Reexamining the Indian Summer Monsoon Rainfall–ENSO Relationship From Its Recovery in the 21st Century: Role of the Indian Ocean SST Anomaly Associated With Types of ENSO Evolution

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Abstract This study found that the relationship between the Indian Summer Monsoon Rainfall (ISMR) and El Niño-Southern Oscillation (ENSO) has recovered since 2001, and the relationship strength is closely related to the summer tropical Indian Ocean (TIO) sea surface temperature (SST) anomaly, with the TIO warming (cooling) indicating a stronger (weaker) relationship. Under the same El Niño/La Niña scenario, different signs of the TIO anomaly indicate distinct atmospheric circulation anomalies over the Indian Ocean, thus affecting the ISMR–ENSO relationship. The TIO anomaly is principally associated with different types of ENSO temporal evolution. Strong El Niño events with an early onset, and the transition of El Niño to La Niña, tend to have a warmer TIO and a stronger ISMR–ENSO relationship, in contrast to most of the cases of a decaying La Niña or a La Niña that persists throughout the year. The result brings a prospect for improving the ISMR prediction.

Plain Language Summary Conventionally, the Indian Summer Monsoon rainfall (ISMR) is affected by warmer- or colder-than-normal sea surface temperature (SST) anomalies in the central-eastern Pacific, known as the El Niño or La Niña phenomenon, respectively. Thus, a negative relationship exists between the ISMR and El Niño–Southern Oscillation (ENSO). Records show that the relationship weakened after 1980, which affected the prediction of ISMR. The mechanisms of the weakening are still under debate. This study found that the relationship has recovered since 2001. The intensity of the relationship is closely related to the tropical Indian Ocean (TIO) SST anomaly during the monsoon season, with a warmer TIO indicating a much stronger ISMR–ENSO relationship, or vice versa. The source of the TIO SST anomaly is largely attributed to different types of temporal evolution of ENSO. These results indicate that prediction of ISMR can be improved by deciding whether to use ENSO as a basis according to the forecast of the TIO SST.

1. Introduction

The Indian Summer Monsoon Rainfall (ISMR) is known to be negatively correlated with the simultaneous central-equatorial Pacific sea surface temperature (SST) anomalies, because developing El Niño (La Niña) events can weaken (enhance) the ISMR through the displacement of the Walker circulation (Sikka, 1980; Webster & Yang, 1992) during the monsoon season (June–September, JJAS). This negative relationship, however, began to weaken in the 1980s (Krishna Kumar et al., 1999). Variability in the Indian Ocean is one of the key factors governing the ISMR–El Niño–Southern Oscillation (ENSO) relationship (Wu & Kirtman, 2004). For example, Ashok et al. (2001) suggested that the concurrent positive Indian Ocean Dipole (IOD) events during El Niños after the 1980s counteracted the influences of El Niño on the ISMR. In addition, Kucharski et al. (2007) argued that concurrent tropical South Atlantic cold (warm) SSTSs during El Niño (La Niña) may impair ENSO’s influences on the ISMR. Other factors include global warming (Azad & Rajeewan, 2016; Wang et al., 2015), the change of ENSO type from Eastern Pacific to Central Pacific ENSO (F. Fan et al., 2017; Krishna Kumar et al., 2006; Wu et al., 2012; Yeh et al., 2009), the Pacific Decadal Oscillation (Krishnamurthy & Krishnamurthy, 2014), and the Atlantic Multidecadal Oscillation (Lu et al., 2006) or the North Atlantic Oscillation (Chang et al., 2001). Apart from these physical interpretations, some
researchers investigated the relationship from the stochastic perspective and showed that the decadal fluctuation was insignificant and could be due solely to stochastic processes (Cash et al., 2017; Gershunov et al., 2001; Yun & Timmermann, 2018). Furthermore, other studies (Maraun & Kurths, 2005; Singh et al., 2020) suggest that the strength of the ISMR–ENSO relationship needs to be examined from the pur-view of epochal changes and it might be influenced by changes in volcanic radiative forcing. In short, the mechanisms by which this relationship weakens has been debated for over two decades.

Recently, we found that the ISMR–ENSO relationship in this century has almost recovered to its pre-1980 level. This phenomenon motivated us to reexamine the ISMR–ENSO relationship and try to look for a simple but relevant factor governing the strength of the ISMR–ENSO relationship. Using a yearly matching index, this study finds that the strength of the ISMR–ENSO relationship is closely related to the summer Indian Ocean basin-wide SST anomaly, which is associated with different types of ENSO evolution.

2. Data and Methods

2.1. Data

We used the CPC Merged Analysis of Precipitation (CMAP) (1979–2020). The ISMR (all-India-monsoon-rainfall) series was obtained from the Indian Institute of Tropical Meteorology for the period 1871–2016, spliced with the spatially averaged index of CMAP precipitation over the Indian Peninsula (10°N–30°N, 70°E–90°E) for the period 2017–2020. The observed SST datasets were the NOAA Extended Reconstructed SST version 5 (ERSST v5; Huang et al., 2017) and Hadley Centre Sea Ice and SST (HadISST v1; Rayner et al., 2003). They were preprocessed to remove linear trends. Other atmospheric variables including 850 hPa winds and 200 hPa velocity potential from the NCEP/NCAR reanalysis (Kalnay et al., 1996) and ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2019) are used. We also analyzed precipitation data (1979–2014) from 45 models (Table S1) of the Atmospheric Model Intercomparison Project (AMIP) of Phase 6 of the Coupled Model Intercomparison Project (CMIP6).

2.2. Matching Index of ISMR and ENSO

Normally, researchers use a sliding-window correlation to quantify decadal changes in the interannual relationship between two variables. Essentially, the correlation between any two vectors can be calculated as the averaged product of corresponding elements of the two standardized vectors. Therefore, the product of the standardized ISMR and Niño3.4 indices, respectively. The multi-year average of the MI values is the same as the ISMR–ENSO correlation; thus, a positive MI anomaly indicates a weaker–than–normal relationship. Compared to the conventional sliding-window correlation which may average out the relationship, the yearly MI can describe the ISMR–ENSO relationship in finer detail.

3. Results

3.1. The Recovery of the ISMR–ENSO Relationship in the 21st Century

The time series of the ISMR and Niño3.4 observations (Figure 2a) shows that the past 60 years can be divided into three periods of 20 years each, according to the relationship strength. The correlations during the three periods are −0.68, −0.26, and −0.60, respectively. This pattern can also be seen from the ISMR–SST correlation maps for the three periods (Figure 1). This feature is robust with respect to different datasets (Figure S1). The negative relationship between the ISMR and central-eastern Pacific SST is weak only during the period 1981–2000, and it strengthens from 2001 to 2020 to an intensity close to its pre-1980 level. Such a decadal variation can also be seen from the sliding correlation series (magenta lines in Figure 2b), which are numerically equal to the sliding average of the MI (black line in Figure 2b). The recent strengthening of
the ISMR–ENSO relationship was missed in past research which was based on a long sliding window (e.g., 25 years or more). Here, the shorter 11 years sliding correlation (magenta dashed line in Figure 2b) shows that the relationship returns to a strong level around 2001 and holds steady until the present.

Notably, the MI series has strong negative skewness; therefore, its mean value (which is also the ISMR–ENSO correlation) may depend heavily on a handful of negative extremums which are mainly caused by strong ENSO events. Thus, the ISMR–ENSO sliding correlation (i.e., the sliding average of MI) is sensitive to the exact timing and magnitude of the negative extremums in the MI series. For example, the major weakening of the ISMR–ENSO relationship in the 1990s is probably because of the mismatched events with strong ENSO in 1997 and 1999. This feature of MI highlights the necessity of studying the ISMR–ENSO relationship at an interannual scale to understand its interdecadal changes.

To investigate the mechanism of changes in the ISMR–ENSO relationship, we analyzed the AMIP simulations of CMIP 6 models to see if the SST variation played an important role. We first selected good models that could realistically simulate the observed weakening trend of the ISMR–ENSO relationship during the 1980s–1990s, based on two criteria: (a) a negative overall ISMR–ENSO correlation (1979–2014); (b) a 1985–1990 average of the 11 years sliding-correlation curve that was 0.05 higher than the 1990–2000 average. A total of 18 models met the above criteria and were selected from the 45 models. The 11-years sliding correlations for each model are shown in Figure 2c. We can see that most of the models capture the observed strengthening of the ISMR–ENSO relationship in this century. Since the AMIP simulations are forced by observed SSTs, the result indicates that the SST variations probably play a role in the recent recovery.

3.2. Link Between the TIO SST and the Strength of the ISMR–ENSO Relationship

The AMIP models (Figure 2c) show that the SST variability may account for the variation in the strength of the post-1980 relationship. Thus, we examined the simultaneous correlation (JJAS) between the observed MI and tropical SSTs for the period 1979–2020 (Figure 3a). The highest correlation is found in the tropical Indian Ocean (TIO), which shows a negative correlation, that is, the TIO cooling (warming) correlates to a weak (strong) ISMR–ENSO relationship. The detrended TIO index has a high correlation of −0.61 (significance level $10^{-5}$) with the MI (Figure 3b). They are also highly matched on a decadal timescale (correlation = 0.92), as shown from the 11 years smoothed series (dashed lines). It is known that the TIO SST has had a significant warming trend since the 1950s under global warming (Dong et al., 2014; Du & Xie, 2008; Xie et al., 2010). Thus, for the detrended TIO series, a decadal cooling (warming) indicates a slowdown...
We speculate that the decadal weakening (strengthening) of the ISMR–ENSO relationship in the 1990s (21st century) might be related to a relative slowdown (acceleration) of the TIO warming during that period.

The high correlation between the TIO and MI motivated us to reexamine the ISMR–ENSO relationship in terms of different signs in the TIO SST anomaly. Figures 3c and 3d show that the ISMR–ENSO correlation increases up to −0.89 under a warm TIO scenario, whereas it deteriorates to almost zero under a cold TIO. Both correlations are in sharp contrast with the correlation −0.51 for the all-sample-case (Figure 2a). Thus, the well-known negative relationship between the ISMR and ENSO is actually conditional on the TIO warming. A warm (cold) TIO may facilitate a stronger (weaker) ISMR–ENSO relationship.

To further validate the robustness of the TIO–MI connection, we analyzed all 45 AMIP models (Figure 3e) and found that models with higher TIO–MI correlation tend to simulate more realistic variation of the ISMR–ENSO relationship. This feature is statistically significant with a high correlation of −0.78 (significance level 10^{-10}). Similar analysis were also conducted using SST in sea areas other than the TIO, but the correlation values are all much small than −0.78 (figure not shown). Therefore, the success of models for the correct simulation of the variation of the ISMR–ENSO relationship relies on their ability to capture the close TIO–MI relationship. This further validates the importance of the TIO SST.

3.3. Physical Linkages Between the TIO SST and the ISMR–ENSO Relationship

3.3.1. Effects of the TIO SST on the ISMR–ENSO Relationship

According to the different sign combinations of the TIO and Niño3.4 indices (JJAS), the observational data can be divided into four categories: warm Niño3.4 with warm TIO (“posNiño_posTIO”), warm Niño3.4 with cold TIO (“posNiño_negTIO”), cold Niño3.4 with warm TIO (“negNiño_posTIO”), and cold Niño3.4 with warm TIO (“negNiño_negTIO”). The composite anomalies of SST, 850 hPa winds, precipitation, and 200 hPa divergent winds are shown in Figure 4 and the list of years for each scenario is shown in the legend of Figure 5.

For the posNiño_posTIO scenario (Figures 4a and 4e), a strong anomalous subsidence center is located over the Indonesian Archipelago and to its west is a weak anomalous ascending center (Figure 4e). Correspondingly, the 850 hPa over the North Indian Ocean (NIO) shows easterly anomalies (Figure 4a), flanked by an anomalous anticyclone over the India Peninsular and an anomalous cyclone over the Somali Peninsular. The northeasterly anomalies over the Somali Peninsular weaken the mean moisture transport toward the Indian subcontinent and, combined with the dry air brought by the anomalous Indian anticyclone, contributes to drought conditions in the Indian Peninsular (Figure 4e). These anomalies cause a stronger negative relationship between the ISMR and El Niño.

In the posNiño_negTIO scenario (Figures 4c and 4g), the cold TIO weakens the zonal gradient of the tropical Indian–Western Pacific SST; therefore, the 850 hPa wind anomalies are almost the opposite of that in the posNiño_posTIO scenario, and a weak descending center is located over the western Indian Ocean (WIO) (Figure 4g) rather than over the Indonesian Archipelago. The generally weak precipitation anomaly over the Indian-western Pacific and the Indian Peninsular causes a weak ISMR-El Niño connection.

The La Niña scenarios are not simply mirrors of the El Niño scenarios. For the negNiño_posTIO scenario (Figures 4b and 4f), warm SST anomalies are mainly concentrated in the NIO. Under its influence, an anomalous ascending center locates over the Arabian Sea and causes above-normal ISMR (Figure 4f).
By contrast, for the negNiño_negTIO scenario (Figures 4d and 4h), the TIO cooling confines the anomalous convection center to the Indonesia Archipelago, and the Indian Peninsula lies in the transition zone between the eastern rising area and the western sinking area. Thus, the ISMR anomaly is vague, and the ISMR-La Niña connection is weak.

3.3.2. Source of the Summer TIO SST Anomaly

To further understand the linkage between the TIO SST and the ISMR–ENSO relationship, the source of the summer TIO SST anomaly was examined from the perspective of ENSO evolution. We plotted the evolution series of Niño3.4 (Figure 5) and TIO (Figure S2) from January to December in each year (1979–2020) for the four scenarios. Cases with negative (positive) MI anomaly are represented by solid (dashed) lines, indicating that the ISMR–ENSO relationship is stronger (weaker) than average. Figure 5a shows that the posNiño_posTIO scenario is mainly El Niño-developing cases. Those with earlier onset (solid lines) tend
to develop into strong El Niño and have a stronger ISMR–ENSO relationship. This is because the earlier onset of El Niño can force the WIO warming via atmospheric bridge (L. Fan et al., 2017), and the warm-cold-warm pattern in the Indian–Pacific Ocean (Figure 4a) in turn facilitates the El Niño development. This positive feedback helps maintain a reduced ISMR during the summer of a developing El Niño.

For the posNiño_negTIO scenario (Figure 5c and Figure S2c), most of the cases are a phase–transition from La Niña to weak El Niño. Thus, the summer TIO cooling (Figure S2c) is a continuation of the spring cooling. Notably, the 1997 extreme El Niño is not associated with warm TIO, possibly because of the strong IOD events with very cold east Indian Ocean SST (Slingo & Annamalai, 2000).

Figure 5. Temporal evolution of the Niño3.4 index for all years from 1979 to 2020 for the four scenarios. The thin solid (dashed) lines indicate stronger-than-normal Indian Summer Monsoon Rainfall (ISMR)–El Niño-Southern Oscillation (ENSO) relationship. The thick black lines indicate the multi-case average.
For the negNiño_posTIO scenario, Figure 5b mainly shows cases of El Niño-to-La Niña. Cases with stronger relationship (solid lines) are characterized by stronger La Niña and warmer JJAS TIO (Figure S2b). The local air-sea interaction during El Niño decay causes the NIO warming in summer (Du et al., 2009; Klein et al., 1999; Xie et al., 2009). It can cause local convergence with abundant ISMR (Figure 4b), and the easterly wind anomalies in the western Pacific which facilitate La Niña development (Figure 5b) (Annamalai et al., 2005). The facilitating effect of the El Niño-to-La Niña cases on ISMR is also reported by Wu et al. (2012).

The negNiño_negTIO scenario (Figure 5d) is mainly La Niña events persisting throughout the year; thus, the La Niña-caused TIO cooling (Figure S2d) can last from boreal spring to JJAS.

In addition to the TIO, we also speculate from the MI definition that the ENSO amplitude may also influence the strength of the ISMR–ENSO relationship. This is verified by Figure S3a, which shows a significant correlation of −0.42 (at the 0.01 significance level) between the MI and the absolute value of Niño3.4. However, compared with the TIO, the ENSO amplitude is less relevant especially on a decadal timescale (Figure S3b).

4. Summary

The ISMR–ENSO relationship intensified in the 21st century and almost reached its pre-1980s level. Its strength is highly correlated with the TIO SST. A warmer TIO indicates a much stronger relationship, whereas a colder TIO indicates that the conventional ISMR–ENSO relationship is almost nonexistent. The source of the TIO SST anomaly in JJAS is closely related to the type of ENSO temporal evolution. The developing cases of strong El Niño with early onset, and the transition cases of El Niño–to–La Niña, tend to have stronger ISMR–ENSO relationship, whereas most of the cases of decaying La Niña, and cases of La Niña persisting throughout the year, are likely to have weaker ISMR–ENSO relationship.

Previous studies have pointed out that the co-occurrence of the IOD and ENSO can affect the ISMR–ENSO relationship (Ashok et al., 2001; Gadgil et al., 2004). However, the feature of this study is that it examines the ISMR–ENSO relationship on an interannual timescale using a yearly matching index, and it identifies the basin-wide TIO SST anomaly as a simpler but more relevant factor to indicate the relationship strength. This result raises the prospect of overcoming the adverse effect of the instability of the ISMR–ENSO relationship on ISMR prediction (Fan, 2019; Wang et al., 2015). Forecasters are advised to use the ENSO predictor only when the TIO is predicted to be warm. Other factors under the TIO cooling need to be further explored. A possible choice is the tropical South Atlantic SST, which is identified from the map of the ISMR–SST correlation for cold TIO only (Figure S4c). The mechanism has been explained by Kucharski et al. (2007), and we found that it mainly works under the scenario of TIO cooling.

To further understand the mechanism of the variation of the ISMR–ENSO relationship, future studies may include the validation of the role of the TIO SST using sensitive numerical experiments, and the cause of the low-frequency variation of the TIO SST which may be associated with changes in the types of ENSO evolution or volcanic eruptions.

Data Availability Statement

The ISMR data is available at https://tropmet.res.in/static_pages.php?page_id=53. The CMAP precipitation, ERSST v5 data and NCEP/NCAR reanalysis data can be downloaded at https://psl.noaa.gov/data/gridded/. The HadISST v1 data is available at https://www.metoffice.gov.uk/hadobs/hadisst/. The ERA5 data are from the Copernicus Climate Change Service (C3S) Climate Date Store. The 45 AMIP models of CMIP6 are available at https://esgf-node.llnl.gov/search/cmip6/. The MATLAB codes of this study are available upon request by email.

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References

Annamalai, H., Xie, S.-P., McCreary, J. P., & Murtagudde, R. (2005). Impact of Indian Ocean sea surface temperature on developing El Niño. Journal of Climate, 18(2), 302–319. https://doi.org/10.1175/JCLI-3268.1
Ashok, K., Guan, Z., & Yamagata, T. (2001). Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophysical Research Letters, 28(23), 4499–4502. https://doi.org/10.1029/2001GL013294
Xie, S.-P., Hu, K., Hafner, J., Du, Y., Huang, G., Tokinaga, H., & Sampe, T. (2009). Indian Ocean capacitor effect on Indo-western Pacific.

Xie, S.-P., Du, Y., Huang, G., Zheng, X.-T., Tokinaga, H., Hu, K., & Liu, Q. (2010). Decadal shift in El Niño influences on Indo-western Pacific and East Asian climate in the 1970s. Journal of Climate, 23, 3352–3368.

Wang, B., Xiang, B., Li, J., Webster, P. J., Rajeevan, M. N., Liu, J., & Ha, K. J. (2015). Rethinking Indian monsoon rainfall prediction in the climate during the summer following El Niño.

Kucharski, F., Bracco, A., Yoo, J. H., & Molteni, F. (2007). Low-frequency variability of the Indian Monsoon–ENSO relationship and the bridge.

Wu, R., & Kirtman, B. P. (2004). Impacts of the Indian Ocean on the Indian summer monsoon–ENSO relationship. Journal of Climate, 17, 4397–4412.

Xie, S.-P., Du, Y., Huang, G., Zheng, X.-T., Tokinaga, H., Hu, K., & Liu, Q. (2010). Decadal shift in El Niño influences on Indo-western Pacific and East Asian climate in the 1970s. Journal of Climate, 23, 3352–3368.

Wang, B., Xiang, B., Li, J., Webster, P. J., Rajeevan, M. N., Liu, J., & Ha, K. J. (2015). Rethinking Indian monsoon rainfall prediction in the climate during the summer following El Niño.

Kucharski, F., Bracco, A., Yoo, J. H., & Molteni, F. (2007). Low-frequency variability of the Indian Monsoon–ENSO relationship and the bridge.

Wu, R., & Kirtman, B. P. (2004). Impacts of the Indian Ocean on the Indian summer monsoon–ENSO relationship. Journal of Climate, 17, 4397–4412.