Space- and time-varying associations between Bangladesh's seasonal rainfall and large-scale climate oscillations

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Abstract Understanding teleconnections of a region’s climate can be beneficial to seasonal outlooks and hydro-climate services. This study aims at analyzing the teleconnections of seasonal rainfall over Bangladesh with selected climate indices, including El Niño/Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) indices. Rainfall data spanning from 1965–2017 in the seven hydrological regions are used to derive three seasonal rains, namely the pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October and November) rains, for correlation- and wavelet coherence (WC)-based teleconnection analyses. Among the three seasonal rains, the post-monsoon rain shows the negative correlations, strongest with the IOD and ENSO indices. Correlations between the pre-monsoon/monsoon rain and climate indices are subject to notable spatial and temporal variations. For instance, correlations between the pre-monsoon/monsoon rain and climate indices are subject to notable spatial and temporal variations. For instance, correlations between the pre-monsoon (monsoon) rain in the South Central (South West) region and the IOD (ENSO) index shift from negative to positive after the 1980s, whereas the comprehensive negative correlations of the post-monsoon rain with the IOD and ENSO indices further enhanced from the early to recent epochs. WC analysis not only corroborates the findings of correlation analysis at shorter time scales (e.g., 1–4 years), but also reveals significant coherence at longer time scales (e.g., 8–16 years). We find that the pre-monsoon and monsoon rains experience the phase change in WC from shorter to longer scales. In contrast, the post-monsoon rain shows the consistent anti-phase WC, more dominant at the longer time scale. Both cor-
Teleconnection analysis of Bangladesh’s seasonal rains

relation and WC analyses indicate that the association patterns of the PDO mimic those of ENSO. Lastly, the analysis results of the AMO suggest quite distinct and significant association between Bangladesh’s rainfall and the Atlantic Ocean.

**Keywords** Teleconnection · ENSO · Correlation · Wavelet analysis

1 Introduction

Teleconnection refers to the remote association of local or regional hydro-meteorological variables with large-scale atmospheric/oceanic circulation patterns. Teleconnection studies play an important role in elucidating mechanisms behind the variability of hydro-meteorological variables and enhancing the prediction skill of seasonal precipitation [1]. Numerous teleconnection studies have revealed that South Asian Monsoon (SAM) is modulated by many large-scale circulation patterns, including the El Niño-Southern Oscillation (ENSO) [4, 6, 17, 30, 37], Indian Ocean Dipole (IOD) [56, 8, 9, 69], Atlantic Multidecadal Oscillation (AMO) [75, 23, 36], and Pacific Decadal Oscillation (PDO) [34, 55, 38, 60, 69]. Among these patterns, ENSO generally affects the SAM variability through the Walker circulation, subject to the change in spatial configurations of sea surface temperature (SST) anomalies in the Pacific Ocean [19]. However, weaker ENSO influence has been recently reported due to more active IOD events [56, 74, 69], the south-eastward shift in the Walker circulation anomalies [40, 41], and forcing from the Atlantic circulations [10].
Even though many teleconnection studies for the SAM regions were available, Bangladesh received relatively little attention. Some studies pointed out that Bangladesh’s rainfall was generally less (more) during El Niño (La Niña) events [e.g., 3, 18]. Later verified that the quantitative correspondence between the strength of ENSO and the country’s summer rainfall was actually weak. In contrast, 52 found moderate correlation between monthly rainfall and the Southern Oscillation Index (SOI) during the period 1981–2004. 51 demonstrated that the impact of ENSO was more pronounced in the recent period (1985–2008) than in the earlier period (1961–1984). Most recent studies, nevertheless, found weak or no significant correlation between Bangladesh Summer Monsoon Rainfall (BSMR) and ENSO indices [2, 4]. In addition to the remote connection to ENSO, 57 and 51 found that Bangladesh’s rainfall was also significantly correlated with nearby SST anomalies over the Bay of Bengal (BoB). 26 and 27 reported that the IOD events strongly modulated sea level variations in the BoB, which might be useful for flood prediction in Bangladesh. 4 indicated that the co-occurrence of the ENSO and IOD events could have prominent impact on Bangladesh’s rainfall. The above studies have advanced the teleconnection studies in Bangladesh, yet there exists a need for a comprehensive examination and comparison of the impacts of different types of ENSO, along with other teleconnection patterns, on Bangladesh’s rainfall.

Numerous studies have suggested two types of ENSO events, namely the Eastern Pacific (EP) and Central Pacific (CP) El Niño [32, 39, 54, 71], can exert different impacts on regional climates [33, 72, 78]. The CP El Niño seemed
to be more active since the late 1970s, resulting from a warmer climate [77].

Further, some studies pointed out that the CP ENSO is more responsible for
drought-inducing subsidence over South Asia than the EP ENSO [e.g., 40]. In
addition, Bangladesh’s rainfall may have simultaneous associations with other
large-scale oscillations. In fact, comparing the relative dominance of multi-
ple teleconnection patterns is preferred because regional climate is commonly
subject to interconnected large-scale climate anomalies [13, 22].

Using conventional composite or correlation analysis for teleconnection
studies poses another concern for the incapability of addressing non-stationarity
and multi-scale relationships between teleconnection patterns and hydro-climatic
variables [75, 17], which should be accounted for owing to the nonlinear nature
of climate systems [68, 40, 37]. Therefore, the better understanding of non-
stationarity underneath teleconnections relies on more adequate techniques,
such as moving-window correlation and wavelet analysis [13]. In particular,
continuous wavelet transform (CWT) [44, 25] that enables the identification
of dominant modes of variations in time is widely used. This robust math-
ematical device is primarily useful in the study of non-stationary associations
using time series data [28]. To quantify the co-varying relationships between
rainfall and climate indices at differing timescales, bivariate wavelet coherency
(BWC) based on the CWT can be adopted [5, 45]. As different teleconnection
indices display strong activities at different periodic scales (e.g., ENSO at 2–7
years; PDO at 15–25 and 50–70 years), similar oscillatory behavior between a
teleconnection and rainfall data can be identified using BWC [46]. Incorporat-
The aforementioned techniques is a must especially when conducting a new teleconnection study for regions like Bangladesh where climate regime shifts are evident.

For the reasons above, this study aimed to (1) quantify the spatio-temporal variations of concurrent correlations between different teleconnection patterns and Bangladesh’s seasonal rainfall based on the long-term (1965–2017) station data across the country, and (2) identify the multi-scale associations between teleconnection patterns and seasonal rainfall using wavelet coherence in order to supplement findings from correlation analysis. Findings from this study are expected to facilitate better management of rainfed and irrigated agriculture, water resources, and other important sectors in Bangladesh closely linked to the outlook of seasonal rainfall. The rest of this paper is organized as follows: Data and methodology used in this study are presented in Sections 2 and 3, respectively. Results and discussion are described in Section 4, followed by concluding remarks in Section 5.

# 2 Study region and data

Bangladesh is mainly a low-lying plain situated in deltas of large rivers flowing from the Himalayas (Fig. 1). The country is bounded by the Meghalaya Plateau, the Assam Hills, and the BoB at the north, east, and south, respectively. As part of the tropical monsoon climate zone, Bangladesh is characterized by warm temperature, high humidity, and notable seasonal variations in rainfall [61]. The country’s annual rainfall amount is 2030 mm on aver-
age, featured with a drastic variation from 1400 mm in the west to > 4400 mm in the east. Four distinct hydrological seasons can be recognized: the pre-monsoon (March to May, MAM), monsoon (June to September, JJAS), post-monsoon (October to November, ON), and winter (December to February) seasons [61, 2]. More than 60% of the total annual rainfall take place in the monsoon season, followed by the pre-monsoon, post-monsoon, and winter seasons. More descriptions regarding the general mechanism of rainfall variability in Bangladesh will be provided in Section 4.1.

2.1 Seasonal rainfall data

We used long-term (1965–2017) daily rainfall data collected at 24 weather stations managed by the Bangladesh Meteorological Department. These stations are evenly distributed over Bangladesh’s territory (Fig. 1). Missing data in the study period for the selected stations were very few (< 0.5%), and have been filled by using simple arithmetic average [31, 50]. After filling missing daily rainfall data, we derived three seasonal rains, that is, the pre-monsoon, monsoon, and post-monsoon rains, which cover ≈98% of the total annual rainfall of the country. Further, to ensure a more reliable, coherent outcome from teleconnection analysis, we grouped the 24 stations into seven “hydrological regions” according to the National Water Management Plan [73, 43], namely the North East (NE), North Central (NC), North West (NW), South Central (SC), South West (SW), South East (SE), and Eastern Hill (EH) regions. Note that we grouped the only station in the estuary region (i.e., Sandwip) into its
nearby SE region in this study. We thus developed 53-year seasonal rainfall time series for the seven regions for ensuing teleconnection analysis.

2.2 Teleconnection indices and other data

In this study, we acquired five teleconnection indices including two ENSO indices, IOD, AMO and PDO, for their significant relationship with South Asian seasonal rainfall as indicated in the previous section. We aimed to scrutinize how these indices are associated with Bangladesh’s rainfall, with a particular focus on revealing any space- and time-varying association patterns. Regarding the ENSO indices, we adopted only NINO1+2 (i.e., Eastern Pacific ENSO) and NINO3.4 (i.e., Central Pacific ENSO), representing the SST anomaly-based ENSO indicators with the specific monitoring regions of 0–10° S & 90–80° W and 5° N–5° S & 170–120° W, respectively [55].

Monthly NINO time series were collected from the Physical Sciences Laboratory of the National Oceanic and Atmospheric Administration (NOAA) by accessing https://psl.noaa.gov/data/climateindices/list/ The IOD is based on the SST anomaly difference between the western equatorial Indian Ocean (50–70° E, 10° S–10° N) and the south eastern equatorial Indian Ocean (90–110° E, 10° S–0°), referred to as Dipole Mode Index (DMI) [56]. Monthly IOD time series were collected from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Dipole Mode Index (DMI) http://www.jamstec.go.jp/frsgc/research/d1/iod/iod/dipole_mode_index.html.
Among the Inter-decadal indices, the AMO represents the long-term variability of North Atlantic SSTs with an estimated period of 60–80 years and an amplitude of 0.4° C, which is the 10-year running mean of detrended Atlantic SST anomalies \[20\]. The amplitude of the AMO is approximately half the standard deviation of the annual mean SST. The PDO is defined as the leading eigenvector of the mean monthly SSTs occurring in the Pacific Ocean, and has a cycle of 20 to 30 years. Positive (negative) values of the PDO index indicate its warm (cool) phase. The warm phase is associated with above normal SSTs along the west coast of North America and below normal SSTs in central and western North Pacific around 45° N \[59\]. Sources of the monthly AMO and PDO time series were available at https://www.esrl.noaa.gov/psd/data/timeseries/AMO/ and https://www.ncdc.noaa.gov/teleconnections/pdo/ respectively. All of the above teleconnection time series were processed to prepare the 53-year (1965–2017) time series for each season (i.e., MAM, JJAS, and ON), which can then be paired with the seasonal rainfall series for teleconnection analysis described next.

Lastly, to discuss the general mechanism of rainfall variability in Bangladesh, we developed composite maps of three atmospheric variables, namely 850-mb vector wind and geopotential height and precipitable water content. We obtained these data from the NCEP/NCAR reanalysis dataset \[30\].

3 Methodology
3.1 Correlation analysis

Significant associations between Bangladesh’s seasonal rainfall and teleconnection indices were identified firstly using correlation analysis. Pearson’s correlation coefficient \( r \) between each of the seasonal rains (i.e., the pre-monsoon, monsoon, and post-monsoon rains) and aforementioned teleconnection indices in the same season (i.e., concurrent correlations) were computed. The \( r \) value was deemed as significant based on a 5% level (\( \alpha = 0.05 \)).

In addition to concurrent correlations, we also performed moving-window correlation analysis [17] to identify non-stationary characteristics of the association between seasonal rains and teleconnections. A temporal window of 20 years was used to compute correlation over that time period, and the computation swept over the entire data set, moving from the first 20-year window (1965–1984) to the last (1998–2017) at a 1-year time step. In total, 34 correlation coefficients corresponding to the number of moving windows from 1965–2017 were obtained. The 34 correlation coefficients were further divided into three chronological sets: the early epoch \{1965–1984, 1966–1985, ..., 1976–1995\}, middle epoch \{1977–1996, 1978–1997, ..., 1987–2006\}, and recent epoch \{1988–2007, 1989–2008, ..., 1998–2017\}. To observe the temporal variations in these correlations, the strongest correlations (i.e., highest absolute value) were identified from the three epochs. This identification process is illustrated in Supplementary Information (Fig. S1). This process was repeated for all the pairs of seasonal rains and teleconnection indices, as well as for each station.
3.2 Wavelet analysis

Multi-scale associations between the teleconnection indices and seasonal rainfall of Bangladesh were detected by wavelet coherence (WC) analysis. WC is based on the classic wavelet technique, which transforms a signal (e.g., a data time series) into scaled and translated versions of an original (mother) wavelet. In this study, a cross wavelet and WC toolbox for MATLAB (available at [http://grinsted.github.io/wavelet-coherence/](http://grinsted.github.io/wavelet-coherence/)) was used for our analysis [24]. In what follows, we briefly describe the essential calculations pertinent to WC analysis.

The continuous wavelet transform (CWT) decomposes the time series into different time scales and produces a two-dimensional wavelet spectrum, enabling the identification of both the dominant modes of variability and their temporal evolution [67, 21, 46]. The CWT is defined as Eq. (1) [21]:

\[
W(\omega, \tau, x(t)) = \frac{1}{\sqrt{\omega}} \int_{-\infty}^{\infty} x(t) \psi^*\left(\frac{t - \tau}{\omega}\right) dt
\]  

where \( \omega \) is the continuous scale factor (frequency); \( \tau \) time shift; \( t \) time; \( x(t) \) the data time series; and \( \psi^* \) the complex conjugate of the wavelet function \( \psi \). In this study, we use the Morlet wavelet function [44], which is commonly adopted in hydrological studies [42] and can be expressed as

\[
\psi(t) = e^{i\omega_0 t}e^{-\frac{t^2}{2}}
\]  

where \( i \) is the imaginary unit, and \( \omega_0 \) the dimensionless frequency (set to 6 according to [67, 24]). The resolution of time and scale is controlled by \( \omega_0 \) (i.e.,
with higher (lower) $\omega_0$, scale resolution increases (decreases) and time resolution decreases (increases). In other words, higher and lower scale resolutions correspond to short- and long-term fluctuations in the time series, respectively. According to [24] and [6], the chosen Morlet wavelet can separate the phase and amplitude of any time series and is very well localized in scale.

To reveal the correlations between two time series in both the time and frequency domains, the cross-wavelet transform (XWT) is used. The XWT provides an unfolding of possible interactions between two processes at different scales [11]. It identifies cross-wavelet power that can reveal areas of high common power between two time series [76]. If $W_x(\omega, \tau)$ and $W_y(\omega, \tau)$ are the CWT of two time series $X$ and $Y$ (e.g., seasonal rainfall and climate index in our case), the XWT between them is defined as

$$W_{xy}(\omega, \tau) = W_x(\omega, \tau)W_y^*(\omega, \tau)$$

(3)

where $W_y^*(\omega, \tau)$ represents the complex conjugate of $W_y(\omega, \tau)$. The WC approach is used for analyzing the degree of coherence of XWT in time-frequency space and can be defined as the absolute square of the smoothed cross-wavelet spectrum, normalized by the smoothed wavelet power spectra [68], as shown in Eq (4):

$$R^2(\omega, \tau) = \frac{|S(\omega^{-1}W_{xy}(\omega, \tau))|^2}{S(\omega^{-1}|W_x(\omega, \tau)|^2) \cdot S(\omega^{-1}|W_y(\omega, \tau)|^2)}$$

(4)

where $R^2(\omega, \tau)$ denotes the coherence coefficient, $W_{xy}(\omega, \tau)$ represents the XWT of two time series, and $S$ is the smoothing operator. [24] defined the
smoothing operator as

\[ S(W) = S_{\text{scale}}(S_{\text{time}}(W(\omega, \tau))) \]  

where \( S_{\text{scale}} \) denotes smoothing along the wavelet scale axis and \( S_{\text{time}} \) smoothing in time. For the Morlet wavelet, \[68\] suggested

\[ S_{\text{time}}(W)\big|_{\omega} = (W(\omega, \tau) * c_{1}^{-\sigma}) \bigg|_{\omega} \]  

and

\[ S_{\text{scale}}(W)\big|_{\tau} = (W(\omega, \tau) * c_{2} \prod(0.6 \omega)) \bigg|_{\tau} \]  

where \( c_{1} \) and \( c_{2} \) are normalization constants, \( \prod \) is the rectangle function, and the empirical factor of 0.6 is the scale decorrelation length for the Morlet wavelet \[67\]. The \( R^{2}(\omega, \tau) \) value ranges from 0 to 1 and measures the cross-correlation of two time series as a function of frequency (i.e., local correlation between the time series in the time-frequency space). Thus, the WC can be interpreted as a decomposition of correlation coefficient at different scales \[15\]. Statistically significant WCs are identified using a Monte-Carlo-based significance test \[24\]. The significance level of each scale is evaluated using the values outside the cone of influence (COI), where the edge effects become essential \[67\].

4 Results and discussion

4.1 Composite analysis for three seasonal rains

Prior to examining the results of teleconnection analysis, we explored the general mechanism of rainfall variability in Bangladesh using composite analy-
sis. We developed composite maps for the anomalous fields of 850-mb vector wind and geopotential height (GPH) and precipitable water during the wet and dry years corresponding to each of the seasonal rains, identified based on the country’s average seasonal rainfall amount higher and lower the 67th and 33rd percentiles, respectively. Fig. 2 depicts the composite vector wind and GPH anomalies, and Fig. 3 shows the composite precipitable water anomalies in the wet and dry years of the three seasonal rains. During the wet years, anomalous southwesterly or southerly induced by the cyclonic circulation over northern India or the eastern coast of India are evidence for the pre- and post-monsoon rains (Figs. 2a and 2c). Surplus precipitable water can be found over Bangladesh or over the BoB (Figs. 3a and 3c), thereby supplying the moisture to the inland of Bangladesh to provide a favorable condition for the development of excess rainfall. In contrast, the anticyclonic circulation along with deficit in the moisture source can be found during the dry years of the pre- and post-monsoon rains. Regarding the monsoon rain, the wet- and dry-composites (Figs. 2b and 2b) show less prominent patterns over the country, except the clear westerly enhancement during the wet years. This could be attributed to the inconsiderable difference between the dry- and wet-year rainfall amount for the monsoon rain (see Fig. S2). Nevertheless, the low-pressure system is intensified over Tibetan plateau during the wet years, setting an environment in favor of moisture transporting from the nearby seas or the confluence with the enhanced trade winds near the equator.
4.2 Concurrent correlations between seasonal rainfall and climate indices

The range of correlation values between seasonal rainfall and climate indices were shown in Fig. 4 by using box plots. Each box plot was created with correlation values observed at the 24 weather stations across the country. Climate indices in the abscissa were ranked by the absolute value of the mean correlation in each box plot in descending order to illustrate the relative dominance of climate indices over the country. The ranking of climate indices varied from season to season. The pre-monsoon and monsoon rains showed mostly positive yet insignificant correlations with the ENSO indices, indicating the overall weak to moderate influence of ENSO on a significant portion of Bangladesh rainfall. Wide interquartile ranges (IQR) and total ranges of the correlations implied that the pre-monsoon and monsoon rains have less consistent association with large-scale climate anomalies, yet the IOD presents the highest correlations with the monsoon rain (over the SE and EH regions).

This finding is partially in line with a previous study indicating that the IOD is more influential than ENSO for the monsoon rain in the particular regions of Bangladesh [4]. Some other studies in the subcontinental scale suggested that the PDO could be another vital factor contributing to the inter-annual variability of monsoon in South Asia [38, 7, 12]. However, our study showed that even though the PDO shows slightly higher dominance than ENSO for the pre-monsoon and monsoon rains in Bangladesh, the overall correspondence between seasonal rainfall and inter-decadal indices is only modest. The post-monsoon rain showed mostly significant negative correlations with all
the indices except the AMO; the most significant association was with the EP ENSO (i.e., NINO1+2), followed by NINO3.4, IOD, and PDO. The AMO showed average positive correlations with the post-monsoon rain, indicating the drastically different association of the Atlantic Ocean in comparison with the Pacific or Indian Ocean.

4.3 Space- and time-varying patterns of correlations

4.3.1 Pre-monsoon

In general, correlations of the inter-annual climate indices with the pre-monsoon rain were modest across the country where only the IOD showed a moderate significant ($p < 0.05$) correlation (see Fig. S3). Such modest correlations with the Indian and Pacific Ocean-driven anomalies can be related to the findings of [66] who showed that the main sources of the pre-monsoon rain variability were the nearby seas, such as the BoB and Arabian Sea. Even though the overall correlations were only modest, we found noticeable space- and time-varying patterns of the correlations across the country. From Table 1 the correlations of the pre-monsoon rain with the IOD showed a gradually varied pattern progressing from negative to positive for the NW, NC, SC, and EH regions from the early to recent epochs. Time-varying correlations with the EP ENSO (i.e., NINO1+2) can also be found, and in the SC and SW regions the correlations became significantly positive in the recent epoch. Similar progression to the significantly positive correlations with the CP ENSO (i.e., NINO3.4) can be
found in the NE and SW regions. Overall, our results suggested a “changing association” between the IOD and ENSO and the pre-monsoon rain of Bangladesh. The in-phase relationship (i.e., positive correlation) with the Indian or Pacific Ocean-driven anomalies has become pronounced over several regions in the recent epoch.

Space- and time-varying patterns of the correlations with the inter-decadal indices (i.e., AMO and PDO) were also examined. The AMO and PDO were mostly positively correlated with the pre-monsoon rain across the country, especially in the early epoch (Table 1 and Fig. S4). However, in the middle to recent epochs, these positive correlations became less significant over the country, except that the NE region still showed significant correlations with both the AMO and PDO. Overall, the pre-monsoon rain in Bangladesh exhibited a more consistent, higher degree of association with the inter-decadal oscillations than the inter-annual climate indices.

4.3.2 Monsoon

The IOD and EP ENSO showed mostly in-phase association with the monsoon rain in the eastern Bangladesh with the most significant correlations observed in the SE and EH regions (Table 2 and Fig. S5). This result is in line with who showed positive anomalies of monsoon rain in the SE region during the EP El Niño events. The in-phase dominance of the IOD and NINO1+2 over the SE and EH regions can be attributed to the remote pressure dipole (i.e., high pressures over the eastern Pacific and low over the Indian region; 

[49]
along with the obstruction of southwesterly monsoonal flow to the north–south elongated hills in the east [2, 51], both of which can enhance monsoon rainfall. Besides, negative correlations (significant in the early epoch) have been observed in the NW region for the IOD index (Table 2), conforming to the findings of several previous studies [18, 57, 4]. Moreover, compared to the EP and CP ENSO, the IOD showed more significant correlations with the monsoon rains in multiple regions. The results echoed the findings of other studies reporting the increasing influence of the IOD over ENSO on Indian monsoon in the territory of Bangladesh [8, 9, 29].

Moving-window correlations between the climate indices and monsoon rain were quasi-stationary over time, unlike the evident changing association with the pre-monsoon rain. Specifically, positive correlations between the IOD (EP ENSO as well) and monsoon rain in eastern Bangladesh (e.g., NE, SE, and EH regions) were consistent over the three epochs. The most notable change in the correspondence can be found between the CP ENSO (i.e. NINO3.4) and the monsoon rain in the SC to SW regions, shifting from anti-phase to in-phase (i.e., negative to positive correlations). Our findings also corroborated that the correlation of CP and EP ENSO respectively with the monsoon over the southwestern and eastern regions tended to become positive in the recent decades, in support to that of [40] who showed that the negative relationship between ENSO and monsoon weakened after 1980s. [10] also found the weakening ENSO-monsoon relationship, attributed the enhanced concentration of greenhouse gases. La Nina’s diminishing trend and reduction in Indian mon-
soon rainfall is also responsible for the weakening ENSO-monsoon relationship in the recent time [58]. Even if the exact causes of the phase shifting (negative to positive) of ENSO’s relationship with part of Bangladesh’s monsoon rain require further investigations, [40] have reported that the southeastward movement of the Walker circulation anomalies can produce normal Indian summer monsoon rainfall even during a strong ENSO event. Other potential causes may be the co-occurrence of the IOD and ENSO events, [48, 53], and the enhanced impact of the IOD as reported by this study and others [e.g., 54, 74, 8, 9]. Similarly, [66] affirmed that the Indian Ocean contributed more moisture to the monsoon rain over the Bangladesh territory.

Among the inter-decadal indices, the AMO showed significant negative and positive correlations with the monsoon rain in western (e.g., SW and NW) and eastern (e.g., NE and EH) Bangladesh, respectively (Table 2 and Fig. S6). In particular, negative correlations in the western region strengthened in the recent epoch. The PDO showed overall in-phase, quasi-stationary association with the monsoon rain in northern Bangladesh with the most significant correlation found in the NE region throughout the period. Unlike the consistent in-phase association in the northern region, the correlation between the PDO and monsoon rain in the SE and EH regions experienced a gradual phase shift from positive to negative in the recent epoch (Table 2 and Fig. S6), partly in agreement with some previous studies [38, 61, 59, 71].
### 4.3.3 Post-monsoon

In contrast with other seasonal rains, the post-monsoon rain in the entire Bangladesh territory showed unanimous negative correlations with all the selected indices except the AMO (Table 3, Figs.5 and 6). The negative correlations with the IOD and ENSO indices, in particular, were the most significant in almost all regions, and the degree of association with these indices was stronger than that of the interdecadal indices. [70] also reported the negative correlation of the EP ENSO with the post-monsoon rain in western Bangladesh. More importantly, our study indicated that such anti-phase correspondence has become more and more pronounced over time (Table 3 and Fig.5). Negative correlations with the IOD and ENSO indices strengthened nearly everywhere from the early to recent epochs, and the hot zones of very significant correlations can be identified from the central to southern regions.

While more research is required for addressing the comparatively less prominent correlations towards the northern regions, some studies [e.g., 62] suggested that the underdeveloped northerly winds during the transition period could be one of the attributions.

Among the inter-decadal indices, the AMO exhibited significant in-phase correspondence with the post-monsoon rain in the NW region; however, some anti-phase, weak correspondence was found in the other parts of the country (Table 3 and Fig.6). Such bimodal association of the AMO with the post-monsoon rain mainly strengthened and remained consistent in the middle and recent epochs. Similar to the inter-annual indices, the PDO was negatively
correlated with the post-monsoon rain in the entire country, and the negative correlation mostly became significant in the recent epoch. Significant influence of ENSO on the post-monsoon rain in Bangladesh mostly agrees with the findings of [66], who showed that the Pacific Ocean, the BoB, and land surface were the main moisture sources inducing the post-monsoon rain in the country. Several other studies have been conducted to detect the relationship between the post-monsoon rain and ENSO in India [41, 65], and they indicated that the in-phase ENSO-post-monsoon relationship enhanced over the recent years. As opposed to their studies, for Bangladesh, our results suggested the anti-phase ENSO-post-monsoon relationship, which were further enhanced over time.

4.4 Wavelet coherence between seasonal rains and climate indices

To supplement correlation analysis, WC capable of revealing any multi-scale relationships between the seasonal rains and climate indices was calculated for all the hydrological regions. Since the multi-scale relationships are too comprehensive to be fully addressed herein, only selected regions that show the most notable WC results with the climate indices are presented in this section.

4.4.1 WC for the pre-monsoon rain

Fig. 7 shows the WC between the inter-annual climate indices and pre-monsoon (MAM) rain at different time scales. In most cases, both the Pearson’s correlation coefficient and WC plots showed similar results at shorter (e.g., 1–4 years)
time scales. For instance, the significant in-phase, short-term relationship between the IOD and MAM rain in the SC and EH regions during 1990–2000 corroborates the results of correlation analysis. In addition to the short-term relationship, WC analysis revealed some long-term correspondence between ENSO and the MAM rain in certain regions. For instance, NINO1+2 (i.e., EP ENSO) showed significant in-phase coherence with the MAM rain in the NC, SC, SW, and EH regions at longer time scales (e.g., 4–8 years and 8–16 years), some of which were undetected in correlation analysis. In the recent epoch, NINO3.4 (i.e., CP ENSO) showed significant in-phase coherence with the MAM rain in the NE region at the 1–4-year scale, in full agreement with correlation analysis. In addition, the NINO3.4-pre-monsoon rain relationship in the EH region showed the phase arrows pointing up (i.e., 90°) at the 4–8-year scale since the 1990s, indicating that the climate index led the MAM rain by 1–2 years.

In consistent with correlation analysis, the pre-monsoon rain in the NE region showed the significant in-phase associations with the AMO in the early and recent epochs (Fig. 8), yet the associations in the two epochs differed from the time scales. In the SE region, in addition to the in-phase association at the shorter time scale in line with correlation analysis, the anti-phase relationship at the longer time scale was found by WC analysis. Such phase-change result is supported with [53], suggesting the opposite relationships between the climate indices and Indian rainfall at different scales. Likewise, the MAM rain over several regions showed the significant in-phase associations at the 1–4-year
scale with the PDO in the early epoch (Table 1 and Fig. 8); however, WC analysis further revealed a clear phase change from the in-phase coherence at the shorter time scale to the anti-phase at the longer time scale in the NC and NW regions.

4.4.2 WC for the monsoon rain

Similar to the result of the pre-monsoon rain, WC for the monsoon (JJAS) rain at shorter time scales mostly supported the findings of correlation analysis. For instance, at the 1–4-year scale, the anti-phase (in-phase) association between the IOD and the monsoon rain in the NW (EH) region in the early (recent) epoch was found significant (Fig. 9). WC analysis additionally showed significant coherence at longer time scales (e.g., with the IOD in the EH region and with the NINO1+2 in the SE and EH regions). [1] reported that the strength of association between the climatic oscillations and the monsoon rain in India varied with time scales, yet our study validated the existence of this time-varying association in Bangladesh. Moreover, the IOD (and ENSO)-monsoon rain relationship in the EH region showed the phase arrows pointing up at longer time scales during 1980–2005, indicating that the climate indices led the JJAS rain by 2–4 years.

Likewise, Fig. 10 shows the WC between the inter-decadal climate indices and monsoon rain at different time scales. The significant anti-phase coherence between the AMO and NW-monsoon in the recent epoch was found (in line with correlation analysis), while the significant in-phase coherence at ≈4-year
scale during 1975–1990 (and at 8–16-year scale during 1980–2000) was identified, indicating the time-varying phase change of the AMO-monsoon relationship in this region. In another region (SW), the more consistent anti-phase coherence with the AMO was found at multiple time scales and different epochs. The significant in-phase association between the PDO and JJAS rain was detected in the NE and NC regions at different time scales. Unlike correlation analysis, the phase change of coherence in the SE region was undetected in WC analysis, suggesting the need for both analyses to better reveal any hidden time-varying association.

### 4.4.3 WC for the post-monsoon rain

In consistent with the results of correlation analysis, Fig. [11] shows the significant anti-phase relationship, at both short and long time scales, between the IOD and ENSO indices and the post-monsoon (ON) rain in the selected regions of Bangladesh. Among the climate indices, NINO1+2 showed longer-scale (8–16 years) coherence significant in all the southern and EH regions, indicating the dominant linkage of the EP ENSO with the ON rain in these regions of the country over other inter-annual indices at longer time scales. Such dominant relationship of the EP ENSO was also detected for the MAM rain (Fig. [7]) and JJAS rain (Fig. [9]) at the southeastern stations.

The WC between the AMO and post-monsoon rain was found significant in the NC regions (Fig. [12]). Such AMO-ON rain relationship indicated that the AMO led the ON rain by 1–2 years as the phase arrows pointing up during
1995–2005. Regarding the PDO-ON rain relationship, on the other hand, it was found significant in the SC region at multiple time scales (Fig. 12); significant WC can also be identified in several other regions (e.g., NE, NC, NW, SW, and SE), all of which are in good agreement with the findings of correlation analysis.

5 Concluding remarks

This study explored the teleconnections of Bangladesh’s seasonal rainfall with large-scale climate oscillations. The pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (ON) rains in the seven hydrological regions across the country were used to assess their concurrent and time-varying associations with five climate indices (i.e., IOD, NINO1+2, NINO3.4, AMO, and PDO) from 1965–2017. Such associations were assessed based on moving-window correlation and WC analyses. Our major findings are summarized below:

1. Overall, the pre-monsoon and monsoon rains were modestly associated with the SST anomalies from the Indian, Pacific, and Atlantic oceans; in contrast, the post-monsoon rain exhibited the strongest associations with these SST anomalies.

2. The pre-monsoon rain in Bangladesh was found to exhibit the time-varying associations with the IOD and ENSO; in particular, the in-phase relationship (e.g., positive correlation) became more pronounced over several regions in the recent epoch.
3. The monsoon rain in eastern Bangladesh experienced the quasi-stationary, in-phase relationship with the IOD and EP ENSO over time, whereas the monsoon rain in the south to southwestern regions exhibited the shifting relationship with the CP ENSO from anti-phase to in-phase. On the other hand, diverse associations with the inter-decadal indices were found: The AMO (PDO) showed significant negative (positive) correlation over western (northern) Bangladesh.

4. The post-monsoon rain in Bangladesh showed unanimous negative correlations especially with the IOD and NINO indices, and such significant anti-phase relationships were further enhanced from the early to recent epochs.

5. WC analysis explored the longer time-scale (e.g., 8–16 years) coherence of the seasonal rains with climate indices, supplementing the findings from correlation analysis. Moreover, some phase changes of the coherence can be detected from shorter to longer scales.

6. To summarize the most significant findings in this study, for each seasonal rain, we listed only those regions showing significant relationships with the climate indices identified from both correlation and WC analyses in Table 4. Information disclosed in the table could provide utility for establishing a more credible seasonal rainfall outlook.

Additional teleconnection patterns to those adopted in this study could potentially yield significant associations with Bangladesh’s seasonal rainfall as well, so incorporating more climate indices in the analysis is one of the
top priorities in the future. Further, from both correlation and WC analyses, we found the time-varying, multi-time-scale relationship between the climate indices and seasonal rainfall; such findings imply that it is essential to establish a nonstationary forecasting model of seasonal rainfall able to account for the regime shift in the predictor-predictand relationship [17]. Such forecasting model should be sensitive enough to automatically detect and select most contributing predictors based on preceding conditions of the large-scale environment. Effective seasonal rainfall forecasting can then be integrated into regional water resources management thereby setting a more rational scheme of water supply (e.g., determine the amount of irrigation water or the optimum timing of fallowing during drought). We are currently in the process of implementing the aforementioned forecasting model as another ongoing research task.

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Declarations

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Conflicts of Interest The authors declare that they have no conflict of interest.

Availability of data and material Data used in this study are available upon request.

Authors’ contributions K. Mahmud conducted the analysis and prepared the manuscript. C-J. Chen designed and oversaw the analysis and revised the manuscript.

Code availability Code used in this study is available upon request.
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Table 1 Maximum value of the 20-year moving-window correlations between the climate indices and pre-monsoon (MAM) rain over different regions of Bangladesh in the three epochs (E, M, R as early, middle, and recent). Significant correlations ($\alpha = 5\%$) are bold.

| Climate Index | Region | NE  | NW  | NC  | SC  | SW  | SE  | EH  |
|---------------|--------|-----|-----|-----|-----|-----|-----|-----|
| IOD E         | 0.23   | -0.27 | -0.37 | -0.55 | -0.17 | 0.28 | -0.41 |
| M             | 0.26   | 0.09  | 0.34 | 0.25 | -0.08 | 0.36 | 0.45 |
| R             | 0.37   | 0.19  | 0.40 | 0.19 | -0.14 | 0.31 | 0.40 |
| NINO1+2 E     | 0.23   | -0.28 | 0.31 | 0.30 | 0.23 | -0.22 | 0.17 |
| M             | -0.27  | -0.08 | -0.18 | 0.40 | 0.53 | 0.17 | 0.17 |
| R             | -0.23  | 0.27  | 0.33 | 0.57 | 0.63 | 0.37 | 0.27 |
| NINO3.4 E     | 0.35   | -0.29 | 0.22 | 0.18 | -0.11 | 0.20 | -0.14 |
| M             | -0.18  | -0.34 | -0.25 | 0.28 | 0.28 | 0.08 | -0.11 |
| R             | 0.57   | -0.29 | 0.18 | 0.44 | 0.47 | 0.26 | 0.28 |
| AMO E         | 0.59   | 0.33  | 0.47 | 0.46 | 0.43 | 0.52 | 0.34 |
| M             | 0.25   | 0.21  | 0.24 | 0.31 | 0.39 | 0.24 | 0.31 |
| R             | 0.58   | 0.15  | -0.25 | 0.30 | 0.42 | 0.27 | 0.42 |
| PDO E         | 0.58   | 0.47  | 0.50 | 0.62 | 0.46 | 0.57 | 0.48 |
| M             | -0.28  | -0.38 | 0.25 | 0.34 | 0.38 | 0.17 | 0.28 |
| R             | 0.48   | -0.28 | 0.33 | 0.36 | 0.43 | 0.21 | 0.34 |
### Table 2
As in Table 1, but for the monsoon (JJAS) rain.

| Climate Index | Epoch | NE  | NW  | NC  | SC  | SW  | SE  | EH  |
|---------------|-------|-----|-----|-----|-----|-----|-----|-----|
| IOD E         |       | 0.36| -0.49| 0.30| 0.48| -0.41| 0.69| 0.65|
| E             |       | 0.23| 0.08| 0.11| 0.32| 0.34| 0.47| 0.54|
| R             |       | 0.40| -0.32| -0.27| -0.34| 0.38| 0.37| 0.66|
| NINO1+2 E     |       | 0.28| -0.23| 0.27| 0.24| -0.25| 0.47| 0.38|
| M             |       | 0.25| 0.32| 0.36| 0.25| 0.18| 0.44| 0.42|
| R             |       | 0.31| 0.23| 0.24| 0.20| 0.15| 0.18| 0.48|
| NINO3.4 E     |       | -0.27| 0.29| 0.33| -0.31| -0.22| 0.25| 0.40|
| E             |       | 0.08| 0.17| 0.30| 0.16| 0.42| 0.27| 0.37|
| R             |       | -0.22| 0.17| 0.26| 0.42| 0.55| 0.18| 0.28|
| AMO E         |       | 0.38| 0.42| -0.23| 0.33| -0.32| -0.34| 0.22|
| M             |       | 0.45| 0.44| 0.19| 0.43| -0.25| 0.58| 0.54|
| R             |       | 0.29| -0.47| -0.35| 0.40| -0.63| -0.39| 0.33|
| PDO E         |       | 0.46| 0.28| 0.33| 0.29| 0.23| 0.38| 0.46|
| M             |       | 0.47| 0.34| 0.40| -0.14| 0.29| 0.26| 0.29|
| R             |       | 0.49| 0.41| 0.50| 0.32| 0.27| -0.25| -0.30|
Table 3 As in Table 1, but for post-monsoon (ON) rain.

| Climate Index | Climate Epoch | Region | Index | NE  | NW | NC | SC | SW | SE | EH |
|---------------|---------------|--------|-------|-----|----|----|----|----|----|----|
| IOD           | E             | -0.30  | -0.28 | -0.30 | -0.43 | -0.42 | **-0.45** | -0.38 |
|               | M             | **-0.49** | -0.42 | **-0.50** | **-0.62** | -0.60 | -0.70 | **-0.58** |
|               | R             | **-0.57** | **-0.59** | **-0.57** | **-0.73** | **-0.67** | -0.69 | -0.50 |
| NINO1+2       | E             | -0.37  | -0.21 | -0.32 | **-0.64** | -0.51 | -0.60 | -0.38 |
|               | M             | **-0.59** | -0.46 | **-0.63** | -0.60 | -0.54 | -0.66 | **-0.54** |
|               | R             | **-0.76** | -0.46 | -0.69 | -0.69 | -0.55 | -0.72 | -0.60 |
| NINO3.4       | E             | -0.30  | **-0.57** | -0.44 | **-0.66** | **-0.66** | -0.62 | **-0.59** |
|               | M             | -0.42  | -0.39 | **-0.48** | **-0.46** | -0.40 | **-0.45** | **-0.45** |
|               | R             | **-0.53** | -0.33 | **-0.58** | **-0.67** | -0.44 | **-0.58** | **-0.50** |
| AMO           | E             | -0.26  | -0.22 | 0.12 | 0.23 | -0.25 | -0.31 | -0.24 |
|               | M             | **-0.31** | **0.47** | -0.23 | 0.29 | 0.35 | 0.19 | **-0.36** |
|               | R             | -0.18  | **0.45** | -0.24 | 0.35 | 0.40 | 0.23 | -0.26 |
| PDO           | E             | -0.15  | -0.14 | -0.29 | -0.43 | **-0.49** | **-0.54** | -0.32 |
|               | M             | **-0.32** | **-0.51** | -0.39 | -0.39 | -0.28 | -0.30 | -0.18 |
|               | R             | **-0.47** | **-0.46** | **-0.62** | **-0.54** | -0.29 | **-0.46** | **-0.34** |
Table 4 Summary of Bangladesh’s seasonal rainfall over sensitive regions showing “both” significant correlation and wavelet coherence with climate indices. Minus sign indicates negative correlation or anti-phase coherence (otherwise positive correlation or in-phase coherence). In the superscript (subscript), E, M, or R denotes significant correlations (WC) identified in the early, middle, or recent epochs. In the subscript, S or L depicts the short or long time scale of WC.

| Climate Index | Pre-monsoon | Monsoon | Post-monsoon |
|---------------|-------------|---------|--------------|
| IOD           | -SC^E_{E,L}, EHM^R_{E,M,L,S} | -NWE^E_{E,S}, SC^E_{M,L,R} | -NE^E_{E,M,L,R}, -NWE^E_{E,R,S} |
|               | SE^E_{M,L,R}, EHM^R_{M,L,R} | -SC^E_{E,M,L,R}, -NWE^E_{E,R,S} | -SC^E_{M,R,S}, -SC^E_{M,L,R} |
|               | -SE^E_{E,L}, EHM^R_{M,L,R} | -SE^E_{E,L}, EHM^R_{M,L,R} | -SC^E_{M,R,L} |
| NINO1+2       | SC^R_{M,L,R}, SW^M_{R,R,L} | SE^E_{M,L,R}, EHR^R_{R,L} | -NE^E_{E,M,L,R}, -NWE^E_{E,R,S} |
|               | -SC^E_{E,M,L,R}, -NWE^E_{E,R,L} | -SE^E_{E,L}, EHM^R_{M,L,R} | -SC^E_{M,R,L} |
| NINO3.4       | NE^R_{E,R,S}, SW^R_{E,R,L} | -NWE^E_{E,R,S} | -NE^E_{E,M,L,R}, -NWE^E_{E,R,S} |
|               | -SE^E_{E,L}, EHM^R_{M,L,R} | -SE^E_{E,L}, EHM^R_{M,L,R} | -SE^E_{E,L}, EHM^R_{M,L,R} |
| AMO           | NE^E_{E,R,S}, SC^E_{E,R,L} | -NWE^E_{E,R,S} | -NE^E_{E,M,L,R}, -NWE^E_{E,R,S} |
|               | -SC^E_{E,L}, SE^E_{E,R,L} | -SC^E_{E,L}, SE^E_{E,R,L} | -SC^E_{E,L}, SE^E_{E,R,L} |
| PDO           | NE^E_{E,R,L}, NWE^E_{E,R,L} | NE^E_{E,R,L}, NCR^E_{E,R,L} | -NE^E_{E,R,L}, -NCR^E_{E,R,L} |
|               | EH^E_{E,R,L}, SW^E_{E,R,L}, SC^E_{E,R,L} | -NE^E_{E,R,L}, -NCR^E_{E,R,L} | -SC^E_{E,L}, -SC^E_{E,R,L} |
|               | SE^E_{E,R,L} | -SE^E_{E,L}, EHM^L_{E,M,R} | -SE^E_{E,L}, EHM^L_{E,M,R} |
Fig. 1 Location of the selected meteorological stations in the seven hydro-climatic regions: North West (NW), North East (NE), North Central (NC), South Central (SC), South West (SW), South East (SE), and Eastern Hill (EH).
Fig. 2 Composite maps of 850-mb vector wind and geopotential height (GPH) anomalies over Bangladesh and its surrounding regions during wet (left column) and dry (right column) years for the (a) pre-monsoon (MAM), (b) monsoon (JJAS), and (c) post-monsoon (ON) seasons using NCEP/NCAR reanalysis datasets during 1965–2017 (with 1981–2010 as climatology). The arrow and shading indicates wind speed and GPH, respectively.
Fig. 3 As in Fig. 3, but for composite maps of precipitable water anomalies
Fig. 4 Concurrent correlations between the climate indices with (a) pre-monsoon, (b) monsoon, and (c) post-monsoon rains across the country. Each boxplot is derived from 24 correlation coefficients corresponding to the selected stations in Bangladesh. In each boxplot, the red dot denotes the mean value of the 24 correlation coefficients, and the circles indicate outliers (falling outside of $1.5 \times$ IQR).
Fig. 5 Spatial variations of correlations between Bangladesh’s post-monsoon rain and inter-annual climate indices (Row 1 for IOD, 2 for NINO1+2, and 3 for NINO3.4). In each row, the first map shows the concurrent correlations for the whole study period, followed by maximum moving window correlations (Max r) for early, middle, and recent epochs. Max r indicates that the correlation at each station used to produce the plot is the maximum one (in absolute value) of the moving window correlations in the designated epoch.
Fig. 6 As in Fig. 5, but for the inter-decadal climate indices (Row 1 for AMO and 2 for PDO).
Fig. 7  Wavelet coherence between the inter-annual climate indices (Row 1 for IOD, 2–3 for NINO1+2, and 4 for NINO3.4) and pre-monsoon (MAM) rain of selected stations showing most significant results. Black lines indicate significant coherence at 5% level. Arrows pointing left (right) denote anti-phase (in-phase) correspondence between two time series. The cone of influence indicates areas affected by the boundary assumption.
Fig. 8 As in Fig. 7, but wavelet coherence between the inter-decadal climate indices (Row 1 for AMO and 2–3 for PDO) and pre-monsoon (MAM) rain.
Fig. 9 As in Fig. 7, but for the monsoon (JJAS) rain (Row 1 for IOD, 2 for NINO1+2, and 3 for NINO3.4).
Fig. 10 As in Fig.8, but for the monsoon (JJAS) rain (Row 1 for AMO and 2 for PDO).
Fig. 11 As in Fig. 7, but for the post-monsoon (ON) rain (Rows 1–2 for IOD, 3–4 for NINO1+2, and 5 for NINO3.4).
Fig. 12  As in Fig.8, but for the post-monsoon (ON) rain (left for AMO and right for PDO)
Supplementary Files

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