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Enhanced impacts of the North Pacific Victoria mode on the Indian summer monsoon onset in recent decades

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Abstract

Victoria mode (VM), the second dominant mode of North Pacific sea surface temperature variability, has been identified as one of the important factors influencing the Indian summer monsoon (ISM) onset. The positive phase of the May VM delays the ISM onset by both tropical and extratropical pathways. Here, we found a significant interdecadal enhancement of their relationship since the early 1990s, which is mainly attributed to the structure changes and increased variance of the VM. In recent decades, the VM has shown more significant warm SST anomalies in the tropical central Pacific, which drive the large-scale divergent circulation more effectively. This enhanced divergent circulation leads to low-level divergence and reduced rainfall in the tropical Asian summer monsoon region. The reduced rainfall excites equatorial Rossby wave response and anomalous easterly winds in the northern Indian Ocean, delaying the ISM onset. Besides, the increased variance of the VM after 1992/1993 stimulates a stronger extratropical Rossby wave train. This stationary Rossby wave train induces a stronger cooling to the northwest of India, which weakens the land-sea thermal contrast and leads to the delayed ISM onset. This finding should be taken into account to improve short-term predictions of the monsoon onset.

Keywords Victoria mode, Interdecadal change, Indian summer monsoon, Monsoon onset

Introduction

The onset of the summer monsoon is a significant event in its seasonal march, marking the large-scale switch in atmospheric circulation from the winter to the summer type (Bombardi et al. 2019, 2020; Chen et al. 2023; Hu et al. 2022b, 2022c; Liu and Duan 2023). The onset of the Indian summer monsoon (ISM) typically occurs in late May and early June (Bombardi et al. 2019; Hu et al. 2022b; Liu and Duan 2023), making the end of the dry season and the beginning of the rainy season, impacting over one billion individuals in the region (Bombardi et al. 2020; Hu et al. 2022c; Wang et al. 2009; Zhang et al. 2024). Changes in ISM onset can be indicative of total monsoonal rainfall (Hu et al. 2022c; Noska and Misra 2016), which is defined as the cumulative rainfall during the entire summer monsoon season (i.e., from monsoon onset to withdrawal). Monsoon onset and total monsoonal rainfall can improve our understanding of the ISM variability and mechanisms. For example, the El Niño-Southern Oscillation (ENSO) is generally considered to be the most dominant factor influencing the ISM (Chen et al. 2023; Hu et al. 2022c; Kumar et al. 1999, 2006). However, the relationship between ENSO

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and the total rainfall during a fixed monsoon season from June to September is not stable, which weakened after the late 1970s (Kumar et al. 1999, 2006; Yang and Huang 2021) and recovered after the early 2000s (Hu et al. 2022c; Yang and Huang 2021; Yu et al. 2021a, 2021b). Meanwhile, after considering the year-to-year variation of ISM onset, the linkage between ENSO and the total monsoonal rainfall has remained stable over the last four decades (Hu et al. 2022c).

The ISM onset is a topic of great importance, which has been extensively researched to identify the factors and mechanisms that influence it (Bombardi et al. 2020; Hu et al. 2022b; Wang et al. 2009; Yu et al. 2021a, 2021b). Previous studies revealed that both tropical and extratropical factors can modulate the variability of the ISM onset. For example, the tropical intraseasonal oscillations are recognized as prominent triggers of the ISM onset, which are more likely to occur during the westerly phase of the 30–60-day oscillation (Hu et al. 2022b; Wang et al. 2009) and the 10–25-day oscillation (Lee et al. 2013; Qian et al. 2019). Besides, a preceding La Niña event tends to be followed by an advanced ISM onset, while the winter El Niño is likely to be succeeded by a delayed monsoon onset (Hu et al. 2022b, 2022c; Joseph et al. 2006; Zhang et al. 2024). ENSO modulates the ISM onset mainly via the anomalous Walker circulation, the western North Pacific anticyclone, and the tropospheric temperature (Hu et al. 2022b; Zhang et al. 2024). In addition to the above tropical factors, recent studies find that extratropical factors like Pacific Decadal Oscillation (PDO) and Victoria Mode (VM) can also affect the ISM onset (Chen et al. 2023; Hu et al. 2023, 2022b; Zhang et al. 2024). The PDO and VM are the first (Liu and Lorenzo 2018; Newman et al. 2016) and second (Ding et al. 2015; Li et al. 2023) dominant modes of the sea surface temperature (SST) anomalies in the extratropical North Pacific Ocean, respectively. The PDO and VM are linearly independent of each other, and both can influence ISM onset through the large-scale divergent circulation and the stationary Rossby wave train (Hu et al. 2023, 2022b; Zhang et al. 2024).

Specifically, Zhang et al. (2024) reported that the VM-associated SST gradient can cause low-level divergence and decreased rainfall over the Indo-China Peninsula, which further excites the equatorial Rossby wave response and anomalous easterly winds over the Northern Indian Ocean. In addition, the VM can also induce an extratropical Rossby wave train that results in cold surface temperature and tropospheric temperature (TT) to the northwest of India, thereby reducing the climatological land-sea thermal contrast (Zhang et al. 2024). Due to the anomalous easterly winds and reduced land-sea thermal contrast, the ISM onset tends to be delayed during the positive phase of the VM (Zhang et al. 2024). However, the relationship between SST anomalies in the Pacific Ocean and ISM is often subject to interdecadal changes (Kumar et al. 1999; Yang and Huang 2021; Yu et al. 2021a, 2021b). It remains elusive whether the impacts of VM on ISM onset also exhibit interdecadal shifts. Based on the recent work of Zhang et al. (2024), this manuscript will analyze the strengthening relationship between VM and ISM onset in recent decades, as well as the possible mechanisms. This manuscript can potentially improve our knowledge of the ISM-SST relationship and also provide suggestions for short-term climate prediction.

Data and methods

The major datasets employed in this study include: (a) ISM onset date derived from the Indian Meteorological Department (Joseph et al. 2006; Pai and Rajeevan 2009; Wang et al. 2009), (b) Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) data (Rayner et al. 2003), (c) Precipitation Reconstruction (PREC) data (Chen et al. 2002), and (d) National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996). The horizontal resolution for the NCEP/NCAR and PREC data is $2.5^{\circ}\times2.5^{\circ}$, and for the HadISST data is $1.0^{\circ}\times1.0^{\circ}$. All these observational and reanalysis datasets cover the analysis period of 1948–2022.

As in previous studies, the VM is defined as the second empirical orthogonal function (EOF2) of the North Pacific SST anomalies (20.5°–65.5°N, 123.5°–260.5°E) (Bond et al. 2003; Ding et al. 2015; Li et al. 2023). Thus the corresponding principal component (PC2) is recognized as the VM index (Zhang et al. 2024). The statistical significance of the linear regression and correlation are estimated by the Fisher z-transformation (e.g., Li and Thompson 2021). Following previous studies, this manuscript mainly focused on the monthly mean field of May, during which the winter-to-summer transition of the Asian summer monsoon occurs (Hu et al. 2023, 2022b; Watanabe and Yamazaki 2014; Xiang and Wang 2013; Zhang et al. 2024).

Results

Figure 1a shows the time series of the ISM onset and the VM index in May, which is more closely linked to the monsoon onset than other months (Zhang et al. 2024). Generally, the VM is positively linked to the ISM onset, with a correlation coefficient of 0.28 during 1948–2022, which is significant at the 95% confidence level. Figure 1b further presents the 17-year running correlation between the VM and the ISM onset, which

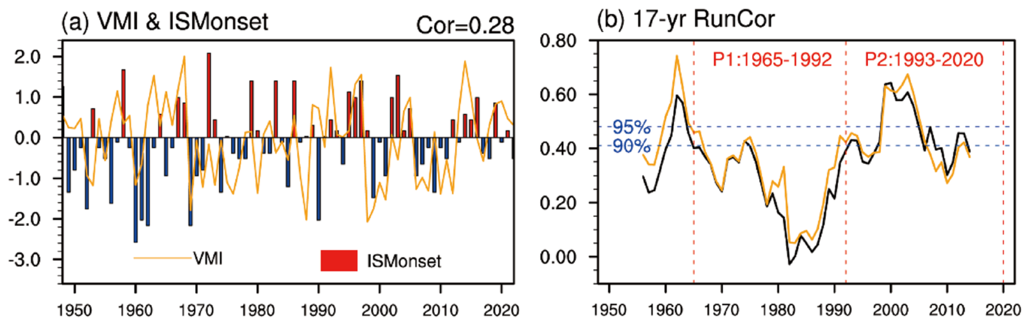

Fig. 1 **a** The normalized time series of ISM onset date (bars) and VM index in May (curve). **b** The 17-year running correlation between the ISM onset date and the VM index, and the 17-year running partial correlation after removing the ENSO in the preceding winter. The horizontal dashed lines highlight the 90% and 95% confidence levels, respectively. The vertical dashed lines denote the two periods of 1965–1992 and 1993–2020

exhibits remarkable interdecadal changes. Specifically, the linkage between VM and monsoon onset is rather weak before the early 1990s, except for a short period around early-1960s. Meanwhile, the relationship between VM and ISM onset has been strengthening in recent decades, especially after 1992/1993. Notice that this interdecadal change in their relationship is largely independent of the preceding ENSO, as revealed by the running partial correlation analysis (Fig. 1b). In order to investigate the interdecadal shift in the VM-ISM onset linkage, this manuscript mainly focused on two periods of equal length, namely, 1965–1992 and 1993–2020. During the earlier period (1965–1992), the correlation coefficient between VM and ISM onset is 0.24 and is statistically insignificant. In contrast, for the second period of 1993–2020, the correlation is 0.50 and is significant at the 95% confidence level. These results suggest that the linkage between VM in May and the ISM onset is much stronger in recent decades, and the former can serve as a useful and effective predictor for the monsoon onset.

Figure 2a shows the correlation map between the VM index and the Pacific SST anomalies in May. As in previous studies, the VM is featured by tripole-like SST anomalies in the Tropical and North Pacific (Bond et al. 2003; Ding et al. 2015; Li et al. 2023; Zhang et al. 2024). Namely, there appears anomalous cold SST around 20°–35°N sandwiched by anomalous warm SST to the north (poleward of 40°N) and south (equatorward of 20°N). This anomalous SST pattern resembles the SST anomalies correlated with the ISM onset, which is shown in Fig. 2b. However, the Pacific SST anomalies associated with ISM onset exhibit remarkable interdecadal changes, which are rather weak and insignificant during 1965–1992 but become obvious and significant during 1993–2020 (Figs. 2c and 2d). This is consistent with the strengthening relationship between ISM onset and VM in recent decades shown in Fig. 1b.

A more important scientific question is why the impacts of VM on ISM onset have been stronger in recent decades. As revealed by Zhang et al. (2024), the VM can modulate the monsoon onset via a tropical pathway that involves large-scale divergent circulation and equatorial Rossby wave response. Figure 3 shows the low-level velocity potential associated with the North Pacific VM in May during different periods. Corresponding to the positive phase of the VM, there appears anomalous low-level convergence over the tropical central-eastern Pacific. Such low-level convergence is associated with the warm SST anomalies underneath, and can lead to low-level divergence around the Indo-China Peninsula and South China Sea via the large-scale divergent circulation (Hu et al. 2022a; Zhang et al. 2024). However, such divergent circulation is weak during the earlier period (1965–1992), since the low-level convergence is mainly confined to the tropical eastern North Pacific, and the low-level divergence is weak and insignificant over the western North Pacific (Fig. 3b). In contrast, for the recent period of 1993–2020, there appears strong and significant low-level convergence over the entire tropical eastern Pacific, as well as obvious and remarkable low-level divergence over the tropical Asian region extending from the Arabian Sea to the Philippine Sea (Fig. 3c).

The stronger low-level divergence associated with the North Pacific VM in recent decades is favorable for the reduced rainfall over the tropical Asian region. This statement is confirmed by Fig. 4, which shows the correlation map between the North Pacific VM and the precipitation as well as low-level winds in different periods. The reduced rainfall associated with the large-scale divergent circulation excite equatorial Rossby waves to the west (Gill 1980; Hu et al. 2024; Matsuno 1966), resulting in anomalous easterly winds over the North Indian Ocean (Fig. 4). Such easterly wind anomalies can hinder the steady establishment of the monsoonal southwesterly winds, thereby delaying the

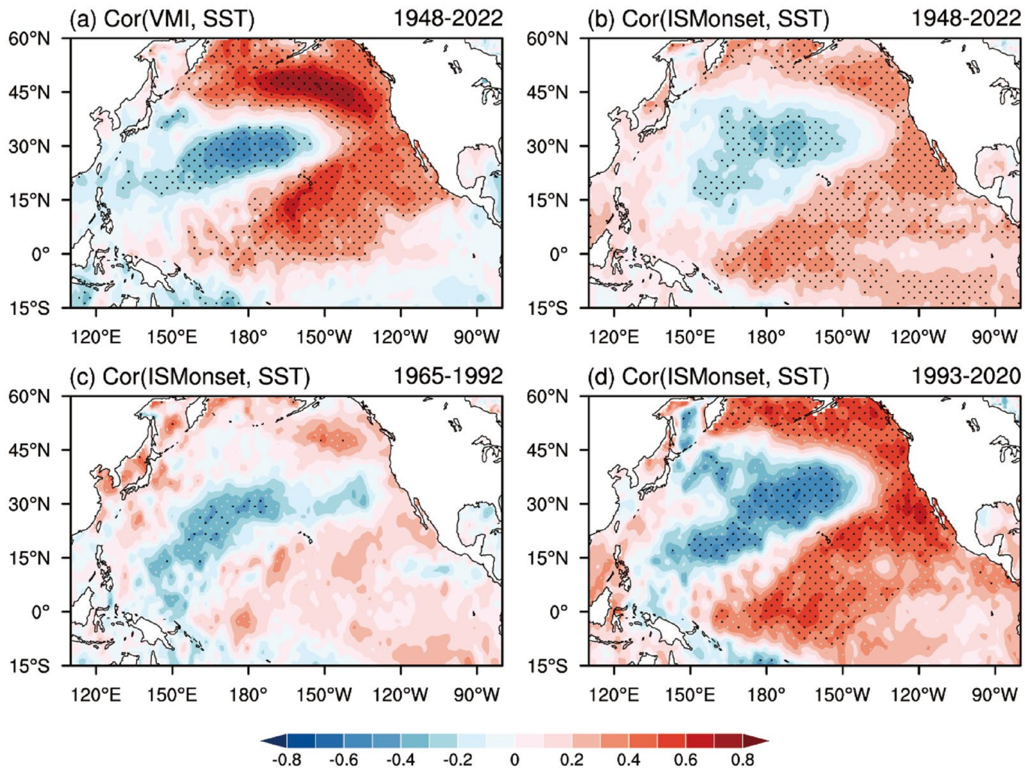

Fig. 2 The correlation coefficient between **a** the VM index and the SST anomalies in May and **b** the ISM onset date and the SST anomalies in May during the entire period of 75 years (1948–2022). **c** and **d** is the same as (**b**), but for the earlier period (1965–1992) and the recent period (1993–2020), respectively. The gray and black dots highlight correlation coefficients that are significant at the 90% and 95% confidence levels, respectively

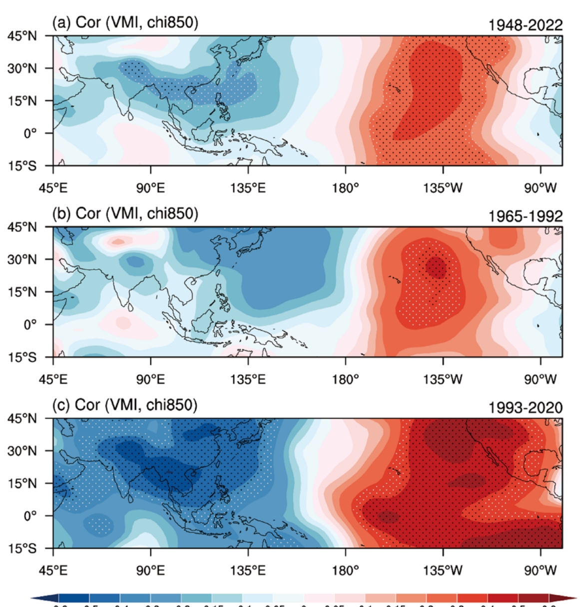

Fig. 3 The correlation coefficient between the VM index and the velocity potential at 850 hPa in May during **a** 1948–2022, **b** 1965–1992, and **c** 1993–2020. The gray and black dots highlight correlation coefficients that are significant at the 90% and 95% confidence levels, respectively

ISM onset. However, due to the weaker (stronger) large-scale divergent circulation in the earlier (recent) period, the reduced rainfall and anomalous easterly winds are also weaker (stronger), which can partly explain the interdecadal shift in the VM-ISM onset relationship.

In addition to the above tropical pathway (divergent circulation and equatorial Rossby wave), Zhang et al. (2024) also reported another pathway involves the extratropical Rossby wave train. As shown in Fig. 5, the North Pacific VM is associated with alternative warm and cold TT in the Northern Hemisphere. For example, corresponding to the cold and warm SST anomalies underneath (Fig. 2), there appears cold and warm TT over the mid-latitude North Pacific and the Bering Sea and around Hawaii, respectively. Besides, the cold TT anomalies over Canada and to the northwest of India are also apparent (Fig. 5). Notice that the ISM is largely driven by the land-sea thermal contrast, namely, the warm Eurasian continent against the cold Indian Ocean (Chen et al. 2019; Chen et al. 2023; Hu et al. 2023, 2022b). The cold TT anomalies to the northwest of India weaken this climatological land-sea thermal contrast, thereby leading to the delayed ISM onset. Although the cold TT anomalies to the northwest of India are apparent in

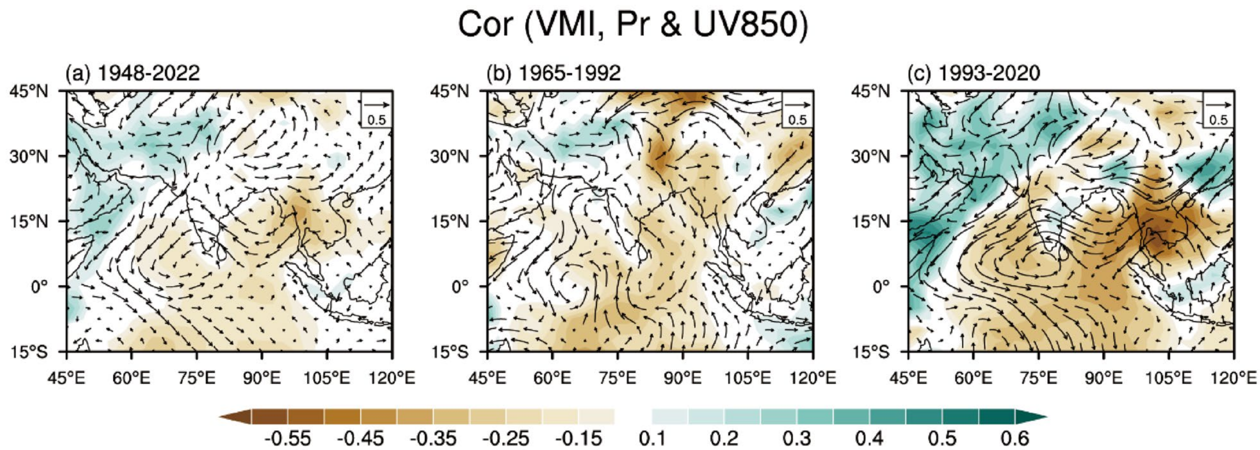

Fig. 4 The correlation coefficient between the VM index and the precipitation (shadings) and winds at 850 hPa (vectors) in May during **a** 1948–2022, **b** 1965–1992, and **c** 1993–2020

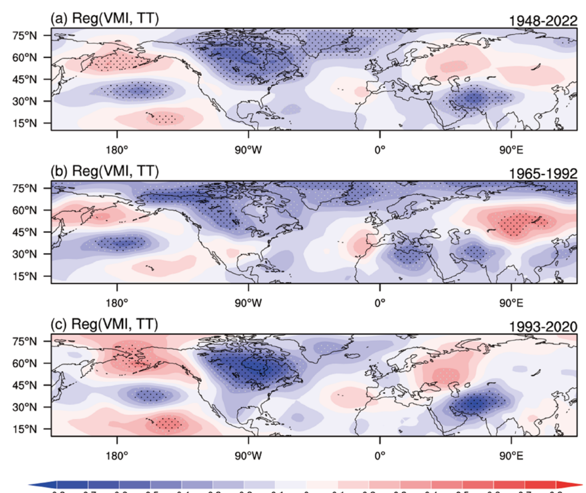

Fig. 5 The anomalous TT regressed onto the normalized VM index in May during **a** 1948–2022, **b** 1965–1992, and **c** 1993–2020. The gray and black dots highlight regression coefficients that are significant at the 90% and 95% confidence levels, respectively

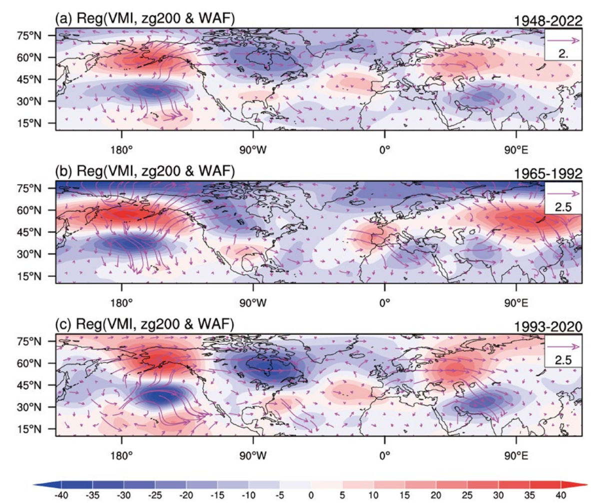

Fig. 6 The anomalous geopotential height at 200 hPa regressed onto the normalized VM index in May during **a** 1948–2022, (**b**) 1965–1992, and (**c**) 1993–2020. The vectors are the associated wave activity flux

both periods, it is much stronger in the recent period of 1993–2020. This feature is consistent with the enhanced VM-ISM onset linkage after 1992/1993.

As reported by Zhang et al. (2024), the warm and cold TT anomalies shown in Fig. 5 are the result of the extratropical Rossby wave train excited by the North Pacific VM. Thus Fig. 6 further shows the upper-level geopotential height anomalies regressed onto the normalized VM index in May, which corresponds well to the TT anomalies. During the positive phase of the North Pacific VM, there appears increased (decreased) geopotential height anomalies over the Bering Sea (mid-latitude North Pacific), which resemble the Western Pacific teleconnection pattern (Aru et al. 2021, 2022). The associated wave activity flux (Takaya and Nakamura 2001) indicates a stationary Rossby wave train that originates from the North Pacific, passes through North America, the North Atlantic Ocean, and Europe, and finally reaches the northwest of India. However, compared to the earlier period (1965–1992), the stationary Rossby wave train is more apparent in the recent period (1993–2020), which is consistent with the stronger cold TT anomalies shown in Fig. 5. Thus, the extratropical pathway can also explain the relationship between VM and ISM onset being more pronounced in recent decades.

The above analysis confirms that the impacts of the North Pacific VM on the ISM onset have strengthened significantly in recent decades, as both the tropical and extratropical pathways have become stronger. The enhanced large-scale divergent circulation and stationary Rossby wave train can be considered as the direct causes, however, what are the root causes of this strengthened VM-ISM onset relationship? To answer this question, Fig. 7 shows the Pacific Ocean SST anomalies associated with VM in these two periods. The SST anomalies of these two periods are markedly different, mainly in their structure and strength. Compared to the earlier period, the warm SST anomalies in the equatorial central Pacific become more apparent and significant. These warm SST anomalies are more favorable for generating low-level convergence, which can effectively drive the large-scale divergent circulation, consistent with the results shown in Fig. 3.

In addition, the amplitude of the warm SST anomalies also increased in the recent period (Fig. 7b) than in the earlier period (Fig. 7a). Figure 7c further shows the 17-year running variance of the North Pacific VM, which also exhibits remarkable interdecadal changes. Notice that the earlier period is featured not only by a weaker VM-ISM onset relationship, but also by weaker VM variance. Meanwhile, the recent period exhibits a stronger linkage between VM and monsoon onset, as well as stronger VM variance. Figure 7d examines the relationship between the 17-year running variance (Fig. 7c) and the running correlation (Fig. 1b), which shows a significant positive correlation. Namely, when the variance of the VM is stronger, its relationship with ISM onset is also stronger. Therefore, the enhanced variance of the VM in recent decades may also contribute to the strengthened VM-ISM onset relationship.

Summary and discussion

The onset of the ISM signifies the arrival of the rainy season and largely indicates the total monsoonal rainfall. Previous studies mainly focused on the tropical factors (e.g., ENSO) modulating the monsoon onset, however, recent studies revealed that extratropical factors like PDO and VM were also important. For example, Zhang et al. (2024) reported that the VM in May can affect the ISM onset via tropical (divergent circulation and equatorial Rossby wave) and

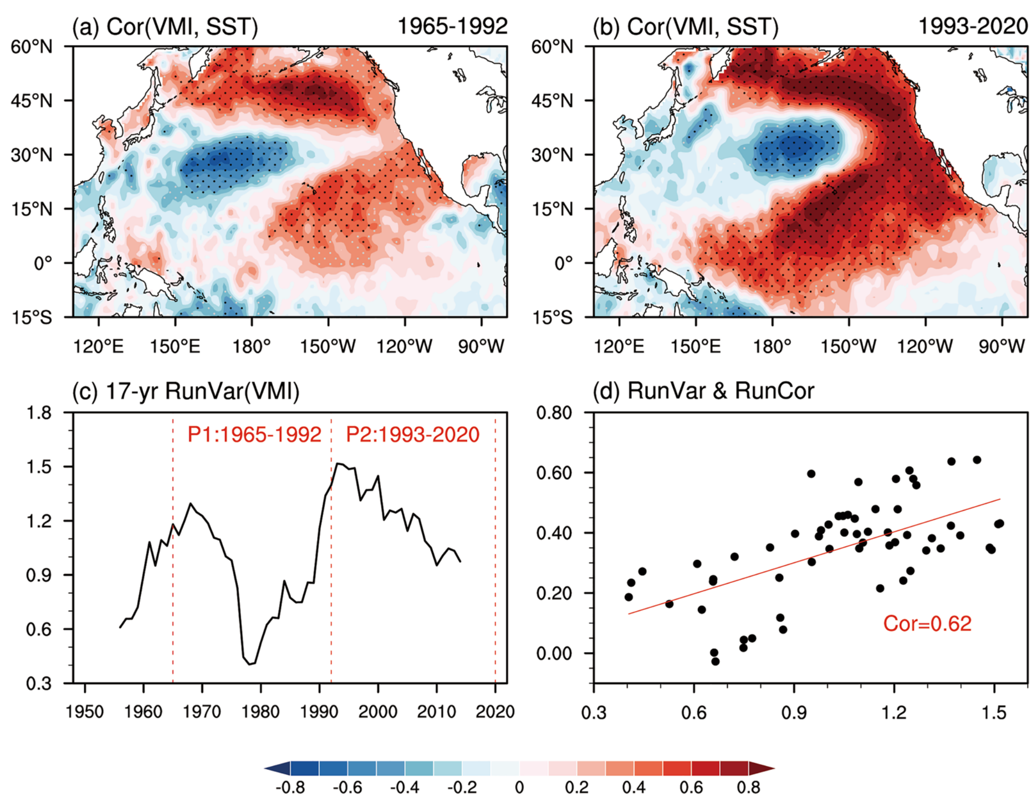

Fig. 7 The correlation coefficient between the VM index and the SST anomalies in May during **a** 1965–1992 and **b** 1993–2020. The gray and black dots highlight correlation cofficents that significant at the 90% and 95% confidence levels, respectively. **c** is the 17-year running variance of the VM index in May. **d** is a scatter of the 17-year running variance of VM index (**c**) and the 17-year running correlation between VM and ISM onset (Fig. 1b)

extratropical (stationary Rossby wave train) pathways. On this basis, this manuscript investigates the interdecadal shift in the VM-ISM onset relationship, as well as the underlying mechanisms.

Recent decades have witnessed an enhancement in the impacts of the North Pacific VM on the ISM onset, which is possibly due to the changes in VM structure and variance. Compared to the earlier period (1965–1992), the VM exhibits more pronounced warm SST anomalies in the tropical central Pacific, which can more effectively drive the large-scale divergent circulation. Such enhanced divergent circulation in recent decades is more favorable to producing low-level divergence in the tropical Asian summer monsoon region, causing a decrease in rainfall. This reduced rainfall can further stimulate an equatorial Rossby wave response, causing anomalous easterly winds that prevent the establishment of the monsoonal southwesterly winds and ISM onset. In addition, the increased variance of the North Pacific VM in recent decades can excite a stronger extratropical Rossby wave train, which produces a stronger cooling to the northwest of India. Such cooling anomalies weaken the climatological land-sea thermal contrast and contribute to the delayed ISM onset.

The enhanced impacts of the North Pacific VM in recent decades suggest that its important role should be taken more into account when considering short-term climate predictions of the ISM onset. However, this manuscript mainly considered the influences of VM, an extratropical factor, on the monsoon onset. Future work needs to analyze the joint role of tropical and extratropical factors on the monsoon onset (Hu et al. 2022b; Yu et al. 2021a, 2021b; Zhang et al. 2024). In addition, this manuscript attributes the interdecadal shift of the VM-ISM onset relationship to the increased variance of VM in recent decades, which still needs to be further investigated. The North Pacific VM can be driven by a number of factors, such as the North Pacific Oscillation, Kuroshio–Oyashio Extension, ENSO, and Tibetan Plateau thermal forcing (Ding et al. 2015; Li et al. 2023; Yu et al. 2022). Recently, Yeh et al. (2018) and Tian et al. (2024) revealed that the southern lobe of the NPO shifted eastward after the mid-1990s, which led to stronger northeasterly trade winds in the subtropical regions. These enhanced trade winds can stimulate more efficient wind-evaporation-SST feedback (Yeh et al. 2018; Tian et al. 2024), thus may contribute to the enhanced variance of VM in recent decades. In addition to the SST anomalies, the changes in the atmospheric basic flow (Figure not shown) may also modulate the extratropical Rossby wave train, thus also contribute to the interdecadal change in the VM-monsoon onset relationship.

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Author contributions
SZ and XQ conceived the study and wrote the initial manuscript in discussion with all the other authors. SZ contributed to the data analysis and generated all the figures. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
The Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) data is available from http://www.metoffice.gov.uk/hadobs/hadisst. The Precipitation Reconstruction (PREC) data is available from https://www.psl.noaa.gov/data/gridded/data.prec.html. The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data is available from http://www.psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html.

Declarations

Competing interests
The authors declare that they have no conflict of interest.

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