Toward role of westerly-monsoon interplay in linking interannual variations of late spring precipitation over the southeastern Tibetan Plateau

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Abstract
A recent study reported a notable westerly-monsoon interplay (WMI) to the northeast of the Tibetan Plateau in boreal summer. However, this study introduces another striking and unique WMI over the southeastern TP (SETP) in late spring (May), emphasizing the critical roles of the upstream mid-latitude westerly and the downstream Bay of Bengal (BOB) summer monsoon (BOBSM) in linking interannual variations of precipitation over SETP. In this study, the research SETP domain (22.5°–27.5°N, 87.5°–97.5°E) as well as a westerly index (WI) over the pivotal upstream westerly domain (22.5°–30°N, 65°–80°E) and a monsoon index (MI) over the pivotal downstream BOBSM domain (12.5°–22.5°N, 87.5°–100°E) are defined to investigate connections between the westerly and BOBSM and their combined effects on precipitation over SETP. The results indicate that the mid-latitude westerly and BOBSM show opposite effects on precipitation over SETP. The weaker westerly and the stronger BOBSM correspond to enhanced SETP precipitation, and vice versa. The enhanced BOBSM acts as a predominant role on the strengthening of precipitation, while the decelerated westerly plays a secondary dynamical amplification role. To quantify their synergistic roles in linking SETP precipitation, a WMI index is defined. Statistical analysis suggests that this newly defined WMI index has a higher positive correlation with the precipitation over SETP. The correlation has a prominent increase compared to individual correlations between WI/MI and SETP precipitation, and dynamic conditions in high WMI index years are more favorable for the formation of SETP precipitation. The possible mechanism is that the BOBSM southerly strengthens and the southern branch of the upstream mid-latitude westerly weakens in high WMI index years, resulting in an anomalous cyclone over the northwestern BOB and an anomalous anticyclone over the western TP. The anomalous cyclone resembles a Rossby wave response to the increased precipitation over SETP, and the precipitation in turn contributes...
1 | INTRODUCTION

The Tibetan Plateau (TP), with an average elevation of over 4000 m above sea level and an area of around 2.5 million km², is the highest highland in the world. The TP is termed as the “roof of the world,” exerting striking impacts on the regional and global climate (Bothe et al., 2011; Duan & Wu, 2009; Son et al., 2020; Wu et al., 2007; Yanai et al., 2006; Yao et al., 2012). Because of the huge and high topography, the TP can bifurcate and/or block the movements of mid-to-lower tropospheric zonal and meridional winds surrounding it (Huang & Zhou, 2004; Jiang et al., 2008; Li et al., 2012; Lin et al., 2016), manifesting the so-called “mechanical” forcing (Wu et al., 2007). As is known, the Asian domain is famous for the monsoon climate (Li & Pan, 2006). Occurrences of various weather/climate changes and extreme drought or flood events largely depend on activities of the Asian summer monsoon (ASM; Webster & Hoyos, 2004; Chen et al., 2006; Liu et al., 2011; Ding et al., 2008, 2009, 2020; Wang, He, et al., 2009; Wang et al., 2021). It is suggested that the TP can play an important role in regulating the Asian monsoon, exerting the so-called “air-pump” forcing (He et al., 2019; Wu, 1997; Wu et al., 2007; Wu, Guan, et al., 2012; Wu, Liu, et al., 2012; Wu & Zhang, 1998). The “air-pump” effect tied to the TP can drive the surrounding atmospheric movement through the thermodynamic forcing, thus affecting the onset and maintenance of the large-scale ASM, including the Bay of Bengal (BOB) summer monsoon (BOBSM), the Indian summer monsoon (ISM), the South China Sea summer monsoon (SCSSM), and the East Asian summer monsoon (EASM) (Wu, 1997; Wu, Liu, et al., 2012).

The ASM and mid-latitude westerly are important ingredients in the Asian summer (June, July, and August [JJA]) climate system (Chen et al., 2021). A new study reported a striking summertime westerly-monsoon interplay (WMI) over the so-called monsoon boundary zone (MBZ; a transitional zone between the arid central Asia and humid Asia monsoon area located to the northeast of the TP) (Chen et al., 2021), after the northward displacement of the mid-latitude westerly off the TP (Li et al., 2004; Ye et al., 1959) and the fully northward advancement of EASM into the high-latitude China (Ding & Chan, 2005). The mid-latitude westerly and EASM have synergistic impacts on modulating the interannual JJA precipitation variations over MBZ. This synergistic effect can be amplified by the WMI, through exciting a barotropic cyclonic anomaly over the Mongolia. However, in this study, we identify another remarkable WMI (i.e., the westerly-BOBSM interplay) over the southeastern TP (SETP), which occurs in the late spring (May) and bears an intimate relationship with the contemporaneous interannual variations of rainfall over SETP. Our analyses find that this WMI is connected to the aforementioned TP’s mechanical and thermodynamic forcings. This study introduces this late spring WMI and explores the underlying mechanism responsible for the May SETP precipitation variations on the interannual timescale.

In effect, observations reveal that, compared to the early spring (March and April [MA]), the precipitation in the vicinity of SETP and the corresponding interannual variations are more remarkable in late spring (May) (see Figure 1, left panel). The SETP, which is located in the fertile river valleys, is a densely populated region with famous agro-economy (Wu, 2003). Although the precipitation over TP is mainly concentrated in summer (Bothe et al., 2011; Chen & You, 2017; Hu et al., 2021), the sudden increase of late spring precipitation over SETP and its marked year-to-year fluctuations could also exert profound impacts on local agriculture and animal husbandry development, as well as the water resources management (Chen et al., 2006; Chen & You, 2017; Webster & Hoyos, 2004). Therefore, a better understanding of the late spring precipitation variations in SETP associated with WMI can provide scientific support for flood/
drought mitigation and agricultural planning, which is of great socioeconomic importance.

This paper aims to unravel critical roles of westerly-BOBSM and their synergy in linking interannual variations of late spring precipitation over SETP. The remainder of this paper is organized as follows. Section 2 describes the data and methods used in this study. Section 3 presents the climatological characteristics of spring precipitation/circulation around the TP, explores impacts of the upstream mid-latitude westerly and BOBSM on interannual SETP precipitation variations, and investigates the role of their interaction. Conclusions and discussion are presented in Sections 4.

2 | DATA AND METHODS

2.1 | Data

The data sets used for this study include: (1) monthly atmospheric reanalysis data, obtained from the Japanese 55-year Reanalysis (JRA-55) data set, with a horizontal resolutions of 1.25° × 1.25° (Kobayashi et al., 2015); (2) monthly global precipitation data, taken from version 2.3 of the Global Precipitation Climatology Project, with a horizontal resolution of 2.5° × 2.5° (Adler et al., 2003). In addition, we deploy other reanalysis datasets, the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis 1 (NCEP1; Kalnay et al., 1996) at 2.5° horizontal resolution and the latest generation of ECMWF atmospheric reanalysis (ERA5; Hersbach et al., 2020) at 1.0° horizontal resolution, to compare with JRA-55 for ensuring the robustness of results. The results obtained from NCEP1 and ERA5 are fairly consistent with those obtained from JRA-55 (not shown). Since JRA-55 is more suitable for exploring the year-to-year changes in Eurasian areas (Harada et al., 2016), we just show results obtained from JRA-55 in this study. All these datasets cover the time period of 1980–2019. Here, boreal spring refers to the 3 months of March, April, and May (MAM).

2.2 | Methods

Since we focus on the interannual variations, a Lanczos filter method (Duchon, 1979) is used to extract
interannual signals in variables including precipitation over SETP, westerly index (WI), and monsoon index (MI). We use the 9-year high-pass filtering approach, a widely employed filtering band to extract the corresponding interannual component (Chen et al., 2021; Chen & Song, 2018; Chen & Wu, 2017).

Additionally, several statistical methods are utilized in this study, including correlation analysis, partial correlation analysis, composite analysis, regression analysis, and partial regression analysis. To evaluate the statistical significance of our results, a two-tailed Student’s t test is employed. Here, all data are linearly detrended before analyses to exclude potential impacts of long-term trends in variables.

The vertically integrated horizontal water vapor transport (WVT) and its divergence (WVT_div) are calculated based on the following equations (Sun et al., 2019):

\[
\langle \text{WVT} \rangle = -\frac{1}{g} \int_{p_s}^{p_0} qV dp, \quad (1)
\]

\[
\langle \text{WVT\_div} \rangle = -\frac{1}{g} \int_{p_s}^{p_0} \nabla_p \cdot \left( q\vec{V} \right) dp, \quad (2)
\]

where \( \nabla_p \cdot () \) denotes the horizontal divergence in pressure coordinates; \( g \) is the gravitational acceleration; \( p_s \) is the surface pressure; \( q \) is the specific humidity; and \( \vec{V} = (u, v) \) is the horizontal wind vector (\( u \) and \( v \) represent zonal and meridional wind, respectively).

3 | RESULTS

3.1 | Climatological characteristics of spring precipitation around TP and related circulations

Before discussing the WMI over SETP, it is necessary to scrutinize climatological features regarding the spring precipitation around the TP and associated circulations. From Figure 1, we can clearly observe that in boreal spring, the evident precipitation occurs over SETP (22.5°–27.5°N, 87.5°–97.5°E; black frame in Figure 1), and the SETP precipitation has a conspicuous increasing trend from March to May (Figure 1a–c). Particularly, the precipitation over STEP in late spring (namely, the early rainy season; Chen & You, 2017) enhances drastically compared to early spring (MA), with the center exceeding 11 mm d\(^{-1}\) (Figure 1c). Our results are aligned with the previous studies (Deng et al., 2016; Yu et al., 2021). Note that the interannual variations in MAM precipitation over SETP are also more significant in late spring (May) (Figure 1d–f).

Next, we turn to circulations associated with the climatological spring precipitation in the vicinity of the TP. Previous studies suggested that the profound feature of circulation transitions from early spring to late spring over South Asia is the onset of BOBSM in May (Li & Zhang, 2009; Liang et al., 2005; Wu, Guan, et al., 2012; Wu, Liu, et al., 2012), which is driven and maintained by dynamic and thermodynamic forcings of TP (Wu, 1997; Wu et al., 2007). From 850-hPa winds in Figure 1j–l, we can clearly detect the outbreak of BOBSM from early spring to late spring, along with the strengthening of the India–Burma trough. As such, low-level monsoon southwesterly winds abruptly dominate the BOB in May (Figure 1l), inducing considerable warm and moist water vapor transporting toward SETP, along with stronger in situ low-level convergence. Meanwhile, another noticeable feature of the circulation is that the westerly jet over East Asia has not yet jumped north of TP (Ye et al., 1959), and the mid-latitude westerly at 600 hPa therefore bifurcates due to the blocking effect of TP (Figure 1g–i). Note that the corresponding southern branch is weakened over SETP and its west areas in May compared to the early spring counterparts (Figure 1g–i), thus leading to marked convergence of the wind over SETP in May (Figure 1i), especially over its western portion. The warm/humid airflow carried by BOBSM and the relatively cold air mass brought by the upstream westerly meets near SETP (not shown), both of which could contribute to the localized atmospheric instability and cause the sudden increase of precipitation in May. One may ask why we choose the winds at 600 hPa to delineate features of the upstream mid-latitude westerly in boreal spring. In fact, the strongest correlation between the May precipitation over SETP and the mid-tropospheric westerly occurs near the level of 600 hPa (Figure 2b). Note that our result is slightly different from the previous finding of the strongest level of mid-latitude westerly affecting the summertime precipitation over MBZ, which occurs in the level of 500 hPa (Chen et al., 2021). Such phenomenon may be due to the different research area along with the distinct study period regarding the interannual precipitation variability over SETP.

We surmise that SETP precipitation variations in late spring could be associated with the upstream mid-latitude westerly and BOBSM, which will be verified in the following.

3.2 | Linkage between the westerly/BOBSM and the precipitation over SETP

It is essential to identify atmospheric anomalies connected to the interannual variations in May precipitation
over SETP before investigating the combined effect of the westerly and BOBSM in linking the precipitation fluctuations. Figure 2 shows the correlation patterns between the interannual component of SETP precipitation (defined as the areal mean precipitation over the domain of SETP) in May and tropospheric winds. We can detect strong negative correlations west of SETP (brown frame in Figure 2a), indicating the enhancement of SETP precipitation is closely correlated with the deceleration of mid-latitude westerly in its upstream at 600 hPa. Following the approach of Chen et al. (2021), we correlate the SETP precipitation with the zonal mean wind between 65°-80°E for pressure levels of the middle and lower troposphere to further examine the important role of 600-hPa atmospheric dynamics in the upstream. It is evident that the closest negative linkage between precipitation and upstream zonal wind around 22.5°-30°N do occur at 600 hPa (Figures 2b and S1a). Figure 2c shows the correlation between the May SETP precipitation and the 850-hPa meridional winds. The SETP precipitation is positively correlated with the 850-hPa meridional wind from 87.5° to 100°E, that is, the central BOBSM region (blue frame in Figure 2c), and significant positive correlations extend from BOB to SETP. The linkage between the meridional winds and precipitation over SETP is positively correlated in the lower troposphere, and the strongest positive correlation presents around 90°E at 850 hPa (Figures 2d and S1b), suggesting the enhancement of SETP precipitation corresponds to the strengthening of 850-hPa southerly wind anomalies tied to the onset of BOBSM and the resultant abundant warm/moist water vapor advecting from BOB to SETP. In conclusion, both the upstream mid-latitude westerly and the southerly wind associated with BOBSM are closely linked to May SETP precipitation. Given their close relationships, we therefore consider the zonal and meridional upstream regions of 22.5°-30°N, 65°-80°E at 600 hPa (brown box in Figure 2a) and 12.5°-22.5°N, 87.5°-100°E at 850 hPa (blue box in Figure 2c) as the key westerly and monsoon domains linking the year-to-year changes in late spring SETP precipitation, respectively.

Next, we examine the roles of the upstream mid-latitude westerly and BOBSM. To understand their relative roles in SETP precipitation variations and to illuminate their relationships further, a WI and a MI are constructed. The WI is defined as the area-averaged 600-hPa zonal wind over the westerly domain (Figure 2a), while the MI is defined as the area-averaged 850-hPa meridional wind over the BOBSM domain (Figure 2c). The temporal evolution of the standardized...
WI and MI is shown in Figure 3a, together with the May SETP precipitation, after 9-year high-pass filtering. On the interannual timescale, the WI is significantly negatively correlated with the SETP precipitation, with the temporal correlation coefficient (TCC) $-0.51$ (exceeding the 95% confidence level). However, the correlation between MI and precipitation is higher, with a TCC of $0.76$ (exceeding the 99% confidence level). In addition, WI and MI are closely correlated and the TCC between them is $0.31$ (exceeding the 90% confidence level), which means that the weakening of the southern branch of the upstream mid-latitude westerly usually coincides with the strengthening of the downstream BOBSM and the northward extension of the low-level southerly wind, and vice versa. As such, the mid-latitude westerly and monsoon may exert an antiphase synergistic effect on the late spring SETP precipitation. Furthermore, it is essential to point out that the onset of BOBSM (occurs in early May) is the earliest during the ASM onset process (Mao & Wu, 2006; Wu, Liu, et al., 2012; Yu et al., 2021), leading to seasonal transition of springtime South Asian monsoon circulation from April to May and thus a marked increase in local precipitation in May. BOBSM is followed by SCSSM, and finally by the ISM existing from June to September (JJAS) (e.g., Ding & Chan, 2005; Lin & Wang, 2002; Wu, Guan, et al., 2012; Wu & Zhang, 1998; Yang & Huang, 2021). The ISM index (i.e., the All India Rainfall Index [AIRI]) is a widely employed index to
measure the JJAS ISM rainfall variabilities (Mishra et al., 2012). As such, we use the May MI, rather than the JJAS AIRI, to measure the intensity of BOBSM.

It is worth pointing out that the summertime westerly and EASM exert an in-phase impact on the concurrent precipitation over MBZ (Chen et al., 2021). Because the accelerated upstream westerly usually coincides with the strengthening of EASM, the upstream cold air and downstream warm air collides over MBZ, causing the increased precipitation there (Chen et al., 2021). In this study, however, the decelerated southern branch of mid-latitude westerly (corresponding to upstream 600-hPa easterly wind anomalies; Figure 3b) and the enhanced BOBSM (corresponding to 850-hPa southerly wind anomalies south of SETP; Figure 3c) are linked to the enhanced SETP precipitation. Further, these anomalous winds are connected with a mid-level anomalous anticyclone over the western TP and a low-level anomalous cyclone over the northwestern BOB, respectively. Note that because intensified monsoons are conducive to more active WMIs in both the late spring (Figure 2c) and the boreal summer (Chen et al., 2021), the major difference lies in the role of upstream mid-latitude westerly. In this study, we identify that the decelerated westerly plays an essential role in enhancing concurrent rainfall over SETP, whereas the accelerated westerly leads to an increased JJA rainfall over MBZ (Chen et al., 2021).

One may wonder the roles of decelerated westerly and enhanced BOBSM and their relative contributions to the enhanced rainfall over SETP. From Figure 4a, we can clearly detect stronger-than-normal ascending motion anomalies over SETP, providing favorable dynamical conditions to generate positive in situ precipitation. Further analyses suggest that the enhanced SETP precipitation is tied to striking extratropical–tropical interactions, featured by intrusions of cold advection brought by the westerly and the northward transport of warm advection caused by the outbreak of BOBSM (Figure 4a). To examine the relative contributions of westerly and BOBSM, partial regression analysis is employed (Figure 4b,c) because they are inter-correlated. The strengthened BOBSM circulation contributed largely to these favorable dynamical conditions (Figure 4c), thus playing a dominant role. However, the decreased westerly can enhance local upward motions to some extent through the significant penetration of cold air from roughly 350 hPa into the lower-level of SETP (Figure 4b), playing a secondary dynamical amplification role. Note that the penetration of cold advection associated with the enhanced BOBSM is insignificant (Figure 4c), and meanwhile the warm advection associated with the decreased westerly is fairly weakened.

To sum up, although westerly and BOBSM can exert significant effects on May SETP precipitation, we argue that BOBSM may act as a predominant role, whereas the mid-latitude westerly is of secondary importance. The main reasons are as follows. First, BOBSM has a stronger connection with the SETP precipitation compared to the westerly according to the aforementioned correlation analyses (Figure 3a). Second, BOBSM is linked to more...
favorable dynamical conditions such as the profound air convergence tied to positive vorticity (low pressure) anomalies (Figure 5a,b) and the resultant ascending motion anomalies (Figure 5d,e) as well as the transportation of warm and humid water vapor into SETP (Lin et al., 2016), which are crucial for enhanced precipitation.

3.3 Synergistic effect of westerly and BOBSM and underlying mechanisms

To better understand the May precipitation over SETP, the key is to identify the synergistic effect of the WMI, rather than the individual effect from each component. In effect, the significant negative TCC between WI and MI indicates an intimate out-of-phase relationship between these two systems. Before discussing the combined effect of westerly and BOBSM, following Chen et al. (2021), it is necessary to examine whether there exists an obvious westerlies–BOBSM interaction around SETP. Considering the dominant role of BOBSM that is connected to the cyclonic gyre over the northwestern BOB in the enhanced SETP precipitation (Figure 3b,c), we therefore examine the effect of WMI on the low-level BOB gyre anomaly (Figure S2). It is discerned that the westerly over the upstream key westerly region can decrease the height around BOB through linking a significant abnormal cyclonic anomaly extending from BOB and areas to the west (Figure S2a), with the center locating over the northeastern Arabian Sea (AS), which would facilitate the deepening of the cyclonic gyre over the

**FIGURE 5** Latitude–vertical section (averaged over 87.5°–97.5°E) of relative vorticity (a–c; shadings; unit: 10⁻⁶ s⁻¹) and vertical velocity (d–f; shadings; unit: 10⁻³ Pa s⁻¹) regressed onto the 9-year high-pass-filtered (a,d) May reversed WI, (b,e) May MI, and (c,f) I_WMI. Regression coefficients that are significant at the 95% confidence level are stippled. The gray vertical lines represent the latitudinal range of SETP (22.5°–27.5°N). The black shading indicates the topography.
northeastern BOB. This negative height anomalies weaken evidently after excluding the influence of BOBSM (Figure S2c), indicating that the westerly connected with the BOBSM could strengthen this BOB gyre anomaly. The deepened BOB cyclonic anomaly could in turn decelerate the southern branch of mid-latitude westerly via inducing easterly wind anomalies along the northern flank of the BOB cyclonic anomaly. Thus, BOBSM can decelerate the westerly via regulating the cyclonic gyre over the northwestern BOB. Furthermore, there exist significant southerly wind anomalies tied to BOBSM, which are transported from BOB to SETP along the eastern flank of the cyclonic gyre southwest of SETP and the western flank of the anticyclonic gyre southeast of SETP (Figure S2b). Significant negative geopotential height anomalies tied to the strengthened BOBSM could favor the formation of the anomalous BOB cyclone. After removing the influence of the westerly correlated to BOBSM, the zonal height seesaw pattern decreases obviously (Figure S2d), with the centers shifting southward. Thus, the westerly can amplify southerly winds anomalies via enhancing this height seesaw. The above analyses do delineate a solid WMI around SETP in late spring. In fact, it is documented that the late spring low-level southerlies connected to the BOB cyclonic anomaly is induced by the elevated heating of the TP (Wu, Guan, et al., 2012).

To further show synergistic roles of westerly and BOBSM in precipitation changes over SETP quantitatively, we list the classification of WI and MI, and the corresponding mean precipitation anomaly values (Table 1). When the monsoon intensity is normal, the precipitation anomaly values in particularly strong westerly years (i.e., S + N) are negative (−1.01 mm-day\(^{-1}\)); while the precipitation anomaly values in particularly weak westerly years (i.e., W + N) are positive (1.82 mm-day\(^{-1}\)). These results indicate that when the upstream mid-latitude westerly wind is weak (strong), the SETP precipitation is large (small). Moreover, when the westerly intensity is normal, the precipitation anomaly values in particularly strong monsoon years (i.e., N + S) are positive (2.62 mm-day\(^{-1}\)); whereas the precipitation anomaly values in particularly weak monsoon years (i.e., N + W) are negative (−2.71 mm-day\(^{-1}\)). These results suggest that when the monsoon is strong (weak), the SETP precipitation is large (small). It is important to point out that when the westerly intensity is strong and the monsoon intensity is weak (i.e., S + W), the precipitation decreases dramatically, that is −2.61 mm-day\(^{-1}\). Note that when using an absolute value of 1.0 as the threshold to determine anomaly years of WI and MI, we cannot pick out the “S + S” and “W + W” years. However, when the absolute value of 0.5 is taken as the threshold to judge the abnormal WI and MI years, we can extract the “W + W” year of 2000, which corresponds to positive precipitation over SETP (2.86 mm-day\(^{-1}\)), which also reveals the positive role of the weakened westerly. Moreover, we can also extract that the years with W + S are 1988 and 2006, which respectively correspond to large positive precipitation anomaly values of 3.07 and 3.60 mm-day\(^{-1}\) over SETP. To sum up, we quantitatively establish that the westerly and monsoon have an out-of-phase synergistic effect on year-to-year variations of late spring precipitation over SETP. To be specific, positive SETP precipitation anomalies is the most remarkable in years with W + S, and vice versa.

The above findings suggest that the notable WMI in late spring can significantly impact precipitation variations over SETP, and the cyclonic gyre over the northwestern BOB acts a significant bridge role. To quantify this WMI, we define a WMI index (\(I_{\text{WMI}}\)) using the WI and MI and weighted by referring to the TCCs between the two factors and precipitation over SETP, which is calculated as follows:

\[
I_{\text{WMI}} = \frac{r_1 \times WI + r_2 \times MI}{|r_1| + |r_2|}.
\]

In Equation (3), the \(r_1\) and \(r_2\) represent the TCCs between the SETP precipitation and WI, MI, respectively (\(r_1 = −0.51, r_2 = 0.76\)). This index has a high TCC (\(r = 0.81\); exceeding the 99.9% confidence level) with the precipitation (Figure 3a). The correlation has a prominent increase compared to the individual correlations.
between SETP precipitation and WI, MI, respectively, indicating the more critical role of WMI in enhancing local precipitation than the individual components.

Next, we discuss the role of WMI and the underlying mechanisms. The patterns tied to the strong positive $I_{WMI}$ years (Figure 3d,e) are quite similar to those tied to strong positive SETP precipitation years (Figures 2 and 3b,c), but with enhanced atmospheric anomalies. It can be detected that there is an anomalous anticyclone over the western TP and profound negative zonal wind anomalies over SETP and upstream region at 600 hPa (Figure 3d), which suggests the weakening of the mid-latitude southern branch westerly. At 850 hPa, there is an anomalous cyclone over the northwestern BOB, and positive meridional wind anomalies dominate over BOB and SETP (Figure 3e), indicating the enhancement of BOBSM southerly wind anomalies. The abnormal strong cyclonic WVT over the northwestern BOB can result in considerable water vapor convergence over SETP and its surroundings (Figure 6a), thus connecting to significant positive precipitation condensational heating anomalies in situ (Figure 6b).

In fact, easterly wind anomalies south of the above anticyclonic anomaly, which is tied to a higher $I_{WMI}$ (Figure 3d), are rather beneficial to the weakening of the late spring climatological westerly winds. In addition, a low-level BOB climatological gyre is located west of the strong positive heating anomalies (Figure 3e). This BOB cyclonic gyre corresponding to the enhanced precipitation condensation heating could be understood as a Rossby wave response to latent precipitation condensational heating (Gill, 1980; Wang, Huang, et al., 2009). The diabatic heating is proportional to vertical motions and the latent heat of condensation released by precipitation. Thus, the low-level BOB cyclonic gyre is expected to locate west of the anomalous ascending motions and the increased precipitation. In other words, low-level southerly wind anomalies occur where monsoon sets up and precipitation increases, and the enhancement and northward extension of BOBSM is beneficial to enhanced precipitation over SETP. The latent precipitation condensation heating may sustain and enhance this BOB cyclonic gyre, and this gyre in turn favors enhancement of southwesterly wind anomalies and the anticyclonic anomaly over the western TP. Therefore, the BOB cyclonic gyre is conducive to maintaining the dynamical amplification of the westerly-BOBSM interplay to enhance the precipitation over SETP. We suggest a significant positive feedback between the WMI and precipitation, which is similar to the positive feedback between WMI and summer precipitation over MBZ (Chen et al., 2021).

To sum up, we conclude that the WMI plays an important role in SETP precipitation variations on the interannual timescale. The synergy of the weakening of mid-latitude westerly in conjunction with the enhancement of BOBSM tied to a higher $I_{WMI}$ are more beneficial to enhanced precipitation compared to individual systems, which is demonstrated by dynamic conditions connected to a higher $I_{WMI}$ (Figure 5c,f). Anomalies of positive vorticity and negative vertical velocity are more prominent indeed. Under such environments, the strongest dynamic conditions associated with a higher $I_{WMI}$ can make the water vapor from AS and BOB carried by the monsoon climb over mountains, which links the strongest positive precipitation anomalies over SETP (not shown). Therefore, the newly $I_{WMI}$ can depict the major features of the synergistic effect of the WI and MI on interannual SETP precipitation fluctuations in late spring, which can well reflect the combined effect from the two ingredients.
**4 CONCLUSIONS AND DISCUSSION**

The SETP precipitation in late spring (May) displays a large increase with much stronger interannual variations compared to that in early spring (March–April), which is linked to the interplay between the mid-latitude westerly and BOBSM. The mid-latitude westerly and BOBSM are two key factors responsible for the May precipitation over SETP on the interannual timescale. In late spring, the westerly jet has not yet been jumping northward, and the mid-latitude westerly therefore bifurcates due to the blocking effect of the TP. The cold flow brought by the westerly collides with the warm and humid flow carried by the onset of BOBSM over SETP, which increases atmospheric instability. These conditions create advantageous environments for the occurrence/variabilities of SETP precipitation in May. We further investigate the connection between mid-latitude westerly and BOBSM and their synergistic effect on SETP precipitation, which indicates that the westerly and the monsoon show opposite effects on precipitation, and BOBSM plays the predominant role in precipitation variations. The synergy of weaker (stronger) westerly and stronger (weaker) monsoon causes enhanced (suppressed) precipitation. In addition, WI and MI are negatively related, which means that the weakened upper reaches of the southern branch of the mid-latitude westerly is usually accompanied by the strengthening and northward extension of BOBSM, and vice versa.

We analyze relative roles of WMI in driving May precipitation over SETP by defining a WMI index. This new index has a high correlation \( r = 0.81 \) with the SETP precipitation. The correlation has a prominent increase compared to the individual correlations between WI/MI and SETP precipitation, and the results suggest that dynamical conditions tied to a higher WMI index are more beneficial to enhanced precipitation compared to individual systems. The strong positive (negative) WMI index corresponds to strong upward (downward) motions and enhanced (repressed) precipitation over SETP. The underlying mechanisms are that the southern branch of mid-latitude westerly weakens and the southerly of monsoon strengthens in high positive WMI index years, corresponding to an anomalous anticyclone over the western TP and an anomalous cyclone over the northwestern BOB. As the enhanced southwesterly anomalies tied to BOBSM onset are forced to move upwards along the mountain slope, an anomalous ascending air develops over SETP. The enhanced southwesterly airflow brings abundant water vapor from AS and BOB to SETP, contributing to the local convergence of the water vapor flux and an increase in precipitation over SETP. Meanwhile, the increased precipitation can lead to the positive latent diabatic heating anomalies in situ.

These positive diabatic heating anomalies contribute to the maintenance of the BOB cyclonic anomaly west of SETP and the anticyclonic anomaly over the western TP, manifesting the positive feedback process between the WMI and SETP precipitation.

Furthermore, the following three points deserve further discussion. First, we should acknowledge the limitation of the \( I_{WMI} \) defined in the present study. We merely explore the relationships between westerlies/BOBSM and the precipitation over SETP through defining the \( I_{WMI} \). Whether there exist diverse WMIs around TP from perspectives of selections of the research area based on different time scales (e.g., intraseasonal and interdecadal time scales) and the subject (e.g., air temperatures) are important scientific topics meriting further investigation.

Second, from Figure S3, we cannot observe the WMI near SETP in JJA because of the northward jump of the mid-latitude westerly. However, although without the participation of the westerly, the precipitation and its interannual variations over SETP and BOB is much stronger than that in late spring climatologically due to the enhanced BOBSM/ISM. In such a scenario, the nature of summer precipitation near the SETP is the purely tropical monsoon precipitation without the obvious collision of cold and warm airflows (Figure S4). Thus, the dynamical conditions (i.e., upward motion anomalies) tend to be repressed compared to those in late spring (Figure 4a). However, note that the JJA precipitation is much stronger than that in late spring, which could be attributed to the profound impacts of the monsoon on governing the precipitation amount and its variations. In this paper, our objective is to unveil the unique noticeable WMI phenomenon in late spring prior to the summer season and to explore related mechanisms responsible for SETP precipitation variations merely, not to focus on causes for the strong JJA precipitation and associated variations over South Asia.

Third, the predictability source for the interannual variations of the westerly-BOBSM interplay in May merits further studies from perspectives of atmospheric bridges and oceanic conduits, which may help improve the late spring SETP precipitation prediction.

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**AUTHOR CONTRIBUTIONS**

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