Open Journal of Ecology, 2025, 15(9), 585-601
https://www.scirp.org/journal/oje
ISSN Online: 2162-1993
ISSN Print: 2162-1985

Prediction Method for Summer Precipitation on the Tibetan Plateau Based on Sea Surface Temperature Anomalies in the Indian Ocean

Maji Ni, Zhuojing Xiao, Yang Ci, Yangzong Ciren*

Tibet Climate Center, Tibet Meteorological Bureau, Lhasa, China
Email: *15289103761@126.com

How to cite this paper: Ni, M.J., Xiao, Z.J., Ci, Y. and Ciren, Y.Z. (2025) Prediction Method for Summer Precipitation on the Tibetan Plateau Based on Sea Surface Temperature Anomalies in the Indian Ocean. *Open Journal of Ecology*, **15**, 585-601.
https://doi.org/10.4236/oje.2025.159032

Received: August 6, 2025
Accepted: September 20, 2025
Published: September 23, 2025

Abstract

Using station data from the Tibetan Plateau and monthly reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), the relationship between sea surface temperature in the tropical Indian Ocean and summer precipitation on the Tibetan Plateau was investigated. The conclusions are as follows: 1) When the sea surface temperature in the Indian Ocean uniformly warms, the moisture transported to the Tibetan Plateau increases, leading to more summer precipitation on the Tibetan Plateau; conversely, when the sea surface temperature in the Indian Ocean is cooler, the moisture transported to the Tibetan Plateau decreases, resulting in less summer precipitation on the Tibetan Plateau. 2) When the Somali Jet at 925 hPa is weaker, the Somali Jet at 700 hPa is stronger, which also leads to increased moisture transport from the Indian Ocean to the plateau, causing more summer precipitation on the Tibetan Plateau; whereas, when the Somali Jet at 925 hPa is stronger, the Somali Jet at 700 hPa is weaker, leading to decreased moisture transport from the Indian Ocean to the plateau, resulting in less summer precipitation on the Tibetan Plateau.

Keywords

Indian Ocean Sea Surface Temperature (SST), Tibetan Plateau, Moisture Transport, Summer Precipitation

1. Research Background

The Tibet Plateau, the main body of the Tibetan Plateau, is located in the southwest of China, spanning from 26˚50'N to 36˚53'N and from 78˚25'E to 99˚06'E. With its high altitude and complex terrain, the plateau exhibits an extremely diverse range of climatic conditions. The average elevation of the plateau is over 4000 meters. From southeast to northwest, it successively features tropical, subtropical, temperate, subarctic, and arctic climate zones, with distinct vertical climatic zones present. The plateau has distinct dry and wet seasons, with summer precipitation accounting for 61% of the annual total, decreasing from southeast to northwest. The probability of drought in the main agricultural areas ranges from 57% to 70%, while eastern Tibet is a high-incidence area for floods, debris flows, landslides, and other disasters. Droughts, floods, and other meteorological disasters account for more than 70% of all natural disasters in Tibet.

Previous studies have indicated that there are three moisture transport pathways to the plateau during the flood season. 1) The Indian monsoon transports moisture from the Arabian Sea and the Bay of Bengal to the Tibetan Plateau, which is particularly important for the plateau influenced by the combined effects of westerly winds and upslope winds (winds rising along the western slopes); 2) The Southeast Asian monsoon and the southern airflow on the western side of the subtropical high-pressure system over the northern Pacific Ocean directly transport warm and humid air from the South China Sea to the plateau; 3) The mid-latitude westerly wind belt provides moisture to the northern part of the plateau [1]. Among them, the moisture transport belt carried by the Indian summer monsoon plays a decisive role in the moisture transport during the flood season on the Tibetan Plateau, determining the onset of the flood season and the advancement of the rainband. Moisture from the Arabian Sea, carried by the Somali Cross-Equatorial Jet, crosses the Indian continent and merges with moisture from the Bay of Bengal, reaching the southern part of the plateau along the summer Indian monsoon. It enters the plateau between 85˚E and 100˚E, with the moisture sources being the Arabian Sea and the Bay of Bengal. This is the main source of moisture transport to the plateau. Most of the precipitation during the flood season in Tibet comes from this moisture transport belt [2]. It is evident that the Indian Ocean is the main source of moisture for the plateau. So, what impact does the Indian Ocean sea surface temperature anomaly have on summer precipitation over the plateau?

The sea surface temperature anomaly (SSTA) in the Indian Ocean has a significant impact on the summer atmospheric circulation over East Asia. There are mainly two mechanisms for the physical process by which an enhanced SSTA in the tropical Indian Ocean strengthens the western Pacific subtropical high (WPSH): the "bipolar thermal adaptation" mechanism [3]; and the "Kelvin wave and wave-induced Ekman divergence mechanism" [4] [5].

In addition, Yuan *et al.* [6]pointed out that the warming (cooling) of the sea surface temperature in the tropical Indian Ocean excites an anomalous Walker circulation over the Indian Ocean-Western Pacific through air-sea interaction, strengthening (weakening) the intensity of the Western Pacific Subtropical High (hereinafter referred to as WPSH), which in turn favors the delay (advancement) of the onset of the South China Sea summer monsoon. The consistent characteristic of the sea surface temperature (thermal) difference between the Indian Ocean and the Pacific Ocean during the decaying summers of El Niño and La Niña events may be the main reason for the asymmetric relationship between the anomalous anticyclone (cyclone) in the northwest Pacific and sea surface temperature changes [7].The distribution of Indian Ocean sea surface temperature anomalies (SSTA) in the preceding and concurrent periods is significantly correlated with summer precipitation over the plateau. The SSTA in the equatorial region of the western Indian Ocean-east coast of Africa has the closest relationship with summer precipitation over the plateau. When there is a significant negative (positive) SSTA in the western Indian Ocean during spring and summer, the Indian summer monsoon tends to be stronger (weaker), and summer precipitation over the plateau is generally higher (lower) [8]. Liu *et al.* [9] found that the dipole oscillation of the Indian Ocean sea surface temperature in the preceding winter also has a certain relationship with precipitation and temperature during the flood season on the plateau.

The above studies indicate that the Indian Ocean, as a source of moisture for the plateau, has a significant impact on the summer climate of the plateau and the atmospheric circulation over East Asia through its sea surface temperature anomalies. In order to improve the operational services for climate prediction during the flood season (e.g., May–September), it is necessary to deeply analyze the impact of Indian Ocean sea surface temperature anomalies on summer precipitation over the plateau and establish a prediction model for summer precipitation over the plateau based on Indian Ocean sea surface temperature anomalies.

2. Materials and Methods

The data used include: monthly precipitation data from 38 stations on the Tibetan Plateau, which basically cover the main administrative and climatic regions of the plateau. Due to the lack of data before 1980 for many stations, complete station observations from 1980 onwards were selected for the study, covering the period from 1980 to 2017. Monthly reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) with a horizontal resolution of 2.5˚ × 2.5˚ [10] were also used. Sea surface temperature data were sourced from the Extended Reconstructed Sea Surface Temperature Version 5 (ERSST.V5) provided by the National Oceanic and Atmospheric Administration (NOAA), with a horizontal resolution of 2˚ × 2˚ [11]. The climatological state of various physical quantities in the text refers to the average from 1980 to 2017.

To investigate the relationship between the above two fields, the Singular Value Decomposition (SVD) method was adopted. This is the simplest method with a clear physical meaning for examining the relationship between two (or multiple) fields containing long time series and a large number of grid points (or stations). It can describe the main characteristics of the relationship between two elements with the fewest modes. Its mathematical derivation and application in meteorology have been thoroughly demonstrated by [12], and it has been widely applied. Therefore, further details are not provided here.

3. The Coupling Relationship between Sea Surface Temperature in the Tropical Indian Ocean and Summer Precipitation on the Tibetan Plateau

To reveal the coupling relationship between the precipitation field on the plateau and the sea surface temperature field, Singular Value Decomposition (SVD) was performed on the two fields. Table 1 presents the coupling strength and variance components of the first three modes between the Indian Ocean sea surface temperature (left field) in the preceding winter, preceding spring, and concurrent summer, and the summer precipitation on the Tibetan Plateau (right field). It can be seen that the cumulative squared covariance fraction (SCF) of the first three modes accounts for more than 70% of the total, indicating that these three modes are sufficient to represent the basic characteristics of the left and right fields. The SCF of the first mode for each season is above 50%, specifically 59.7%, 62.8%, and 52.5%, respectively, which can reflect the main features of the left and right fields. From the heterogeneous correlation maps of the first mode for each season (Figure 1(a)-Figure 3(a)), it can be observed that the left field (Indian Ocean sea surface temperature) exhibits a consistent pattern, indicating that the consistent sea surface temperature anomalies across the entire Indian Ocean in the preceding winter, preceding spring, and concurrent summer are most closely related to the summer precipitation on the plateau.

Table 1. Coupling strengths of the first three modes from the SVD analysis between the sea surface temperature field in the preceding winter and summer precipitation on the plateau.

	Mode	The Correlation Coefficient of Modal Time Coefficients	SCF	Cumulative Squared Covariance Fraction
Preceding Winter	1	0.42	59.7%	59.7%
	2	0.70	10.1%	69.8%
	3	0.48	7.5%	77.3%
Preceding Spring	1	0.34	62.8%	62.8%
	2	0.54	11.2%	74%
	3	0.65	4.7%	78.7%
Concurrent Summer	1	0.36	52.5%	52.5%
	2	0.43	12%	64.5%
	3	0.57	7%	71.5%

From the distribution of the right field (summer precipitation on the plateau) in the first three modes in Figure 1-Figure 3, we observe the following patterns: in the preceding winter, there is a largely consistent change across most of the region; in the preceding spring, there is an east-west reverse change; and in the preceding spring's third mode, there is a north-south reverse change. In the concurrent summer, the patterns are a largely consistent change across most of the region, a north-south reverse change, and an east-west reverse change. However, these changes are not significant in the second and third modes, and the corresponding left field (Indian Ocean sea surface temperature) shows no regular pattern. Therefore, based on the above analysis, this study primarily focuses on the first mode. The time coefficients of the first mode between the left and right fields in each season show a positive correlation, with correlation coefficients reaching 0.42, 0.34, and 0.36, indicating that the changes in the left and right fields are in the same direction. Among them, the coupling mode between sea surface temperature anomalies in the preceding winter and summer precipitation on the plateau is the best (Figure 1(a)), showing that when there are significant positive anomalies in the tropical Indian Ocean, there is a significant increase in precipitation across most of the region.

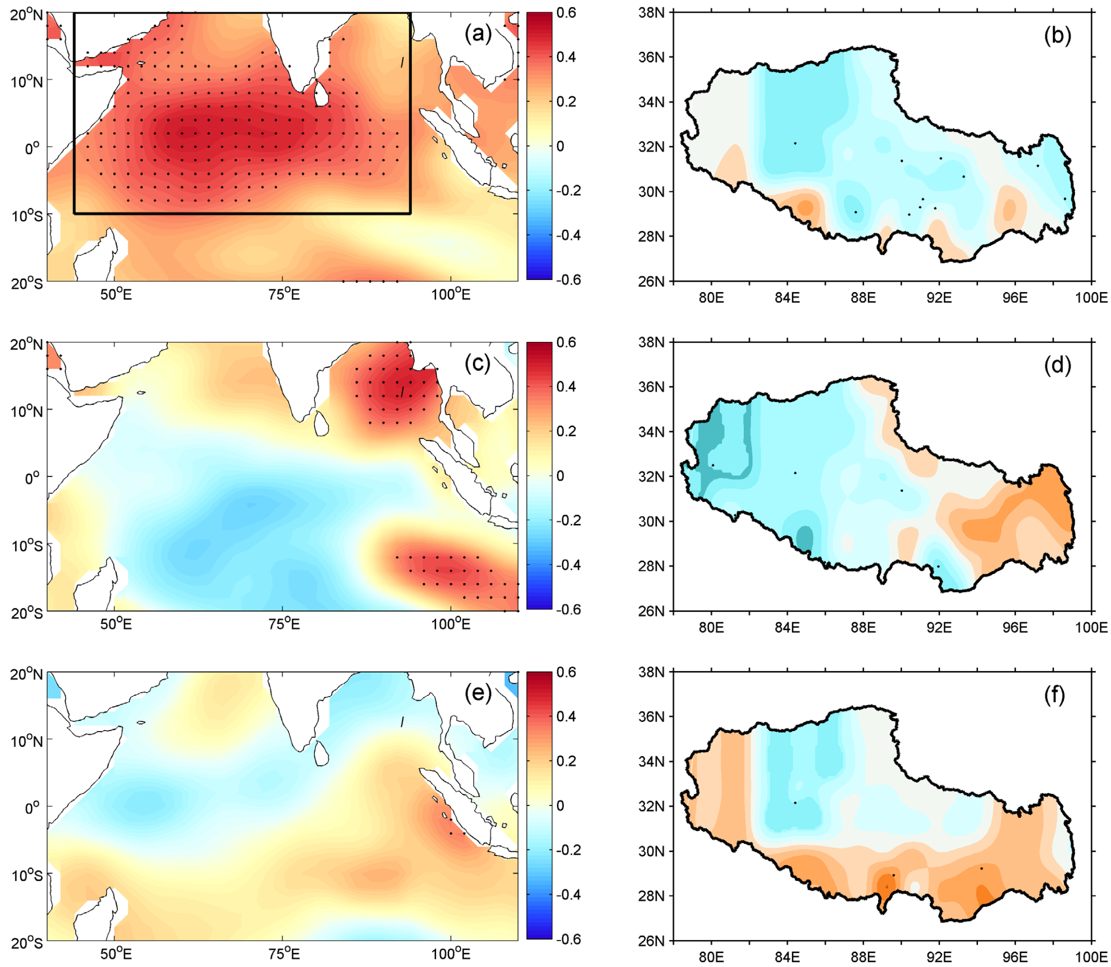

Figure 1. Heterogeneous correlation maps of the first three modes between the left and right fields in the preceding winter (a, b) First mode; (c, d) Second mode; (e, f) Third mode; (a, c, e) Left field (Indian Ocean sea surface temperature); (b, d, f) Right field (Tibetan Plateau precipitation). The dotted areas pass the significance test at $\alpha = 0.05$. The rectangular area in (a) highlights the significant key region of Indian Ocean sea surface temperature.

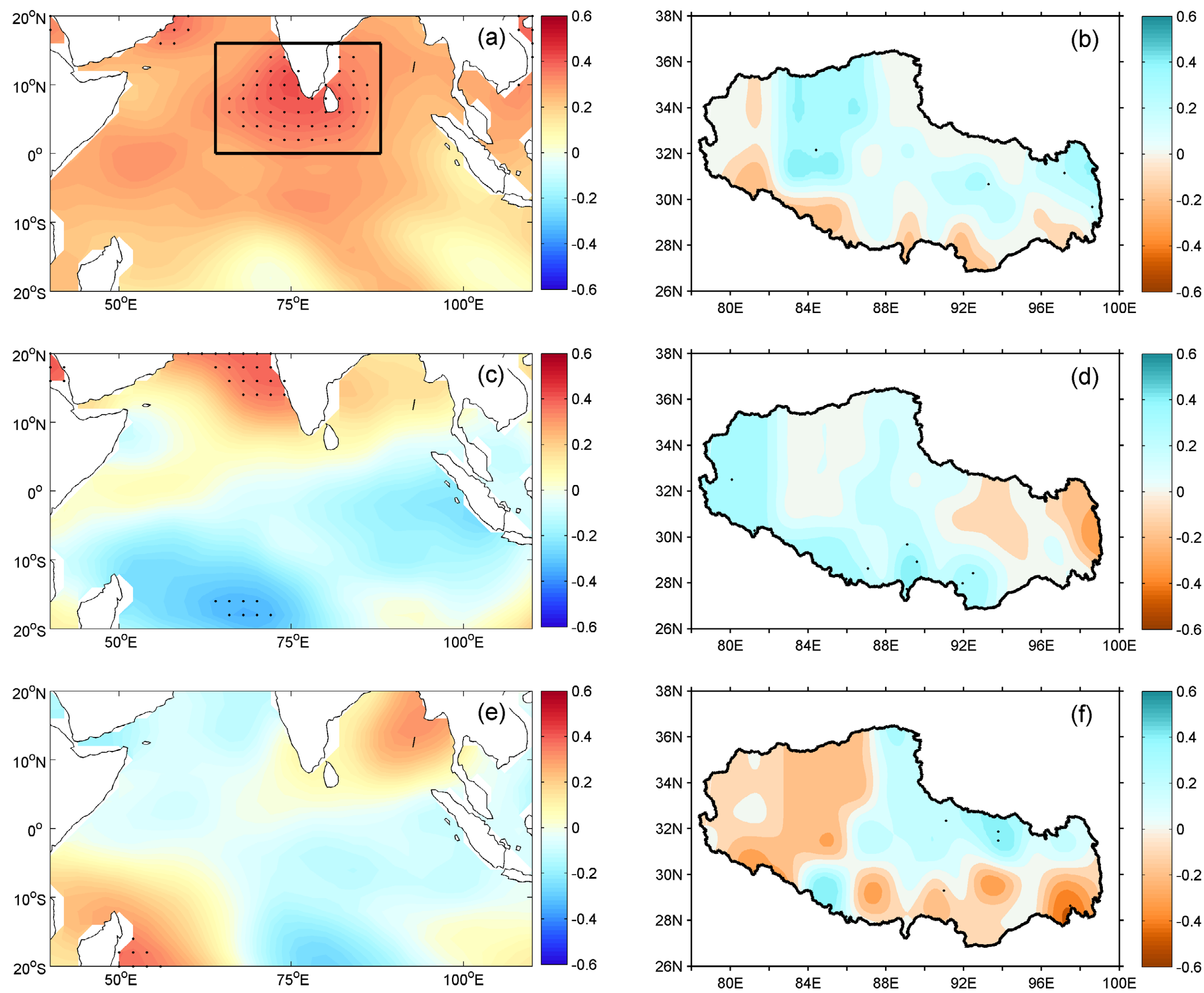

Figure 2. Same as **Figure 1**, but for the preceding spring.

From the distribution of the time coefficients of the left and right fields in the preceding winter shown in **Figure 4**, it can be seen that there is a significant positive correlation between the interdecadal trends and interannual variations of the left and right fields, with a correlation coefficient of 0.42, passing the significance test at $\alpha = 0.01$. However, there are also years with opposite-phase distributions in interannual variations, such as 1983, 1984, 1985, 1999, 2000, 2001, 2008, 2010, and 2015. This indicates that the consistent warming of the Indian Ocean sea surface temperature in the preceding winter does not always coincide with an increase in summer precipitation on the Tibetan Plateau. This may be due to changes in the Indian Ocean sea surface temperature anomalies, which serve as an external forcing factor, during the subsequent spring and summer. It also highlights the complexity of the factors influencing summer precipitation anomalies on the plateau. So, how do sea surface temperature anomalies in the preceding winter Indian Ocean affect summer precipitation on the plateau in later periods? The regions that pass the significance test for the first mode of the left field in each season are defined as key sea surface temperature regions (**Figure 1(a)-Figure 3(a)**). The persistent correlation characteristics from season to season indicate good persistence. The correlation coefficients of sea surface temperature in the key regions between the preceding winter and spring, the preceding spring and concurrent summer, and the preceding winter and concurrent summer are 0.54, 0.61, and 0.60 ($\alpha = 0.01$), respectively. The SVD analysis revealed that the key sea surface temperature region in the Indian Ocean in the preceding winter is a good indicator for predicting summer precipitation on the Tibetan Plateau, as it exhibits the highest sustained correlation with summer precipitation patterns over the Tibetan Plateau. Which indicates that SST variations within this area have a significant and consistent influence on the atmospheric circulation patterns that drive summer precipitation in the Tibetan Plateau region. Therefore, the sea surface temperature in the key Indian Ocean region in the preceding winter (10˚S to 20˚N, 44˚E to 94˚E) is standardized and defined as the Sea Surface Temperature Index (SSTI).

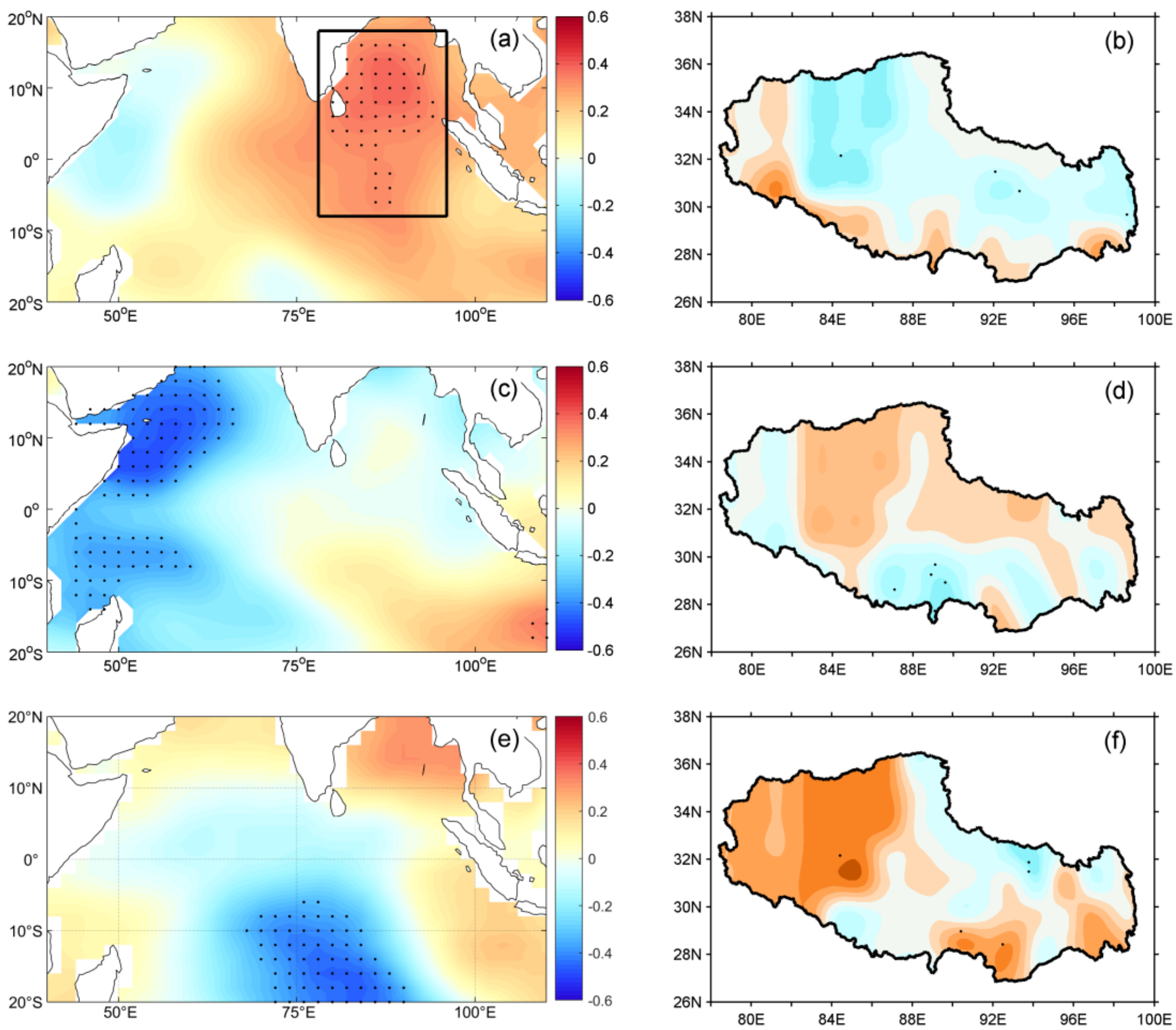

Figure 3. Same as **Figure 1**, but for the concurrent summer.

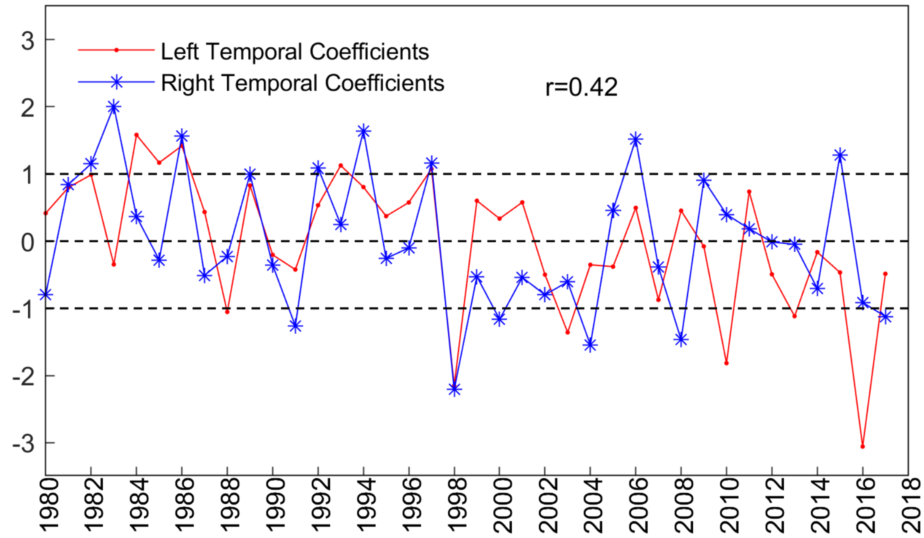

Figure 4. Distribution of temporal coefficients for the first mode of the left and right fields in the preceding winter.

4. Possible Reasons for the Influence of Anomalous Indian Ocean Sea Surface Temperature in the Preceding Period on Summer Plateau Precipitation

Atmospheric circulation anomalies are the direct cause of climate anomalies. To further reveal the relationship between anomalous sea surface temperature in the preceding period and summer plateau precipitation, we calculated the anomalous summer atmospheric circulation field regressed onto the SST Index (SSTI). In the 500 hPa geopotential height field for summer (Figure 5(a)), there is a wave train of "- + - +" from Europe to Central Asia and then to the plateau. A similar configuration exists in the upper-level 200 hPa field (Figure 5(b)). There is a negative anomaly over Iran in Central Asia and a positive anomaly over the Tibetan Plateau, indicating an eastern type of South Asian High. In the mid-to-upper level (500 hPa, 200 hPa) wind fields (Figure 5(c), Figure 5(d)), a cyclonic circulation is visible over Iran, while an anticyclonic circulation is present over the Tibetan Plateau. Enhanced divergence at the upper levels of the plateau strengthens the pumping effect, favoring the convergence of moisture at the mid-to-lower levels, leading to an increase in moisture over the plateau.

During summer, the southwest monsoon prevails over the Indian Ocean, while the southeast monsoon prevails over the western Pacific. In the lower-level 700 hPa wind field (Figure 5(e)), a prominent southeast wind transports warm and humid air from the tropical western Pacific, the South China Sea, and the Bay of Bengal westward to the Indian subcontinent. Some of this air turns into a southerly wind, forming an anticyclonic shear that transports moisture to the plateau. This moisture transport path also exists in the mid-level wind field. A significant southwest wind transports moisture northward from the tropical Indian Ocean and the Arabian Sea, and is then transported to the Tibetan Plateau by westerly winds in the southern part of the cyclonic wind field over northern India. It can be seen that the two main channels for transporting moisture to the plateau are both reflected in the regression field. So, how does a consistently warm Indian Ocean sea surface temperature affect these two moisture transport channels?

The anomalous southwest monsoon from the Indian Ocean meets the anomalous easterly winds from the northwestern Pacific in the central equatorial Indian Ocean (**Figure 5(e)**), favoring the development of convection and upward motion above. In the zonal vertical circulation circle along the equator (**Figure 5(f)**), there is anomalous upward motion in the central Indian Ocean and anomalous downward motion over the western Pacific, with the vertical pumping effect strengthening the anomalous easterly winds in the lower-level wind field blowing from the western Pacific towards the Indian Ocean. Meanwhile, in the upper-level 200 hPa wind field (**Figure 5(d)**), a significant anomalous westerly wind is visible blowing from the Indian Ocean towards the western Pacific, forming a strong anomalous zonal Walker circulation between the Indian Ocean and the western Pacific. Studies have suggested that the anomalous downward motion over the western Pacific, induced by the anomalous Walker circulation spanning the tropical Indian Ocean and western Pacific triggered by warming in the tropical Indian Ocean, suppresses local convection development, which is conducive to the development and intensification of the western Pacific subtropical high [6] [7].

The western Pacific region is dominated by a significant anticyclonic circulation (**Figure 5(c)**, **Figure 5(e)**). Corresponding to the lower-level anticyclone, in the upper-level 200 hPa wind field (**Figure 5(d)**), the western Pacific region is controlled by a cyclonic circulation, with convergence at upper levels and divergence at lower levels. This high-low level configuration weakens convection and favors the development of downward motion, indicating a stronger western Pacific subtropical high.

There are mainly two additional explanations for the physical mechanism by which positive sea surface temperature anomalies (SSTA) in the tropical Indian Ocean enhance the western Pacific subtropical high: 1) The "two-stage thermal adaptation" mechanism: Positive SSTA in the northern Indian Ocean, through sensible heating, induces an anomalous cyclonic circulation near the surface to its east. The anomalous southerly winds on the eastern side of this cyclonic circulation transport a large amount of moisture northward, leading to positive anomalous precipitation near the southern China coast. The vertical profile of latent heat heating from the positive anomalous precipitation shows an increase in heating rate with height in the mid-to-lower troposphere, thereby inducing anomalous southerly winds in the mid-to-lower layers and enhancing the western Pacific subtropical high to its east [3]; 2) The "Kelvin wave and wave-induced Ekman divergence" mechanism: Positive SSTA in the tropical Indian Ocean excites a warm Kelvin wave through moist adiabatic adjustment, resulting in anomalous low pressure in the lower layers of the tropical Indian Ocean and western Pacific. Due to the effects of pressure gradients and Ekman pumping, there is low-level divergence in the extraequatorial northwestern Pacific, forming an anomalous anticyclone and enhancing the western Pacific subtropical high [4] [5].

Since the positive sea surface temperature anomalies (SSTA) in the tropical Indian Ocean during spring and summer are a response to the preceding winter's El Niño, the positive SSTA in the tropical Indian Ocean acts as a "capacitor" that transmits the influence of the preceding winter's ENSO on the summer's western Pacific subtropical high. Therefore, the tropical Indian Ocean plays the role of a "capacitor": during the mature phase of the winter El Niño, the air-sea interaction in the Indian Ocean is characterized by the atmosphere forcing the ocean, with the Indian Ocean sea surface temperature gradually rising under the forcing of El Niño, entering a "charging" state; in the summer after the decay of El Niño, the air-sea interaction in the tropical Indian Ocean shifts to the ocean forcing the atmosphere, influencing the western Pacific subtropical high through warm Kelvin waves and wave-induced Ekman divergence, at which point the tropical Indian Ocean is in a "discharging" state [5].

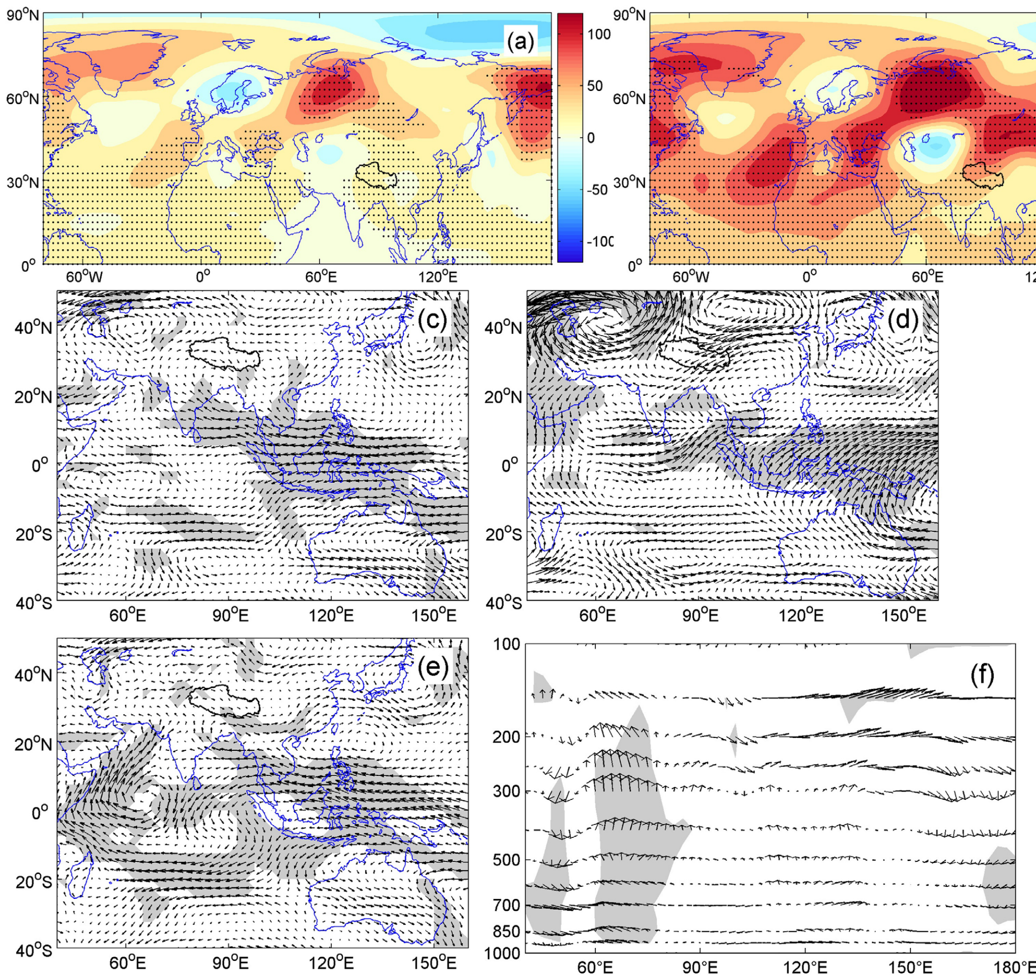

Figure 5. Regression of the sea surface temperature index (SSTI) in the key region of the Indian Ocean (10˚S - 20˚N, 44˚E - 94˚E) during the preceding winter onto the summer (a) 500 hPa geopotential height field; (b) 200 hPa geopotential height field (repeated for clarity); (c) 500 hPa wind field; (d) 200 hPa wind field; (e) 700 hPa wind field; (f) average vertical circulation between 5˚S and 5˚N. Shaded and dotted areas pass the significance test at $\alpha = 0.05$. (c, d, e) Wind speeds are 3 m/s. (f) To maintain the same order of magnitude as the regression coefficients for horizontal speeds, the regression coefficients for vertical speeds are multiplied by 500.

Relevant studies have emphasized the role of the zonal sea surface temperature (SST) gradient between the tropical Indian Ocean and the Pacific Ocean on the western Pacific subtropical high (WPSH) [4]. The anomalous zonal SST gradient, with warming in the western Indian Ocean and cooling in the eastern Pacific, drives anomalous easterly winds in the equatorial western Pacific. Through Ekman pumping, this leads to divergence in the planetary boundary layer over the extra-tropical northwestern Pacific, resulting in the intensification of the WPSH. It is evident that the warming of the Indian Ocean enhances the WPSH, facilitating the transport of moisture from the South China Sea and the Bay of Bengal towards the plateau.

To analyze the potential impact of Indian Ocean SST on another water vapor pathway (as depicted in **Figure 5(e)**), it is first necessary to understand the spatial distribution characteristics of the Somali Cross-Equatorial Jet (SMJ). **Figure 6(a)** shows the distribution of meridional wind speed V along the equator (5˚S - 5˚N) as a function of longitude and height during summer. Five major pathways can be identified: 40 - 55˚E, 83 - 90˚E, 105 - 110˚E, 120 - 135˚E, and 145 - 150˚E. The first is the Somali Jet, the second is the cross-equatorial airflow over the Bay of Bengal, and the last three are collectively referred to as the Australian Cross-Equatorial Airflows [13]. Among them, the Somali Jet (SMJ) is the strongest, with the largest spatial span, centered at 40 - 55˚E and present from near the surface to the 700 hPa level.

Past studies have primarily defined the intensity index of the Somali Jet from both pressure levels and regions, and generally consider the wind speed at 925 hPa to be more representative. From the variation of average meridional wind with height in the core wind speed region of the Somali Jet (40 - 55˚E, 5˚S - 5˚N) [13] (as shown in **Figure 6(b)**), it can be seen that the maximum value occurs at the 925 hPa level.

Based on the previous analysis, there is a positive correlation between Indian Ocean sea surface temperature (SST) and the Somali Jet, meaning that when the Indian Ocean SST is anomalously warm, the Somali Jet is stronger. However, Wang *et al.* [14] found that the interannual variations of the Somali Jet and the Australian Cross-Equatorial Airflow exhibit mostly out-of-phase and occasionally in-phase relationships when studying their different configurations and impacts. When the Somali Jet weakens and the Australian Cross-Equatorial Airflow strengthens in summer, indicating an out-of-phase variation, the atmospheric and oceanic anomalies in the tropical Indian Ocean-Pacific region manifest as a developing classic eastern El Nino pattern, corresponding to a consistent cold phase in the Indian Ocean. That is, when the Somali Jet is stronger, the Indian Ocean SST is cooler.

Why do opposite results occur? To investigate the reasons, the correlation between the average meridional wind speed V in the core wind speed region of the Somali Jet (40 - 55˚E, 5˚S - 5˚N) at 92 5hPa, 850 hPa, and 700 hPa and the SST in the Indian Ocean during the preceding winter and spring, as well as the concurrent summer, and the following autumn and winter, were calculated separately (as shown in **Figure 7**).

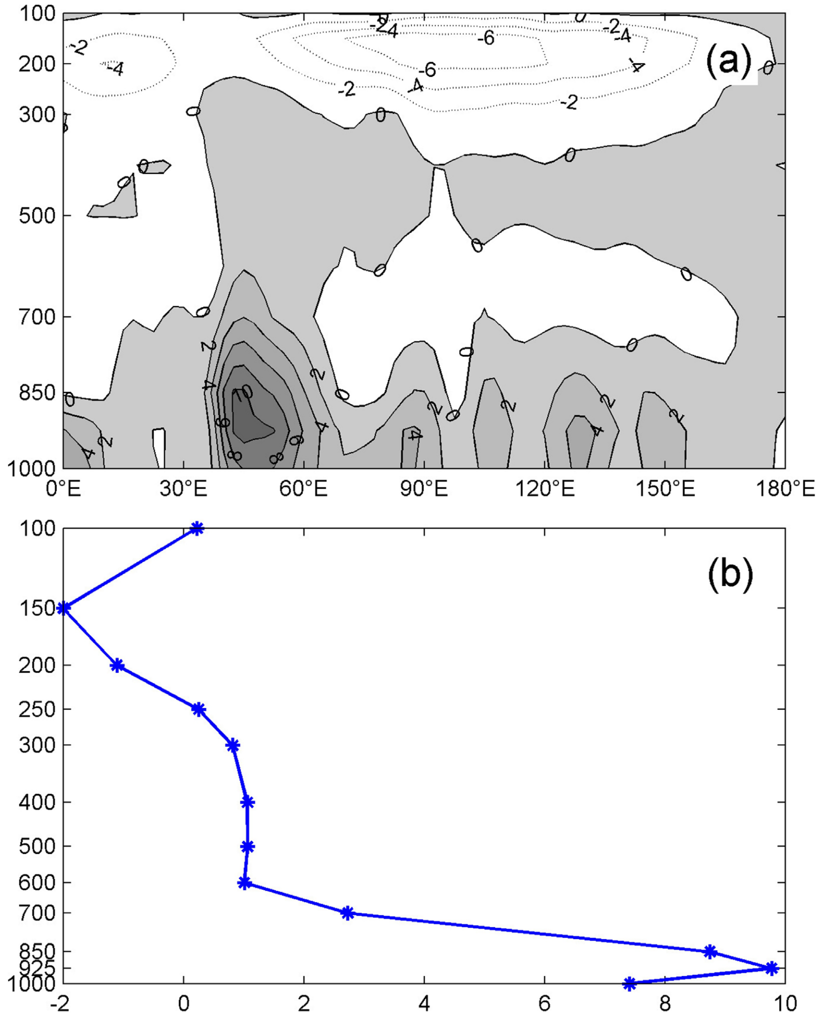

Figure 6. (a) Distribution of meridional wind speed V along the equator (5˚S - 5˚N) as a function of longitude and height during summer; (b) Variation of average meridional wind with height in the core wind speed region of the Somali Jet (40 - 55˚E, 5˚S - 5˚N).

As shown in **Figure 8**, the relationship between the Somali Jet at 925 hPa and 700 hPa and the Indian Ocean sea surface temperature (SST) is exactly opposite. When the Somali Jet at the 925 hPa level is stronger, the Indian Ocean SST is cooler; when the Somali Jet at the 700 hPa level is stronger, the Indian Ocean SST is warmer. A correlation analysis was conducted for the Somali Jet (40˚ - 55˚E, 5˚S - 5˚N) at various levels. The strength variations of the Somali Jet at 925 hPa and 700 hPa exhibit an out-of-phase relationship, with a correlation coefficient of -0.75, passing the significance test ($\alpha = 0.01$). This out-of-phase relationship is very significant both interannually and interdecadally (**Figure 8**). The strength of the Somali Jet at 850 hPa is positively correlated with that at 700 hPa, with a correlation coefficient of 0.52 ($\alpha = 0.01$), but there is no significant relationship with the strength of the Somali Jet at 925 hPa, with a correlation coefficient of 0.05. Based on the previous analysis, the strengths of the upper and lower layers of the Somali Jet vary oppositely on interannual and interdecadal timescales. When the Indian

Ocean SST is warmer, the Somali Jet at the 925 hPa level is weaker, while the Somali Jet at the 700 hPa level is stronger. Therefore, in the 700 hPa wind field regressed by SSTI (**Figure 5(e)**), the stronger Somali Jet is conducive to more moisture from the Indian Ocean being transported to the plateau. Why was the 700 hPa level chosen to observe the moisture transported to the plateau? It is mainly because the average elevation of the plateau is above 3000 meters, and moisture transport at lower levels cannot reach the plateau. A correlation analysis was conducted between plateau precipitation and the strength of the Somali Jet at various levels. The best correlation was found with the 700 hPa level, followed by the 850 hPa level, and an out-of-phase relationship was observed with the 925 hPa level (**Figure 8**).

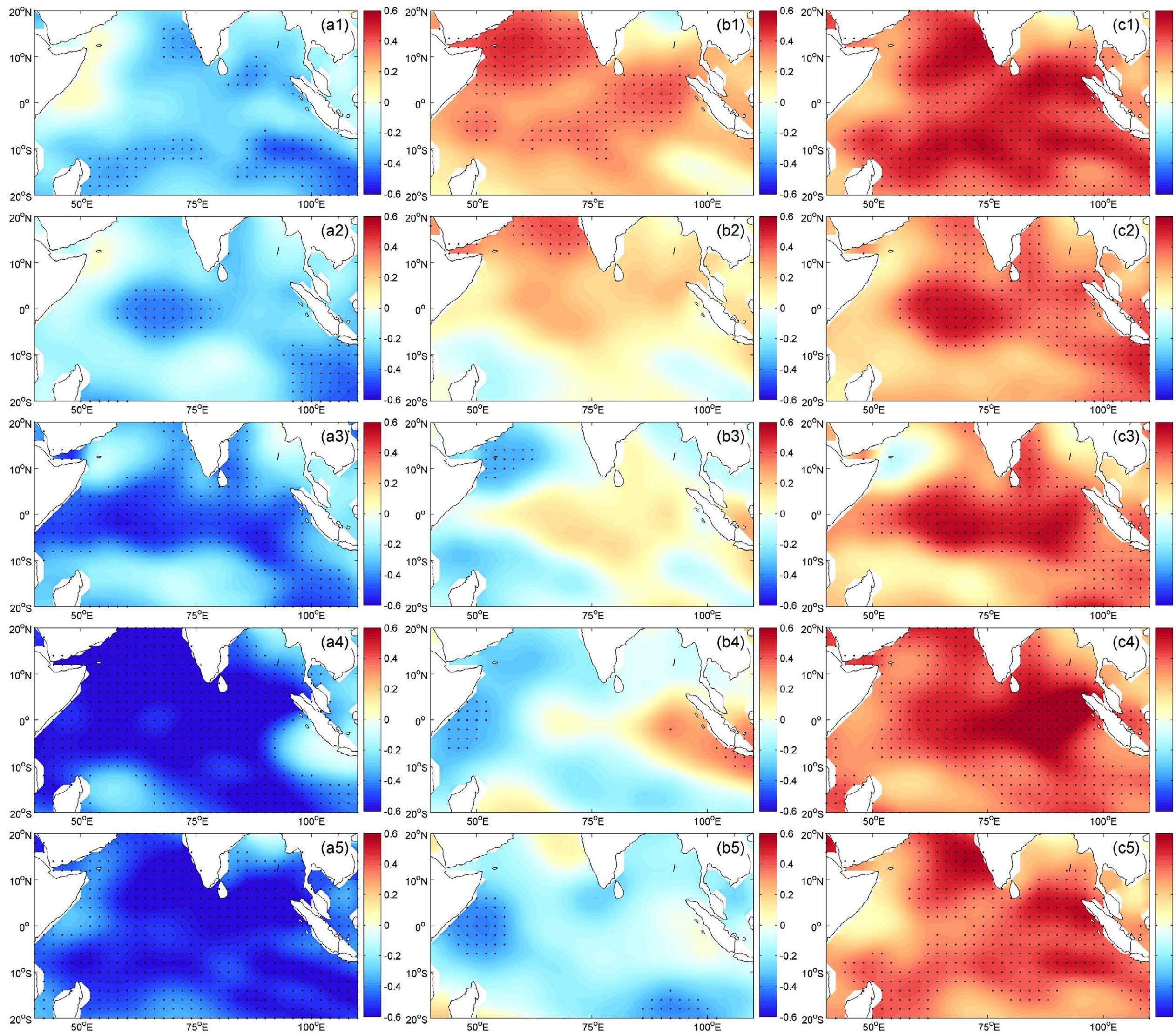

Figure 7. Correlation between the average meridional wind speed V in the core wind speed region of the Somali Jet (40˚ - 55˚E, 5˚S - 5˚N) and Indian Ocean SST (a1-a5): 925 hPa V; (b1-b5): 850 hPa V; (c1-c5): 700 hPa V; (1-5): Indian Ocean SST for the preceding winter, preceding spring, concurrent summer, following autumn, and following winter. The dotted areas pass the significance test at $\alpha = 0.05$.

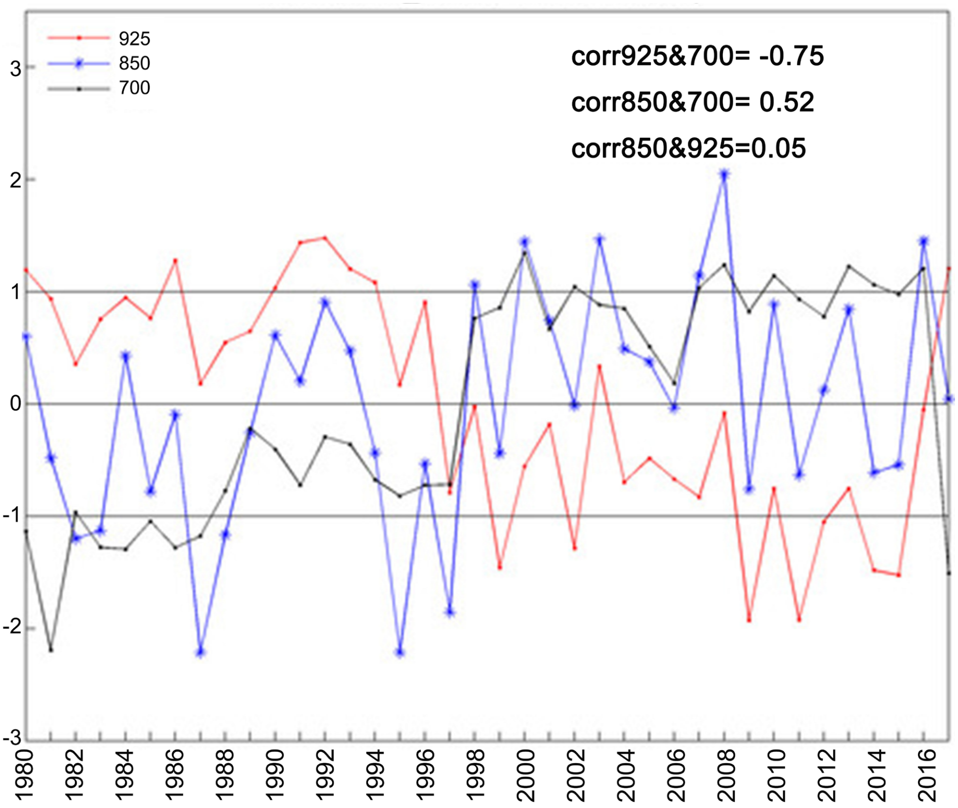

Figure 8. Interannual variations of the average meridional wind speed V at different levels in the core wind speed region of the Somali Jet (40˚ - 55˚E, 5˚S - 5˚N).

5. Conclusion and Discussion

This study examines the relationship between Indian Ocean sea surface temperature (SST) anomalies, which serve as the primary source of moisture for the Tibetan Plateau, and summer precipitation over the Tibetan Plateau through three moisture transport pathways. It analyzes the coupling modes between Indian Ocean SST and precipitation anomalies over the Tibetan Plateau, as well as the potential impact of the dominant mode SST anomalies on summer precipitation over the plateau. The following conclusions are drawn:

1) Singular value decomposition (SVD) of Indian Ocean SST and summer precipitation over the Tibetan Plateau reveals that the left field (Indian Ocean SST) of the first mode for each season exhibits a consistent pattern, capturing the main features of both the left and right fields. This indicates that the consistent SST anomalies across the entire Indian Ocean during the preceding winter, spring, and concurrent summer are most closely related to summer precipitation over the plateau. Among these, the coupling mode between the preceding winter SST anomalies and summer precipitation over the plateau is the most optimal, with significant positive anomalies in the tropical Indian Ocean leading to significantly above-average precipitation across most of the region. The key SST regions in the left field of the first mode for each season show good persistence and significance in correlation. Therefore, the SST index (SSTI) in the key region of the Indian

Ocean (10˚S - 20˚N, 44˚E - 94˚E) during the preceding winter is considered a good indicator for predicting summer precipitation over the plateau.

2) Based on the analysis of the summer atmospheric circulation field regressed by SSTI, a wave train of "- + - +" exists from Europe to Central Asia and then to the plateau. There is a cyclonic circulation in the upper layers over Iran, an anticyclonic circulation over the Tibetan Plateau, and the South Asian High is of the eastern type. The enhanced divergence in the upper layers over the plateau strengthens the pumping effect, which is conducive to the convergence of moisture in the mid-lower layers, leading to an increase in moisture over the plateau. In the regressed low-level wind field, the two most significant pathways for moisture transport to the plateau are prominent. We further analyze the potential impact of uniformly warm SST anomalies in the Indian Ocean on these two moisture transport pathways.

3) In the zonal vertical circulation circle along the equator, there is anomalous upward motion in the central Indian Ocean and anomalous downward motion over the western Pacific. The vertical pumping effect strengthens the anomalous easterly winds blowing from the western Pacific to the Indian Ocean in the low-level wind field, and significant anomalous westerly winds blowing from the Indian Ocean to the western Pacific in the upper layers, forming a strong anomalous zonal Walker circulation between the Indian Ocean and the western Pacific. According to the research analysis by [6], this is conducive to the development and strengthening of the western Pacific subtropical high. The western Pacific region exhibits a prominent anticyclonic circulation, indicating a stronger-than-normal western Pacific subtropical high. Furthermore, the main physical mechanisms through which positive SST anomalies (SSTA) in the tropical Indian Ocean enhance the western Pacific subtropical high — the "two-level thermal adaptation" mechanism and the "Kelvin wave and wave-induced Ekman divergence" — further explain how Indian Ocean warming strengthens the western Pacific subtropical high and, consequently, enhances the moisture transport to the plateau from the South China Sea and the Bay of Bengal. Relevant studies emphasize the role of the zonal SST gradient between the tropical Indian Ocean and the Pacific in influencing the western Pacific subtropical high.

4) The interannual and interdecadal variations in the strength of the Somali Jet at upper and lower levels are opposite. When the Indian Ocean sea surface temperature is warmer, the Somali Jet at 925 hPa is weaker, while it is stronger at 700 hPa. The correlation between plateau precipitation and the strength of the Somali Jet at 700 hPa is the strongest, which is conducive to more moisture from the Indian Ocean being transported to the plateau. Based on the above, the mechanism by which uniformly warming sea surface temperatures in the Indian Ocean affect plateau precipitation may be as follows: Uniformly warm (cool) sea surface temperatures in the Indian Ocean strengthen (weaken) the western Pacific subtropical high, thereby increasing (decreasing) the moisture transported to the plateau from the South China Sea and the Bay of Bengal; correspondingly, the Somali Jet at 700

hPa is stronger (weaker), leading to increased (decreased) moisture transport from the Indian Ocean to the plateau.

Overall, the uniform warming of Indian Ocean sea surface temperature (SST) affects precipitation on the Tibetan Plateau through the following mechanisms: Uniform warm (cold) SST in the Indian Ocean intensifies (weakens) the Western Pacific Subtropical High (WPSH), thereby increasing (decreasing) the water vapor transported to the Plateau from the South China Sea and the Bay of Bengal. Correspondingly, uniform warm (cold) SST in the Indian Ocean cause the Somali Jet at the 700 hPa level becomes stronger (weaker), which leads to an increase (decrease) in the water vapor transported to the Plateau from the Indian Ocean.

This study focused on the sea surface temperature (SST) in the Indian Ocean and its predictive power for summer precipitation on the Tibetan Plateau. However, it is important to recognize that other factors, such as the El Niño-Southern Oscillation (ENSO) and Tibetan Plateau snow cover, also play significant roles in shaping the region's climate. Future research should aim to integrate these various factors into a comprehensive framework to improve the understanding and prediction of precipitation patterns over the Tibetan Plateau.

Funding

This study was supported by the Department of Forecasting and Networking, China Meteorological Administration (Grant No. FPZJ2025-128, FPZJ2025-129).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Li, Y.H. and Zhai, Y.J. (2013) Relationship between Summer Drought/Flood on the Tibetan Plateau and Large-Scale Circulation. *Arid Meteorology*, **31**, 845-858.

[2] Lin, Z.Q., Tang, S.Y., He, X.H., *et al.* (2011) Characteristics of Moisture Transport and Precipitation Anomalies during the Flood Season on the Tibetan Plateau. *Meteorology*, **37**, 984-990.

[3] Wu, G.X., Liu, P., *et al.* (2000) Impact of Indian Ocean Sea Surface Temperature Anomalies on the Western Pacific Subtropical High—A Two-Level Thermal Adaptation in the Atmosphere. *Journal of Meteorology*, **58**, 513-522.

[4] Terao, T. and Kubota, T. (2005) Eastwest SST Contrast over the Tropical Oceans and the Post El Niño Western North Pacific Summer Monsoon. *Geophysical Research Letters*, **32**, L15706. https://doi.org/10.1029/2005gl023010

[5] Xie, S., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G., *et al.* (2009) Indian Ocean Capacitor Effect on Indo-Western Pacific Climate during the Summer Following El Niño. *Journal of Climate*, **22**, 730-747. https://doi.org/10.1175/2008jcli2544.1

[6] Yuan, Y. and Li, C.Y. (2009) Possible Impacts of Different Modes of Sea Surface Temperature Anomalies in the Tropical Indian Ocean on the Onset of the South China Sea Summer Monsoon. *Chinese Journal of Atmospheric Sciences*, **33**, 325-336.

[7] Yan, H.M., Li, Q.Q., Yuan, Y., *et al.* (2013) Anomalies in the Atmospheric Circulation over the Northwestern Pacific in Summer and Their Relationship with Sea Surface

Temperature Changes in the Tropical Indian-Pacific Oceans. *Chinese Journal of Geophysics*, **56**, 2542-2557.

[8] Jia, L. and Zhou, S.W. (2003) Impact of Indian Ocean Sea Surface Temperature Anomalies on the Indian Monsoon and Summer Precipitation over the Tibetan Plateau. *Plateau Meteorology*, **22**, 132-137.

[9] Liu, Q.C., *et al.* (2005) Relationship between the Dipole Oscillation of Indian Ocean Sea Surface Temperature and Precipitation and Temperature during the Flood Season on the Tibetan Plateau. *Plateau Meteorology*, **24**, 350-356.

[10] Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., *et al.* (1996) The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, **77**, 437-471. https://doi.org/10.1175/1520-0477(1996)077<0437:tnyrp>2.0.co;2

[11] Smith, T.M., Reynolds, R.W., Peterson, T.C. and Lawrimore, J. (2008) Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006). *Journal of Climate*, **21**, 2283-2296. https://doi.org/10.1175/2007jcli2100.1

[12] Wallace, J.M., Smith, C. and Bretherton, C.S. (1992) Singular Value Decomposition of Wintertime Sea Surface Temperature and 500-Mb Height Anomalies. *Journal of Climate*, **5**, 561-576. https://doi.org/10.1175/1520-0442(1992)005<0561:svdows>2.0.co;2

[13] Wang, W.P. and Yang, X.Q. (2008) Variability of the Somali Jet and Its Relationship with the East Asian Summer Monsoon and Precipitation Anomalies in China. *Meteorological Science*, **28**, 139-146.

[14] Wang, W.P. and Yang, X.Q. (2014) Different Configurations of Interannual Variability in the Somali Jet and the Australian Cross-Equatorial Flow and Their Impacts. *Meteorological Science*, **34**, 591-600.