Detection of intraseasonal oscillations in the Bay of Bengal using altimetry

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Abstract
Air–sea and mixed layer dynamics in the Bay of Bengal (BoB) respond strongly to Intraseasonal Oscillations (ISOs) that primarily operate on three observed time scales: the 30–90 day Madden-Julian Oscillation, the 10–20 day quasi-biweekly oscillation, and the synoptic-scale 3–7 day oscillation of the monsoon trough. In this research, we focus on local and basin-wide signals, zonal and meridional propagation, and variability of ISOs with respect to the strength of the summer monsoon season over a multi-decadal period (1993–2016). For the first time, this study examines the relationship between larger- and shorter-period ISOs in SLA and shows the usefulness of altimetry data in Indian monsoon studies. We compare ISOs in SLA during years with summer monsoons of varying strengths, finding notably stronger circulation and larger amplitude of all ISOs in years with stronger summer monsoons theorized in part to be due to the first-baroclinic mode forcing from low-level winds ($R^2$ values of 0.61, 0.67, and 0.64 in the northern, central, and southern Bay, respectively), although it is important to note the influence of other local forcings, such as mesoscale eddies and coastal Kelvin waves. We demonstrate that 30–90 day variability of SLA is initially forced by equatorial processes and strengthened by local processes in the BoB, as higher-amplitude SLA ISOs were consistently observed in the southern and eastern Bay. Local processes like coastal Kelvin waves were found to strongly influence the 10–20 day quasi-biweekly signal, as was seen in the high-amplitude 10–20 day SLA ISOs found in the eastern BoB. The synoptic signal also revealed a zonal pattern consistent with coastal Kelvin wave intensification and eddy generation.

KEYWORDS
altimetry, Bay of Bengal, intraseasonal oscillations, Madden-Julian oscillation

1 | INTRODUCTION

The Bay of Bengal (BoB) experiences ISOs on a variety of time scales, including the 30–90 day signal due to Madden-Julian Oscillation (MJO) events, the quasi-biweekly 10–20 day signal, and the 3–7 day signal representative of synoptic-scale events as a response to oscillations of the monsoon trough, all of which have only recently been observed in oceanic variables due to ever-improving satellite capabilities (Subrahmanyam et al., 2018). These ISOs are responsible for variation from...
mean conditions of monsoonal rainfall and are central in modulating active (wet) and break (dry) monsoon conditions (Goswami and Ajaya Mohan, 2001; Wang et al., 2001).

The MJO is an atmosphere–ocean coupled event that regulates wet and dry conditions in the tropical Indian and Pacific Oceans (Madden and Julian, 1971; Madden and Julian, 1972; Zhang, 2005). MJO events are defined as an eastward-propagating circulation anomaly that propagates at speeds of 3–5 m/s on a length scale on the order of 10,000 km (Majda and Biello, 2004). In the BoB, MJO events have also shown northward propagation (Fu et al., 2003). MJO-related ISO events drive a unique ocean–atmosphere feedback loop of alternating upwelling and downwelling Rossby waves that drive concurrent outgoing longwave radiation (OLR) anomalies and fluctuations in mixed layer depth (Grunseich et al., 2011). Li et al. (2016) investigated the impacts of the ocean mixed layer depth on monsoonal surface heat flux forcing, finding that although primary SST variability is through surface heat forcing, the secondary source of variability is although mixed layer dynamics. Li et al. (2016) found that shallow MLDS nearly double the amount of preconvection warming and increase cooling following each ISO event by 20%. Oceanic equatorial Rossby waves directly impact the SST anomalies responsible for the triggering of MJO events (Oliver and Thompson, 2010; Webber et al., 2012; Rydbeck et al., 2017). Composite analysis conducted by West et al. (2018) found that more than one third of preconvection warming for MJO events was due to oceanic properties. They found through a mixed layer heat budget that advection was more influential than entrainment for raising sea surface temperature anomalies and increasing local convection (West et al., 2018). In addition, intraseasonal currents associated with Rossby waves can advect high seasonal mean temperatures to initiate strong convection events (West et al., 2018). The feedback system between equatorial Rossby waves in the BoB and MJO events is highly coupled (Pai et al., 2011). Oceanic mixed layer processes such as changes in salinity stratification (leading to thick barrier layer formation, suppression of entrainment cooling, and feeding of relatively warm water in the mixed layer) are tightly coupled with atmospheric ISOs and strongly influence the active-break spells (Li et al., 2017a; 2017b). During the summer months, this larger-period ISO is referred to as the boreal summer ISO (BSISO; Yasunari, 1981; Krishnamurti and Subrahmaniyam, 1982; Chen and Murakami, 1988; Wang and Xie, 1997; Lee et al., 2013).

The quasi-biweekly mode has been well investigated with respect to its synoptic structure and characteristics and is related to westward-propagating surface pressure cells (Murakami, 1979; Krishnamurti and Ardanuy, 1980; Chen and Chen, 1993; Chatterjee and Goswami, 2004). These cells result in a roughly biweekly periodicity observed in cloud cover, rainfall, and monsoonal winds in the upper and lower troposphere and the two cells are typically centered about 15°–20°N and the equator (Krishnamurti and Bhalme, 1976; Chen and Chen, 1993). However, there is still insufficient quantification of the relationship between this quasi-biweekly signal and how surface waters in the BoB react with respect to sea level anomalies (SLA). Krishnamurti and Ardanuy (1980) determined that application of the 10–20 day mode was able to predict approximately 70% of monsoon break periods (lasting typically 3–4 days) over a 30-year period. Improved understanding of the oceanic response to this mode is necessary for further improvement of rainfall prediction.

Lower-period alternations between active and break days are attributed to oscillations of the axis of the monsoon trough. The most frequent duration of break and active periods is 3–4 days (Krishnamurti and Ardanuy, 1980). In the BoB, Nitta et al. (1985) detected a 6-day spectral peak in the northern Bay due to westward-propagating depressions along the monsoon trough. Additionally, northwestward tracks of monsoon lows have been related to 5–9 day ISOs along the east coast of India (Hartmann andMichelsen, 1989).

SLA, unlike sea surface temperature and salinity, do not experience precipitative contamination due to propagation of convective monsoon conditions or riverine input, but instead represent the dynamic response of the oceanic response to ISOs well, while sea surface temperatures represent a combination of dynamic and thermodynamic responses to atmospheric forcing. Through the exploration between ISOs and SLA, one can develop a clear spatial and temporal understanding of how oceanic conditions respond to atmospheric events. Propagation of ISOs in the BoB in SLA directly alters the depth of the mixed layer and can enhance or weaken surface heat fluxes (quantified by Li et al. (2016) to double preconvection warming and increase cooling by 20% following each event) that contribute to monsoonal rainfall (Li et al., 2016; West et al., 2018) and therefore has the potential to play a significant role in the preconditioning of oceanic conditions for heavy rainfall. In addition, the BoB also experiences high mesoscale eddy activity reflected in SLA in the 10–90 day frequency band (Fischer et al., 2002; Cheng et al., 2017). This research applies satellite-derived sea level anomalies with the objective of comparing ISOs in SLA in the BoB during strong and weak monsoon seasons, defined by the Indian Institute of Tropical Meteorology (IITM) Pune, India as having June through September Indian rainfall greater than 10% (for strong seasons) or less than −10% (for weak seasons) of the long-term seasonal mean. The following work is organized as follows: Section 2 describes our methodology, Section 3 presents our
results and discussion with respect to ISOs in SLA in the BoB, and Section 4 concludes this paper.

2 | DATA AND METHODOLOGY

The SLA gridded product and its derived geostrophic currents used in this study is processed and distributed by the Copernicus Marine Environment Monitoring Service (CMEMS, marine.copernicus.eu) by merging observations from a variety of altimetric satellite missions. Although the near-real time product spans from January 1, 1993 to May 15, 2017, we focus on only the full years of data (1993–2016). This product possesses a 0.25° horizontal grid spacing. Altimeter-derived SLA, unlike many satellite-derived oceanic parameters, does not experience contamination from cloud cover, which allows for observation of the response to the surface of the BoB to ISOs in all weather conditions. The inverse barometer correction, which accounts for variations in SLA due to atmospheric pressure variations where a 1-mb increase in atmospheric pressure depresses the sea surface by about 1 cm, has been applied via:

\[
IB_{\text{Corr}} = -9.948(P_{\text{atm}} - 1013.3),
\]

where \( IB_{\text{Corr}} \) is the correction for the inverse barometer effect (in mm), the scale factor 9.948 is empirically derived (Wunsch, 1972) and 1013.3 is the static inverse barometer correction referenced by the Topex/Poseidon altimetry mission (Jason-1 Products Handbook, 2016).

Daily winds from the European Center for Medium-range Weather Forecasts (ECMWF) ERA-interim product were used during this time period at 1.0° horizontal grid spacing during this time (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. Berrisford et al., 2011). ERA-Interim better captured the dynamics of the hydrologic cycle, stratospheric circulation, and has reduced biases than the previously used ERA-40 reanalysis (Berrisford et al., 2011). A Butterworth 4th order recursive time filter was applied via the techniques described in Subrahmanyam et al. (2018) to isolate each ISO. The periods extracted were that of 30–90 days (to study the MJO-BSISO), 10–20 days (to study the quasi-biweekly ISO), and 3–7 days (to extract synoptic variability). The daily sampling of these products is sufficient for extraction of these signals.

3 | RESULTS AND DISCUSSION

3.1 | Annual variation of SLA in the Bay of Bengal

Due to monsoon-driven surface current reversal, eddying, and river outflow into the BoB, SLA and resultant geostrophic currents experience notable. The circulation in the BoB is largely tied to monsoonal processes, which influence wind-driven transports and stratification (Shenoi et al., 2002; Schott et al., 2009). Surface winds over the BoB are weaker than their Arabian Sea counterpart (Shenoi et al., 2002). This leads to basin-wide warmer sea surface temperatures that drive strong convective activity (Shenoi et al., 2002). In hindcast and satellite observations, Cheng et al. (2013) found that intraseasonal variability of sea surface heights in nearly all regions of the BoB are primarily driven by equatorial intraseasonal winds, the reflection of equatorial Kelvin waves as coastally trapped waves, and eddy activity. However, local and basin-scale SLAs in the BoB have never before been contextualized within the 10–20 day and 3–7 day periodicities to further isolate mechanisms of intraseasonal oscillations in SLA nor have these shorter-period oscillations been temporally compared with the 30–90 day MJO-induced ISO in SLA in the BoB. This research therefore permits advanced understanding of the interplay between the ISOs of different periodicities in the BoB.

To observe the spatial variability of SLA in the BoB and explore the impacts of seasonality, monthly SLA and geostrophic currents are presented for the peaks of the winter and summer monsoons (January and July, respectively) and their intermonsoon periods (April and October) for years the strongest summer monsoon season during the altimetry era (1994) and the weakest (2002) as defined by the Indian Institute of Tropical Meteorology (Trott et al., 2017). Strong (weak) monsoon seasons are defined in relation to the long-term (1871–1990) June–July–August–September mean Indian rainfall. If a summer monsoon season exceeds a 10% increase (decrease) in Indian rainfall in reference to the long-term mean, it is defined by the Indian Institute of Tropical Meteorology (IITM), Pune, India as a strong (weak) summer monsoon season. It is important to note that monsoonal “break periods” refer to subseasonal atmospheric dry conditions and “break seasons” refer to seasonally low precipitation. Basin-wide SLA are highest during the summer monsoon (Figure 1e–f). During this time, the Summer Monsoon Current is clear at 5°N flowing eastward from the southern tip of India into the BoB, resulting in northward flow to 14°N in July during the strong summer monsoon seasons and only extends to approximately 10°N during the weak summer monsoon season. In the winter monsoon, the Winter Monsoon Current is clear at the same location as the Summer Monsoon Current, but flowing westward at the southern tip of India, transporting relatively fresh waters from the BoB into the southeastern Arabian Sea (Wijesekera et al., 2016a; 2016b). Prior to the summer monsoon (April), there are low SLA in the northern Bay and an observed zonal SLA gradient throughout the Bay, with higher SLA in the western Bay. The spatial distribution of high and low
SLA has been identified as a response to coastally trapped Kelvin waves (Nienhaus et al., 2012). These Kelvin waves trigger the initiation of westward-propagating Rossby waves (Schott et al., 2009). In all observed months, there is eddying in the BoB, with the largest-amplitude eddies in April and July (Figure 1). Year-to-year variability is additionally attributed to Indian Ocean Dipole (IOD) or El Niño-Southern Oscillation (ENSO) events, which have been observed to alter coastal wave development (Clarke and Liu, 1994; Sengupta et al., 2004; Miyama et al., 2006; Fournier et al., 2017).

3.2 | Wavelet analysis of SLA in the BoB

Two identifiable features in the basin-wide timeseries of SLA in the BoB are the seasonal SLA cycle and a positive long-term basin-wide trend of 0.365 cm/year (Figure 2a). The benefit of wavelet analysis over a simple Fourier transform is the ability to temporally investigate high-power periodicities within the targeted frequency ranges and identify the timing of particularly strong ISO events. In the unfiltered timeseries of SLA, it is clear that the spectral peak observed in the applied wavelet analysis is strong at the 180-day semiannual and 365-day annual signals (Figure 2e). This 180-day periodicity has been attributed to the second baroclinic mode due to basin resonance and wind forcing (Cheng et al., 2017). 180-day variability is almost entirely forced by propagation of equatorial signals into the BoB (Han et al., 2011). The amplitude of the filtered 30–90 day signal (≤2.93 cm) indicates a substantial response to MJO forcing (Figure 2a), which is suppressed during the observed summer monsoon seasons (Figure 2b). The amplitude for the 10–20 day signal (≤0.38 cm; Figure 2c) and 3–7 day synoptic signal (≤0.07 cm; Figure 2d) are much smaller than that due to MJO (Figure 2).

3.3 | Basin-scale SLA ISOs

Direct comparison of the observed ISOs in the northern, central, and southern Bay reveals a notable meridional difference in intraseasonal behavior of SLA throughout the BoB (Figure 3). In the unfiltered signal, the highest SLAs associated with the increasing basin-wide trend are of a similar magnitude throughout the full Bay, although the largest variability is in the southern Bay, followed by the northern Bay, with the smallest variability in the central Bay (respective standard deviations of 5.47, 5.03, and 4.35 cm). The seasonal cycle of SLA in the BoB correlates well with the low-level wind forcing (R^2 values of 0.61, 0.67, 0.64 in the northern, central, and southern Bay, respectively). SLA in the southern Bay are more sensitive to equatorial processes (due to proximity) that lead to this increased variability. The strongest 30–90 day ISO in SLA is in the southern Bay, with the maximum amplitude of 4.51 cm (2.78 cm in the northern Bay and 2.75 cm in the central Bay) and standard deviation of 1.34 cm (0.75 cm in the northern Bay and 0.86 cm in the central Bay), which is not unexpected due to the contribution of the first baroclinic mode dominated by equatorial Kelvin and Rossby waves that can feed energy into the 30–90 day periodicity in addition to that introduced by MJO events (Cheng et al., 2017). As a result, the northern and central BoB are more similar to each other than the southern BoB signal, as these regions are less strongly tied to equatorial processes (Figure 3).

In the 10–20 day signal, the largest amplitudes are again in the southern BoB (1.04 cm maximum amplitude, standard deviation of 0.24 cm), signifying either an increase in intra-seasonal equatorial forcing, increased local forcing (attributed to mesoscale eddies and the coastal Kelvin waves that form them), or a combination of both. The high mesoscale eddy activity in this region has been shown to influence
local SLA within the 20–90 day frequencies (Li et al., 2015; Cheng et al., 2017). Like its larger-period equivalents, the 3–7 day synoptic variability in SLA are strongest in the southern BoB and weakest in the central Bay (southern Bay has maximum amplitude of 0.13 cm and standard deviation of 0.3 cm, northern Bay has maximum amplitude of 0.11 cm and standard deviation of 0.02 cm, and central Bay has maximum amplitude of 0.64 cm and standard deviation of 0.02 cm).

### 3.4 Meridional propagation of ISOs in SLA

Seasonality and meridional propagation were further studied for all three periodicities (30–90, 10–20, and 3–7 day). For all studied periodicities, ISOs were stronger in active monsoon seasons than break monsoon seasons shown respectively in red and green in Figure 2 (Figure 4). The only active monsoon season during this time period is in 1994, while there were break monsoon seasons in 2002, 2004, 2009, 2014, and 2015. The 30–90 day signal interestingly is in-phase throughout the entire basin, hence the high-amplitude oscillations throughout the year that is not seen in any of the break years (Figure S1). After February, there is a different meridional distribution of the signal between the northern and southern Bay, likely due to interactions induced by equatorial processes that amplify that of the MJO events (Cheng et al., 2013). This is consistent with the results of Cheng et al. (2017), although they did not study SLA variation on temporal scales less than 30 days. We find that the 10–20 day signal has the largest amplitudes south of 8°N. The amplitude at this latitude is persistent from April to September of active monsoon years, but in break monsoon years is exceptionally weak in the southern BoB during July, when the summer monsoon season typically reaches maturity, although this is due to individual seasons being out of phase with one another (Figure S2). There is no clear meridional propagation of the 3–7 day synoptic signal (Figure 4 and Figure S3) as the signal far too noisy, indicating either that SLA is less responsive to synoptic forcing than other parameters such as sea surface salinity or that current altimetric observations are insufficient to resolve ISOs with such a short periodicity (Subrahmanyam et al., 2018).

### 3.5 Zonal propagation of ISOs in SLA

The dynamic response in the BoB to intraseasonal variability involves westward propagating Rossby waves (Figure 5) triggered by coastal Kelvin waves on the eastern boundary of the BoB. It should be noted that as there is a different number of strong monsoon years than weak monsoon years, there is some inherent smoothing of random variability when the five break monsoon years (filtered for each ISO period) were directly averaged, although the individual signals are shown for all ISO periods in the supplemental materials. The
FIGURE 3  Time-series of daily SLA (solid lines) and wind magnitude for the northern Bay box (14°–18°N, 85°–95°E), central Bay box (10°–14°N, 85°–95°E) and southern Bay box (5°–10°N, 85°–95°E) for (a)–(c) unfiltered SLA and filtered SLA at periods of (d)–(f) 30–90 day, (g)–(i) 10–20 day, and (j)–(l) 3–7 day. Boxes are delineated in Figure 1.

FIGURE 4  Time-latitude Hovmöller diagrams of daily SLA (cm) for average years with active summer monsoon seasons and years with break summer monsoon seasons longitudinally averaged over 85°–95°E filtered at periods of (a),(b) 30–90 day, (c),(d) 10–20 day, and (e),(f) 3–7 day.
overall zonal propagation signal is still clear in all three ISOs of study (particularly for the 30–90 day signal and the 10–20 day signal) and there is a clear zonal pattern. In the 30–90 day response, the signal propagates westward at approximately the same speed throughout the year in both strong and weak monsoon seasons (Figure 5a–b and Figure S4). In the active monsoon season, the western boundary of the BoB is characterized by a higher-amplitude 30–90 day signal, while the amplitude is zonally uniform in the composite of weak monsoon years. In the 10–20 day signal, both monsoon conditions have a stronger response in the eastern Bay. The annual cycle is dominated by westward propagation, but during the summer monsoon season the propagation either stops (Figure 5c) or becomes slightly eastward (Figure 5d and Figure S5). This is similar to the propagation pattern of mesoscale eddies in the BoB due to a combination of the beta effect, advection, and topography (Dandapat and Chakraborty, 2016). The smoothing of random variability is most significant in the 3–7 day synoptic signal, which is characterized by low-amplitude, noisy signals (Figure S6). Despite the transient nature of the 3–7 day synoptic signal in SLA, there is still a stronger signal in the eastern Bay that indicates either possible energy propagation from the higher-period 10–20 day signal or the influence of coastal Kelvin waves in the eastern Bay on SLA ISOs at a multitude of periodicities.

4 | CONCLUSION

SLAs in the BoB were investigated to better understand and quantify the upper-ocean response to ISOs at three major periodicities: 30–90, 10–20, and 3–7 days (typically attributed to synoptic variability). The 30–90 day signal generally signifies the presence of a MJO event and low-frequency equatorial processes, the 10–20 day signal represents the quasi-biweekly signal due to a westward-propagating atmospheric double-cell structure about 15–20°N and slightly north of the equator, and the 3–7 day synoptic signal is due to oscillations in the monsoon trough. We discover an interesting meridional distribution of ISOs. The highest-amplitude ISOs for each period were found to be strongest in the southern BoB, indicating the important influence of equatorial processes on SLA variability within all ISO periods observed. We find stronger ISOs in years with active summer monsoon seasons that coincided with a more active surface circulation. We directly compared ISOs in years with strong and weak summer monsoon seasons and found differences in amplitude as well as seasonality. Basin-wide and regional ISOs in SLA show the dominance of equatorial processes and secondary influence of local processes such as coastal Kelvin waves and mesoscale eddy generation on SLA in the BoB. For the first time, SLA was used to directly compare ISOs of multiple periodicities to isolate their
individual influences. The 10–20 day ISOs were generally constrained to the southern BoB, while 3–7 day synoptic variability was very low-amplitude and showed the noisiest spatial and temporal distribution. For future studies, higher spatial and temporal resolution is necessary to better quantify and track the response of SLA to synoptic-scale events. SLA is a useful approach for the study of ISOs in the BoB as it does not experience contamination by clouds and, unlike salinity, is not contaminated by riverine discharge. Further investigations of satellite-derived altimetric observations are critical for understanding of Indian monsoon dynamics. We hope future altimetric missions like NASA's Surface Water Ocean Topography (SWOT) mission will improve spatial coverage to detect these oscillations much better than current altimetric measurements.

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