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RESEARCH ARTICLE

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Interannual variability of monsoon onset and withdrawal in Bangladesh

Carlo Montes[1] | **Nachiketa Acharya**[2] | **Mathew A. Stiller-Reeve**[3,4] | **Colin Kelley**[5] | **S. M. Quamrul Hassan**[6]

[1]International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico

[2]Center for Earth System Modeling, Analysis, and Data (ESMAD), Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, Pennsylvania, USA

[3]University of Bergen, Centre for Climate and Energy Transformation (CET), Faculty of Social Sciences, Bergen, Norway

[4]NORCE Norwegian Research Centre, Bergen, Norway

[5]Appalachian State University, Boone, North Carolina, USA

[6]Bangladesh Meteorological Department, Dhaka, Bangladesh

Correspondence
Carlo Montes, International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico.
Email: c.montes@cgiar.org

Abstract

This research investigates the interannual variability of monsoon onset and withdrawal in Bangladesh, both of which are major climate features shaping multiple societal activities. There is considerable research on the monsoon timing in South Asia, but with much less focus on Bangladesh. We applied a local monsoon onset and withdrawal definition to observations and the latest-generation high-resolution gridded precipitation data from the Climate Hazards Center for the period 1981 through 2018. We analyzed the interannual variability in monsoon timing in Bangladesh and its teleconnection with the sea surface temperature anomalies (SSTA) over the Pacific Ocean (El Niño Southern Oscillation, ENSO) and the Indian Ocean (IO). The monsoon starts with early significant rains in northeast Bangladesh and propagates westward, and a similar pattern is observed for withdrawal, which tends to be more homogeneous in time and space. A high spatial and temporal variability in monsoon onset and withdrawal is observed in Bangladesh, with a within-country average range of around 1 month despite it being a country of relatively small size. The association between monsoon onset and withdrawal and ENSO and IO is addressed at the country and regional level by analyzing composites for different ENSO and IO phases and associated atmospheric circulation and moisture transport. A similar association between monsoon onset and ENSO and IO phases was found, with generally earlier (later) onset dates during the negative (positive) phase of ENSO and IO. Monsoon withdrawal shows a clearer association with ENSO, with earlier (later) dates during the positive (negative) phase. Monsoon withdrawal is earlier during the negative IO phase. SSTA-induced anomalies in circulation and moisture transport contribute to anomalies in monsoon timing. Results suggest both ENSO and IOD can be potentially used as sources of predictability of monsoon onset and withdrawal over specific regions of Bangladesh.

KEYWORDS

rainy season, sea surface temperature, South Asian monsoon, teleconnection

1 | INTRODUCTION

The main goals of this work are to statistically analyze the primary regional patterns of variability in monsoon onset and withdrawal in Bangladesh and assess the interannual influence of large-scale teleconnections. These are important issues for a country that features a monsoonal climate with rainfall concentrated typically from June to September and even earlier in the northeast region of the country (Ahmed & Karmakar 1993; Stiller-Reeve et al. 2015). This seasonality is responsible for shaping multiple activities that directly depend on the timing and amount of the summer rains, as well as associated changes in relevant meteorological variables such as air temperature and humidity. Both the monsoon onset and withdrawal are crucial attributes for agricultural planning in terms of the timing of land preparation, sowing, and transplanting dates of summer crops during the main growing season, and dates of planting and harvest of winter crops (Acharya & Bennett 2021; Ray et al. 2015).

The timing of the South Asian monsoon has been widely studied, with previous studies mostly focused on the South Asian domain and on large-scale features (Bombardi et al. 2019; Wang & Fan 1999). In this way, multiple criteria and atmospheric variables have been used to characterize the monsoon timing variability and associated mechanisms (Carvalho et al. 2016; Wang et al. 2009; Zeng & Lu 2004), while others have assessed long-term trends (Bollasima et al. 2013; Singh et al. 2014). Since the monsoon onset and withdrawal are typically influenced by local and regional mechanisms (Wang et al. 2017), multiple approaches have been proposed to explain its dynamics. In addition to the basic large-scale features, namely, continental heating, the northward shift in meridional wind, and the associated increase in water vapor transport, other large-scale and regional mechanisms have been documented to drive the transition. The latter include circulation anomalies induced by intraseasonal oscillations (Karmakar and Misra, 2019), the passage of deep convection over the adjacent ocean (e.g., the Bay of Bengal) propagating into the continent, and the influence of the Tibetan plateau on circulation (Fasullo & Webster 2003; Yanai et al. 1992). Furthermore, large-scale earlier or advanced monsoon onset have been associated with sea surface temperatures (SSTs) anomalies over the Indian and Pacific oceans (Lau & Yang 1997; Sun et al. 2017). Likewise, El Niño (La Niña) years have been reported as associated with later (earlier) than normal onset of the monsoon season in India (Adamson & Nash 2014; Joseph et al. 1994; Xavier et al. 2007) and farther East (Wang et al. 2013).

Targeted studies that evaluate the monsoon in Bangladesh have been very limited. The study of Ahmed and Karmakar (1993) can be regarded as the first to establish a climatology of monsoon onset and withdrawal. Recently, Stiller-Reeve et al. (2015) highlighted the heterogeneity of results obtained from a set of often-used monsoon onset definitions using coarse-resolution rainfall data and the differences between these results and the perception from local stakeholders in Bangladesh. Here, we take a step further and discuss interannual variability of monsoon timing across Bangladesh and possible teleconnections with the large-scale features. There is a need to consider the regionality of the monsoon transitions in more detail in Bangladesh, as well as understanding the relationship between monsoon timing and large-scale features such as the SST over the Pacific and Indian oceans in order to generate predictive statistical models. This is why we aim to characterize this variability using high-resolution data and local methods, and also analyze how the resulting patterns relate with SST.

2 | DATA AND METHODS

2.1 | Datasets

2.1.1 | Stations and gridded precipitation

Daily gridded precipitation data from the Climate Hazards Group InfraRed Precipitation with Station product (CHIRPS v2; Funk et al. 2015) were used. This gridded product is generated by merging high-resolution Tropical Rainfall Measuring Mission 3B42 v7 thermal infrared-derived satellite precipitation (Huffman et al. 2007), ground truth rainfall observations from rain gauges, monthly precipitation climatology from the Climate Hazards Group's Precipitation Climatology (CHPClim; Funk et al. 2015), and simulated precipitation from the National Oceanic and Atmospheric Administration (NOAA) Climate Forecast System V2. Data from January 1981 to December 2018 were selected at the highest available spatial resolution of $0.05^\circ \times 0.05^\circ$, which in the current case allows a good spatial coverage of the relatively small area of Bangladesh. In addition, observed precipitation data from rain gauges were provided by the Bangladesh Meteorological Department and used here as a background ground truth observational reference. These rainfall data correspond to daily time series spanning the period from January-1981 to December-2017 for a total of 27 stations. Only stations with missing data less than 10% were included.

2.1.2 | SST and atmospheric reanalysis

El Niño-Southern Oscillation (ENSO) and Indian Ocean SST (IO) indices were generated in order to assess the relationship between large-scale remote atmospheric teleconnections and monsoon timing in Bangladesh. The influence of ENSO phases was examined by analyzing monthly time series of SST anomalies (SSTA) obtained from the Extended Reconstructed Sea Surface Temperature Version 5 (ERSSTv5) product (Huang et al. 2017), provided by the National Oceanic and Atmospheric Administration. Although differences have been described in the monsoon onset in Asia associated with different regions of the equatorial Pacific (Wang et al. 2013), we averaged SSTA over the central Niño 3.4-region of the Pacific Ocean (120°–170°W, 5°S–5°N) and for the period spanning the transition period May–June (MJ) for onset dates, and September–October (SO) for withdrawal. Similarly, the linkage between monsoon timing and IO SSTA was examined by analyzing monthly time series of the eastern box of the IO Dipole, which corresponds to the monthly time series of SSTA in the eastern (90°–110°E, 10°S–0°) IO (Saji et al. 1999; Zhao & Nigam 2015). The same 2-month MJ and SO were considered. Alongside, reanalysis data from the European Center for Medium-range Weather Forecasts ERA5 (C3S 2017) product were used to characterize near-surface and vertical circulation. These data comprise hourly u and v wind and specific humidity (q) for 27 ERA5 vertical levels from 1000 to 100 hPa. Daily time series for the period 1981–2018 were obtained by aggregating the original hourly values.

2.2 | Methods

2.2.1 | Defining monsoon onset and withdrawal in Bangladesh

Multiple definitions aimed at accurately determining the monsoon establishment have been proposed for different monsoon regions (Fitzpatrick et al. 2015). These definitions vary from local, where the onset/withdrawal date is defined after processing single-point precipitation (Marteau et al. 2009; Moron & Robertson 2014), to regional, where large-scale seasonal evolution of precipitation or other related variables (e.g., wind direction, outgoing longwave radiation) is considered (Wang et al. 2009; Zeng & Lu 2004). In this work, local monsoon onset and withdrawal dates were calculated using the approach proposed by Stiller-Reeve et al. (2014). Local definitions like the one used here are best suited to applications in agricultural research and development, where, for example, the objective definition of the duration of the rainy season is of great relevance and can have numerous applications in the development of operational products. The definition of Stiller-Reeve et al. (2014) allows calculating the monsoon timing for every single location using pentad (mm day^{-1}) precipitation as a meteorological variable after a threshold parameter amount bounding monsoon-like conditions is defined, and specific seasonal rainfall transition criteria are met. For an annual time series of pentad precipitation ($n = 73$), the algorithm works by assigning a value of 1 to rainfall pentads exceeding the threshold amount. Then, 6-pentad moving windows are taken chronologically and compared against a previously defined and regionally compiled set of 6-pentad time series representing combinations of wet and dry pentads during onset and withdrawal transitions. Monsoon onset and withdrawal are defined when the 6-elements array matches an existing 6-pentad combination, which is detailed in Stiller-Reeve et al. (2014). This method was shown to reduce the number of false onsets, which is important for very high-resolution data sets such as CHIRPS where manual corrections are not possible. In the present study, a single threshold rainfall parameter was calculated from April to November (pentads 12 to 67) as a way to include the months where precipitation concentrates. For each annual time series, the interannual average of the median pentad precipitation was calculated and then averaged regionally and found to be 8 mm day^{-1}. Although the monsoon timing has been shown to be sensitive to threshold rainfall values (e.g., Wang et al. 2013), we consider this threshold to be subjectively sound when compared to the opinions of farmers around the country, which usually aligned with monsoon definitions using thresholds of between 5 and 10 mm day^{-1} (Stiller-Reeve et al. 2016).

2.2.2 | Assessing interannual variability and teleconnections with SST

Both ENSO and IO SSTA are recognized as two major drivers of monsoon precipitation variability, interannually in South Asia (Khandu et al. 2017) and subseasonally in Bangladesh (Rimi et al. 2018). Here, considering both oceanic phenomena as potentially triggering interannual and seasonal rainfall anomaly fluctuations, the linkage between ENSO and IO phases and monsoon onset and withdrawal was explored. The influence of ENSO phases was examined by analyzing monthly time series of ERSSTv5 SSTA averaged over the Niño 3.4-region. Positive and negative ENSO phases were defined as the 2-month MJ and SO running average SSTA >0.5°C and negative SSTA < -0.5°C. The linkage with IO was examined by analyzing monthly SSTA values, defining positive and negative IO phases when IO SSTA >0.75 SD and IO SSTA < -0.75 SD, being SD the standard deviation (Jongaramrungruang et al. 2017).

2.2.3 | Atmospheric features associated with ENSO and IO phases

Composite anomalies of 850-hPa circulation from ERA5 reanalysis were calculated in order to visualize the circulation patterns occurring during positive and negative ENSO and IO phases influencing monsoon transitions in Bangladesh. Similarly, meridional circulation anomalies were calculated for the box covering the Bay of Bengal and Bangladesh between 0°–27°N and 85°–95°E (see Figure 4a). In addition, anomalies of the Integrated Water Vapor Transport (IVT) were calculated in order to explore possible SSTA-induced mechanisms. IVT was obtained from ERA5 wind components (m s^{-1}) and q (kg kg^{-1}) as (e.g., Schmitz & Mullen 1996; Zhu & Newell 1998):

$$\mathrm{IVT}=\sqrt{\left(\frac{1}{g}\int_{1000\,hPa}^{300\,\mathrm{hPa}} qu\,dp\right)^2+\left(\frac{1}{g}\int_{1000\,hPa}^{300\,\mathrm{hPa}} qv\,dp\right)^2} \quad (1)$$

where g is the gravitational acceleration and p is the pressure level.

3 | RESULTS AND DISCUSSION

3.1 | Mean features and interannual variability in monsoon onset and withdrawal

Results show that the climatological onset and withdrawal dates in Bangladesh are June 1st and September 24th, respectively. However, the climatological maps indicate important spatial differences (Figure 1a,b). Figure 1a shows a southwestward propagation of monsoon onset, which follows a dominant East–West gradient component, with onset dates ranging from pentad 23 to 37 (April 25th to July 4th, respectively). The interannual variability ranges from 2 to 9 pentads, which follows a pattern similar to the average conditions, with

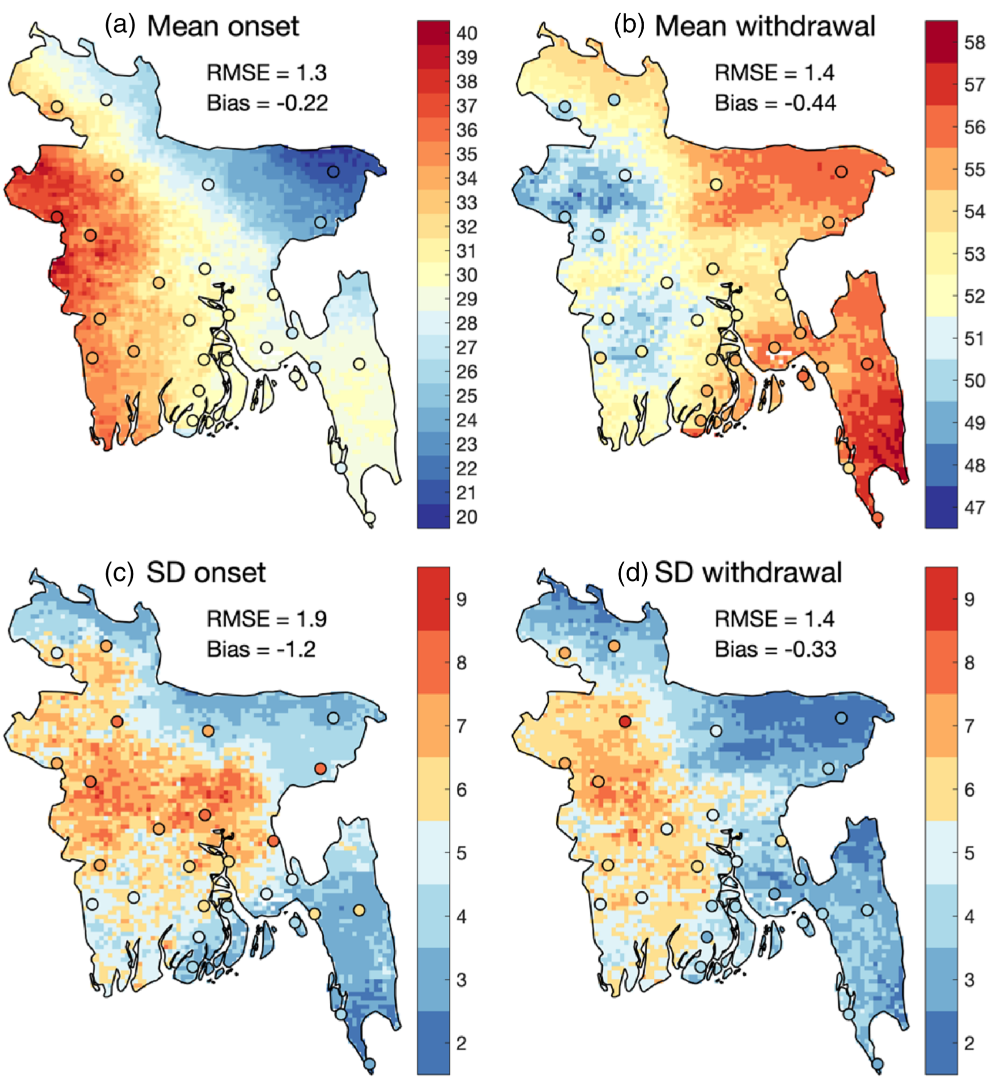

FIGURE 1 Climatology (1981–2017) of (a) monsoon onset and (b) withdrawal in Bangladesh, and (c),(d) their corresponding interannual local standard deviation (SD) for CHIRPS and station data (dots). All values are expressed in pentads. The corresponding RMSE and bias and between CHIRPS data and stations are displayed

lower–higher variability over regions with earlier–later onset (Figure 1c). These regional features in monsoon onset are statistically consistent with observed withdrawal dates (Figure 1b), which shows a dominant West–East gradient, ranging from Julian pentad 49 to 57 (September 2nd to October 7th, respectively). The standard deviation in withdrawal dates looks similar to onset dates both in distribution and magnitude, where areas of lower–higher variability present later–earlier dates (Figure 1d). The narrower range of amplitude suggests that the withdrawal is a more homogeneous phenomenon in relation to the onset (Figure 1a,b), and is similar to results obtained by Stiller-Reeve et al. (2014) after applying the same local definition to coarser resolution rainfall data. However, the pattern differs from many previously published monsoon onset progressions as discussed in Stiller-Reeve et al. (2015).

The time series of country-average onset and withdrawal dates exhibit significant interannual variability (Figure 2a). Monsoon onset varies from pentad 28 to 35 (May 18th to June 22nd, respectively), with a spatial standard deviation of 6 pentads, which implies a range of temporal and spatial differences of around 1 month. Similarly, withdrawal dates range from 47 to 59 (September 20th to October 20th, respectively), with a spatial standard deviation of 4.4 pentads, suggesting a larger–smaller range of temporal–spatial variability in onset than withdrawal dates. More generally, the range of interannual variability is very similar for both onset and withdrawal (Figure 2b). These spatial features suggest that earlier onset areas are in turn those of later withdrawal, which is consistent with previously described patterns of monsoon seasonal progression in Bangladesh (Ahmed & Karmakar 1993; Lau & Yang 1997; Stiller-Reeve et al. 2014).

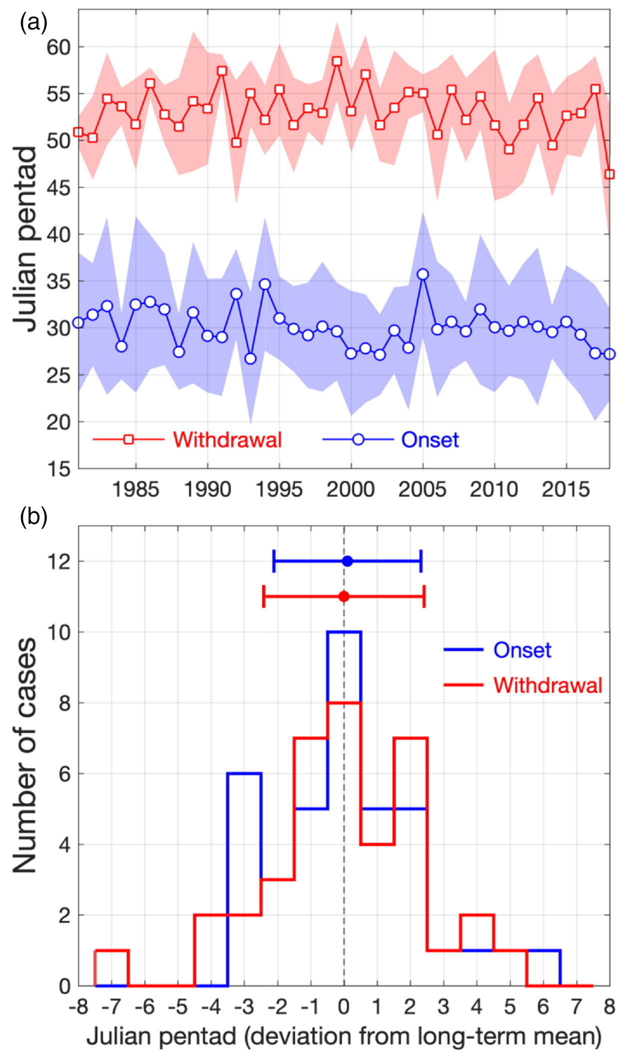

FIGURE 2 (a) Time series of country-averaged CHIRPS monsoon onset and withdrawal (1981–2018; shaded area is the spatial standard deviation), and (b) histograms of interannual country-average onset and withdrawal dates presented as the deviation from the long-term mean

3.2 | The relationship with SSTA

Teleconnections between monsoon timing and SSTA were examined as a way to investigate drivers of interannual variability. A composite analysis based on positive and negative phases of ENSO and IO was performed. Regional maps of monsoon onset and withdrawal, expressed as the departure from the long-term average, for positive and negative phases of ENSO and IO are displayed in Figure 3. Dominant earlier onset dates are observed for the negative ENSO phase, which is less clear for the positive phase (Figures 3a,b). The influence of ENSO on monsoon onset is similar to the one reported in the literature for other areas in South Asia (Li et al. 2018; Noska & Misra 2016). The latter is indicative of earlier onset dates during the negative ENSO phase over a large region, excluding the northeast region (Sylhet division), which presents an opposite sign. That region (Sylhet division) was highlighted by Stiller-Reeve et al. (2015) and Basher et al. (2018) due to its particular regime of pre-monsoon rains, which are characterized by severe local storms bringing important rainfall amounts (>900 mm) during the pre-monsoon season from the northwest (pre-monsoon circulation), contributing to the contrasting anomalies associated with ENSO phases. Figures 3c,d show dominant later (earlier) withdrawal dates and the negative (positive) ENSO phase. These results agree with those found by Fitzpatrick et al. (2016), where significant rank correlations were found between a pre-monsoon ENSO index and the agronomic monsoon onset of Marteau et al. (2009) over the Bay of Bengal, consistent

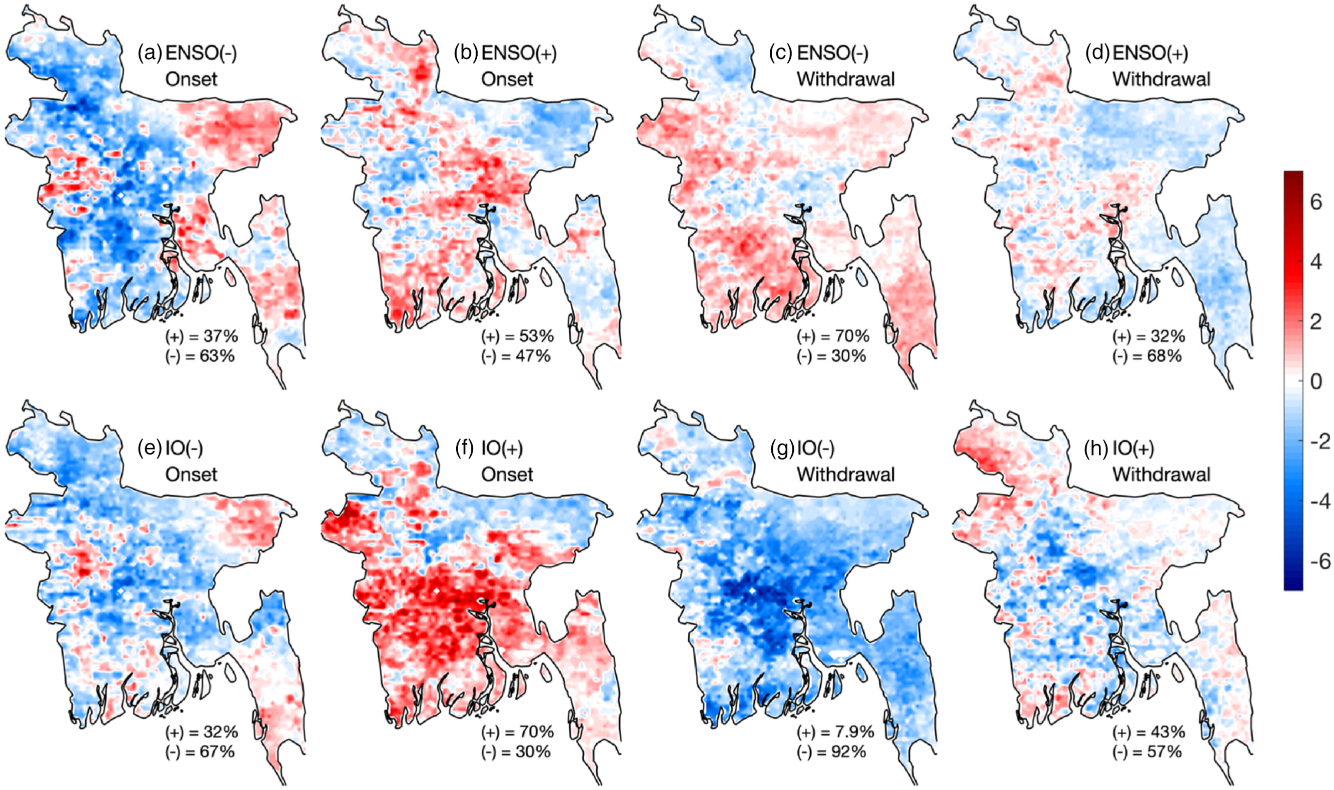

FIGURE 3 Maps of average monsoon onset and withdrawal anomalies during negative (−) and positive (+) (a)–(d) ENSO and (e)–(h) IO phases. (+) and (−) signs at the bottom of each map represent the percentage of positive and negative anomalies, respectively. Color bar expressed in pentads

with previous studies in South Asia (Moron & Robertson 2014).

The relationship between IO phases and monsoon timing is presented in Figures 3e-h. Both the negative and positive phases lead to a very similar pattern of monsoon onset dates, with most of the country presenting earlier (later) dates during the negative (positive) IO phase, except for the northeast where the pattern is opposite (Figure 3e,f). These anomalies look similar to ENSO, but the maps of Figures 3e,f suggest a greater association between IO and monsoon timing. On the other hand, Figures 3g shows widespread earlier withdrawal dates during the negative IO phase, and a more diffuse pattern for the case of the positive phase (Figure 3h).

3.3 | Circulation anomalies associated SSTA during monsoon onset and withdrawal transitions

Composites of IVT and 850-hPa circulation anomalies for ENSO and IO phases are presented in Figure 4. Consistent with dominant earlier onsets during ENSO negative phase (Figure 3)), Figures 4a shows west winds and positive IVT anomalies over most of the domain, with a northward circulation component over Bangladesh that is consistent both with the basic flow and a strengthening of northerly wind that can enhance the transport of water vapor from the ocean to the continent, leading to an earlier occurrence of significant rains. Previous studies have described the increasing pressure and temperature contrast between the sea and the continent and the northward migration of the jet stream as the warm season approaches (Lau & Yang 1997; Yanai et al. 1992). Conversely, the positive ENSO phase (Figure 4b) is associated with a westward 850-hPa circulation anomaly, which is recognized as a prevailing feature of the tropical premonsoon circulation (Wang et al. 2013; Yu et al. 2017). The latter translates into dominant-negative anomalies of IVT, but whose magnitudes are relatively smaller over Bangladesh. Notwithstanding, the negative IVT anomalies and southward wind might prevent the monsoonal circulation. Sun et al. (2017) state that persistent El Niño events (warm phase) can induce later monsoon onset over the Bay of Bengal, adjacent to Bangladesh, and conversely for La Niña. A similar pattern of anomalies is observed for the positive and negative phases of ENSO during the withdrawal of the monsoon (Figures 4c,d). In this case, an enhanced moisture transport and an 850-hPa northward circulation in the northern part of

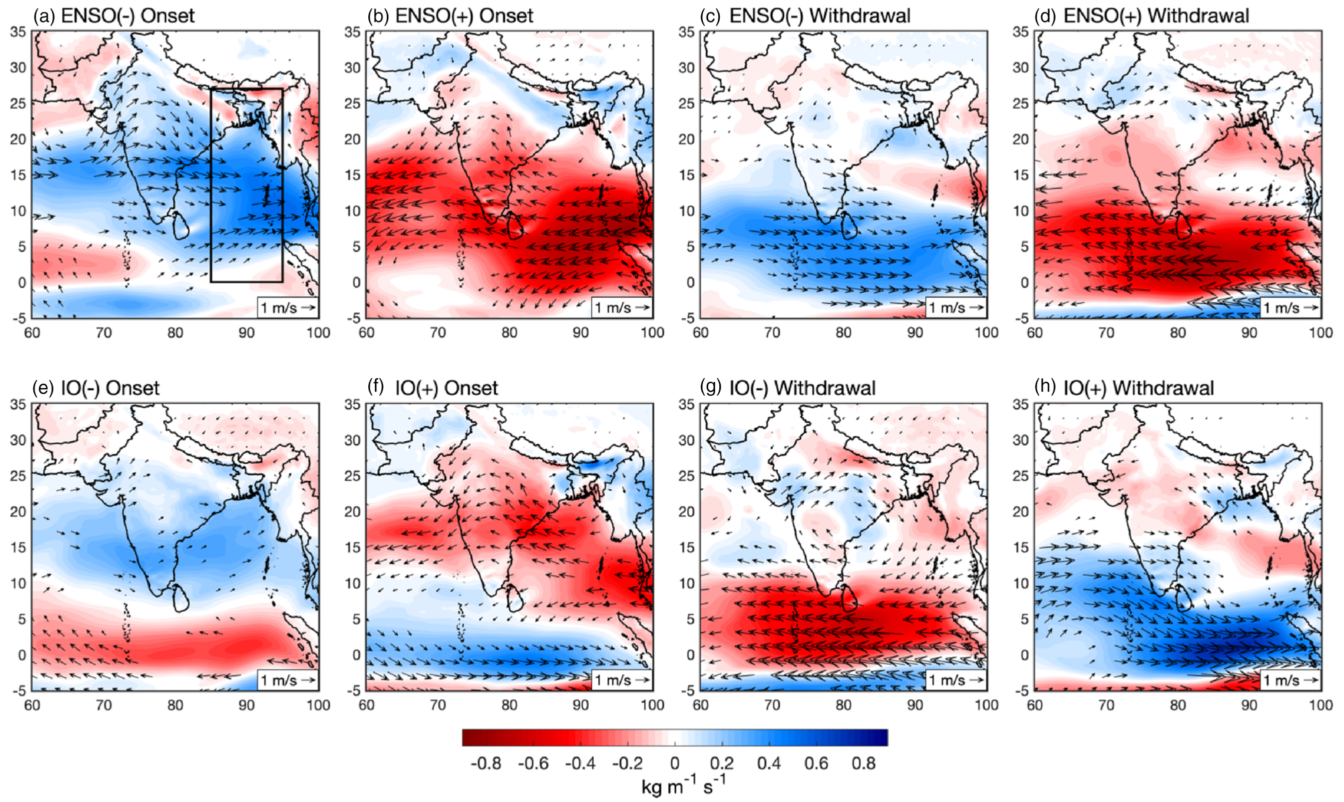

FIGURE 4 Composites of IVT magnitudes (colored areas) and 850-hPa circulation anomalies (wind vectors) during the negative (−) and positive (+) phase of ENSO and IO and monsoon onset and withdrawal. Only vectors exceeding the 95% confidence interval are displayed. The rectangle in (a) is used in Figure 5

the Bay of Bengal may explain the widespread later monsoon withdrawal in Bangladesh (Figure 3b). Conversely, the negatives anomalies in IVT and the southward wind anomaly may explain the dominant earlier monsoon withdrawal during the positive phase of ENSO (Figure 4d), likely driven by high pressures acting as a blocking system to the southern flow.

Circulation anomalies during the monsoon onset and IO phases are observed similar to the case of ENSO. The negative IO phase is associated with positive IVT anomalies and a wind field at 850-hPa with a weaker north component, which can explain the earlier onset dates (Figure 4e). Similarly, Figure 4f shows negative IVT anomalies and an eastward wind component that can delay the onset of the monsoon. On the other hand, circulation during the withdrawal period is very different from ENSO. In this case, negative anomalies of IVT and a strong anticyclonic flow over the northern part of the domain (Figure 4g) might prevent the development of rains, advancing the withdrawal of the monsoon, as observed in Figure 3g. Although the widespread positive anomalies in IVT are associated with positive IO (Figure 4h) and the southerly wind component over the north part of the Bay of Bengal, winds do not seem to develop significantly over Bangladesh (Figure 3g).

Previous studies have highlighted the impact of SSTA-induced teleconnections on the humidity convergence and convection, and consequently on the monsoon timing in Asia (Jiang & Li 2011; Wang et al. 2013). The composite anomalies of meridional circulation during monsoon onset and withdrawal and the positive and negative phases of ENSO and IO are displayed in Figure 5, averaged along the area shown in Figure 4a. In general, it is observed that the negative (positive) ENSO phase during monsoon onset is associated with positive (negative) vertical circulation anomalies over Bangladesh, and conversely during the withdrawal period (Figure 5c,d), which are consistent with the above described anomalies in monsoon timing and circulation. More significant anomalies are observed during the onset period and IO phases (Figure 5e,f) especially in the middle and upper atmosphere, which can impact the development of the convection, and therefore, the timing of the monsoon onset (Wu et al. 2014). Despite the widespread anomalies in withdrawal dates during the negative phase of IO (Figure 3(g)), no clear association with meridional circulation is observed.

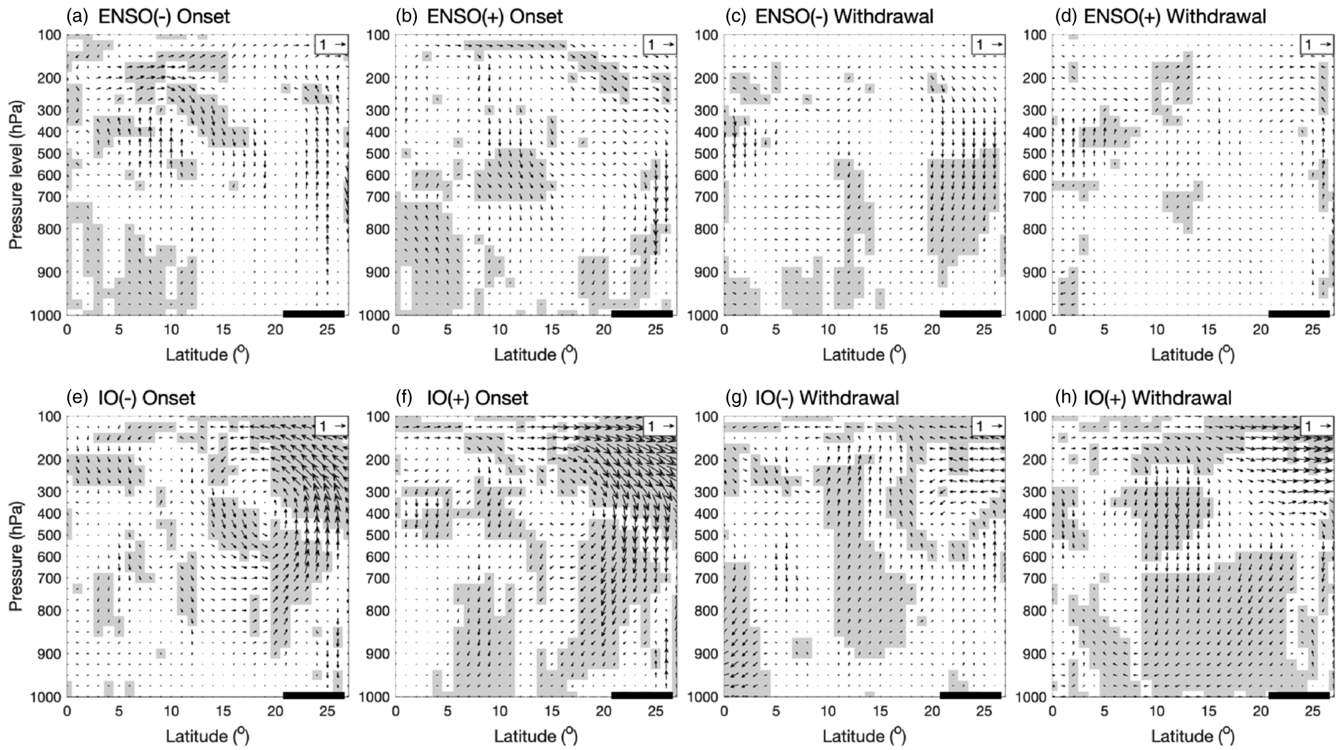

FIGURE 5 Composite anomalies of meridional circulation (vertical velocity is multiplied by 100) averaged between 85° and 95°E longitude during (a), (b) monsoon onset and (c), (d) withdrawal for the positive (+) and negative (−) phase of ENSO. Shaded areas represent the 95% confidence level of both vertical and meridional wind velocity. Black thick line at the bottom represents the location of Bangladesh

4 | SUMMARY AND CONCLUSIONS

The present study assessed features in observed interannual variability of monsoon onset and withdrawal in Bangladesh using a local definition and high-resolution rainfall data. The teleconnection between monsoon timing's variability and the Pacific (ENSO) and IO SSTA was also examined at the country and regional scale.

The high-resolution data clearly illustrates the significant spatial and temporal variability of the monsoon timing across the relatively small area of Bangladesh. These results, which are based solely on the seasonal course of precipitation, indicate that the bulk of monsoon onset occurs during May and June following a dominant westward propagation. Earlier dates are observed over the northeastern region of Bangladesh, similar to the previous study of Ahmed and Karmakar (1993). This is mainly due to the fact that other meteorological variables such as wind direction are not considered in the monsoon onset–withdrawal definition over an area where strong pre-monsoon rains are triggered by different atmospheric forcings (Basher et al. 2018; Murata et al. 2011). The monsoon withdrawal occurs on average between September and October, with lower interannual variability observed over northeastern Bangladesh (Figure 1d).

The connection between monsoon timing and ENSO is clearer for withdrawal dates than for onset at the country level. Results also show contrasting anomalies between the northeast and the rest of the country. The composites of monsoon onset and ENSO show later–earlier dates during the positive–negative phase, except for the northeast region of Bangladesh. On the other hand, monsoon withdrawal dates show a higher association with IO phases.

The potential relationship between large-scale phenomena associated with SSTA and the monsoon shows significant regionality across Bangladesh. This regionality has emerged from the use of the particularly high-resolution data in our study. In some areas, there appears to be a connection, whereas in others there is not. The results show that if we consider connections between IO and ENSO in the Bangladesh monsoon then we should analyze at the regional-rather than the country-scale. In addition, the influence of the developing and decaying phases of ENSO should be addressed in future studies, which have been associated with differences in monsoon rainfall and circulation in South Asia (e.g., Chowdary et al. 2017). In addition, other drivers of variability associated with different regions of the Pacific Ocean have been described as having varying influences on the monsoon onset in other areas of Asia (Wang et al. 2013), which should be addressed in future studies for Bangladesh.

Other large-scale drivers such as circulation anomalies should also be explored in order to develop operational products. However, our results suggest the potential use of these teleconnection indices individually or in combination with other sources of predictability to generate predictive statistical models to inform stakeholders about the monsoon timing at the seasonal scale in Bangladesh.

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AUTHOR CONTRIBUTIONS

Carlo Montes: Conceptualization; Data Curation; Formal Analysis; Methodology; Software; Visualization; Writing – original draft; writing – review and editing. **Mathew Stiller-Reeve:** Conceptualization; writing – original draft; writing – review and editing. **Colin Kelley:** Writing – original draft; writing – review and editing. **S. M. Quamrul Hassan:** Writing – original draft; writing – review and editing. **Nachiketa Acharya:** Writing – original draft; writing – review and editing.

ORCID

Carlo Montes https://orcid.org/0000-0003-4828-5589

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