Variability of Intraseasonal Oscillations and Synoptic Signals in Sea Surface Salinity in the Bay of Bengal

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ABSTRACT

Intraseasonal oscillations (ISOs) significantly impact southwest monsoon precipitation and Bay of Bengal (BoB) variability. The response of ISOs in sea surface salinity (SSS) to those in the atmosphere is investigated in the BoB from 2005 to 2017. The three intraseasonal processes examined in this study are the 30–90-day and 10–20-day ISOs and 3–7-day synoptic weather signals. A variety of salinity data from NASA’s Soil Moisture Active Passive (SMAP) and the European Space Agency’s (ESA’s) Soil Moisture and Ocean Salinity (SMOS) satellite missions and from reanalysis using the Hybrid Coordinate Ocean Model (HYCOM) and operational analysis of Climate Forecast System version 2 (CFSv2) were utilized for the study. It is found that the 30–90-day ISO salinity signal propagates northward following the northward propagation of convection and precipitation ISOs. The 10–20-day ISO in SSS and precipitation deviate largely in the northern BoB wherein the river runoff largely impacts the SSS. The weather systems strongly impact the 3–7-day signal in SSS prior to and after the southwest monsoon. Overall, we find that satellite salinity products captured better the SSS signal of ISO due to inherent inclusion of river runoff and mixed layer processes. CFSv2, in particular, underestimates the SSS signal due to the misrepresentation of river runoff in the model. This study highlights the need to include realistic riverine freshwater influx for better model simulations, as accurate salinity simulation is mandatory for the representation of air–sea coupling in models.

1. Introduction

Intraseasonal oscillations (ISOs) in the Bay of Bengal (BoB) have become a burgeoning topic of interest due to the constantly improving coverage and accuracy of models and observations in the northern Indian Ocean, as well as their impact on monsoon variability. Most of the previous studies have focused on precipitation, sea surface temperature (SST), and atmospheric dynamics, with a few researchers directly focusing on sea surface salinity (e.g., Subrahmanyam et al. 2018; Li et al. 2017; Seelanki et al. 2018). Rainfall events directly freshen the surface layer of the BoB and indirectly contribute to the outflow from several major river systems that discharge into the BoB, thus favoring differential oceanic responses to ISOs in the northern, central, and southern BoB (Schott et al. 2009). Salinity is further modulated by the southwest monsoon current advecting high salinity waters from the Arabian Sea into the BoB on intraseasonal time scales and by mesoscale eddy variability (Schott et al. 2009; Dandapat and Chakraborty 2016; Mahadevan et al. 2016a,b). Highly dynamic heat and moisture fluxes drive the ISOs in the BoB and bring in seasonal and complex subseasonal variability (Goswami et al. 2016; Weller et al. 2016; Sanchez-Franks et al. 2018). The ISOs of the BoB can be categorized into three major components of atmospherically driven coupled air–sea oscillations: the 30–90-day signal associated with the monsoon ISO (MISO) and Madden–Julian oscillation (MJO), the quasi-biweekly 10–20-day
signal, and the synoptic 3–7-day mode associated with the oscillations in the monsoon trough (Subrahmanyan et al. 2018).

The MJO is characterized by eastward propagating (~5 m s⁻¹) equatorial atmospheric waves, which modulate the intensity of tropical cyclogenesis and monsoonal intensity (Madden and Julian 1971; Madden and Julian 1972; Zhang 2005). The MJO operates with a periodicity on the order of 30–90 days (Zhang 2005). The MJO is a large-scale movement of strong cloud convection and precipitation, which directly alters the surface circulation of the BoB, as studied by Grunseich et al. (2011) using altimeter observations. MJOs force equatorial Kelvin waves that propagate northward along the eastern coastline (Cheng et al. 2013). These Kelvin waves can alter the mixed layer variability and directly change the rate of air–sea heat flux in the BoB (Oliver and Thompson 2010). The relationships between the MJO and surface fluxes over the BoB have been well studied, with the conclusion that there is a strong influence of air–sea interactions induced by the MJO on surface heat, momentum, and buoyancy fluxes of the BoB (Shinoda et al. 1998; Woolnough et al. 2000).

Deep convective systems significantly contribute to heavy precipitation associated with the active phase of the MJO systems (Yuan and Houze 2010; Kim et al. 2018). In boreal summer, another larger-period ISO propagates northward over the BoB—the monsoonal ISO (Suhas et al. 2013; Li et al. 2013; Zhang et al. 2018). The MISO typically operates on a periodicity of 30–60 days and is historically traced using precipitation anomalies (Sikka and Gadgil 1980; Goswami 2005). Unlike the MJO, which is primarily confined to the equatorial latitudes, the MISO has a well-defined convective structure with northward propagation in the BoB (Kemball-Cook and Wang 2001; Suhas et al. 2013; Li et al. 2018), which is not captured in the Real-time Multivariate MJO (RMM) indices (Kikuchi et al. 2011). For the purposes of this study, the 30–90-day events will be characterized as MJO-MISO events, unless they are confirmed by the RMM indices to be MJO events, like the one in October–November 2015.

Quasi-biweekly ISOs with periods of 10–20 days have been observed in the BoB in observational data as well as numerical models (Sengupta et al. 2001; Kiladis and Weickmann 1997). The synoptic structure of the 10–20-day mode is that of a double cell, with either two cells of high pressure or two of low pressure, where one cell is centered around the equator and the other cell of similar magnitude is centered about 15°–20°N (Chen and Chen 1993). The northern cell of the double cell is generated as a convective anomaly in the western Pacific and propagates westward into the BoB. The southern cell originates in the equatorial Indian Ocean and merges with the northern cell as it moves over the BoB, forming a convective band that then propagates westward or northwestward over India (Chatterjee and Goswami 2004; Kikuchi and Wang 2009). Significant rainfall occurs around the low centers, greatly contributing to monsoon rainfall totals (Chen and Chen 1993; Chatterjee and Goswami 2004; Kikuchi and Wang 2009). Observed meridional currents reveal westward vertically propagating biweekly waves in the equatorial Indian Ocean with zonal wavelengths ranging from 2100 to 6100 km generated by subseasonal wind variability, characteristics of the quasi-biweekly double-cell 10–20-day ISO (Chen and Chen 1993; Sengupta et al. 2004).

Sengupta et al. (2001) compared the development and propagation of oceanic and atmospheric quasi-biweekly oscillations and noted a sharper oceanic spectral peak due to oceanic processes, motivating the importance of this study. The 10–20-day ISO relationship between atmospheric convection and surface oceanic processes was statistically confirmed by Vecchi and Harrison (2002).

The shorter period synoptic mode of 3–7 days is closely related to the active and break phases of oscillations over the monsoon trough region. These synoptic-scale systems cause rainfall events with the arrival of atmospheric depressions (low pressure systems) energized by moist convection (Shukla 1987; Mak 1987; Goswami et al. 2003). These atmospheric depressions are shear instabilities energized by moist convection coupled with high surface-level cyclonic vorticity (Goswami et al. 2003). These synoptic systems modulate the frequency and intensity of monsoonal atmospheric depressions, resulting in an inverse relationship between ISO anomalies and high-energy synoptic Indian monsoon disturbances (Goswami et al. 2003). There have been extensive analyses of the interaction between surface heat fluxes and atmospheric convection on a variety of oscillatory periods, but there is a lack of understanding on the interplay of parameters such as salinity in the BoB to the ISOs.

Intraseasonal oscillations are central to the prediction of intraseasonal rainfall associated with the Indian summer monsoon over the Indian subcontinent and Southern Asia. This study is based on the use of recently acquired (and currently being acquired) long-term satellite-derived sea surface salinity (SSS) data in the BoB. The objective of this work is to explore the variability and dynamics of ocean–atmosphere coupled ISOs and synoptic signals in the BoB. To address this objective, ISOs are first identified at the aforementioned periodicities in the observations, reanalysis products, and model simulations. Then, the identified events are dynamically investigated, first with the 30–90-day events,
then the 10–20-day events, and then the 3–7-day events. We conclude our results by conducting a heat budget and salt budget analysis to understand the overall effect of each dynamical process on the BoB. The manuscript is organized as follows. Section 2 describes the datasets and methodology for studying ISOs. Section 3 explains our results. Section 4 summarizes the major findings.

2. Data and methods

a. Data

Tracing the magnitude and location of MJO events requires a multivariate analysis. Wheeler and Hendon (2004) introduced a seasonally independent index based on the empirical orthogonal functions (EOFs) of 850- and 200-hPa zonal winds and satellite-observed outgoing longwave radiation (OLR). The pair of principal component time series that Wheeler and Hendon (2004) extracted is called the Real-time Multivariate MJO Series 1 (RMM1) and Series 2 (RMM2). RMM1 and RMM2 are used to trace MJO propagation in the Indian Ocean and are appropriate for use in this study.

Evaporation and 10-m winds are provided from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim global atmospheric reanalysis, available daily at 1° spatial resolution from 1979 to present (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/; Berrisford et al. 2011). ERA-Interim is an improvement of the previous reanalysis ERA-40 as it better encapsulates the dynamics of the hydrological cycle, stratospheric circulation, and processes, resulting in smaller biases (Berrisford et al. 2011). ERA-Interim uses ECMWF’s Integrated Forecasting System (IFS) and is coupled to an ocean wave model resolving 24 wave directions and 30 wave frequencies (Berrisford et al. 2011).

Precipitation data are from version 1.2 of the Global Precipitation Climatology Project (GPCP) daily estimates at 1° resolution (https://rda.ucar.edu/datasets/ds728.3/). This dataset is provided by the University Corporation for Atmospheric Research (UCAR) and is available from October 1996 through December 2017 (Huffman et al. 2016). GPCP v1.2 precipitation is obtained from multisatellite observations (Huffman et al. 2016).

NASA’s Soil Moisture Active Passive (SMAP) mission is used to retrieve SSS at a gridded horizontal resolution of 0.25° (Entekhabi et al. 2010). SMAP has a repeat cycle of 8 days and achieves near-perfect global coverage every 3 days (Fore et al. 2016). NASA’s Jet Propulsion Laboratory provides daily SMAP SSS data starting 1 April 2015, interpolated using the 8-day running mean. We use the most recent SMAP version 4.0, which accounts for galaxy and land contamination corrections and reduced brightness temperature biases (Fore et al. 2016).

Soil Moisture and Ocean Salinity (SMOS) data used in this study are the most up-to-date debiased SMOS SSS level 3 data generated by the Ocean Salinity Center of Expertise at the Centre Aval de Traitement des Données SMOS (CATDS). This new dataset has adjustments to previous versions in dynamical areas such as river plumes, which are highly relevant in the BoB.

To compare the response of SST to coupled ocean–atmosphere ISO events, we apply daily SST data from 1996 to 2017 provided by the Group for High Resolution Sea Surface Temperature (GHRSTT) analysis provided by the Canadian Meteorological Center (CMC). For the rest of this manuscript, this product will be referred to as CMC SST. These data merged infrared SST observations from the (A)TSR series of radiometers from ERS-1, ERS-2, and Envisat, AVHRR from NOAA-16, -17, -18, and -19 and MetOp-A, and microwave data from TMI, AMSR-E, and WindSat, supplemented with in situ observations from buoys and ICOADS ship data (Braun 2008; Martin et al. 2012; https://podac.jpl.nasa.gov/dataset/CMC0.2deg-CMC-L4-GLOB-v2.0). The gridded horizontal resolution of this CMC SST dataset is 0.2° × 0.2°.

Multisatellite observations (Liebmann and Smith 1996) of daily OLR data from 1 June 1974 through 31 January 2017 are taken from NOAA’s Interpolated OLR product at a 2.5° gridded horizontal resolution (https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html).

Salinity was also obtained from a coupled operational analysis using the NCEP Climate Forecast System version 2 (CFSv2; Saha et al. 2013) to cover the period from 2012 to 2017 at 6-hourly intervals. CFSv2 has superior seasonal and subseasonal prediction capability and a dynamically appropriate understanding of MJO events (Saha et al. 2010, 2014; https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2). CFSv2 operational forecasts and the corresponding reanalysis accurately reproduce the Indian summer monsoon rainfall by reducing ocean–atmosphere modeling biases that historically favor unusually dry conditions (Narapasetty et al. 2015, 2018). Pathak et al. (2017) explored the 10–60-day periods of active and break phases of the Indian summer monsoon using CFSv2 and ECMWF ERA-Interim data to explain the moisture sources of different regions of the Indian Ocean, reaffirming that both datasets are appropriate for this region of study.

Global Hybrid Coordinate Ocean Model (HYCOM) simulated SSS data are compared with those of CFSv2 to
better understand ISO variability in the BoB. HYCOM has a 1/12° horizontal resolution and is run by the Naval Oceanographic Office (NAVOCEANO) Major Shared Resource Center using atmospheric forcing from the Navy Global Environmental Model (NAVGEM). As a generalized coordinate ocean model, HYCOM is isopycnal in the open ocean, uses a terrain-following coordinate in shallow coastal regions, and z-level coordinates in the mixed layer to accurately model realistic ocean flow (Bleck and Boudra 1981). HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers and is well described in Bleck and Benjamin (1993), Bleck (2002), Chassignet et al. (2003), and Halliwell (2003).

Flux data for the heat budget analysis are from the TropFlux project, which provides daily high-accuracy heat and momentum flux data for the 30°N–30°S latitudes. It is primarily derived from bias-corrected ERA-Interim reanalysis data for turbulent and longwave fluxes and derives shortwave fluxes from the International Satellite Cloud Climatology Project (Praveen Kumar et al. 2012). TropFlux data are available daily with a 1° horizontal grid resolution.

b. Methods

To investigate the impacts of ISOs on atmospheric and oceanic parameters, we utilize a Butterworth fourth-order recursive time filter that extracts the desired signal of ISOs with periods of 30–90 days, 10–20 days, and the synoptic signal of the 3–7-day period. As explained by Krishnamurti and Subrahmanyam (1982) and Krishnamurti et al. (2017), the response function of this filter is given by

\[ W(z) = \frac{a(1-Z^2)}{1 + b_1Z + b_2Z^2}, \tag{1} \]

where \( W(z) \) is the response function, \( Z = e^{-i\omega \Delta T} \), \( \omega \) is the frequency, \( \Delta T \) is the sampling interval, and \( a, b_1, \) and \( b_2 \) are constants that determine the sharpness of the filter. A recursive filter is optimal to avoid edge effects associated with phase shifts (Zhao et al. 2017). Murakami (1979) applied this type of recursive filter to 4–5-day convective oscillations and lauded the ability of the filter to temporally detect anomalous peaks in a time series. Krishnamurti et al. (2017) applied this type of filter to the study of ISOs in ocean heat content in the BoB to extract the 30–60-day signal during the south-west monsoon season (June–September).

Continuous wavelet analysis is particularly useful for analyzing multiple oscillations over a fixed time frame. Morlet wavelet analysis using a continuous wavelet transform was applied to determine the timing and magnitude of oscillations over a variety of periods, described in Morlet (1983) as

\[ \psi(\eta) = \pi^{-1/4} e^{i \omega_0 \eta} e^{(-1/2)\eta^2}, \tag{2} \]

where \( \omega_0 \) is the dimensionless frequency and \( \eta \) is dimensionless time (Torrence and Compo 1998; Grinsted et al. 2004). While a discrete wavelet transform is more appropriate for noise filtering of a time series, this research opted for a continuous wavelet transform, which is more useful for extracting selected features (Grinsted et al. 2004). Continuous wavelet transform allows characterization of a wave’s frequency and time for feature extraction by applying a wavelet as a bandpass filter to a time series (Grinsted et al. 2004). Because the wavelet is not entirely localized in time, there is an edge effect, which is marked by a cone of influence (COI).

Composites are created following a methodology similar to Chatterjee and Goswami (2004), where a box averaged time series for GPCP daily precipitation in the BoB averaged over the 5°–18°N, 85°–95°E region is created for 2015–17. An ensemble empirical mode decomposition (EEMD) analysis is carried out with 100 ensemble members and a standard deviation of 0.5 on the time series in order to extract dominant periods of oscillation (Huang and Wu 2008; Wu and Huang 2009). Intrinsic mode functions 2 and 3 are found to have periodicities similar to the 10–20-day oscillation. These were then averaged and the resulting time series is bandpass filtered with a fourth-order Butterworth bandpass filter. The filtered time series is normalized to its own standard deviation to create an index for the 10–20-day mode and peaks are identified above one standard deviation. Peaks are further restricted to May–October to include the Indian summer monsoon period.

Identified peaks are taken to be day 0, as in Chatterjee and Goswami (2004), and the subsequent 15-day phase composite is created by subtracting and adding 7 days to get day −7 and day +7, respectively. Each phase is then averaged together to create the full 2015–17 composite.

A heat budget and salt budget were computed in the BoB using the methodology described in Nyadjro et al. (2012), Swenson and Hansen (1999), and Kurian and Vinayachandran (2007). The heat budget equation can be described as

\[ \frac{\partial T}{\partial t} = \frac{Q_s}{\rho_0 C_p h} - \left( \frac{\partial U T}{\partial x} \right) - \left( \frac{\partial V T}{\partial y} \right) - (W_x \Delta T) h^{-1} + D, \tag{3} \]

where \( T \) is the vertically averaged HYCOM temperature within the mixed layer \( h \) and \( \partial T/\partial t \) is its temporal rate of change. Surface fluxes are from TropFlux. The
terms $U$ and $V$ are HYCOM zonal and meridional currents, $W_e$ is the entrainment velocity, $Q_s$ is TropFlux’s net near-surface flux, $C_p$ is the specific heat capacity of seawater, and $\Delta T$ is the difference between the temperature below the mixed layer and the average mixed layer temperature. The entrainment velocity is computed as in Stevenson and Niiler (1983):

$$W_e = H \left( \frac{\partial h}{\partial t} + \mathbf{v} \cdot \nabla h + w_h \right),$$

(4)

where $\mathbf{v} \cdot \nabla h$ is the horizontal velocity at the base of the mixed layer multiplied by the horizontal gradient of the MLD, where $\partial h/\partial t$ is the rate of the mixed layer deepening and $w_h$ is the vertical velocity at the base of the mixed layer. The term $H$, the Heaviside unit function, equals zero for a shoaling mixed layer ($\partial h/\partial t < 0$) and equals 1 for a deepening mixed layer ($\partial h/\partial t > 0$). The term $D$ represents the residual term, which includes diffusion and diapycnal mixing.

The mixed layer salt budget follows the work of Delcroix and Hénin (1991), Rao and Sivakumar (2003), and Nyadjro et al. (2012) and can be written as

$$\frac{\partial S}{\partial t} = (E - P) S - \left( \frac{\partial S}{\partial x} U \right) - \left( \frac{\partial S}{\partial y} V \right) - (W_e \Delta S) h^{-1} + D,$$

(5)

where $S$ is mixed layer salinity, $E$ and $P$ are ECMWF evaporation and precipitation, respectively, $\partial S/\partial t$ is the temporal rate of change of $S$, and all other variables are the same as in the heat budget equation. From left to right, the terms in Eq. (5) are salinity tendency, sea surface freshwater flux, zonal and meridional salt advection, entrainment, and residual processes.

3. Results

a. ISO identification

The 30–90-day ISOs are driven by MJO and MISO events (Zhang 2005). According to RMM1 and RMM2—the multivariate indices used to identify the intensity, location, and eastward propagation of MJO events developed by Wheeler and Hendon (2004)—there are a multitude of MJO events during May–October (to cover the premonsoon through postmonsoon time period) during 2005–17 (Fig. 1). Phase space region 2 represents an MJO event in the Arabian Sea, while the phase space region 3 represents an MJO event over the BoB, and this study particularly emphasizes MJO events over the BoB. There are notable MJO events detected in May of 2005, 2013, and 2017, in June of 2007, 2015, 2016, and 2017, in July of 2008, in August of 2011 and 2012, in September of 2006 and 2009, and in October of 2008 (Fig. 1). The strongest events in the BoB during the period of study were in May of 2005 and August of 2011, denoted by RMM indices far from the central circle (Fig. 1). The SMAP SSS data cover the MJO events in June of 2015, 2016, and 2017 for which we are able to give a more in-depth discussion in relation to these MJOs.

To justify the usage of CFSv2 and SMOS, the two products are compared with SMAP, which is already known to capture the behavior of ISOs in the BoB (Subrahmanyam et al. 2018), and the result is depicted in Taylor diagrams (Figs. 2a,c,d,e). In all the regions of the BoB, SMOS has a lower root-mean-square difference (0.386 psu for SMOS and 0.521 for CFSv2) and higher correlation coefficient (0.831 for SMOS and 0.735 for CFSv2) when compared to SMAP. Throughout the BoB, the standard deviations of the three products are similar (ranging from 0.594 psu for SMOS to 0.733 psu for CFSv2), but in the northern BoB, SMAP shows higher standard deviation than the other two products (0.930 psu for SMAP, 0.503 psu for SMOS, and 0.506 for CFSv2). The relationship between the three products in the central BoB is similar to that of the southern BoB (Figs. 2d,e).

A further confirmation of the ability of the three products to detect ISOs of multiple periodicities in the BoB is presented in Fig. 3. To span all the full years of the CFSv2 observational analysis product, the comparison begins in 2012. Prior to this time period, this reanalysis product severely underestimates surface salinity variability, so it has not been included. Even so, there is a notable difference between the CFSv2 SSS and the satellite-derived products. In the BoB, seasonal SSS peaks in CFSv2 precede those of SMAP and SMOS (Fig. 3a), which could be due to the fast response of the model to freshwater sources. The seasonal salinity minima associated with increased freshwater flux from the postsummer monsoon season are well captured in the satellite-derived products, but not at all in CFSv2, indicating insufficient detection of freshwater sources. The 30–90-day signals (MJO and MISO) in CFSv2 are weaker than satellite products (Fig. 3b), CFSv2 compared well with SMOS in the BoB in terms of amplitude of the 10–20-day ISO while SMAP 10–20-day amplitudes were substantially larger (Fig. 3c). The high amplitudes of the 10–20-day signal seen in SMAP are due to the higher spatial coverage of SMAP compared to SMOS, and are evident in the weaker 3–7-day synoptic signals in SMOS. The newest SMOS–LOCEAN product has global coverage at the expense of temporal sampling, which results in global coverage every four days. This is not fine enough to see the 3–7-day synoptic signal
in SMOS. However, as CFSv2 is a 6-hourly product and the SMAP 4.0 product has daily coverage, the temporal sampling is appropriate for the 3–7-day synoptic signal in both these products. We presume that the difference in SMAP SSS and CFSv2 5-m salinity would throw light on the impacts of surface freshwater flux (precipitation minus evaporation), freshwater discharge into the BoB, and the advection of salinity by surface currents.

Satellite-derived salinity reflects all sources of salinity variability, including the components of surface freshwater flux (precipitation minus evaporation), river runoff, and advective fluxes. However, CFSv2 salinity relies

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**FIG. 1.** Phase space plots of Real-time Multivariate MJO Series 1 (RMM1) and Series 2 (RMM2) for May–October in the years 2005–1717. Points within the middle circle (RMM < 1) signify weak MJO while the eight quadrants represent the approximate spatial location of the MJO signal.
on seasonal salinity climatology with atmospheric forcing, so that differences between CFSv2 salinity and the satellite-derived salinity will show the impacts of interannual river runoff and interannual advection. The difference between the unfiltered SMOS SSS and CFSv2 salinity and the difference between the unfiltered SMAP SSS minus CFSv2 salinity (Fig. 4a) are nearly identical, but the SMOS unfiltered data are more smoothed due to the data being every four days in SMOS rather than daily in SMAP. However, this does not interfere with the 30–90-day ISO, as for the most part the two differences are in phase and of similar magnitude (Fig. 4b). The impact of sampling rate on the amplitude of the 10–20-day cycle is very clear and favors higher sampling for detecting individual 10–20-day events (Fig. 4c). SMAP SSS also detects the 3–7-day synoptic signal with the amplitude varying between $-0.05$ and $+0.05$ psu (Fig. 4d).

The oceanic component of CFSv2 derives from the Geophysical Fluid Dynamics Laboratory (GDFL) Modular Ocean Model version 4 (MOM4). In MOM4, concerns with inaccurate river discharge are due to poor quantification of coastal waves and tidal processes, as well as the depth limitation. Riverine discharge generally does not impact only the uppermost layer of CFSv2, but cascades down the vertical column due to excessive mixing (Parekh et al. 2016). This second concern is not an issue in this study as we only compare the first layer of CFSv2 to better understand the air–sea interactions over intraseasonal periods. The riverine discharge and freshwater fluxes in MOM4 typically derive from a river model; however, CFSv2 integrates oceanic data from the NCEP Global Ocean Data Assimilation System (GODAS; Behringer and Xue 2004; Behringer 2007) and atmospheric data from the NCEP–Department of Energy Global Reanalysis 2 (Kanamitsu et al. 2002). GODAS integrates sea level from altimetry, Argo salinity, and temperature profiles from XBTs, TAO, TRITON, PIRATA, and Argo (Kanamitsu et al. 2002). Additionally, satellite-derived salinity represents a skin
salinity (typically characterized by higher variability) while CFSv2 refers to a bulk salinity over the top 10 m.

b. Detection of 30–90-day ISOs

The 30–90-day ISOs in salinity during 2012–17 are more easily detected in the satellite-derived salinity than in the CFSv2 product (Fig. 5). The SMOS and SMAP signals during the period of overlap (2015–17) are very similar, with peaks in January of 2016 and 2017. The monsoonal periods of 2016 and 2017 align with low 30–90-day ISOs, while there are notable 30–90 day events in June 2016 and May–June 2017 that are coincident with an MJO event in the BoB (Fig. 1). The October 2015 MJO event is better captured in both SMOS SSS and SMAP SSS with larger negative amplitude, and both products identify this period as a region of higher-than-normal MJO activity. There is also a significant MJO event in October–November that is detected by the satellite-derived salinity products that is not shown in Fig. 1 (as it is after the monsoonal period) but is further investigated in Figs. 6 and 7 using a multiparameter approach to isolate the ocean and atmosphere during active and break MJO conditions.

In the BoB, the region of highest annual SSS variability is in the northern BoB due to the riverine freshwater flux and high precipitation rates, which is also reflected in the 30–90-day ISO (Fig. 5). The aforementioned October–November 2015 MJO event is the northern, central, and southern BoB in all the products, but the highest amplitude, associated with a large negative SSS anomaly in SMOS and SMAP, is evidently seen in the northern BoB. The highest-amplitude MJO events during the period 2012–17 peak in either October or November and appear suppressed in the monsoon

![Fig. 3. Time series of box averaged (5°–18°N, 85°–95°E) SMOS SSS (red; psu), SMAP SSS (black; psu), and CFSv2 5-m depth salinity (green; psu) in the Bay of Bengal from 2012 through 2017 for (a) original unfiltered data, and for filtered data with (b) 30–90-day period ISO, (c) 10–20-day period ISO, and (d) 3–7-day period synoptic signal.](image-url)
season, with the exceptions of the May 2012 event and June 2015 event. The highest peak and strongest event are undoubtedly that of the October–November event of 2015, which we explored spatially with respect to multiple parameters.

Launched in January 2015 with data available as of April 2015, the SMAP SSS mission provides the highest-resolution coverage of global salinity observations. To better understand how satellite-derived skin SSS responds to MJO events, we investigate how atmospheric and oceanic parameters were impacted by the October–November MJO event of 2015, which was the strongest observed MJO event in the SMAP era (Fig. 6). The “0 day” signal is on 18 October 2015, which was the day of maximum convection over the BoB. On 3 October, 15 days prior to the peak MJO-related convection in the BoB, strong southwesterly winds are found in the western Arabian Sea and throughout the BoB (Fig. 7), providing moisture for the rainfall events on this day in the northeastern BoB and over Myanmar (Fig. 6).

Leading up to the day of maximal convection (18 October), the southwestern BoB is anomalously saline (Fig. 6). However, the strongest freshwater fluxes are in the outflow regions of the Ganges–Brahmaputra river system in the northern BoB, not necessarily in regions of highest precipitation (Fig. 6). The rainfall events south of India following 18 October and in the southern BoB correspond to fresher surface waters.

Spatial comparison of OLR (Fig. 7) confirms the cloud cover associated with the precipitation-dominated regions in Fig. 6. The two major sources of cloud cover are the tropical cyclone on 8 October 2015 and the precipitation between the equator and 10°N (Fig. 10). The BoB is dominated by OLR greater than 220 W m\(^{-2}\) (no

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**Fig. 4.** Time series of the differences between SMOS SSS and CFSv2 5-m SSS (red curve) and between SMAP SSS and CFSv2 5-m SSS (black curve) over a box (5°–18°N, 85°–95°E) in the Bay of Bengal from 2012 through 2017 for (a) the unfiltered original time series, and for filtered time series with (b) 30–90-day ISO, (c) 10–20-day ISO, and (d) 3–7-day synoptic signal.
convection regime) coincident with regions of high evaporation 10 days prior to 23 October. Every 5-day interval following 23 October shows OLR below 220 W m$^{-2}$ (convection regime), particularly on 2 November (+10 days; Fig. 7). The interaction between atmospheric and oceanic parameters in October–November 2015 provides a spatial overview of the impacts of the MJO event as it propagated northeastward across the BoB.

Further analysis of the timing of the basinwide distribution of 30–90-day $P - E$ ISOs reveals an interesting relationship (Fig. 8). When evaporation exceeds precipitation, the corresponding surface layer of the ocean favors higher salinities and when precipitation exceeds evaporation, fresher surface waters result. A comparison of the 30–90-day CFSv2 SSS anomalies and the 30–90-day $P - E$ (as well as the two unfiltered time series in the BoB) shows close correspondence between the parameters dips in $P - E$ (evaporation-dominated conditions) and MJO events, signifying the ability of CFSv2 to model dry phases of the MJO (Fig. 8). However, CFSv2 is inferior to satellite-derived SSS with respect to fresher conditions, typically associated with riverine discharge (Fig. 3).

To isolate the influence of precipitation in the $P - E$ balance, the 30–90-day $P - E$ was directly compared to 30–90-day CFSv2 5-m salinity (Fig. 9). The 30–90-day $P - E$ signal generally shows a consistent northward propagation in the first half of each year, and shows year-to-year propagation variability after July (Fig. 9). However, the salinity propagation is not so clear, likely due to the advective flux component (as precipitation and evaporation are not the sole parameters influencing SSS and CFSv2 has shown poor simulation of riverine discharge).

Further comparison of the 30–90-day signal between the northern, central, and southern basin gives additional insight to the meridional signal propagation (Fig. 10). In these basins, $P - E$ 30–90-day events align relatively well in all regions of the BoB. From the information on the occurrence of MJOs (from Fig. 1) during the study period, the high-amplitude 30–90-day signal indicates the occurrence of premonsoon northward propagating ISOS (Li et al. 2013, 2018) in most

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**Fig. 5.** Time series of 30–90-day filtered SMOS SSS (red; psu), SMAP SSS (black; psu), and CFSv2 5-m depth salinity (green; psu) for the (a) northern BoB (14°–18°N, 85°–95°E), (b) central BoB (10°–14°N, 85°–95°E), and (c) southern BoB (5°–10°N, 85°–95°E) regions from 2012 to 2017.
years (except for the aforementioned 2012 and 2015 events; Fig. 14).

c. Detection of 10–20-day ISOs

A second coupled ocean–atmosphere phenomenon is the quasi-biweekly 10–20-day ISO. Salinity signals in the BoB show a variety of amplitudes on the 10–20-day time scale, with SMAP SSS having the strongest signal overall (Fig. 11). SMAP is a daily product from satellite observations, and thus captures freshwater fluxes and real-time observations in high resolution. SMOS is also a satellite product, but has a very weak 10–20-day signal due to its poor temporal resolution (4 days) compared to SMAP and CFSv2, and is thus unable to capture the daily variability necessary for the 10–20-day mode. CFSv2 5-m salinity has the correct temporal variability (6 hourly) but still lacks the strong variability that observed in SMAP. This is likely due to two main causes: depth and model parameterization. SMAP and SMOS are both measuring skin SSS, whereas CFSv2 provides first salinity value at 5-m depth. This difference of 5 m may account for some of the loss of variability. The primary reason, however, may be due to the model’s parameterization of freshwater flux into the BoB from river runoff, which causes much of the salinity signal in the top 5-m layer of the BoB.

The composite diagrams of the 10–20-day mode are based on precipitation anomalies in the BoB and are

![Composite diagrams of GPCP precipitation anomalies (mm day$^{-1}$; filled) and SMAP salinity anomalies (psu; contour lines, with negative contours in black and positive contours in white) during the cycle of 2015 MJO event of 30-day period. The respective anomalies are obtained relative to the respective October–November mean of 2015–17. The “0 day” panel is in reference to the day of strongest convection at 15°N (18 Oct) during the 2015 MJO event.](image-url)
characteristic of the northernmost cell of the double cell structure that is typical of this mode of variability (Fig. 12; Chen and Chen 1993; Chatterjee and Goswami 2004; Kikuchi and Wang 2009). From day $-7$ to day 0, the signal propagates westward, apparently out of the western Pacific (Kikuchi and Wang 2009). From day 0 onward, the precipitation signal then propagates northward and dissipates. It has been shown that the 10–20-day pulse in precipitation with the northernmost cell of the double cell structure, seen most clearly here, is accompanied by a vortex of wind near the surface (Chatterjee and Goswami 2004). This vortex in wind is translated to the BoB and the surface ocean currents respond by advecting higher salinity waters along with the monsoon current farther east into the BoB (Murty et al. 1992). Although the expected signal is for positive (negative) salinity anomalies to coincide with negative (positive) precipitation anomalies, that is not shown to be the case here (see day $-1$, day 0, and day +1). Instead the freshwater runoff from land where precipitation was highest dominates the other, ocean-based signals. At day +5 and day +7 distributions, there is some coincidence with negative $P - E$ and positive salinity contours in the northern BoB. At day $-5$ and day $-7$ distributions, there is some coincidence with negative $P - E$ and positive salinity contours in the central BoB.

This pattern of salinity, however, is consistent with a regional breakdown of salinity patterns, where the northern BoB has the strongest salinity signal, followed by the central, and finally the southern BoB (Fig. 13). As

![Fig. 7. Composites of OLR anomalies (W m$^{-2}$) and 10-m wind vectors during the cycle of 2015 MJO event for a 30-day period. The respective anomalies are obtained relative to the respective October–November mean of 2015–17. The “0 day” panel is in reference to the day of strongest convection at 15°N (18 Oct) during the 2015 MJO event.](image-url)
in Fig. 12, the strongest salinity signals occur in the northern BoB due to the freshwater flux from river runoff due to increased precipitation over land (Figs. 12 and 13). This overall pattern, however, is not reflected in all sources of salinity. SMAP has the strongest signal, although it is clearest in the northern BoB in late 2016 and 2017 (Figs. 3, 4, and 13). The 10–20-day mode is primarily centered in the northern BoB, and thus it follows that the higher changes in salinity are seen in the northernmost plot for SMAP (Figs. 12 and 13). SMAP is processed to daily averages although the global coverage of the original data is every 8 days (with near-global coverage every 3 days) and thus is able to adequately capture the 10–20-day signal. CFSv2 5-m salinity has a stronger signal than SMOS and has the temporal capability to capture the 10–20-day signal, but the greatest changes in salinity for CFSv2 occur in the southern BoB. This disparity between CFSv2 and the satellite products can be attributed to the inclusion of freshwater fluxes. SMAP is a satellite product and includes freshwater runoff and fluxes by default. CFSv2, however, is a simulated product and may have improper representation of freshwater flux—both the local precipitation and river water flux. The changes in CFSv2 salinity are largely controlled by changes in the monsoon current pulling higher salinity waters out of the Arabian Sea, causing a pulse in the southern BoB rather than the northern BoB.

The 10–20-day signal of the atmospheric component is due to a double-cell propagation of two high pressure or low pressure centers (which directly impacts the balance between evaporation and precipitation) westward and northward between January and May (Fig. 14). For the rest of the year, the 10–20-day $P - E$ propagates southward. Note that $P - E$ generally has uniform amplitude throughout the entire basin, except for stronger events like those in October–November 2016 and June 2017. The 10–20-day salinity in CFSv2 is stronger only in recent years, with strongest signals in 2016 and 2017. Negative salinity anomalies should correspond with strong negative periods of positive $P - E$ but this is not always the case, which likely has to do with the way in which freshwater flux is incorporated in CFSv2. There is a slight northward propagation of $P - E$, but this pattern is far less pronounced in salinity.

d. Detection of 3–7-day synoptic-scale events

Synoptic-scale events are a result of atmospheric highs and lows associated with fluctuations in weather
disturbances and in the monsoon trough. The monsoon trough is characterized by the locations of minimum sea level pressure within the monsoon region. The monsoon trough is an elongated low pressure region parallel to the Himalayan Mountains and associated depressions are capable of producing a year’s worth of rainfall over short time scales. It is a major semipermanent feature in the lower troposphere and is extremely influential on summer monsoon rainfall activity (Sikka 1977). Activation of the monsoon trough occurs 2–3 days prior to the formation of a depression, which can break up a prolonged break spell in the BoB and trigger additional low or midtropospheric cyclones along the Indian west coast. These transient features are present on both short-term (3 day) and medium-term (4–10 day) scales. The synoptic systems cause considerable amounts of rainfall and heavy flooding in river basins (Krishnamurthy and Ajayamohan 2010). These atmospheric systems significantly contribute to seasonal rainfall and Krishnamurthy and Ajayamohan (2010) have found that these low pressure systems capture the dominant daily rainfall pattern in active monsoon seasons. The west-northwestward direction of the movement of these synoptic systems results in a large amount of continental rainfall, particularly over central India. The location, number, and duration of these systems are closely related to the strengthening of low-level monsoon winds and intraseasonal modes of Indian rainfall (Krishnamurthy and Ajayamohan 2010). On average, 14 depressions form during the summer monsoon season in the northern Indian Ocean (Sikka 2006), but there is much year-to-year variability (Goswami et al. 2003). The slow development of longer-period ISOs allows for prediction of rainfall weeks in advance (Xavier 2002; Borah et al. 2015). Improved understanding of ISOs on shorter time periods is then central to realistically predicting wet and dry spells of the Indian summer monsoon as the mean monsoon rainfall is modulated by the ISOs (Goswami and Xavier 2003; Goswami et al. 2003).

Additional modulators of synoptic variability are the larger-scale variabilities such as the Indian Ocean dipole (IOD) and El Niño–Southern Oscillation (ENSO) (Singh et al. 2001; Krishnan et al. 2011). Tracks of low pressure systems are mode clustered and have a longer

**Fig. 9.** Hovmöller plots of 30–90-day filtered GPCP precipitation minus ECMWF evaporation ($P - E$) (mm day$^{-1}$; fill) superimposed with the 30–90-day filtered CFSv2 5-m depth salinity anomalies (contoured every 0.1 psu where positive values are in green and negative values are in black) averaged over the box $85^\circ$–$95^\circ$E in the Bay of Bengal for each year from 2012 to 2017.
northwestern extension during positive IOD events, particularly during the peak monsoon months of July and August (Singh et al. 2001). IOD events can either intensify or weaken the impact of ENSO events on the Indian monsoon rainfall (Ashok et al. 2001). For example, a positive IOD resulted in enhanced rainfall (despite an El Niño event) in 1983, 1994, and 1997, and in 1992 a negative IOD event worked in conjunction with El Niño to produce a very dry monsoon season. In this study, we compare the timing and magnitude of 3–7-day synoptic events with major tropical depressions and seasonality. Many of the 3–7-day SST events occur before and after the summer monsoon season, 3–7-day precipitation anomalies peak during the summer monsoon season and during major tropical storms, and 3–7-day SSS events respond to both.

The year 2005 was characterized with high tropical storm activity, particularly in January and September.
through December according to the India Meteorological Department. The beginning of the year had El Niño conditions, which later shifted to La Niña conditions by October, which is consistent with the increased 3–7-day synoptic signal throughout the BoB (Figs. 15 and 16). The 2006 cyclone season in the BoB had the highest number of storms during July through September (with nine identified depressions and severe cyclonic storm Mukda), coincident with the peaking positive IOD phase, which counteracted the 2006 El Niño conditions (according to the oceanic Niño index). During 2006, there is a clear signal throughout all parts of the BoB (Fig. 15) that shows oceanic preconditioning of the synoptic events with high SSTs, followed by the precipitation events, freshening the surface salinity (Fig. 15).

**Fig. 12.** Composites of the 10–20-day ISO in $P - E$ anomalies from GPCP precipitation and ECMWF evaporation (shaded; mm day$^{-1}$) and SMAP salinity anomalies with a contour interval of 0.5 psu (black contours are negative and green contours are positive; psu) for 2015–17 based on an index derived from the Bay of Bengal, showing a mean 15-day oscillation as in Chatterjee and Goswami (2004).
The annual distribution of synoptic depressions was relatively well spaced, but the extremely severe cyclonic storm Sidr in November dominated the ISO signals during this time. Sidr propagated northward throughout the BoB during 11–16 November and intensified throughout its propagation. This timing aligns with the development of the very strong 2007/08 La Niña at the same time as positive IOD conditions, both of which are conducive to strong cyclonic storm development (Singh et al. 2001; Krishnan et al. 2011). The effects of this La Niña event on the 3–7-day synoptic variability continued into April of 2008, when another storm (extremely severe cyclonic storm Nargis) again passed northward throughout the BoB from 27 April to 3 May. The year 2009 was primarily dominated by strong El Niño conditions and experienced only two depressions, two cyclonic storms, and one severe cyclonic storm (Aila). However, 2010 shifted from El Niño conditions to La Niña conditions, resulting in features like extremely severe cyclonic storm Giri during 20–23 October in the BoB. The 2011 La Niña is also thought to have had a direct impact on the 3–7-day variability. The strongest storm to note in the BoB in 2011 was very severe cyclonic storm Thane, which was during 25–31 December 2011. On account of the El Niño conditions throughout much of 2012, the impacts of the positive IOD event were suppressed, resulting in a very late start to the 2012 cyclone season in the northern Indian Ocean. During the season, only three systems formed, although two were cyclonic storms (Murjan and Nilam, both in October), both of which are found in Figs. 15 and 16 in all parameters. The year of 2013 was a neutral year with respect to ENSO and IOD events and was not a notably strong or weak cyclone season. The 2014 season was again neutral and was only characterized by one storm: extremely severe cyclonic storm Hudhud in October, the signal of which is very clearly seen in the central BoB in Fig. 16.

In the year 2015, the north Indian Ocean cyclone season was more active over the Arabian Sea than the BoB according to the India Meteorological Department, but there were two events with tracks in the BoB: depression BOB01 and deep depression BOB03. The suppression of any stronger storms is likely due to the strong El Niño conditions. BOB01 occurred in June and deep depression BOB03 occurred in November, concurrent with the MJO event (Fig. 1). In 2015, a strong 3–7-day synoptic signal in precipitation begins in June due to BOB01 and the onset of the southwest monsoon season (Fig. 15). A 3–7-day precipitation signal as a response to BOB03 is also present in late November 2015 (Fig. 15). In November 2015, the 3–7-day signals are also seen in SSS and SST, but the June SSS and SST signals occur prior to the southwest monsoon season (June–September) and therefore prior to the June event of BOB01 (Fig. 15).

The 2016 north Indian Ocean cyclone season was particularly intense, with cyclonic storm Roanu, cyclonic storm Kyant, depression BOB04, cyclonic storm Nada, very severe cyclonic storm Vardag, and depression ADB02 all passing through the BoB. All of these events occur between May and December, which is reflected in the 3–7-day precipitation signal. However, the 3–7-day SST and SSS signals appear to respond more strongly to the onset and end of the southwest monsoon season (Figs. 15 and 16). In 2017, there were six tropical depressions with tracks through the BoB (cyclonic storm Maarutha, severe cyclonic storm Mora, deep depression BOB05, depression BOB06, and deep depression BOB08). The two strongest events (Maarutha and Mora) occurred in April and May, which coincide with strong 3–7-day signals in SMAP SSS anomalies, GPCP precipitation anomalies, and SST anomalies in the BoB (Figs. 15 and 16). A less extreme but still notable synoptic signal due to deep depression BOB03 is evident in all three parameters (3–7-day anomalies of SSS, SST, and precipitation) throughout June 2017 (Figs. 15 and 16). BOB05 in October, BOB06 in November, and BOB08 in December are all evident in the 3–7-day signals in SST and SSS (Fig. 15). With respect to the 3–7-day synoptic signal, we note that although the bulk of the

![Fig. 13. Time series of 10–20-day filtered SMOS SSS (red; psu), SMAP SSS (black; psu), and CFSv2 5-m salinity (green; psu) for the (a) northern BoB (14°–18°N, 85°–95°E), (b) central BoB (10°–14°N, 85°–95°E), and (c) southern BoB (5°–10°N, 85°–95°E) boxes from 2012 to 2017.](image-url)
annual precipitation and oceanic response peaks during the southwest monsoon season, year-to-year variability is strongly connected to the IOD and ENSO events over the entire BoB.

e. Heat and salt budgets

As SSS anomalies are produced by complicated and multiple forcing processes, we have computed a mixed layer heat and salt budget from 2005 to 2012, in coordination with the temporal coverage of the monthly HYCOM product (Figs. 17 and 18). The total temperature tendency ($dT/dt$ in Fig. 17) represents the HYCOM change in monthly temperature and contains all components of the temperature equation, including the residual term. With respect to the heat budget, surface heat flux showed the highest-amplitude seasonal cycle, with a strong influence on the total temperature tendency, and is consistent with previous studies (de Boyer Montégut et al. 2007; Vialard et al. 2012; Thangaprakash et al. 2016). This term is reflective of air–sea heat fluxes, which are highest during the intermonsoon period before the Indian summer monsoon. Upwelling-driven entrainment, the second-largest term, also followed a consistent seasonal cycle as in Vialard et al. (2012). Shenoi et al. (2002) noted that in this region, the upwelling term is dominant during the summer monsoon, cooling the upper ocean more strongly than the atmosphere can warm it, which is reflected in our heat budget as well (Fig. 17). The highest year-to-year variability was in both the zonal and meridional temperature advection terms, and the same was also true for the salt budget (Fig. 18). When the East India Coastal Current (EICC) is strong and southward, there is a net flow of heat from the BoB to the equator (Fig. 17b) and when the EICC is northward, equatorial waters feed into the Summer Monsoon Current and have a warming influence on the BoB. The regions with the largest residual term (the difference between the temperature tendency and sum of the surface net heat flux, advection, and entrainment terms) are expected to experience high mesoscale and submesoscale activity (Schiller and Oke 2015). A heat budget analysis from Prend et al. (2019) comparing the northern and southern BoB using mooring data found that the mixed layer temperature tendency in the northern BoB is particularly responsive to the extension of riverine freshwater plumes, which

![Fig. 14. Hovmöller plots of 10–20-day filtered GPCP precipitation minus ECWMF evaporation ($P - E$) (mm day$^{-1}$; fill) and CFSv2 5-m depth salinity anomalies [only negative contours (black) are shown and contour interval is 0.1 psu] averaged over 85°–95°E in the BoB from 2012 to 2017.](image-url)
shoaled the mixed layer and intensified warming beneath the surface, revealing the importance of conducting a salt budget analysis in conjunction with a heat budget analysis.

Surface freshwater flux had a continually freshening influence on the mixed layer in the BoB except during the 2012 positive IOD and La Niña event, when the evaporation and precipitation rates were roughly equivalent (Akhil et al. 2014). Otherwise, this region is known to have precipitation rates that exceed evaporation rates, particularly during the southwest monsoon season (Nyadjro et al. 2012). Zonal and meridional salinity advection terms reflect the high salinity gradients in the region and the mixed layer salinity responds to events such as the 2012 La Niña year, characterized by a negative salinity tendency term as well as freshening in both the zonal and meridional advection terms (Wilson and Riser 2016). Salinity advection in the BoB is a function of the reversing surface currents, extremely high riverine discharge, equatorial advection, and exchange between the BoB and the Arabian Sea (Rao and Sivakumar 2003; Sengupta et al. 2016). Although the entrainment term in the salt budget showed similar seasonality to the entrainment term in the heat budget, its overall contribution to the salinity tendency is very small (with a maximum freshening influence of about 0.1 psu), reflecting the notably high salinity stratification in the BoB (Fig. 18). In the salt budget analysis done by Rao and Sivakumar (2003), salinity entrainment variability is so small in magnitude that they elect not to show it. The zonal and meridional advection terms had a freshening and saltening impacts, respectively, that are of approximately the same magnitude on the mixed layer (Fig. 18b; Rao and Sivakumar 2003). Like the advection terms of the heat budget, the direction and magnitude of the EICC strongly influence the inflow and outflow of salt from the BoB. However, the salt budget advection also varies depending on discharge from the

![Image](Fig. 15. Time series of 3–7-day filtered daily HYCOM SSS (blue; psu), GPCP precipitation (black; mm day$^{-1}$), CMC SST (red; °C), and SMAP SSS (green; psu) in the Bay of Bengal (averaged over 4°–18°N, 85°–95°E) from 2005 through 2017.)
Ganges–Brahmaputra river system, the likely source of variability in the residual term.

4. Conclusions

The purpose of this work is to explore the variability and dynamics of ocean–atmosphere coupled ISOs and synoptic signals in the BoB. We explored three primary forcings: the 30–90-day ISO driven by the MJO, the 10–20-day ISO due to quasi-biweekly double-celled atmospheric forcing, and the 3–7-day synoptic/weather signal mostly responsive to synoptic weather disturbances or systems. We found high-amplitude 30–90-day ISOs in the surface freshwater flux (precipitation minus evaporation) that was reflected in SMAP and SMOS SSS as well, though CFSv2 was only effective at detecting the “dry” MJO phases and underestimated freshwater flux. We found differences in the signals among the northern, central, and southern BoB in SSS that is commonly attributed to the influence of discharge from major river systems. We also find dissimilar ISO signals among the different regions of the BoB due to poleward propagation of the 30–90-day precipitation ISO. This propagation is mirrored in 30–90-day SSS, although it is particularly strong in the northern BoB, again due to riverine freshwater inputs.

We extended our investigation of the multivariate response to the MJO event in October–November 2015 via spatial observations at 5-day intervals. Prior to the day of peak convection in the BoB (18 October 2015), the BoB is characterized by strong southwesterly winds and higher rates of evaporation than precipitation. On 23 October (and all subsequent time intervals) there is a shift from evaporation-dominant conditions to significant precipitation along the southern BoB and southern Indian subcontinent. In the central and southern BoB,
SMAP SSS anomalies are spatially similar to the balance between precipitation and evaporation (where evaporation-dominant conditions favor high salinity regions and precipitation-dominant conditions favor fresher SSS), although the northern BoB is very fresh due to Ganges–Brahmaputra discharge. OLR clearly reflects the shift of a high-OLR (no convection regime) BoB during the 15 days leading up to the day of peak convection, followed by the next 15 days of a low-OLR (intense convection) basin with reference to a threshold of 220 W m\(^{-2}\). SST appears to be slightly lagged behind the other parameters, as the basinwide shift from anomalously high SSTs to anomalously low SSTs does not begin to occur until 5 days (though daily observation may identify the impact in SST less than 5 days) following the day of peak convection (18 October).

The quasi-biweekly oscillations were studied with a 10–20-day periodicity. The double-celled structure of the 10–20-day quasi-biweekly oscillations resulted in a more uniform basinwide response than the other high period ISOs. The 10–20-day mode in salinity is best represented by SMAP salinity anomalies, which are strongest in the northern BoB due to freshwater flux from river runoff following the significant rain events of the northernmost cell of the double cell structure. An advantage of SMAP is that SMAP has a higher coastal resolution than SMOS and that SMOS has higher contamination from land surface emissions and experiences more radio frequency interference (RFI) noise (El Hajj et al. 2018; Bao et al. 2019). Because CFSv2 assimilates in situ salinity, its poor ability to capture ISOs partially stems from a lack of Argo profiler deployment due to shallow bathymetry (Akhil et al. 2016). Therefore, SMAP’s success in detection of ISOs is primarily attributed to a higher spatial sampling of more accurate SSS measurements than SMOS or those assimilated by CFS. Although there is a smaller immediate signal following each 10–20-day event, the strongest salinity signals follow with a 3-month lag, especially around the coastlines and in the northern BoB where precipitation was strongest over land. Like the 30–90-day signal, the 10–20-day signal in CFSv2 salinity at 5-m depth had much lower amplitudes than those in the observed SMAP SSS and did not show clear propagation patterns as found in precipitation or SMAP.
Synoptic signals with a period of 3–7 days are primarily due to oscillations in the monsoon trough or weather disturbances, and we found a combined impact of tropical storms and seasonality on atmospheric and oceanic 3–7-day signals. Peak 3–7-day synoptic signals in SST occurred before and following the southwest monsoon season (June–September), peak precipitation 3–7-day signals occurred during the southwest monsoon season, and 3–7-day signals in SSS showed a combined influence of both. We compared major tropical storms with tracks in the BoB during 2005 through 2017 and related our results to IOD and ENSO conditions. We find a variety of northward-propagating and southward-propagating events, reinforcing the forcing of oscillations in the monsoon trough.

In this study, we analyzed the SSS signatures of the 30–90-day ISO, the 10–20-day ISO, and the 3–7-day synoptic events in the BoB using satellite observations, reanalysis products, and model simulations, finding that the satellite products provide a more robust ISO signal in SSS. Our analysis also found that for all ISOs, the SSS response in the BoB was regionally specific, with the northern BoB being dominated by riverine processes and the southern BoB being controlled primarily through mixed layer processes. While the model simulations were able to adequately capture some of these features, CFSv2 was unable to capture the freshwater fluxes in the northern BoB, allowing for a significantly reduced ISO signal; however, CFSv2 was able to show the 30–90-day signal during its phases of suppressed convection where precipitation and freshwater input would not be an issue. The strength of ISO signals in satellite salinity products compared to models suggests a greater need to include river discharge in models and improve salinity products. Salinity is perhaps the best parameter to see how precipitation events from the atmosphere are translated to the ocean and to study how the ocean responds to these events, and our understanding of these phenomena will greatly improve as satellite observations increase and greater efforts are made to model salinity in these dynamically complex regions.

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