On Synergy between Convective Equatorial Signals and Monsoon Intraseasonal Oscillations in the Bay of Bengal

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ABSTRACT: The relationship between eastward-propagating convective equatorial signals (CES) along the equatorial Indian Ocean (EIO) and the northward-propagating monsoon intraseasonal oscillations (MISOs) in the Bay of Bengal (BOB) was studied using observational datasets acquired during the 2018 and 2019 MISO-BOB field campaigns. Convective envelopes of MISOs originating from just south of the BOB were associated with both strong and weak eastward CES (average speed; $6.4 \text{ m s}^{-1}$). Strong CES contributed to $\approx 20\%$ of the precipitation budget of BOB, and they spurred northward-propagating convective signals that matched the canonical speed of MISOs (1–2 m s$^{-1}$). In contrast, weak CES contributed to $\approx 14\%$ of the BOB precipitation budget, and they dissipated without significant northward propagation. Eastward-propagating intraseasonal oscillations (ISOs; period 30–60 days) and convectively coupled Kelvin waves (CCKWs; period 4–15 days) accounted for most precipitation variability across the EIO during the 2019 boreal summer as compared with that of 2018. An agreement could be noted between high moisture content in the midtroposphere and the active phases of CCKWs and ISOs for two observational locations in the BOB. Basin-scale thermodynamic conditions prior to the arrival of strong or weak CES revealed warmer or cooler sea surface temperatures, respectively. Flux measurements aboard a research vessel suggest that the evolution of MISOs associated with strong CES are significantly influenced by local enhanced air–sea interactions, in particular the supply of local moisture and sensible heat, which could enhance deep convection and further moisten the upper troposphere.

SIGNIFICANCE STATEMENT: Eastward-propagating convective signals along the equatorial Indian Ocean and their relationship to the northward-propagating spells of rainfall that lead to moisture variability in the Bay of Bengal are studied for the 2018 and 2019 southwest monsoon seasons using observational datasets acquired during field campaigns. Strong convective equatorial signals spurred northward-propagating convection, as compared with weak signals that dissipated without significant northward propagation. Wave spectral analysis showed CCKWs (period 4–15 days), and eastward ISOs (period 30–60 days) accounted for most of the precipitation variability, with the former dominating during the 2018 boreal summer. High moisture periods observed from radiosonde measurements show agreement with the active phases of CCKWs and ISOs.

KEYWORDS: Atmosphere–ocean interaction; Convective-scale processes; Large-scale motions; Monsoons; Intraseasonal variability

1. Introduction

The South Asian summer monsoon or southwest monsoon (SWM) is characterized by subseasonal episodes of active and break (above- and below-average rainfall and convective activity; Webster et al. 1998) phases in the Bay of Bengal (BOB), referred to as monsoon intraseasonal oscillations (MISOs; Sharmila et al. 2013; Witman 2017). Although the large-scale structure of MISOs shows broad year-to-year resemblance, detailed spatiotemporal characteristics of MISO-produced rainfall are complex, scattered, and variable (Goswami 2012; Pokhrel and Sikka 2013). As a result, even after more than three centuries of research following Halley (1686) and Blanford (1886), complete knowledge of processes governing the distribution and variability of monsoon rainfall remains elusive. MISOs’ inherent variability is modulated by variants of intraseasonal oscillations (ISOs; period 30–60 days) and synoptic and mesoscale weather systems of various origins, ocean and land surface boundary conditions, and internal dynamics (Goswami et al. 2003; Choudhury and Krishnan 2011). During boreal summer,
MISOs originate south of BOB (~5°S) in the equatorial Indian Ocean (EIO) and start propagating northward displaying a tilted northwestern band as a part of the dominant tropical ISOS known as the boreal summer ISOS (BSISOs). While the boreal winter ISOS [identified as Madden–Julian oscillations (MJOs)] have been regarded as applicable to all seasons, they exhibit weaker variability during the boreal summer (Madden and Julian 1972, 1994; Wheeler and Hendon 2004; Zhang 2005). Thus, the BSISOs dominate the boreal summer (June–October) and MJOs during boreal winter (December–April), with May and November being transitional months during which either mode may prevail (Kikuchi et al. 2012).

The northward component of BSISOs, also identified as MISOs, propagates into the South Asian region, while its MJO-like eastward counterpart travels toward the western Pacific (Annamalai and Slingo 2001; Lawrence and Webster 2002; Hoyos and Webster 2007; Krishnamurthy and Shukla 2007; Rajeevan et al. 2010). In the development stages of BSISOs, in addition to its eastward component, large-scale atmospheric systems such as convectively coupled equatorial waves (CCEWs; period 3–17 days) may interact with MISOs. Such interactions influence the frequency and intensity of atmospheric systems, especially extreme weather events such as tropical cyclones, giving rise to organized convection and circulation that favor either active or break conditions affecting the overall rainfall variability (Lubis and Jacobi 2015; Sakaeda et al. 2020; Ferrett et al. 2020; Lubis and Respati 2021; Peatman et al. 2021). These ubiquitous disturbances in the EIO also carry eastward- or westward-propagating organized atmospheric systems of meso- to planetary scales, traveling parallel to the intertropical convergence zone either along the equator or within a few degrees of latitude thereof (Kiladis et al. 2009). In general, CCEWs obey barotropic Matsuno (1965) solutions in the horizontal, but moist processes (e.g., clouds) akin to the vertical structure are complex and deviate from the theory for dry waves (Wheeler and Kiladis 1999; Straub and Kiladis 2002; Wheeler et al. 2000). With convection being their regular dominant energy source, CCEWs and ISOS can contribute to the vertical exchange of energy and momentum, thus playing an essential role in moistening or preconditioning the middle troposphere for subsequent deep convective events. Although these disturbances may not follow large-scale divergence patterns forced by dry waves, they suppress/enhance regional convection and interact with other waves, background winds and topographical features (Roundy and Frank 2004). Furthermore, some studies demonstrate that different wave modes do not necessarily occur in isolation but coexist while undergoing mutual interactions (Roundy 2008; Masunaga 2009; Yasunaga and Mapes 2012).

Commonly, bands of enhanced clouds and precipitation as well as associated circulation anomalies are observed over EIO oriented from the northwest to southeast, and they interact with BOB internal dynamics via air–sea sensible and latent heat fluxes (Krishnamurthy and Shukla 2007; Rajeevan et al. 2010; Weller et al. 2016). ISOS can also be embedded in the vertical structure of the Indian Ocean atmosphere during certain key phases of equatorial waves aloft, thus modulating near-surface meteorology to set optimal conditions for convection. The development of convective weather systems relies on available moisture, the variability of which is crucial for the distribution of rainfall. Both the EIO and BOB exhibit high rainfall variability on intraseasonal scales (Hoyos and Webster 2007), with mesoscale convective systems (MCs) producing most of the precipitation over BOB (Virts and Houze 2016). This variability dramatically affects the quality of life in the southeastern Asian continent, where ~78% of the annual rainfall is produced during the monsoon period (Dhar and Nandargi 2003).

For this reason, further insights on the dynamics of rainfall during active phases of MISOs are needed to achieve accurate forecasts beyond current forecasting capabilities that considerably deteriorate beyond the two-week mark, notwithstanding the theoretical predictability limit of around 25 days (Goswami and Xavier 2005). Understanding the impacts of equatorial convective disturbances such as ISOS and CCEWs on daily rainfall variability at regional scales can help improve predictability, for which high-resolution space–time datasets are needed from the EIO and BOB covering both ocean and atmosphere. Such datasets, however, are recherché.

As such, atmospheric and oceanic data were collected during the 2018 and 2019 boreal summers as a part of the monsoon intraseasonal oscillations in the Bay of Bengal (or MISO-BOB) Research Initiative sponsored by the U.S. Office of Naval Research. The project encompassed the EIO and BOB, with research vessels (R/V) equipped with an extensive suite of instruments conducting both atmospheric and ocean measurements. MISO-BOB campaign also deployed ground measurement stations in several countries, collecting surface and upper air measurements. Figure 1 illustrates the MISO-BOB geography, with a chronology of cruises listed in Table 1. In situ atmospheric and ocean-surface observations by R/V are used in this study, including atmospheric profiles obtained via daily radiosondes releases at an enhanced frequency. Additional data used include upper-air data from radiosonde launching stations across the BOB provided by the Indian Meteorology Department (IMD).

This study aims to investigate the nexus between atmospheric convective signals in the EIO and those propagating northward as MISOs in BOB under varying conditions of convective signals propagating in the equatorial belt [or convective equatorial signals (CES)]. Ship/land datasets were analyzed alongside satellite and reanalysis products to elicit multiscale physical processes that underlie MISOs in the study domain, ranging over large-scale equatorial disturbances (e.g., CCEWs and ISOS) and their interactions with atmospheric moisture. The data and methods used are described in section 2. Results and discussion are given in section 3, followed by concluding remarks in section 4.

2. Data and method

The documentation and analysis of large-scale coupled systems such as CCEWs and ISOS require wide spatial and temporal coverage that can only be obtained from satellite and global models. Many past studies have greatly contributed in this regard, including delving into the structure, dispersion characteristics, and propagation of planetary wave disturbances.
To study the vertical distribution of these disturbances as well as their interaction with upper levels of the atmosphere, in particular moisture variability, three-dimensional high-resolution data are required, for which radiosonde measurements during MISO-BOB field campaigns were used in conjunction with the Tropical Rainfall Measuring Mission (TRMM) and reanalysis global model (ERA5) datasets as described below. Measurements were also conducted aboard R/Vs Tommy Thompson in 2018 and Sally Ride in 2019, with each campaign composed of two expeditions (leg 1 and leg 2); for R/V tracks, see Fig. 1. Radiosondes were released from various land sites in the EIO, including augmenting the frequency of those launched from WMO sites. Another highlight was the deployment of five long-term deep moorings along a longitudinal transect in the central BOB during cruise 2 of 2018 and their retrieval during 2019 cruise 1. Since this study concerns local atmospheric variability due to ISOs, only the profiles collected during stationary legs and the land stations were used.

### a. Radiosonde dataset

High-resolution atmospheric radiosonde profiles of pressure $P$, air temperature $T_a$, relative humidity (RH), and wind speeds and direction were collected up to 30 km of altitude at WMO and auxiliary sites. The University of Notre Dame operated these land sites in Sri Lanka, Maldives, and Seychelles, as well as radiosonde releases from the R/Vs. Radiosonde release sites of IMD are also shown in Fig. 1, and the release frequency was twice daily.

### b. Supplementary datasets

#### 1) TRMM RAINFALL

The TRMM Multisatellite Precipitation Analysis (TMPA) dataset (3B42–V7) was used as a proxy for moist convection to study convective disturbances along the EIO and BOB. This daily-accumulated precipitation product is generated from the research-quality 3-hourly TRMM TMPA (3B42) on

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**Table 1. MISO-BOB cruises.**

<table>
<thead>
<tr>
<th>MISO-BOB cruise</th>
<th>Period</th>
<th>Start/End points</th>
<th>Research vessel (R/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 leg 1</td>
<td>4–17 Jun</td>
<td>Chennai, India</td>
<td>Tommy Thompson</td>
</tr>
<tr>
<td>2018 leg 2</td>
<td>30 Jun–20 Jul</td>
<td>Colombo, Sri Lanka</td>
<td>Tommy Thompson</td>
</tr>
<tr>
<td>2019 leg 1</td>
<td>27 May–25 Jun</td>
<td>Phuket, Thailand</td>
<td>Sally Ride</td>
</tr>
<tr>
<td>2019 leg 2</td>
<td>6 Jul–4 Aug</td>
<td>Chennai, India</td>
<td>Sally Ride</td>
</tr>
</tbody>
</table>
a 0.25° × 0.25° grid (Huffman et al. 2010), covering our area of interest in the tropics and subtropics. Such merged TRMM data product compares well to ground-based radar measurements over the ocean, especially for tropical, non-frontal precipitation (Huffman et al. 2007).

2) ECMWF REANALYSIS

Meteorological fields from the ECMWF ERA5 reanalysis were used to compare synoptic-scale conditions at the bay before and after the arrival of equatorial convective disturbances. They provide 6-hourly analysis fields at a resolution of 31 km and is produced using 4D-Var data assimilation from ECMWF’s Integrated Forecast System (IFS), with 137 hybrid sigma/pressure (model) levels in the vertical, the top level being at 0.01 hPa (Hersbach et al. 2020). Atmospheric data such as the air and sea surface temperature (SST) and $U$ and $V$ winds were used for each case during the 2018 and 2019 boreal summers. Surface or single-level data containing 2D parameters such as the convective available potential energy (CAPE), a measure of the available energy for convection (per unit mass) and related to the potential maximum vertical speed of a rising air mass, prior to the arrival of the equatorial disturbances was also used as a measure of regional atmospheric instability due to buoyancy forces. Finally, the vertically integrated moisture was used as a measure of moisture convergence/divergence in BOB during the equatorial convective events.

c. Filtering technique and wave analysis

Time indices for the CCEWs and ISOs were acquired by applying a wave-filtering technique to precipitation data from TRMM (depicted via the wave–frequency domain highlighted by the black boxes in Fig. A1 of the appendix, which include ISOs, Kelvin, equatorial Rossby, mixed Rossby gravity, and westward/eastward inertia–gravity waves), followed by averaging the filtered data at each respective radiosonde launch over 5°S–5°N. From wave decomposition analysis, CKKWs and eastward-propagating ISOs were identified with the highest variability during the 2018 and 2019 boreal summers in the EIO. The eastward ISO range includes eastward wavenumbers 0–5 and periods of 30–60 days, whereas the Kelvin filter includes periods 2.5–17 days and eastward wavenumbers 1–14. These thresholds were selected according to Straub and Kiladis (2002). The wave-filtered data were obtained by taking the inverse transform of a previous Fourier transform along the longitudinal direction, and in time, selecting the coefficients outside the desired wave ranges (i.e., ISO and Kelvin) to zero. Although the nonlinear interactions between these waves can lead to a null state from the superposition principle for convectively coupled waves, this filtering technique remains an effective method for allocating the wave component and the nonlinear modulation effects that occur within the same filter band (Roundy 2008).

This study follows a zonal wavenumber–frequency wavelet analysis similar to Yasunaga and Mapes (2012), to retrieve the phases and amplitudes of ISOs and CCEWs with the aim of analyzing the equatorial convective signal’s (CCEWs and ISOs) effects on the local atmospheric moisture variability (i.e., the standard deviation of fluctuations about the mean). Both filtered and unfiltered data are utilized to differentiate the patterns associated with wave-like versus anomalies from nonlinear behavior that occur outside of the wavenumber–frequency Kelvin and ISO band. Here, the method was applied to TRMM TMPA data averaged between 5°S and 5°N for all the longitudes corresponding to the stationary locations of radiosonde launches. The method is exemplified for the eastward 30–60 ISO in Fig. 2, where the time series of normalized wave-filtered precipitation and its temporal change is calculated for May–August 2019. The phase and amplitude as functions of longitude and time are calculated from the filtered precipitation time–longitude section and its time derivative. The constructed phase diagram shown in Fig. 2b corresponds to the time series enclosed in the black rectangles of Maldives location from Fig. 2a, with a color corresponding the color coding of the standardized wave-filtered precipitation. Cool colors indicate suppressed regional convection by the equatorial wave, whereas warm colors correspond to regional enhanced convection. The start and the end of the sample time series are highlighted, respectively, by $t_s$ and $t_e$. Starting on an active phase and advancing in a clockwise direction through phases of suppressed convection and then through phases of enhanced convection, and so on. In terms of the interpretation of the phase diagram, phase 1 is the wettest (most convective) phase, since standardized wave-filtered precipitation is at its maximum, and the opposite, phase 5, is the driest (least convective) phase since standardized wave-filtered precipitation is at minimum. In contrast, phases 3 and 7 are considered transitional phases since the sign of standardized wave-filtered precipitation changes from negative to positive and back from positive to negative, respectively. Last, the amplitude of waves is the distance from the origin of the phase diagram (Fig. 2c).

3. RESULTS AND DISCUSSION

a. Relation between MISOs and large-scale equatorial convective disturbances

Convective equatorial signals are observed to propagate eastward with speeds ~6.4 m s$^{-1}$ for both 2018 and 2019 boreal summers, as seen from the orange dashed lines of Figs. 3a and 4a. This result is consistent with the eastward-propagating BSISO mode, having similar speeds to its winter counterpart MJO (Knutson et al. 1986; Zhang and Ling 2017; Wang et al. 2018). For most CES, as they arrive just south of BOB in EIO (around 88°E), convective envelopes appear to travel northward into BOB, in some cases reaching up to 12°N. A correlation is apparent between the intensity of CES and their extent of northward travel into BOB. In this study, strong and weak CES are classified according to their relative precipitation budget (PB), or quantitatively the amount of precipitation brought in during boreal summer along the EIO belt from 82° to 92°, highlighted by the black boxes on Figs. 3a and 4a. Strong convective equatorial signals (SCES), shaded in orange, are found to supply ~20% of the precipitation budget in BOB during boreal summer, while weak convective equatorial signals
WCES, gray-shaded in these figures, contribute ~14%. Convective bands with northward propagation with speeds of 1–2 m s\(^{-1}\) are observed to ensue from strong CES, and they have characteristics of a northward BSISO mode (Wang and Xie 1997; Kembal-Cook and Wang 2001; Sengupta and Ravichandran 2001; Hoyos and Webster 2007) or specifically identified as MISOs in BOB (Sharmila et al. 2013). In contrast, the weak CES are followed by exiguous convection and appear to be incapable of triggering MISOs. Plausible MISO events (or lack thereof) are highlighted by blue ovals in Figs. 3b and 4b for both boreal summers. Active MISOs are named according to subsequent strong CES and are further analyzed against MISO-BOB campaign observations.

In 2018, the arrival of the first strong CES south of BOB quickly followed sustained southerly to southwesterly winds over the region, with strengthening and deepening of cross-equatorial flow and enhanced cloudiness and rainfall on 25 May, marking the start of boreal summer with the monsoon onset four days later over Kerala (India) on 29 May (Mausam 2018). The 2018 MISO-BOB campaign occurred near the end of the northward progression of the monsoon onset (i.e., onset over Kerala) in the central BOB. The projected MISOs captured during the beginning of the cruise (~4 June) were characterized by active conditions with intermittent, heavy rain, while the latter part of the cruise was relatively clear with little precipitation (Shroyer et al. 2021). Despite the paucity of MISOs observations originating from CES during the 2018 cruise period (marked in the ordinate of Fig. 3), one strong CES and one weak CES case were identified and further analyzed.

The 2019 southwest monsoon exhibited a more gradual advancement with characteristic strengthening and deepening of cross-equatorial flow and enhanced cloudiness and rainfall over some areas of BOB and the southern Andaman Sea, starting from 24 May and gradually shifting northward during the onset phase over Kerala on 8 June (Balachandran et al. 2019). It has been noted by the Indian Meteorological Department that 2019 is the strongest southwest monsoon season since 1994, during which the BOB branch was classified as more “active” (i.e., more convection) relative to the Arabian Sea branch, resulting in a delayed onset of monsoons in the region of Kerala, the southernmost part of the Indian peninsula. This delay in the 2019 monsoon onset, including the highly active conditions, especially at the end of the season have been associated with the influence of an extreme positive
Indian Ocean Dipole that peaked during the month of October (Sankar et al. 2021; Ratna et al. 2021). However, warm SST anomalies from the central equatorial Pacific led to low-level divergence and decreased rainfall over India during the month of June (Ratna et al. 2021). Here, the delay of the monsoon onset can be classified from the gap between the arrival of the first strong CES (29 May) and the start of the MISO propagation (8 June) in BOB. Observations from 2019 MISO-BOB R/V cruises coincide with MISO signals projected from two strong CES. Three CES (two consecutive strong and a weak CES) were identified and further analyzed for the 2019 boreal summer.

To relate CES to the spatial distribution of BSISO phases in BOB, historical BSISO indices of Kikuchi (2020) were consulted. During 2018 strong CES, the BSISO transitioned via phases 2, 3, and 4. Phase 3 is characterized by elongated convection over the IO, with the highest values in the eastern EIO. Phase 3 is characterized by splitting convective bands, with one part moving eastward while the other spanning northwest in the BOB and the Arabian Sea. In phase 4, the northward-propagating component covers most of the Indian subcontinent (see Fig. 4 of Kikuchi 2021). The observed precipitation bands that propagate northward in BOB, which seem to be originating from the convection zone south of BOB (M1 in Fig. 3b), agree with the BSISO phases identified above. Conversely, throughout the weak CES event in 2018, the BSISOs followed phases 7 through 8, which are unfavorable for convection over this region. These phases of BSISOs agree with the lack of precipitation bands along the BOB as observed by the weakening of the signal south of BOB on Fig. 3b upper blue oval.

During the first strong CES event in 2019, SCES1, the BSISO was found mostly in phase 2 while transitioning to phase 3.
During 2019 SCES2, the BSISO transitioned from phase 1, where convection is starting to develop in EIO, to phase 2. During 2019 WCES1, the BSISO shifted from phase 1, to phase 2, ending in phase 3. For 2019 SCES1 and SCES2, multiple precipitation bands are observed to propagate northward through BOB arising from the initial convection band (M1 and M2 blue ovals in Fig. 4b). Although the convective envelope is dissipating in 2019 weak CES, bands of precipitation appear to develop north of BOB as seen by the top blue oval in Fig. 4b, which would ascribe to the pertaining favorable BSISO phases. A descriptive summary for 2018 and 2019 CES is given in Table 2.

Overall, abundant scattered rainbands are observed as persistent elements in the northern BOB for both 2018 and 2019 cases (Figs. 3b and 4b). Dynamically, this region is characterized by high precipitation during the summer monsoon due to the high intensity of the vertical uplift of moisture provided from the regional-scale circulation, where a combination of SST increases and vertical temperature/humidity distribution have shown to enhance large-scale dynamics by further intensifying the ascending circulation (Pokhrel et al. 2018). Hence, local conditions in the northern BOB tend to dominate the moisture transport processes, leading to convection. Notwithstanding, the available moisture supply for MISOs is related to the nature of CES that arrive south of BOB, especially to the overall precipitation variability therein.

Further information on CES can be gleaned from Fig. 5, where decomposed precipitation for CCKWs and eastward

![MISO-BOB Cruise Period](image)

Fig. 4. As in Fig. 3, but for boreal summer 2019.

### Table 2. Descriptive summary of CES during boreal summers 2018 and 2019.

<table>
<thead>
<tr>
<th>Year</th>
<th>SWM onset</th>
<th>CES</th>
<th>Days (10-day cycle)</th>
<th>PB (%)</th>
<th>BSISO phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>25–29 May</td>
<td>SCES1</td>
<td>20–27 May</td>
<td>20.8</td>
<td>2, 3, and 4</td>
</tr>
<tr>
<td>2018</td>
<td>25–29 May</td>
<td>WCES1</td>
<td>23–24 Jul</td>
<td>14.3</td>
<td>7, 8, and 1</td>
</tr>
<tr>
<td>2019</td>
<td>18 May–9 Jun</td>
<td>SCES1</td>
<td>28 May–6 Jun</td>
<td>20.0</td>
<td>2 and 3</td>
</tr>
<tr>
<td>2019</td>
<td>18 May–9 Jun</td>
<td>SCES2</td>
<td>12–21 Jul</td>
<td>19.7</td>
<td>1, 2, and 3</td>
</tr>
<tr>
<td>2019</td>
<td>18 May–9 Jun</td>
<td>WCES1</td>
<td>16–25 Aug</td>
<td>13.6</td>
<td>1, 2, and 3</td>
</tr>
</tbody>
</table>
ISO are shown for both 2018 and 2019 boreal summers. Both CCKWs and eastward ISO were analyzed considering their high variability during 2018–19 in the EIO. Although relatively high values are observed from equatorial Rossby waves (see Fig. A1 of the appendix), they exhibited low variability in the EIO for both 2018 and 2019 BS (not shown), and thus were omitted from further analysis.

The left panels in Fig. 5 show low variability for the eastward ISO in the EIO during 2018 as compared with 2019 boreal summer where strong variability bands are observed to cover most EIO and mid- to high latitudes in the BOB and the Indian subcontinent. In contrast, high variability is observed for CCKWs in EIO (where they are trapped) during the 2018 boreal summer as well as during the 2019 boreal summer reaching up to 4°N. The aggregated high variability of eastward ISO and CCKWs for the 2019 boreal summer alludes to the formation of more CES relative to the 2018 boreal summer (further depicted in Fig. A2 of the appendix).

From these eastward ISO and CCKW phase decompositions in the EIO (Fig. A2), one can interpret that strong CES are composed of a larger combination of active ISO and CCKW phases whereas weak CES seem to be attributed to ISO variability only.

The connection between in situ moisture variability in BOB to the local phase (i.e., Fig. 2) of ISO and CCKWs of each CES was examined using radiosonde profiles taken during stationary legs of 2018 and 2019 research cruises. Since our focus is on convection over BOB, Port Blair was chosen for comparison to exclude (unrelated) orographic precipitation. As moisture enhances the propensity for convection, high-resolution atmospheric profiles provide insights on local and passing convective weather systems, which can be placed vis-à-vis the local phase and amplitude of eastward-propagating ISOs and CCKWs, as in Fig. 2. Left and right panels of Fig. 6 show comparisons of radiosonde profiles, respectively, from Port Blair and (stationary) R/V during leg 1 in 2018. Top panels show the specific humidity time series with shading indicating the humidity anomaly. The middle and bottom panels show the time series as a function of the amplitude of CCKWs and ISOs, respectively, with red/blue indicating the wet/dry phases.

For Port Blair in June/July 2018, high-frequency moisture variability in the lower troposphere [Fig. 6a(i)] fairly agrees with active-break cycles of CCKWs [Fig. 6a(ii)]. Particularly, during active MISO (M1; gray shaded), an active peak is observed in phase with positive moisture anomaly around 7 June (magenta box). Eastward ISO, however, transitioned from the active to dry phase at that time [Fig. 6a(iii)]. The beginning of the 2018 leg-1 cruise was marked by the end of active MISOs (magenta box) where high moisture anomalies [Fig. 6b(i)] are observed to agree with the active phase of the CCKWs at least initially [Fig. 6b(ii)]. This is followed by a suppressed state with sparse convective periods in Fig. 6b(i–iii). No correspondence between radiosonde moisture and CCKW/ISO phases is clearly observed thereafter, at which time eastward ISOs appear at a constant amplitude suppressed phase [Fig. 6b(iii)].

During the 2019 active MISO period (M2; gray shaded), high moisture anomalies are observed in both Port Blair and during the leg-2 cruise. At Port Blair, the high (active) peaks of both CCKWs and eastward ISOs agree with the high moisture anomaly period as seen in Fig. 7a(i) (magenta box), notwithstanding the missing data. The remaining period of active MISOs is related to high moisture in the midtroposphere and is found to agree with the extent of an active ISOs [Fig. 7a(iii)]. For 2019 leg 2, an acute high moisture anomaly is observed on 17 July [Fig. 7b(i)], agreeing with both ISO and CCKW active phase transition (magenta box). Subsequently, high moisture
anomalies are observed in the lower troposphere, aligning with an active peak of the CCKWs and ISOs. Thereafter, the ISOs remained in an active phase with predominantly moist atmospheric conditions until the end of the cruise.

**b. The BOB thermodynamics with respect to CES**

BOB conditions before or during arrival of CES are examined by respectively considering a minus or plus 7-day averaged period from the first day of SCES1 and WCES1 (see Table 2).
Figure 8 shows the SST (shading), CAPE (green contours), and mean surface wind vectors for 2018 and 2019 CES. Warmer SSTs are observed prior to strong CES as compared with weak CES for both 2018 and 2019. For the cases of weak CES, a distinctive band of warm SST is observed to expand over the EIO, while relatively cooler SSTs persist over a wide region of BOB, which could be attributed to freshwater cooling from rainfall, except at the northern bay. For strong CES, a positive gradient of CAPE is observed with higher values concentrating on the eastern Indian coast. During weak CES, the northward gradient of CAPE is relatively weak. Overall, southwesterly surface winds, a characteristic regional trait during the boreal summer, is observed during all cases, with stronger winds during the passing of weak CES.

Figure 9 shows the difference between mean SST and air temperature (Ta) in shading and the mean precipitation in green contours during the arrival of CES. For cases of strong CES, SST-Ta contours (left panels) show higher (warmer) values across the EIO and BOB, with a larger extent in BOB for the 2018 case. For the weak CES cases, however, lower SST relative to air temperatures (negative values) are observed at the western BOB for the 2018 case while for the 2019 case SSTs were slightly warmer relative to Ta. Although noticeable precipitation appears throughout BOB during both strong CES and weak CES cases, higher amounts of mean rainfall are observed in the central BOB during strong CES compared to weak CES.

In situ MISO-BOB R/V observations show a local perspective of BOB conditions during active MISOs, as seen in Figs. 10a and 11a for 2018 and 2019. A decomposition of precipitation anomaly time series is shown in Figs. 10b and 11b for CCKWs and eastward ISO at stationary cruises (leg 1 in 2018 and leg 2 in 2019) locations to illustrate their relative impact during each cruise.

The 2018 ship observations captured numerous convective events, particularly from the stationary leg-1 location (~14°N; see Fig. 1). Winds increased during such convective events followed by a decrease in SST where positive peaks in heat fluxes mark active exchanges of heat from the ocean surface to the atmosphere. Leg 1 was characterized by high-frequency episodes of precipitation, from which those with the largest amount of rainfall occurred during the active MISO (gray shaded). This active
period was marked by constructive interference of ISOs and CCKWs (Fig. 10b) to produce elevated precipitation observed early in the cruise. The rest of the precipitation events therein, however, appear to develop as a result of favorable local conditions and advected systems from land rather than arriving from the south (Fig. A3 in the appendix). Inactive conditions prevailed during the second leg of the cruise, where observations covered the central BOB with N–S transects. This absence of convection in the central BOB can be, in part, attributed to the unfavorable dynamical conditions owing to lack of CES.

The constant roaming during leg 1 in 2019 precluded capture of passing weather events albeit active convection was present in BOB. Even after the arrival of SCES1, where freshwater from heavy precipitation is expected to “cool” ocean temperatures, SST show increasing values from N–S transects (6–9 June). The second half of leg 2 was marked by active MISO (M2; gray shaded) with high-frequency episodes of precipitation, similar to those during 2018 leg 1. The beginning of the active MISO appears to be dominated by CCKWs with a transitional eastward ISOs, followed by constructively interfering ISOs and CCKWs (Fig. 11b) generating the heavy precipitation events observed at the end of the cruise. Increasing latent heat and spikes of sensible heat fluxes were observed following a slow decrease in SST from leg 1 to leg 2. The precipitation events between 7 and 10 July were found to be not arriving from the southern bay, and hence not related to MISO events (Fig. A4 in the appendix).

Overall, only a part of the precipitation events measured during 2018 and 2019 are ascribed to convective episodes brought into the southern bay by strong CES (M1 and M2). It is reiterated that the northern BOB manifests other convective events, including those advected from the land and those developed locally, but delving into them is outside the scope of this paper.

4. Conclusions

This study examined the nature of convective disturbances across EIO and their relationship to MISO variability in BOB.
during the boreal summers of 2018 and 2019 using data from MISO-BOB field campaigns. To the authors’ knowledge, MISO-BOB provides the most extensive ship and land-based record hitherto for capturing the Bay’s transition between active and break spells of monsoons from both atmosphere and ocean perspectives. Convective envelopes arriving from just south of BOB were observed to originate from eastward-propagating convective equatorial signals (CES) along the EIO. The CES signals, propagating with average speeds of \( \sim 6.4 \text{ m s}^{-1} \), were classified as “strong” and “weak” based on their precipitation budget for each boreal summer. Strong CES were estimated to bring 6% more precipitation to the BOB than weak CES. In addition, the (spatial) extent of travel of convective envelopes into the south of BOB appeared to be

![Image of meteorological time series and decomposed precipitation anomalies](image-url)

Fig. 10. (a) Meteorological time series of in situ measurements from R/V legs 1 and 2 during 2018 MISO-BOB expedition, showing, from top to bottom, wind speed (m s\(^{-1}\); blue) and direction (°; orange), SST-T\(_a\) (°C; magenta) and precipitation (mm; green), and latent (dark blue) and sensible (light blue) covariance fluxes and SST (yellow), with sensible heat flux measurements adjusted for better comparisons. (b) Decomposed precipitation anomalies (mm day\(^{-1}\)) for eastward ISOs (blue) and CCKWs (orange) over averaged stationary cruise location leg 1: (85°–86°E, 15°–16°N) during the 2019 boreal summer. The green dashed line marks the SWM onset over Kerala for each respective year. Gray dash-outlined boxes indicate the duration of the stationary cruises during MISO-BOB. Gray-shaded sections mark the northward propagation of convection from SCES highlighted by the blue oval in Fig. 3.
dependent on the strength of CES. Strong CES seemingly prompted convection over southern BOB with northward propagation speeds of 1–2 m s⁻¹, which as identified as MISOs (i.e., northward-propagating BSISOs into BOB originating at ~5°S and propagating at similar speeds). Conversely, weak CES appear to dissipate without significant northward propagation. The 2018 monsoon onset was marked by the arrival of the first strong CES over the south of BOB, highlighting the start of boreal summer. During 2019 monsoon, a lag between the arrival of the first strong CES over southern BOB and the evolution of MISOs resulted in a gradual advancement of southwest monsoon into BOB. During the
arrival of strong CES, the BSISO transitioned through phases 2, 3, and 4, classified as active periods (wet envelope) propagating eastward and then northwestward into BOB covering a substantial swath of the Indian subcontinent.

Eastward ISOs and CCKWs are found to produce the largest variability along EIO during the 2019 boreal summer, facilitated by enhanced production of CES via propagating phases with constructive interference, as compared with 2018 when the ISO variability was relatively low. The corresponding phase and amplitude of eastward ISOs and CCKWs were determined for two radiosonde-launch stations in BOB (Port Blair and the stationary cruises of R/V), followed by an of wave-filtered precipitation data. Moisture anomaly from high-resolution radiosonde profiles as well as calculated phase/amplitude time series showed some broad consistency, especially during the active MISO phases. High specific humidity values (positive anomaly respective to the mean) throughout the troposphere coincided with convectively active stages of the CCKWs over Port Blair and leg-1 R/V location for the 2018 boreal summer. Little agreement was found between the ISOs and the moisture variability at these locations for the same time period. In contrast, moisture anomalies for 2019 R/V leg 2 and Port Blair showed agreement with the ISO phase in comparison with 2018 where high moisture anomalies during active MISO aligned with active stages of both CCKWs and ISOs. More observations from stationary locations in BOB, specifically for lower latitudes, are needed to gain further insight into the atmospheric moisture variability and its relation to ISOs and CCKWs.

The conditions in BOB prior to and during the arrival of CES were examined at basin and local scales using reanalysis fields and in situ (stationary) R/V observations. Prior to the arrival of strong CES, for 2018 and 2019, warmer SSTs covered BOB with positive CAPE gradients advancing toward the eastern coast of the Indian peninsula. As a result of high rainfall episodes from strong CES, conditions in BOB prior to the arrival of weak CES showed cooler SSTs, with a negative gradient of SST from the EIO toward BOB, and concentrated CAPE values at SST “hot spots” in northern BOB. Mean conditions during strong CES showed warmer SST relative to air temperature across the EIO and BOB. Although significant precipitation occurs throughout BOB during both strong and weak CES cases, higher amounts of mean rainfall are observed in the central BOB during strong CES than during weak ones. By bringing more moisture into BOB, strong CES contribute more to the principal processes in the column-integrated moist static energy budgets associated with initiating stages of MISO propagation (Wang and Li 2020). During the developing stages of convection, favorable conditions like high SSTs can enhance evaporation, further moistening the BOB atmosphere and resulting in more precipitation. Furthermore, strong baroclinic divergence and vorticity anomalies can be induced from the strong convection in the equatorial region leading to a positive gradient of barotropic vorticity toward the north of BOB enhancing MISO (Jiang et al. 2004).

Results from flux observations at the stationary legs of R/V [i.e., leg 1 (2018) and leg 2 (2019)] during strong CES (identified as associated with MISOs) indicated an enhanced supply of moisture by local air–sea interactions, which sets favorable thermodynamic conditions for convection, particularly for deep convection that further moisten the upper troposphere. This also accounts for the development of local convective events in the northern BOB. The prevailing atmospheric conditions over BOB observed using both field measurements and reanalysis data showed enhanced heat transfer from the ocean to the atmosphere, as seen from positive spikes of sensible (and high values of latent) heat fluxes, which may lead to
FIG. A2. Decomposition of (left) eastward ISO and (right) CCKW active (solid red lines) and weak (blue dashed lines) modes for (bottom) 2018 and (top) 2019.
accompanying enhanced transfer of moisture into the troposphere. Further investigations are needed to quantify the moisture deposited into the upper troposphere by deep convection and to clarify the role of CES in the formation of strong convective events associated with MISOs. The conclusions of this study are merely representative of conditions during the MISO-BOB campaigns and thus may not be generalized to all MISO events, but it is our hope that these observations provide insights into how eastward ISOs and CCKWs act as precursors to the northward-bound MISO events that carry substantial precipitation to the Indian subcontinent.

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Data availability statement. Community-supported data are available online: Tropical Rainfall Measurement Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; https://disc2.gesdisc.eosdis.nasa.gov/data/), ERA5 data from the

Fig. A3. IR brightness temperature maps (K) for cases of local or/and land advected convection in the northern BOB during 2018. Cut-off colored bar highlight areas with high probability of precipitation, where redder and bluer colors indicate heavy and light precipitation, respectively.
European Centre for Medium-Range Weather Forecasts (https://cds.climate.copernicus.eu), and the Global Sounding Dataset (http://weather.uwyo.edu/upperair/sounding.html). Project-supported data are embargoed under the agreement between the United States and India until 2025 as one step in fostering international collaboration. After this period, data may be requested from the corresponding author.

APPENDIX

Supporting Information

Figure A1 contains wavenumber–frequency spectra for the symmetric and antisymmetric components of precipitation over 5°S–5°N from January 2018 to December 2019, with dispersion curves for the various wave types superimposed. Figure A2 shows Hovmöller diagrams of the decomposed precipitation for eastward ISO and CCKW modes, highlighting their respective “active” and “break” phases. Also shown are IR brightness temperature maps for cases of local or/and land advected convection in the northern BOB during 2018 (Fig. A3) and 2019 (Fig. A4).

REFERENCES


