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Bay of Bengal upper-ocean stratification and the sub-seasonal variability in convection: Role of rivers in a coupled ocean-atmosphere model

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सार – बंगाल की खाड़ी (BoB) में वर्षा और नदियों से बड़ी मात्रा में ताजा जल प्राप्त होता है, जिसके परिणामस्वरूप समुद्र के ऊपर मीठे जल का स्तरीकरण हो जाता है। इस लवणता स्तरीकरण को समुद्र की मिश्रित परत और अवरोध परत को प्रभावित करते हुए अंतर-ऋतुनिष्ठ समय पैमाने पर संवहन और समुद्री सतह के तापमान (SST) को प्रभावित करने के लिए जाना जाता है। इस लेख का उद्देश्य स्वस्थाने महासागर प्रेक्षणों और युग्मित मॉडल प्रयोगों का उपयोग करके SST में अंतर-ऋतुनिष्ठ परिवर्तिता और संवहन पर लवणता स्तरीकरण के प्रभाव की मात्रा निर्धारित करना है। यह देखा गया कि मॉनसून अंतर-ऋतुनिष्ठ दोलन (MISO) SST में अंतर-ऋतुनिष्ठ परिवर्तिता और अंतर्निहित महासागर स्थितियों के आधार पर वर्षा के विभिन्न स्तरों को प्रदर्शित करता है। SST में सबसे बड़ी अंतर-ऋतुनिष्ठ परिवर्तिता उत्तर-पश्चिमी BoB में सबसे बड़ी संवहन परिवर्तिता का कारण नहीं बनती है, बल्कि SST में मध्यम परिवर्तिता और MISOs से जुड़ी वर्षा गहन मिश्रित परत और मोटी अवरोध परत की स्थिति से सम्बंधित होती है। युग्मित महासागर-वायुमंडलीय मॉडल में नदी के मीठे जल के प्रवाह का यथार्थवादी निरूपण, SST में अंतर-ऋतुनिष्ठ परिवर्तिता और वर्षा परिवर्तिता में सुधार करता है। उत्तर-पश्चिमी खाड़ी में मोटी अवरोध परतें मिश्रित परत के ठंडे संरोहण का क्षीणन करती हैं, और उच्च मिश्रित परत ताप सामग्री मॉनसून कम दबाव प्रणाली (LPS) की उत्पत्ति के लिए अनुकूल समुद्री स्थितियाँ प्रदान करती है, जिससे भारत में वर्षा प्रभावित होती है। युग्मित मॉडलों का उपयोग करते हुए प्रचालन पूर्वानुमान के लिए इस अध्ययन के महत्वपूर्ण पहलू हैं।

ABSTRACT. The Bay of Bengal (BoB) receives a large amount of freshwater from rains and rivers, resulting in large upper-ocean stratification due to the freshening effect. This salinity stratification has been theorized to impact sea-surface temperature (SST) and convection on intra-seasonal time scales by affecting the ocean mixed layer and the barrier layer. This article aims to quantify the impact of salinity stratification on the sub-seasonal variability in SST and convection by using *in situ* ocean observations and coupled model experiments. It is shown that monsoon intra-seasonal oscillations (MISOs) exhibit varied levels of intra-seasonal variability in SST and rainfall based on the underlying ocean conditions. The largest intra-seasonal variability in SST does not cause the largest convection variability in the north-western BoB. Instead, moderate variability in SST and rainfall associated with MISOs co-occur with deep mixed layer and thick barrier layer conditions. Realistic representation of river freshwater fluxes in a coupled ocean-atmosphere model leads to improved intra-seasonal SST and rainfall variability. Thick barrier layers in the north-western Bay attenuates the entrainment cooling of the mixed layer and the high mixed layer heat content provides conducive oceanic conditions for the genesis of monsoon low-pressure systems (LPS), thereby affecting rainfall over India. This study has important implications for operational forecasting using coupled models.

Key words – Indian summer monsoon, Rivers, Monsoon intra-seasonal oscillations, Mixed layer, Barrier layer, Low-pressure systems, Bay of Bengal.

1. Introduction

The importance of Indian Summer Monsoon rainfall (ISMR), occurring during the boreal summer months of June to September, cannot be over-emphasized. It is a vital source of freshwater that supports the agriculture, economy, lives and livelihood of millions of people residing in the country (Gadgil & Gadgil, 2006). The

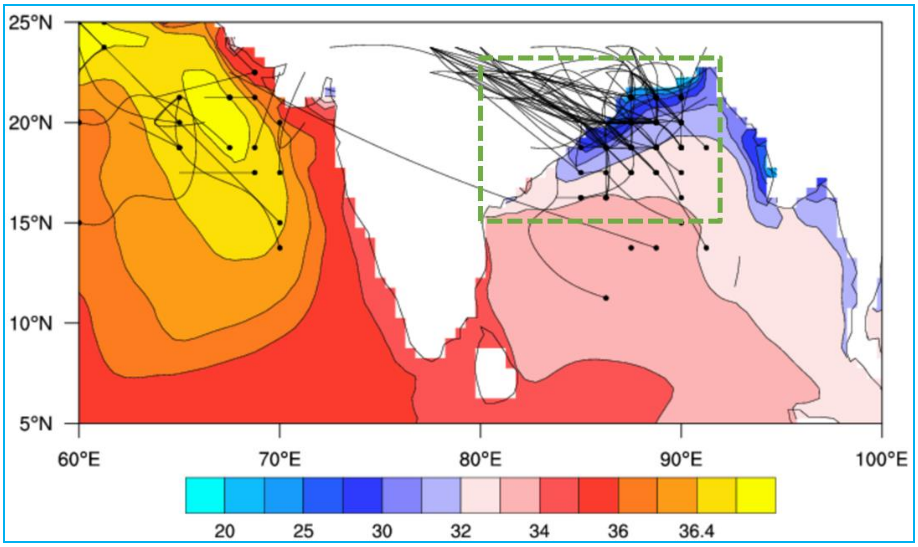


Fig. 1. The tracks of monsoon low-pressure systems for the period 1981-2017. The tracks were detected using an LPS tracking algorithm using JRA55 reanalysis mean sea-level pressure data. The contours represent the sea-surface salinity (PSU) from the Simple Ocean Data Assimilation dataset. Also shown is the Bay of Bengal box (15-23º N; 80-92º E)

rainfall during monsoon months is not homogenously distributed over the country, neither spatially nor temporally. Various interesting sub-seasonal modes of variability govern large sub-seasonal fluctuations in rainfall. The 30-60 day mode of the monsoon intra-seasonal oscillations (MISOs) is the dominant mode, which manifests itself as northward propagating cloud bands from the equator to the foothills of the Himalayas. The intermittent northward propagation of deep convection brings rainfall to the Indian sub-continent and is associated with the monsoon active-break cycles (Krishnamurti & Ardanuy, 1980; Krishnamurti & Bhalme, 1976; Murakami *et al*., 1984; Ramamurthy, 1969; Sikka & Gadgil, 1980; Yasunari, 1980). Earlier studies have also shown that the variability in convection associated with the 30-60 day band is much higher over the Indian Ocean sector compared to the Pacific Ocean (Kripalani *et al*., 1995). The large-scale modulation of the monsoon circulation by MISOs provides conducive conditions for the genesis and north-westward propagation of monsoon low-pressure systems (LPS) (Goswami *et al*., 2003). In their journey from the north-western Bay of Bengal (BoB) to central and north-western India, these systems cause intense rainfall activity over central India and the Western Ghats (Goswami *et al*., 2003; Krishnamurthy & Ajayamohan, 2010). They are often associated with flooding in various river basins across India.

Fig. 1 shows the tracks of LPS for the period 1981-2017 detected using mean sea-level pressure (SLP) from the Japanese 55-year Reanalysis (Kobayashi *et al*., 2015) using an LPS tracking algorithm (Srivastava *et al*., 2017). It is evident that these systems form preferentially over the north-western BoB (15-23° N; 80-92° E, referred to as the BoB box henceforth), a region that exhibits very low salinity (<33 psu) due to heavy rainfall and freshwater discharge from the Ganga-Brahmaputra river basins. The stable stratification in the BoB due to freshwater results in a shallow mixed layer and the formation of thick barrier layers, which can enhance the warming of the surface mixed layer (Bhat *et al*., 2001; Rao *et al*., 2011; Vinayachandran *et al*., 2002). Further, MISOs are also known to cause sizeable intra-seasonal surface heat flux anomalies, resulting in large fluctuations in the intra-seasonal sea-surface temperature (SST) anomalies (Sengupta & Ravichandran, 2001). These SST anomalies are thought to aid convection in this region. MISOs were earlier thought to have an atmospheric origin (Jiang *et al*., 2004; Lawrence & Webster, 2002; Wang & Xie, 1997). However, studies with coupled model experiments conclude that ocean-atmosphere coupling has a vital role in modulating MISO characteristics (Fu *et al*., 2003, 2007; Kemball-Cook *et al*., 2002; Lin *et al*., 2011; Seo *et al*., 2007; Sharmila *et al*., 2013; Waliser *et al*., 2001; Wang *et al*., 2009).

Various observational studies have shown that salinity variations in the BoB affect ocean stratification by changing the mixed layer depth (MLD) and the barrier layer thickness (BLT) (Rao & Sivakumar, 2003; Rao *et al*., 2011; Vinayachandran *et al*., 2002). Li *et al*. (2017a) have shown that though the MLD fluctuations are mostly of oceanic origin, the strong wind speed during the active phase of MISO enhances the surface wind stress and the turbulent mixing, thereby deepening the MLD. Deep mixed layers and reduced surface heat flux due to cloudy conditions attenuate the SSTs and cause basin-wide cooling. The above discussion indicates the interaction between two opposing processes: the freshening of the upper ocean from rain and river inflow tries to shoal the mixed layer by changing the salinity stratification. At the same time, the enhanced wind speed enhances the turbulent mixing, thereby deepening the mixed layer. Our knowledge of the complex interactions between the freshwater flux, upper-ocean stratification, MISOs and convection is fragmented and needs to be revisited. Li *et al*. (2017b) investigated the impact of salinity stratification on convection using an ocean general circulation model (OGCM) and found that it has a weak overall impact on MISO precipitation events when we consider the monsoon season as a whole. They find some association of stratification with air-sea interactions associated with MISOs and convection, especially during the developing stage of the monsoon season. As mentioned earlier, earlier modeling studies emphasize the importance of using coupled models for studying MISO characteristics. Further, the LPS activity is strongly governed by MISOs and the interactions cannot be represented by an OGCM. Therefore, the impact of stratification on convection at sub-seasonal time scales must be explored using coupled models.

Li *et al.* (2017b) also explored the role of freshwater fluxes (rain and river discharge) on the intra-seasonal SST variability associated with MISOs. They report a 20% enhancement in intra-seasonal SST variability in response to the surface heat flux (SHF) forcing associated with a shallow mixed layer and a thick barrier layer. The association of freshwater with warming in the north-western BoB has also been noted in observational and ocean modeling studies (Behara and Vinayachandran, 2016; Sengupta *et al*., 2016). Recently, (Srivastava *et al*., 2022) found that including the representation of rivers in coupled models improves the simulation of upper-ocean stratification in the BoB, forming thicker barrier layers and causing mixed layer warming during peak monsoon months. An overall improvement in the ISMR seasonal prediction skill is also noted. Improved air-sea interactions associated with MISOs result in enhanced LPS lifetime and improved sub-seasonal variability of ISMR (Srivastava *et al*., 2023). Therefore, in this study, the impact of upper ocean stratification on the intra-seasonal variability in rainfall is explored using a coupled model which has a realistic representation of riverine freshwater.

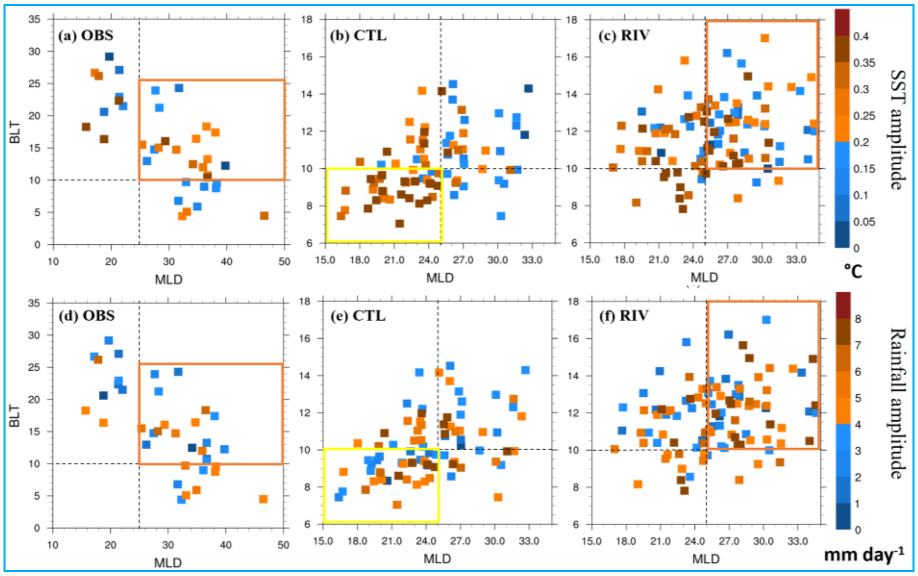
This article is organized as follows: Section 2 describes the data used, the model and the methodology. Section 3 describes the association of MLD and BLT with SST and convection. Section 4 discusses the association of the upper ocean stratification with monsoon LPS. The major findings of the study and implications for seasonal predictability are summarized in Section 5.

2. Data, methods and model

Argo floats serve as a valuable source of in-situ sub-surface ocean data. These floats drift with the ocean currents and move up and down from the ocean surface to mid-water levels, collecting information. Temperature and salinity profiles measured by the Argo floats were obtained from the Coriolis Global Data Acquisition Center of France period 2005-2017. This upper-ocean data is valuable in assessing the upper ocean stratification in the BoB box. The ocean mixed layer depth is defined using a potential density criterion using the 0-200 m temperature and salinity profiles interpolated to 1 m vertical resolution. The depth at which the potential density increase from the surface value is equivalent to a temperature decrease of 0.5 °C is taken as the MLD (de Boyer, 2004; Li *et al*., 2017a). The isothermal layer depth (ILD) is defined as the depth where temperature decreases by 0.5 °C from the surface value. Barrier layer thickness (BLT) is hence taken as BLT = ILD-MLD.

Daily rainfall data from the Tropical Rainfall Measuring Mission (TRMM) and daily SST data from Optimum Interpolation Sea Surface Temperature (OISST) were taken to identify the variability associated with MISO and LPS events. A monsoon intra-seasonal oscillation index (MISI) is defined to identify the MISO active phases. Since the major focus is on the 30-60 day MISO mode, the index is defined as the 20-100 day band pass filtered rainfall anomalies averaged over a box in central India (16.5° N-27.5° N, 74.5° E-86.5° E), standardized by its standard deviation. MISI > +1 is the peak of an active phase. LPS are tracked in the model and observations using a sea-level pressure-based tracking algorithm (Srivastava *et al*., 2017). Such automated algorithms enable us to sift through the large volumes of model simulations and observations. Japanese 55-year reanalysis data (JRA55, Kobayashi *et al*., 2015) SLP data is used to track the systems in observations. To quantify the model skill, rainfall data from the India Meteorological Department at one-degree resolution (Rajeevan *et al*., 2008) and Extended Reconstructed Sea Surface Temperature (ERSST) dataset (Huang *et al*., 2017) is used.

The Climate Forecast System version 2 (CFSv2) is a fully coupled ocean-atmosphere-land-sea ice model (Saha *et al*., 2014). The Global Forecast System (GFS) (Moorthi *et al*., 2001) is the atmospheric component that is coupled to the Modular Ocean Model 4 (MOM4) (Griffies *et al*., 2004),



Figs. 2(a-f). (a) Scatter plot of the SST amplitudes (ºC) associated with active MISO events occuring under different mixed layer and barrier layer conditions in the BoB box (shown in Fig. 1). (b), (c) same as (a) but for CTL and RIV run respectively. (d-f) same as (a-c) but for rainfall amplitude (in mm day^{-1}). The orange box in (a, c, d, f) denote the double-large events (DL events, MLD > 25m, BLT > 10m) and the yellow box in (b, e) denotes the double-small events (MLD < 25m, BLT < 10m)

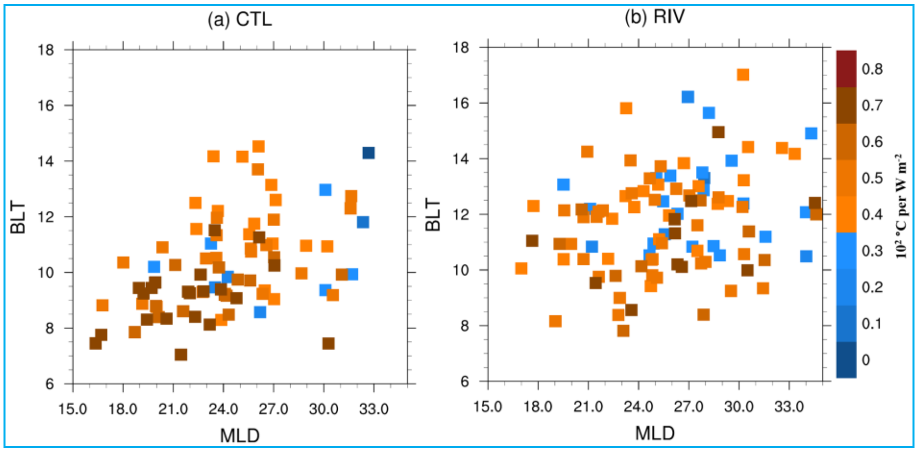
the Noah land surface model (Ek *et al*., 2003) and a sea-ice model (Winton, 2000). CFSv2 (at T126 resolution) is currently used at the National Centers of Environmental Prediction (NCEP) for operational seasonal prediction. The high-resolution (T382) version of this model is used by the India Meteorological Department (IMD) for operational seasonal prediction in India. The model has shown reasonably good skill at simulating the Indian monsoon and its different modes of variability (Rao *et al*., 2019; and references therein). CFSv2 does not have an online river-routing component; instead, climatological annual mean river runoff is prescribed to the ocean model. This model configuration is termed the CTL run. Recently, an online routing model was coupled with the CFSv2 (referred to as the RIV run henceforth) to enable realistic, daily varying river freshwater fluxes to the ocean model (Srivastava *et al*., 2022). Such a coupling is shown to improve the upper-ocean salinity stratification in the BoB and impact the seasonal prediction skill of ISMR. These two model configurations are taken to study the impact of upper-ocean stratification on sub-seasonal monsoon variability. 37-year seasonal hindcasts (1981-2017, February initial conditions) with ten ensemble members were carried out using the CTL and RIV run and are analyzed in this study.

Using the MISI index based on TRMM data, 37 active events were identified in observations. In the model simulations, MISI is defined on each ensemble member separately. This gives numerous MISO events. Therefore, for simplicity of analysis, only those MISO events which exhibit coherent northward propagation from the equator to 18° N are considered for the model simulations. Thus, 83 MISO events for the CTL run and 103 MISO events in the RIV run are selected for further investigation.

3. MLD, BLT and intra-seasonal variability in convection and SST

The interaction of freshwater with the upper ocean can cause shoaling of MLD and the formation of thick barrier layers due to the salinity stratification. Active (break) phase of MISOs, on the other hand, cause deepening (shoaling) of MLD due to enhanced (reduced) wind stress. Li *et al.* (2017a) have shown that intra-seasonal variability in MLD, BLT and ILD arises primarily out of the ocean's internal instability, with MISO-induced fluctuations playing a weaker secondary role. Their study indicates the importance of intra-seasonal river discharge fluctuations on the salinity fluctuations, which can be studied using the RIV run. We, therefore, focus on the MLD and BLT variability in the BoB box, which receives significant river discharge.

Figs. 2(a-f) show the variation of intra-seasonal SST and rainfall amplitude associated with MISO events under different MLD and BLT conditions. The rainfall amplitude is defined as the difference between the convection peak and the post convection minimum of the



Figs. 3(a&b). The ratio (102 °C per W m^{-2}) of SST and the surface heat flux (SHF) forcing for the different active MISO events in (a) CTL run and (b) RIV run

20-100 day bandpass filtered rainfall anomaly averaged over the BoB box, divided by two. Similarly, the SST amplitude is defined as the difference between the bandpass filtered SST anomaly minima during convection and the post convection maximum, divided by two. MLD and BLT are averaged over lag -15 to lead +10 of the convection peak. It is evident that the thickest barrier layer events are associated with the shallowest MLDs. These events are associated with the highest SST amplitudes [Fig. 2 (a)], understandably because the shallow MLD conditions lead to greater heating by the surface heat flux and the thick barrier layers impede entrainment cooling. The deep mixed layer events (MLD > 25 m) exhibit a greater variability in BLT, with deep mixed layers being associated with both thin (less than 10 m) and thick (greater than 10 m) barrier layers. The SST amplitude differentiates between thin and thick barrier layer events. The majority of MISO events with deep MLD and thick BLT have a moderate SST amplitude, while those with thin BLT have smaller SST amplitude.

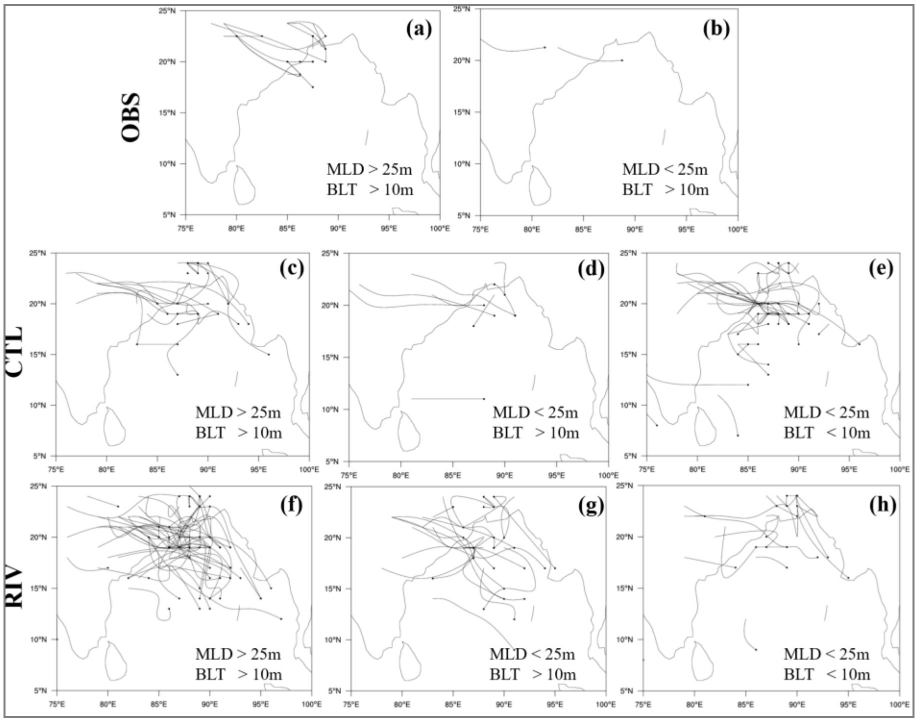
It might be somewhat intuitive to conclude that the strongest intra-seasonal variability in SSTs might lead to a similar variability in rainfall. Li *et al.* (2017b) investigated this to some extent and found that MLD, BLT and SST interact in a non-linear manner and the overall impact on rainfall is relatively weak. The BoB box selected by them covers the central Bay, while we wish to focus on north-western BoB, which is more likely to affect intra-seasonal rainfall variability by affecting monsoon LPS. It is interesting to note that in the north-western BoB, BLT is greater than 10m for the majority of the active MISO events. There are no events with a shallow MLD (MLD < 25 m) and thin BLT (BLD < 10 m. The rainfall amplitudes corresponding to these events are shown in Fig. 2 (d). The events with the strongest SST variability (MLD < 25 m; BLT > 10 m) do not exhibit the largest rainfall amplitudes; rather, they are associated with moderate amplitudes. Moderate to strong rainfall amplitudes occur under deep MLD and thick BLT conditions [MLD > 25 m, BLT > 10 m, denoted by the orange box in Figs. 2 (a-d)]. The conditions for convection should have been more conducive for the events with shallow MLD and thick BLT due to the larger SST variability. This peculiar aspect will be addressed in the subsequent sections. We next discuss the variability simulated by the CFSv2. For simplicity, we segregate the MISO events into three different categories:

(*i*) Double-large (DL): MLD > 25 m; BLT > 10 m.

(*ii*) Shallow MLD, thin BLT (SMTB): MLD < 25 m; BLT > 10 m.

(*iii*) Double-small (DS): MLD < 25 m; BLT < 10 m.

CFSv2 has a biased representation of MLD and BLT, with the CTL run simulating too shallow mixed layers and thin barrier layers (Srivastava *et al.*, 2022, 2023). This is evident from Figs. 2(b&e). Unlike observations, the majority of the active MISO events are associated with very shallow MLD and thin BLT [DS, MLD < 25 m, BLT < 10 m, denoted by yellow box in Figs. 2 (b&e)]. Due to the shallow MLDs, they exhibit the largest SST amplitudes and moderate to strong rainfall variability. The events with shallow MLD and thick BLT (SMTB, MLD < 25 m; BLT > 10 m) exhibit large SST and rainfall amplitudes, but the number of such events is less. Deep MLD and thick BLT conditions (DL events, MLD > 25 m; BLT > 10 m), which exhibit somewhat coherent variability in SST and rainfall in observations, is not well simulated in the CTL run. Figs. 2(c&f) shows the SST and rainfall amplitudes as simulated by the RIV run. The excessive number of DS events reduces considerably in



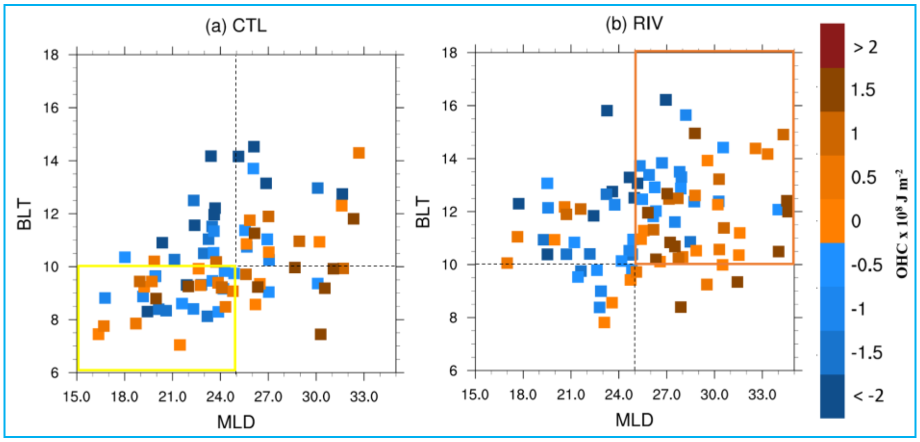
Figs. 4(a-h). The LPS tracks occurring under different mixed layer and barrier layer conditions for (a, b) Observation; (c-e) CTL run and (f-h) RIV run. The MLD and BLT conditions are mentioned in the figure legends

RIV, as in observations that simulate nil events in this category. A significant increase in DL events is noted in RIV. RIV also simulates a large number of events in the SMTB category. The SST amplitudes in the SMTB and DL categories look identical, with both linked to moderate to high SST amplitudes [Fig. 2 (c)]. However, they can be differentiated by looking at the rainfall amplitude [Fig. 2 (f)]. As in observations, DL events in the RIV runs are associated with moderately strong rainfall and SST variability.

The SST variability can not only be controlled by changes to MLD and BLT, but it is also dependent on the atmospheric surface heat flux forcing (SHF). As in Li *et al.* (2017b), the impact of SHF on SST is quantified using SST/SHF ratio. This is computed as the ratio of intra-seasonal SST amplitude to intra-seasonal SHF amplitude and is shown in Figs. 3(a&b). CTL run exhibits the largest values in the bottom left corner, indicating the significant impact of MLD and BLT on SSTs in the CTL run. RIV run does not exhibit such high values in the bottom left corner. Rather, moderate values of the ratio are uniformly distributed across the range of different upper-ocean conditions. This indicates that in the presence of realistic river freshwater fluxes in the RIV run, the excessive control of ocean stratification on SST due to shallow MLDs, which we observe in the CTL run, reduces. What causes the large rainfall amplitude associated with deep MLD and thick BLT conditions in observations and RIV run? This aspect is addressed in the next section.

4. Monsoon low-pressure systems

The discussion in the preceding section suggests strong intra-seasonal variability in convection associated with deep MLD and thick BLT conditions. Several observational and modeling studies posit a strong association between upper-ocean salinity stratification and MISO-associated convection (Vinayachandran *et al*., 2002; Rao and Sivakumar, 2003; Rao *et al*., 2011; Sengupta *et al*., 2016; Li *et al*., 2017b). Though the mechanisms responsible for such an interaction are mostly qualitative, a strong consensus exists on the definite impact on rainfall. We go a step further into these arguments and isolate the role of LPS in controlling the intra-seasonal rainfall variability. The monsoon LPS are embedded in the large-scale monsoon circulation and the intra-seasonal circulation anomalies strongly dictate their genesis and propagation. It is well known that these systems are responsible for the enhanced rainfall during active monsoon phase, whereas very few systems form in the BoB during break phases (Goswami *et al*., 2003;



Figs. 5(a&b). The intra-seasonal anomalies in the mixed layer heat content (OHC × 108J m^{-2}) averaged over lag -10 to lead +10 from the MISO peak for (a) CTL run and (b) RIV run. As in Fig. 2, the yellow box denotes DS events while the orange box denotes the DL events

Sikka, 2006; Krishnamurthy and Ajayamohan, 2010; Srivastava *et al*., 2017). Since the MISO convection shows some dependence on the underlying salinity stratification, it is possible that they can alter the LPS characteristics as well. Hence, we investigate the LPS genesis and propagation for the MISO events shown in Figs. 2(a-f) using an automated feature tracking algorithm (Srivastava *et al*., 2017).

Figs. 4(a-h) illustrates the LPS genesis (black dots) and the propagation trajectory (black curves) for observations and model simulations for the different MLD and BLT conditions (DL, SMTB and DS categories). Though the sample size for observations is limited, it is evident that LPS activity is stronger for DL events compared to the SMTB events. There are no MISO events in observations for the DS category. Frequent LPS genesis occurs under DL conditions which can explain the greater number of moderate rainfall amplitude events in this category [orange box in Fig. 2 (d)]. The LPS activity in model simulations further supports this. CTL run has the maximum number of MISO events in the DS category [yellow box in Fig. 2(b, e)], which is also associated with frequent LPS genesis and propagation [Fig. 4 (e)]. LPS genesis is also favored in the model for DL events. RIV run simulates the maximum synoptic activity for DL events, whereas the LPS activity is restricted for SMTB events. CTL and RIV models differ only in terms of riverine freshwater flux and the associated changes to salinity stratification. Therefore, their synoptic activity differences can be said to emanate from this aspect. The relatively subdued synoptic activity for SMTB events explains the smaller intra-seasonal rainfall amplitudes [Fig. 2(e)] despite having moderate to large intra-seasonal SST amplitudes [Fig. 2 (c)]. Though DL events have moderate SST amplitudes, LPS activity is favored for such events and hence, they can cause moderate to large intra-seasonal variability in rainfall [Fig. 2(f)]. The improved distribution of MISO events in RIV run under different MLD and BLT conditions translated to the synoptic time scales through the scale interactions between them.

LPS activity in the CTL run indicates that both shallow and deep MLD conditions render conducive conditions for LPS genesis, while BLT has a limited role in impacting LPS. However, in the presence of realistic river freshwater fluxes, the underlying BLT conditions strongly govern LPS activity. Decreased entrainment cooling due to the thick barrier layers insulates the deep mixed layers, which fosters more LPS. Due to thinner barrier layers, shallow mixed layers are not well insulated from the sub-surface. Warmer mixed layer temperatures for such events might theoretically be more conducive for convection; but increased entrainment due to the thin BLTs likely attenuates the warm mixed layer conditions rather quickly and hence does not result in large synoptic activity. The mixed layer integrated ocean heat content (OHC) should be greater for DL events since a deeper mixed layer can retain a larger heat content and the thicker barrier layer attenuates the entrainment cooling. OHC is calculated for the model simulations using the expression:

$$OHC = C_p \int_{5m}^{MLD} \rho(z) T(z) dz$$

where, C_p is the specific heat capacity of seawater, $\rho(z)$ and $T(z)$ denote the water density and temperature at depth z, respectively. The bandpass filtered OHC anomalies are then composited with respect to the coherently propagating MISO events, averaged over lag - 10 days to lead +10 days of the MISO peak. Figs. 5(a&b) show a scatter plot of these anomalies with respect to different MLD and BLT conditions. It indicates that most of the positive OHC anomalies are concentrated when MLD > 25 m; and BLT > 10 m. Weaker OHC for DS category events causes weaker convective activity [Fig. 2 (f), Fig. 4(g)]. Some positive OHC anomalies also occur under other MLD and BLT conditions, which indicates that processes other than salinity stratification can also affect LPS genesis. However, the role of such processes is weaker. Therefore, moderate SSTs under deep MLD and thick BLT conditions (DL events) associated with a stronger MISO linked circulation causes strong LPS activity, leading to a larger intra-seasonal rainfall amplitude.

5. Conclusions and implications

Due to rainfall and river discharge, salinity stratification in the Bay of Bengal (BoB) is known to affect the mixed layer and barrier layer processes. It has been hypothesized to impact convection at sub-seasonal time scales. Numerous studies with OGCMs have shown the significant impact of river freshwater on SST in the BoB during summer monsoon months. Ocean salinity stratification also interacts with monsoon intra-seasonal oscillations (MISOs). MISOs are thought to be mostly of atmospheric origin but coupled modeling studies have shown that air-sea interactions are vital to simulate realistic MISO characteristics. Recently, Li *et al.* (2017a) have shown that intra-seasonal MLD and BLT variability in the BoB arise out of the ocean's internal instability and the MISO-associated circulation plays a limited role. The association of salinity stratification with convection is mainly supported by qualitative arguments and is somewhat quantified by the ocean model-based studies (Li *et al.*, 2017b). This relationship is revisited in this study using coupled model experiments. Earlier OGCM-based studies have been limited by the unavailability of river discharge observations at a daily step. This hurdle is overcome by coupling a river routing model to a coupled land-atmosphere-ocean model (Srivastava *et al.*, 2022,2023). Such a coupling ensures that the surface runoff fluxes generated by the land model reach the ocean at a daily time-step. Using *in-situ* observations and coupled model experiments, the association of SST and rainfall variability with salinity stratification is studied at intra-seasonal and synoptic time scales. Since the genesis of monsoon low-pressure systems (LPS) is favored in the north-western BoB (15-23° N; 80-92° E, BoB box shown in Fig. 1), the impact of salinity stratification is studied in the region. The significant findings are summarized below:

(*i*) The largest intra-seasonal variability in SST is observed with shallow mixed layers and thick barrier layers (MLD < 25 m, BLT > 10 m: SMTB events). The largest SST variability, however, does not translate to large variability in rainfall.

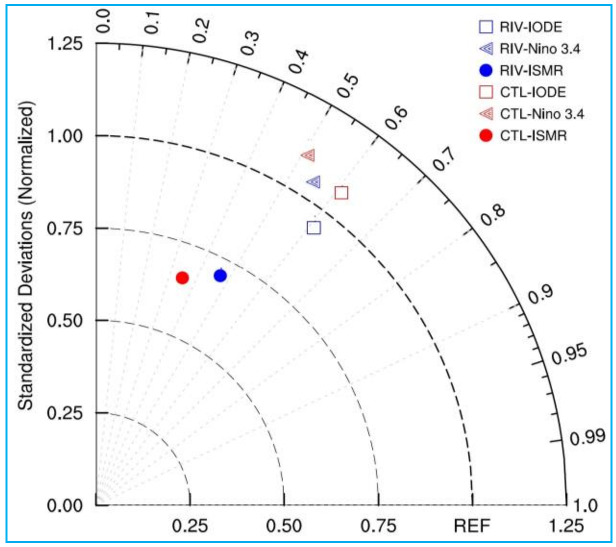


Fig. 6. Taylor diagram depiction of the model skill for AISMR, Nino 3.4 and IODE for the CTL run (red) and the RIV run (blue)

(*ii*) Moderate intra-seasonal variability in SST is associated with deep mixed layers and thick barrier layers (MLD > 25 m, BLT > 10 m: DL events). These conditions cause a similar moderate intra-seasonal variability in rainfall.

(*iii*) LPS genesis in the BoB box is favored for DL MISO events, while lesser systems form under SMTB conditions. This explains the moderate intra-seasonal rainfall amplitudes associated with DL events compared to SMTB events.

(*iv*) Due to the specification of annual climatological mean runoff in CTL run, it generates numerous MISO events under shallow mixed layer and thin barrier layer category (MLD < 25 m, BLT < 10 m: DS events), unlike observations. However, the associated large variability in SST leads to moderate variability in rainfall.

(*v*) The provision of realistic river discharge in RIV run improves the distribution of MISO events with respect to MLD and BLT conditions. Though moderate SST variability is observed for both SMTB and DL events, moderate to large variability in rainfall is associated with frequent LPS genesis under DL conditions.

(*vi*) Mixed layer heat content anomalies associated with MISO events indicate that larger mixed layer heat content under DL conditions provides conducive conditions for frequent LPS genesis and propagation.

Taylor diagram in Fig. 6 shows the model skill (defined as the anomaly correlations coefficiemt between observations and model simulations for June-September mean fields) for All Indian Summer Monsoon Rainfall (AISMR), the Nino 3.4 index and the Indian Ocean Dipole east pole index (IODE). It is apparent that the RIV run has a greater skill for AISMR, while the Nino 3.4 and IODE skill are almost similar. The improvement is reported to come from a better representation of upper-ocean stratification in the BoB and the improved representation of sub-seasonal modes of ISMR variability (Srivastava *et al.* 2022,2023). The strong control of ocean salinity stratification on synoptic scale processes and the MISO variability is demonstrated in this study. This aspect should be well represented in operational models for better ISMR forecasts.

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