

Intraseasonal Oscillation Intensity Variations of the Atmospheric Heat Source over the Tibetan Plateau and Their Relationship with Summer Precipitation

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ABSTRACT: This study investigates intraseasonal oscillation intensity (ISOI) variations of the atmospheric heat source over the Tibetan Plateau (TP) during 1979–2020 and their relationship with local summer precipitation. Our analysis reveals that 10–20-day oscillation predominates over TP, followed by 20–30-day oscillation. ISOIs of both periodicities exhibit significant interannual and decadal variations, with notable weakening trends, particularly over the southern TP. Further analysis indicates a strong relationship between the ISOI and the north–south reversed variations in precipitation across the TP. Mechanically, a weakening of the 10–20-day ISOI correlates with decreased water vapor transport from the Bay of Bengal and the Arabian Sea into the southern TP. This reduction, combined with upper–lower circulation anomalies, leads to a downdraft over the southern TP and reduced precipitation here. Conversely, when the 20–30-day ISOI weakens, water vapor transport from the Arabian Sea into the southern TP diminishes while accumulating over the northeastern TP. Together, an anticlockwise meridional circulation occurs between the northern and southern TPs, causing decreased precipitation in the southern TP and increased precipitation in the northern TP. Dynamic diagnostics further identifies that negative temperature advection and changes in nonadiabatic heating dQ/dt are crucial for the downdraft over the southern TP when the 10–20-day ISOI weakens. In contrast, the weakening of the 20–30-day ISOI involves horizontal relative vorticity and temperature advection in midlevel and upper level, along with dQ/dt in lower levels, which contributes to the downdraft over the southern TP. Meanwhile, the updraft over the northern TP is predominantly linked to horizontal relative vorticity.

SIGNIFICANCE STATEMENT: Intraseasonal oscillation intensity (ISOI) variations can influence climate changes across multiple scales. This study focuses on recent variations in ISOI over the Tibetan Plateau (TP), an area where such effects remain poorly understood. We explore the relationship between ISOI and the north–south reversed variations in summer mean precipitation over the TP, revealing the associated potential physical mechanisms and dynamical processes. Our findings highlight the significant connection between ISOI and climate changes.

KEYWORDS: Climate variability; Intraseasonal variability; Oscillations

1. Introduction

The atmospheric intraseasonal oscillation (ISO) was initially discovered in the tropics (Madden and Julian 1971, 1972). Subsequent studies have revealed significant atmospheric ISO phenomena in mid–high latitudes as well (Jeong et al. 2008; Mao et al. 2010; Wen et al. 2011; Yang and Li 2016). ISO serves as a vital link between synoptic-scale anomalies and long-term climate changes, playing a crucial role in global weather and climate events. Associated with large-scale circulation patterns, ISO can influence local or downstream precipitation anomalies

(Mao et al. 2010), tropical cyclone activities (Bi et al. 2015; Zhang et al. 2023), monsoon onset and development (Wang and Duan 2015; Karmakar and Misra 2019; Liu et al. 2023), and the occurrence of extreme weather events (Hsu et al. 2016; Zhang et al. 2021; Muhammad and Lubis 2023).

The Tibetan Plateau (TP), acting as an elevated heat source, directly heats the midtroposphere, significantly impacting weather and climate changes locally and beyond (Wu and Zhang 1998; Duan and Wu 2005; Wu et al. 2012; G. Li et al. 2016; Wu et al. 2016; Han et al. 2024; Luo et al. 2024). Recent studies have identified TP as an active center of ISO in midlatitudes, with robust ISO signals observed in various meteorological elements, including the heat source (Nitta 1983; Fujinami and Yasunari 2004, 2009; Yang et al. 2017; Zhong et al. 2020). The dominant ISO periodicity of the TP's heat source is 10–20 (Wang and Duan 2015; Zhu et al. 2018; Ren et al. 2019; Wang et al. 2019; Zhong et al. 2020) or 10–30 days (Yang and Li 2017), with complex propagation features and origins.

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ISO signals propagate to the TP both from low latitudes, such as the equatorial western Pacific, the Philippine Sea, and the south side of the TP (Krishnamurti and Subrahmanyam 1982; Zhang et al. 2009; Wang and Duan 2015; Yang and Li 2017; Yang et al. 2017), and from mid- and high latitudes (Wang and Duan 2015; Yang et al. 2017; Wang et al. 2018), with the former being more frequent (Wang and Duan 2015; Wang et al. 2017).

The ISO intensity (ISOI) exhibits variations not only on the interannual scale (Li and Mao 2019; Yao et al. 2019; Cao et al. 2021; Yang et al. 2024) but also on the longer scale (Jones and Carvalho 2011; Chang et al. 2015; Rushley et al. 2019; Liu et al. 2022), influencing multiscale climate changes. The ISOI of the environmental factors has a significant impact on the frequency of tropical cyclone genesis in the western North Pacific, surpassing the effects of seasonal mean anomalies and synoptic component intensity (Cao et al. 2021). Distinct patterns in atmospheric wave train propagation were observed in strong and weak ISOI years, resulting in differing upward motion depths over southern China (Zeng and Sun 2023). In the past six decades, the 20–60-day ISOI of northward-propagating ISO modes of the Indian summer monsoon has presented a notable decreasing trend. This trend correlates with a decrease in extreme rainfall events during the monsoon's active phase but an increase during the break and transition phase (Karmakar et al. 2015). Additionally, Joseph et al. (2022) noted that the increased intensity of the equatorial Madden–Julian oscillation seems to play a pivotal role in lengthening the active/break spells of the Indian summer monsoon.

Several studies have examined the influence of interannual variation in the ISOI of the heat source over the TP on precipitation changes over China. Yu et al. (2018) demonstrated that ISOI can serve as a predictor for climate variations in eastern China. They found that high quasi-biweekly oscillation ISOI is associated with a clear distinction between drought and flood conditions in the middle and lower reaches of the Yangtze River, with a more rapid transition between these extremes. This variability contributes to deviations in the extension forecast of precipitation for this region. Tian et al. (2023) found that precipitation anomalies are pronounced south of the Yangtze River during years with strong ISOI of the TP heat source, while during years with weak ISOI, the Jianghuai region and South China exhibit a dipole pattern in precipitation anomalies.

However, the specific variation of ISOI over the TP in recent years is still unclear and needs to be further explored. Additionally, recent attention has focused on the north–south reversal changes in summer precipitation over the central and eastern TPs, with factors and mechanisms explored from various perspectives (Duan et al. 2012; B. Li et al. 2016; Y. Liu et al. 2021; Li et al. 2021; Yu et al. 2023; Wu et al. 2023; Wang et al. 2023). The warming of the upper troposphere, associated with global warming, increases the frequency of vortices over the northern TP by strengthening the westerly jet, leading to increased precipitation in that region (Li et al. 2021; Wang et al. 2023). An abnormal anticyclone over the northeastern TP has been identified as a significant factor in the drying trend over the southern TP (Wang et al. 2022). This raises the

question of whether there is a close relationship between variations in ISOI of the TP heat source and local summer mean precipitation changes. This study aims to address this question by examining the variations in TP ISOI over the past 40 years, focusing on its spatiotemporal variations and propagation characteristics. Additionally, we investigate the relationship between TP ISOI variations and local summer precipitation changes, along with the underlying physical mechanisms.

This paper is organized as follows: Section 2 describes the data and methodology. Section 3 presents the variations in ISOI over the TP. Section 4 investigates the relationship between TP ISOI variations and local summer mean precipitation. Section 5 explores the potential mechanisms underlying this relationship, and section 6 provides a summary and discussion.

2. Data and methodology

a. Dataset

The daily element, including horizontal wind field, vertical velocity, air temperature, and pressure, was obtained from the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ and 12 vertical levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa) to calculate the atmospheric apparent heat source, and other circulation data containing vorticity, divergence, and vertically integrated water vapor flux were also extracted from JRA-55. Meanwhile, the surface-sensible heat flux and latent heat release from Duan et al. (2018) (referred to hereafter as “Duan2018”) based on satellite and 80 meteorological observations, as well as radiation flux data from GEWEX-SRB (<https://opendap.larc.nasa.gov/opendap/SRB/contents.html>), were utilized here. The high-resolution ($0.25^\circ \times 0.25^\circ$) daily precipitation data (CN05.1; Wu and Gao 2013) obtained by interpolation based on 2416 meteorological stations in China were also employed here.

b. Methodology

In this study, we focused on the summer (June, July, and August) during the period of 1979–2020. The vertically integrated atmospheric apparent heat source $\langle Q_1 \rangle$ was derived from the JRA-55 reanalysis dataset based on the residual budget analyses (Yanai 1961; Yanai et al. 1973):

$$C_p \left[\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T + \left(\frac{p}{p_s} \right)^k \omega \frac{\partial \theta}{\partial p} \right] = Q_1, \quad (1)$$

$$\langle Q_1 \rangle = \frac{1}{g} \int_{100}^{p_s} Q_1 dp, \quad (2)$$

where T denotes the temperature, $\mathbf{V}$ is the horizontal wind vector, and p_s and p are the surface pressure and air pressure, respectively. The term $k = R/C_p$, where R and C_p indicate the gas constant and the specific heat of dry air at constant pressure, respectively. The term θ is the potential temperature,

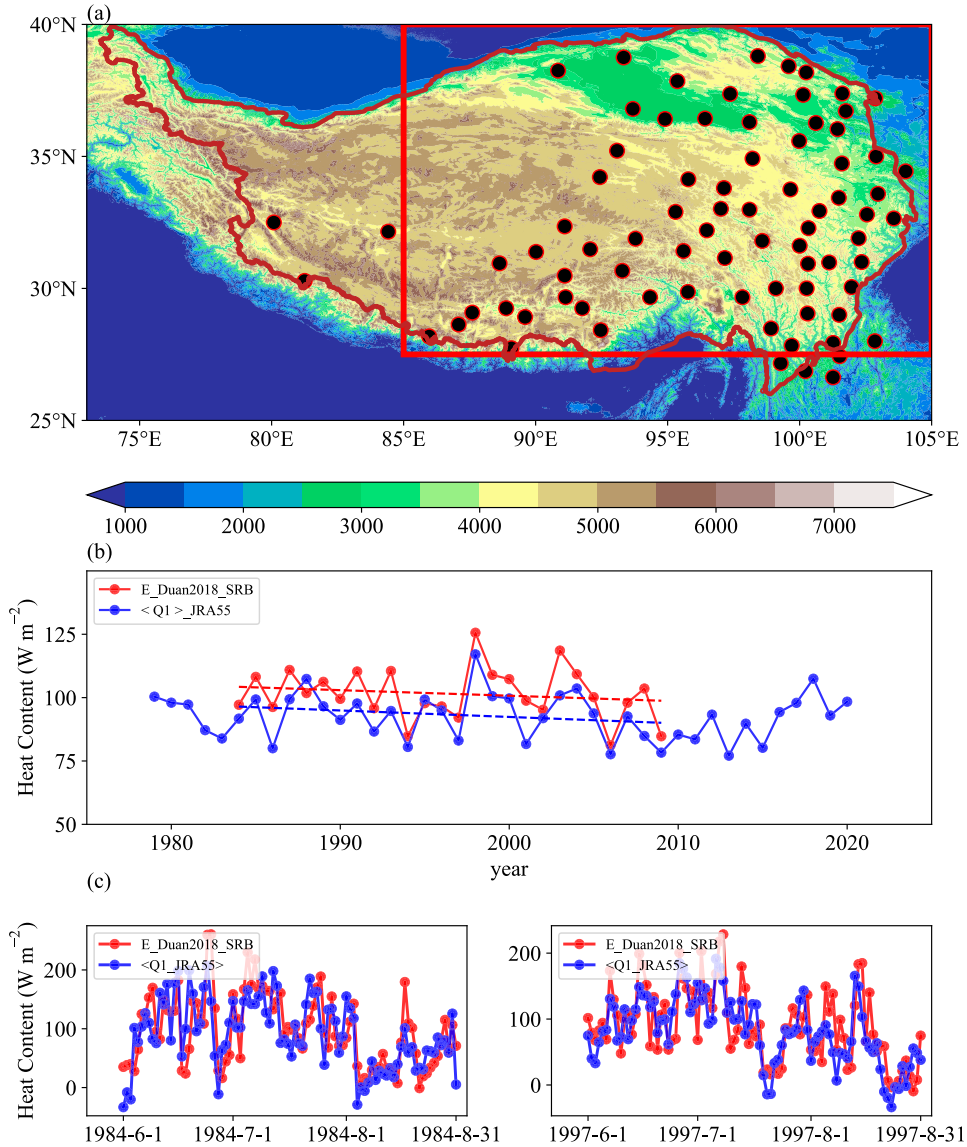


FIG. 1. (a) The distribution of 80 observational stations over the TP, and the red rectangle (27.5°–40°N, 85°–105°E) indicates the key areas for comparison between E_Duan2018_SRB and $\langle Q_1 \rangle$ derived from JRA-55. (b) Time series of the E_Duan2018_SRB and $\langle Q_1 \rangle$ _JRA-55 (W m^{-2}), and dashed lines indicate their linear trends in summer during the period 1984–2009, respectively. (c) Daily summer series of the E_Duan2018_SRB and $\langle Q_1 \rangle$ _JRA-55 (W m^{-2}) in 1984 and 1997.

and ω is the vertical velocity. Furthermore, the atmospheric heat source in an air column was calculated by using the dataset Duan2018 and GEWEX-SRB based on the energy budget formula (denoted as “E_Duan2018_SRB”; Duan and Wu 2008; Wang et al. 2012):

$$\text{E_Duan2018_SRB} = \text{SH} + \text{LH} + \text{RC}, \quad (3)$$

where SH and LH are the surface-sensible heat flux and latent heat release, respectively. The term RC is the net radiation flux of the air column, calculated by the following formula:

$$\begin{aligned} \text{RC} = R_{\text{TOA}} - R_{\text{SFC}} &= (S_{\text{TOA}}^{\downarrow} - S_{\text{TOA}}^{\uparrow}) - (S_{\text{SFC}}^{\downarrow} - S_{\text{SFC}}^{\uparrow}) \\ &\quad - (F_{\text{SFC}}^{\downarrow} - F_{\text{SFC}}^{\uparrow}) - F_{\text{TOA}}^{\uparrow}, \end{aligned} \quad (4)$$

where R_{TOA} and R_{SFC} represent the atmospheric top radiation flux and surface radiation flux, respectively. The term S is the shortwave flux, F is the longwave flux, and the symbols “ $\uparrow$ ” and “ $\downarrow$ ” represent upward and downward radiation fluxes, respectively. The calculated E_Duan2018_SRB spans from 1984 to 2009.

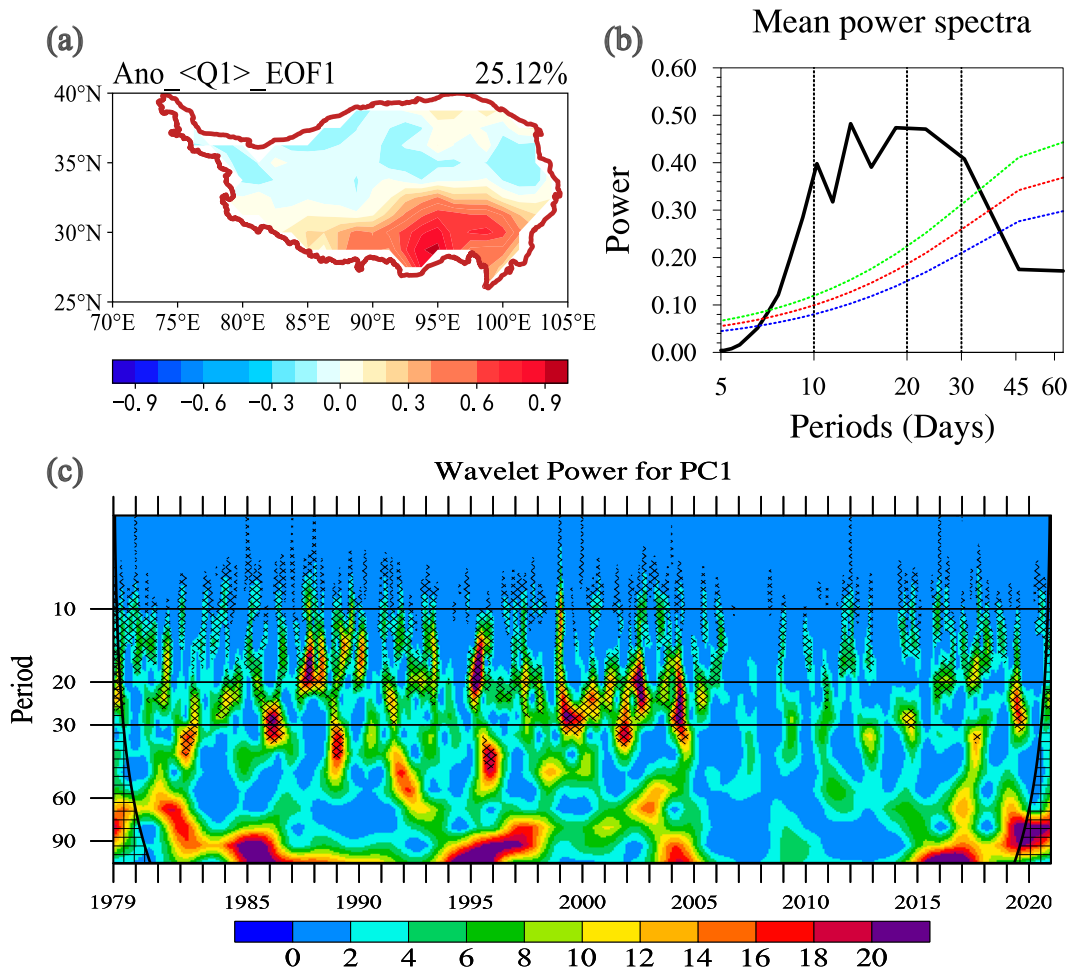


FIG. 2. (a) The first leading EOF mode of the intraseasonal component of $\langle Q_1 \rangle$ for the 42 summer seasons during the period of 1979–2020; (b) mean power spectra of the PC1 of the EOF mode for 42 years; the red dashed line represents the Markov red noise spectrum; and the blue and green dashed lines indicate the prior and posterior 90% confidence bounds, respectively; (c) wavelet analysis of the PC1, hatched areas, and black curve indicate significance levels passing the 95% threshold and the cone of influence.

E_Duan2018_SRB is calculated by using observational data and can be used here as a comparison to verify the reliability of the $\langle Q_1 \rangle$ derived from the JRA-55 over the TP region during the period of 1984–2009. Figure 1a shows the geographical distribution of 80 stations used in E_Duan2018_SRB with only three stations located west of 85°E. Therefore, we made this comparison in the domain of 27.5°–40°N, 85°–105°E. They show similar variations both on interannual and long-term scales, with a correlation coefficient of 0.83 passing the 99% significance test (Fig. 1b). We also present their intraseasonal variations between two sets of data in 2-yr samples (Fig. 1c). It shows obviously consistent variations with the correlation coefficients of 0.71 and 0.74 in 1984 and 1997, respectively, and the mean correlation coefficient of daily summer data of E_Duan2018_SRB and JRA-55 $\langle Q_1 \rangle$ can reach 0.60 for a total of 26 years. In addition, previous studies have also confirmed the adaptability of JRA-55 to calculate the atmospheric heat source over the TP in terms of trend (Wang et al. 2019), interannual (Hu et al. 2016), and intraseasonal variations (Wang

et al. 2019; B. Q. Liu et al. 2021). Hence, it is reasonable that the $\langle Q_1 \rangle$ derived from JRA-55 is selected for further analyses in this study.

The raw data undergo preprocessing to extract the intraseasonal component. Initially, the climatological annual cycle (daily climatology and its first three harmonics) is eliminated from the daily $\langle Q_1 \rangle$ sequence from 1979 to 2020. Subsequently, a 5-day running mean is applied to filter out synoptic fluctuations, which was widely used in various studies related to the atmospheric ISO (Lee et al. 2013; Yang et al. 2014; Li et al. 2015; B. Q. Liu et al. 2021). Furthermore, wavelet analysis and power spectrum analysis are conducted to identify the dominant periodicity of the ISO of $\langle Q_1 \rangle$. The Lanczos filtering method (Duchon 1979) is employed to isolate signals within the desired band. It is important to note that the effective degrees of freedom of the filtered data must be recalculated, which can be conducted by referring to the method of Bretherton et al. (1999) if a significance test is required. Once the predominant periodicity of $\langle Q_1 \rangle$ ISO is determined, the annual summer variance of

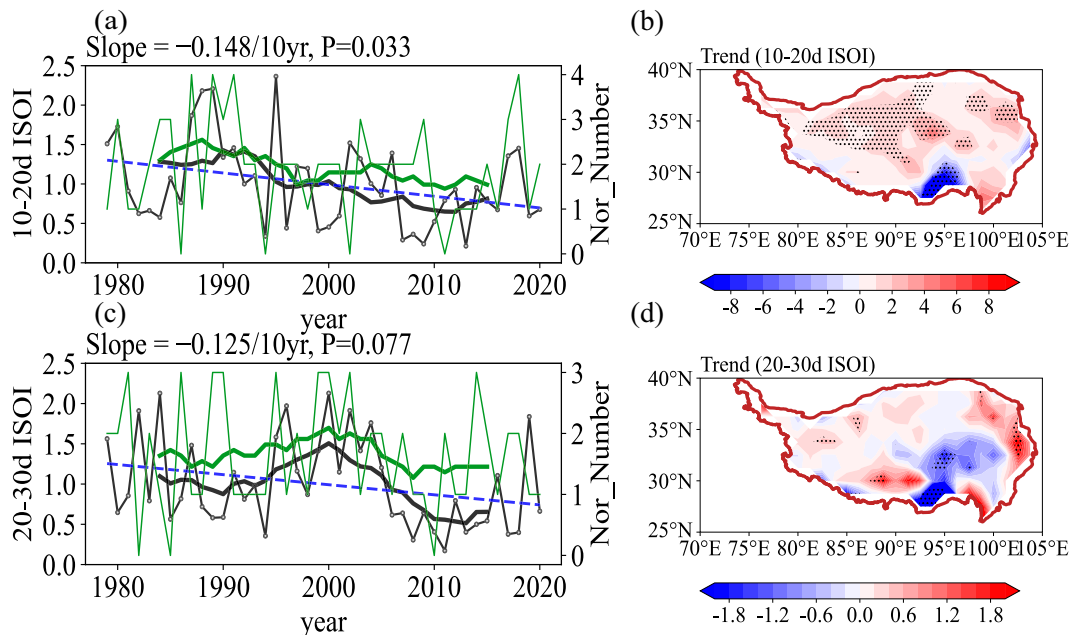


FIG. 3. Time series of TP ISOI (thin black lines) and the frequency of significant ISO events propagating from low latitudes (thin green lines) and their 11-yr running means (thick lines) for (a) 10–20 and (c) 20–30-day oscillations, respectively. The blue dashed lines in (a) and (c) indicate the linear trend in TP ISOI. Spatial distributions of the long-term trend in (b) 10–20 and (d) 20–30-day TP ISOIs in summer from 1979 to 2020, and the dots indicate areas passing the 90% significance test.

the filtered $\langle Q_1 \rangle$ with this specific periodicity is defined as the ISOI (Teng and Wang 2003; Nie and Sun 2022; Tian et al. 2023).

3. Variations in ISOI over the TP

The first leading EOF mode of the intraseasonal component of $\langle Q_1 \rangle$ over the TP exhibits a distinct north–south reverse pattern, with a prominent center over the southern TP, highlighting the significance of the intraseasonal variations in this region (Fig. 2a). The corresponding principal component PC1 is used for power spectrum analysis (Li and Mao 2019). Figure 2b reveals a dominant signal within the 10–30-day oscillation range, with peaks at approximately 10, 13, 18, and 23 days. Previous researches have mainly focused on the 10–20-day oscillation over the TP (Wang and Duan 2015; Zhu et al. 2018; Wang et al. 2019; Zhong et al. 2020), with some studies also considering the 10–30-day oscillation (Yang and Li 2017; Tian et al. 2023). According to Fig. 2c and Fig. S1a in the online supplemental material, we can see that the 10–20-day oscillation is evident in nearly every year, while the 20–30-day oscillation is significant in some years, with a peak at 23 days. The 20–30-day oscillation is even stronger than the 10–20-day signal in certain years, especially around 2000 (Fig. 2c). This is also reflected in the annual power spectrum (Fig. S1b). However, after 2005, the 20–30-day oscillation becomes nearly absent (Fig. 2c and Fig. S1a). This suggests that the 20–30-day oscillation is significant and distinct from the 10–20-day oscillation. Therefore, it is appropriate to separate 10–20-day and 20–30-day oscillations for further analysis, as subsequent results reveal

significant differences between these periodicities in terms of their variations and their relationship with summer precipitation.

a. Spatiotemporal characteristics of the TP ISOI

EOF analysis is applied to the 10–20-day filtered daily $\langle Q_1 \rangle$ over the TP from 1979 to 2020, and the summer variance of PC1 from this EOF mode is taken as the 10–20-day ISOI. Similarly, the 20–30-day ISOI is derived in the same manner. Clearly, in Figs. 3a and 3c, both the 10–20 and 20–30-day ISOIs over the TP display significant interannual variations and long-term weakening trends. Specifically, the 10–20-day ISOI shows a weakening with a slope of $-0.148 (10 \text{ yr})^{-1}$ ($p < 0.05$), while the 20–30-day ISOI has a slope of $-0.125 (10 \text{ yr})^{-1}$ ($p < 0.1$). In addition, the 20–30-day ISOI also represents obvious decadal variations, with two weakening periods in the 1980s [slope: $-0.47 (10 \text{ yr})^{-1}$] and 2000s [$-1.73 (10 \text{ yr})^{-1}$]. The second weakening period is particularly significant with a larger decline. This indicates that the weakening of 20–30-day ISOI from 1979 to 2020 is predominantly driven by the substantial decline observed in the 2000s. Spatially, in Fig. 3b, the 10–20-day ISOI notably weakens over the southern slope of the TP, while other regions exhibit relatively minor but significant strengthening. Regarding the 20–30-day ISOI (Fig. 3d), the weakening domain is more widespread, while the strengthening domain is concentrated in a relatively small region over the northeastern TP. In brief, there are distinct spatial and temporal characteristics between the 10–20-day and 20–30-day oscillations.

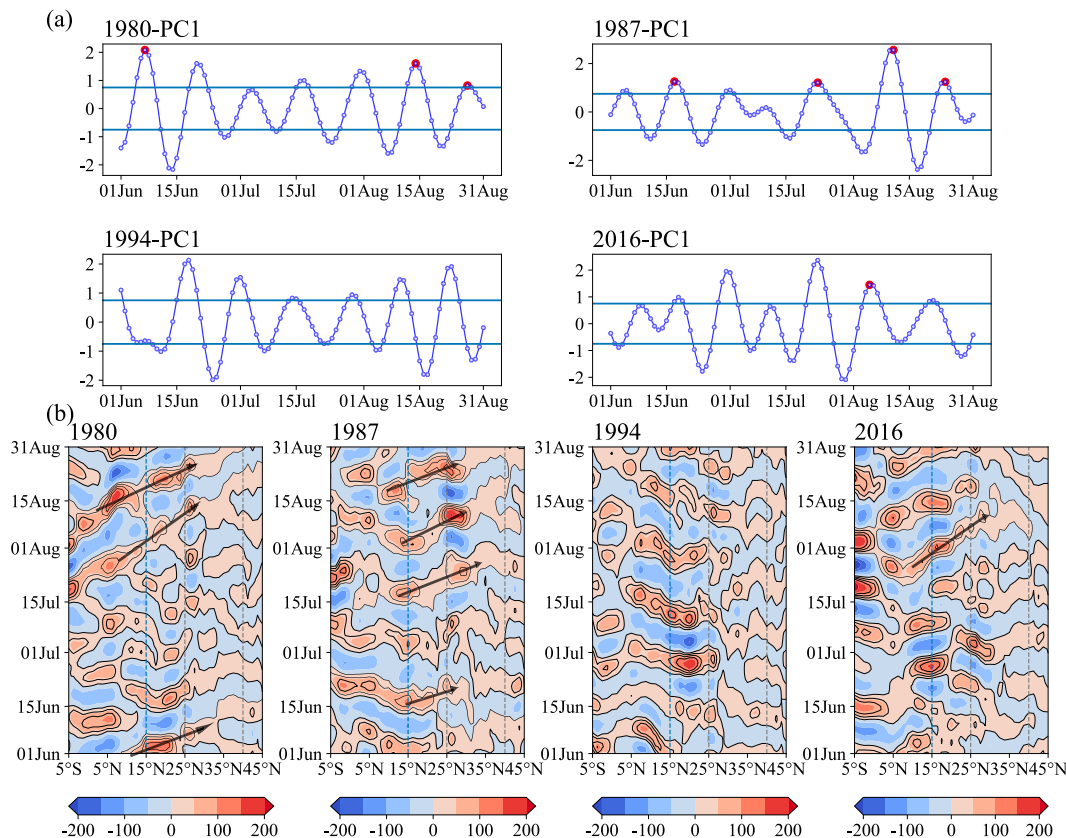


FIG. 4. (a) PC1 of the first EOF pattern and (b) Hovmöller diagrams along 70°–100°E of 10–20-day filtered $\langle Q_1 \rangle$ for 1980, 1987, 1994, and 2016. The black arrows in (b) and red circles in (a) indicate the significant northward events and the peak days of them, respectively.

b. Propagation frequency of the ISO associated with the TP ISOI

The propagation characteristics of ISO over the TP are intricate. Wang and Duan (2015) pointed out that the predominant path for the 10–20-day signals is from low latitudes to the TP. Additionally, Cheng et al. (2020) have shown that the northward propagation frequency of precipitation ISO is the key factor in the interdecadal variations of precipitation ISOI over South China. Given this context, we investigate whether the variations in TP ISOI are related to the propagation frequency of ISO over the TP. This analysis focuses on the predominant propagation path of ISO from low latitudes.

Three major criteria were used to identify significant northward propagation events of ISO: 1) The absolute values of the peak and trough (prior to the peak) of the ISO event must both exceed 0.75 standard deviations of the PC1 to ensure significance; 2) the ISO signal must originate at least from 15°N and propagate into the TP (25°N); and 3) the ISO signals should exhibit significant northward propagation characteristics and demonstrate good temporal continuity according to the Hovmöller diagrams. Using these criteria, noncontroversial significant northward ISO events were selected. Figures 4a and 4b provide examples from 4 years, showing the PC1 and the meridional propagation features of the 10–20-day filtered $\langle Q_1 \rangle$. Furthermore, the numbers

of significant northward propagation events are counted for every summer in Table 1 and Figs. 3a and 3c. Obviously, in Fig. 3a, the frequency of northward propagation events and the 10–20-day ISOI show a good agreement, with a correlation coefficient of approximately 0.34, significant at the 95% level. The correlation coefficient between their 11-yr running means is 0.85 ($p < 0.05$). Additionally, there are 34 northward propagation events in the first 15 years (1979–93) but a total of 26 events in the last 15 years

TABLE 1. Numbers of the 10–20-day $\langle Q_1 \rangle$ ISO events propagating from low latitudes to the TP are listed for every summer from 1979 to 2020.

Year	Count	Year	Count	Year	Count	Year	Count
1979	1	1990	3	2001	2	2012	1
1980	3	1991	4	2002	0	2013	1
1981	1	1992	2	2003	3	2014	1
1982	1	1993	2	2004	2	2015	2
1983	2	1994	0	2005	2	2016	1
1984	3	1995	2	2006	2	2017	3
1985	3	1996	2	2007	2	2018	4
1986	0	1997	2	2008	2	2019	1
1987	4	1998	1	2009	3	2020	2
1988	1	1999	2	2010	1		
1989	4	2000	2	2011	0		

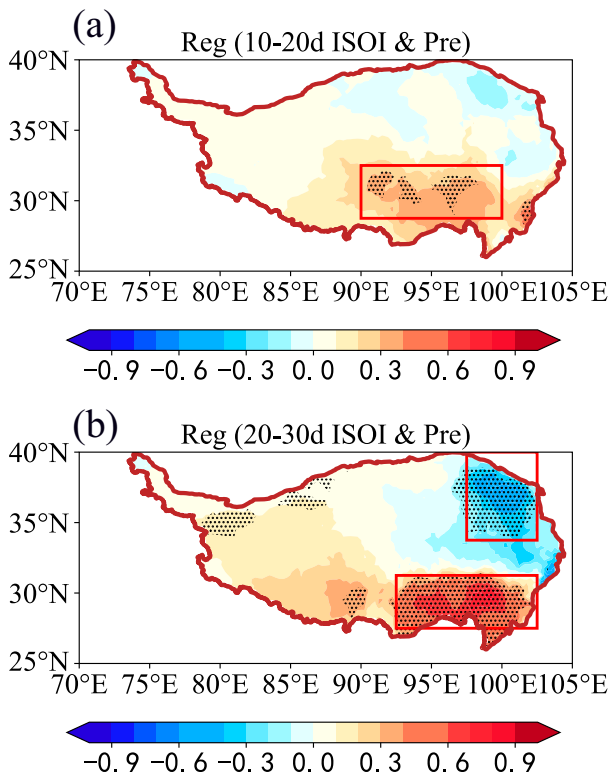


FIG. 5. Distributions of the regression coefficients of the precipitation on the (a) 10–20-day and (b) 20–30-day ISOI indices over the TP during the 42 summers from 1979 to 2020. The red boxes in (a) (28.75° – 32.5° N, 90° – 100° E) and (b) (27.5° – 31.25° N, 92.5° – 102.5° E; 33.75° – 40° N, 97.5° – 102.5° E) roughly represent the key precipitation areas affected by 10–20-day and 20–30-day ISOIs, respectively. The dotted areas exceed the 90% confidence level.

(2006–20) (Table 1). This suggests a decreasing trend in the frequency of northward propagation events, consistent with the weakening trend observed in the TP ISOI (Fig. 3a). In a word, the frequency of 10–20-day ISO events propagating from low latitudes to the TP appears to play an important role in the multiscale variations of the TP ISOI.

Similarly, according to the same criteria, the number of significant northward propagation events for 20–30-day ISO is counted for every summer, which is shown in Fig. 3c. Obviously, the frequency of these northward events exhibits similar decadal variations to the 20–30-day ISOI, with a correlation coefficient of 0.88 ($p < 0.05$) between their 11-yr running means, reflecting a pattern of weakening–strengthening–weakening–strengthening. However, over the long term, there is no obvious trend change in the number of northward events. Therefore, the frequency of northward 20–30-day ISO events mainly impacts the TP ISOI on the interdecadal scale.

4. Relationship between TP ISOI variations and local mean precipitation

Previous studies have pointed out that the interannual changes in ISOI over the TP can affect the precipitation in

downstream areas, including the middle and lower reaches of the Yangtze River (Yu et al. 2018), Jianghuai region, and South China (Tian et al. 2023). However, the relationship between the TP ISOI variations and local summer precipitation remains unclear. The following analysis will address this issue.

Due to sparse observational stations over the western TP, the precipitation from the central and eastern TPs is considered more reliable. The regression coefficients of summer precipitation over the TP on the 10–20-day and 20–30-day ISOI indices are shown in Figs. 5a and 5b, respectively. It can be seen that when the 10–20-day and 20–30-day ISOIs weaken, precipitation over the southern TP declines markedly. However, the key areas of associated precipitation changes are not identical for these two oscillations. For the 10–20-day ISOI, the primarily affected region spans roughly from 28.75° to 32.5° N and 90° to 100° E, while for the 20–30-day ISOI, it extends from 27.5° to 31.25° N, and 92.5° to 102.5° E, with the 10–20-day ISOI affecting areas further north (Fig. 5a). Furthermore, an increase in precipitation over the northeastern TP is significantly associated with a weakened 20–30-day ISOI (Fig. 5b). In short, a weakening of the 10–20-day TP ISOI is closely linked to the decreased precipitation over the southern TP, whereas a weakening of the 20–30-day TP ISOI is intimately related to the reduced precipitation over the southern TP but increased precipitation over the northeastern TP. This pattern aligns with the observed “dry in the south and wet in the north” precipitation distribution over the TP, which has attracted much attention in recent years (Li et al. 2021; Y. Liu et al. 2021; Wang et al. 2022, 2023).

5. Potential mechanisms underlying this relationship

a. The related large-scale circulations

The previous section has revealed the summer mean precipitation variations over the TP may be related to the $\langle Q_1 \rangle$ ISOI. However, different associations between TP precipitation and these two oscillations have been observed. To investigate these differences, we first regressed the vertically integrated water vapor flux and moisture flux divergence onto the ISOI indices for these two oscillations.

In Fig. 6a, we find that the anticyclonic anomalies in the Bay of Bengal (BOB) and northern Arabian Sea associated with the 10–20-day ISOI pump water vapor into the southern TP along with the southwest airflow. Actually, this corresponds well to the occurrence of 10–20-day ISO northward propagation events, with more water vapor from the BOB and the Arabian Sea to the southern TP during their westward movement (Wang and Duan 2015). Therefore, when the 10–20-day ISOI is stronger, more northward ISO events occur (section 3b), resulting in increased accumulation of water vapor over the southern TP. Consequently, the actual decline of 10–20-day ISOI in recent years corresponds to a reduction in moisture influx into the southern TP, with the counterpart of decreased precipitation in that region (Figs. 3a and 5a).

In contrast, for the 20–30-day signals, moisture is transported northward primarily from the Arabian Sea to the western TP, where it then transitions into westerly airflow toward

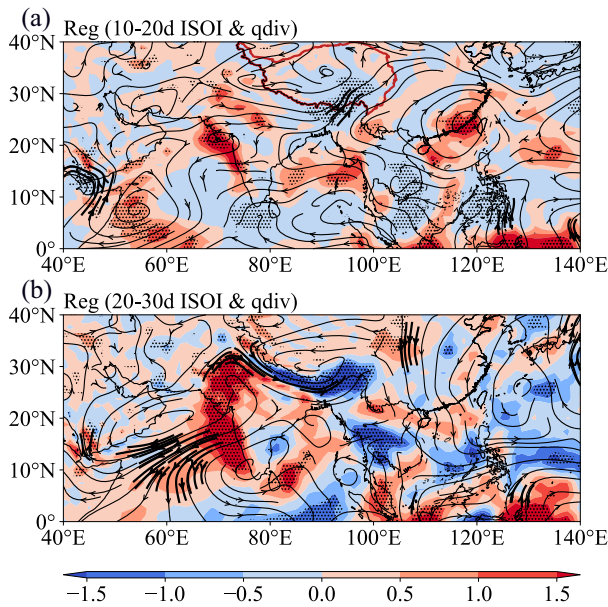


FIG. 6. The regression coefficients of the vertically integrated water vapor flux (vectors; $\text{kg m}^{-1} \text{s}^{-2}$) and moisture flux divergence ($10^{-5} \text{ kg m}^{-2} \text{s}^{-2}$) onto the (a) 10–20-day and (b) 20–30-day ISOI indices over the TP during the 42 summers from 1979 to 2020. The dotted areas and bold vectors exceed the 90% confidence level.

the southeastern TP under the dynamic effect of the cyclonic anomaly over the southern TP, serving as the key water vapor channel associated with the 20–30-day ISOI. Consequently, when the 20–30-day ISOI weakens, the slowdown of this water vapor transport with the weakening of the abnormal cyclone over the southern TP is closely tied to the reduction in precipitation over the southern TP (Figs. 3c, 5b, and 6b). Regarding the northern TP, previous studies (Chen et al. 2012; Gao et al. 2014; Zhang et al. 2019) have identified the northwestern TP, controlled by the westerly system, as a crucial water vapor source for the northern TP precipitation. However, our analysis (Fig. 6b) reveals that the southerly airflow on the eastern side of the TP, rather than the westerly, is more crucial for increasing precipitation over the northeastern TP when the ISOI weakens. Thus, the southerly airflow strengthens with the weakening in 20–30-day ISOI, transporting more water vapor from the South China Sea and the western Pacific to the northeastern TP, corresponding to enhanced moisture convergence and increased precipitation in this region.

The regressed fields of the large-scale circulations onto ISOIs of these two oscillations are given in Fig. 7. When the 10–20-day ISOI strengthens, an anomalous anticyclone over the north of the BOB is observed at the upper level, extending to the northern TP (Fig. 7a). Then, the northern TP is controlled by a robust westerly wind, leading to air divergence over the southern TP but convergence over the northeastern TP. At 500 hPa (Fig. 7e), a strong southwesterly flow extends toward the southern TP, forming a weak anomalous cyclone over the central TP and inducing significant convergence. Coupled with the divergence pattern at the upper level, the

ascending motion over the southern TP is stimulated, associated with more precipitation in this region (Fig. 7c). However, the recent 10–20-day ISOI weakens, corresponding to the downdrafts and subsequent decrease in precipitation over the southern TP. Moreover, weak anomalous divergence at lower levels and vertical motion is observed over the northern TP (Figs. 7c,e), suggesting that the 10–20-day ISOI has minimal associations with precipitation changes in this region.

Regarding the 20–30-day ISOI, because of the shallower convective activity over northern TP compared to that over southern TP, a point to be further explored in the following (Fig. 8b), the upper-level circulation is clearly presented at 300 hPa (Fig. 7b). In Fig. 7b, an anomalous cyclone covering the entire TP is squeezed by an anticyclone over southwestern China, forming a northwest–southeast tilted dipole distribution of the upper-level circulations. This configuration induces strong divergence, dispersing southerly wind over the southern TP. At 500 hPa, an abnormal cyclone over the southwestern TP extends the southerly airflow toward the southern TP, promoting significant airflow convergence (Fig. 7f). The combination of upper- and lower-level circulations leads to vigorous upward movements (Fig. 7d), being more crucial for the increased precipitation over southern TP. However, given the weakening of the 20–30-day ISOI (Fig. 3c), it is plausible that weak 20–30-day ISOI corresponds to downward motion and subsequently reduced precipitation over the southern TP. Furthermore, the divergent southerly airflow at the upper level over the southern TP migrates northward to the northern TP, resulting in convergent airflow here (Fig. 7b). At 500 hPa, the northeastern TP experiences anticyclonic circulation with divergent flows (Fig. 7f), leading to significant subsidence and reduced precipitation (Fig. 7d). Therefore, the recent actual decline in 20–30-day ISOI has a close association with the increased precipitation over the northeastern TP.

b. Different internal atmospheric dynamic mechanisms for these two oscillations

In light of the preceding investigation, it is evident that the 20–30-day ISOI is closely related to precipitation over both the southern and northeastern TPs, whereas the 10–20-day ISOI is primarily associated with precipitation over the southern TP. We will now further explore the underlying physical dynamics responsible for these differences.

Figures 8a and 8b show the regressions of the meridional circulation onto the ISOIs of 10–20-day and 20–30-day oscillations, respectively. The average longitude ranges considered are 90° – 100°E for the 10–20-day ISOI and 92.5° – 102.5°E for the 20–30-day ISOI, based on the key precipitation areas associated with the ISOI shown in Figs. 5a and 5b. Obviously, when the 10–20-day ISOI strengthens (Fig. 8a), a robust oblique updraft occurs over the southern TP, with airflow rising to approximately 300 hPa before merging into southerly airflow that exits the TP region. This indicates that there may be some interactions between the 10–20-day ISOI and the oblique vertical motion over southern TP, accompanied by evident variations in local summer precipitation. In contrast, when the 20–30-day ISOI strengthens, a vertical and deep

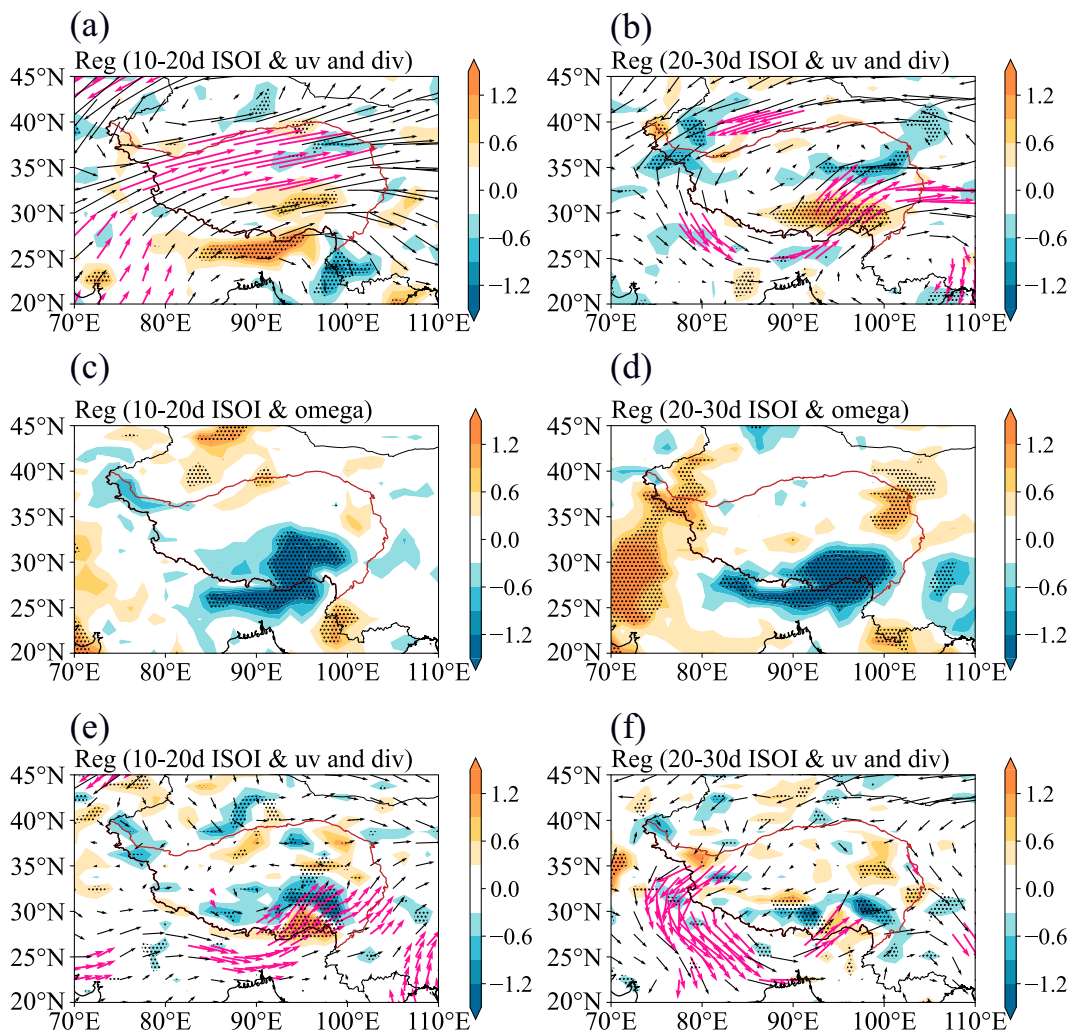


FIG. 7. As in Fig. 6, but for the wind fields (sectors; m s^{-1}) and divergence (shaded; 10^{-6} s^{-1}) at (a) 200, (b) 300, and (e), (f) 500 hPa, and the omega field (shaded; $10^{-2} \text{ Pa s}^{-1}$) at 400 hPa for (a), (c), (e) 10–20-day ISOI index and (b), (d), (f) 20–30-day ISOI index, respectively. The pink vectors and dotted areas exceed the 90% confidence level.

updraft develops over the southern TP, reaching up to around 200 hPa. Importantly, a portion of these updrafts rises to approximately 300 hPa and then flows northward to the northern TP before descending around 35°N , forming a shallow downdraft. This creates a closed meridional circulation between the northern and southern TPs (Fig. 8b). Additionally, when considering the zonal average within the longitude range of $97.5^{\circ} \sim 102.5^{\circ}\text{E}$, corresponding to the key precipitation area over the northern TP related to the 20–30-day ISOI (Fig. 5b), a more pronounced positive meridional circulation is observed, particularly evident in the downdraft over the northern TP (Fig. 8c). Clearly, this notable meridional circulation associated with the 20–30-day ISOI is closely related to the summer mean precipitation over both the southern and northeastern TPs.

Further, Fig. 9 shows the meridional–vertical structures of the regressions of the divergence and relative vorticity onto the ISOIs of two oscillations. In Fig. 9a, we find that when

10–20-day ISOI strengthens, the lower-level shallow convergence and upper-level deep divergence occur over the southern TP, corresponding well to the strengthened precipitation in this region. Additionally, the lower-level divergent airflow can be seen over the northern TP; however, there is no upper-level convergent flow appearing over the northern TP, resulting in the absence of an obvious downdraft. Meanwhile, in Fig. 9c, we can see the emergence of the lower-level positive vorticity and upper-level negative vorticity appear over the southern TP, which corresponds well to the lower-level anomalous cyclone over the central TP (Fig. 7e), promoting the increased precipitation over southern TP. However, there is no significant vorticity configuration over northern TP.

If the 20–30-day ISOI strengthens, there is an orthostatic divergence configuration favorable to the occurrence of deep convection over the southern TP, characterized by lower-level convergence and upper-level divergence (Fig. 9b). This configuration aligns well with the vorticity pattern, showing positive

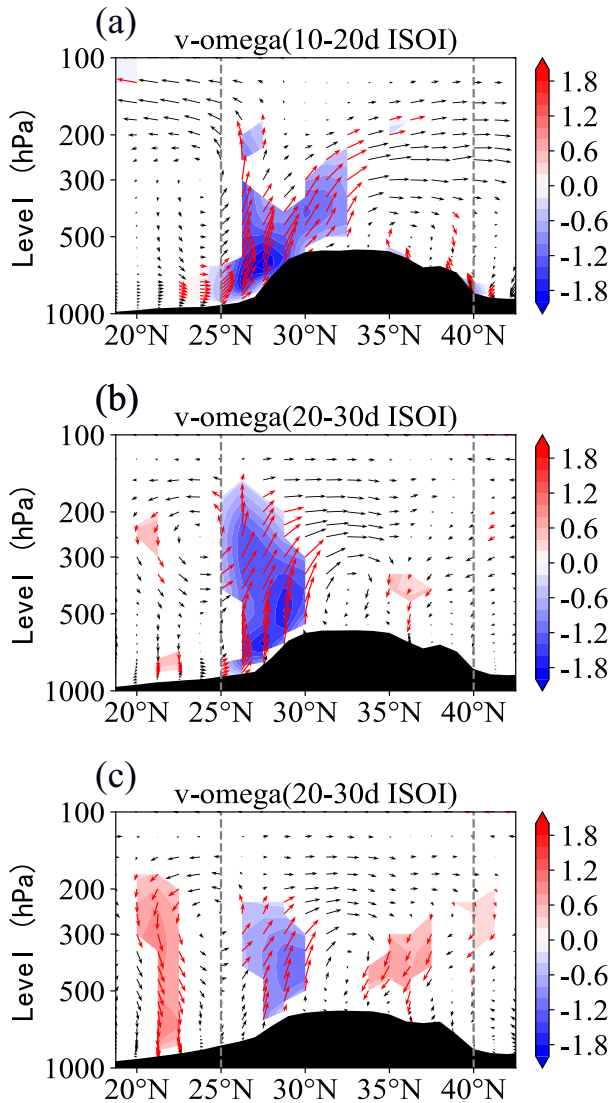


FIG. 8. As in Fig. 6, but for the meridional v (m s^{-1})–vertical ω ($10^{-2} \text{ Pa s}^{-1}$) wind speeds of (a) 90° – 100°E for the 10–20-day ISOI, (b) 92.5° – 102.5°E , and (c) 97.5° – 102.5°E for the 20–30-day ISOI, respectively. The red vectors and the shaded areas indicate the v and ω exceeding the 90% confidence level. The two gray dashed lines represent the longitudinal domain of the TP.

vorticity in the lower layer and negative vorticity in the upper layer (Fig. 9d). In contrast to the 10–20-day ISOI, significant upper-level convergence and positive vorticity appear over the northern TP when the 20–30-day ISOI strengthens, together with lower-level divergence and negative vorticity, which is connected with the downdraft and a decrease in precipitation (Figs. 9b,d).

In summary, the recent weakening of the 10–20-day ISOI has been associated with divergence and negative vorticity in the lower levels and convergence and positive vorticity in the upper layers over the southern TP. This configuration is conducive to the formation of a southward-inclined downdraft, which aligns with a reduction in precipitation. In contrast, the

recent weakening of the 20–30-day ISOI is closely linked to the formation of an orthostatic lower-upper circulation configuration over the southern TP. This configuration, characterized by divergence and negative vorticity in the lower levels and convergence and positive vorticity in the upper layers, supports the development of a vertical and deep downdraft. Simultaneously, a shallow circulation field appears over the northern TP, featuring lower-level convergence (positive vorticity) and upper-level divergence (negative vorticity), which facilitates a shallow updraft here. Consequently, an anticlockwise meridional circulation forms between the north and south of the TP, closely tied to the increased precipitation over the northern TP and decreased precipitation over the southern TP.

The question of why the rising motion associated with 10–20-day ISOI becomes tilted and moves northward, even extending to the north of the TP, while the rising motion related to 20–30-day ISOI gradually forms a complete meridional circulation, thus having intimate associations with the precipitation over the north and south sides of the TP, is crucial. Therefore, further diagnosis of the vertical motions over the southern TP stimulated by the ISOI of these two oscillations is needed according to the omega equation:

$$\frac{\left(\sigma \nabla^2 + f^2 \frac{\partial^2}{\partial p^2}\right) \omega}{A} = \frac{f \frac{\partial}{\partial p} [\mathbf{V}_g \cdot \nabla (f + \zeta_g)]}{B} - \frac{\nabla^2 \left[\mathbf{V}_g \cdot \nabla \frac{\partial \Phi}{\partial p} \right]}{C} - \frac{\frac{R}{c_p p} \nabla^2 \frac{dQ}{dt}}{D}, \quad (5)$$

where σ denotes the static stability parameter, f denotes the planetary vorticity, ∇ denotes the horizontal gradient operator, ζ refers to the relative vorticity, Φ refers to the geopotential, and Q refers to the nonadiabatic heating. Term A represents the Laplace of vertical velocity and is proportional to $-\omega$; term B mainly depends on the variations of horizontal relative vorticity advection with height $[-(\partial/\partial p)(-\mathbf{V}_g \cdot \nabla \zeta_g)]$; term C is the Laplace of temperature advection and is proportional to the horizontal temperature advection $(-\mathbf{V}_g \cdot \nabla T)$; and term D represents the Laplace of nonadiabatic heating and is proportional to the variations of Q with time dQ/dt .

Obviously, significant positive relative vorticity advection is observed around 200 hPa over the southern TP, while negative relative vorticity advection is evident over the northern TP when 20–30-day ISOI strengthens (Fig. 10b). The absolute value of positive (negative) relative vorticity advection increases with height, promoting ascending (descending) motion [Eq. (5)]. This indicates that vorticity advection in the upper troposphere is a crucial factor for stimulating a complete meridional circulation, associated with the dipole distribution of precipitation variations over the TP when the 20–30-day ISOI enhances. However, corresponding to the enhancement of 10–20-day ISOI, the vorticity advection has no significant distribution. Additionally, positive temperature advection can increase local temperature and promote ascending motion, as indicated by the omega Eq. (5) in term C. As

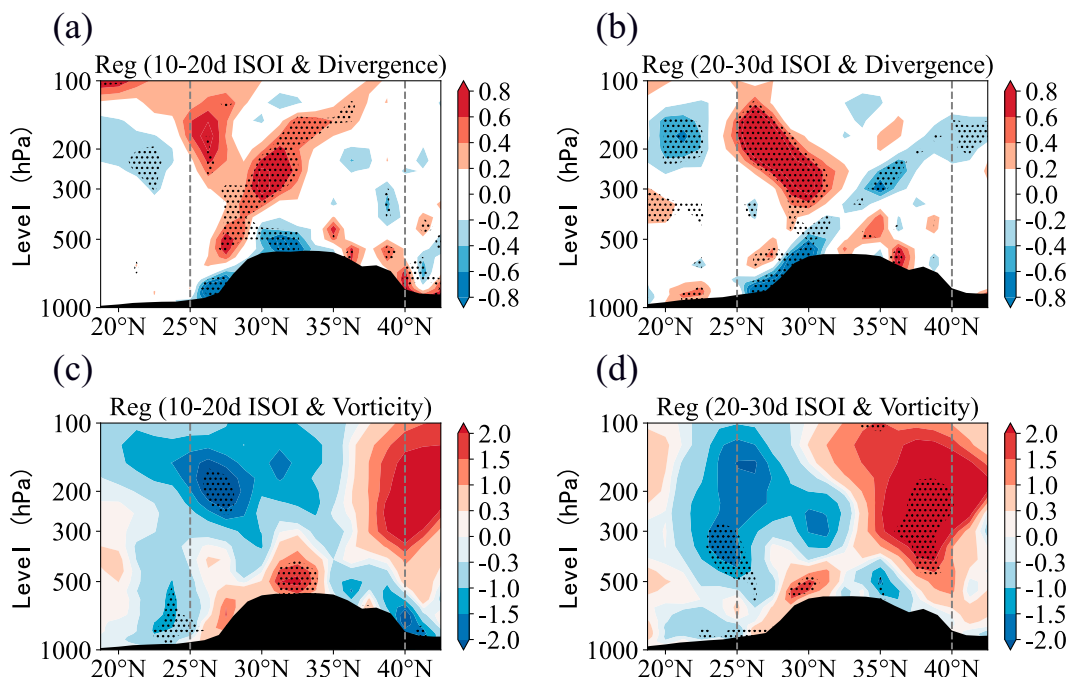


FIG. 9. Meridional-vertical structures of the regressions of divergence (10^{-6} s^{-1}) and vorticity (10^{-6} s^{-1}) onto (a),(c) 10–20-day and (b),(d) 20–30-day ISOI indices. The dotted areas exceed the 90% confidence level, and the two gray dashed lines represent the longitudinal domain of the TP.

in Fig. 10c, positive temperature advection over the south of the TP tilts northward with height extending to the north of the TP region, especially prominent in the midlevel and upper level, guiding an oblique updraft over the southern TP (Fig. 8a), but in Fig. 10d, positive temperature advection is more upright extending to approximately 300 hPa and then moving northward, leading to an airflow diverging from the vertical and deep updraft and moving northward as it rises at 300 hPa, corresponding well to Fig. 8b. This suggests that positive temperature advection in middle and upper layers of the troposphere plays a significant role in affecting vertical motion over the southern TP when the ISOI of the two oscillations strengthens. Regarding term D of the omega equation, positive dQ/dt will boost the occurrence of ascending motion. Specifically, in Fig. 10e, when 10–20-day ISOI enhances, the positive dQ/dt tilts from the south of the TP to the southern TP particularly below 400 hPa, which is conducive to the tilted updraft (Fig. 8a). However, it is straighter over the southern slope of the TP in the lower troposphere with 20–30-day ISOI enhancing (Fig. 10f), facilitating the formation of the vertical updraft there (Fig. 8b).

In short, the recent weakening of the 10–20-day ISOI is associated with negative temperature advection in midlevel and upper level and negative dQ/dt in the lower levels, which tilts southward with decreasing height and facilitates a southward-inclined downdraft over the southern TP. However, when the 20–30-day ISOI weakens, a north–south distribution of relative vorticity advection occurs in the upper troposphere, with positive relative vorticity advection over the northern TP and negative relative vorticity advection over the southern TP. This results in an updraft over the northern TP and a downdraft over

the southern TP. Additionally, guided by negative temperature advection near 300 hPa, a northerly airflow converges into the downdraft over the southern TP. Coupled with negative dQ/dt in the lower troposphere, this enhances the downdraft. Consequently, an anticlockwise meridional circulation forms between the northern and southern TPs, corresponding to increased precipitation over the northern TP and decreased precipitation over the southern TP.

6. Summary and discussion

Using JRA-55 reanalysis data and CN05.1 precipitation data from 1979 to 2020, we analyzed the characteristics of the variations in summer $\langle Q_1 \rangle$ ISOI of 10–20-day and 20–30-day signals over the TP. Meanwhile, we also examined the relationship between ISOIs of two oscillations and local summer mean precipitation, along with the associated mechanisms. The main conclusions are as follows:

- 1) The ISOI over the TP exhibits significant interannual and decadal variations. In addition, both the 10–20-day and 20–30-day ISOIs have notably weakened in the past 40 years, with the weakening of the 20–30-day ISOI being more widespread, especially over the southern TP. Additionally, the variations of TP ISOIs are significantly related to the frequency of ISO events propagating northward from low latitudes. The 10–20-day ISOI is closely associated with northward ISO events on multiple time scales, while the 20–30-day ISOI is primarily linked to the decadal variations in the frequency of these northward ISO events.

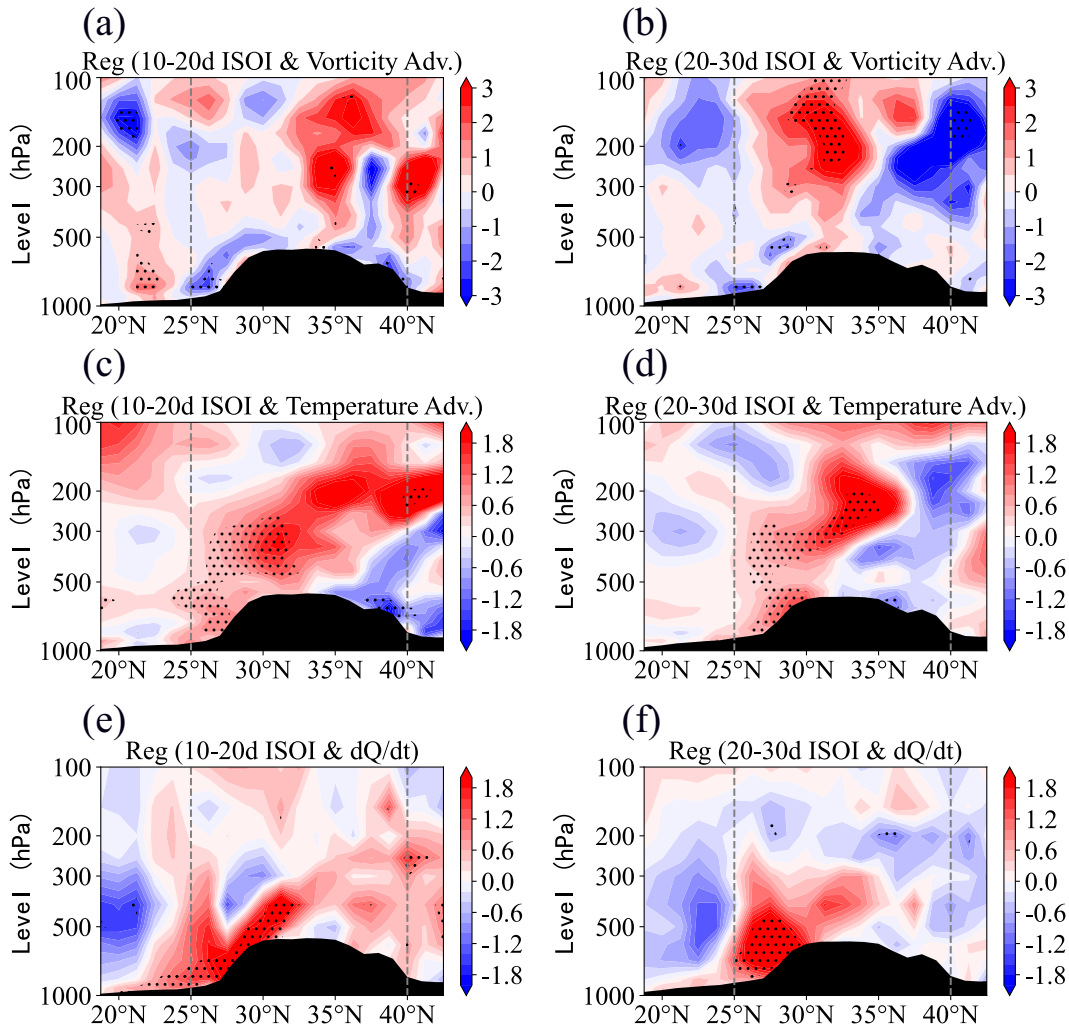


FIG. 10. As in Fig. 9, but for the (a),(b) horizontal relative vorticity advection (10^{-11} s^{-2}), (c),(d) horizontal temperature advection (10^{-6} K s^{-1}), and (e),(f) variations of nonadiabatic heating with time ($10^{-4} \text{ W m}^{-2} \text{ s}^{-1}$). The dotted areas exceed the 90% confidence level, and the two gray dashed lines in (a)–(f) represent the longitudinal domain of the TP.

- 2) Recent variations of TP ISOI are closely related to the north–south reversed changes in summer mean precipitation over the TP. When the 10–20-day ISOI weakens (strengthens), summer precipitation decreases (increases) over the southern TP. In contrast, when the 20–30-day ISOI weakens (strengthens), it is associated with reduced (increased) precipitation in the southern TP and increased (decreased) precipitation in the northern TP.
- 3) Mechanistically, when the 10–20-day ISOI weakens (Fig. 11a), the lower-level northeast airflow over the southern TP suppresses water vapor convergence from BOB and the Arabian Sea. An abnormal anticyclone over the central TP enhances divergence over the southern TP. Additionally, an anomalous cyclone in the upper layer north of the BOB induces easterly flow over the northern TP, which thereby boosts air convergence over the southern TP. These large-scale circulation patterns in both the upper and

- lower layers facilitate the downdrafts over the southern TP, corresponding to decreased precipitation there.
- 4) In recent years, as the 20–30-day ISOI has weakened (Fig. 11b), enhanced easterly flow over the southern TP has resulted in greater water vapor loss. Simultaneously, strengthened southerly flow over the eastern side of the TP has increased water vapor transport from the South China Sea and western Pacific to the northeastern TP. An abnormal lower-level anticyclone over the southwestern TP has strengthened northerly flow over the southern TP, promoting divergence. In the upper layer, a north–south dipole pattern with an anticyclone over the northeastern TP and a cyclone over the southwestern China has increased airflow convergence over the southern TP and divergence over the northeastern TP. These combined upper- and lower-level circulation patterns create an anticlockwise meridional circulation between the northern and southern TPs, being

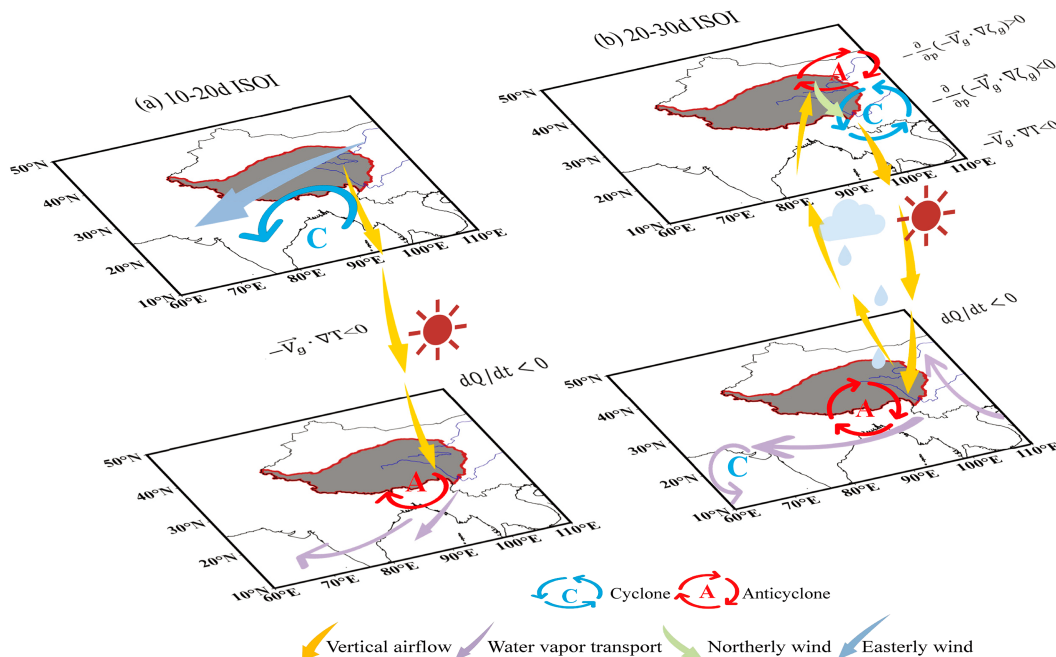


FIG. 11. Schematic diagram showing the variations in summer mean precipitation over the TP when the (a) 10–20-day and (b) 20–30-day $\langle Q_1 \rangle$ ISOI weakened in recent years, the key circulation systems, and physical processes.

closely related to the increased precipitation in the north-eastern TP and decreased precipitation in the southern TP.

- 5) Further diagnostics reveal that when the 10–20-day TP ISOI weakens (Fig. 11a), negative temperature advection in the midlevel and upper levels, along with negative dQ/dt in the lower levels, tilts southward with decreasing height. This configuration is conducive for the downdraft over the southern TP. In contrast, when the 20–30-day TP ISOI weakens (Fig. 11b), positive relative vorticity advection develops in the upper levels over the northern TP, while negative relative vorticity advection occurs over the southern TP. This pattern stimulates an updraft over the northern TP and a downdraft over the southern TP. Additionally, negative temperature advection near 300 hPa directs a northerly airflow converging into this downdraft over the southern TP. Coupled with negative dQ/dt in the lower levels, this strengthens the downdraft, forming an anticlockwise meridional circulation between the northern and southern TPs.

This study mainly focuses on the variations in summer ISOI of two different oscillations over the TP in the past 40 years and provides a detailed analysis of their relationships with local summer mean precipitation. The large-scale circulations and the critical vertical motions associated with these two ISOIs exhibit distinct performances, but why do these discrepancies arise? In our study, there is a significant positive correlation between the 10–20-day TP ISOI time series and the frequency of northward propagation events. Thus, the meridional transportation from low latitudes to TP should be a crucial process leading to the intensification of 10–20-day TP ISOI. This will inevitably go along with some specific characteristics of the circulation patterns: the robust southwest airflows over southeastern TP in the

lower layer (Fig. 7e), the declining updraft from lower latitudes to southern TP (Fig. 8a), and the oblique temperature advection and dQ/dt during the underlying physical process (Figs. 10c,e). All of these reflect the prominent interaction between low latitudes and the TP.

Conversely, for the 20–30-day ISOI, the positive correlation between it and the number of northward ISO events is only obvious on the interdecadal scale. The pronounced cyclonic abnormal over the southwestern TP in the lower layer (Fig. 7f), the upright updraft over southern TP (Fig. 8b), the upper-level noticeable vorticity advection, and the erect temperature advection and dQ/dt (Figs. 10b,d,f) all mean that the local dynamic effects of the TP itself may be more important for the relation of 20–30-day ISOI with summer mean precipitation. Therefore, the root causes behind these different circulation patterns analyzed in this study are primarily determined by the inherent characteristics of these two oscillations, including their propagation frequency and intensity, and maybe their different origins and propagating pathways. Many studies have characterized the 10–20-day oscillation over the TP, including its propagation path, source region, and physical mechanisms (Wang and Duan 2015; Hu et al. 2016; Zhong et al. 2020). However, the propagation characteristics of the 20–30-day oscillation over the TP remain less clear, necessitating further research. In addition, the relationship between ISOI and summer mean fields is complicated involving interactions between different time scales, and more physical processes about energy conversion also need to be further explored.

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Data availability statement. The JRA-55 reanalysis data can be freely accessed on the website <https://rda.ucar.edu/dssearch/?words=Jra55>. The daily precipitation CN05.1 can be freely accessed on the website <https://ccrc.iap.ac.cn/resource>. The radiation flux data GEWEX-SRB can be freely accessed on the website https://opendap.larc.nasa.gov/opendap/SRB/GEWEXSRB_Rel4-IP/Longwave_monthly_landonly_utc_1/1987/contents.html.

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