]. Journal of Geophysical Research Atmospheres, 2016, 121(4): 1493-1510.

[24] Zhao Yufei, Zhu Jiang, Xu Yan. Establishment and assessment of the grid precipitation datasets in China for recent 50 years[J]. Journal of the Meteorological Sciences, 2014, 34(4): 414-420.

[25] Wei Fengying. Statistical diagnosis and prediction techniques of modern climate[M]. Beijing: China Meteorological Press, 2007: 160-169.

[26] Lin Bin. Multiple linear regression analysis and its application[J]. China Science and Technology Information, 2010(9): 60-61.

[27] Zhu K W, Guan X D, Huang J P, et al. Precipitation over semi regions of North Hemisphere affected by Atlantic multidecadal oscillation[J]. Atmospheric Research, 2021, 262: 105801, doi: 10.1016/j.atmosres.2021.105801.

[28] Zhao Yong, Huang Anning, Yang Qing, et al. Relationships between the anomalies of surface sensible heat in the Tibetan Plateau and Iran Plateau and summertime precipitation in north Xinjiang[J]. Acta Meteorologica Sinica, 2013, 71(4): 660-667.

[29] Chen Jiayi, Zhao Yong. Effects of the summer heating over the Iranian Plateau and the Tibetan Plateau on precipitation over the Tarim Basin[J/OL]. Plateau Meteorology. [2022-06-06]. http://kns.cnki.net/kcms/detail/62.1061.P.20220520.1052.002.html.

[30] Lu Xing, Zhao Yong. The relationships between north Africa subtropical high and summer precipitation over Central Asia[J]. Arid Land Geography, 2022, 45(4): 1050-1060.

[31] Yang Qing, Wei Wenshou, Li Jun. Temporal and spatial variations of atmospheric water vapor in the Taklimakan Desert and surrounding areas[J]. Bulletin of Science, 2008, 53(Suppl. 2): 64-70.

[32] Huang W, Feng S, Chen J, et al. Physical mechanisms of summer precipitation variations in the Tarim Basin in northwestern China[J]. Journal of Climate, 2015, 28(9): 3579-3591.

[33] Wu G X, Liu Y M, He B, et al. Thermal controls on the Asian summer monsoon[J]. Scientific Reports, 2012, 2: 404, doi: 10.1038/srep00404.

[34] Li Y, Huang J, Ji M, et al. Dryland expansion in northern China from 1948 to 2008[J]. Advances in Atmospheric Sciences, 2015, 32(6): 870-876.

[35] Huang J P, Ma J R, Guan X D, et al. Progress in semi arid climate change studies in China[J]. Advances in Atmospheric Sciences, 2019, 36: 922-937.

[36] Hu Ruji, Jiang Fengqing, Wang Yajun, et al. A study on signals and effects of climatic pattern changes from warm dry to warm wet in Xinjiang[J]. Arid Land Geography, 2002, 25(3): 194-200.

[37] Shi Yafeng, Shen Yongping, Hu Ruji. Preliminary study on signal, impact and foreground of climatic shift from warm dry to warm wet in northwest China[J]. Journal of Glaciology and Geocryology, 2002, 24(3): 219-226.

[38] Zhang Jiabao, Deng Zifeng. Introduction to Xinjiang precipitation[M]. Beijing: China Meteorological Press, 1987: 255-263.

[39] Wang Tianzhu, Zhao Yong. Relationships between thermal anomalies over the Qinghai-Xizang Plateau and Tropical Indian Ocean in May with summer rainfall in Xinjiang[J]. Plateau Meteorology, 2021, 40(1): 1-14.

[40] Liu Yimin, Wang Ziqian, Zhuo Haifeng, et al. Two types of summertime heating over Asian large scale orography and excitation of potential vorticity forcing II. Sensible heating over Tibetan-Iranian Plateau[J]. Scientia Sinica (Terrae), 2017, 47(3): 354-366.

[41] Watanabe T. Role of regional thermal contrast over West Asia in interannual variation in atmospheric moisture transportation over the Indian Ocean and neighboring areas at summer monsoon onset[J]. Journal of Geophysical Research Atmospheres, 2015, 120(23): 1493-1510.

[42] Zhao Y, Wang M Z, Huang A N, et al. Relationships between the West Asian subtropical westerly jet and summer precipitation in northern Xinjiang[J]. Theoretical and Applied Climatology, 2014, 116: 403-411.

[43] Yang Lianmei, Zhang Qingyun. Interannual variation of summer precipitation in Xinjiang and Asian subtropical westerly jet stream[J]. Journal of Applied Meteorological Science, 2008, 19(2): 171-179.

Note: Figure translations are in progress. See original paper for figures.