Influence of the Western Pole of the Indian Ocean Dipole on Midsummer Precipitation over the Tibetan Plateau (Postprint)

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Abstract

Using monthly summer precipitation data from the Tibetan Plateau region and Indian Ocean Dipole index data from 1987 to 2016, the relationship between the two was analyzed. The results indicate that midsummer precipitation over the plateau exhibits a strong correlation with the western pole index, which characterizes anomalous sea surface temperatures in the western Indian Ocean. During positive anomaly years of the western pole index, plateau precipitation increases by 10%-30%, with the most significant increase occurring in the central plateau, while the opposite occurs during negative anomaly years. Mechanism analysis reveals that during positive western pole anomaly years, enhanced deep convection over the South China Sea and western Pacific warm pool, a westward and southward shift of the western Pacific subtropical high, and weakening of the Indian thermal low facilitate the penetration of tropical water vapor deep into the plateau interior. Additionally, anomalous enhancement of the eastern component of the South Asian high, combined with anomalous low-level convergence, contributes to increased plateau precipitation. Simultaneously, the local zonal circulation over the plateau exhibits an anomalous convergence and upward motion area above 400 hPa near the central plateau (around 90°E), which promotes the development of mesoscale vortex low-pressure systems such as warm and moist shear lines and Tibetan Plateau vortices in the central plateau, resulting in increased precipitation. This study analyzes seasonal differences in regional precipitation from the perspective of plateau climate change responding to interannual oceanic variations, which may provide new insights for plateau climate prediction.

Full Text

Impact of the Western Pole of the Indian Ocean Dipole on Midsummer Precipitation over the Tibetan Plateau

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Abstract

Using monthly summer precipitation data from the Tibetan Plateau region and Indian Ocean Dipole index data from 1987-2016, this study analyzes the relationship between them. Results show that midsummer precipitation over the plateau exhibits a strong correlation with the western pole index (IOD_W) that represents anomalous sea surface temperatures in the western Indian Ocean. During positive IOD_W anomaly years, precipitation across the plateau increases by 10–30%, with the most significant increases exceeding 40% in central plateau regions; the opposite pattern occurs during negative anomaly years. Mechanism analysis reveals that in positive IOD_W years, enhanced deep convection over the South China Sea and western Pacific warm pool, combined with a westward-southward shift of the western Pacific subtropical high and weakening of the Indian thermal low, facilitates deeper penetration of tropical moisture into the plateau interior. Additionally, anomalous enhancement of the eastern component of the South Asian High, coupled with low-level anomalous convergence, contributes to increased plateau precipitation. Simultaneously, the local zonal circulation over the plateau creates an anomalous convergence and upward motion zone near 90°E above 400 hPa, promoting the development of warm-wet shear lines, plateau vortices, and other mesoscale low-pressure systems in central plateau regions, resulting in enhanced precipitation. This study examines seasonal differences in regional precipitation from the perspective of plateau climate responses to interannual oceanic variability, offering new insights for plateau climate prediction.

Keywords: Tibetan Plateau; midsummer precipitation; Indian Ocean Dipole; western pole; OLR

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1. Data and Methods

1.1 Data

The study period spans 1987-2016. Monthly summer (June–August) precipitation data from 39 observation stations across the Tibetan Autonomous Region

(Fig. 1) were obtained from the Tibet Meteorological Information Network Center. The monthly Indian Ocean Dipole Mode Index (DMI) was downloaded from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) website (http://www.jamstec.go.jp/). The DMI is calculated as the anomalous sea surface temperature gradient between the western equatorial Indian Ocean (50°E-70°E, 10°S-10°N) and the southeastern equatorial Indian Ocean (90°E-110°E, 10°S-0°N). Specifically:

$$DMI = SST_W - SST_E$$

where SST_W represents the western pole index (IOD_W) and SST_E represents the eastern pole index (IOD_E).

Reanalysis data from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) were used, with a horizontal resolution of 2.5°$×2.5°.*Variablesincludezonalandmeridionalwindfields*, *verticalvelocity*, *a* The reliability of OLR data for plateau precipitation research has been validated in numerous studies.

1.2 Methods

Empirical Orthogonal Function (EOF) decomposition was applied to analyze spatiotemporal characteristics of plateau precipitation. The North et al. method was used to calculate error ranges for eigenvalue significance testing. The eigenvalue λ_j error range is:

$$e_j = \lambda_j \sqrt{2/n}$$

where n is the sample size. When adjacent eigenvalues satisfy $\lambda_j - \lambda_{j+1} \geq e_j$, the corresponding EOF modes are considered significant signals.

Correlation analysis and composite analysis were also employed, with Student' s t-test used to assess statistical significance of composite results.

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2. Spatiotemporal Distribution Characteristics of Summer Precipitation over the Plateau

EOF analysis was performed on midsummer (July-August) monthly precipitation anomaly fields from 39 stations. The first three modes explain 42.9%, 21.4%, and 9.5% of the variance respectively, all passing the North et al. significance test, indicating significant separation. The cumulative variance contribution of the first three modes reaches 73.8%, effectively representing plateau precipitation spatiotemporal distribution characteristics during the study period.

The first eigenvector shows a uniform change pattern across the entire plateau (Fig. 2a), with a slight gradient decreasing from southeast to northwest and a large value area in the Yarlung Zangbo River basin. Positive (negative) time coefficients indicate above-normal (below-normal) precipitation across the region (Fig. 2b). The second eigenvector exhibits a dipole pattern between northern and southern Tibet (Fig. 2c), showing a trend of less precipitation in northern Tibet and more in southern Tibet in recent years (Fig. 2d). The third eigenvector shows an inverse relationship between southeastern precipitation and the rest of the plateau (Fig. 2e), reflecting the anti-correlation between areas influenced by the Bay of Bengal moisture transport channel along the Hengduan Mountains and other plateau regions. This mode exhibits strong decadal characteristics, shifting from negative to positive after 2000, indicating reduced precipitation in the Bay of Bengal channel region and increased precipitation elsewhere.

3. Relationship Between Plateau Precipitation and Indian Ocean Dipole Index

3.1 Correlation Between Precipitation and Dipole Index

Correlation coefficients were calculated between the DMI index and the first three EOF modes of midsummer plateau precipitation, as well as monthly precipitation (June–August). The first precipitation mode shows significant correlation with July DMI, while the other two modes do not (table omitted). At the monthly scale, the index correlates well with July precipitation but not significantly with June or August (table omitted). However, given the strong persistence of sea surface temperature, this discrete correlation pattern seems inconsistent with conventional linear inference.

Decomposing the DMI formula and correlating IOD_E and IOD_W separately with plateau precipitation reveals that IOD_W shows much stronger and more persistent correlations than IOD_E, both for the first precipitation mode and at monthly scales (Table 1). July and August precipitation correlate significantly with January IOD_W, while June precipitation correlates significantly with IOD_W from the previous winter (December–February). In contrast, IOD_E shows no significant correlation with any plateau precipitation mode or monthly precipitation (Table 1). These results indicate that midsummer (July–August) plateau precipitation is significantly modulated by IOD_W, which represents equatorial western Indian Ocean SST anomalies. Unlike June precipitation, which is primarily influenced by mid-latitude westerly moisture transport, July precipitation is mainly affected by moisture transport along its southern margin when the westerly jet weakens and shifts northward, explaining the poor correlation between Indian Ocean SST anomalies and June plateau precipitation.

Table 1 Correlation coefficients between Indian Ocean Dipole index and plateau precipitation

	Precipitation Mode 1	Precipitation Mode 2	Precipitation Mode 3	July	August
DMI	0.43*	0.23	0.18	0.38*	0.39*
IOD_W	0.54**	0.31	0.22	0.50**	0.51**
IOD_E	0.21	0.15	0.11	0.19	0.18

*Significant at 95% confidence level, **significant at 99% confidence level*

3.2 Relationship Between Western Pole Index Anomalies and Plateau Precipitation Distribution

Since July IOD_W index and July precipitation show significant correlations, positive anomaly years were defined as those with standardized IOD_W index > 1, and negative anomaly years as < -1. Composite analysis of July precipitation was then performed for these years, calculating precipitation anomaly percentages relative to the 1987-2016 climatology.

During positive IOD_W years (Fig. 4a), precipitation was above normal across most of the plateau except for a small western area, with increases of 10-30% and local increases exceeding 40% in central plateau regions. Conversely, during negative IOD_W years (Fig. 4b), precipitation was below normal across most of the plateau except for a small western area, with decreases of 10-30% and reductions exceeding 40% in central regions. The spatial correlation between July precipitation and January IOD_W index (Fig. 4c) shows the best correlation in central plateau areas, passing the 95% significance test. Similar patterns are found for August precipitation (Fig. 4f), though with slight eastward displacement compared to July. These results demonstrate that when equatorial western Indian Ocean SST anomalies are warm (cold), most plateau regions, especially the central and eastern parts, experience abundant (scarce) precipitation.

Table 2 IOD_W index abnormal years for January and June

	Positive Anomaly Years	Negative Anomaly Years
January IOD_W	1992, 1995, 1998, 2004, 2012	1989, 1996, 1999, 2006, 2010
June IOD_W	1991, 1994, 1997, 2003, 2011	1988, 1995, 1998, 2005, 2009

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4. Large-Scale Circulation Fields in IOD_W Anomaly Years

4.1 Wind Field and Water Vapor Transport Characteristics

Using the anomalous years defined in Table 2, we examine circulation and water vapor flux changes over the plateau during IOD_W anomaly years. At 500 hPa (Fig. 5), the climatological mean shows the western Pacific subtropical high centered near 30°N, 140°E, with an Indian thermal low to the south of the plateau, westerlies to the north, southwesterly winds over the southeastern plateau, and weak winds over the central-western plateau.

In positive IOD_W years (Fig. 5b), anomalous easterlies appear over the tropical Indian Ocean, opposite to the southwest monsoon flow. This anomalous easterly weakens the Somali jet and Indian thermal low, generates an anomalous anticyclone over central-eastern India, and shifts the western Pacific subtropical high westward and southward. Southwest winds behind the anomalous anticyclone ridge over central-eastern plateau, while the northern plateau westerly jet weakens to anomalous northeasterlies, creating an anomalous convergence zone over the plateau. At 100 hPa (Fig. 5d), the South Asian High transitions from a monopole pattern to a dipole pattern, with the western body centered over the Iranian Plateau weakening (cyclonic circulation) and the eastern body over the northern Tibetan Plateau strengthening (anticyclonic circulation). These two anticyclone centers correspond to different thermal structures: the Iranian Plateau is a dynamically-driven subsidence center, while the Tibetan Plateau is a thermally-driven ascent center. Combined with anomalous divergence over the plateau, this upper-level divergence and low-level convergence configuration favors convective weather systems.

Climatological water vapor transport at 500 hPa (Fig. 5a) shows moisture reaching the plateau primarily via the upper-level Somali jet from the tropical Indian Ocean to the Bay of Bengal, then relayed by southerly winds ahead of the Indian thermal low trough—an Indian monsoon-related pathway with limited East Asian monsoon contribution. In positive IOD_W years (Fig. 5b), enhanced deep convection over the western Pacific warm pool and South China Sea increases mid-tropospheric moisture. The westward-southward shifted western Pacific subtropical high and weakened Indian thermal low allow moisture from the South China Sea and western Pacific warm pool to reach the plateau interior via cross-equatorial flow near 105°E and southerly winds ahead of the anomalous subtropical ridge. This represents an East Asian monsoon-related anomalous moisture channel, demonstrating that East Asian monsoon strength is a crucial factor for plateau moisture availability.

Enhanced moisture from the South China Sea and western Pacific warm pool explains increased plateau precipitation in positive IOD_W years but not why precipitation deviations concentrate in central rather than southeastern regions near moisture channels. Analysis of the meridional-vertical circulation along 28°N–35°N (Fig. 6) reveals that climatologically, the plateau low-level thermal low is strong, with westerlies dominating above 400 hPa. In positive IOD_W years (Fig. 6b), westerly anomalies appear west of 90°E and easterly anomalies east of 90°E above 400 hPa, creating a strong anomalous convergence zone over central plateau. Additionally, the anomalous anticyclone over the northern plateau (Fig. 5b) favors cold air intrusion from Siberia, while warm moist air from the southward-extended western Pacific subtropical high easily forms warm-wet shear lines and plateau vortices in central plateau regions. Since most plateau vortices and shear lines originate in central plateau areas and develop locally under moist rotational effects, they readily cause anomalous precipitation increases in midsummer.

4.2 OLR Field Characteristics

OLR values primarily reflect radiation from the surface or cloud tops, showing good consistency with cloud distribution. Jiang et al. demonstrated negative correlations between summer Tibetan Plateau precipitation and OLR, while Wang et al. found OLR valley values in July–August reflect precipitation distribution patterns well.

July climatological OLR (Fig. 7a) shows convection centers over the Bay of Bengal and South China Sea, with vigorous convection also over the plateau. In positive IOD_W years (Fig. 7b), significant negative OLR anomalies appear over the western Pacific warm pool, South China Sea, eastern Arabian Sea, and central-eastern plateau, indicating enhanced convection and increased cloudiness. This aligns with Jia et al.' s OLR analysis of drought/flood years over the plateau and matches the circulation analysis. Negative IOD_W years show roughly opposite characteristics, with more pronounced reductions in moisture flux and cloudiness over central plateau. Circulation and moisture flux patterns for August precipitation are similar (figure omitted), though with the 500 hPa western Pacific subtropical high positioned slightly northward and stronger, and the 100 hPa South Asian High dipole pattern present but without closed centers. Moisture flux from the South China Sea and Bay of Bengal weakens meridionally while strengthening zonally.

In summary, when equatorial western Indian Ocean SST anomalies are warm (cold) in preceding seasons, midsummer exhibits anomalous easterlies (westerlies) over the equatorial Indian Ocean, weaker (stronger) Indian thermal low, and westward-southward (eastward-northward) shifted western Pacific subtropical high. This allows more (less) moisture from the South China Sea and western Pacific warm pool to penetrate the plateau interior, combined with low-level anomalous convergence (divergence) and upper-level anomalous divergence (convergence), creating favorable (unfavorable) conditions for precipitation formation. Furthermore, anomalous convergence and upward motion (divergence and subsidence) above 400 hPa over central plateau (near 90°E), plus a "cold north, warm south" circulation configuration, facilitates (suppresses) development of local convective systems, causing more (less) precipitation in central plateau regions.

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5. Conclusions

As the world' s highest and topographically most complex region, factors influencing midsummer precipitation over Tibet are extremely complicated and multifaceted. This study examined connections between the IOD_W index and midsummer plateau precipitation, analyzing anomalous circulation and water vapor flux characteristics, with OLR fields providing corroboration. The main conclusions are:

1) EOF analysis of plateau precipitation from 1987-2016 reveals the first three modes explain 71.1% of variance, all passing North et al. significance tests. Correlation analysis shows IOD_W index correlates significantly with the first precipitation mode and July-August precipitation, indicating that preceding equatorial western Indian Ocean SST anomalies provide a good indicator for midsummer plateau precipitation.
2) In positive (negative) IOD_W anomaly years, midsummer plateau precipitation is generally 10-30% above (below) normal, exceeding 40% in central plateau regions. Correlation patterns show the best relationship between IOD_W index and central plateau precipitation.
3) Circulation analysis reveals that in positive (negative) IOD_W years, the western Pacific subtropical high shifts southward (northward) and westward (eastward), the Indian thermal low weakens (strengthens), moisture from the South China Sea and western Pacific warm pool increases (decreases), the eastern component of the South Asian High strengthens (weakens), and low-level convergence (divergence) enhances, resulting in above-normal (below-normal) precipitation across the plateau. Additionally, anomalous convergence (divergence) above 400 hPa over central plateau (near 90°E), combined with a "cold north, warm south" circulation pattern, favors (suppresses) development of low-vorticity systems, causing larger precipitation deviations in central plateau regions. OLR composite analysis confirms these conclusions.

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6. Discussion

This study identified relationships between Indian Ocean SST anomalies and plateau precipitation through correlation analysis, yielding useful conclusions. However, this approach may overlook influences from other oceanic regions such as the Arabian Sea and Bay of Bengal. Additionally, the precipitation data are from sparse station observations, which may introduce errors. Using higher-resolution gridded precipitation data (e.g., satellite products) for teleconnection analysis could improve results.

Notably, the IOD_W index region most closely related to midsummer plateau precipitation matches the region most closely related to spring plateau sensible heating in previous studies. Since spring plateau sensible heating anomalies significantly influence downstream precipitation, potential linkages between winter equatorial western Indian Ocean SST, spring plateau sensible heating, and summer plateau precipitation warrant further investigation. The mechanisms connecting these three factors remain to be explored.

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