Monsoons to Mixing in the Bay of Bengal

Multiscale Air-Sea Interactions and Monsoon Predictability

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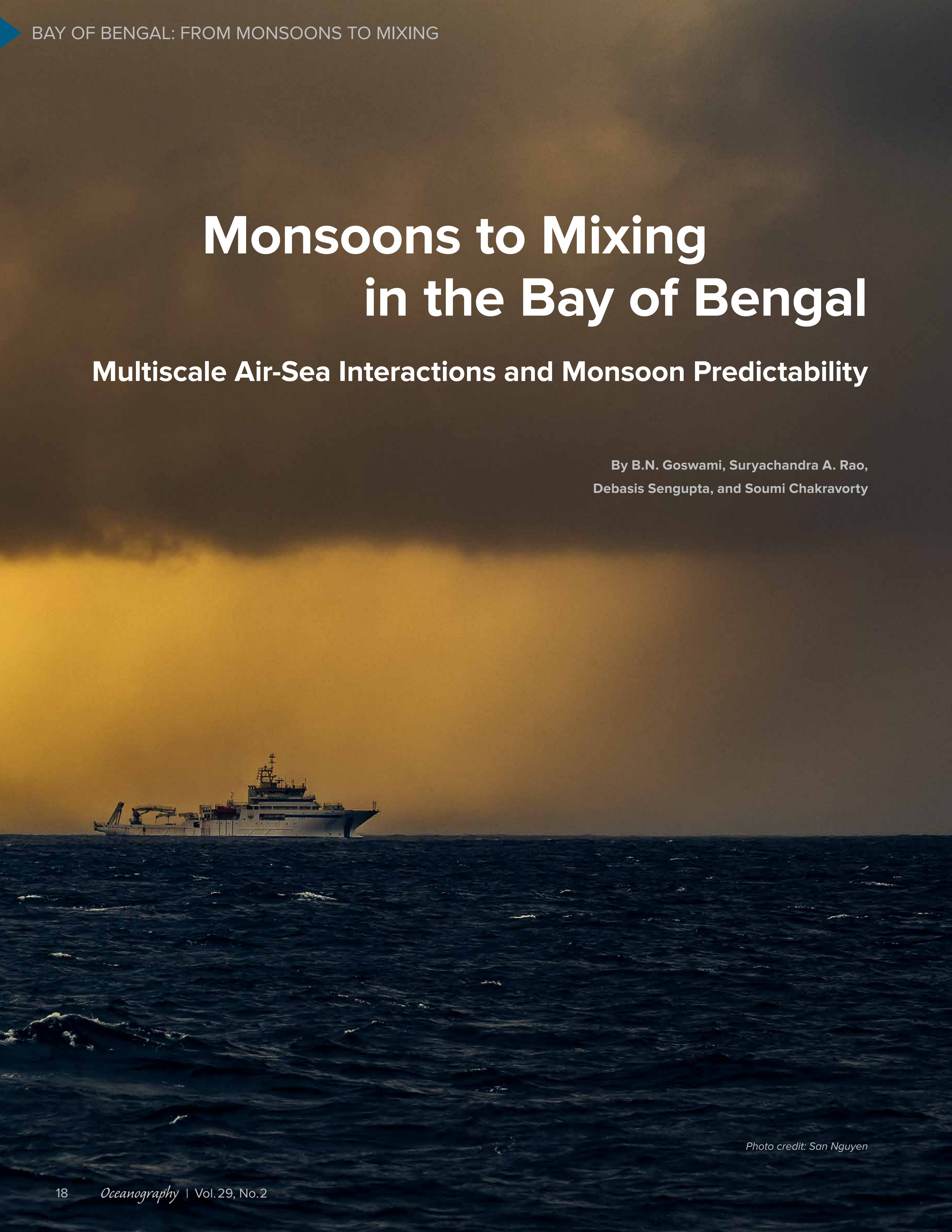

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ABSTRACT. Skillful prediction of the "active" and "break" spells of monsoon intraseasonal oscillations during the South Asian monsoon season is crucial for the socio-economic fate of one-sixth of the world's population, yet it remains a grand challenge problem. The limited skill of our coupled weather and climate models is largely due to our inability to represent the complex multiscale interactions of the north Indian Ocean and the atmosphere. Air-sea interactions are at the heart of not only the climatological mean annual cycle of the South Asian monsoon but also its synoptic, subseasonal, interannual, and decadal variability. With high local monsoon precipitation and discharge from major rivers (Ganges-Brahmaputra, Irrawaddy), the Bay of Bengal (BoB) exhibits the lowest surface salinities in the tropics as well as unique thermal stratification, making it a natural laboratory for studying multiscale interactions ranging from planetary-scale monsoons to submesoscale mixing in freshwater pools. The current ocean component of coupled models is inadequate for simulating the BoB's upper-ocean thermal structure with fidelity. To further improve monsoon forecasts on intraseasonal and interannual time scales, we need new high-resolution and high-frequency observations over the BoB to fill the gap in our understanding of how the ocean mixes in highly fresh regions, and we need modeling of processes that will convert this understanding to parameterizations of mixing that can be used to improve large-scale ocean models.

THE SOUTH ASIAN MONSOON COUPLED CLIMATE

The remarkably predictable annual appearance of the South Asian summer monsoon is associated with year-to-year variations in the intensity and distribution of rainfall over India that result in large-scale droughts and floods (Figure 1a) and thus significantly affect the country's food production and gross domestic product (Gadgil and Gadgil, 2006). Two of the most important variations in South Asian monsoon rainfall are the interannual variability of the seasonal mean rainfall over India (Figure 1a) and the subseasonal variability of daily rainfall (Figure 1b).

Flood and drought years are those years that depart significantly from the long-term mean record of Indian summer monsoon rainfall (ISMR) and have normalized values greater than +1 or less than −1, respectively (Figure 1a). Many monsoon-related floods and droughts are unrelated to external forcing such as the El Niño-Southern Oscillation (ENSO) and instead are of "internal" origin. Some important questions relevant to the predictability of the seasonal mean South Asian monsoon include: What drives the monsoon's large-amplitude internal interannual variability? What role do subseasonal oscillations play in producing the internal variability? What is the predictability of the internal variability? Reliable forewarning of a drought or flood year is critical knowledge for policymakers, so they can plan for food security, and for farmers and water managers, so that they can plan crop strategy. Monsoon forecasts also influence market sentiments and affect the country's economy in several indirect ways. However, ISMR remains a difficult system to predict (Goswami, 1998), owing largely to its vigorous subseasonal variability that manifests in the form of "active" and "break" spells within the season (Figure 1b). As Figure 1b illustrates for three different years, the frequency and duration of the active (above the mean) and break (below the mean) spells can influence the seasonal mean and its year-to-year variability.

Back-to-back large-scale droughts during 2014 and 2015 led to serious water crises in several parts of India. However, in contrast to the twin droughts of 1965 and 1966, India managed the 2014 and 2015 twin droughts without a serious food crisis and without a significant decrease in total average food production compared to the previous decade. Against the backdrop of a serious groundwater decrease in most parts of India, this remarkable achievement resulted from better water and crop management. This improved management was possible only because the farmers and policymakers began to trust the improved forecasts of seasonal mean rainfall and active/break spells of the South Asian monsoon. While predicting the mean South Asian monsoon rainfall a season in advance and predicting active/break spells 20–25 days in advance remain grand challenge problems, the improvements in prediction of both processes during the past decade have clearly been useful, as demonstrated over the past two years in India.

While the seasonal prediction skill of coupled models has been slow to improve (Krishna Kumar et al., 2005; Rajeevan et al., 2012), recent improvements to models and data assimilation have now pushed the skill of seasonal prediction models closer to the potential predictability limit (Pokhrel et al., 2015). Further improvement to model predictions of the seasonal mean, however, are possible only with greater knowledge of Indian Ocean dynamics and its connection to the Indian summer monsoon rainfall (George et al., 2016). Enhanced predictive skill of coupled models for both seasonal mean and active/break spells would bring enormous benefits, but can only be achieved by making key improvements to the forecasting system, which involves a coupled ocean-atmosphere model and a coupled ocean-atmosphere data assimilation system. Improvements to the formulation of some of the physical processes in the oceanic and atmospheric components of the coupled models will improve the forecast skill of the models. In this article, we highlight the crucial role the Bay of Bengal's (BoB's) thermal structure plays in determining the air-sea interactions that control both interannual variability of the seasonal mean South Asian monsoon and its subseasonal variability. Most coupled models fail to simulate the thermal structure over the BoB with fidelity primarily due to poor representation in the ocean models of mixing over the highly fresh and stratified region.

While elevated orography (i.e., Tibet and the Himalayas) is essential to the existence of the South Asian monsoon (Molnar et al., 2010), the annual migration of the Intertropical Convergence Zone (ITCZ) that governs monsoon rainfall is controlled by the annual evolution of the sea surface temperature (SST) in the Indian Ocean (e.g., Lindzen and Nigam, 1987; Möbis and Stevens, 2012). During the boreal summer, the northern Indian Ocean receives heat from the atmosphere while the southern Indian Ocean loses heat to the atmosphere (Figure 2); the situation reverses during the boreal winter. To maintain the observed annual SST cycle requires shallow meridional circulation (Schott et al., 2002) to transport heat south across the equator during summer and north during winter. While direct observational evidence of this meridional circulation and its transport is still lacking, models indicate that the Ekman transport forced by monsoon winds should greatly facilitate this cross-equatorial, seasonally reversing meridional transport (Figure 2). Note that the winds south of 10°S do not change direction with the seasons. While the

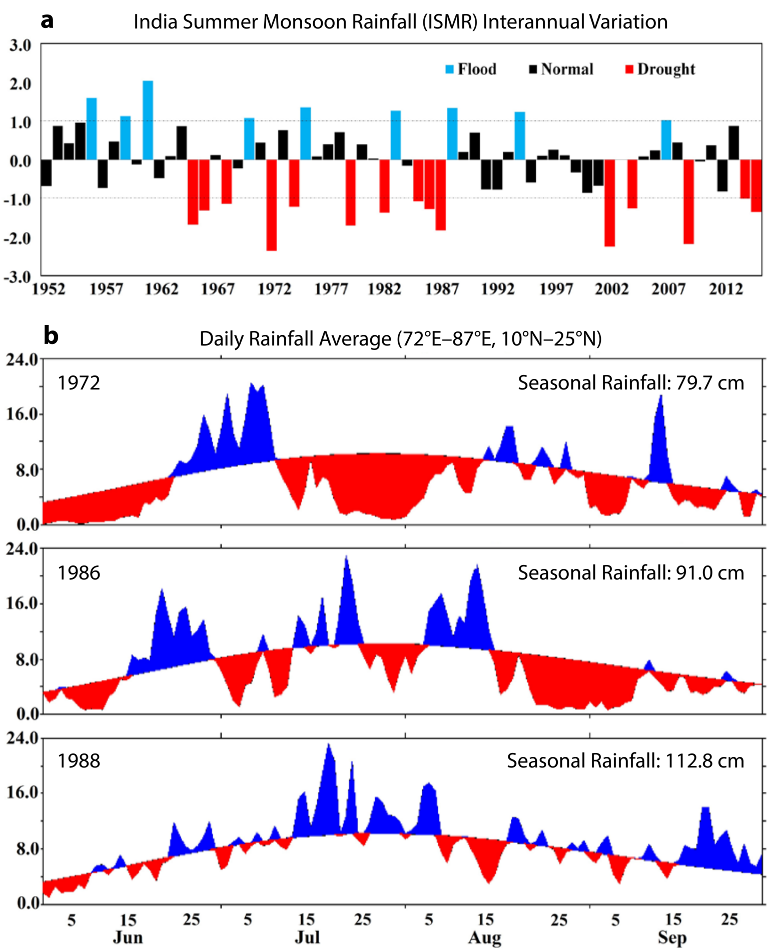

FIGURE 1. (a) Interannual variation of June–September all India summer monsoon rainfall (ISMR) between 1952 and 2015. The departures of individual year ISMRs from the long-term mean (~86 cm) normalized by its standard deviation (10% of the long-term mean) are shown. (b) Daily rainfall from June 1 to September 30 for three different years. The years 1972 and 1986 were drought years while 1988 was a flood year. Positive (negative) departures from long-term daily climatology are shaded blue (red) to highlight the active and break spells.

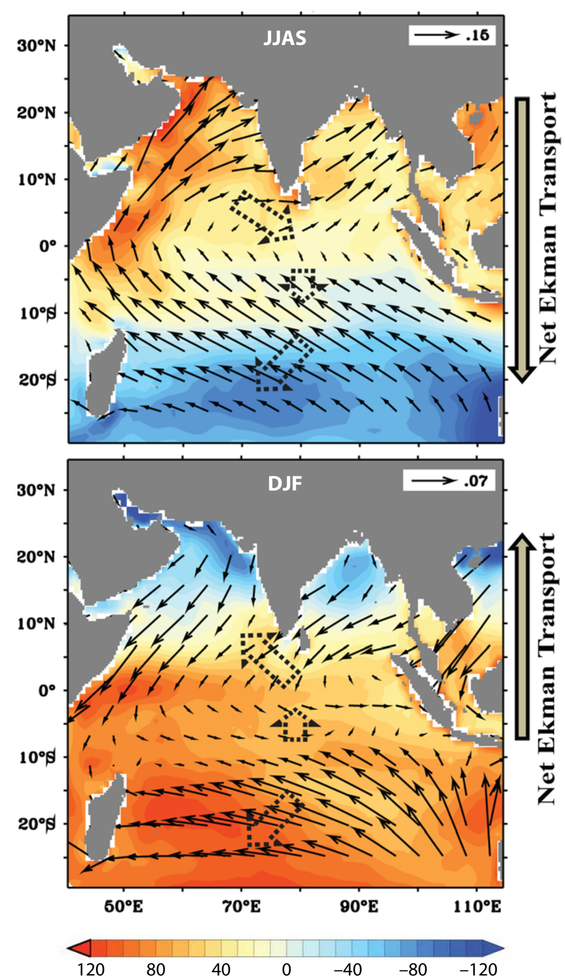

FIGURE 2. Objectively analyzed surface net heat flux in W m^{-2} (shading) and European Centre Reanalysis (Uppala et al., 2005)) surface winds stress in N m^{-2} (vectors) during the months of June, July, August, September (JJAS) and December, January, February (DJF) over the tropical Indian Ocean. The big arrows indicate implied Ekman flow in the ocean.

southward transport in summer may extend to the deep southern tropics (south of 20°S), the northward transport in winter is expected to be confined to the region north of 10°S (Figure 3).

The South Asian monsoon can be seen as a manifestation of the northward seasonal migration of the zonally oriented rain band, namely the ITCZ. ITCZ movement in turn is governed by the annual SST cycle in this region, and indicates that the seasonal cycle of the South Asian monsoon is essentially maintained by large-scale ocean-atmosphere interaction (Webster et al., 1998; Loschnigg and Webster, 2000). In this view, it is easy to see that air-sea interaction could lead to interannual variations in the South Asian monsoon. For example, weak winds in a weak monsoon year would lead to weaker southward transport of heat, leaving the northern BoB with higher SST and heat content during the following summer. This pattern then leads to vigorous synoptic disturbances (atmospheric lows and depressions) and stronger monsoon winds the following year, with stronger southward transport of ocean heat. Ocean reanalysis indicates a significant difference in mean meridional circulation during the northern summer between strong and weak monsoon years (Figure 3d). This air-sea interaction process could lead to biennial oscillation of the South Asian monsoon (Loschnigg et al., 2003). Therefore, skillful prediction of seasonal mean monsoon rainfall requires that the models simulate the SST and thermal structure over the BoB with fidelity.

INTRASEASONAL OSCILLATIONS: MONSOON BUILDING BLOCKS

While prediction of the total rainfall in India during the monsoon season is useful for policymakers, farmers and water managers are more interested in knowing the variations within the season. In reality, the seasonal mean monsoon rainfall is the sum of contributions from vigorous subseasonal oscillations (i.e., active and break spells; Goswami, 2012) and synoptic disturbances that form within the subseasonal spells (see Figure 1b). In the temporal domain, the monsoon intraseasonal oscillations (MISOs) are dominated by 30–60 day and 10–20 day modes when the amount of rainfall fluctuates vigorously, comparable to the annual cycle, and with three to four times the amplitude of the seasonal mean monsoon rainfall (Figure 2.3, of Goswami, 2012). While the seasonal mean South Asian monsoon is a manifestation of the seasonal northward migration of the ITCZ (Webster et al., 1998), the boreal summer is characterized by two maximum precipitation zones, one over the continent (continental ITCZ) and the other over the ocean centered around 5°S (the oceanic ITCZ; Figure 2.1d of Goswami, 2012). The dominant MISO mode (30–60 days) arises from a fluctuation of the ITCZ and is characterized by repeated northward propagation from the oceanic ITCZ location to the continental ITCZ location over about 20 days. An active spell of monsoon occurs when the peak positive phase of the MISO (intraseasonally fluctuating ITCZ) coincides with the climatological mean position of the continental ITCZ and strengthens it, while a break spell occurs when the peak negative phase of the MISO weakens the continental ITCZ significantly. The evolution and northward propagation can be described by two indices called MISO1 and MISO2 based on an Extended Empirical Orthogonal Function (EEOF) analysis of rainfall (Suhas et al., 2013). Using precipitation data from the Tropical Rainfall Measuring Mission (TRMM), the composite evolution of eight MISO phases is constructed based on the two MISO indices (Figure 4). The northward propagation of the rain band from the oceanic position (phase 2) to the continental position (phase 6, clockwise) and beyond (phase 8) is evident.

The MISO influences the seasonal mean monsoon rainfall in more ways than one. As the spatial structure of the MISO significantly influences the seasonal mean pattern of precipitation in

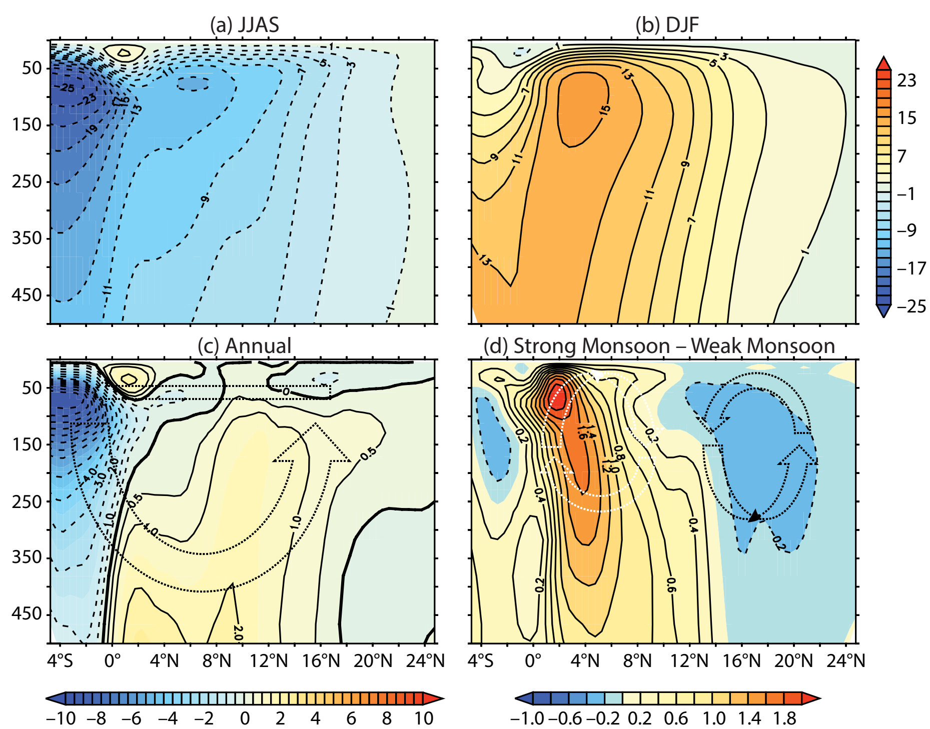

FIGURE 3. Climatological mean meridional stream function in the tropical Indian Ocean during (a) JJAS, (b) DJF, and (c) annual mean calculated from the velocity field of the Simple Ocean Data Assimilation (SODA) analysis (Carton and Giese, 2008). (d) Composite difference in the meridional stream function between strong and weak monsoons.

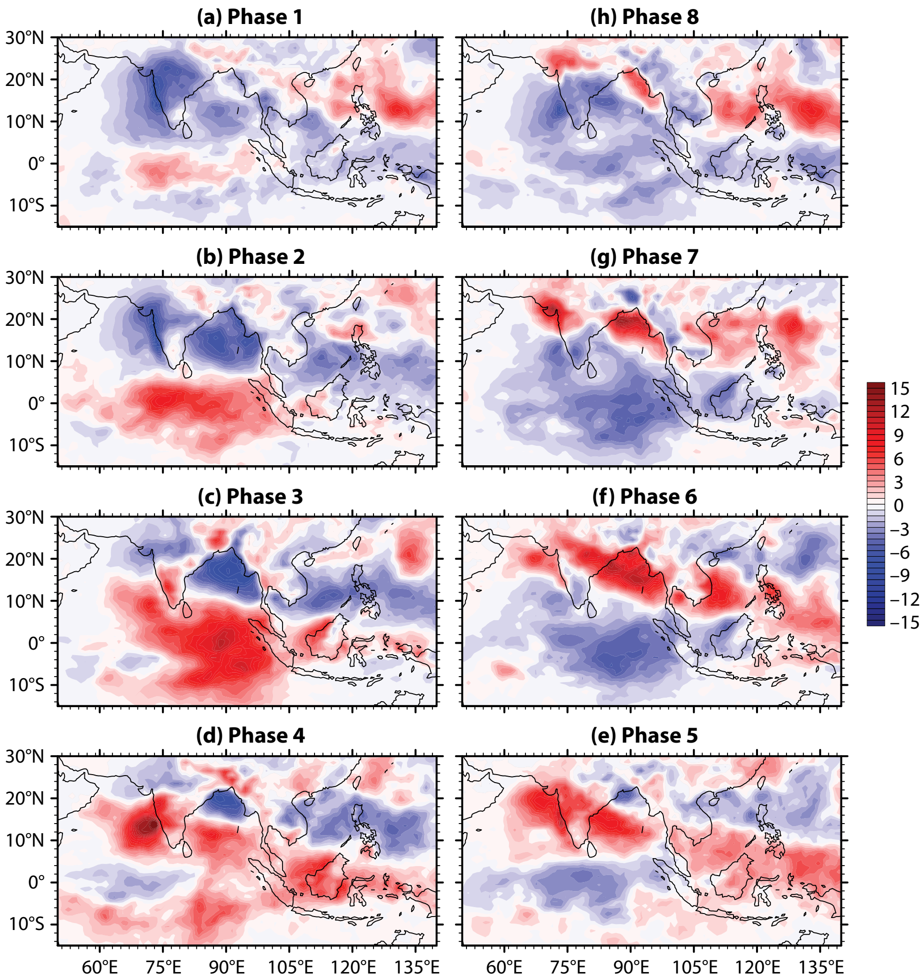

FIGURE 4. Eight phase composites of precipitation (mm day^{-1}) from the Tropical Rainfall Measuring Mission (TRMM) satellite based on the MISO1 and MISO2 indices (Suhas et al., 2013) indicating the evolution of the monsoon intraseasonal oscillations (MISOs) and their northward propagation.

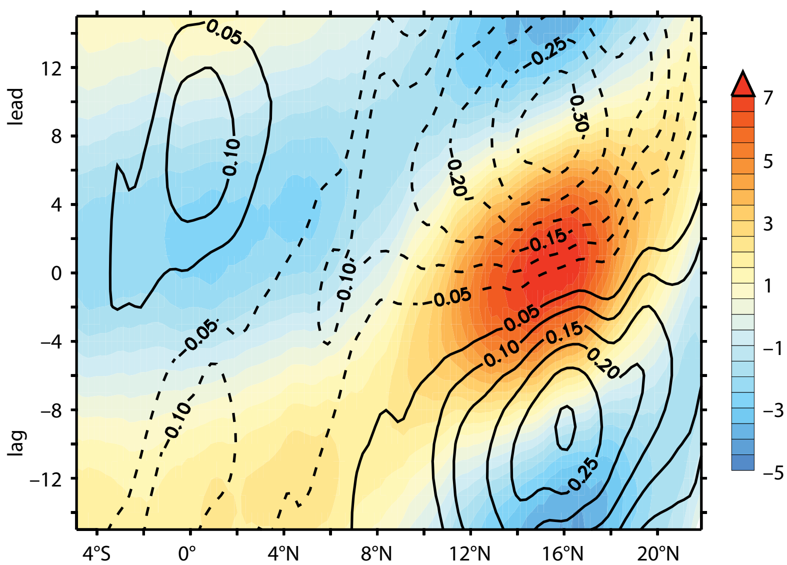

FIGURE 5. Regression of TRMM precipitation (shaded) and Optimum Interpolation Sea Surface Temperature (contours) with respect to a time series of MISO filtered (20–100 days) precipitation averaged over a 5° × 5° box around 85°E and 15°N as a function of lead or lag (days).

northern summer, the frequency and duration of the active and break spells can contribute to the seasonal mean rainfall and its interannual variability (Goswami et al., 2006). For example, most droughts are associated with long breaks (Joseph et al., 2011). More importantly, the MISO also modulates the occurrence of synoptic disturbances, with four to five times more monsoon low-pressure systems (LPSs) occurring during active spells compared to break spells (Goswami et al., 2003). Therefore, MISOs represent a basic building block of the South Asian monsoon (Goswami et al., 2006). However, MISOs are potentially predictable only about three to four weeks in advance (Goswami and Xavier, 2003). As far as the interannual variability of the monsoon is concerned, the contribution of MISOs represents internal variability that limits the predictability of the seasonal mean (Goswami and Xavier, 2005). Thus, the prediction of seasonal mean monsoon rainfall one season in advance remains a challenging problem and makes prediction of MISO phases and their intensity a very attractive and useful alternative, even if those predictions can be made only two to three weeks in advance (Xavier and Goswami, 2007).

Air-sea interactions over the BoB are at the heart of both the evolution and the northward propagation of MISOs (Sengupta et al., 2001; Sharmila et al., 2013). These air-sea interactions are largely dominated by net heat flux variations at the surface, which are as large as 80–100 W m^{-2} into or out of the ocean (see Figure 2.18 of Goswami, 2012) and are associated with subseasonal changes in cloudiness and surface winds. The ocean's response to surface heat fluxes leads to a phase lag between SST and atmospheric convection, with precipitation lagging behind SST by about a quarter of a period, or about 7–10 days (Figure 5). This means that a coupled ocean-atmosphere model is essential for simulating and predicting the space-time characteristics of MISOs. For any skillful prediction of MISOs, it is crucial for a model to simulate two characteristics—the northward propagation of about 1° latitude per day and the phase relationship between SST and precipitation. The large heat flux and the shallow mixed layer in the BoB ensure a large diurnal SST cycle over the region that is capable of influencing the intraseasonal SST oscillations (Mujumdar et al., 2011). Closer to the equator, in addition to heat flux, ocean dynamics plays an important role in air-sea interaction. This is evident in the quasi-biweekly mode (QBM) of the atmosphere that arises from unstable equatorial Rossby waves (Chatterjee and Goswami, 2004). The QBM of the atmosphere drives a QBM of the equatorial ocean through generation of an oceanic mixed Rossby gravity wave (MRG; Sengupta et al., 2004). Thus, to improve MISO predictions, a model must accurately simulate variability in air-sea flux at multiple scales as well as air-sea interactions.

While most coupled ocean-atmosphere models still have difficulty simulating these MISO features (Sabeerali et al., 2013), some models such as the CFSv.2 (Coupled Forecast System model version 2 of the US National Centers for Environmental Prediction) are now able to simulate these MISO characteristics with some fidelity (Sabeerali et al., 2013; Sharmila et al., 2013). Using this opportunity, the Indian Institute of Tropical Meteorology (IITM), Pune, India, has set up an Extended Range Prediction System (ERPS) for forecasting MISOs. Based on a large ensemble of retrospective forecasts, work at IITM has demonstrated that MISOs could be predicted with useful skill more than 15 days in advance (Abhilash et al., 2013, 2014a,b). For the past two years, the prediction system has been used to make real-time forecasts of MISOs up to 20 days ahead for the India Meteorology Department. These forecasts are updated every five days and have been extremely useful for agricultural advisory, water management, and many other applications.

PIVOTAL ROLE OF THE BAY OF BENGAL

The BoB's geography, with its warm waters, high column-integrated moisture, and Myanmar orography, leads to very heavy precipitation over the entire northern BoB during boreal summer, thereby keeping the center of monsoon convective heating to the east of India (Xie et al., 2006). The monsoon winds strengthen in response to this elevated heating, giving rise to enhanced upwelling and cooling in the western Arabian Sea, which also acts to restrict active atmospheric convection to the east of 70°E. Thus, the BoB plays a crucial role in sustaining the observed distribution of monsoon precipitation.

The enormous freshwater discharge from the Ganges-Brahmaputra, Irrawaddy, and several other major rainfed rivers makes the northern BoB one of freshest regions of the world ocean (Figure 6). This physical setting results in a unique vertical ocean structure, with a fresh, shallow mixed layer overlying a highly stratified pycnocline and a warm upper ocean. Several features of the thermodynamic structure of the northern BoB are not clearly understood or captured by coupled ocean-atmosphere models (see below). However, it is clear that the BoB plays an important role in determining monsoon precipitation by facilitating the genesis of monsoon lows and depressions, and controlling the air-sea interactions associated with the MISOs (Figure 5). Figure 6 shows the genesis and track of lows and depressions for the past 30 years computed from daily Modern-Era Retrospective analysis for Research and Applications (MERRA) reanalysis using a vortex detection and tracking algorithm. It is clear that the LPSs are generated largely over the highly fresh northern BoB, where salinity is lower than ~33 psu.

Because of this region's shallow mixed layer and thermal stratification, heat fluxes associated with MISOs result in large SST anomalies (up to 1–2°C) on intraseasonal time scales (Sengupta and Ravichandran, 2001), with potential to significantly modulate the convective activity on this time scale. The unique thermal stratification of the BoB also fosters new atmospheric lows and depressions that can form, intensify, and move away quickly one after the other (Bhat et al., 2001). The frequent genesis of lows and depressions strengthens the South Asian monsoon.

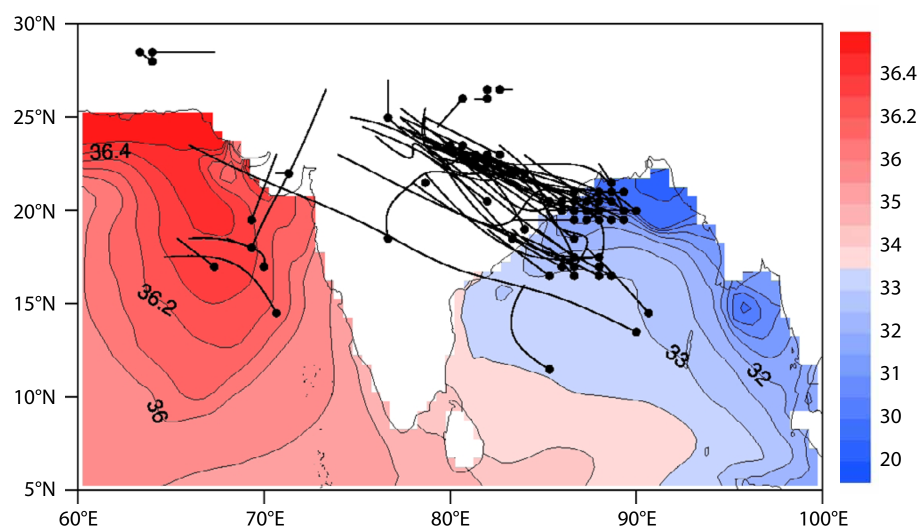

FIGURE 6. Location and tracks of low-pressure systems as derived by a vortex tracking algorithm from the Modern-Era Retrospective analysis for Research and Applications (MERRA) reanalysis against the background of mean salinity during JJAS (in psu) in the northern Indian Ocean.

MODEL BIASES: WHY VERTICAL MIXING?

Significant bias in the simulation of the BoB's SST and vertical thermal structure is likely to seriously affect the ability of a coupled model to either simulate or predict the LPSs and the MISOs (and therefore the seasonal mean monsoon). Such a bias would also influence calculation of the heat transport by meridional circulation and thereby introduce error into the simulation of SST over the north BoB during the following year. Thus, such biases in simulating the BoB's thermal structure are a limiting factor in improving skill of monsoon forecasts both on seasonal and subseasonal time scales.

Most state-of-the-art coupled models still have significant systematic errors in simulating mean SST and vertical thermal structure. As an example, Figure 7 shows

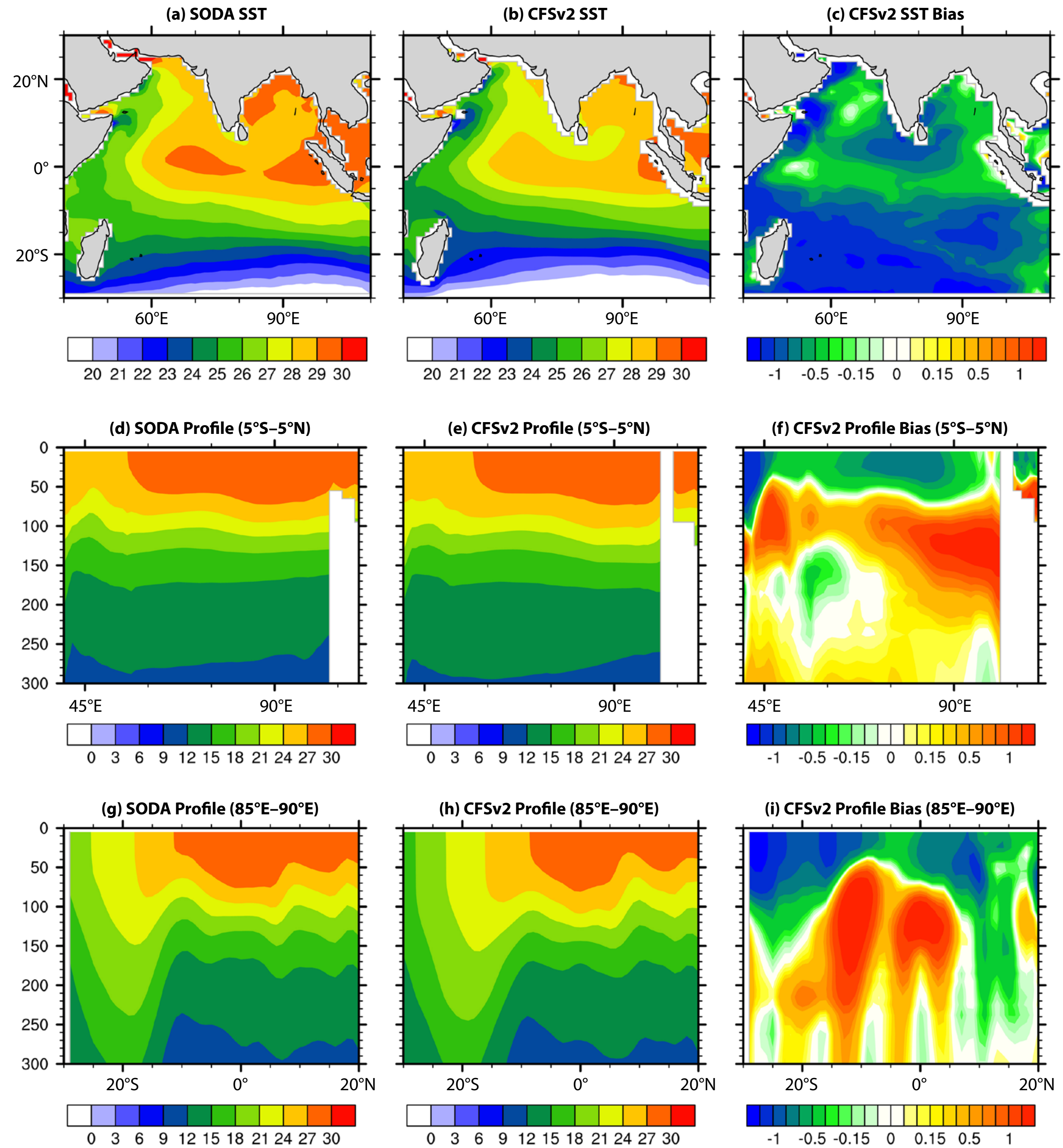

FIGURE 7. Bias of the CFSv.2 model in simulating the SST (c) and vertical thermal structure in zonal direction along the equator (f) and in the north-south direction along 85°E (i) during JJAS.

the estimated biases of the CFSv.2 model over the tropical Indian Ocean sector. The CFSv.2 model has a cold SST bias over the whole northern Indian Ocean except for the coast of Arabia, where there is a warm bias. The biases in simulating the vertical thermal structure along the equator (Figure 7, middle panels) and longitudinally along the Bay of Bengal (a north-south section along 87°E is shown here) are typical of most models. The diffusion of a simulated thermocline along the equator is a generic problem in most z-coordinate ocean models. It is interesting to note that the model fails to simulate the shallow mixed layer over the BoB, and that the cold surface temperature bias seems to penetrate well below the surface mixed layer. In order to improve simulation of the thermal structure, it is imperative that we understand the processes that control the thermal structure over the BoB region and represent them adequately in the models.

What is responsible for the biases seen in Figure 7? It is often difficult to separate contributions to errors in the upper-ocean thermal structure in a coupled model that arise from errors in the forcing (fluxes of heat and momentum) and errors in representing physical processes in the ocean (e.g., vertical mixing). As SSTs are controlled largely by net heat fluxes, errors in simulating the types and distribution of clouds in atmospheric models lead to errors in simulating SSTs. It has been shown that improved cloud microphysical parameterization significantly reduces the cold SST bias in the CFSv.2 model (Hazra et al., 2015). A high-resolution atmospheric component in a coupled model can reduce the SST bias in the northern Indian Ocean by better resolving cloud types and distribution (Ramu et al., 2016). However, the improved models still suffer from inadequate representation of large-scale Indian Ocean dynamics, coupled processes involving feedback among SST, atmospheric convection, winds (Narapusetty et al., 2015), and Indian summer monsoon teleconnections (Ramu et al., 2016). In particular, the ocean components of the coupled models have serious deficiencies in capturing the shallow, salinity-dominated stratification in the Bay of Bengal. A part of the SST bias and incorrect thermal structure in models may be related to inadequate representation of river discharge and biases in simulating local precipitation. Moreover, a significant part of the biases in SST and upper-ocean salinity and temperature structure may be related to missing or improper parameterization of physical processes that determine stratification and mixing in ocean models. A striking example of air-sea interaction mediated by the shallow, fresh mixed layer and deep, warm subsurface layer in the BoB can be seen in SST cooling due to cyclone-induced mixing. Even strong tropical cyclones in the post-monsoon season give rise to SST cooling under the storm track in the northern BoB by less than 1°C (Sengupta et al., 2008; Singh et al., 2012), while similar cyclones over the Arabian Sea cool SST by more than 3°C, with important implications for cyclone intensification (Balaguru et al., 2012, 2014).

How does the ocean mix vertically in this region? What are the roles of inertial oscillations, internal waves, and double diffusion in the mixing of momentum, heat, and salt? The nonlocal K-profile parameterization (KPP) scheme (Large et al., 1998) was developed to account for some of these processes and is widely used in ocean models (including MOM4 in CFSv.2). However, it seems inadequate to simulate the thermal structure in the highly freshwater-dominated BoB region. It appears that we are still missing some fundamental physical processes related to mixing in such a low-salinity ocean. In particular, the stirring of low-salinity water from rivers and rainfall by mesoscale eddies, the creation of fronts in confluence regions between eddies, and the possible role of submesoscale fronts in renewing and sustaining shallow stratification are important processes that must be properly represented in forecast models. Many of the articles in this issue of *Oceanography* are devoted to these topics, and we appear to be on the threshold of new and exciting findings about the upper layer of the Bay of Bengal.

CONCLUSIONS AND A WAY FORWARD

Vigorous monsoon intraseasonal oscillations are building blocks of the South Asian monsoon, not only contributing to the seasonal mean and its interannual variability but also modulating the frequency of synoptic weather system occurrences (the LPSs). The very large horizontal scale and air-sea interactions that control the vigor and spatiotemporal characteristics of MISOs indicate that a global coupled ocean-atmosphere model is required to simulate and predict them. The BoB's fresh, shallow mixed layer overlying a highly stratified pycnocline and its warm subsurface layer strongly influence air-sea interaction, and thereby the vigor and propagation characteristics of the MISOs. The BoB's SST and thermal stratification, key players in this air-sea interaction, are governed by the region's shallow salinity-dominated stratification and the nature of vertical mixing. In particular, the role submesoscale processes play in mixing in the BoB may be crucial in setting the oceanic manifestations and air-sea interactions involved in MISOs. This is analogous to the small-scale, unresolved processes that determine the clouds and precipitation in the atmospheric manifestations of the planetary-scale MISOs. Therefore, the predictability of MISOs and, by default, that of the seasonal mean monsoon and the synoptic disturbances, depends on multiscale interactions involving submesoscale to planetary-scale processes. The warm SST throughout the summer monsoon season and the freshwater pool make the northern Indian Ocean and the BoB unique places in the world where multiscale interactions in the atmosphere as well as in the ocean can flourish and are manifest in the interactions among the oceanic and the atmospheric components.

The current generation of global coupled models has begun to simulate MISOs with some fidelity, but the skill of prediction remains limited due to significant biases in simulating the mean climate. For example, most coupled climate models have a large "dry bias" in simulating precipitation over the South Asian monsoon region and a large bias in simulating the mean temperature profile over the Indian Ocean in general and the BoB in particular. The deficiency in parameterization of convection schemes appears to be a major factor responsible for the dry bias of the models in simulating monsoon precipitation. Considerable effort is being devoted to improving the parameterization of convection schemes and thereby improving simulation of monsoon precipitation. Equally important are the problems of bias in the ocean's thermal structure and proper parameterization of vertical mixing in ocean models.

Considerable progress has also been made in the parametrization of ocean mixing, ranging from very simple mixing schemes to those that are more advanced such as variants of the KPP scheme. However, several problems remain. In addition to thermocline diffusion in many areas (a problem analogous to the dry bias of monsoon precipitation), these schemes are inadequate for simulating the thermal structure in highly fresh ocean regions such as the BoB. Biases in simulation of thermal structure could be reduced by enhanced modeling approaches, including improved vertical and horizontal resolution. For example, the KPP scheme in isopycnal ocean models seems to improve thermocline diffusion (Llicak et al., 2012). However, it appears that there is still a gap in our understanding of how mixing actually occurs in such a fresh and stratified ocean. This seems to be due to the lack of enough high-resolution and high-frequency observations to understand the interaction between very small scales (submesoscales) and larger synoptic and basin scales. There is an urgent need to design an experiment to collect such data to unravel the missing physics needed to improve parameterization of mixing. Realizing this need, the Ministry of Earth Sciences, Government of India, supports a program called Ocean Mixing and Monsoon (OMM; http://www.tropmet.res.in/monsoon/index.php) under the Monsoon Mission program. Some early results are presented in this issue of *Oceanography*. The program's objective is to apply the understanding gained from analysis of these high-resolution and high-frequency data in process models to improve parameterization of mixing applicable to freshwater regions such as the BoB.

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ACKNOWLEDGMENTS

BNG is thankful to the Ministry of Earth Sciences, Government of India, for the Pisharoty Professorship and to the Indian Institute of Science Education and Research (IISER), Pune, for facilities, and to Ankur Srivastava and Gibies George for help preparing figures. SC thanks Department of Science and Technology, Government of India, for the INSPIRE Faculty Fellowship and IISER, Pune, for support.

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ARTICLE CITATION

Goswami, B.N., S.A. Rao, D. Sengupta, and S. Chakravorty. 2016. Monsoons to mixing in the Bay of Bengal: Multiscale air-sea interactions and monsoon predictability. *Oceanography* 29(2):18–27, http://dx.doi.org/10.5670/oceanog.2016.35.