Interaction of Sea Surface Temperature and Precipitation during Indian Ocean Dipole years in the Bay of Bengal

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Abstract

Satellite data of Sea Surface Temperature (SST) and Precipitation from the Tropical Rainfall Measuring Mission (TRMM) were analyzed to investigate the interactions between them in Indian Ocean Dipole (IOD) years in the Bay of Bengal (BoB), located at 5° N - 25° N and 80° E-100° E region. In an agricultural country like Bangladesh, the success or failure of sufficient rainfall and its effects on agricultural production and water scarcity on regional basis are always of great concern. Even, a small fluctuation in the seasonal rainfall can have devastating impacts on agricultural sector. Understanding of these variability's especially the extreme droughts and floods are of great importance because the country's economy has bounded with the availability of monsoon rainfall. The SST has shown a significant relation with precipitation but there was some time lag. However, IOD did not show much regular influences on precipitation pattern. The investigation also reveals that SST was not the main parameter to occur the precipitation variation in the Bay. There may exist some other factors such as oceanic heat content, incoming solar radiation, wind etc, which might influence the seasonal/annual precipitation. Future study may reveal the other factors that control the precipitation pattern in the Bay including the whole Bangladesh land.

Keywords: Bay of Bengal, IOD, SST, Monsoon, Precipitation.

Introduction

The Indian monsoon has often been used as a proxy for the Asian monsoon as a whole, even when, other than the northeast part of India, there is no significant correlation between the rainfall over Bangladesh and rainfall over India (Kripalani et al. 1996). The Indian monsoon experiences strong intra-seasonal and inter-annual variations. Circulation patterns associated with such variations of the Indian summer monsoon resemble each other (Goswami and Mohan, 2001; Ferranti et al., 1997). Charney and Shukla, et al.(1981) hypothesize that tropical

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climate has a potential impact because a significant part of its long-term variability is determined by slowly varying climate parameters like SST rather than by synoptic scale variability. However, the ability of SST to predict the seasonal mean monsoon has not been firmly established (Krishnamurthy and Kirtman, 2008). It has been shown that more than 50% of the north Indian Ocean tropical cyclone intensities have negative correlation with SST (Ali et al., 2013b). Namias and Canyan, (1981)) concluded that patterns of lower atmospheric anomalies are more consistent with the upper ocean thermal structure than with SST alone.

To explore the teleconnection between sea surface temperature (SST) and summer monsoon rainfall in Bangladesh, a total of 90 yrs (1912-2001) monthly rainfall data from the months of May (pre-monsoon month), and June through September (monsoon months) and SST of the Bay of Bengal for twelve stations were thoroughly examined (Salahuddin et al., 2006). A significant positive correlation (r = 0.64) was found between the All-Bangladesh Monsoon Rainfall (ABMR) and SST over the Bay of Bengal in the month of June. All other contemporaneous monthly correlations were not found to be significant (Salahuddin et al., 2006). The teleconnections between Bangladesh summer monsoon rainfall (BSMR) and sea surface temperature (SST) anomalies over different parts of the ocean have been examined from the years 1961 to 2008 (48 yrs). The SST over the Bay of Bengal was positively correlated with BSMR but the values did not significantly differ. The correlation between SST over Indian Ocean for the month January, March, April and May, and BSMR was found to be insignificant (Rahman et al., 2013). Chowdhury (1994) identified that the positive SOI is favourable for the occurrence of floods and negative SOI for drought. Sadhuram and Murthy (2008) found that a positive high and significant correlation occurs between February SST anomaly over eastern Indian Ocean (northwest of Australia) and Indian summer monsoon rainfall (ISMR).

Indian summer monsoon, a part of the Asian monsoon system, is a regular annual phenomenon, which brings heavy rainfall to India and adjacent countries during summer monsoon season (June to September) that contributes about 70% - 90% of rainfall in most parts of the country (Shukla et. al., 2013). The rainfall during October-November-December (OND) over south India, commonly referred as winter monsoon rainfall, which contributes about 50% of annual rainfall in the east cost of Indian Peninsula (Shukla et al., 2013). The winter monsoon is highly variable both spatially and temporally. During the winter monsoon season, the prevailing wind becomes north-easterly and the zone of maximum rainfall migrates to southern India and Sri Lanka. Over the years, there are many instances of the years with flood (strong monsoon) or drought (weak monsoon)
during which South India, as a whole, receives excess or deficient seasonal rainfall, respectively (Shukla et al., 2013).

The Indian Ocean Dipole Mode Index (IODMI), defined as the area-averaged SST anomaly difference between the tropical western Indian Ocean (50°E–70°E, 10°S–10°N) and the tropical south-eastern Indian Ocean (90°E–110°E, 10°S-equator), is positive, that leads to droughts over the Indonesian region, and heavy rains and floods over the East Africa (Saji et al., 1999). The IOD plays an important role as a modulator of the Indian monsoon rainfall, and influences the correlation between the Indian summer monsoon rainfall (ISMR) and El Nino-Southern Oscillation (ENSO) (Ashok et al., 2001). The Indian Ocean Dipole (IOD) mode exerts an influence on Malaysian temperatures also. When it co-occurs with ENSO, it tends to weaken the ENSO influence particularly during October–November–December (OND). However, it appears to have an appreciable influence only during an April-May-June (AMJ) period, when it occurs in the absence of an ENSO event. Despite the strong influence of the ENSO, the warming rates during the 42-year period appears to be least affected by inter-annual variability (Tangang et al., 2007). Many researchers have studied the predictability/trends of the Indian summer monsoon using dynamical as well as statistical models (Shukla et al., 2013). Influence of ENSO and IOD on winter monsoon rainfall (WMR) has been investigated by Kumar et al. (2003) and interesting relationships were traced out. Kripalani and Kumar(2004) extended the study between the northwest monsoon rainfall and IOD. The inter-annual variation of ISMR has significantly affected the Indian agriculture and its’ economy (Webster et al., 1998). The frequent droughts and floods are the manifestations of year to year variability of ISMR (Krishnamurthy and Shukla, 2000). Ashok et al. (2004) examined the ISMR anomalies during pure IOD and ENSO events and found that while they were co-occurring, positive IOD significantly reduces the effect of El Nino on ISMR. Li et al. (2001)) established that the Indian Ocean SST has positive correlation with ISMR due to high surface evaporation.

The previous studies revealed that rainfall and precipitation can significantly affect a country’s agriculture growth including the overall economy. The distribution of SST in the Bay of Bengal as well as Indian Ocean plays a role in determining monsoon rainfall variations. The relationship between the Bay of Bengal SST and the monsoon rainfall in Bangladesh is poorly investigated, particularly with regards to predicting monsoons that usually occur 1 or 2 months earlier (Salahuddin et al., 2006). Indian Ocean Dipole (IOD) index plays an important role in shaping the weather conditions in the Indian Ocean and surrounding areas (Shaha et al., 2013). Thus the current study investigates the inter-relation among the SST, precipitation and IOD.
The specific objectives of the study are as follows:

a. To examine the precipitation variability in the Bay of Bengal
b. To examine the SST variability in the Bay of Bengal
c. To investigate the inter-relation between SST and precipitation during IOD years.

![Image](image.png)

**Figure 1.** The Study area (white colour sea portion) in the Bay of Bengal (78°E-100°E and 5°N-25°N).

**Material and Methods**

The study areas in the Bay of Bengal (78°E-100°E and 5°N-25°N) domain are shown in Fig. 1. The SST and precipitation data were collected from different sources in NETCDF format. Ferret data visualization and analysis software was used to interpret those data. The Tropical Rainfall Measuring Mission (TRMM) is a satellite-based program to measure tropical rainfall and to help quantify the associated distribution and transport of latent heat, which drives the global atmospheric system. It is a joint United States–Japan mission launched from Tanegashima, Japan, on 27 November 1997 (Simpson et al., 1996; Kummerow et al. 1998). Sea surface temperature (SST) is retrieved from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). These TMI SSTs were calculated using a radiative transfer-based retrieval algorithm, which precisely accounts for SST and wind effects on surface emissivity as well as atmospheric effects on brightness temperatures (Gentemann et. al., 2004). TMI data were produced by Remote Sensing Systems and sponsored by the NASA Earth Sciences Program. Data are available at www.remss.com/missions/tmi. Asia-Pacific Data-Research Centre (APDRC) provides several types of data sets in a
same platform. SST data from 2002 to 2015 years and precipitation data from 1998 to 2015 were downloaded from APDRC data sites derived from TRMM.

The IOD index is calculated using the Reynolds OIv2 SST analysis (Reynolds et al., 2002), made available through the IRI Data Library, and is updated weekly (retrieved on 01September-2016) from http://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php. The IOD index was downloaded for the years 1981-2015.

Results and Discussion

**Basin-averaged monthly mean SST (°C) and precipitation (mm/month)**

![Figure 2. a) Monthly climatology of SST (°C) and b) monthly variations of precipitation (mm/month)](image)

The basin-averaged SST was showed an semi-annual variability with a peak during March-April (29.8°C) and the secondary peak was during October (29.2°C) (Fig. 2a). The basin-averaged monthly mean climatology of precipitation was showed an annual peak during June-September (>7 mm/month) and lowest value showed during December-March (Fig. 2b). There was a time lag between high SST and high precipitation. Precipitation was started to increase from May and continued till September.


Long time basin averaged SST during 2002-2015 revealed a distinct Meridional variation, whereas 14°N latitude line was the boundary. Northern and western bay had showed temperature of less than 27°C, whereas southern and eastern bay showed gradually higher SST towards equator (Fig. 3a). Long time basin averaged precipitation during 1998-2015 revealed a distinct zonal variation, whereas 88°E longitude line was the boundary. Western bay had showed precipitation of less than 4.5 mm/day, whereas eastern bay exhibited gradually
higher precipitation (5-14 mm/day) towards north-east (Fig. 3b). The prevailing wind has a south-easterly component at the station, due to deflection caused by the coastal hills. Thus, the orographic effect in the east and the north-eastern part of the country appears to enhance the rainfall amounts in that area (Salahuddin et al., 2006).

**Figure 3.** Averaged SST (2002-2015) and precipitation (1998-2015) in the Bengal a) Long time basin averaged SST and b) precipitation.

**Monthly mean climatology of SST**

The spatial distribution of sea surface temperature (SST) during January exhibited a decrease from south to north direction. The lowest SST of 25 °C was seen in north, while the highest of 29.5 °C was seen near the south-eastern corner of the
bay. The spatial distribution showed 4.5°C cooling from south to north direction (Fig. 4.Jan). In February, the SST distribution was similar to that of January except the region of warmer temperature extended further towards north.

The highest SST of 29.5°C was seen in the south-east corner. The coolest temperature in the north was 25°C which was confined compared to January. The meridional difference in SST was 4.5°C (Fig. 4.Feb). During March the basin-wide SST showed a general warming of 1°C compared to previous month, though the variation from south towards head bay reduced (3.5°C) compared to February. The lowest SST of 26.5°C was seen in the north, while the highest of 30°C was seen near the south-east corner of the bay (Fig. 4.Mar). The warming trend was seen during March and further intensified in April, whereas temperature increased to 30-31°C in the south of 14°N. But the lowest SST was 29.5°C near the north-western corner and the highest of 31°C was found along the south, south-east and also south-western coast. A further reduction of the spatial contrast of SST from north to south direction reduced to 1.5°C in April indicating the basin-wide warming (Fig. 4.Apr). The basin-wide SST was the warmest in May with highest value of 31°C near the northern bay. The SST, in general, was in excess of 30°C along the bay but the region surrounding the southern part of Sri Lanka showed a distinct cold water patch (29.5°C). The basin-wide SST contrast further reducing by 1.5°C, indicating the continuous warming in May (Fig. 4.May). In June the basin-wide SST exhibited a cooling of less than 28.5°C along the southern bay. The most prominent feature of the SST distribution was a region of cold water patch extending from southern part of Sri Lanka with a thermal front. This patch was 1.5°C cooler than the ambient temperature. The meridional difference of SST was 2°C. The basin-wide SST was reduced to ~30°C (Fig. 4.Jun).

In July, the basin-wide SST of 29°C was noticed. But the exception was in the region west of Sri Lanka, which was showed further cooling. The lowest SST was 28°C, which was 1°C cooler than the ambient water temperature. The cold water patch extended towards the north-eastern bay with an average of 28°C, was further extended towards the north (Fig. 4.Jul). The cold water patch was extended maximum towards the north-eastern bay with an average of 28°C during August. The lowest SST was about 27.5°C and the highest was about 30°C (Fig. 4.Aug). The basin-wide SST pattern was reduced in September compared to the previous month except the coastal warming near head bay and north-eastern bay. The cold SST region, which encompassed the southern tip of the Peninsular India and Sri Lanka, was confined in a small area (Fig. 4.Sep). In October, this cold water was about to vanish and the basin-wide SST showed a warming (29.5°C) once again. The low spatial variation of 2°C was observed again during October (Fig. 4.Oct). The northern bay showed cooling trends in November with SST of 27.5°C. This SST was about 1.5°C cooler than the rest of the basin (Fig. 4.Nov).
This cooling was further intensified in December with the lowest SST of 25.5°C in the northern bay. The meridional temperature difference was about 4.5°C with the warmest waters of 29.5°C to the southern bay (Fig. 4.Dec). During December-February, low temperature occupied the northern bay, while during April-May, the highest temperature occupied almost the entire bay. During June-July and October the bay was experienced with moderate temperature but southern part of it showed comparatively lower temperature (Fig.4).

**Figure 4.** Monthly climatology of SST °C during 2002-2015

In summary, SST was showed a strong seasonal (semi-annual) cycle. The amplitude of the seasonal cycle in the north was about 6°C with the coolest of about 25°C during January and the warmest of 31°C during May and October.
The amplitude of the seasonal cycle in the south was about 3°C with coolest of 28°C during August and the warmest of 31°C during April - May. The seasonal cycle of SST showed two warming period during April-May and October. The highest spatial variability occurred during January when SST varied 6°C from south to north direction. The least spatial variability occurred during May, which was about 2°C. An interesting feature of the SST distribution in the southwestern bay was the appearance of a thermal front with a region of cold water around Sri Lanka in May. This thermal front further developed in June and peaked in August. By October, this feature was about to diminish. This must be associated with Indo-Sri Lankan upwelling system (Fig.4). When the SST is contemporaneous with or leads the summer monsoon season, a strong relation between the SST and monsoon rainfall has not been detected, as expected by the Charney-Shukla hypothesis. A possible reason is that, on a daily or sub-seasonal time scale, the intra-seasonal variability of the monsoon may be masking the atmospheric response due to slowly varying components such as ENSO (Krishnamurthy et al., 2008).

Monthly mean climatology of precipitation
The spatial distribution of precipitation in January showed very little precipitation (< 4 mm/day) in the region south of 8°N, while no precipitation was noticed in north of the line. The maximum value was observed in the region along Sri Lanka (Fig.5.Jan). In February most part of the Bay showed no precipitation, while near Sri Lanka the magnitude of precipitation was decreased compare to the previous months (Fig.5.Feb). During March, the entire bay exhibited a similar precipitation pattern like February (Fig.5.Mar). In April, the entire bay showed a slight increasing precipitation pattern towards north-east compared to that of March, but the intensity was low (< 4 mm/day) like that observed in January-March (Fig.5.Apr).

In May, the spatial distribution pattern of precipitation was changed from meridional to zone, across the western bay (highest values of 4 mm/day) to eastern bay (highest values of 24 mm/day). The precipitation was started to increase during May, especially along the north-eastern corner (Fig.5.May). The precipitation exhibited a drastic change in its distribution patterns during June with a higher precipitation in the bay except the region close to Sri Lanka and Indian coast. Huge net precipitation was concentrated in a region encompassing the north-eastern bay with the maximum value of 36 mm/day. The spatial variation showed the maximum value of 30 mm/day from west to east direction (Fig.5.Jun). Salahuddin et al. (2006)) reported a significant positive correlation between Bangladesh summer monsoon rainfall (BSMR) and SST over the Bay of Bengal in the month of June but all other contemporaneous monthly correlations were not found to be significant. In July, the pattern of precipitation remained similar, but
the magnitude was higher. The highest precipitation of 40 mm/day was found in the north-eastern bay. The precipitation was more extended towards north. However, the precipitation around Sri Lanka was observed to be very low, which was similar to the values of May-June. This was the highest precipitation compared to other months. The spatial variation showed maximum of 32 mm/day from the west to east direction (Fig.5.Jul). During August, the distribution pattern was similar to that of July with a tapering effect (Fig.5.Aug). In the month of September, the entire bay showed drastic reduction of precipitation with highest value of 20 mm/day near the north-eastern part of the bay (Fig.5.Sep).

Figure 5. Monthly climatology of precipitation (mm/day) during 2002-2015

In October, the precipitation showed further reduction in its values, while the entire Bay showed a similar precipitation (< 10 mm/day) (Fig.5.Oct). In November, the spatial distribution pattern changed again from zonal to meridional, whereas precipitation was reduced towards the north. The maximum precipitation was observed near south-western bay, which was about < 12 mm/day. The spatial variation showed 10 mm/day from north to south (Fig.5.Nov). During December, precipitation was found to be similar to
November but intensity was different. In the south the precipitation exhibited an increasing trend with maximum value of 16 mm/day near Sri Lanka. The spatial variation was observed to be the maximum of 14 mm/day from north to south direction (Fig.5.Dec).

**Time-series of SST, Precipitation and IOD pattern**

![Time series of SST, Precipitation and IOD pattern](image)

**Figure 6.** Time series of (a) SST from 2002-2015, (b) precipitation from 1998-2015 and (c) IOD index from 1981-2015

The basin-averaged monthly time-series of precipitation for the year 1998 to 2015, showed less variability. The annual pattern of variability was clearly discernible with peak precipitation occurs during June -August. There was an increasing trend of precipitation from 2010-2014 and also a slight increasing trend from 2002-2004 (Fig. 6.a). The basin-averaged monthly time-series of SST for the year 2002 to 2015, showed fluctuating patterns. The annual pattern of variability was clearly discernible with the peak SST that occurs during April-May. There was an increasing trend of peak SST from 2002-2005 and also from 2011-2015 (Fig. 6.b). The basin-averaged monthly time-series of Indian Ocean Dipole (IOD)
for the year 1985 to 2015, showed very fluctuating patterns. The black vertical dot line represented positive IOD years and red vertical dot line represented negative IOD years. There were some positive IOD years such as: 1982, 1983, 1991, 1992, 1995, 1998, 2007, 2009, 2013 and 2016 and negative IOD years such as: 1984, 1993, 1997, 1999, 2002, 2011, 2014 (Fig. 6.c). The air–sea interaction process is unique and inherent in the Indian Ocean, and is shown to be independent of the El Nino/Southern Oscillation (Saji et al., 1999). They also found the correlation between the IOD and ISMR and claimed that the relationship between the IOD and Indian Monsoon is not clear. The relation between IOD year and precipitation was not so significant (Fig. 6). The IOD events affect the Indian summer monsoon on their own and thus apparently weaken or strengthen the influence of the ENSO on the ISMR (Ashok et al., 2001). Rahman et al. (2013)) identified that the impact of ENSO on Bangladesh summer monsoon rainfall (BSMR) was opposite to the earlier period (1961-1984) but recent period (1985-2008) has been increasing with positive impact on BSMR.

Conclusions

An increasing trend of precipitation from the year 2010- to 2014, was clearly matched with an increasing trend of SST during the year 2011-2015, whereas positive IOD was also intensified during the same period (Fig. 6). The annual patterns of variability was clearly discernible with peak SST occurs during April-May, whereas precipitation was started to increase from the month of May and it gradually peaked during June-July. In such, a time lag was seen between peak SST and peak precipitation periods. The remote sensing as well as modelling study using multi-source data set can be a milestone for these types of research. In such, cooperation of stakeholders is essential to manage the Oceanographic data for validation. The features of Walker and Hadley circulation, Oceanic heat content etc, during different phases of summer monsoon can be explored in the further study.

References


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