Using drifter observations to unearth the mysteries of Monsoons in the Bay of Bengal

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***Abstract*—This study uses drifters and minimet drifters to characterize investigate the onset of summer monsoons and their active-break periods in the Bay of Bengal. The Indian subcontinent receives abundant seasonal rainfall as a result of Monsoon Intra-Seasonal Oscillations (MISO). MISO propagation in the Bay of Bengal (BoB) leads to active phases (intervals of relatively high rainfall) and break phases (intervals of little or no rainfall). There are considerable differences in the air-sea interactions in the two phases. The onset and duration of the active and break periods are not well predicted, and errors in simulating and predicting these affects the weather forecasting across the globe. Monsoon Intra-Seasonal Oscillations in the Bay of Bengal (MISOBOB) program from USA and Ocean Mixing and Monsoons program from India brought in teams of scientists to intensively observe air-sea interaction in the context of Monsoons. As a part of MISOBOB, 30 drifters and 5 minimet drifters were deployed in the central BoB. Here we investigate whether the different phases associated with the MISOs can be detected using surface measurements from these autonomous instruments. With observations from multiple drifters, it is also possible to compare the spatial gradients in the diel cycles of SST over the length scale of an order of 100km or less (i.e. within (sub)mesoscale length scales) during both phases. These spatial statistics during active and break phases are not well known in the BoB from in-situ measurements. Similarly, observations from minimet drifters could be used to compare spatial gradients in wind speeds. Such gradients over length scales of an order of 100 km or lesser can lead to horizontal gradients in diurnal warm layer properties and thus provide a mechanism for submesoscale and mesoscale horizontal mixing of surface waters.**

***Index Terms*—Monsoons, Drifters, Bay of Bengal, Spatial gradients**

I. Introduction

The Bay of Bengal plays an important role in governing the regional and global weather patterns by nurturing the Indian Summer Monsoons. This phenomenon directly impacts more than one-third of the human population, providing almost 90% of the annual precipitation to the Indian subcontinent during the months of June to November [1]. Although monsoons are considered seasonal, intra-seasonal oscillations with varying time periods dominate the rainfall. Studies show Monsoon Intra-Seasonal Oscillations (MISO) is majorly composed of two time-scales: A 10-20 day mode [2] which propagates westward into the subcontinent and 30-60 day mode [3]–[5] which tends to move northwards from the near equator. All of these oscillations are characterized by two different phases: active phase and break phase [6], [7]. During the break phase, low wind speeds and clear skies are common in the Bay, leading to strong diel cycles in temperature. High wind speeds, high precipitation rates with overcast conditions is typical during the active phase of the monsoons, which further leads to a suppression in the diel cycles of temperature in the Bay [7], [8]. Considering the intricate nature of the air-sea coupling, many studies have observed MISO signatures in Sea Surface Temperature (SST), sub-surface temperature, Surface fluxes, winds and currents in the Bay [9]–[13]

Variability in rain due to MISO have large impacts on the the agricultural produce on the Indian landmass [14], [15]. Considering the contribution of agriculture to the Indian economy, forecasting the MISO beforehand is highly important [14]. Despite the increased skillset in terms of our understanding of MISO, forecasting such tropical oscillations using an atmospheric general circulation models is often erroneous [14], [16]. Coupled atmosphere-ocean models, on the other hand were found to show enhanced predictability of MISO and associated rainfall [17]–[19]. In order to further improve the forcasting skill of MISO, the ocean component of the coupled models and the air-sea interaction processes has to be represented better [6], [20], [21].

Until early 2000's, the knowledge of the upper ocean structure of the Bay during the MISO was limited considering the sparse sampling from ship and buoy networks. The rise

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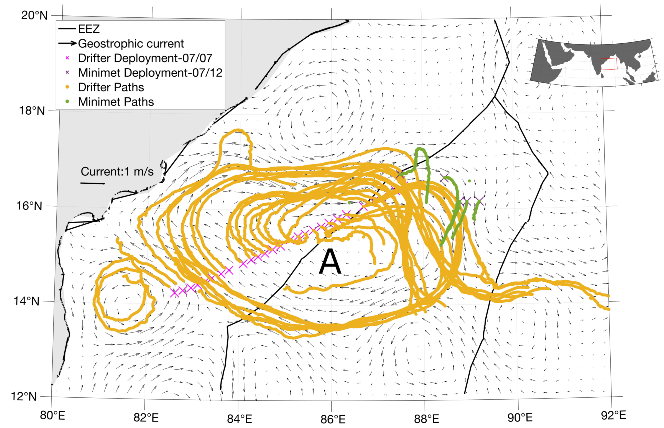


Fig. 1. Map of the Bay of Bengal showing drifter and minimet drifter paths during MISOBOB Intensive Observational Period (IOP) 2019. The deployment dates and the deployment position for drifters and minimet drifters are indicated in the legend of the figure. Geostrophic currents derived from AVISO are shown as black arrows.

of satellite observations played an important role in better representing the basin-wide surface evolution in the Bay [22]. While the upper ocean evolution over the basin-wide length scale and over intra-seasonal timescales or longer were well observed in the Bay, constraints in the pass time of the satellites, sparse resolution of the sampling and the biases associated with such measurements, studying (sub)mesoscale ocean processes and associated air-sea interaction at diurnal time scales in the Bay was difficult [21], [23], [24]. Recent field campaigns like Air-Sea Interaction Regional Initiative in the Bay of Bengal (ASIRI) and Monsoon Intra-Seasonal Oscillations in the Bay of Bengal (MISOBOB) programs from USA and Ocean Mixing and Monsoons program from India were aimed to reduce these knowledge gaps and improve our understanding of the Bay in terms of (sub)mesoscale ocean processes and associated air-sea interaction [20], [25].

In this study, we use observations of SST and wind speeds from drifters and minimet drifters deployed during the MISOBOB program to understand the different phases of MISO in the Bay. We also use the drifter and minimet pairs to quantify spatial gradients in SST, diel cycles of SST and wind speeds over a length scale of O(1-100 km). Such metrics are not well observed in the Bay to the best of our knowledge.

II. Observational Datasets

Drifters and minimet drifters deployed during MISOBOB Intense Observational Period Leg-2 [25] over the central Bay of Bengal from July 06 to August 04 2019 was used in this study (Figure 1). Thirty surface drifters [26] with an initial separation of 20 km were deployed about 300km off the Indian coast on July 07, 2019 (i.e. in the western side of the Bay of Bengal). The drifters were drouged at 15 m and tracked the mesoscale flow (indicated as A in figure 1). The drifters measured temperature at 0.2m depth and Sea Level Pressure (SLP) with a time resolution of 15 minutes.

Five minimet drifters drouged at 100 m were deployed in the Bay (figure 1) [27], [28]. One minimet drifter was deployed on July 12. Another minimet drifter was deployed on July 17, while three remaining minimet drifters were deployed on July 23, 2019. The minimet drifters measure the same variables as drifters but additionally measure wind speeds at a height of 0.5 m every 30 minutes. In order to adjust the wind speeds to a standard height of 10 m, we use a correction factor of 1.6 (1.8) for wind speeds less (greater) than 15 m/s [29].

III. Results

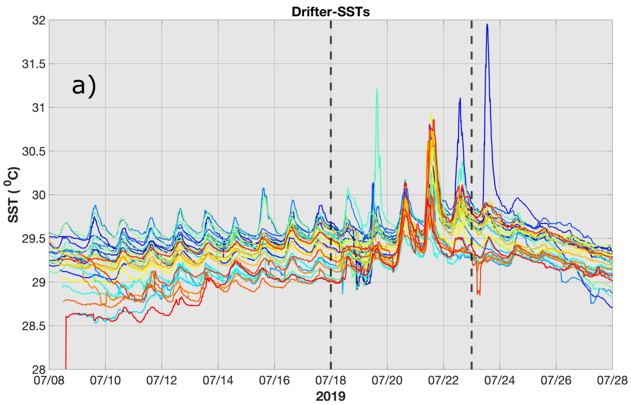
A. Detecting the different phases of Monsoon

SST observations from the drifters can be used to identify the different phases in the Bay (figure 2a). We can infer that the Bay encounters a break phase from July 08 to July 22. Depending on the amplitude of the diel cycles in SST, the period from July 08 to July 17 is referred to as the weak break phase while we refer the period of July 18 to July 22 as a strong break phase. From July 23 onwards, the Bay encountered an active phase.

The regimes which we defined above is found even in the time series of wind speeds measured from the minimets (figure 2b). The wind speeds of 8-12 m/s were observed during the weak break phase while during the strong break phase the speeds dropped to a range of 2-6 m/s. In case of the active phase, the wind speeds increased to values around 12-14 m/s.

B. Emperical Orthogonal Function Analysis of Drifter SSTs

Empirical Orthogonal Functions (EOFs) is useful to extract patterns in the observations from a space-time field [30]. Thus EOFs can be used to extract the common patterns of SST across a mesoscale eddy during the cruise using drifters (figure 3). Such patterns and metrics are shown over a Bay-wide spatial scale and seasonal time scale by [24]. The high resolution observations reported here over a mesoscale eddy are not well observed in the Bay. Mode-1 of the EOFs can



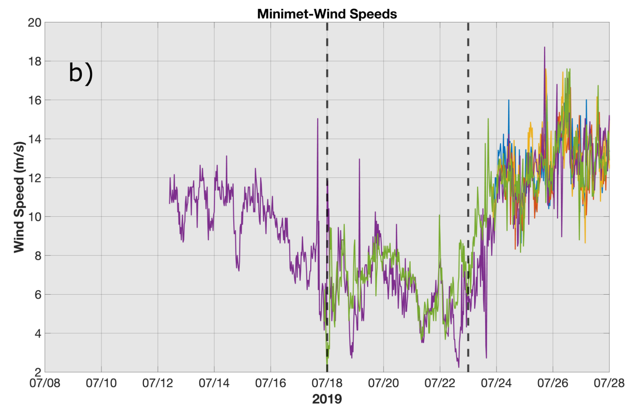


Fig. 2. a) SST time series as measured from drifters at 0.2 m depth and b) Wind speeds at 10 m height from July 08 to July 27, 2019. The black dashed lines on July 18 and July 23 2019 in this figure and subsequent figures are used to split this time series into 3 regimes depending on the diel variations of SST.

be used to describe the diel variations across all the different regimes discussed above and it explains 77 % of the variance in the data (figure 3). On calculating the net heating/cooling across the 3 regimes, it was found that the bay heated by around 0.2 K during regime-1 (over 8 days) and by around 0.25 K during regime-2 (over 4 days). In regime-3, it was calculated that the bay cooled by around 0.5 K.

C. Drifter Paths and Spatial variability in SSTs

The diel variability in SSTs and the flow within the mesoscale eddy during the break and active phases can be visualised spatially using drifters. In case of the break phase, the drifters tend to show higher diel variability in SSTs all over the Bay when compared to the active phase (figure 4 a,c). The drifter paths during the break phase were nearly along the geostrophic currents measured from remote sensing (figure 4b). This implies that either the influence of wind driven Ekman motion was either negligible or the Ekman depth is shallower than 15 m since the drifter is drouged to 15 m depth. Based on a simple scaling analysis as mentioned in [31], the Ekman depth is approximately 82 m deep. Hence, the influence of wind driven Ekman motion is negligible in the break phase. The drifters in active phase were instead

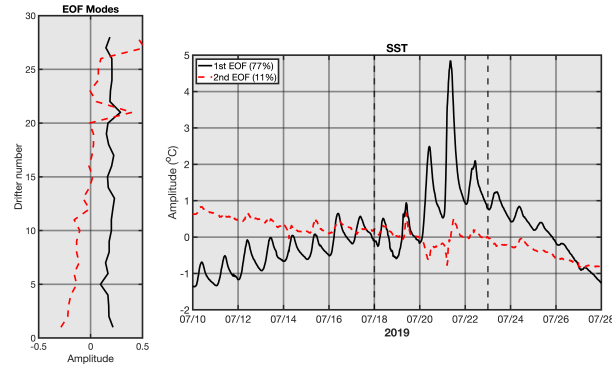


Fig. 3. The left subplot shows the amplitude of SST as a function of drifter number, which basically shows the contribution of each drifter to the different EOF modes. The right subplot shows the amplitude of different EOF modes as a function of time. An estimate of the total variation in 1^{st} EOF mode of a particular drifter can be found by multiplying the amplitude of 1^{st} EOF mode as a function of drifter number to the amplitude of the 1^{st} EOF mode as a function of time. This is used to calculate the net heating/cooling across the regimes

travelling across the geostrophic currents and thus the wind-based Ekman motion dominates the motion of drifters during this phase.

The SST maps as seen in figure 4 b,d indicate that the ocean surface is inhomogeneous with strong horizontal gradients. Simultaneous measurements from 28 drifters allows us to quantify the spatial gradients in SST over length scales of O(1-100 km) (i.e. (sub)mesoscale) by plotting a scatter plot of SST differences and separation distance (figure 5). In case of the weak break phase, we observe that the majority of the temperature differences are spread to about 0.5 K irrespective of the separation distance (figure 5a). The temperature differences get intense to values about 0.6-0.7K for a separation distance of 30-60 km. The temperature differences between drifter pairs are as high as 0.25-0.3 K when the separation distances are O(5-10 km) with temperature differences of O(0.1 K) for separation distance of O(1-2 km) (figure 5d). Similar range of values are also observed in the case of strong break phase (figure 5b,e). The major differences when compared to the weak break phase is that the temperature difference can get as intense as 1.6-1.8 K for separation distances of O(60-80 km). The temperature differences for separation distance of O(1-10 km) are slightly higher for the strong break phase when compared to the weak break phase (figure 5 a,b,d,e). In case of the active phase, the temperature differences reduce to values of about 0.15-0.5 K over a separation distance of O(30-100 km). The temperature differences are around 0.05-0.15 K for separation distances of O(1-10 km) for the active phase (figure 5e,f).

Such temperature differences during the break phase over O(1-100 km) could be because of differences in diel cycles of SSTs, drifters moving in different watermasses, differences in advection and mixing etc. In order to understand the differences in diel cycles between drifter pairs as a function

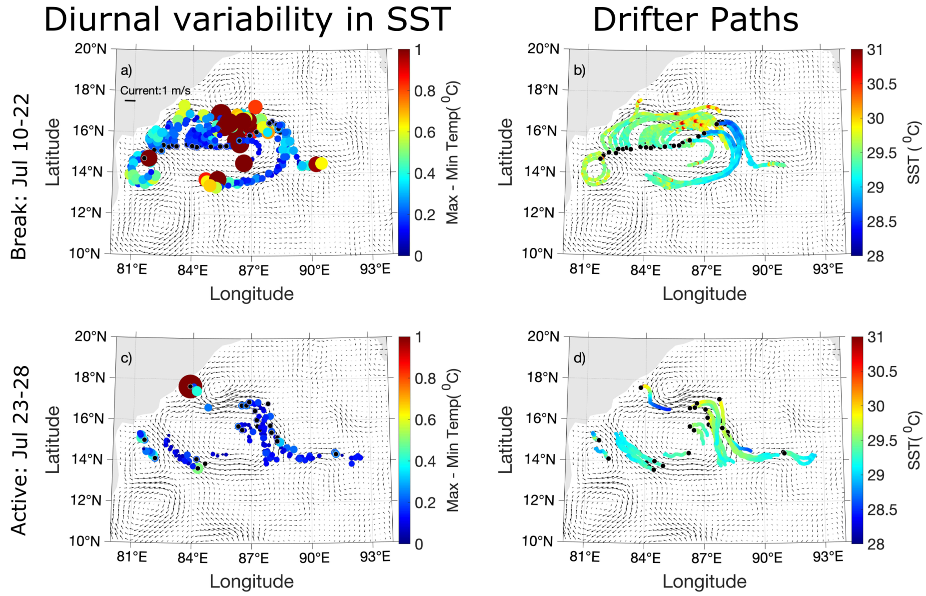


Fig. 4. a) The difference between maximum and minimum temperature during a diel cycle for each drifter b) Drifter paths with the color-bar indicating the SST values for the break phase of the monsoon (i.e. from July 10 to July 22, 2019). c),d) are the same as a) and b) respectively for the active phase of the monsoon (i.e. from July 23 to July 28). The black dots in subplot b) and d) indicate the starting point of the drifter (as to visualise their sense of motion). Background arrows are the geostrophic currents derived from AVISO, an altimetry product.

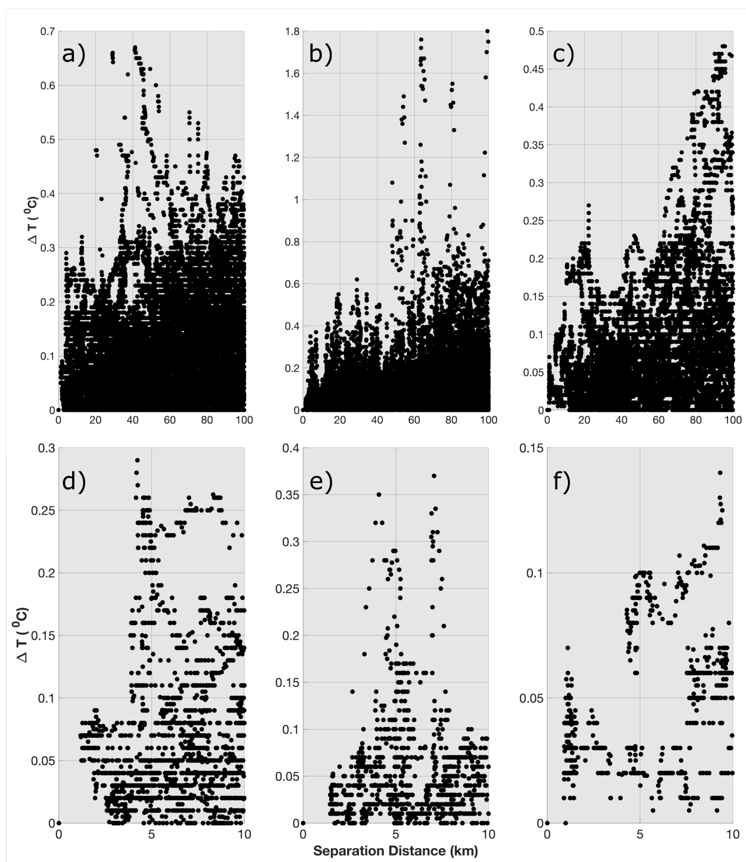


Fig. 5. Scatter plot of SST differences in drifter pairs against separation distances for a) Weak Break phase (July 08-July 17) b) Strong Break phase (July 18-July 22) and c) Active phase (July 23-July 28). a), b), c) are limited to a separation distance of 100 km. d), e), f) are similar to a), b), c) but are limited to a separation distance of 10 km. NOTE: Notice the different Y-axis limits in all the subplots.

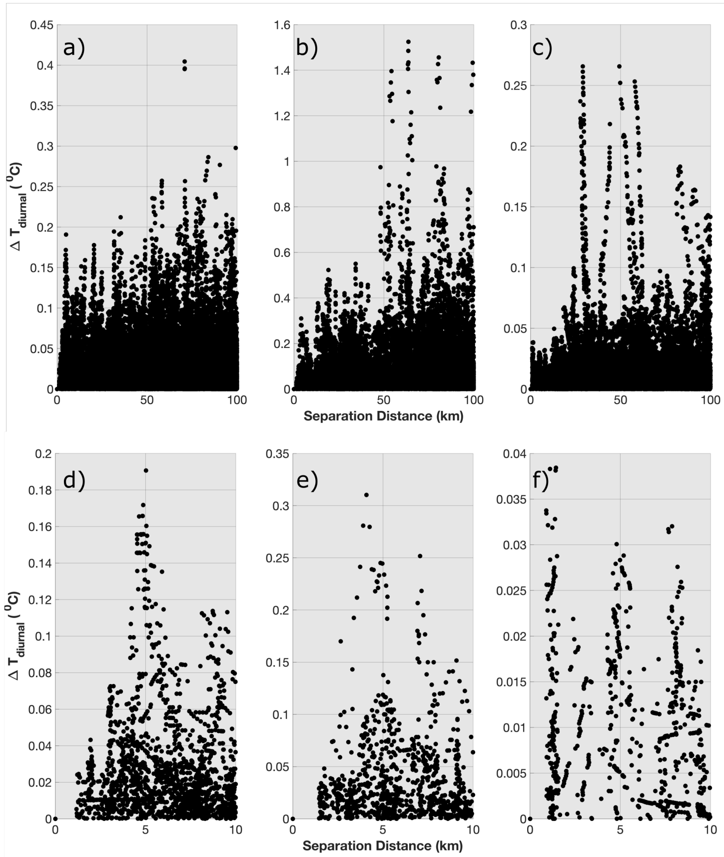


Fig. 6. Scatter plot of $\triangle T_{diurnal}$ in drifter pairs against separation distances for a) Weak Break phase (July 08-July 17) b) Strong Break phase (July 18-July 22) and c) Active phase (July 23-July 28). a), b), c) are limited to a separation distance of 100 km. d), e), f) are similar to a), b), c) but are limited to a separation distance of 10 km. NOTE: Notice the different Y-axis limits in all the subplots.

of separation distance, we use the concept of foundation temperature as defined by [32]. Foundational temperature (T_f) is defined as the temperature just before sunrise (i.e. when the upper ocean is well mixed and assuming that there is no pre-existing stratification due to diurnal warming). T_f is linearly interpolated between those points as to create a foundational temperature trend. This trend would account for heating/cooling for time periods greater than the diel scales. Diel variation in SST for each drifter is calculated as the difference between the SST from the drifter and T_f over a diel cycle. The difference in the diel variation in SST for a drifter pair $(\triangle T_{diurnal})$ is compared with separation distance (figure 6). In case of the weak break phase, we observe that the majority of the differences in diel cycles are spread to about 0.2-0.3 K irrespective of the separation distance (figure 6a). The differences in diel cycles of SST between drifter pairs are as high as 0.1-0.2 K when the separation distances are O(5-10 km) with such differences being negligible for separation distance of O(1-2 km) (figure 6d). When compared to the weak break phase, the differences in diel cycles can be stronger with O(0.4-0.6 K) for separation distances of O(20-100 km). The differences in diel cycles can get as intense as 1.2-1.6 K for separation distances of O(60-80 km). The differences in diel cycles for separation distance of O(1-10 km) are slightly higher for the strong break phase when compared to the weak break phase (figure 6 a,b,d,e). In case of the active phase, the temperature differences reduce to values of about 0.05-0.1 K over a separation distance of O(30-100 km), with some anomalously high diel cycle differences. The diel cycle differences are negligible for separation distances of O(1-10 km) for the active phase (figure 6c,f). Such differences in SST and diel cycles of SST over length scales of an order of 100 km or less could provide a mechanism for submesoscale and mesoscale horizontal mixing of surface waters due to horizontal gradients in diurnal warm layer properties [33].

D. Spatial variability in Wind Speeds

Minimet drifter pairs could be used to understand the spatial gradients in wind speeds for separation distances of O(1-100 km) (figure 7). Considering the deployment strategy of minimet drifters, we only could quantify the wind speed differences during the active phase only. We observe wind speed differences of O(4 m/s) over a length scale of O(10-100 km) with some anomalously high wind speed differences of O(6-10 m/s) during the active phase (figure 7). This shows that

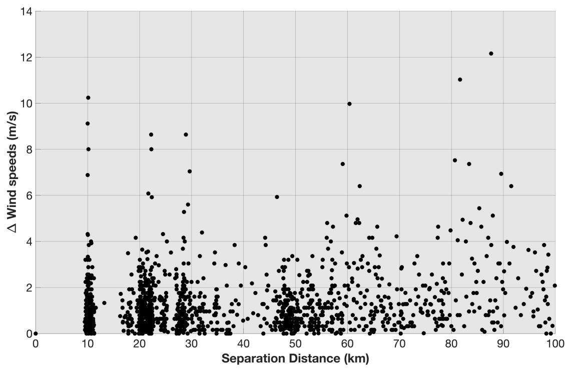


Fig. 7. Scatter plot of Wind speed differences in minimet drifter pairs against separation distances for active phase (July 23-July 28)

the wind speed gradients exists even during the active phase. Such large differences could influence upper ocean processes over (sub)mesoscale length scales.

IV. Discussions

We studied the different MISO phases using observations from drifters and minimet drifters from July 08 to July 28, 2019. We find that 77% of the variance in SSTs from drifters using EOF analysis is due to the diel cycles in SSTs. This study also compares the drifter paths during the different MISO phases and understand the role of wind-driven Ekman motion on the drifter movement, with Ekman motion dominating in the drifters during the active phase. Using a rich network of such autonomous instruments allows us to compute and understand the spatial differences in SSTs and winds. It also allows us to visualize the spatial differences in the nature of diel cycles in SST. We observe that spatial gradients in SST and its diel cycle to be higher during the break phase when compared to the active phase. But even within the break phase, we find a lot of variability in the spatial gradients: the spatial gradients are more intense during the strong break phase when compared to the weak break phase. Reduction of wind speed during the strong break phase could be a major reason behind the same. In the case of wind speeds during the active phase , we observe differences higher than 4 m/s within O(10-100 km). All of these results show that even in the case of organized tropical oscillations such as the MISO, we observe variability in SSTs, its diel cycles and wind speeds at O(1-100 km). Finally, the importance of considering such smaller scale spatial gradients are necessary to get an accurate representation of air-sea interaction processes which in-turn is necessary for a better forecasting of different phases of MISO and its associated rainfall patterns.

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