The Warming of the Arabian Sea Induced a Northward Summer Monsoon over the Tibetan Plateau

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ABSTRACT: Summer monsoon precipitation over the Tibetan Plateau (TP) has significant impacts on the ecology, economy, and Asian climate, but has exhibited anomalous spatial distribution since the early twenty-first century. To explore its distribution and attribution, this study investigated the northernmost boundary of the summer monsoon over the TP (TPSM) and the related precipitation. The TPSM and related precipitation extended poleward in response to the rising Arabian Sea surface temperature (ARB_SST) in the late spring and early summer. A warming Arabian Sea leads to the westward movement of the Indian summer monsoon (ISM) circulation and moisture convergence with a higher moisture layer, which exerts a midlatitude wave train that exhibits a dipole mode (a west cyclone and an east anticyclone) over the TP. Consequently, the west trough and southerly are strengthened, which is conducive to transporting more poleward moisture mass from the moisture layer over the ISM zone through the midwestern TP. Furthermore, it contributes to the poleward TPSM and precipitation in the northern TP by coupling with the dipole mode. These findings help explain the wetting of the Asian dryland and its effects on the Northern Hemispheric climate.

KEYWORDS: Dynamics; Climate sensitivity; Water vapor; Monsoons; Precipitation

1. Introduction

The Tibetan Plateau (TP) is the world’s highest and largest plateau, averaging over 4000 m above sea level and spanning one-fifth of the Asian region. The high TP topography causes unique montane barriers and thermodynamic effects, leading to westerly and tropical southerly wind activity over the TP and the surrounding area (Mölö et al. 2014). Generally, the TP is severely influenced by cold westerlies during cold seasons, which are responsible for frozen ground and snow cover; consequently, the TP acts as a cold source because of its high albedo and reflection of short radiation. However, during warm seasons, the TP acts as a heat source because of its low albedo and absorption of short radiation, corresponding to monsoon circulation and relatively high soil moisture (Wu et al. 2017). The TP, as a heat source is important because it occurs in the middle troposphere and its temperature and diabatic heating is higher than that in other regions at the same level. Strong heat sources enhance the low pressure and thermal contrast between the TP and its surrounding area; consequently, most areas of the TP are influenced by convergent moisture flow, which is associated with the Indian summer monsoon (ISM) and East Asian summer monsoon (EASM).

The aforementioned monsoon circulation and related moisture flow occurring over the TP are defined as TP monsoons.

In 1957, cyclone circulation was initially proposed, which drives convergent southerly and tropical moisture masses to the TP in the warm season. The cyclone is contrary to the circulations of anticyclone and the cold–dry westerly during the entire cold season over the TP (Tang et al. 1979). Along with summer monsoon onset over the TP (TPSM), westerly retreats co-occur with southerly advances poleward over the TP. Therefore, the TPSM generally dominates the climate mode of the wet southeast and dry northwest (Duan et al. 2013), which results in nonuniform meridional diabatic heating. The TPSM also favors the release of condensation latent heat and further strengthens the South Asian high over the upper troposphere (Ye and Gao 1979). In this case, the TP is recognized as a potentially valuable area in terms of its dynamic and thermodynamic influences on the circulation, energy, and hydrological cycles of the climate system (Liu et al. 2017; Wu et al. 2017).

The TPSM is closely related to the asymmetric distributions of temperature and sensible heat flux over the TP. The rising temperature over the TP decreases the thermal contrast between the TP and the Indian Ocean, which leads to a northward shift of the subtropical jet, favoring the poleward retreating of the cold westerly circulation and the onset of the Asian monsoon (Liu et al. 2017). The surface sensible heat flux during the spring prevails over the latent heat flux at the ground surface (Wu et al. 2017), which results in strong cyclonic circulation over the TP and correspondingly contributes to convergence of the subtropical moisture mass. Thus, diabatic heating-related cyclones are the dominant TPSM circulation. Concurrent with global warming, the warming rate over the TP has increased to twice the average level (Xu et al. 2009), which has triggered glacier shrinking, early snow

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melting, and the occurrence of later snow (Kraaijenbrink et al. 2017). Thus, climate warming has led to remarkable variations in the TP temperature and water phase, being accompanied by significant changes in surface and atmospheric diabatic heating. Consequently, diabatic heating drives anomalous low pressure that pumps an increased amount of moisture mass from low-latitude oceans to the TP and East Asia and transfers water vapor from the lower to the upper troposphere, modulating the southerly monsoon circulations and TPSM (Wang et al. 2019). However, studies have shown limitations in the variations and impact factors of the TPSM position.

Except for proving thermal conditions over TP, the literature has proven that the warm Indian Ocean basin mode (IOBM; Niu et al. 2022) not only strengthens tropical convection over the Indian Ocean but also influences the circulation of the TPSM. Wang and Duan (2015) suggested that the enhanced equivalent potential temperature results in the destabilization of the lower troposphere, which occurs under the warm IOBM and contributes to moisture advection toward the TP. Moreover, the effects of southerly winds on tropical moisture flux have been identified, which facilitates the development and maintenance of the TPSM. Tropical convection heating also interacts with the TP diabatic heating in summer and exhibits a dipole mode of heating (Hu and Duan 2015; Jiang and Ting 2017). Zhang et al. (2019) found reverse variation in the diabatic heating between the eastern TP and the ISM domain with two teleconnections, and observed a tripole precipitation pattern involving the TP, Indian Peninsula, and northern China. The dipole and tripole modes among the eastern TP and ISM domain govern two branches of water vapor transported to the TP and the Asian dryland, which originate from the Arabian Sea and the Bay of Bengal (BOB), respectively (Zhao et al. 2022). As reported in the literature, the ISM cloud mass and moisture advection can be transported across the southern TP, enhancing the TPSM (Zhou et al. 2022).

Along with the ISM change through the BOB (Chen et al. 2012; Yao et al. 2013), a significant decadal shift of the TPSM has occurred since the early twenty-first century (Tang 1995), and in situ observations verify an increase in summer precipitation over the northern TP, extending to Asian drylands. These variations are linked to the expanding TPSM circulation (Zhang et al. 2021) but contradict the anomalous meridional movement of ISM positions. Therefore, investigating the causes of the TPSM anomalies and their linkage with ISM anomalies is necessary. As dynamical effects and external forcing factors influence TPSM/ISM, this study investigated TPSM variations.

Using daily European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA5), the variations in the northernmost boundaries of the TPSM in the past 42 years (1979–2020) were analyzed, and their relationships with meridional wind and meridional moisture flux over the southern TP were investigated. Next, the dynamic processes and possible relationships between sea surface temperature (SST) and the TPSM were explored.

2. Data and methods

The data used in this study were obtained as follows: First, the global atmospheric circulation data, including vertical velocity, geopotential height, specific humidity, and air temperature, were obtained from ERA5 (https://cds.climate.copernicus.eu/; Hersbach et al. 2020), with a horizontal resolution of 0.25° × 0.25°. ERA5 was also used to calculate the moisture flux linked with the precipitation, TPSM position, westerlies, and ISM circulation. Second, the daily CPC precipitation at 0.5° × 0.5° resolution (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html) was used to investigate precipitation on the northernmost boundary of the TPSM; its suitability in various areas, including the TP, has been proven (Ma et al. 2021). Third, the monthly mean SST data were derived from the Hadley SST dataset (HadISST) with a horizontal resolution of 1° × 1° for 1979–2021 (Rayner et al. 2003). Finally, the 30-m terrain data were collected from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model V2 (https://search.earthdata.nasa.gov/).

Based on the wind direction, the moisture flux differences, convergence belt of westerly and southerly winds, precipitation in every pentad, and dry/wet conditions are distinct on both sides, and the northernmost boundary of the TPSM is defined to describe the TPSM position, which is discriminated according to the following pentad factors (Zhang et al. 2016):

\[
0^\circ < V_d < 180^\circ \text{ or } 270^\circ < V_d < 360^\circ,
\]

\[
(V_d - V_n) > 10^\circ,
\]

\[
u > 0 \text{ m s}^{-1}, \quad v > 0 \text{ m s}^{-1}, \quad D < 0 \text{ kg m}^{-2} \text{ s}^{-1},
\]

\[
\theta_e - \theta_n > 1 \text{ K},
\]

\[
p > 1 \text{ mm day}^{-1},
\]

where \(V_d\) is the 500-hPa wind direction; using one grid \((i, j)\) as a reference, \(s\) is the grid \((i, j - 1)\), \(n\) is the grid \((i, j + 1)\), \(i\) and \(j\) are order numbers of longitude and latitude, respectively; \(u\) and \(v\) are 500-hPa zonal wind and meridional wind, respectively; \(D\) is water vapor flux divergence; \(\theta\) is pentad pseudoequivalent potential temperature at 500 hPa; and \(p\) is pentad total precipitation. All other variables are pentad averaged results. We selected 500 hPa because the average height of the TP is 4000 m, close to 600 hPa; therefore, 500 hPa might indicate low troposphere characteristics over the TP.

The wave activity flux method proposed by Takaya and Nakamura (2001) is used to verify the wave pattern propagating in the midlatitudes. In addition, the climatic trend rates and correlation coefficients are calculated, the Monte Carlo method is applied to verify the significance.

The Community Earth System Model (CESM1.4, version 4) developed by the National Center for Atmospheric Research is a coupled climate model composed of models for the atmosphere (CAM), ocean, land, and sea ice (Hurrell et al. 2013). Model components are available at
The atmospheric component is the Community Atmospheric Model version 5.1 (CAM5.1) with a finite-volume dynamic framework with a horizontal resolution of 1.9° × 2.5° and 30 vertical layers of the σ-p vertical coordinates. In this study, the model was employed to investigate the effect of Arabian Sea warming on the ISM, TPSM, other atmospheric circulations, and precipitation over the TP. Several physical processes were represented in the CAM5.1 model, and the SST initial field was set. The control experiment was performed based on the averaged SST from 1979 to 2021. The sensitivity experiment was forced by the Arabian SST from April to September, with a rising SST at 1.5 times the standard deviation larger than the averaged SST, which is close to the 90th percentile of SST variation. The control and the sensitivity experiments were conducted for 37 years.

3. Results

a. The northernmost boundaries of TPSM

Figure 1 shows spatiotemporal characteristics in the positions of TPSM activity, which appears from the 24th to the 61th pentads. Variations in the northernmost boundary of the TPSM provide clues to the active zone of the TPSM; its climatological position locates at approximately 37°N, with a latitudinal activity range of more than 5°, which reaches the scale of synoptic systems such as the TP vortex and shortwave trough. The northernmost boundary of the TPSM extends relatively north of the TP from the 31th to the 50th pentad (Fig. 1b). We investigated the frequency of the northernmost boundaries of the TPSM at the longitude grid larger than averaged TPSM position 37°N in every pentad. The northernmost boundary of the TPSM frequently mainly occurs from...
the 40th to the 47th pentads, with a total frequency of 64.4%, as shown in Fig. 1c. Figure 1c also shows the time series of the northernmost boundary of TPSM from the 40th to the 47th pentads. The northernmost boundary of the TPSM showed a large activity range and a significant increasing trend from 1979 to 2020, which reveals the northward extension of the TPSM, and can reach the northern edge of the TP and sometimes the dryland in western China, contributing to the warm and wet climate in the Asian drylands (Zhang et al. 2021; Zhao and Dai 2021). Northward monsoons and related precipitation have also been observed over central Asia (Ramisch et al. 2016), accompanied by a substantial rise in moisture availability during the Holocene at approximately 12 ka (Wang et al. 2010; Doberschütz et al. 2014). These results indicate a close relationship between the northward extension of the TPSM and climate change. The northernmost boundary of the TPSM is beyond the 1979–2020 climatic position after 2000.

Figure 2a shows the climatological precipitation distribution in summer; the largest center of precipitation is in the Indian continent, which indicates the climatological position of the ISM. Precipitation exhibits a decreasing distribution from the southeast to the northwest. With the northward extension of the TPSM, precipitation in the northernmost boundary, hinterland, and southwest of the TP increased. Figure 2b shows an increase precipitation trend along the contour line of 150 mm. The precipitation in the Bay of Bengal and western Indian Peninsula also increases, and which occurs on the west of the climatological position of the ISM over the Indian Peninsula (19°–25°N, 76°–88°E), which indicates that the ISM...
has extended westward. Whether there are necessary linkages between the westward ISM and precipitation in the northern TP is discussed in the following section.

To exhibit precipitation variation in the northernmost boundary of the TPSM, we selected nine stations distributed on both sides of the climatological northernmost boundary of the TPSM. The precipitation at all the stations exhibited a consistently increasing trend in the TPSM activity ranging between 35° and 40°N (figure omitted), which is significant correlation (0.91) with the precipitation at the representative stations. Figure 2c shows the time series of the precipitation in summer at the representative stations; it was 28 mm higher in the post-2000 period than in the pre-2000 period, indicating a significant increase. Precipitation is highly sensitive to TPSM activity, and the correlation coefficient between precipitation and TPSM position is significant, further identifying the northward extension of precipitation corresponding to the northward TPSM.

b. Relations between TPSM and meridional moisture flux

The increased TPSM precipitation and northward extension of the TPSM were directly related to circulation anomalies over the TP. Yu et al. (2022) found that southerly water vapor imports from the southern boundary of the TP are important contributors to the precipitation of the TP. Particularly notable is that water vapor transported from the BOB and Indian Peninsula is more favorable for precipitation than local evaporation over the TP (Trenberth and Fasullo 2013). Zhu et al. (1998) reported that the topography of the TP had no effect on the northward movement of the front cloud. However, some front clouds from the BOB across the Himalayan Mountains are affected by tropical cyclones, resulting in significant precipitation over the TP. When the tropical cyclones over the BOB shift to north of 15°N in the longitudes of 85°–90°E, they can induce precipitation anomalies over the TP with more than 80% probability (Dai 1974). Moreover, such tropical cyclones via the BOB are responsible for more than half of the spring precipitation and approximately 20% of the summer precipitation over the TP (Xiao and Duan 2015). Long waves across the TP could help tropical cyclones transport water vapor in the BOB to the TP in spring (Zhou et al. 2022). However, research is limited on the relationship between the tropical moisture flux and precipitation in the northern TP and thus requires further exploration.

Figure 3a shows the linear trends of meridional moisture flux and climatic distributions of moisture flux in the post-2000 period; the increasing trend of meridional moisture flux displays enhanced meridional moisture transportation above 4 km (600 hPa) over the TP. This is significant in the TP hinterland in the post-2000 period, and its distributions are in accordance with the precipitation (Fig. 2b). Compared with the conditions in the pre-2000 period, the meridional moisture flux increased over the western and middle TP in the post-2000 period, originating from the ISM domain, including the BOB, Indian Peninsula, and Indian Ocean. The increased moisture flux over the middle troposphere was mainly due to moisture convergence and evaporation over the Indian Peninsula and Indian Ocean. Therefore, the westward tendencies of meridional moisture flux illustrate the westward movement of the ISM in the post-2000 period (He et al. 2021; Niu et al. 2022). Moreover, such variations in ISM-related moisture affecting the TP are likely to be transported through the midwestern TP but not via the BOB and southeastern TP. The westward moisture flux via the TP was linked to the enhanced meridional moisture flux over the northernmost part of the TPSM, favoring the northward extended precipitation zone. Furthermore, this linkage is possibly affected by the large-scale thermal gradient between the TP and Indian Peninsula (McManus et al. 2004; He et al. 2021; Niu et al. 2022).

Figures 3b and 3c illustrate differences in specific humidity between the post- and pre-2000 periods, over the ISM zone along 20°–25°N and the southern TP along 30°–35°N, respectively. Increased specific humidity over the ISM zone appears in the west of 100°E and the midwestern TP in the post-2000 period, and they seem linked. As indicated in the literature, the northern Indian Ocean has experienced anomalous warming, exceeding the convective threshold of 26°C in the post-2000 period, which exerts deeper convection and stronger moisture convergence (Gadgil et al. 1984), and thus thickens the moisture layer in the middle troposphere over the ISM zone and tropical ocean, which is conducive to thickening the moisture layer over TP by southerly anomalies. In addition to being a major greenhouse gas, water vapor is an effective carrier of condensation latent heating. Thus, the higher water vapor is conducive to the more static instability of the atmosphere (Lambert and Taylor 2014) and further maintains the deeper convection and the higher moisture layer, indicating a positive feedback.

Such positive moisture anomalies above 4 km mainly result from physical processes variations, such as surface warming, moisture convergence, and vertical moisture transportation by vertical velocity. Figure 3e shows the profile of the vertical velocity over the ISM domain (20°–25°N, 80°–95°E), which indicates a thick ascending layer and enhanced large-scale ascending motion, with values less than ~0.006 Pa s⁻¹ up to the 450–300-hPa level in the mid- to upper troposphere. This is helpful for intense moisture convergence in the post-2000 period and further favors additional water vapor in the mid- to upper troposphere. However, there is an opposite anomaly in the east of the BOB, suggesting a westward extension of the ISM zone. Increasing ascending motion over the north of the Himalayan barrier and the southern TP (30°–35°N, 80°–100°E) is in accordance with the observed vertical motion in the ISM domain (Figs. 3d,e), especially over the west of the Indian Peninsula.

The enhanced vertical motion is closely related to the increased temperature over the TP and the Indian Ocean with global warming. Ocean warming since 2000 has led to an increased convection intensity and induced a dry bias over land by modulating the meridional land–sea thermal gradient and Hadley circulation (Roxy et al. 2015). It has undergone substantial intensification over the Indian Ocean since the 1980s, compared with weakening variations since the 1950s (Tokinaga et al. 2012), showing a significant increase of 9.5% in monsoon rainfall for the per degree increase
in temperature. Studies could explain weakened ISM changes east of the BOB but not the deepening vertical motion over the western Indian Peninsula. Thus, the zonal difference in the ISM activity should be discussed.

As the above analysis, the TPSM and the precipitation in the northern TP correspond to variations in the meridional moisture flux across the southern TP and over the ISM domain. To verify these associations, we investigated the correlation coefficients between the TPSM and related meridional winds and meridional moisture flux (Fig. 4). The significant correlation at the 90% confidence level identifies the possible linkage between TPSM and precipitation in the northern TP, meridional wind, and meridional moisture flux over the southern TP. The southerly moisture flux possibly links the TPSM to the ISM; however, this requires further investigation.

To further investigate the variations in tropical water vapor and ISM-related moisture flux in the mid-TP section, we explored the longitude–time profile of meridional moisture flux in the midtroposphere at 30°–35°N. As shown in Fig. 5, the meridional moisture flux is high in the eastern TP (100°–105°E), owing to the ISM circulation over the BOB, and influences the water vapor transport there (Xiao and Duan 2015). However, meridional moisture flux in the eastern TP showed a decreasing trend with a negative anomaly in the post-2000 period (Fig. 5c). By contrast, there is a secondary belt of meridional moisture flux over the mid-TP section (80°–95°E), which manifests an increasing trend with a positive anomaly in the post-2000 period and has an obvious correlation with precipitation at the northernmost boundary of the TPSM (Fig. 5a). This anomaly of the meridional moisture

![Fig. 3](image-url)
flux over the TP exists throughout the summer (Fig. 5, lower panels) and is associated with the cyclonic ISM circulations over the Indian Peninsula. Zhang et al. (2019) suggested a teleconnection linking the Indian cyclone, anticyclone over the eastern TP and the wave trough over northern China, which could explain how the southerly transports moisture flux through the mid-TP over the middle troposphere. Furthermore, influenced by the SST changes and Hadley circulation, the meridional differences of the ISM over the Indian Peninsula respond to distinct diabatic heating patterns between the TP and ISM, which exhibit a tripole pattern and a dipole pattern (Zhao et al. 2022), and drive meridional moisture transportation from the BOB and Arabian Sea, respectively. Moreover, the deepening wave trough over Lake Balkhash and west of the TP helps strengthen moisture transportation toward the TP and central Asia (Ma et al. 2021; Zhang et al. 2021).

c. Relations between TPSM and Arabian SST

Establishing a linkage among the moisture layer, vertical motion with TPSM precipitation, tropical circulation, and potential drivers is essential. Studies have shown that the warming of the northern Indian Ocean strengthens upward motion and local rainfall, owing to an increase in moisture availability (Dhame et al. 2020; Zhao and Zhang 2016). Moreover, meridional differences are in the ISM domain because of meridional asymmetric temperature variation and the related movement of the Hadley circulation (Roxy et al. 2015). This did not explain the intense southerly wind and meridional water vapor transport related to the TPSM. Figure 6a shows a significant increasing SST trend over the northern Indian Ocean and Arabian Sea in April-June (AMJ), and the increasing SST trend over the Arabian Sea is relatively high, therefore, the correlation coefficient between Arabian SST (ARB_SST) in AMJ and the northernmost boundaries of the TPSM is shown in Fig. 6b, which indicates a significant positive correlation with a coefficient higher than 0.35 in the most of the Arabian Sea, and less than 0.35 over the southeastern section. To reveal how ARB_SST regulates the TPSM, we defined SST within the zone of 5°–25°N, 50°–75°E as ARB_SST index, which exhibits an increasing trend of SST in AMJ, with a trend correlation coefficient of 0.54 (Fig. 6c). Such variations in Arabian Sea warming have been proven to be associated with tropical cyclones (Fan et al. 2020), and they can drive anomalous circulations and weather variations in the ISM zone.

Scatter correlations among ARB_SST and TPSM, precipitation, and meridional wind were significant, especially for the TPSM, with coefficients of 0.49, 0.35, and 0.29, respectively (Figs. 6d-1), above the 95%, 90%, and 90% significance confidence levels, respectively. From the moving correlations between ARB_SST and precipitation, TPSM, and meridional wind in July and August, a difference between the post-2000 and pre-2000 periods was found (figure omitted): the correlation is more significant and higher in the post-2000 period than in the pre-2000 period. The results further demonstrate the significant influence of ARB_SST on anomalous ISM circulations and meridional winds over the southern TP, which induces increased meridional moisture flux in the northern TP and is favorable for precipitation.

d. Mechanism on Arabian SST linking with TPSM anomalies

The literature has suggested that the TPSM and related meridional wind anomalies are closely related to diabatic heating over the TP, which results in cyclonic circulations and moisture convergence (Wu et al. 2017). SST has been proven to affect the ISM and moisture flux toward the TP. Arabian Sea SST warming occurs from March to October (figure omitted), which exhibits simultaneous air-sea interaction, low-frequency activity, and interaction (Gao et al. 2019), affecting monsoon circulation in JJA. To explore circulation anomalies over the TP in summer corresponding to the Arabian SST in AMJ, Fig. 7a shows the regression fields of 500-hPa geopotential height and vertical velocity in August upon the Arabian SST during AMJ. The results display a cyclone anomaly west of the TP and Lake Balkhash, which helps deepen the climatological wave trough west of the TP and enhance southwest flow, resulting in moisture flux from the tropical Indian Peninsula and the Arabian Sea to the TP. Moreover, there is an anticyclonic anomaly east of the TP that spans from the south of Lake Baikal to the northeast of the TP. The dipole mode with a west cyclone and an east anticyclone over the TP generates anomalous southerly winds that transport warm and moist air to the northern boundaries of the TPSM domain through the midwestern TP. When
considering the dipole mode, the entire midlatitude circulation anomaly resembles an enhanced Silk Road pattern (SRP; Lu et al. 2002).

The regressed high-latitude circulations are like a Eurasian teleconnection (Wallace and Gutzler 1981), with a cyclone spanning from central Siberia to the Kara Sea and a significant anticyclonic anomaly throughout Europe. The circulation anomaly from the Kara Sea to northern China appears as a positive Arctic–Eurasia pattern (Cohen et al. 2014) and exerts an anticyclone anomaly accompanied by an anomalous southeast wind over the northeast of the TP, which induces southerly EASM to the northernmost boundary of the TPSM. Such circulation anomalies also weaken westerly and water vapor outputs across the eastern boundary of the TP, increasing the probability of moisture convergence over the TP. As aforementioned, anomalous Arabian SST possibly changes the mid- to high-latitude circulations and wave trains, which is similar to the impacts of Indian Ocean warming (Krishnan and Sugi 2001). To the southeast of the TP, the anomalous north wind prevents the summer monsoon circulation from transporting moisture flux from the BOB to the TP and southwestern China. Thus, the warming of the Arabian Sea and related circulation anomalies may have led to the drying of the southeastern TP and southwestern China.

Figure 7b shows the regressed vertical velocity in August in the ISM zone upon the Arabian SST during AMJ. The
ascending motion anomaly appears over the eastern Arabian Sea (60°–70°E) and Indian Peninsula (70°–85°E); however, these anomalies in the west of the climatological position of the ISM (19°–25°N, 76°–88°E), and the descending anomaly appears over the BOB (85°–95°E). The results indicate that the warming Arabian Sea is helpful for the westward movement of the ascending motion of the ISM and ISM circulation.

To verify the effects of the warming Arabian Sea on the summer monsoon circulation and precipitation over the TP, we performed a sensitivity experiment on the warming Arabian Sea. The sensitivity experiment was forced by the Arabian SST from April to September by increasing SST by 1.5 times the standard deviation, i.e., larger than the averaged SST from 1979 to 2021; the purpose of such an experiment was to describe the impacts of warming monthly SST anomalies in 2000–21. The reason to use 1.5 times the standard deviation in the sensitivity experiment is that in four cases from 1979 to 2021 the SST is beyond 1.5 times the standard
deviation, which is close to the 90th percentile, has occurred in recent years; this is regarded as an SST anomaly and a probable future trend. The control experiment was based on the averaged SST from 1979 to 2021. The sensitivity simulations of geopotential height and vertical velocity at 500 hPa during August (Fig. 8a) are similar to the regressed results (Fig. 7a), which show the midlatitude and high-latitude wave-like patterns that link with the dipole mode, showing the west cyclone and an east anticyclone around the TP. Such anomalies could deepen the wave trough over the west of the TP and strengthen the related southwest flow; thus, the moisture mass can be transported from the Indian Peninsula and the Arabian Sea to the TP. Moreover, there is a cyclone anomaly over the west of the BOB and Indian Peninsula, along with an anticyclonic anomaly dominating most of the BOB. Such anomalous circulations are possibly linked with Kelvin waves and reveal the westward shift of the ISM, enhanced ISM, and vertical circulation over the Indian Peninsula (Fig. 8c). They also favor southerly flow anomalies over the mid-TP along 80°–95°E, which are responsible for moisture flux and the
convection of cloud mass transported to the west of 95°E. The zonal circulation anomalies over the tropical zone demonstrate cyclonic circulation anomalies over India and Pakistan and over northern Africa and an anticyclonic anomaly over eastern Africa, suggesting anomalous Walker circulation.

The wave activity flux indicates energy dispersal in the mid- to high latitudes (Fig. 8b), especially in the midlatitudes across the northwest and northeast of the TP, which is linked to a dipole mode over the TP. Similar to results in the literature, the midlatitude wave train is closely related to the diabatic heat forcing of the ISM on an interannual scale (Kripalani and Kulkarni 2001; Stephan et al. 2019; Son et al. 2021); decadal-scale forcing includes diabatic heating due to the precipitation linked the Arabian Sea and ISM, and North Atlantic SST forcing (Lin et al. 2016; Son et al. 2021). The simulation results indicate that the midlatitude wave is also a response to diabatic heating due to the warming Arabian Sea, and the excited wave energy propagates from tropical to midlatitudes through central Asia. Additionally, there is northward wave energy dispersion starting from northern Africa, where there are cyclonic vorticity anomalies and baroclinicity structures due to negative vorticity over the upper troposphere that corresponds to ISM diabatic heating (figure omitted). The literature suggested that the northward Rossby wave energy propagation paths occur under a background of positive southerly wind and zero zonal wind velocity (Son et al. 2021). The vorticity anomalies over subtropical regions seem closely related to anomalous Walker circulation, which corresponds to circulation perturbation and diabatic heating over the Arabian Sea and ISM zone.

The simulated precipitation (Fig. 8d) is positive over the western and northern TP, whereas it is negative over the eastern TP and southwestern China, corresponding to the westward shift of the ISM and decreased moisture flux from the BOB, which was also verified by increased precipitation over the Indian Peninsula. Moreover, there are increasing trends of precipitation over the Asian drylands, and the related zone extends to the west and north edge of the TP. Although the circulation configuration differs, the distribution of increased precipitation in northern China and the eastern TP is very similar to the tripole precipitation pattern over the Indian Peninsula, the eastern TP, and northern China (Zhang et al. 2019). Therefore, whether the tripole circulation is associated with the westward shift of the ISM and Arabian SST requires further analysis. Contrary to increasing precipitation over the northern TP, the warming of the Arabian SST leads to an anticyclone anomaly over the southeastern TP and BOB (Fig. 8a), suppressing precipitation there.

Selected from in situ representative stations (Fig. 1) located in the northern TP, the variable differences between the sensitivity and control experiments were analyzed in Fig. 9, including precipitation, wind speed, and the northernmost boundary of the TPSM in August, and the data retrieved from the 11th to the 37th years were analyzed. In most years, the anomalies of precipitation, meridional winds, and TPSM position are positive; they are within 3 mm day⁻¹, 3 m s⁻¹, and 4°, and the mean values are 0.42 mm day⁻¹, 0.38 m s⁻¹, and 0.57°, respectively; the positive ratio reaches 82%, 74%, and 70%; additionally, most of the positive precipitation anomalies correspond to the positive meridional wind and northward TPSM. The sensitivity experiment identified the influences of increasing Arabian SST on the southerly wind and moisture flux transported to the TP, which further induces northward TPSM and rising precipitation with the help of a dipole mode, displaying as a west cyclone and an east anticyclone anomaly over the TP.

4. Conclusions and discussion

Since the early twenty-first century, summer precipitation has been decreasing in the eastern TP and increasing in the midwestern and northern TP, indicating the westward and northward expansion of the TPSM circulation. The TPSM fronts are modulated by the interactions between the westerly and southerly circulations, and their seasonal transitions are directly linked to the position of the Asian monsoon circulations and moisture flux. In the post-2000 period, the TPSM extended northward, with significantly enhanced precipitation over the midwestern and northern TP. Enhancing southerly wind flow, which strengthens the advection of warm and humid water vapor from the south of the TP, contributes to the precipitation of the TPSM. The southerly moisture flux to the northern TP is directly linked to the dipole mode anomaly, showing as a west cyclone and an east anticyclone over the TP, and linking to the warming Arabian Sea.

The warming Arabian Sea favors a westward shift of the ISM and a westward extension of the ascending branch in
Walker circulation, strengthening the ascending motion and thickening the moisture layer over the west of the Indian Peninsula. On the one hand, such anomalies partially prevent warm moisture from the eastern TP via the BOB, decreasing precipitation over the eastern TP; on the other hand, they facilitate the transportation of moisture flux via the midwestern TP and thus contribute to increasing precipitation over the western and northern TP. Similar to the impacts of the warming Indian Ocean on ISM diabatic heating due to condensation latent heating, the coupling of warming ARB_SST and westward ISM exerts a midlatitude wave train and induces a dipole mode over the TP, which drives more northward moisture flux and ISM cloud mass to the northern TP by relaying southerly. The circulation anomalies finally led to a northward TPSM and precipitation. The mechanism is illustrated in Fig. 10.

Studies have shown that the warming trends of the Arabian Sea and western Indian Ocean are significantly affected by El Niño, which enhances the magnitude and frequency (Roxy et al. 2014). Additionally, El Niño is indirectly related to TPSM. In addition to the Arabian Sea, multiscale variabilities of other oceans are important factors associated with the TPSM, such as the multidecadal oscillation, the tripole SST pattern in the North Atlantic (Lin et al. 2016), and the interdecadal Pacific oscillation (Wang and Duan 2015). Arctic ice loss leads to the summer Arctic–Eurasia pattern with anticyclones in the southwest of Lake Baikal (Seth et al. 2019), which possibly drives the East Asian monsoon to the northeast of the TP (Yu et al. 2022). Furthermore, regarding the upper level, it was suggested that the upper-tropospheric cooling over the most Indo-Tibetan landmass changes temperature structure through stratosphere–troposphere interactions (Yu et al. 2004), and its impacts on TPSM require further research.

For the TP, glacier shrinkage and evident snow melting in spring both occur under the background of global warming, with a temperature increase at the rate of 0.35°C decade⁻¹ over the TP (Xu et al. 2017). This change has resulted in significant river water losses and subsequent rises in the warming rate to 0.39°C decade⁻¹ in the Asian drylands (Hu et al. 2014). These variations led to a decrease in the meridional temperature gradient between the Asian drylands and the TP, which possibly influenced the northward subtropical westerly jets and southerly winds over the TP. To the south, the temperature gradient among the TP, the Indian Peninsula, and the Arabian Sea is also linked with meridional wind anomalies. In conclusion, in addition to the Arabian Sea, the impacts of many other forcing factors and global warming on the TPSM are worthy of further consideration (Chen and Sun 2021).

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Data availability statement. The ERA5 data were obtained from https://cds.climate.copernicus.eu/, at 0.25° × 0.25° resolution; the daily CPC precipitation data at 0.5° × 0.5° resolution were from https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html; the monthly mean SST data were derived from the Hadley Centre Sea Surface Temperature dataset (HadISST), with a horizontal resolution of 1° × 1° during 1979–2021, at https://www.metoffice.gov.uk/hadobs/hadisst/; and the 30-m digital elevation model data were collected from the ASTER Global Digital Elevation Model V2 at https://search.earthdata.nasa.gov/.
REFERENCES


