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Collaborative Observations of Boundary Currents, Water Mass Variability, and Monsoon Response in the Southern Bay of Bengal

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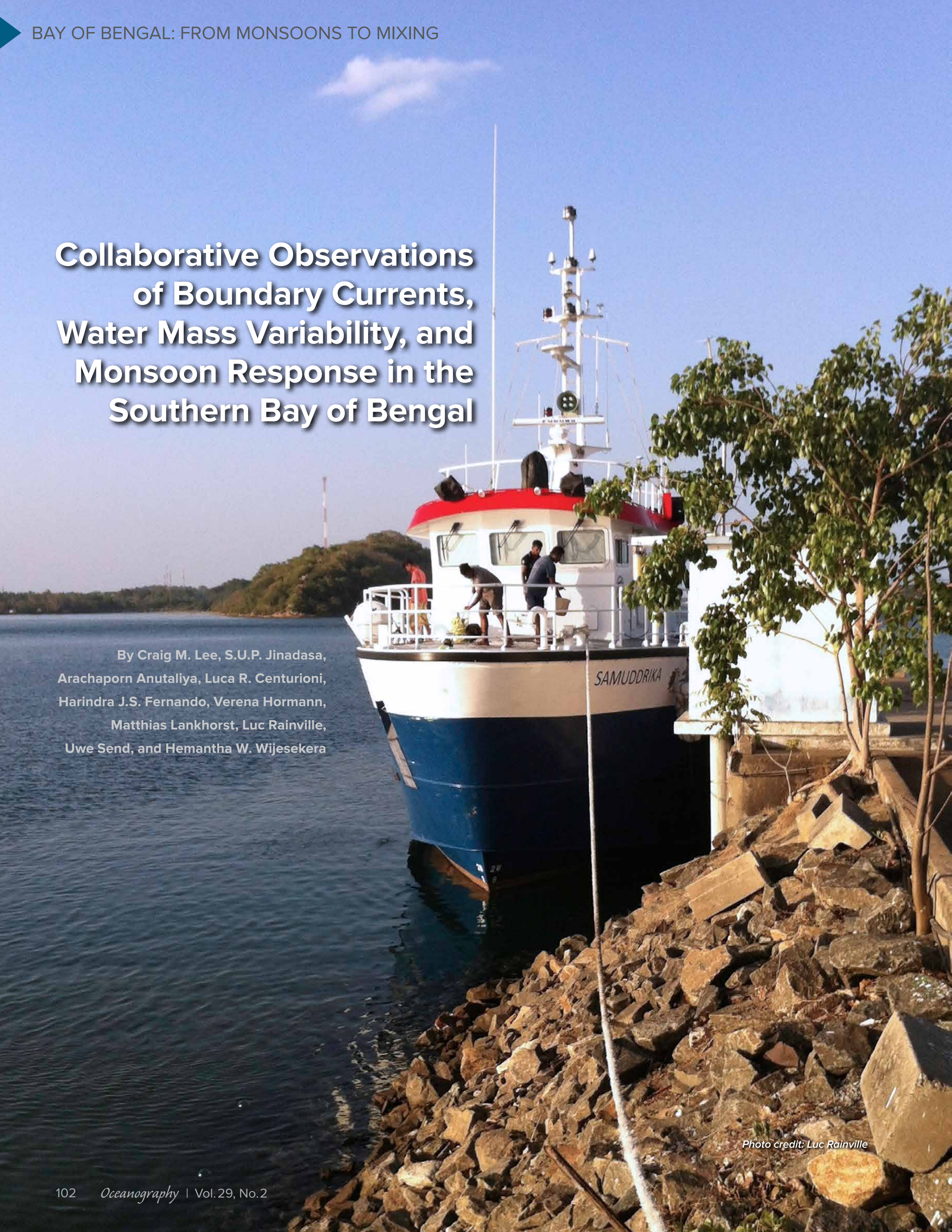

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ABSTRACT. The region surrounding Sri Lanka modulates monsoon-driven exchange between the Bay of Bengal and the Arabian Sea. Here, local circulation impacts the pathways followed by the boundary currents that drive exchange, thereby modulating mixing and water mass transformation. From 2013 to 2016, an international partnership conducted sustained measurements around the periphery of Sri Lanka, with the goal of understanding how circulation and mixing in this critical region modulate exchange between the Bay of Bengal and the Arabian Sea. Observations from satellite remote sensing, surface drifters, gliders, current meter moorings, and Pressure Inverted Echo Sounders capture seasonally reversing monsoon currents off the southern tip of Sri Lanka, trace the wintertime freshwater export pathway of the East India Coastal Current, and document the deflection of currents running along the east coast of Sri Lanka by cyclonic and anticyclonic eddies. Measurements also reveal energetic interleaving, indicative of mixing and stirring associated with these flows. Circulation inferred from satellite remote sensing and drifter tracks sometimes differs from that indicated by in situ sections, pointing to the need for observing systems that employ complementary approaches toward understanding this region.

INTRODUCTION

The seas around Sri Lanka serve as conduits for exchange between the Bay of Bengal and the Arabian Sea. Large riverine discharge and excess precipitation into the Bay of Bengal produce an annual net freshwater surplus (Rao and Sivakumar, 2003). In the adjoining Arabian Sea, net evaporation and inflow of high-salinity water masses from the Red Sea and the Persian Gulf produce an annual net salt surplus (Chatterjee et al., 2012). Seasonal exchanges of water between the two basins modulate the impacts of these large, asymmetric inputs by removing freshwater from the Bay of Bengal and exporting saline waters from the northern Arabian Sea (Shetye et al., 1996; Jensen, 2001; Schott and McCreary, 2001; Shankar et al., 2002). These exchanges represent an important contribution to the northern Indian Ocean salinity balance, maintaining the observed broad increase in upper-ocean salinity southward through the Bay of Bengal and northward into the Arabian Sea (Figure 1c,d).

Monsoon forcing produces distinctive, seasonal circulation patterns within the Bay of Bengal. During the winter northeast monsoon, northeasterly winds drive equatorward flow, carrying fresh Bay of Bengal water south in the East India Coastal Current (EICC; Figure 1c; McCreary et al., 1996; Shetye et al., 1996; Durand et al., 2009). More recently, Wijesekera et al. (2015) document subsurface intensified northward currents east (offshore) of the EICC. This provides a potential pathway for import of high-salinity Arabian Sea water into the Bay of Bengal during the northeast monsoon, when surface currents instead favor export of relatively fresh Bay of Bengal water into the Arabian Sea. Argo float temperature and salinity, Aviso sea surface height, and models show that an anticyclonic eddy, typically positioned off the Sri Lankan coast, deflects part of the EICC eastward to form the East Sri Lanka Jet (ESLJ; Figure 1c). The ESLJ forces much of the Bay of Bengal freshwater to take a circuitous eastward path that eventually turns south and west to join the Winter Monsoon Current (WMC), the main wintertime communication pathway between the Bay of Bengal and the Arabian Sea (Rao et al., 1989; Vinayachandran et al., 2005). Coastal Kelvin waves, generated by westward-propagating Rossby waves impinging on the Sri Lankan and Indian coasts from the Bay of Bengal and equatorial Indian Ocean, also act to modulate the WMC (Schott et al., 1994). It is likely that the properties of freshwater masses exported out of the Bay of Bengal depend strongly on their exit pathways—whether it is the direct route following the Sri Lankan coast or the more convoluted path through the southern Bay of Bengal.

Remotely sensed sea surface temperature (SST), salinity (SSS), and height (SSH) from January 2014 illustrate these wintertime patterns (Figure 1a,c,e). SSH and surface geostrophic velocities from Aviso (Figure 1a) show a strong, distinct, continuous EICC that flows southward along the Indian and Sri Lankan coasts, following the coastline westward at the southern end of Sri Lanka to join the west-flowing WMC. The weaker (Figure 1a,c; weaker horizontal SSH gradients and resulting surface geostrophic currents) ESLJ separates from the EICC at approximately 8°N, flowing north to form the eastern boundary of a cyclonic eddy and eventually turning east, but without clear connectivity to the WMC. Both January and July 2014 monthly average near-surface salinity from the Aquarius satellite (Melnichenko et al., 2014) reveal the expected broad increase, from the fresh northern Bay of Bengal to the more saline Arabian Sea (Figure 1c,d). In January, fresh Bay of Bengal surface waters trace the path of the EICC and the ESLJ, penetrating farthest to the south in the eastern part of the basin. Remote sensing does not capture the subsurface northward transport of Arabian Sea water observed by Wijesekera et al. (2015), pointing to the importance of complementary in situ observations. As observed previously (e.g., Rao et al., 1989), relatively cool SST extends across the Bay of Bengal (Figure 1e), which coincides with broad surface cooling over the winter period (Goswami et al., 2016, in this issue).

During the southwest (summer) monsoon, southwesterly winds (Figure 1d) reverse upper-ocean flow between the Arabian Sea and the Bay of Bengal (Summer Monsoon Current [SMC]; Figure 1d; Murty et al., 1992; Schott and McCreary, 2001; Jensen, 2001; Vinayachandran et al., 2013) and drive coastal upwelling south of Sri Lanka (Murty et al., 1992; Vinayachandran et al., 2004). The SMC entrains this upwelled water, carrying it northeastward into the Bay of Bengal interior. Wind stress curl associated with southwest monsoon winds drives Ekman pumping east of Sri Lanka, forming a cyclonic gyre, the Sri Lanka Dome (SLD; Figure 1b; Vinayachandran and Yamagata, 1998). While the summer monsoon winds drive poleward flow east of India, the western side of the SLD produces equatorward currents along the Sri Lankan coast. Energetic atmospheric forcing and mesoscale variability driven by the southwest monsoon likely drive diapycnal mixing and lateral stirring of the SMC during its northward transit, modifying Arabian Sea waters prior to their delivery into the northern Bay of Bengal (Vinayachandran et al., 2013).

Maps of 2014 summertime (July) SSH and geostrophic surface velocity reveal the SMC entering the Bay of Bengal south of Sri Lanka and continuing east, following the perimeter of a distinct SLD to turn north in mid-basin and then south along the Sri Lankan coast (Figure 1b). A series of eddy-like features off the Indian coast makes it difficult to distinguish what, if any, of the Arabian Sea inflow penetrates into the northern Bay of Bengal within monsoon-driven currents along the western boundary. Surface velocities suggest that Arabian Sea waters instead move north in the eastern half of the basin, consistent with surface salinity patterns that show higher salinities penetrating further north in the eastern Bay of Bengal. Inflowing Arabian Sea waters create a cool SST tongue (Figure 1f and Rao et al., 2006) that becomes less distinct as the SMC flows north, perhaps due to mixing with warmer surface waters in the Bay of Bengal. Elevated SST in the western Bay of Bengal may be the result of solar warming (Goswami et al., 2016, in this issue) acting on shallow mixed layers created by the large freshwater inputs in the northern basin.

The seasonal cycle of mean surface currents, computed by averaging Aviso geostrophic surface velocity from 1993 to 2013 along sections extending from the Sri Lankan coast eastward at 8°N and southward at 80.5°E, illustrates variability in spatial structure associated with the monsoons. To the east of Sri Lanka, the 8°N section, situated in the latitudinal range of the SLD, reveals southward currents within 200 km of the coast during both northeast (EICC) and southwest (western side of the SLD) monsoons, with northward flow during the intermonsoon periods (Figure 2a). Thus, the boundary current there reverses its direction four times a year, forced by local winds and seasonal eddies. Further offshore, mean currents flow southward, except during the southwest monsoon, when the SMC drives northward flow in the central and eastern basin.

Currents within 200 km of the southern tip of Sri Lanka exhibit a clear reversal, with the westward WMC during the winter monsoon and eastward SMC during the summer (Figure 2b). Variability associated with the equatorial current system dominates further to the south, with eastward currents during the intermonsoon periods, commonly referred to as "Wyrtki jets," forced by westerly wind bursts (Wyrtki, 1973; O'Brien and Hurlburt, 1974; Nagura and McPhaden,

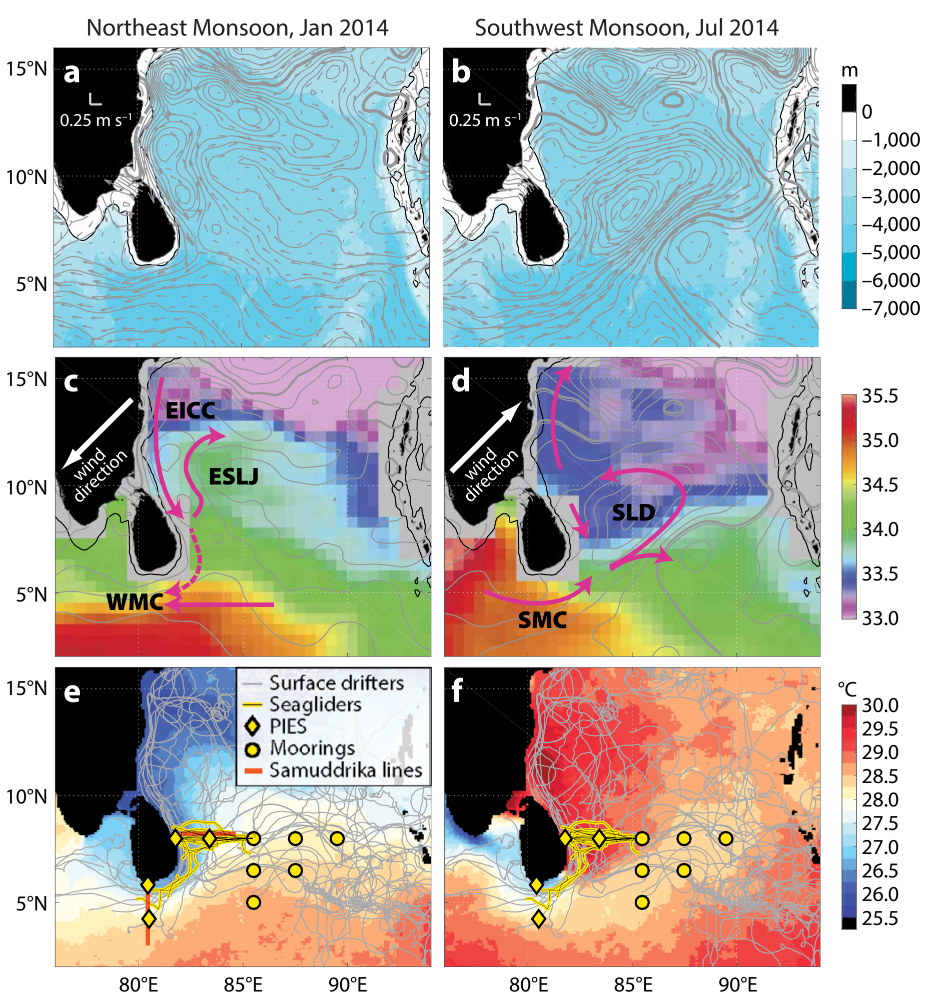


FIGURE 1. Monthly averaged absolute dynamic height (contours) and surface geostrophic velocity from Aviso (vectors) for (a) January 2014, and (b) July 2014. Contour interval is 2 cm, the 1.0 m contour is bold, and bathymetry is in color. Monthly average, optimally interpolated sea surface salinity (color) from Aquarius (Melnichenko et al., 2014) for (c) January 2014, and (d) July 2014. Gray contours delineate sea surface height (SSH) with 5 cm contour interval and the 1.0 m contour in bold. Magenta arrows provide schematic representations of currents discussed in the text. EICC = East India Coastal Current. ESLJ = East Sri Lanka Jet. WMC = Winter Monsoon Current. SLD = Sri Lanka Dome. SMC = Summer Monsoon Current. Monthly average, optimally interpolated sea surface temperature (color; Remote Sensing Systems, National Oceanographic Partnership Program, and NASA) for (e) January 2014, and (f) July 2014. Symbols and colored lines mark the locations of observing assets, with thin gray lines marking drifter trajectories. Glider and drifter tracks depicted in (e) and (f) are for the entire year (2014).

2010, 2012; Iskandar, and McPhaden, 2011) and westward flow during both the winter and summer monsoons.

Circulation in the region surrounding Sri Lanka thus modulates monsoon-driven exchange between the Bay of Bengal and the Arabian Sea. Boundary currents flowing along the periphery of Sri Lanka drive exchanges that reverse with the monsoon winds. The wintertime EICC carries relatively fresh waters from the northern Bay of Bengal into the WMC for export to the Arabian Sea, while in summer, the SMC brings high-salinity Arabian Sea waters into the Bay of Bengal. Energetic mesoscale features can deflect these currents into more circuitous, offshore pathways (e.g., ESLJ, Figure 1c, and SLD, Figure 1d) that provide greater opportunity for mixing and modification of the source water masses.

Since 2013, an international team has collaborated to conduct sustained measurements around the periphery of Sri Lanka, with the goal of understanding how circulation and mixing in this critical region modulate exchange between the Bay of Bengal and the Arabian Sea (Wijesekera et al., in press). Partner programs include the US Office of Naval Research Air-Sea Interactions Regional Initiative (ASIRI), the Indian Ocean Mixing and Monsoon (OMM) program, the Sri Lankan National Aquatic Resources Research and Development Agency (NARA) Coastal Currents Observations Program (CCOP), the US Naval Research Laboratory (NRL) Effects of Bay of Bengal Freshwater Flux on the Indian Ocean Monsoon (EBOB) project, and the joint US, Sri Lanka, Singapore Remote Sensing of Atmospheric Waves and Instabilities (RAWI) initiative. This paper provides an overview of this highly collaborative effort, along with highlights of early results.

COLLABORATIVE OBSERVATIONS IN THE SOUTHERN BAY OF BENGAL

Collaborative efforts focused on characterizing variability in circulation and mixing, and the resulting impact on interbasin exchange, in the region around Sri Lanka. The in situ measurement program and Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) modeling conducted by the NRL group build on the picture provided by satellite remote sensing by quantifying seasonal variability in circulation and water mass properties below the surface. A complementary suite of platforms and approaches provided continuous measurements over a two-year period, while resolving monthly (and shorter, for some measurements) time scales. Significantly, collaborative efforts between NARA (Sri Lanka), NRL, Scripps Institution of Oceanography, the University of Notre Dame, and the University of Washington Applied Physics Laboratory (United States) collected repeated high-resolution sections, small-scale ocean turbulence measurements, and shallow-water moored observations in boundary currents flowing around the perimeter of Sri Lanka; these measurements extended to the coast to capture these important flows. Surface drifters and moorings provided more distributed observations of the central Bay of Bengal. Taken together with satellite remote sensing, these observations provide a novel perspective on the monsoon cycle of circulation in this critical region. A brief description of the various measurement platforms used in these programs follows.

Research Vessels

Two research vessels conducted conductivity-temperature-depth (CTD) and small-scale ocean turbulence surveys, and provided logistical support for servicing moorings (Figure 3a), Pressure Inverted Echo Sounders (PIES), drifters, and Seagliders. R/V *Samuddrika*, operated by NARA, deployed drifters, serviced Seagliders and PIES, and occupied CTD and Turbulence Profiler (Figure 3b) sections extending east from Trincomalee, between 7.5°N and 8.5°N, and south from Weligama, at 80.4°E (Figure 1e, orange lines). Jinadasa et al. (2016, in this issue) report results from these efforts. R/V *Roger Revelle*, operated by the Scripps Institution of Oceanography deployed moorings and conducted extensive hydrographic surveys in international waters 200 nautical miles from the Sri Lankan coast. Wijesekera et al. (2015, and 2016, in this issue) report results from these cruises.

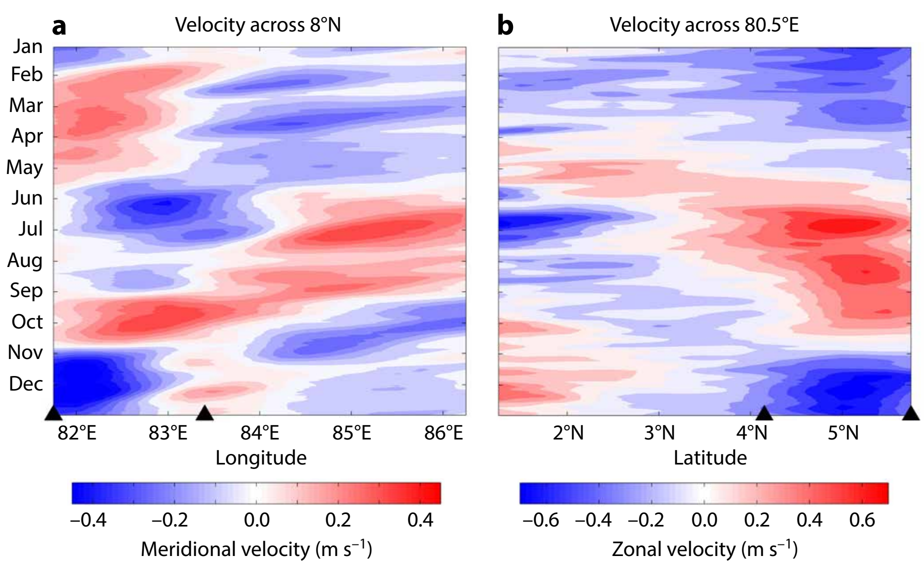


FIGURE 2. The average (1993–2013) annual cycle of surface geostrophic velocity derived from satellite altimetry for (a) the zonal section east of Sri Lanka at 8°N, and (b) the meridional section south of Sri Lanka at 80.5°N. These are the two sections marked by yellow diamonds and red lines in Figure 1e. Black triangles mark the locations of the Pressure Inverted Echo Sounders (PIES).

Drifters

Surface Velocity Program (SVP) drifters (Figure 3c) provided valuable observations of the seasonally reversing circulation in the southwestern Bay of Bengal. A total of 64 satellite-tracked SVP drifters, drogued at 15 m depth (Niiler, 2001; Maximenko et al., 2013), were deployed near Sri Lanka between 2013 and 2014 (Figure 1e,f, light gray lines). As part of a collaboration between NARA and Scripps Institution of Oceanography, three SVP drifters were deployed each month to sample near-surface currents and SST. Releasing drifters in this fashion allowed the array to trace seasonal variations in circulation pathways. SST and GPS position were recorded every 15 minutes, with data transmitted to shore at one-to-two hour intervals. Local fishing vessels picked up a significant number of drifters shortly after deployment, resulting in shortened missions. Nonetheless, the surviving drifters unveiled new circulation pathways and provided observations for evaluating numerical ocean circulation models (Wijesekera et al., 2015, 2016, in this issue).

Seagliders

Long-endurance, autonomous Seagliders (Figure 3d) characterized temporal variability in boundary current structure by conducting repeat occupations of sections radiating out from the coast of Sri Lanka. Seagliders are buoyancy-driven vehicles that profile from the sea surface to 1,000 m depth while collecting measurements of temperature, salinity, dissolved oxygen, chlorophyll fluorescence, and optical backscatter (Eriksen et al., 2001). They steer by controlling pitch and roll, and can thus navigate between waypoints to conduct surveys and occupy sections. Depth-averaged water velocity is calculated by comparing glider displacement measured by GPS position at the start and end of each dive with displacement estimated from a hydrodynamic flight model. Absolute geostrophic velocity normal to the section can then be estimated by referencing geostrophic shear to the depth-averaged velocity.

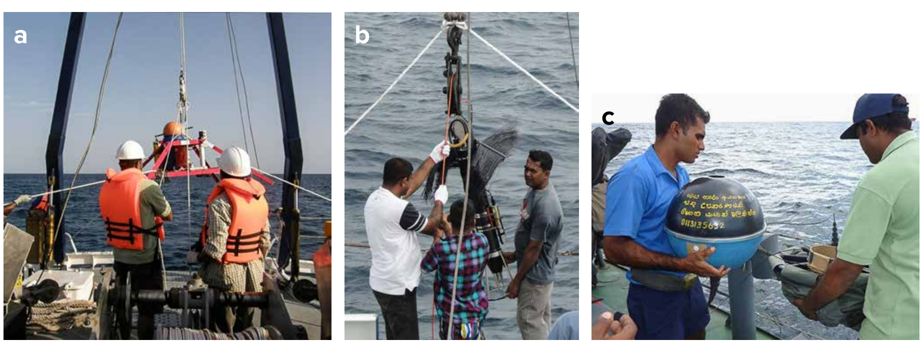
Seaglider operations were conducted in a partnership between NARA and the Applied Physics Laboratory of the University of Washington. Although initial plans involved sampling sections running east along 8°N and south along 80.3°E, intense fishing activity and vessel traffic near the southern tip of Sri Lanka created challenging conditions for glider operations, effectively focusing efforts on the 8°N line. Seaglider sampling along 8°N extended from February 2014 to February 2016, with seven missions executing 2,537 dives along a section that extended from the coast to as far as 375 km offshore (Figure 1e,f, yellow lines). This provides 18 occupations, with sampling in all months except July and August. Logistical challenges resulted in a large sampling gap that spans January to August 2015. The timing of this gap resulted in more sections being collected in autumn and early winter than in other periods.

Moorings

NRL deployed an array of six moorings in the southern Bay of Bengal, sited such that northern sites sampled the relatively fresh waters of the northern Bay of Bengal while southern elements captured high-salinity waters from the Arabian Sea (Figure 1e,f, yellow circles). A triangular configuration, with roughly 165 km separation between sites, was selected to resolve both meridional and zonal flows. Each mooring was equipped with up- and down-looking acoustic Doppler current profilers (ADCPs) to collect velocity profiles over the upper 500 m, temperature and conductivity sensors, and microstructure packages for measuring turbulence. The moored array sampled for 20 months, capturing two winter and two summer monsoons. Wijesekera et al. (2016, in this issue) report findings from the mooring array.

Pressure Inverted Echo Sounders

PIES (Figure 3e) provide time series of boundary current transport across key lines running south and east from Sri Lanka. They measure bottom pressure and acoustic travel time, which can be used to reconstruct the sheared part of the boundary flow (see Box 1). Together with satellite altimetry, this system provides estimates of volume transport



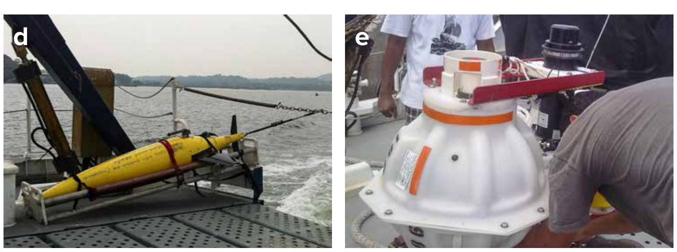


FIGURE 3. Instrumentation used in the southern Bay of Bengal included (a) an acoustic Doppler current profiler (ADCP) mooring shown being deployed by R/V *Samuddrika*, (b) an ocean turbulence probe pictured during deployment from R/V *Samuddrika*, (c) a surface drifter, (d) a Seaglider, (e) PIES, and (f) a meteorological station located at Beruwala, Sri Lanka.

BOX 1. BOUNDARY CURRENT TRANSPORT MONITORING WITH PIES

By Arachaporn Anutaliya

Flow around Sri Lanka is a potential conduit for freshwater and heat exchange between the Bay of Bengal and the Arabian Sea. As part of the US Office of Naval Research Air-Sea Interactions Regional Initiative (ASIRI), our goal is to provide a better understanding of the physical structure of this flow, its response to monsoon winds, and its long-term variability. In particular, the study focuses on flow in the upper layer that contains the boundary circulation that mediates much of the exchange between these two basins.

Toward this goal, we are analyzing satellite altimetry, ship-based historical conductivity-temperature-depth (CTD), and Pressure Inverted Echo Sounder (PIES) measurements. The surface flow is well observed by gridded Ssalto/Duacs satellite altimeter products (http://www.marine.copernicus.eu); their record length is over 21 years, and they resolve the boundary current and its variability on intraseasonal through interannual time scales (Figure 2). The typical vertical distributions of the currents can be examined with the CTD measurements collected from 1960 to 2011 and ongoing glider transects. PIES deployed to the east and south of Sri Lanka (Figure 1) measure pressure and acoustic travel time, which represent two different vertical integrals over the water column. The differences between the PIES data (collected from the deployment sites bracketing the boundary current) can be used together with satellite altimetry, exploiting vertical a priori information from CTD data, to yield the transport and vertical structure of the upper-layer flow with high temporal resolution.

In the boundary regime off Sri Lanka, flow and hydrography are complex enough that the traditional empirical relation between acoustic travel time and vertical structures, such as dynamic height, temperature, and salinity (known as "GEMs"; Meinen and Watts, 2000) is not well established. The first year of PIES data show that even two vertical integrals, pressure fluctuation and travel time, are not enough to describe the upper-layer variability (Figure S1). Therefore, a new approach that uses acoustic travel time, pressure fluctuations, and satellite altimetry will be exploited to estimate transport in the upper layer. The CTD data show that shear-derived transport in the upper 200 m, relative to the surface, can be estimated from simulated travel time and pressure integrated from the surface to 2,000 m. The estimated shear transport agrees well with that computed directly from the CTD profiles with a correlation coefficient of 0.88 (Figure S2). This permits calculation of total transport in the upper layer when referencing to the surface using altimetry, as follows. Geopotential height of a pressure surface, $\varphi(p)$, can be decomposed into geopotential height at the surface, $\varphi(0)$, and pressure integral of specific volume anomaly, α:

$$\varphi(p) = \varphi(0) + \int_0^p \alpha(p')\,dp'.$$

The horizontal velocity, v, and thus the transport, Tr_{200}, across a transect bracketed by points A and B then is

$$\int_{x_A}^{x_B} v(p)\,dx = \frac{1}{f}\,[\varphi_B(p) - \varphi_A(p)], \text{ and}$$

$$Tr_{200} = \frac{1}{f}\int_0^{200} [(\int_0^p \alpha_B(p') - \alpha_A(p')\,dp') + (\varphi_B(0) - \varphi_A(0))]\,dz,$$

where f is the Coriolis parameter. Pressure and travel time measured by the PIES will be used to estimate the double integral on the right-hand side of the equation, which is the upper-layer shear transport referenced to the surface. Figure S2 shows the linear fit of the shear transport from historical CTD data against the same quantity from simulated pressure and travel time data. Estimated shear transport derived from PIES data has an expected root-mean-square error of less than 2 Sv. The second component in the equation above, which is the depth integral of the surface geopotential height, can be estimated from the surface measurement of the satellite altimetry.

Measurements collected by Seagliders sampling along the PIES lines provide an extensive collection of contemporaneous profiles that will be used to improve the relationship between the upper-layer transport and PIES measurements. Continuous measurements of surface currents by satellite and of shear flow using PIES will allow continuous observation of boundary current transports. This will enable investigation of variability and the governing mechanism of the flow, and thus allow a better understanding of heat and freshwater exchange in the northern Indian Ocean.

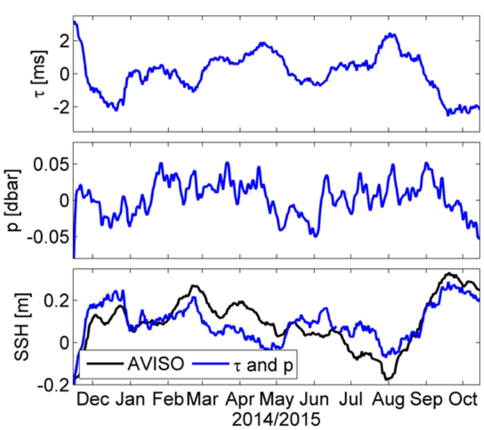


FIGURE S1. (top) Travel time and (middle) pressure fluctuation collected from the offshore PIES eastward of Sri Lanka, and (bottom) best fit of sea surface height calculated from travel time and pressure fluctuation compared to the Aviso sea surface height.

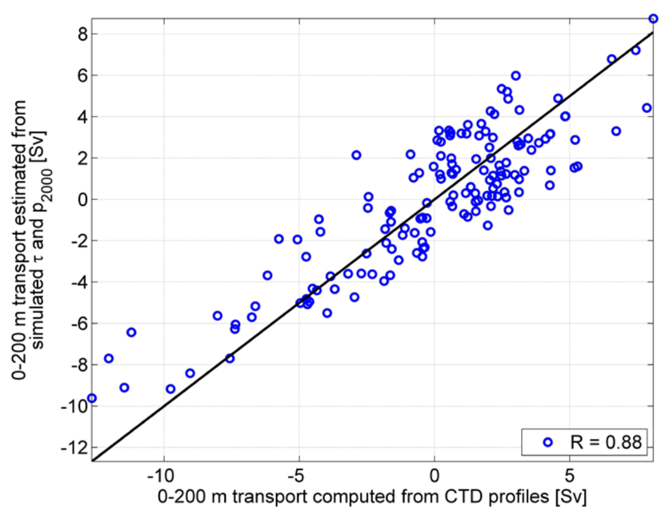


FIGURE S2. Relationship between shear 0–200 m transport (relative to surface) computed from the CTD profiles in the upper 200 m layer, and upper-layer shear transport estimated from simulated travel time and pressure at 2,000 m depth (our approximation for the deep offshore PIES; most CTD data only extend to 2,000 m). A similar simulation for the more inshore shallow PIES at 600 m gives an even better correlation.

across sections confined by any pair of PIES. Giving high temporal resolution but only a horizontal integral, these data are very complementary to the gliders operating in the same sections.

A collaborative effort between NARA and Scripps Institution of Oceanography deployed a pair of PIES bracketing the boundary current (8°N, 81.75°E and 8°N, 83.4°E) off the east coast of Sri Lanka in November 2014, followed by two additional PIES deployed to the south of Sri Lanka (5.85°N, 80.3°E and 4.15°N, 80.3°E) in December 2015 (Figure 1e,f, yellow diamonds). These locations were chosen largely based on altimetry analyses such as those in Figure 2, which reveal the typical extent of the boundary current regime.

Atmospheric Boundary Layer Measurements

A collaborative effort undertaken by the University of Notre Dame, the US Army Research Laboratory, and NARA deployed an array of three boundary layer and upper atmospheric sounding stations (Sri Lanka, Seychelles, and Singapore; Figure 3f) to investigate atmospheric dynamics at time scales of 7–30 days. Site separation was chosen to resolve northwesterly atmospheric disturbances through the Bay of Bengal as well as along equatorial Indian Ocean. Each site collected an extensive set of meteorological variables along with momentum, heat, and moisture fluxes measured from flux towers.

MONSOONAL VARIABILITY OF CIRCULATION PATHWAYS

Observations collected by drifters, Seagliders, and moorings illustrate shifts in circulation pathways associated with the monsoon cycle. Drifters resolve seasonal changes in pathways, and key sections occupied by Seagliders document boundary current structure and provide the water mass observations needed to understand the role of these shifts in driving fluxes of heat and salt. Measurements collected by the mooring array sample the deep basin, extending the boundary sections provided by Seagliders.

Northeast Monsoon

During the winter monsoon, drifter trajectories (December-January-February panel in Figure 4) reveal surface circulation pathways consistent with those inferred from remotely sensed SSH (Figure 1a). Drifters deployed off the east coast of Sri Lanka move southward, hugging the coast in a narrow band and eventually turning west to move into the Arabian Sea. Drifters traveled at their fastest speeds during their passages along the southern end of Sri Lanka, with the envelope of paths widening and speeds slowing after entering the Arabian Sea. Many of the drifters deployed further to the north, off the Indian coast, also follow the coastline south, albeit with less direct pathways that suggest interaction with eddies and other mesoscale features during the southward drift. Although sample size is small, none of the 10 drifters released in winter 2014 left the Sri Lankan coast to follow the anticipated ESLJ. The drifters suggest that, during winter 2014, the primary export pathway to the Arabian Sea may be the direct route associated with the EICC.

A Seaglider section along 8°N, occupied in early December 2015, suggests more complex patterns. A 25 m deep near-surface fresh layer extends from the Sri Lankan coast to roughly 83.6°E, with near-surface salinity increasing sharply eastward (Figure 5d). West of 82.5°E, absolute geostrophic meridional velocity points southward, consistent with satellite observations (Figure 5a,b) that suggest a narrow, nearshore EICC removing fresh Bay of Bengal water from the basin. However, isopycnals slope downward east of 82.5°E, driving a broad region of northward geostophic flow that extends

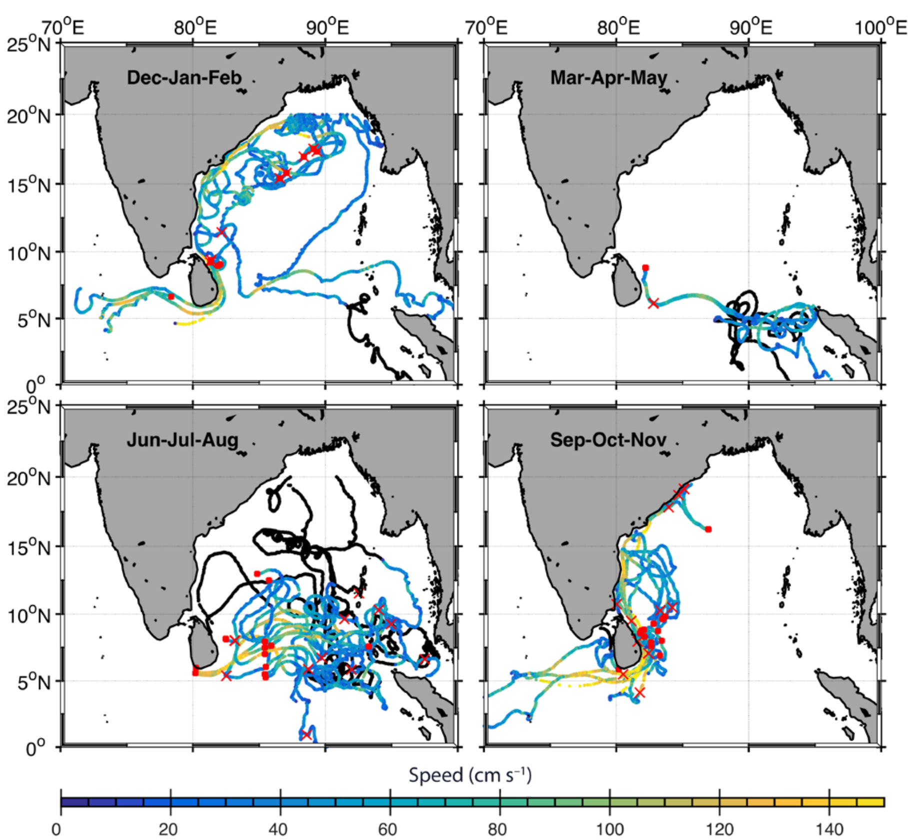


FIGURE 4. Drifter tracks (2013–2014) plotted by deployment month. Red dots mark deployment locations, color indicates speed, and black lines mark drifters without drogues. Tracks between the deployment sites (red dots) and the red x's are from the time frame indicated on the plot. Tracks beyond the red x's mark drift after the indicated time period. Losses due to fishing activity resulted in the absence of tracks in March, April, and May.

to 85°E (Figure 5c). This north-flowing region includes roughly 75% of the near-surface fresh layer, perhaps waters that have been detrained from the EICC and redirected northward through interaction with an impinging cyclonic gyre, as seen in SSH maps from this period (Figures 1a and 5a). Although the glider sections do not resolve the fate of this north-flowing branch, it may represent the export pathway attributed to the ESLJ.

Southwest Monsoon

Drifters released during the summer monsoon followed largely eastward pathways (June-July-August panel in Figure 4). Even those deployed in the boundary current at the southern tip of Sri Lanka moved offshore, into the central Bay of Bengal, before turning north, consistent with circulation observed in maps of SSH and surface geostrophic velocity (Figure 1b). While most drifters moved northeast into the Bay of Bengal or followed arcs that approximate the perimeter of the SLD, a few took southward paths that are difficult to reconcile with surface currents estimated from altimetry. Near the end of the 2014 southwest monsoon, an anticyclone off the Sri Lankan coast (not shown), rather than the SLD, draws inflowing Arabian Sea water around its perimeter to produce a more northerly path, while freshwater flows southward along the coast.

A Seaglider section along 8°N, occupied in late August 2014 (toward the end of the summer monsoon) captures strong temperature-salinity fronts between 82.7°E and 83.5°E (Figure 6d). Steeply sloping isopycnals, associated with an anticyclonic feature off the east coast of Sri Lanka, support strong, surface-intensified northward geostrophic flow (Figure 6c). Associated water mass properties indicate that this flow carries high-salinity Arabian Sea water toward the northern Bay of Bengal, consistent with the circulation expected from examination of drifter tracks (Figure 4) and SSH (Figures 1b and 6a). Between this frontal region and the coast of Sri Lanka, a surface-intensified southward flow carries a 40 m thick layer of fresh Bay of Bengal water away from the basin (Figure 6c,d). Although the glider-based section captures this 50 km wide feature, surface geostrophic velocity from remotely sensed SSH depicts northward currents extending inshore to the coast, pointing to the limitations of gridded SSH products near the boundaries. The section also reveals extensive interleaving of water masses, indicative of lateral stirring, in the region where waters from the Bay of Bengal and the Arabian Sea meet (Figure 6d). Sections collected in August 2015 from R/V *Roger Revelle* captured similarly strong fronts and interleaving.

Intermonsoon Periods

Fishing pressure left the spring intermonsoon period (March-April-May panel in Figure 4) with only one successful drifter deployment, but drifters released off the east coast of Sri Lanka during the autumn intermonsoon (September-October-November panel in Figure 4) brought greater success. Three were carried by a southward boundary current, perhaps the beginning of the WMC, around the southern end of Sri Lanka and then westward into the Arabian Sea. As during winter, drifters accelerated as they transited around the southern tip of the island and slowed upon reaching the Arabian Sea. A larger fraction of the

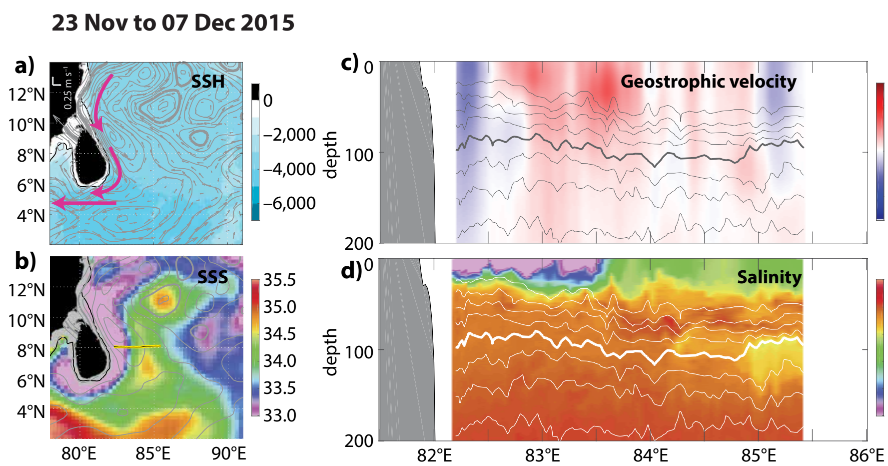


FIGURE 5. Seaglider section from November to December 2015. (a) Absolute dynamic height and surface geostrophic velocity, plotted as in Figure 1a. (b) Sea surface salinity, plotted as in Figure 1c, with a yellow line marking the 8°N Seaglider track. (c) Absolute northward geostrophic velocity for the zonal section at 8°N, occupied in November–December 2014 by Seaglider. (d) Salinity for the November–December 2014 section. Both sections are plotted as a function of depth (upper 200 m of the 1,000 m range) and longitude, with white contours marking isotherms at 2°C intervals and the 20°C isotherm in bold.

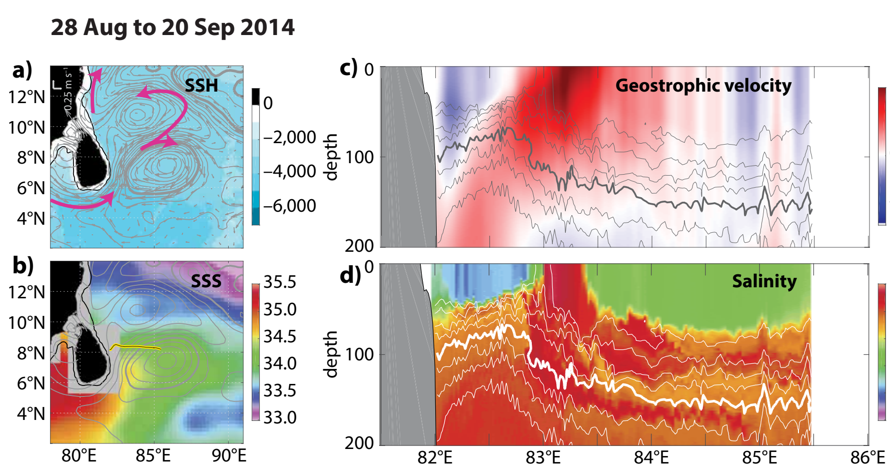


FIGURE 6. Seaglider section, same as in Figure 5, but from August to September 2014.

drifters followed a cyclonic loop, eventually impinging on the Sri Lankan coast between 10°N and 15°N to turn southward in a flow that resembles the EICC. Corresponding glider sections along 8°N (not shown) reveal patterns of geostrophic velocity that are consistent with the circulation captured by drifters, but also show significant variability over the monthly time scale of the section occupations as well as strong subsurface variability.

The Seasonal Cycle at Mid-basin

Time series of temperature and velocity profiles collected by moored instruments at 8°N, 85.5°E show a clear seasonal cycle in upper-ocean velocity (Figure 7). Observations reveal upper-ocean cooling and strong, surface-intensified northeastward currents during the southwest monsoon, consistent with SMC penetration into the Bay of Bengal discussed above. Currents turn southeastward during the fall intermonsoon, perhaps driving mid-basin freshwater export. Northeastward flow returns during the northeast monsoon, though surface trapped and much weaker than that seen during summer. Wijesekera et al. (2016, in this issue) provide an extensive discussion of observations collected by the mooring array.

SUMMARY

A combination of remote-sensing and in situ observations resolves seasonal shifts in the boundary currents and circulation pathways around Sri Lanka, which play an important role in brokering communication between the Bay of Bengal, the Arabian Sea, and the equatorial Indian Ocean (e.g., Schott et al., 1994; Vinayachandran and Yamagata 1998; Jensen, 2001). Satellite remote sensing and drifters suggest that during the 2014 northeast monsoon, freshwater left the Bay of Bengal within the EICC and followed a direct path southward along the Sri Lankan coast while the more circuitous route of the ESLJ played a smaller role. During this period, drifters moved southward along the Sri Lankan coast without offshore detours, and SSH-derived surface geostrophic currents were weak within the ESLJ relative to those associated with the EICC. Sections collected by Seaglider provide a different perspective, showing the majority of the near-surface fresh layer moving north, detrained from the EICC. Freshwater leaving via the shorter EICC pathway might experience less mixing, and thus less dilution, than waters that follow longer paths. Circulation differences inferred from remote sensing and drifters, and also from high-resolution sections, suggest caution should be taken when interpreting limited observational data. During the southwest monsoon, Arabian Sea waters entering with the SMC bypass the Sri Lankan coast and instead follow SLD-imposed circulation to enter the Bay of Bengal mid-basin. Freshwater flows south in a narrow band along the coast of Sri Lanka, creating a strong front with more saline, north-flowing Arabian Sea waters. Strong interleaving associated with this frontal region suggests significant mixing between these disparate water masses, with the potential to modify waters exported from and imported to the Bay of Bengal. Jinadasa et al. (2016, in this issue) focus on these critical mixing processes.

These early results point to the regional observing achievable through truly collaborative, multi-platform approaches. Benefits here include persistence over two monsoon cycles, sampling at a wide range of temporal and spatial scales, and access to the critical, nearshore regions through which the important boundary currents pass. Local logistical and political support are crucial for maintaining sustained, long-term operations. Scientific benefits will compound as the team integrates the many measurements collected as part of this program. Examples presented here include merging of remote-sensing, drifter, and glider observations to achieve a more comprehensive view of regional circulation. Future work will incorporate temperature and salinity profiles collected at the PIES sites into the interpretation of travel time data for barotropic and baroclinic transport. The resulting transport time series, taken together with Seaglider sections, drifter tracks, and the mid-basin mooring array, will provide a new perspective on how circulation in the seas surrounding Sri Lanka modulate the salinity balance of the neighboring Bay of Bengal and Arabian Sea.

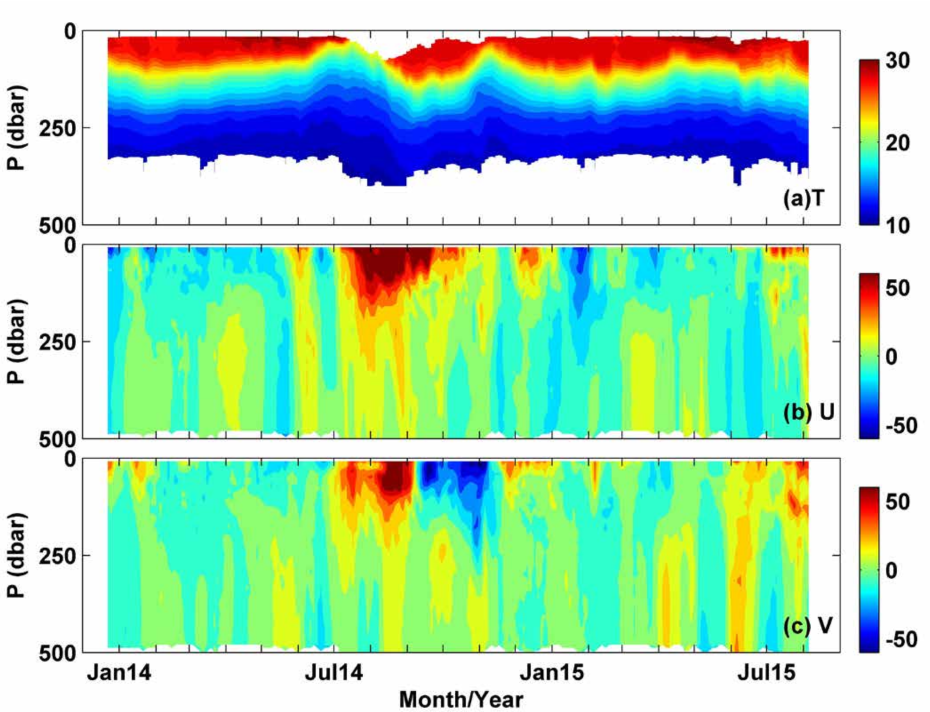


FIGURE 7. The 20-month record of (a) temperature and (b) eastward and (c) northward velocity for the mooring located at 8°N, 85.5°E. Time series have been low-pass filtered at 72 hours to remove inertial oscillations and tides.

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