EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 95 NUMBER 30
29 July 2014
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Mixing to Monsoons: Air-Sea Interactions in the Bay of Bengal

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More than 1 billion people depend on rainfall from the South Asian monsoon for their livelihoods. Summertime monsoonal precipitation is highly variable on intraseasonal time scales, with alternating "active" and "break" periods. These intraseasonal oscillations in large-scale atmospheric convection and winds are closely tied to 1°C–2°C variations of sea surface temperature in the Bay of Bengal.

Despite their importance, ocean-atmosphere coupled models have low skill in predicting intraseasonal oscillations due to poorly constrained surface fluxes and inadequate representation of advection and mixing. A major challenge to improved monsoonal forecasting is a dynamical understanding of oceanic and atmospheric interplay across a wide range of spatiotemporal scales.

To improve understanding of the circulation, upper ocean dynamics, and air-sea interactions in the Bay of Bengal, the United States, India, and Sri Lanka recently embarked on an international collaborative research program. This 5-year (2013–2017) initiative brings together major resources and scientists from more than 20 research institutes and universities.

The program's overarching goal is improved prediction of the South Asian monsoon, particularly on intraseasonal time scales. The major objectives are to understand and quantify dynamical processes and boundary transports that control freshwater and saltwater exchanges between the Bay of Bengal and the Arabian Sea, to observe small- to large-scale atmospheric phenomena that modulate air-sea exchanges and upper ocean heat content, and to examine oceanic responses to buoyancy and wind stress forcing using observations and high-resolution air-sea coupled models.

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One program within the initiative, the Air-Sea Interactions in the Northern Indian Ocean (ASIRI)–Ocean Mixing and Monsoons (OMM) program, aims to improve predictive monsoon models through study of air-sea fluxes and upper ocean processes in international waters.

Another program, ASIRI–Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB), is focusing on the dynamics of freshwater, upper ocean processes, and air-sea interactions; it will integrate observations of boundary currents around Sri Lanka to study their response to atmospheric variability. In addition, the ASIRI–Remote Sensing of Atmospheric Waves and Instabilities (RAWI) project will monitor atmospheric waves, instabilities, and turbulence by deploying remote sensing arrays on island nations across the equatorial Indian Ocean.

Monsoon Dynamics and the Bay of Bengal

Bay of Bengal dynamics are marked by seasonal wind and current reversals and shifts in precipitation. In summer, southwesterly winds carry moisture-laden air and bring rainfall to much of eastern and central India, Bangladesh, and the eastern Bay of Bengal. Terrestrial precipitation is discharged into the northern part of the bay via the Ganges-Brahmaputra-Meghna, Irrawady, and other major river systems. In winter, northeasterly winds carry dry air from the Asian continent over the bay, promoting evaporation and cooling surface waters, while accumulating moisture and causing rainfall over southern India and Sri Lanka.

Large freshwater contributions influence the structure of the upper layers of the Bay of Bengal, resulting in a fresh, shallow, mixed layer overlying a highly stratified pycnocline. These shallow mixed layers respond quickly to surface forcing and are likely to influence monsoonal intraseasonal oscillation dynamics. The formation of shallow, salt-stratified layers must depend on lateral and vertical processes because river water must be moved horizontally from the boundaries and spread across the interior of the bay. Researchers therefore expect that the study of the three-dimensional (3-D) dynamics that control stratification and circulation in the basin will lead to improved understanding of monsoonal intraseasonal oscillation variability.

ASIRI envisions a cascade of upper ocean physical processes acting together to determine stratification in the Bay of Bengal. Freshwater from rivers and saline water from the Arabian Sea and southern Bay of Bengal are carried along the boundaries in basin-scale currents. An active mesoscale eddy field stirs water in the interior, transforming broad lateral differences in temperature and salinity into increasingly sharp gradients. At scales of about 10 kilometers and smaller (the submesoscale), such fronts develop 3-D circulations. Further interactions between submesoscale features and the surface wind field lead to instabilities, vertical exchange, and irreversible turbulent mixing. Because these processes, along with buoyancy input and mixing driven by air-sea interactions, set the upper ocean stratification and circulation, they also influence local biogeochemical cycling and the bay ecosystem. Thus, the Bay of Bengal offers an exciting location for a multiscale atmosphere-ocean integrative study of these globally significant processes.

Field Effort

The first field season of the ASIRI collaboration occurred in November and December 2013. Efforts included extensive work from U.S. (R/V *Roger Revelle*), Sri Lankan (R/V *Samudhrika*), and Indian (R/V *Sagar Nidhi*) vessels; the deployment of multiple moorings and gliders; and an augmentation of the number of profiling floats and drifters currently active in the Bay of Bengal. Multiscale surveys mapped the lateral and vertical distribution of salinity, temperature, currents, mixing, and optical properties from tens of meters to 1000 kilometers. Researchers also conducted the first large-scale marine mammal survey in the bay. In addition, hydrographic surveys were complemented by process studies at strong fronts using autonomous wave-powered profilers and rapid shipboard sampling of meteorological and oceanic properties. These efforts included a training component for young scientists from Sri Lanka and India.

The fall 2013 work demonstrated the broad range of scales relevant to the heat and salt budgets of the upper Bay of Bengal:

basin-scale distributions of heat, salt, and mixed layer properties (Figures 1a and 1b); mesoscale eddies and fronts (Figure 1c); submesoscale fronts and filaments (Figure 1d); and numerous small-scale features including nonlinear bores (Figure 1e), high-frequency internal waves, and turbulent mixing (Figure 1d). Strongly nonlinear dynamics were observed at small lateral scales, including frontogenesis, frontolysis, and interaction between fronts and near-inertial waves.

The understanding gained from the field observations will be used to improve the parameterization of physical processes in numerical models, particularly in the upper layers where communication with the atmosphere shapes the monsoon. Observational efforts, including the RAWI remote sensor deployment, will continue through 2016. In addition to maintaining moored and autonomous assets, future efforts will expand field sampling with the addition of detailed air-sea flux and oceanic turbulence measurements.

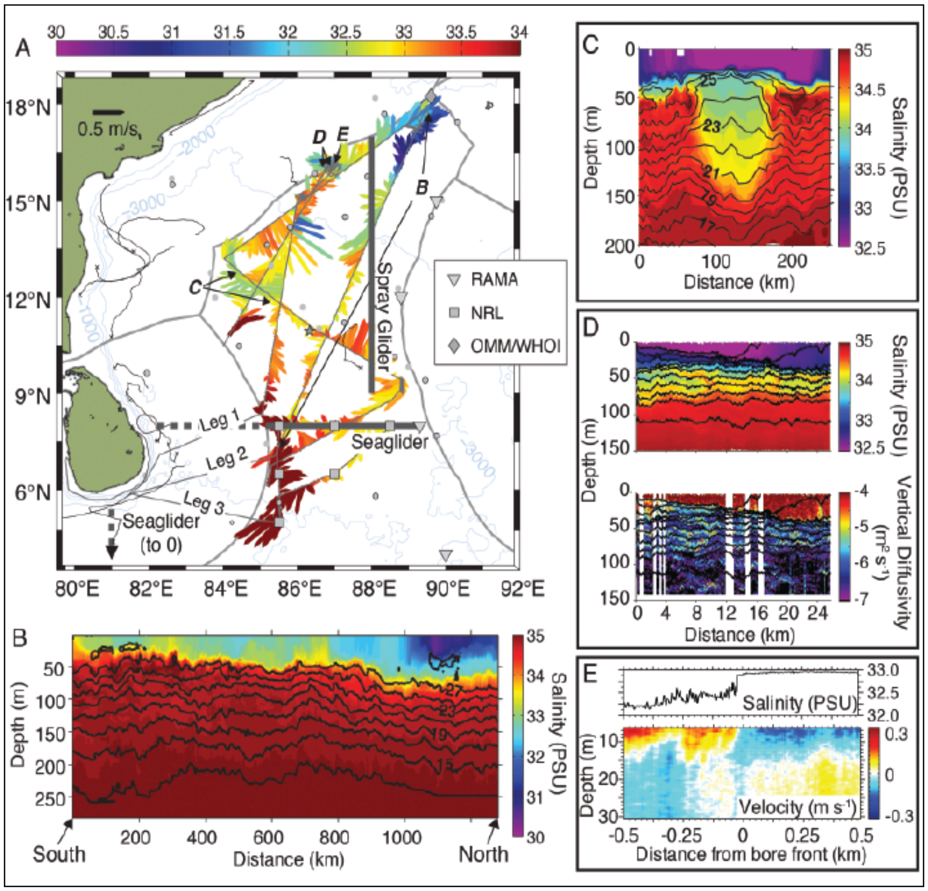

Fig. 1. (a) Field map showing the 2013 R/V Revelle *survey tracks, glider missions (solid gray lines, U.S. supported; dashed gray lines, Sri Lankan supported; gray star, December 2013 deployment of Woods Hole Oceanographic Institution turbulence glider), Argo floats (black-outlined gray circles, Indian National Centre for Ocean Information Services; gray circles, international Argo), drifters (thin black tracks), and mooring locations. Ship transects show velocity vectors at approximately 40 meters depth, colored by near-surface salinity. The 2013 program mapped large-scale gradients across the Bay of Bengal. (b) Northeast distance-depth section. Gliders will continue this effort through along- and across-basin transects while time series are being gathered at a number of moorings, including the sustained Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. The field program focused on stirring and mixing processes, including (c) the mesoscale eddy field that stirs lateral density gradients, (d) submesoscale fronts that induce three-dimensional circulation, and (e) small-scale features such as nonlinear bores, which alter the characteristics of the mixed layer on time scales of minutes.*

Additional Information

The overall initiative includes the following broad programs: The ASIRI initiative of the U.S. Office of Naval Research; the OMM initiative of India's Monsoon Mission supported by the Ministry of Earth Sciences, New Delhi; the Coastal Currents Observations Program of the National Aquatic Resources Research and Development Agency (NARA), Sri Lanka; the EBOB initiative of the U.S. Naval Research Laboratory; and RAWI, a joint initiative between NARA, Seychelles, Singapore, and the U.S. Army Research Laboratory. All programs involve scientific collaboration, education, and capacity building. The principal investigators of the project are listed in Table S1 in the additional supporting information in the online version of this article.

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