# Inter-annual Variation of Summer Southwest Monsoon Rainfall over the Monsoon Core Region of the Eastern Bay of Bengal and its Relationship with Oceans

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## Abstract

Using rainfall data from the Observation and, ERA5 reanalysis of sea surface temperature, this study examined the inter-annual variation of summer southwest monsoon rainfall on the eastern Bay of Bengal (BoB) mainland Indochina regions associated with ENSO. The composite study exhibits decreased rainfall in the eastern coastal region of BoB, and an increase in the northern Indo-Myanmar region during the developing phase of El Nino, but vice versa during the decay phase. Morlet wavelet power-spectrum analysis was performed on normalized rainfall anomalies to investigate the presence of significant signals that might be embedded in the study period. Further correlation analysis demonstrates that abnormal rainfall in the above two regions is controlled by different mechanisms. The Monsoon Core region rainfall anomaly is related to local convection and water vapor flux in the developing phase of El Niño. The anomalous anticyclone circulation in the upper troposphere helps strengthen rainfall. A strong/weak Myanmar southwest monsoon (MSwM) in the developing or decaying phase of El Niño can bring excess/less moisture to wet/dry the local southwest summer rainfall. In northern Indo-Myanmar, the anomalous rainfall is not only on the intensity of the MSwM but also on the frequency of western disturbances, and further findings need to be studied.

**Keywords:** Mainland Indochina, Southwest Monsoon, Rainfall, ENSO, MSwM

# 1. Introduction

The MSwM has an important for the social and economic activities of residents within its zone of influence. Previous studies found that large air-sea interactions, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), are essential factors contributing to variations in precipitation [1]–[4]. El Niño alters atmospheric circulation and affects the climate remotely via atmospheric wave adjustments by changing the atmospheric convection over the central-to-eastern equatorial Pacific [5], [6]. In this study, we will consider the area average of mainland Indochina region, between latitude of 5°N-40°N and longitude 80°E-120°E (see **Fig. 1)**. Numerous studies have investigated the relationships between ENSO and regional climate of Northern Indian Ocean (NIO) [7]–[9]. Many studies investigated the feedback of the IOD on the climate of the NIO and its neighbouring regions [10]–[12]. Sein et al., (2022) and Tsai et al., (2015) found a high correlation between the ENSO, IOD, and mainland Indochina rainfall, especially in Myanmar. During the MSwM season, the considerable rainfall amount can found across Myanmar, with the northern study region is significantly up above than the rest of the country. The rainfall over study area is directly correlated with the positive phase of the ENSO and the positive phase of IOD, implying that El Nino events result in flood events in the region during JJAS [15].

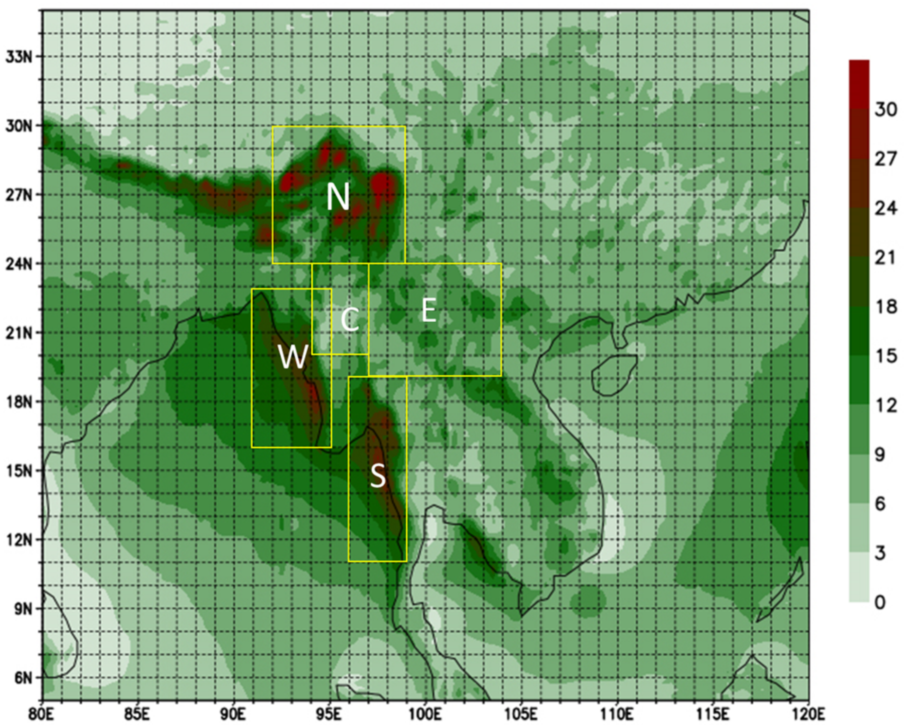


**Fig. 1** – *The climatology JJAS rainfall (mm per day) on mainland Indochina during 1981-2020. The yellow box shows the divided region for the further analysis by homogeneous rainfall distribution zones.*

The present study finding the southwest summer rainfall of the study region linked with ENSO events. The results exhibited that an opposite response of summer rainfall anomalies to the developing and decaying phases of El Niño. We propose a mechanism different from that of previous research to explain the variation of precipitation southwest along the eastern BoB regions. The remainder of the study is constructed as follows: the data and methodology is explained in Section 2; Section 3 figured out the characteristics of the summer rainfall and gives the results of composite and correlation analyses and discussion; and Section 4 presents a summary of this study.

## 2. Data and Methods

ERA5 reanalysis dataset (0.25° x 0.25° spatial resolution) is applied for this study from 1981 to 2020 [16]. Actual rainfall data from 79 observation gauges of meteorological stations from the Department of Meteorology and Hydrology, Government of Myanmar (DMH) are used to test the confident level of reanalysis data (Fig. 2). The sea surface temperature (SST) of ERA5 dataset are used to defined the indices, Dipole Mode Index (DMI) and El Nio–Southern Oscillation (ENSO). We define the average anomalous SST of the NINO3.4 index, the India Ocean Dipole (IOD) and its index DMI [17] to highlight the signal of the inter-annual variability. All the data were filtered with a 4- to 160-month band-pass filter, and their long trends were removed. The empirical orthogonal function (EOF) analysis, composite, and regression methods were used to analyze the inter-annual variations of the MSwM rainfall. And Morlet power spectrum analysis are performed to analysis the fine frequency pattern of principel component test result [18]. In addition, the normal, developing and decay years of ENSO were designated by 0, +1 and -1.

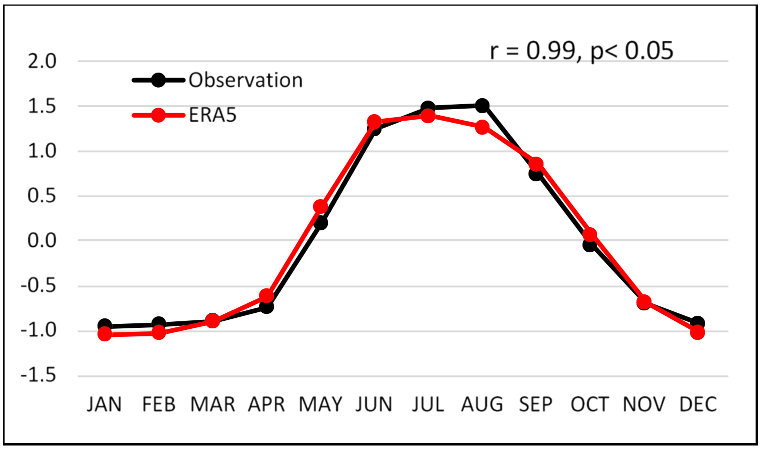


**Fig. 2** – *The relationship between ERA5 and gauged observed monthly-normalized rainfall averaged over longitudes 92ºE - 103ºE and latitudes 10ºN - 30ºN for the period 1981-2010.*

## 3. Results and Discussion

### 3.1 Precipitation differences in the two regions

The complexity of the MSwM rains has attracted a lot of interest. The root mean square (RMS) of the rainfall anomaly during the summer monsoon season (June-September, also called JJAS) over mainland Indochina showed that there are two maximum locations. The monsoon core (MC) zone, designated in Fig. 1 as "W" (91°-96°E and 16°-23°N), and "S" (96°-99°E and 11°-19°N), is situated along the eastern BoB coastline region. The other center, indicated as "N" in Fig. 1, is situated in northern Myanmar and northeastern India (NMI). In addition, it has peak daily rainfall over 92°-99°E and 24°-30°N region. This peak displays the orographic influence of the Himalayan foothills and precipitation that is tethered to mountains [18], [19].

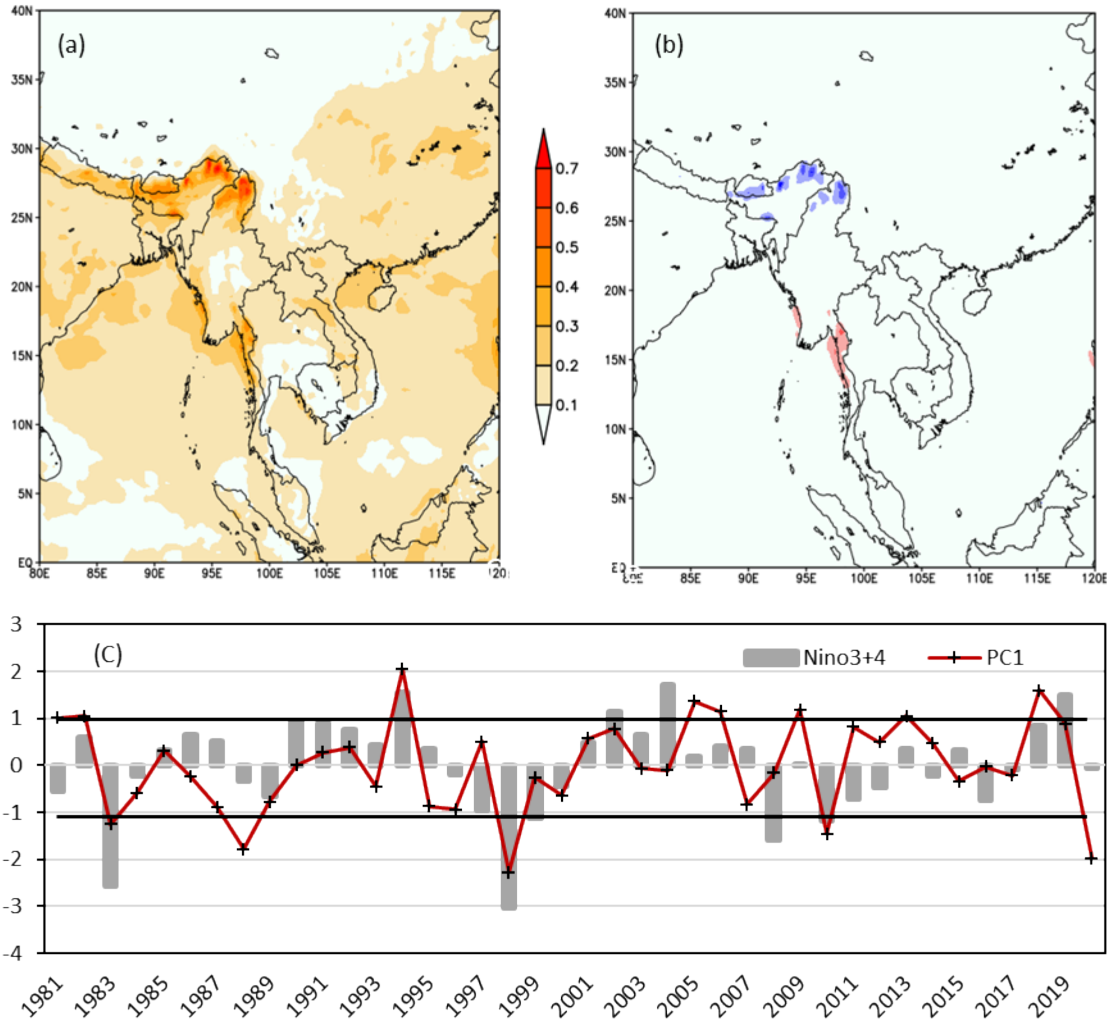


**Fig. 3** – *(a) RMS of MSwM (JJAS) rainfall anomaly; (b) 1st EOF mode of MSwM rainfall anomaly,(c) The principal components (PCs, red line) of the 1st EOF mode and the 40-year time series for the Niño-3.4 index (shaded gray, °C), two black lines marked the range of the anomaly of the PCs.*

The MSwM rainfall variability across mainland Indochina is depicted in Fig. 3.b as the EOF mode with a variance of 22.3%. With a modest reduction over the northern part of the research area along the east-west Himalaya foothill region, the EOF develops as a dipole-like mode. The monsoon core region, where extends from south to north, exhibits a significant rise, which is similar to the outcome of Fig. 3a. The EOF mode's principal components (PCs, Fig. 3c) show a clear inter-annual fluctuation. Additionally, the PCs and Nio-3.4 index exhibit the same variance tendency during both positive or negative ENSO years.

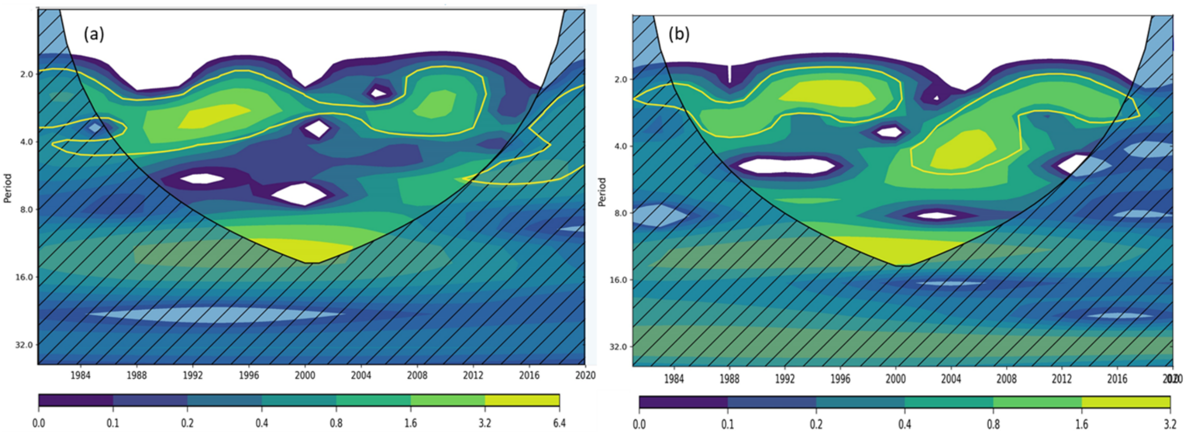


**Fig. 4** *The wavelet power spectrum of MSwM rainfall over (a) the Monsoon Core region and (b) the Northern Indo-Myanmar region from 1981 to 2020 using the Morlet wavelet method. The yellow rings represent the significance at a 95% confidence interval for the wavelet power (shaded color). The hatched lines area means the "cone of influence," which is influenced by the edge effect.*

The detrended rainfall time series was passed through wavelet analysis. It was observed 2–4 years of the power spectrum between 1988 and 2000 and between 2008-2012 with a weak signal, which is statistically significant at 95% confidence level (Fig. 4a). The power spectrum of 8-12 years was observed between around 2000, in both regions. The results indicate the inter-annual variability pattern of MSwM rainfall over the study region, which can be associated with ENSO. The power signal of NMI is weaker than MC, and the period cycle variations are not significant. The 2-4 years of the periodicity of the power spectrum was observed that be linked with IOD in summer [2]. The decadal variability of a signal has been observed in the 2000s, which can be linked with Pacific Decadal Oscillation (PDO) systems. A 2–7 year variability pattern is linked to ENSO effect, according to the previous study, whereas a 7–12 year variability pattern is linked to PDO [20]–[22].

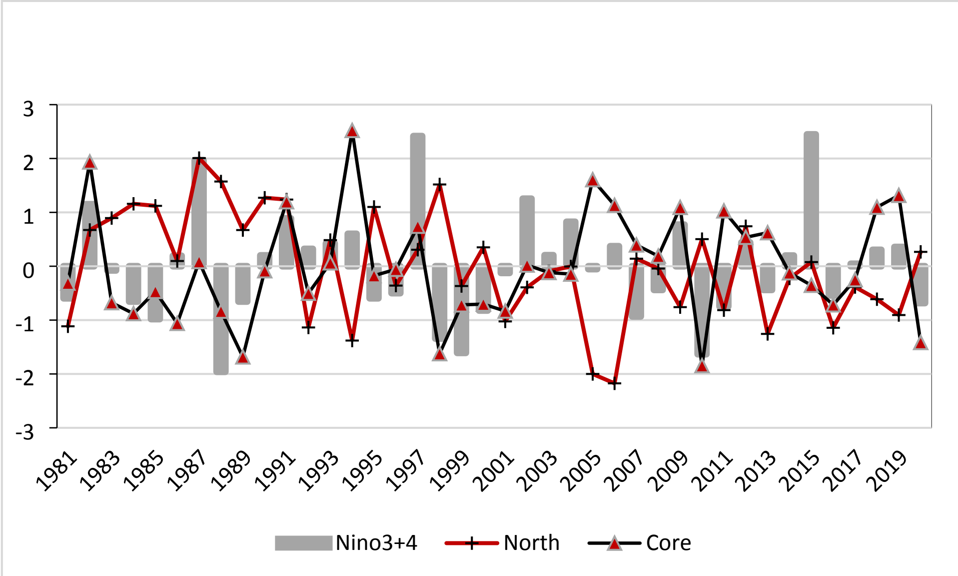


**Fig 5** – *40-year normalized time series of JJAS rainfall for the MC (black line, mm $d^{-1}$), the NMI (red line, mm $d^{-1}$), and the Niño-3.4 index (gray shaded, °C).*

Additionally, we chose the MC and the NMI (Fig. 1b, W, S, and N) since they are two relatively small domains, to thoroughly examine the rainfall pattern. A 40-year of MSwM rainfall time series for the MC, the NMI, and the Nio-3.4 index was utilized to determine whether there were any correlations between them (Fig. 5). With correlation coefficient values of 0.41 (99% significance), the result explained an antagonistic link between the MC and the NMI rainfall anomalies. Less rain falls in the NMI while the MC has above-average precipitation. With correlation coefficients of 0.48 and 0.50, respectively (all are 2-tailed significant at the 0.01 level), the Nio-3.4 and DMI index demonstrated favourable associations with the MC rainfall. The NMI rainfall, however, does not significantly correspond with any index (Table.1). This indicates that other mechanisms that are in agreement with earlier studies [19], [23], [24]. The results of the EOF analysis are supported by the climatology time series of JJAS rainfall, demonstrating the strong correlations between ENSO occurrences and MSwM rainfall over the IOD.

**Table 1**- Correlation between two regions and two Indices.

| | North | Core |
|---|---|---|
| Nino34 | -0.06 | 0.48** |
| DMI | 0.04 | 0.50** |

** Correlation is significant at the 0.01 level (2-tailed).

### 3.2 Composite results

The following years are used to create a composite to show the unusual atmospheric circulation conditions when are related the officially recognised ENSO years [25]. We chose 1981, 1982, 1994, 2005, 2006, 2009, 20131, and 2018 as positive strong cases and 1983, 1988, 1998, 2010, and 2020 as negative weak cases based on normalized anomalies above the threshold +/- 1 **(**see Fig3.c).

Fig. 6 shows the composited anomalies of rainfall in JJAS. The wet years (see Fig. 6. a) have significant positive anomalous over the main study area with a weak negative anomaly in rest of area, as in Fig. 3.b. During the dry years, a nearly similar reverse trend was seen (Fig. 6. b).

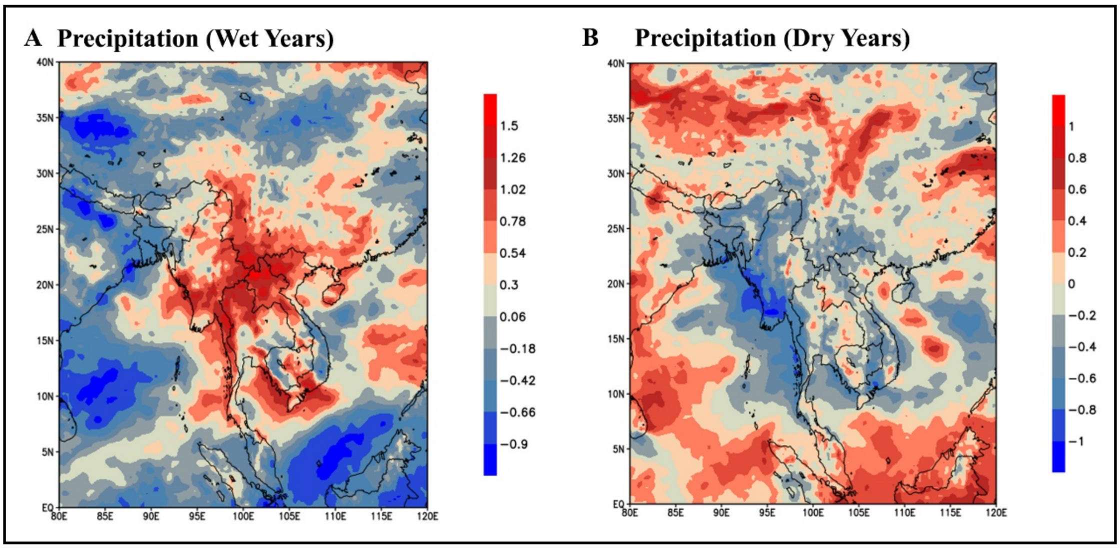


**Fig. 6** - *Composite anomalous rainfall (mm/month) of (**A**) Wet years and (**B**) Dry years by using ERA5 data between 1981 and 2020 with significance at the 95% confidence level.*

### 3.3 The Correlation Coefficient

This section presents results from correlation and demonstrates how ENSO affects the rainfall over the region. Fig.7 shows the correlation coefficient between MSwM rainfall, and the Indian Ocean (IO) and Pacific Ocean (PO) SST. The first panel shows the correlation of rainfall with SST for the normal year (JJA-0) (Fig. 7a). The result shows positive SST around the ENSO region than the rest of equatorial regions and positive dipole mode of IO has the higher correlation value with rainfall. The second panel (positive wet year cases) presents the summer JJAS(+1) in the ENSO developing phase (Fig. 7b), while the last panel (negative dry years cases) presents the JJAS(-1) in the ENSO decaying phase (Fig. 7c). However, IOD positive dipole mode can found only in wet years (Fig. 7b) with no clear pattern during dry years (Fig. 7c).

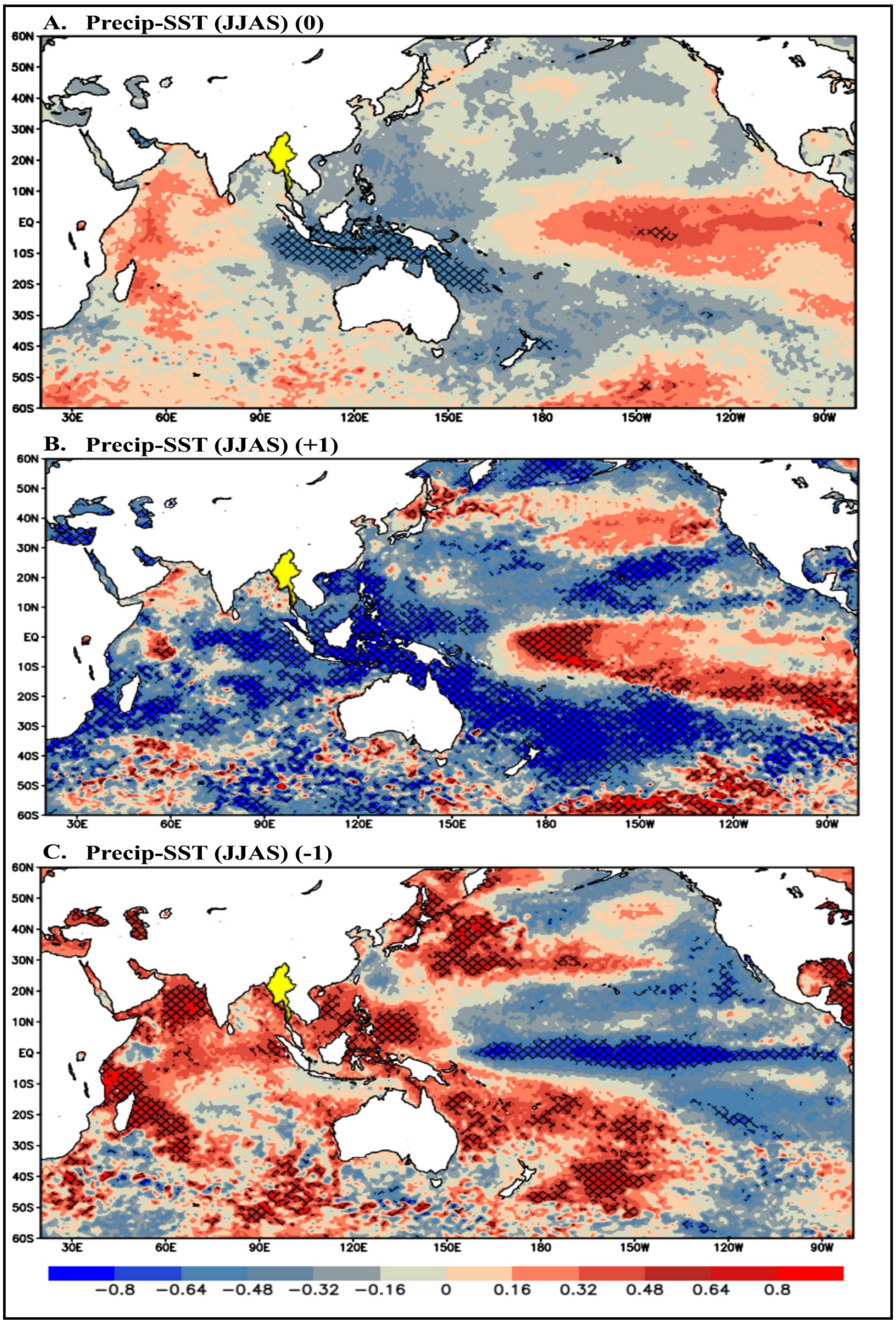


**Fig. 7** - *Correlation shaded map between the JJAS mean rainfall over the major study region (Yellow shaded) and Global JJAS SST (**A**) normal, (**B**) exceed rainfall, and (**C**) less rainfall years based on the result of **Fig.3c**, respectively.* A *significant correlated (hatched) area is displayed at the 95% of confidence level.*

Over 40 years (1981-2020), there is a correlation and a lagged relationship between the southwest monsoon rain and SST trends (Fig. 7). It is useful to see how the JJAS rainfall varies from year to year depending on broad-scale global influences. In Fig. 7b-c, the area of statistically significant correlation is shown as the positive or negative values for both wet and dry years. The findings also demonstrated a relationship between excessive rainfall in the research area and above- or below-average SST in the PO, Nino 3-4 (ENSO) and western IO with the opposing pattern of eastern IO (DMI). More information regarding the results of the statistical study can be found below.

**Table 2** - A lagged association between rainfall and index based on **Error! Reference source not found.**

| Index | JJAS(Normal) | JJAS(Wet) | JJAS(Dry) |
|---|---|---|---|
| **NINO** | 0.36 (p=0.24) | 0.20 (p=0.75) | **-0.76 (p<0.05**) |
| **DMI** | 0.44 (p<0.01) | **0.82 (p=0.09)** | 0.37 (p=0.41) |

The fluctuation in southwest monsoon rainfall from 1981 to 2020 was somewhat positively correlated with the SST anomalies of ENSO (r = 0.36, p = 0.24) and DMI (r = 0.44, p 0.01). When there are wet years, the Nino index exhibits a negative contemporaneous reaction with a highly significant association of 0.82 (p 0.09) with DMI (**Table 2**). On the other hand, it exhibits favourable negative values – 0.76 (p = 0.41) for ENSO with positive DMI (r = 0.82, p 0.09). Both indices are well defined for the future prediction of the study area for JJAS rainfall.

The outcomes are in line with the earlier composite study (Fig. 3.b). Over the studied area, the dipole-like form of rainfall is accurately portrayed. The results suggest that warming or cooling of the IO can either boost or lessen ENSO's influence on summer monsoon rainfall [8]. Moreover, the exceed rainfall over the study regions is linked to positive SST in the IO and the PO especially in equatorial region, which promote the reaction of the Hadley and Walker Circulation. [26]. Warming PO and IO boost convective activity of that region, which helps the Subtropical Westerly Jet (SJW) to fluctuate across the Indian continent [27]. The existence of the divergence above PO and convergence upper air circulation over IO at equatorial 200 hPa layer support in brought moisture from ocean to continent and supports the rainfall pattern during the wet years. However, reverse pattern can be found in dry years (see Fig.8 a, b). Moreover, the warm up over the Asia continent and cool down over IO (see Fig.8a) correspond to the north-south transfer of moisture for the MSwM regions during wet years, with the opposite circulation patterns are found in the dry years(see Fig. 8b**).**

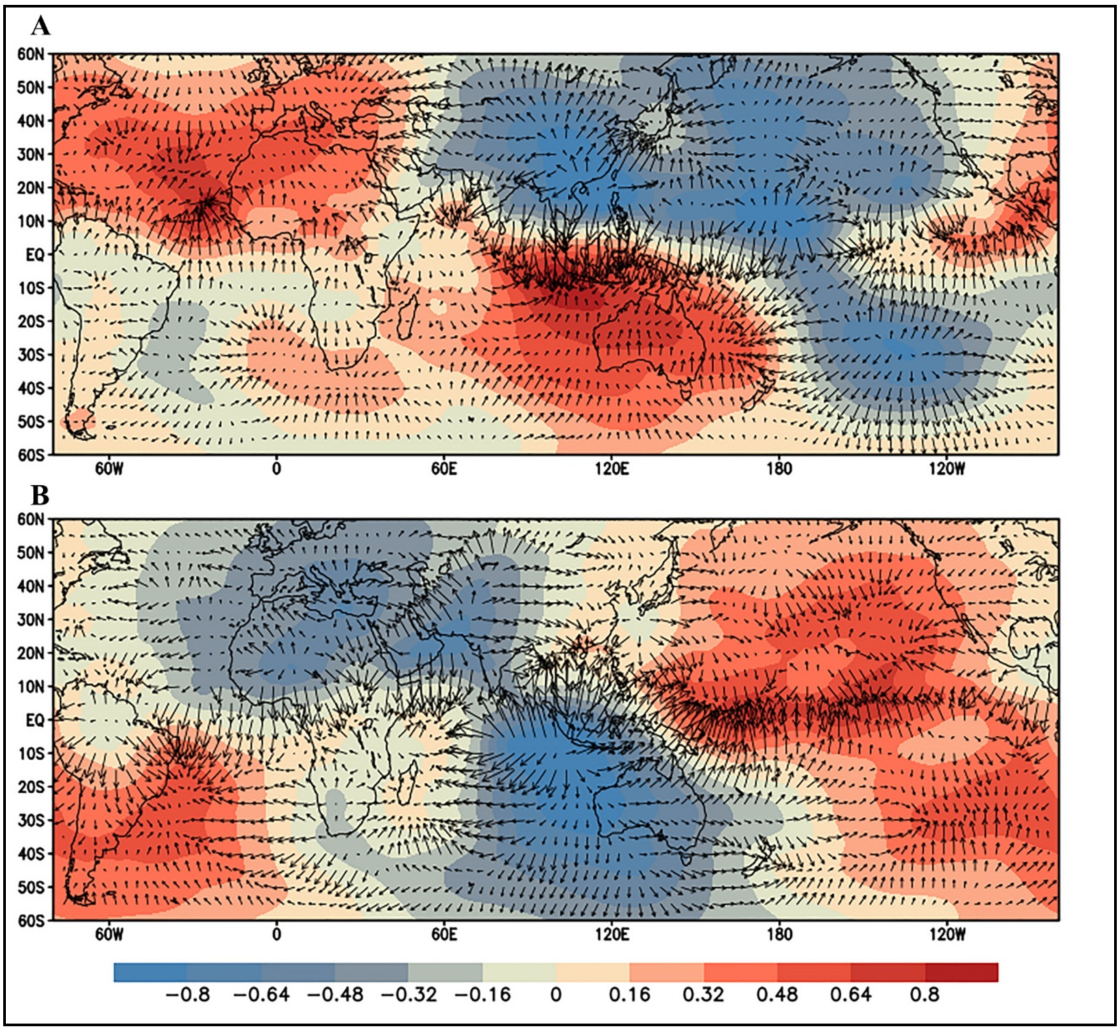


**Fig. 8** - *200 hPa convergent/divergent winds and velocity potential (shaded, m2 s$^{-1}$) for (**A**) wet years and (**B**) dry years during 1981-2020.*

The Walker circulation on two ocean areas for wet years (as El Niño years) is show in Fig.8a. The shifting pattern indicates that ENSO remoted the Indo-Pacific Walker Circulation, which was found over tropical equatorial region of both oceans, by the pattern of ascending regions over the mainland Indochina and PO, and descending over the IO, respectively, for wet years (see Fig. 8a). Similarly, the ascending (rising) shifting movement over the warming mainland Indochina and the descending (sinking ) atmospheric movement over the cool down eastern IO have a strong Hadley circulation resulting in the wet years, with reverse shifting in dry years.

## 4. Conclusions

The key investigation of this study is that cooling and warming of the two of global major oceans (PO and IO) SST have the teleconnection to the inter-annual variability of MSwM rainfall over the eastern BoB region, such as: IOD (DMI) and ENSO (Nino3-4). Furthermore, less rainfall can be expected during La Nia and excess during El Nino phases of PO with DMI negative and positive. This study investigated the inter-annual variations of monsoon rainfall in the regions MC and the NMI. Variations related to the atmospheric circulation linked with ENSO and IOD were found. Our primary analysis was based on EOF methods, composites, and correlation of MSwM rainfall referenced to the Niño-3.4 SST and DMI SST index.

A correlation analysis between rainfall, IOD, and Niño-3.4 found a positive correlation over the MC but a weak correlation at the NMI in the MSwM season following El Niño (JJAS(+1)). Their results suggested that the feedback of the NMI rainfall to ENSO varies greatly from case to case due to the rainfall over NMI being driven by other mechanisms. We double-check the correlation, as shown in Fig. 7 and 8, and find that it is alike to the previous studies' results. Why do the EOF and correlation illustrate a close relationship between MSwM rainfalls with ENSO over the NMI with very low values? High monsoonal variations that are independent of ENSO could be the cause. Another factor could be the variable regional responses to the various climate regimes. We leave the door open for further research on this issue.

## Data Availability

### Source Data

Reanalysis rainfall, SST netcdf4 data for this study were downloaded from the ECMWF data portal. This is a fifth-generation ECMWF reanalysis dataset with a geographical resolution of 0.25°x0.25° for global climate parameters over the previous decades are used to support the findings of this study and are included within the article. Data is now freely available from 1950 to the present by registration at ECMWF [28].

The actual monthly rainfall observation data from 79 observation stations used to support the findings of this study was provided under permission by Myanmar's Department of Meteorology and Hydrology (DMH) and hence cannot be freely distributed. Requests for access to these data should be made to the Director-General of DMH, Myanmar. https://www.moezala.gov.mm/

### Software availability

Open Grads (OpenGrADS - Home), Climate data operator (https://code.mpimet.mpg.de/ ), and IBM SPSS are mainly used for this study. Among these first two are open-source applications for everyone.

## Conflicts of Interest

I declared that there is no potential conflict of interest with any of the following statements.

1. For any component of the submitted work, the author received no cash or services from a third party (government, commercial, private foundation, etc.). (including but not limited to grants, data monitoring board, study design, manuscript preparation, statistical analysis, etc.).
2. The author is not affiliated with any entity that has a direct or indirect financial interest in the manuscript's subject matter.
3. The author was involved in the following aspects of the project: (a) idea and design, or data analysis and interpretation; (b) authoring the article or critically reviewing it for essential intellectual content; and (c) approval of the final version.
4. This work has not been submitted to and is not currently being reviewed by, any other journal or publishing venue.
5. The author has no patents that are broadly relevant to the work, whether proposed, pending, or issued.
6. The author received no payment or services from a third party for any aspect of the submitted work (government, commercial, private foundation, etc.). (including but not limited to grants, data monitoring board, study design, manuscript preparation, statistical analysis, etc.).

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