

The Monsoon Circulation of the Arabian Sea

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LONG-TERM GOALS

Understand how local and remote forcing act to drive the seasonal evolution of upper ocean stratification and circulation in the Arabian Sea. Specific objectives include:

1. Document an annual cycle of stratification, watermass variability and circulation in the Arabian Sea.
2. Quantify the annual cycle of exchange between the Arabian Sea and the Bay of Bengal.
3. Characterize the generation and westward propagation of annual (and faster) Rossby waves across the Arabian Sea and their impact on stratification and the timing of seasonal reversals in circulation.
4. Assess the relative importance of local forcing, including coastal upwelling, Ekman pumping, advection and mixing in determining the intensity and phasing of the western boundary's response to the monsoons.

WORK COMPLETED

Analysis efforts have focused around glider-based sampling off the southern tip of Sri Lanka and in the central Arabian Sea (Fig 1).

- Collaborative analyses of sections occupied off the east coast of Sri Lanka, observations collected by Pressure Inverted Echo Sounders (PIES) drifters capture wintertime export of freshwater within the East India Coastal Current, reveal significant interleaving (indicative of energetic stirring) and document the existence of an undercurrent in the opposite direction to the surface flow (Lee et al., 2016; Anutaliya et al., 2017).
- Ongoing work uses the multi-year time series of meridional sections extending south from the southern tip of Sri Lanka (provided by Seagliders) and, in collaboration with Anutaliya, Send, McClean and Sprintall, measurements collected near the endpoints of the line with PIES to investigate the exchange flow between the Arabian Sea and Bay of Bengal. Seasonal averages of the exchange section capture upper ocean inflow of fresh waters from the Bay of Bengal into the Arabian Sea during the Northeast Monsoon (Fig. 2) and a subsurface, eastward flux of more saline Arabian Sea water during the Southwest Monsoon (Fig. 3). Observations in the central Arabian Sea characterize the spread of high

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14. ABSTRACT Analyses of data collected by the Northern Arabian Sea Circulation, Autonomous Research program focused on understanding the physics that govern the annual cycle of stratification, watermass variability and circulation in the Arabian Sea. Collaborative analyses of data collected by long endurance gliders and Pressure Inverted Echosounders (PIES) capture wintertime export of freshwater within the Sri Lanka current and document the existence of an undercurrent that opposes the surface flow. Four years of repeat occupations of a section extending southward from the southern tip of Sri Lanka document westward, near-surface flow hugging the Sri Lanka coast, transporting freshwater from the Bay of Bengal into the Arabian Sea during the Northeast Monsoon. The circulation reverses and moves offshore during the Southwest Monsoon, with more saline waters from the northern Arabian Sea carried into the Bay of Bengal by eastward, subsurface flow. Additional efforts focused on the physics of Arabian Sea barrier layers and on circulation over the Seychelles Plateau.					
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salinity waters back to formation regions in the Red Sea, Persian Gulf and Gulf of Oman (Figs. 4 and 5). Two papers detailing these analyses are in preparation.

- A wintertime mid-basin experiment focused on upper ocean dynamics and barrier layer formation in the Arabian Sea, with two gliders characterizing spatial variability around a rapidly profiling ALAMO float (Fig. 7). Collaborative analysis (with S. Jayne, WHOI, and A. Shcherbina, APL-UW) of the resulting data are ongoing.
- We contributed to a collaborative paper that provides an overview of the NASCar program (Centurioni et al., 2017) and a methods paper that detailed the use of model-based planning approaches for autonomous platforms (Lermusiaux et al., 2017).
- NASCar also supported ongoing training in both science analysis and glider operations for researchers at the Indian National Centre for Ocean Information (INCOIS). Lee conducted short courses at the INCOIS facility in Hyderabad, India on glider operations and data analysis, and Lee and Rainville provided guidance for formation of the INCOIS glider facility.
- Gliders deployed as part of NASCar also sampled near the Seychelles, detecting topographically trapped waves as well as Equatorial waves, impacting the circulation around the Seychelles Plateau (Castillo-Trujillo et al., 2020; Arzeno, Giddings, Rainville and Pawlak, in preparation).

PRODUCTS

- Lee, C.M., S.U.P. Jinadasa, A. Anutaliya, L.R. Centurioni, H.J.S. Fernando, V. Hormann, M. Lankhorst, L. Rainville, U. Send, and H.W. Wijesekera, 2016: Collaborative observations of boundary currents, water mass variability, and monsoon response in the southern Bay of Bengal. *Oceanography* 29(2):102–111, <http://dx.doi.org/10.5670/oceanog.2016.43>.
- Centurioni, L.R., V. Hormann, L.D. Talley, I. Arzeno, L. Beal, M. Caruso, P. Conry, R. Echols, H.J.S. Fernando, S.N. Giddings, A. Gordon, H. Graber, R.R. Harcourt, S.R. Jayne, T.G. Jensen, C.M. Lee, P.F.J. Lermusiaux, P. L'Hegaret, A.J. Lucas, A. Mahadevan, J.L. McClean, G. Pawlak, L. Rainville, S.C. Riser, H. Seo, A.Y. Shcherbina, E. Skillingstad, J. Sprintall, B. Subrahmanyam, E. Terrill, R.E. Todd, C. Trott, H.N. Ulloa, and H. Wang. 2017. Northern Arabian Sea Circulation-Autonomous Research (NASCar): A research initiative based on autonomous sensors. *Oceanography* 30(2):74–87, <https://doi.org/10.5670/oceanog.2017.224>.
- Lermusiaux, P.F.J., P.J. Haley Jr., S. Jana, A. Gupta, C.S. Kulkarni, C. Mirabito, W.H. Ali, D.N. Subramani, A. Dutt, J. Lin, A.Y. Shcherbina, C.M. Lee, and A. Gangopadhyay. 2017. Optimal planning and sampling predictions for autonomous and Lagrangian platforms and sensors in the northern Arabian Sea. *Oceanography* 30(2):172–185, <https://doi.org/10.5670/oceanog.2017.242>.
- Anutaliya, A., U. Send, J.L. McClean, J. Sprintall, L. Rainville, C.M. Lee, S.U.P. Jinadasa, A.J. Wallcraft and E.J. Metzger. 2017. An undercurrent off the east coast of Sri Lanka, *Ocean Sci.*, 13, 1035-1044, <https://doi.org/10.5194/os-13-1035-2017>.
- Castillo-Trujillo, A. C., I.B. Arzeno. S.N. Giddings, G. Pawlak, J. McClean, and L. Rainville, 2020. Circulation around and atop the Seychelles Plateau. 2020. Submitted to JGR.

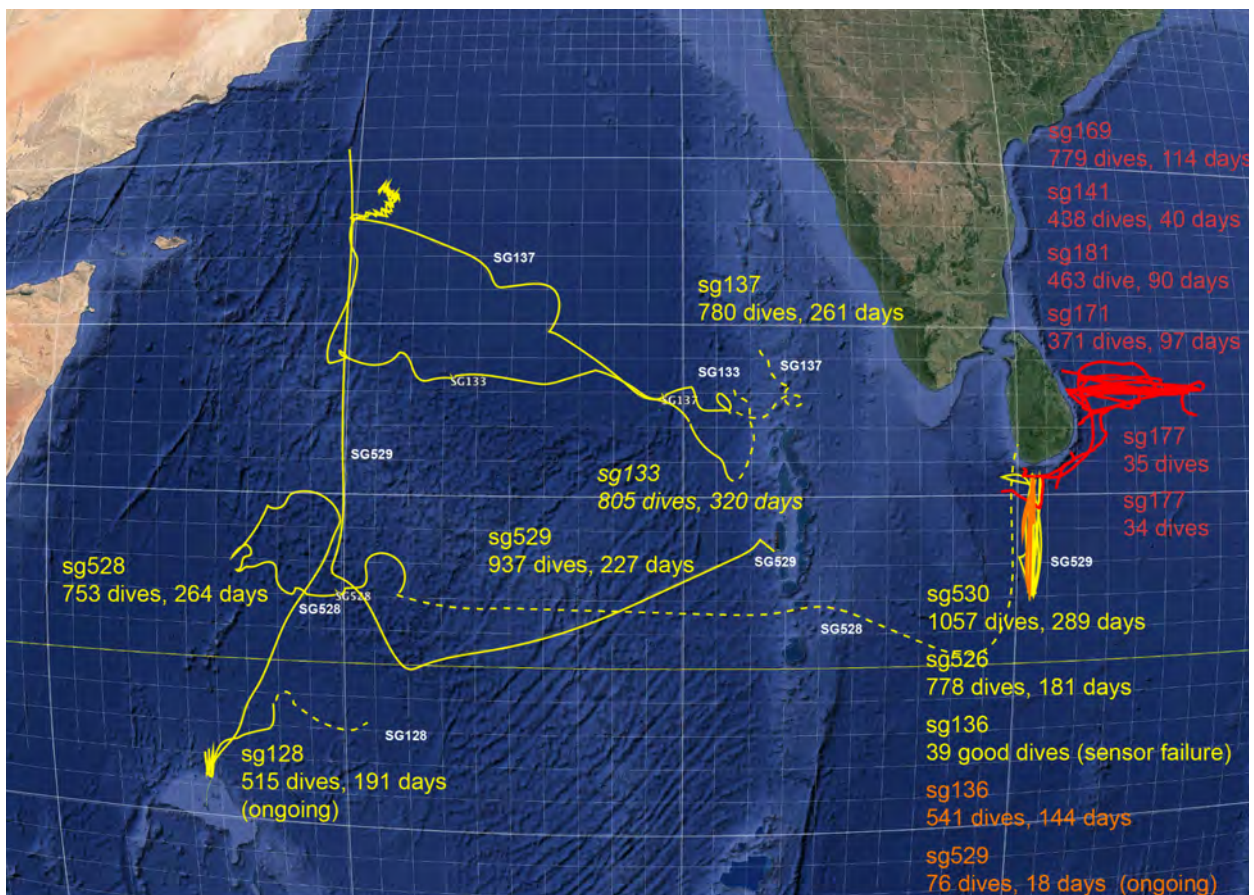


Figure 1. Sampling with Seagliders in the Arabian Sea and Bay of Bengal. Yellow tracks mark sampling during the NASCAR program, red the preceding ASIRI program and orange the follow-on MISOBBOB project.

Northeast Monsoon DJF

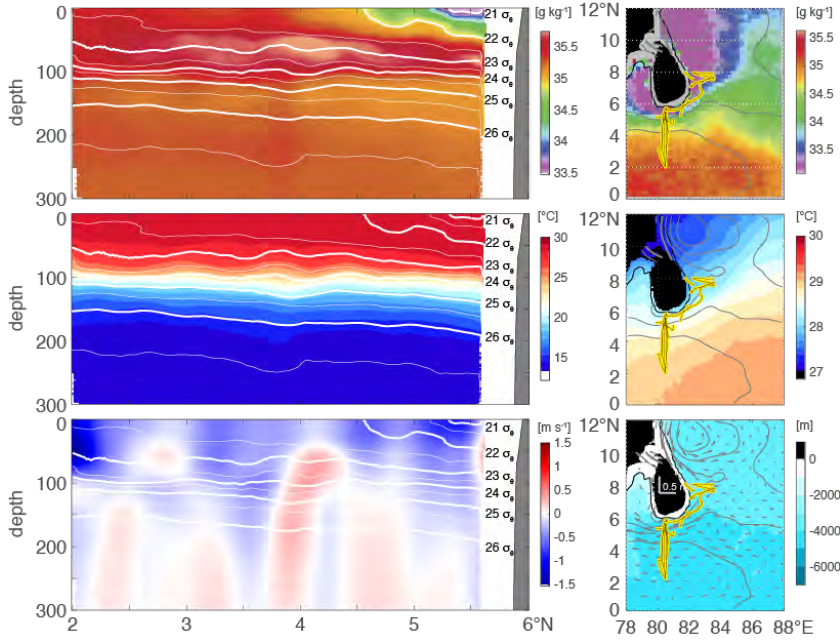


Figure 2. Average absolute salinity, temperature, and geostrophic eastward velocity along the Exchange section during the Northeast monsoon (Dec-Jan-Feb). The surface maps on the RHS show the tracks during this season.

Southwest Monsoon JJA

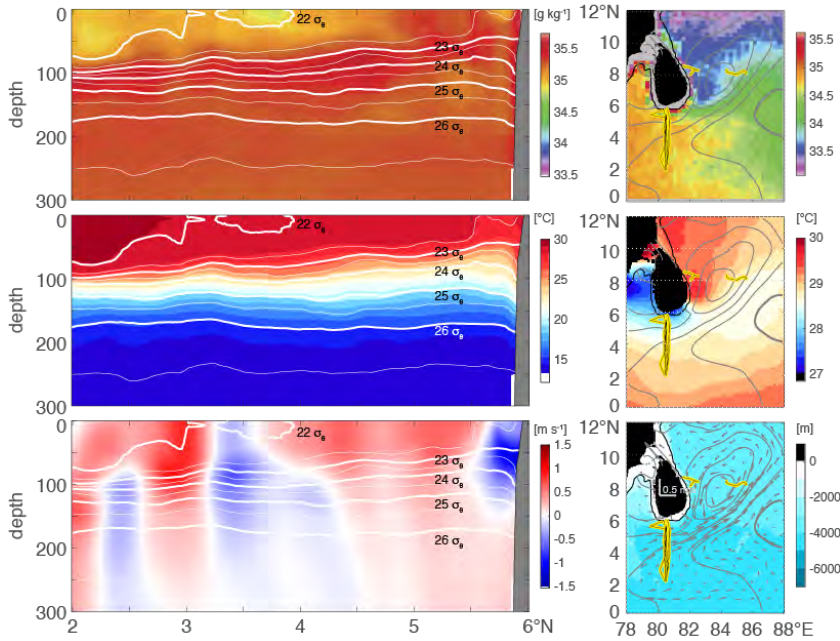


Figure 3. Average absolute salinity, temperature, and geostrophic eastward velocity along the Exchange section during the Southwest monsoon (Jun-Jul-Aug). The surface maps on the RHS show the tracks during this season.

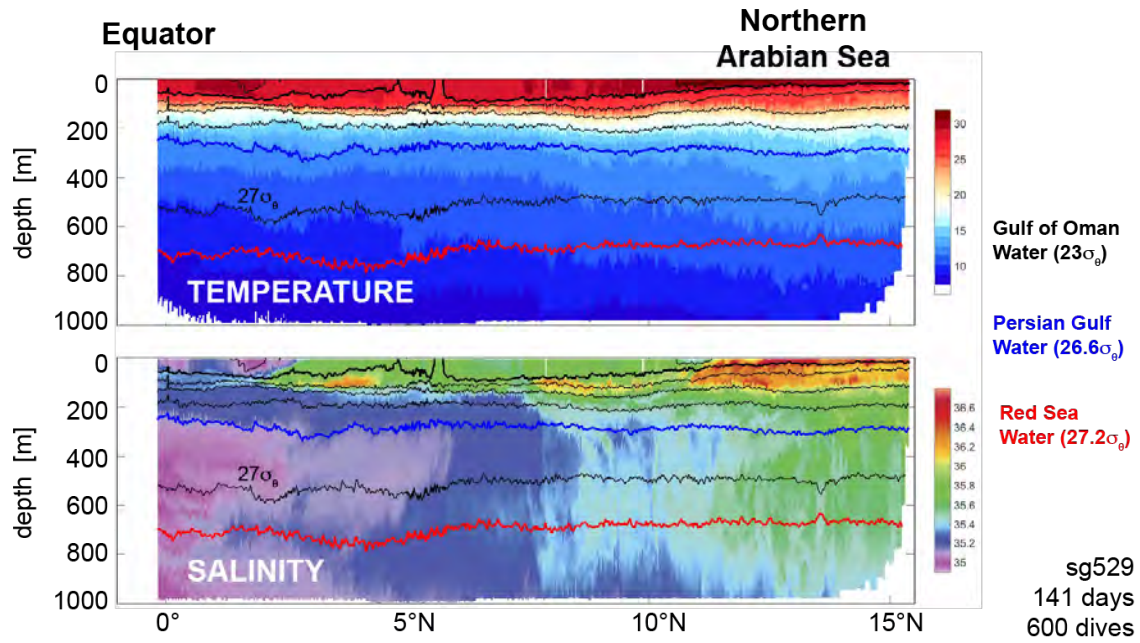


Figure 4. Sections of temperature (top) and salinity (bottom) as a function of latitude and depth collected by SG529. Typical densities of Gulf of Oman (23 kg m^{-3} , black), Persian Gulf (26.6 kg m^{-3} , blue), and Red Sea (27.2 kg m^{-3} , red) are indicated by the bold contours.

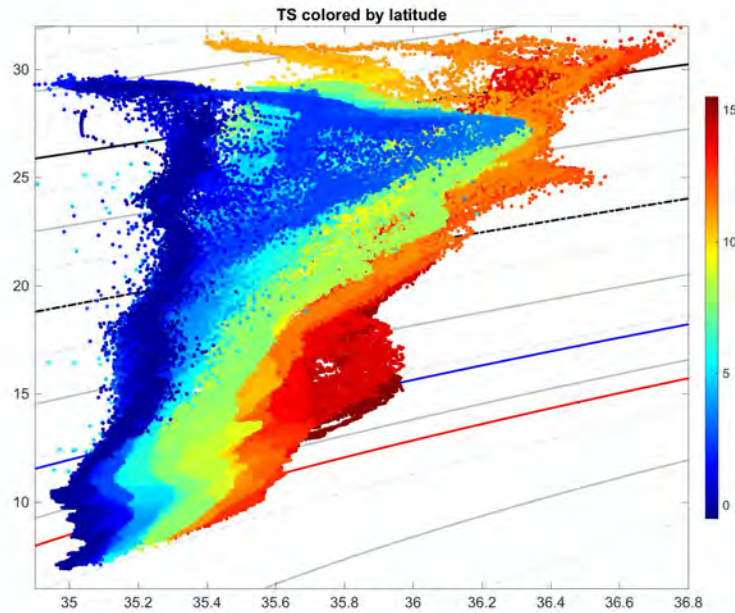


Figure 5. T-S diagram along the section depicted in Fig. 1, colored by latitude. Typical potential densities of Gulf of Oman (23 kg m^{-3} , black), Northern Arabian Sea (25 kg m^{-3} , dashed black), Persian Gulf (26.6 kg m^{-3} , blue), and Red Sea (27.2 kg m^{-3} , red) waters are indicated by the bold contours.

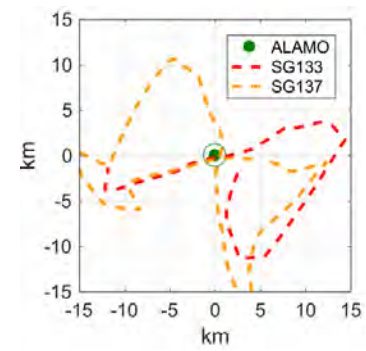
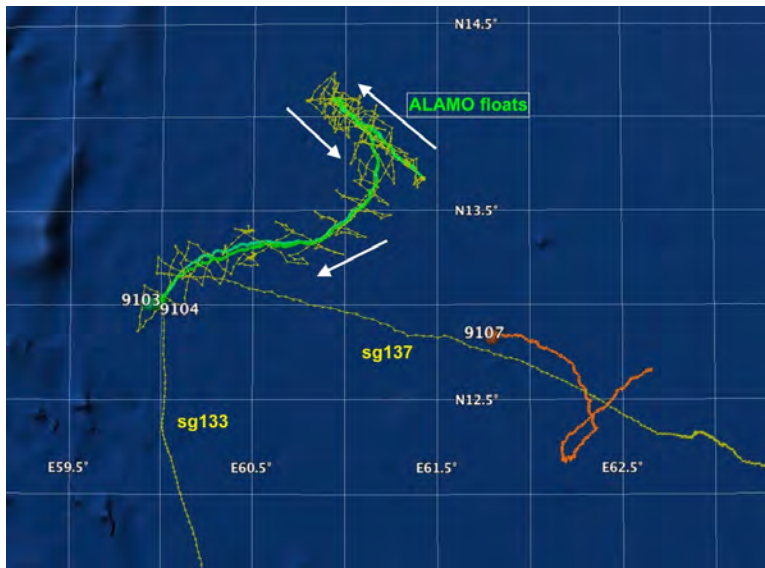


Figure 6. Tracks of the NASCar ALAMO floats (green and orange), and of the Seagliders SG133 and SG137. Gliders were surveying a butterfly pattern in the moving reference frame of the float (white arrows).

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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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Photo credit: Luc Rainville

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,

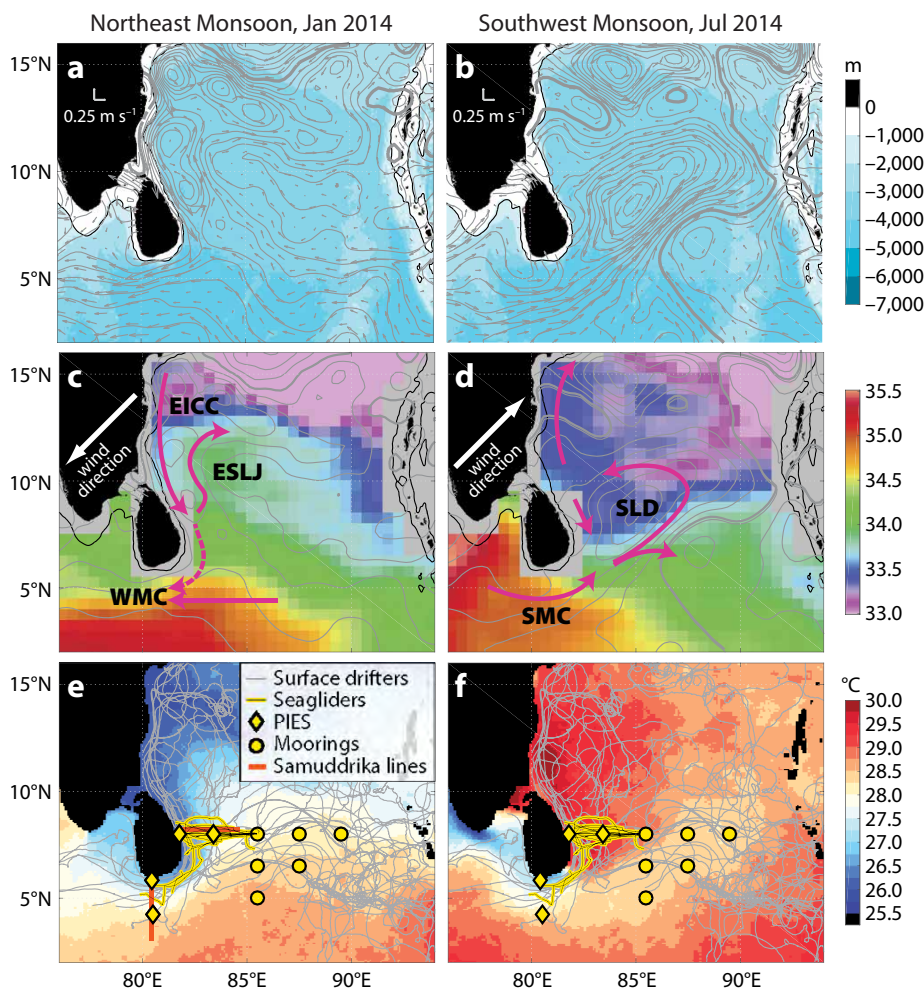


FIGURE 1. Monthly averaged absolute dynamic height (contours) and surface geostrophic velocity from Aviso (vectors) for (a) January 2014, and (b) July 2014. Contour interval is 2 cm, the 1.0 m contour is bold, and bathymetry is in color. Monthly average, optimally interpolated sea surface salinity (color) 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 winter-time 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.

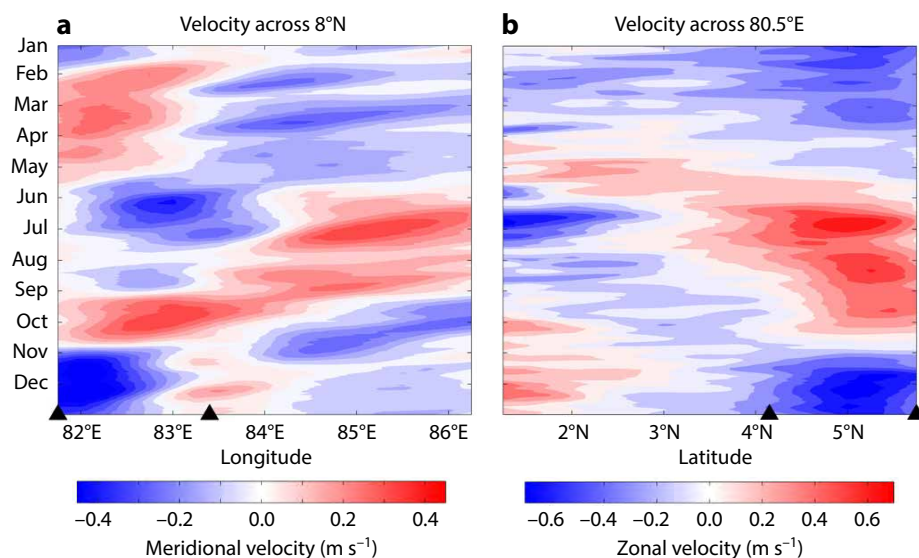


FIGURE 2. The average (1993–2013) annual cycle of surface geostrophic velocity derived from satellite altimetry for (a) the zonal section east of Sri Lanka at 8°N, and (b) the meridional section south of Sri Lanka at 80.5°N. These are the two sections marked by yellow diamonds and red lines in Figure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

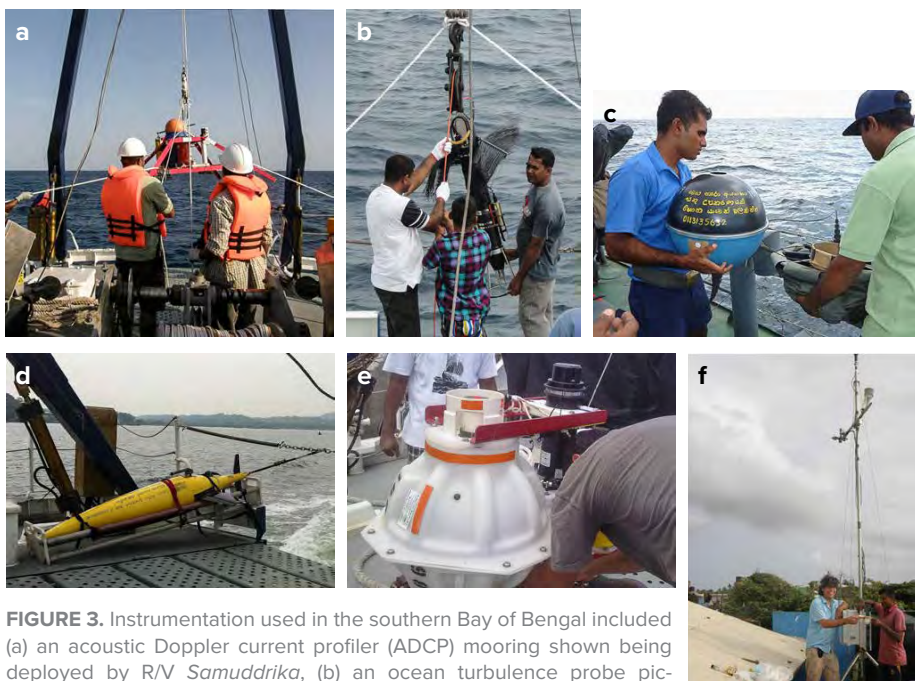


FIGURE 3. Instrumentation used in the southern Bay of Bengal included (a) an acoustic Doppler current profiler (ADCP) mooring shown being deployed by R/V *Samudrika*, (b) an ocean turbulence probe pictured during deployment from R/V *Samudrika*, (c) a surface drifter, (d) a Seaglider, (e) PIES, and (f)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

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

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

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.

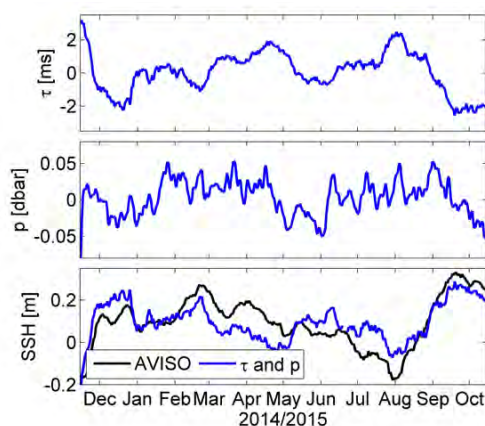


FIGURE S1. (top) Travel time and (middle) pressure fluctuation collected from the off-shore PIES eastward of Sri Lanka, and (bottom) best fit of sea surface height calculated from travel time and pressure fluctuation compared to the Aviso sea surface height.

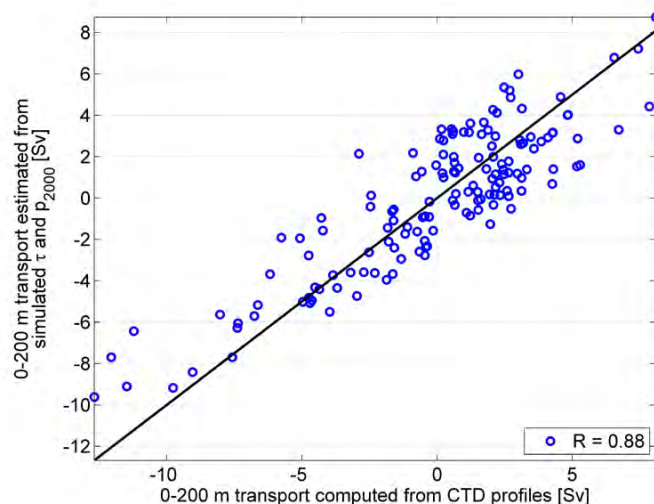


FIGURE S2. Relationship between shear 0–200 m transport (relative to surface) computed from the CTD profiles in the upper 200 m layer, and upper-layer shear transport estimated from simulated travel time and pressure at 2,000 m depth (our approximation for the deep offshore PIES; most CTD data only extend 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 geostrophic flow that extends

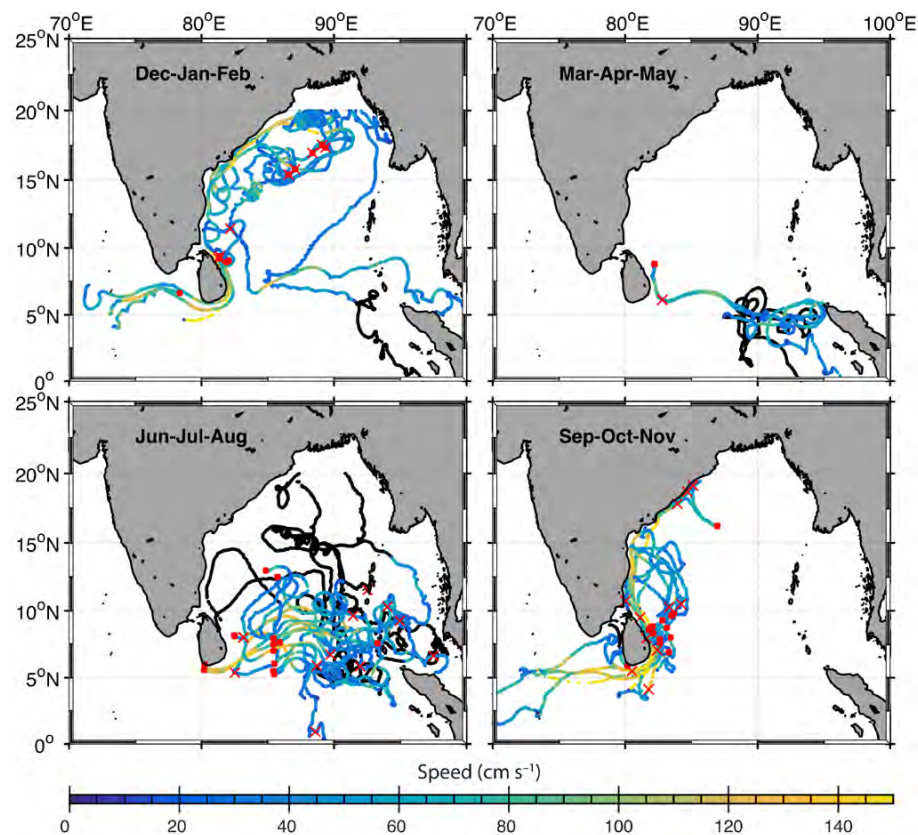


FIGURE 4. Drifter tracks (2013–2014) plotted by deployment month. Red dots mark deployment locations, color indicates speed, and black lines mark drifters without drogues. Tracks between the deployment sites (red dots) and the red x's are from the time frame indicated on the plot. Tracks beyond the red 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

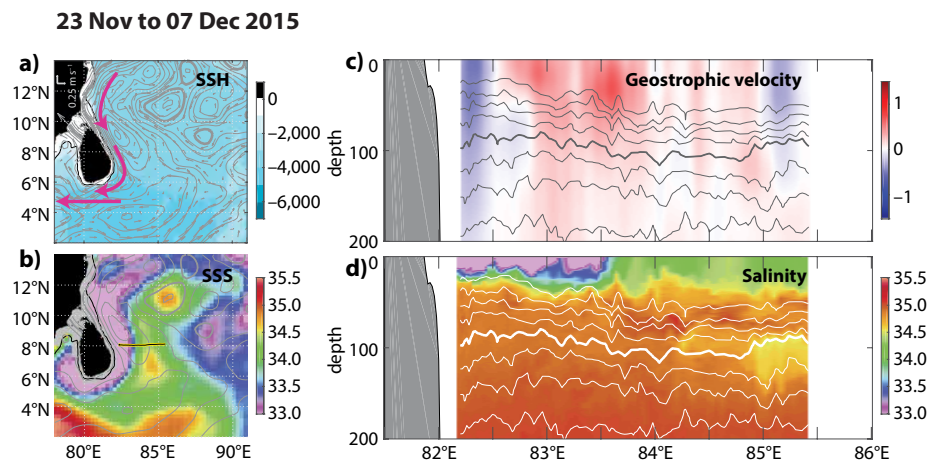


FIGURE 5. Seaglider section from November to December 2015. (a) Absolute dynamic height and surface geostrophic velocity, plotted as in Figure 1a. (b) Sea surface salinity, plotted as in Figure 1c, with a yellow line marking the 8°N Seaglider track. (c) Absolute northward geostrophic velocity for the 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.

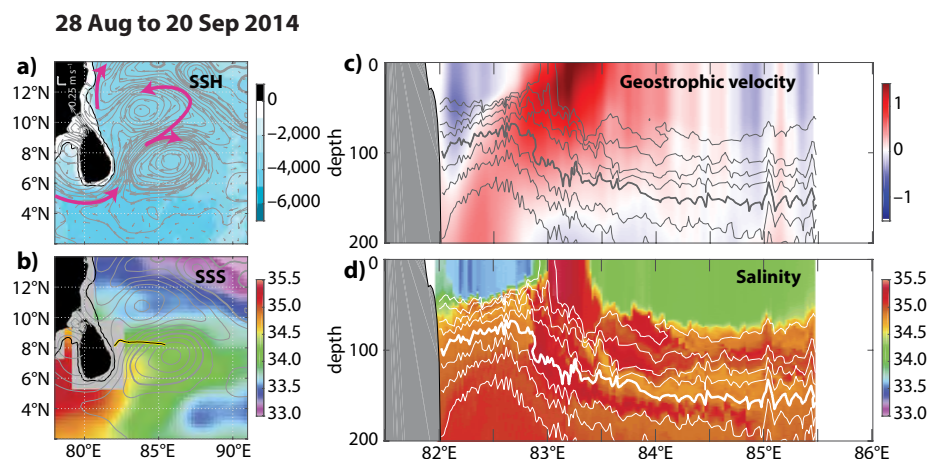


FIGURE 6. Seaglider section, same as in Figure 5, but from August to September 2014.

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. 

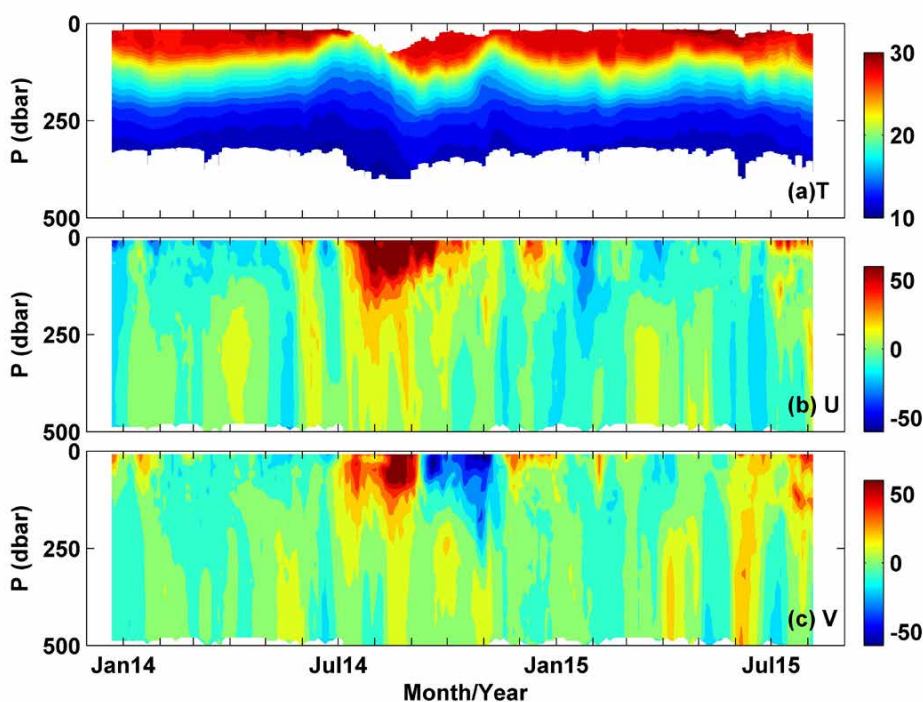


FIGURE 7. The 20-month record of (a) temperature and (b) eastward and (c) northward velocity for the mooring located at 8°N, 85.5°E. Time series have been low-pass filtered at 72 hours to remove inertial oscillations and tides.

REFERENCES

- Chatterjee, A., D. Shankar, S.S.C. Shenoi, G.V. Reddy, G.S. Michael, M. Ravichandran, V.V. Gopalkrishna, E.P. Rama Rao, T.V.S. Udaya Bhaskar, and V.N. Sanjeevan. 2012. A new atlas of temperature and salinity for the North Indian Ocean. *Journal of Earth System Science* 121(3):559–593, <http://dx.doi.org/10.1007/s12040-012-0191-9>.
- Durand, F., D. Shankar, F. Birol, and S.S.C. Shenoi. 2009. Spatiotemporal structure of the East India Coastal Current from satellite altimetry. *Journal of Geophysical Research* 114, C02013, <http://dx.doi.org/10.1029/2008JC004807>.
- Eriksen, C., T. Osse, R. Light, T. Wen, T. Lehman, P. Sabin, J. Ballard, and A. Chiodi. 2001. Seaglider: A long-range autonomous underwater vehicle for oceanographic research. *IEEE Journal of Oceanic Engineering* 26(4):424–436, <http://dx.doi.org/10.1109/48.972073>.
- 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>.
- Jensen, T.G. 2001. Arabian Sea and Bay of Bengal exchange of salt and tracers in an ocean model. *Geophysical Research Letters* 28(20):3,967–3,970, <http://dx.doi.org/10.1029/2001GL013422>.
- Iskandar, I., and M.J. McPhaden. 2011. Dynamics of wind-forced intraseasonal zonal current variations in the equatorial Indian Ocean. *Journal of Geophysical Research* 116, C06019, <http://dx.doi.org/10.1029/2010JC006864>.
- Jinadasa, S.U.P., I. Lozovatsky, J. Planella-Morató, J.D. Nash, J.A. MacKinnon, A.J. Lucas, H.W. Wijesekera, and H.J.S. Fernando. 2016. Ocean turbulence and mixing around Sri Lanka and in adjacent waters of the northern Bay of Bengal. *Oceanography* 29(2):170–179, <http://dx.doi.org/10.5670/oceanog.2016.49>.
- Maximenko, N.A., R. Lumpkin, and L. Centurioni. 2013. Ocean surface circulation. Pp. 283–304 in *Ocean Circulation and Climate*. G. Siedler, S.M. Griffies, J. Gould, and J.A. Church, eds, International Geophysics Series, vol. 103, Academic Press.
- McCreary, J.P., W. Han, D. Shankar, and S.R. Shetye. 1996. Dynamics of the East India Coastal Current: Part 2. Numerical solutions. *Journal of Geophysical Research* 101:13,993–14,010, <http://dx.doi.org/10.1029/96JC00560>.
- Meinen, C.S., and D.R. Watts. 2000. Vertical structure and transport on a transect across the North Atlantic Current near 42°N: Time series and mean. *Journal of Geophysical Research* 105(C9):21,869–21,891, <http://dx.doi.org/10.1029/2000JC900097>.
- Melnichenko, O., P. Hacker, N. Maximenko, G. Lagerloef, and J. Potemra. 2014. Spatial optimal interpolation of *Aquarius* sea surface salinity: Algorithms and implementation in the North Atlantic. *Journal of Atmospheric and Oceanic Technology* 31:1,583–1,600, <http://dx.doi.org/10.1175/JTECH-D-13-00241.1>.
- Murty, V.S.N., Y.V.B. Sarma, D.P. Rao, and C.S. Murty. 1992. Water characteristics, mixing and circulation in the Bay of Bengal during southwest monsoon. *Journal of Marine Research* 50:207–228, <http://dx.doi.org/10.1357/002224092784797700>.
- Nagura, M., and M.J. McPhaden. 2010. Wyrki jet dynamics: Seasonal variability. *Journal of Geophysical Research* 115, C07009, <http://dx.doi.org/10.1029/2009JC005922>.
- Nagura, M., and M.J. McPhaden. 2012. The dynamics of wind-driven intraseasonal variability in the equatorial Indian Ocean. *Journal of Geophysical Research* 117, C02001, <http://dx.doi.org/10.1029/2011JC007405>.
- Niiler, P.P. 2001. The world ocean surface circulation. Pp. 193–204 in *Ocean Circulation and Climate*. G. Siedler, J. Church, and J. Gould, eds, International Geophysics Series, vol. 103, Academic Press.
- O'Brien, J.J., and H.E. Hurlburt. 1974. Equatorial jet in the Indian Ocean: Theory. *Science* 184:1,075–1,077, <http://dx.doi.org/10.1126/science.184.4141.1075>.
- Rao, R.R., M.S. Girish Kumar, M. Ravichandran, B.K. Samala, and N. Sreedevi. 2006. Observed mini-cold pool off the southern tip of India and its intrusion into the south central Bay of Bengal during summer monsoon season. *Geophysical Research Letters* 33, L06607, <http://dx.doi.org/10.1029/2005GL025382>.
- Rao, R.R., R.L. Molinari, and J.F. Festa. 1989. Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean: Part 1. Description of mean monthly mixed layer depth, and sea surface temperature, surface current, and surface meteorological fields. *Journal of Geophysical Research* 94:10,801–10,815, <http://dx.doi.org/10.1029/JC094iC08p10801>.
- Rao, R.R., and R. Sivakumar. 2003. Seasonal variability of sea surface salinity and salt budget of the mixed layer of the north Indian Ocean. *Journal of Geophysical Research* 108(C1):787–809, <http://dx.doi.org/10.1029/2001JC000907>.
- Schott, F.A., and J.P. McCreary. 2001. The monsoon circulation of the Indian Ocean. *Progress in Oceanography* 51(1):1–123, [http://dx.doi.org/10.1016/S0079-6611\(01\)00083-0](http://dx.doi.org/10.1016/S0079-6611(01)00083-0).
- Schott, F., J. Reppin, J. Fischer, and D. Quadfasel. 1994. Currents and transports of the Monsoon Current south of Sri Lanka. *Journal of Geophysical Research* 99(C12):25,127–25,141, <http://dx.doi.org/10.1029/94JC02216>.
- Shankar, D., P.N. Vinayachandran, and A.S. Unnikrishnan. 2002. The monsoon currents in the north Indian Ocean. *Progress in Oceanography* 52(1):63–120, [http://dx.doi.org/10.1016/S0079-6611\(02\)00024-1](http://dx.doi.org/10.1016/S0079-6611(02)00024-1).
- Shetye, S.R., A.D. Gouveia, D. Shankar, S.S.C. Shenoi, P.N. Vinayachandran, D. Sundar, G.S. Michael, and G. Nampoothiri. 1996. Hydrography and circulation in the western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research* 101:14,011–14,025, <http://dx.doi.org/10.1029/95JC03307>.
- Vinayachandran, P.N., P. Chauhan, M. Mohan, and S. Nayak. 2004. Biological response of the sea around Sri Lanka to summer monsoon. *Geophysical Research Letters* 31, L01302, <http://dx.doi.org/10.1029/2003GL018533>.
- Vinayachandran, P.N., T. Kagimoto, Y. Masumoto, P. Chauhan, S.R. Nayak, and T. Yamigata. 2005. Bifurcation of the East India Coastal Current east of Sri Lanka. *Geophysical Research Letters* 32, L15606, <http://dx.doi.org/10.1029/2005GL022864>.
- Vinayachandran, P.N., D. Shankar, S. Vernekar, K.K. Sandeep, P. Amol, C.P. Neema, and A. Chatterjee. 2013. A summer monsoon pump to keep the Bay of Bengal salty. *Geophysical Research Letters* 40:1,777–1,782, <http://dx.doi.org/10.1002/grl.50274>.
- Vinayachandran, P.N., and T. Yamagata. 1998. Monsoon response of sea around Sri Lanka: Generation of thermal domes and anticyclonic vortices. *Journal of Physical Oceanography* 28:1,946–1,960, [http://dx.doi.org/10.1175/1520-0485\(1998\)028<1946:MROSTA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0485(1998)028<1946:MROSTA>2.0.CO;2).
- Wijesekera, H.W., T.G. Jensen, E. Jarosz, W.J. Teague, E.J. Metzger, D.W. Wang, S.U.P. Jinadasa, K. Arulananthan, L.R. Centurioni, and H.J.S. Fernando. 2015. Southern Bay of Bengal currents and salinity intrusions during the northeast monsoon. *Journal of Geophysical Research* 120:6,897–6,913, <http://dx.doi.org/10.1002/2015JC010744>.
- Wijesekera, H.W., E. Shroyer, A. Tandon, M. Ravichandran, D. Sengupta, S.U.P. Jinadasa, H.J.S. Fernando, N. Agarwal, K. Arulananthan, G.S. Bhat, and others. In press. ASIRI: An Ocean-Atmosphere initiative for Bay of Bengal. *Bulletin of the American Meteorological Society*, <http://dx.doi.org/10.1175/BAMS-D-14-00197.1>.
- Wijesekera, H.W., W.J. Teague, E. Jarosz, D.W. Wang, T.G. Jensen, S.U.P. Jinadasa, H.J.S. Fernando, L.R. Centurioni, Z.R. Hallock, E.L. Shroyer, and J.N. Moum. 2016. Observations of currents over the deep southern Bay of Bengal—with a little luck. *Oceanography* 29(2):112–123, <http://dx.doi.org/10.5670/oceanog.2016.44>.
- Wyrtki, K. 1973. An equatorial jet in the Indian Ocean. *Science* 181:262–264, <http://dx.doi.org/10.1126/science.181.4096.262>.

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Northern Arabian Sea Circulation- Autonomous Research (NASCar)

A RESEARCH INITIATIVE BASED ON AUTONOMOUS SENSORS

By Luca R. Centurioni, Verena Hormann, Lynne D. Talley, Isabella Arzeno, Lisa Beal, Michael Caruso, Patrick Conry, Rosalind Echols, Harindra J.S. Fernando, Sarah N. Giddings, Arnold Gordon, Hans Graber, Ramsey R. Harcourt, Steven R. Jayne, Tommy G. Jensen, Craig M. Lee, Pierre F.J. Lermusiaux, Pierre L'Hegaret, Andrew J. Lucas, Amala Mahadevan, Julie L. McClean, Geno Pawlak, Luc Rainville, Stephen C. Riser, Hyodae Seo, Andrey Y. Shcherbina, Eric Skillingstad, Janet Sprintall, Bulusu Subrahmanyam, Eric Terrill, Robert E. Todd, Corinne Trott, Hugo N. Ulloa, and He Wang





ABSTRACT. The Arabian Sea circulation is forced by strong monsoonal winds and is characterized by vigorous seasonally reversing currents, extreme differences in sea surface salinity, localized substantial upwelling, and widespread submesoscale thermohaline structures. Its complicated sea surface temperature patterns are important for the onset and evolution of the Asian monsoon. This article describes a program that aims to elucidate the role of upper-ocean processes and atmospheric feedbacks in setting the sea surface temperature properties of the region. The wide range of spatial and temporal scales and the difficulty of accessing much of the region with ships due to piracy motivated a novel approach based on state-of-the-art autonomous ocean sensors and platforms. The extensive data set that is being collected, combined with numerical models and remote sensing data, confirms the role of planetary waves in the reversal of the Somali Current system. These data also document the fast response of the upper equatorial ocean to monsoon winds through changes in temperature and salinity and the connectivity of the surface currents across the northern Indian Ocean. New observations of thermohaline interleaving structures and mixing in setting the surface temperature properties of the northern Arabian Sea are also discussed.

INTRODUCTION

The Arabian Sea, in the northwestern Indian Ocean, plays a critical role in the Asian monsoon and associated precipitation over the Indian subcontinent. The seasonal monsoonal winds in turn force the seasonally varying circulation in the Arabian Sea (Schott and McCreary, 2001; Trott et al., 2017), but the feedback and adjustment processes between the ocean circulation, sea surface temperature (SST), and the atmosphere are not well understood.

The overarching goal of the Office of Naval Research (ONR)-funded Northern Arabian Sea Circulation-autonomous research (NASCar) initiative is to improve our understanding of the role that western tropical Indian Ocean processes, particularly those in the northern Arabian Sea, play in the onset and evolution of the Indian monsoon. The working hypothesis that connects the observational and modeling components of NASCar is that our limited knowledge of the local air-sea fluxes in the northwestern Indian Ocean limits the skills of models in correctly forecasting the onset and intraseasonal-to-interannual variability of the Asian monsoon, and that such fluxes are influenced by ocean mesoscale

and submesoscale dynamics, planetary waves, and upper-ocean mixing, in addition to important ocean-atmosphere feedbacks (Vecchi et al., 2004).

The hypothesized central role that oceanographic processes in the northern Arabian Sea play in the seasonal modulation of the Asian monsoon is accompanied by the realization that new in situ observations of currents, air-sea interactions, and meso- to submesoscale interior processes are needed to improve our physical understanding and our ability to forecast oceanic and atmospheric conditions in the region.

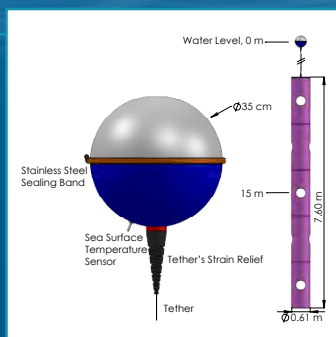
In situ oceanographic observations in the northern Arabian Sea have been difficult to obtain for over two decades because of piracy, with the notable exception of measurements from Global Climate Observing System subarrays such as the Global Drifter Program (GDP), Argo, the High-Resolution Expendable Bathythermograph/Expendable Conductivity-Temperature-Depth (HR XBT/XCTD) network, the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al., 2009), and the developing Indian Ocean Observing System (IndOOS) effort in the northeastern

Arabian Sea. Although the frequency of piracy incidents is declining, the region from the east coast of Africa to the central Arabian Sea (65°E) and from 5°S to 22°N is classified as high risk by the United Kingdom Hydrographic Office, and access by scientific research vessels remains restricted, particularly in the oceanographically critical regions of the Somali Current, the Red Sea, the Persian Gulf outflows, and the Arabian Peninsula upwelling system.

The complexity of the physical processes involved and the need to collect observations on scales ranging from one meter to thousands of kilometers in a region that is difficult to access with oceanographic research ships require a novel approach. The central objectives of the NASCar initiative are to exploit state-of-the-art autonomous instruments (Box 1) to address outstanding scientific questions about oceanographic processes in the northern Arabian Sea, to fill the observational gap accrued over the past two decades, and to demonstrate the maturity of an approach that does not rely on the use of dedicated research vessels and fixed mooring installations.

Several key features differentiate the northern Indian Ocean from the Atlantic and Pacific Oceans and affect the air-sea fluxes of heat and momentum over the basin. The presence of land to the north limits the ocean's poleward transport of heat and upper-ocean ventilation (Schott et al., 2009). Furthermore, the weak zonal component of the equatorial trade winds leads to mean downwelling along the equator (Wang and McPhaden, 2017), which results in high SSTs throughout the tropical Indian Ocean. Another remarkable feature is the drastic difference in sea surface salinity (SSS) across the northern Indian Ocean sub-basins—the Arabian Sea and the Bay of Bengal (Figure 1). In the northern Arabian Sea, evaporation largely exceeds precipitation, while

Box 1. Autonomous NASCar Assets



Surface Lagrangian SVP Drifter

SVP drifters use drogues centered at 15 m depth and are designed to follow the water with an accuracy of 0.01 m s^{-1} for winds up to 10 m s^{-1} . All drifters carry an SST sensor, and many of them also measure atmospheric pressure. Using two-way Iridium satellite communications, the data are available through the Global Telecommunication System in near-real time. They can also be configured to measure surface wind, salinity, and subsurface temperature. Undrogued drifters can measure directional spectral properties of surface waves. See <http://ldl-drifter.org> for more details.



Profiling Floats

Profiling floats (standard Argo floats and the smaller, air-deployable ALAMO floats) use a buoyancy engine to move up and down in the water column. The pump moves oil from an internal reservoir to an external reservoir, changing the volume of the float and hence its density. A CTD on the float measures pressure, temperature, and salinity during its ascent. Profiling floats can be configured for a variety of profiling depths and frequency of cycling missions, and can be reprogrammed via two-way Iridium communication. See Jayne et al. (2017, in this issue), Jayne and Bogue (2017, in this issue), and <http://www.argo.ucsd.edu> for more details.



Underwater Gliders

Three varieties of autonomous underwater gliders (Rudnick, 2016) have been used during NASCar. Seaglid (Eriksen et al., 2001) measured temperature, salinity, and depth-averaged currents over the upper kilometer during missions lasting up to eight months. A Spray glider (Sherman et al., 2001; Rudnick et al., 2016) focused on sampling near the equator during a three-month mission. In addition to a CTD, the Spray glider carried a small acoustic Doppler current profiler (Todd et al., 2017) to measure profiles of horizontal currents near the equator where geostrophic estimates are not possible. A Slocum glider with an externally mounted turbulence package (Wolk et al., 2009; Fer et al., 2014) collected profiles of the dissipation rate of turbulent kinetic energy in the vicinity of the Mascarene Plateau during a month-long mission. All gliders telemetered real-time data via the Iridium network, and raw data are processed after recovery of the gliders.



HR-XBT

XBTs provide temperature profiles from the near surface to about 800 m depth, with drops from ships of opportunity spaced 20–30 km apart on the frequently repeated (~ 7 –10 times per year) transect IX12 from Fremantle, Australia, to the Red Sea. Overall, around 250–350 XBT profiles are available along IX12 in any month of the year. The closely spaced “HR” hydrographic profiles are used to study the time variability of geostrophic transport (0–800 m) of the coastal boundary current system in the Arabian Sea.

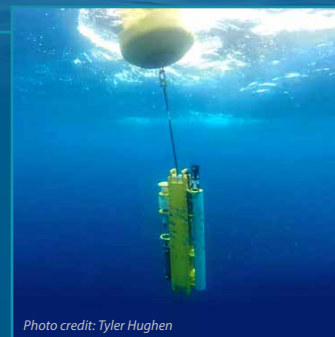


Photo credit: Tyler Hughen

Wirewalker Wave-Powered Profilers

The Wirewalker profiling system uses energy from surface ocean waves to drive a vehicle vertically along a wire. In the case described here, a pair of Wirewalkers was configured to profile temperature, conductivity, and pressure over 120 m and 200 m with a profile return rate of 12 min and 20 min, respectively, and telemeter the data over the Iridium satellite. See Pinkel et al. (2011) for more details.



Miniature Wave Buoys

The Miniature Wave Buoy (MWB) is a compact, inexpensive, easy-to-deploy/recover, oceanographic buoy that uses state-of-the-art GPS technology to measure waves. Significant wave heights up to 16 m and wave frequencies between 1 sec and 20 sec have been reported. MWBs support moored or drifting deployments of up to one year. Sampling rate, types of spectral data reported, and reporting intervals are user configurable. Spectra and sea state data are transmitted via the Iridium satellite network, and are available to users through the MWB website or by email.

the opposite is true in the Bay of Bengal, which is also affected by runoff from major rivers, resulting in SSS differences between the northern Arabian Sea and Bay of Bengal in excess of 5 psu (Gordon et al., 2016).

In the northern Arabian Sea, a strong southwesterly atmospheric jet, known as the Findlater jet (Findlater, 1969), develops during the summer southwest monsoon, with associated strong positive (negative) wind stress curl on its northwest (southeast) side, and induces strong upwelling off the coasts of Somalia and the Arabian Peninsula as well as downwelling to the southwest of the jet. The strong southwest monsoon winds and associated downwelling cause summertime

surface mixed layer deepening in about the same region where wintertime cooling and northeast monsoon winds create a deep mixed layer in winter (Figure 1c), resulting in a unique pattern of semi-annual mixed layer deepening in the northern Arabian Sea.

The northern Arabian Sea circulation and its western boundary current, the Somali Current, are strongly seasonal in response to the monsoon reversal (Schott et al., 2009). The southwest monsoon is associated with the powerful northward Somali Current, along with northward cross-equatorial flow that separates from the coast at about 3°N and 10°N to form the Southern Gyre and Great Whirl, respectively. During the northeast

monsoon, the reversed wind forcing is associated with a weaker southward Somali Current. During the two inter-monsoon periods (i.e., approximately March–April and October–November), westerly equatorial winds result in equatorial ocean convergence and the eastward surface “Wyrтки jets” (Wyrтки, 1973).

Differences of the phasing of the northern Arabian Sea winds and the Somali Current boundary current system show that much remains to be understood about the physics of the seasonal current evolution, which includes remote forcing through planetary waves and cross-equatorial flow of the East African Coastal Current as well as seasonal asymmetry in the strength of the southwest versus the

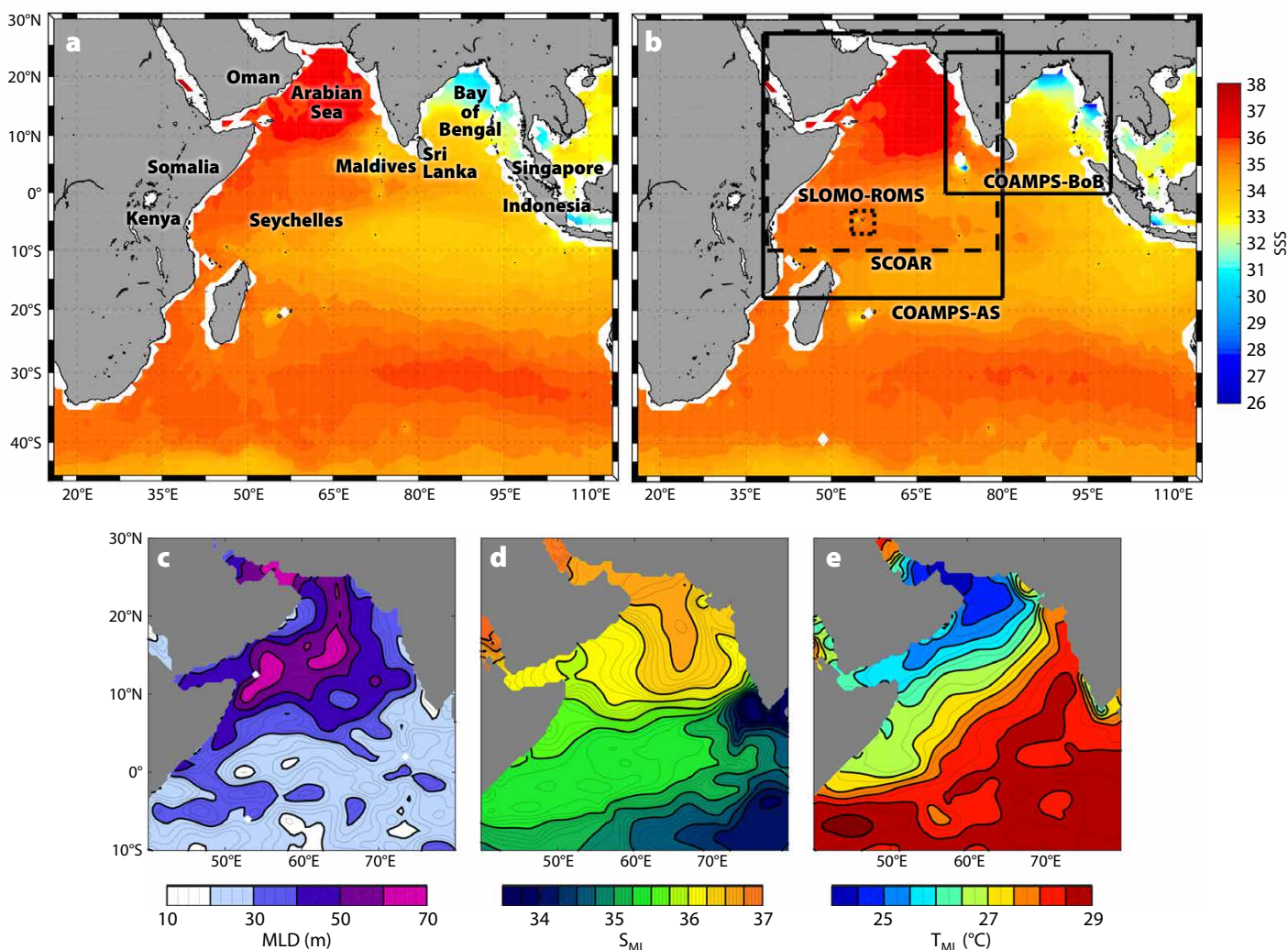


FIGURE 1. Mean remotely sensed sea surface salinity (SSS; 2012–2014) from the Aquarius satellite mission (T. Lee et al., 2012) during the (a) northeast monsoon (January–February), and (b) southwest monsoon (July–August). Several model domains (see Box 2) are superimposed in (b). Climatological mixed layer properties in January from the Argo-based Monthly Isopycnal/Mixed-layer Ocean Climatology (MIMOC; Schmidt et al., 2013). (c) Depth. (d) Salinity. (e) Temperature.

northeast monsoon forcing. Reversal of the Somali Current from its southward northeast monsoon state can occur as early as March, before the onset of the summer monsoon. The early reversal of the Somali Current cannot be explained by westward-propagating, equatorially trapped Rossby waves (Lighthill, 1969; Leetmaa, 1972). Instead, annual downwelling Rossby waves, initiated during the previous southwest monsoon and propagating westward from the tip of India in November, may be responsible for its early reversal (Beal et al., 2013). NASCar is focusing closely on the Somali Current system seasonal evolution through observations and modeling to further refine these descriptions and hypotheses.

The remarkable seasonal changes of the northern Arabian Sea surface circulation cause interbasin exchanges of water masses that lead to interleaving and frontal features. Saline waters from the northwestern Arabian Sea meet the wintertime influx of fresher Bay of Bengal water at a broad salinity front crossing the northern Arabian Sea (Figure 1). There, high SSS destabilizes the stratification, contributing to the semiannual deepest and coolest mixed layers compared with the thinner and warmer mixed layers in the eastern northern Arabian Sea, which are influenced by the fresher, highly stratified Bay of Bengal inflow. Waters of different salinities (but similar densities) interleave vertically and create strong thermohaline stratification of different types, including barrier layers (Lukas and Lindstrom, 1991) and double diffusive layering (e.g., Schmitt, 1994).

In a barrier layer, strong salinity stratification creates a surface mixed layer within a deeper isothermal layer. Persistent barrier layers of about 40 m thickness in the southeastern part of the northern Arabian Sea that are associated with the fresh Bay of Bengal inflow (Figure 1e; de Boyer Montégut et al., 2014) can reduce vertical heat fluxes through the base of the mixed layer, allowing for higher SSTs. A mini warm pool, characterized by high SSTs ($>30^{\circ}\text{C}$), develops through this

mechanism in the southeastern Arabian Sea and is linked to the monsoon onset vortex (Rao and Sivakumar, 1999). In contrast, barrier layers in the central northern Arabian Sea during the southwest monsoon are associated with much deeper mixed layers and weaker overall stratification. These barrier layers are less persistent and likely play a lesser role in atmospheric feedbacks. On the other hand, the “tilting” mechanism (Cronin and McPhaden, 2002), likely responsible for formation of barrier layers in the central Arabian Sea, may also be relevant for water mass subduction and ventilation of intermediate water masses in the basin.

Other thermohaline arrangements, often marked by temperature and salinity inversions, can create conditions for enhanced vertical mixing through double diffusion, a form of convective mixing arising from the differences in molecular diffusivities of heat and salt. Depending on whether the salinity or the temperature stratification is inverted, double diffusion takes the salt-fingering or the thermal-diffusive form. Introduction of high-salinity water through evaporation and nearby marginal sea outflows makes salt fingering more prevalent in the northern Arabian Sea and could facilitate lower SSTs, in contrast to barrier layers that facilitate higher SSTs.

The thermohaline structures of the northern Arabian Sea, the strong upwelling off the coasts of Somalia and Oman (C.M. Lee et al., 2000; Schott et al., 2009), and the swift (in excess of 2 m s^{-1}) northward Somali Current all contribute to modulation of the air-sea fluxes over large parts of the Arabian Sea. This modulation, in turn, affects the atmospheric moisture transport and subsequent changes in precipitation over South Asia and particularly the Indian subcontinent (Izumo et al., 2008), one of the most densely populated regions of the world. Improving the accuracy of marine and atmospheric predictions is therefore important for society as well as for commercial navigation and associated security-at-sea operations in an area of piracy activities.

SCIENTIFIC HYPOTHESIS AND PROGRAM DESIGN

NASCar was designed around three main hypotheses:

Hypothesis 1. The SST anomalies observed along the coast of Somalia, in the Great Whirl region, and off the coast of Oman affect ocean-atmosphere moisture fluxes (Vecchi et al., 2004), which can trigger intraseasonal oscillations of the southwest monsoon.

An accurate determination of the occurrence and strength of these SST anomalies requires advanced understanding of the dynamics of the Somali Current and its variability, connectivity to the interior northern Arabian Sea circulation, and energetics.

Hypothesis 2. Increasing mixed layer temperatures in the northern Arabian Sea trigger the onset of the southwest monsoon in spring.

The rate of warming, and therefore the timing and character of the monsoon, depends on the upper-ocean vertical structure. SSS gradients affect the temperature structure of the upper northern Arabian Sea through horizontal thermohaline filamentation and vertical interleaving driven by mesoscale and sub-mesoscale dynamics. Fresh barrier layers can enhance springtime warming, while mixing them away allows the ocean to cool. In contrast, high salinities in the northwestern Arabian Sea lead to salinity destabilization and widespread double diffusion, enhancing surface cooling or slowing warming.

Hypothesis 3. Kelvin waves generated in the western equatorial region during the intermonsoon periods, and Rossby waves generated at the eastern boundary (Sumatra) and Indian coast, connect the western and eastern basins in the northern Indian Ocean.

Upper-layer current and wind reversals drive interbasin exchanges south of Sri Lanka. The combination of mesoscale activity related to planetary waves

and interbasin exchanges sets water mass properties of the mini warm pool west of India, where strong modulation of the subsequent year's monsoon can occur.

Based on these scientific hypotheses, the northern Indian Ocean has been partitioned into four regions (Figure 2), each targeted with dedicated autonomous assets described in Box 1. The meteorological and modeling (Box 2) components are discussed separately.

Region 1. The Somali Boundary Current System

To address Hypothesis 1, this NASCar component is concerned with collecting observations of the oceanic inter- and intraseasonal variability of the Somali Current region for at least three seasonal cycles. The ultimate goal is to assess the relative importance of local

and remote forcing, to establish how and when the Somali Current connects with the interior Arabian Sea, and to validate the numerical models, which, in turn, are utilized to describe in full the seasonal development of the Somali boundary current system. The main observational tools are Surface Velocity Program (SVP) Lagrangian drifters, Argo and Air-Launched Autonomous Micro-Observer (ALAMO) profiling floats, XBTs, and expendable Wave Buoys. In recent years, the deployment rate of GDP drifters in the Arabian Sea has declined in connection with incidents of piracy. NASCar is relying on regular monthly to biweekly deployments of SVP drifters and on other autonomous assets deployed from Voluntary Observing Ships departing from Mombasa, Kenya. Other deployment opportunities are provided by the US Navy and the US Naval

Oceanographic Office. Wind stress measurements from satellite synthetic aperture radar (SAR) images complement the in situ ocean observations.

Region 2. Interior Dynamics of the Northern Arabian Sea

To address Hypothesis 2 and assess the skill of current-generation numerical models, a focused and coordinated multiplatform Lagrangian drift experiment using drifters, gliders, and floats was conducted to study the structure and dynamics of the upper ocean in the central part of the northern Arabian Sea down to about 200 m depth. A target area (12°N–15°N, 60°E–65°E) with a high concentration of interleaving features and deep mixed layers was identified based on historical data and models. The experiment is described in detail in Box 3.

Region 3. The Equatorial Region and the Mascarene Plateau

This component has been designed to address questions of how large-scale ocean processes interact with the atmospheric surface layer through instabilities, turbulence, and vertical advection/subsidence over different time scales, and how these phenomena couple with upper-ocean mixing processes to drive surface heat, moisture, and momentum fluxes (i.e., addressing Hypotheses 1 and 3). New Global Climate Observing System observations (i.e., Argo and GDP arrays; RAMA moorings at 66°E) are complemented by (1) autonomous underwater gliders with repeated occupations of sections between the Seychelles, Oman, and the Maldives to sample latitudinal and longitudinal contrasts in upper-ocean structures associated with the monsoon forcing, and (2) a pair of rapidly profiling, drifting Wirewalker systems (Pinkel et al., 2011; Lucas et al., 2016) deployed at 1°S, 55.5°E to investigate diurnal cycling in the mixed layer and fine-scale temperature and salinity interleaving in the thermocline along the equator.

Embedded in the equatorial circulation

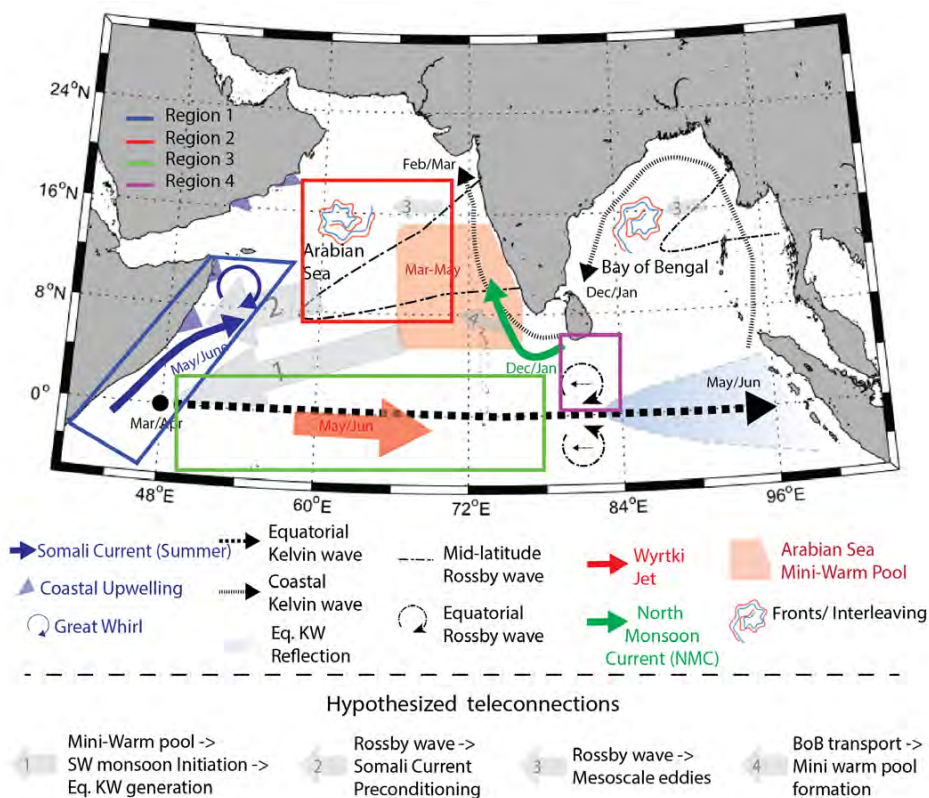


FIGURE 2. Schematic of the processes and hypothesized teleconnections between the Arabian Sea, the Bay of Bengal, and the equatorial Indian Ocean. Physical processes consist of a combination of planetary waves, seasonal-to-subseasonal atmospheric variability, and air-sea interactions that are preconditioned by each region's unique mixed layer, as well as thermohaline and thermocline characteristics. The Northern Arabian Sea Circulation-autonomous research (NASCar) initiative regions referenced in the text are also shown.

and planetary wave regime, the complex and seasonal circulation of the Seychelles, which lie atop the broad, shallow Mascarene Plateau (Figure 3c), represent a significant modeling challenge. The Seychelles Local Ocean Modeling and Observations (SLOMO) component focuses on the development of predictive capabilities of the region. SLOMO, in partnership with the Seychelles, is developing a foundational data set for regional- and local-scale modeling efforts, while providing guidance for the larger-scale

NASCar efforts. Relevant processes include variability in surface waves, currents, stratification, and the seasonal internal wave climate, as well as connection of these processes with the large-scale oceanic circulation. The SLOMO array (i.e., moored acoustic Doppler current profilers, thermistors, CTDs, acoustic Doppler velocimeters, and occasional releases of autonomous CODE-style drifters [Davis, 1985]) were deployed in December 2015 along with vessel-based hydrographic surveys.

Region 4. Northern Arabian Sea/ Bay of Bengal Interbasin Exchanges and Connectivity

Two primary pathways for the export of surface Bay of Bengal freshwater are thought to exist. The indirect path follows the eastern boundary of the Bay of Bengal, spreading southward along the western rim of the Indonesian maritime continent and then turning westward within the tropical latitudes to reach the western margins of the Indian Ocean. The direct, seasonal path follows the



Box 2. NASCar Numerical Modeling

The complex local and remote processes that influence the Arabian Sea circulation challenge a single numerical ocean general circulation model (OGCM) to realistically simulate flows over the broad range of spatial and temporal scales that characterize this basin. The NASCar modeling efforts aim to enhance understanding of physical processes in the Arabian Sea so that reliable ocean forecasts can be developed. A range of ocean model simulations are being used that are strongly eddy-active, forced either by atmospheric reanalysis or fully coupled to an active atmospheric model on both regional and global grids, with some using data assimilation. Figure 1b shows the model domains. A summary of key modeling approaches follows.

Regional Coupled Models

Two regional configurations of the US Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) have been used to provide daily nowcasts since June 2015. COAMPS includes fully coupled atmosphere, ocean, and surface wave submodels that exchange fluxes every 10 minutes as well as tides and assimilated atmospheric and oceanic observations using 3Dvar with a 12-hour update cycle (Jensen et al., 2016). The goal is to study the impact of westward-propagating equatorial waves on eddies, the Somali boundary current system, resulting air-sea interactions and water exchanges between the Arabian Sea and the Bay of Bengal.

The Scripps Coupled Ocean-Atmosphere Regional (SCOAR WRF-ROMS) model (Seo et al., 2014) has been run for the 2001–2010 period (and is being extended to the NASCar period) to examine scale-dependence of air-sea coupling in the Arabian Sea (Seo, in press). Scale separation of the coupling is enabled via an online, two-dimensional LOWESS filter (Seo et al., 2016) that is applied to SST and currents at every coupling interval (six-hour), allowing for a robust assessment of small-scale coupling effects on the circulation of the Arabian Sea. It features a 9 km resolution for both the ocean and the atmosphere, with matching grids and land-sea mask.

Global Ocean Model

A global 0.1° Parallel Ocean Program (POP) simulation, coupled to a sea ice model (CICE), run in the Community Earth System Modeling (CESM) framework, and forced with atmospheric reanalysis for 60 years, is used to understand how the dominant dynamics of the Somali Current system vary spatially along the African coast and with season by constructing full monthly momentum budgets from the archived POP runs. This model is also being used to understand changes in the circulation and

the potential vorticity in the central Arabian Sea. Output from a high-resolution preindustrial climate model simulation using these same 0.1° POP/CICE components in the Accelerated Climate Model for Energy (ACME) v0.1 is used to examine changes in the Somali Current circulation arising from interannual variability associated with large-scale climate modes influencing the circulation of the Arabian Sea.

Regional Ocean Model

The Regional Ocean Modeling System (ROMS) has been set up for the Seychelles with a stretched grid ranging from 1 km around the main islands of the Seychelles to 5 km offshore, with 16 surface-intensified vertical levels, and validated with SLOMO observations. The goal is to investigate the local circulation and water mass properties.

Ensemble Regional Modeling and Optimal Planning System

The MIT Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS; Haley and Lermusiaux, 2010; Haley et al., 2015) was used in real time for February–April 2017, issuing three-day ensemble ocean forecasts daily. MSEAS provided multiresolution downscaling from HYCOM (1/12°) to high-resolution nested and tiled domains, including tidal forcing, implicit two-way nesting, and 50 to 200 member ensembles, from 1/25° to 1/225° resolution. The ocean fields and their uncertainties were input to the MIT Optimal Planning System (NASCar-OPS) to provide forecasts of reachable sets, reachability fronts, and probabilistic paths of gliders and floats (Lermusiaux et al., 2016, 2017, in this issue). MSEAS and NASCar-OPS are used for optimal path planning and to guide persistent ocean sampling with autonomous vehicles as well as to quantify the dynamics and variability of circulation features.

Large Eddy Simulations (LES)

Vertical turbulent mixing processes that govern SST on hourly to weekly time scales are investigated with LES and turbulence closure modeling, coupled through model-data comparison. LES has column model geometry and horizontal domains of several hundred meters to resolve mixed layer turbulence in diurnal cycling down to orders of 1 m in long-time simulations. Of particular interest are forcing input from surface waves and the balance between surface evaporation and the horizontal divergence of salinity fluxes carried by laterally mixing submesoscale ocean processes.

western boundary of the Bay of Bengal around the southern tip of Sri Lanka and directly into the Arabian Sea. This NASCar component, focused on inter-basin exchange, relates to Hypotheses 2 and 3 and seeks to understand the relative importance of the two pathways. The Bay of Bengal freshwater reaching into the western tropical Indian Ocean eventually spreads into the western Arabian Sea, primarily in boreal summer. Salt input from the Arabian Sea to the Bay of Bengal passes along the southern tip

of Sri Lanka within the thermocline, mostly in the 50–150 m depth range (e.g., Wijesekera et al., 2015). Recent observations point to the existence of a seasonally reversing undercurrent east of Sri Lanka (Arachaporn Anutaliya, Scripps Institution of Oceanography, *pers. comm.*, 2017) that could provide a means of salt exchange between the Bay of Bengal and the Arabian Sea.

NASCar augments the existing Global Climate Observing System network with autonomous sampling by drifters, gliders,

floats, Pressure Inverted Echo Sounders (PIES), and drifting profilers. Multiyear occupation of a transect along 80.5°E between the southern tip of Sri Lanka and 2°N has been maintained by Seagliders at 20-day intervals and a pair of PIES near the ends of the transect.

To address the inherent challenges of comparing in situ observations and model output, NASCar also includes a Lagrangian particle tracking approach (Döös et al., 2013), where virtual particles are seeded offline in simulated

Box 3. NASCar Coordinated Multi-Platform Lagrangian Drift

Vertical interleaving, frontal subduction, and barrier layer formation are difficult to observe within a strong mesoscale eddy field (Shcherbina et al., 2015). Adopting a Lagrangian frame of reference in the near surface nullifies mesoscale advection and permits detailed investigations of the structure and evolution of small-scale features (Shcherbina et al., 2009).

An array consisting of 10 SVP barometer (SVPB) drifters, two Seagliders, five ALAMO floats, and 12 APEX floats was deployed in the northern Arabian Sea along a 1,300 km line crossing the target area from northwest to southeast (Figure 1c) from a ship of opportunity (US Naval Oceanographic Office) during the 2017 intermonsoon season.

Two ALAMO floats, rapidly profiling between 0 m and 300 m depth, provided a Lagrangian frame of reference (mixed layer and upper pycnocline) every two hours. Remarkably, the floats stayed within a few kilometers of each other throughout their 50-day, 325 km drift (Figure B3-1). See online supplemental material for an animation of their tracks.

Two Seagliders, profiling to 1,000 m every four to five hours, followed the target floats; they navigated a 20 km × 20 km “bowtie” pattern in the Lagrangian reference frame and provided a synoptic three-dimensional

context for the high-resolution float measurements. The navigation was handled by an automated system that ingested real-time asset locations, made a statistical forecast of the reference frame translation, transformed the survey pattern from the Lagrangian reference frame to geographic coordinates, and transmitted the navigation information to the gliders. The forecasts were fairly accurate (Figure B3-1), owing to rather simple and predictable mesoscale advection and weak wind forcing during this particular deployment.

To assist the ALAMO floats and Seaglider operations, the future float positions and the glider reachability sets were forecasted daily (see http://mseas.mit.edu/Sea_exercises/NASCar-OPS-17). To account for uncertainties, ensemble forecasts (Lermusiaux, 2007) were issued and the dynamic probability of float positions and of reachable points for the gliders were computed in real time (Lermusiaux et al., 2017, in this issue). The overall Lagrangian reachability planning system showed predictive skills for long periods of time. The skill was mostly governed and limited by the accuracy of the larger mesoscale field.

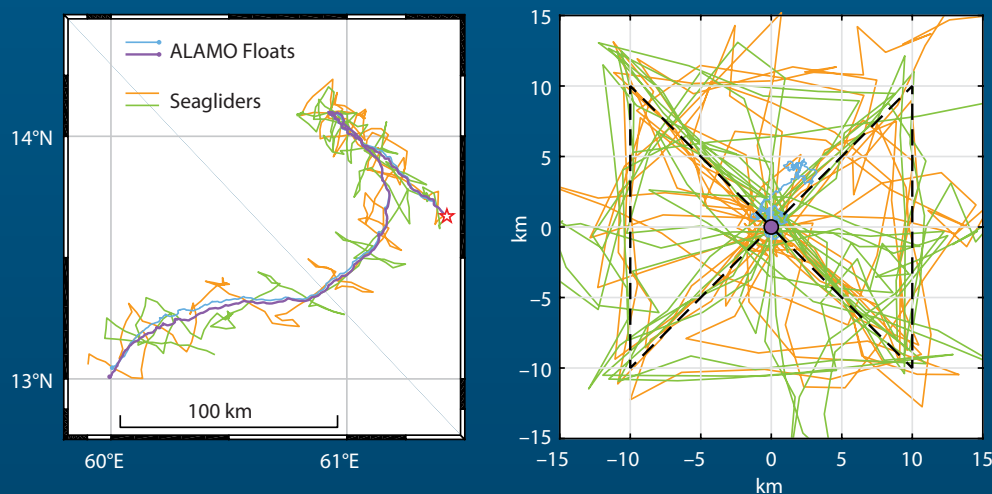


FIGURE B3-1. Trajectories of the ALAMO floats and the Seagliders during the coordinated Lagrangian drift (March 4–April 23, 2017) in geographic coordinates (left) and in the Lagrangian reference frame (right) following the ALAMO floats.

velocity fields generated by the global HYbrid Coordinate Ocean Model (HYCOM) with 1/12° spatial and daily temporal resolutions.

Meteorological Component

In addition to the SAR measurements in the Somali Current region, multiple daily radio soundings, a meteorological flux tower, and remote sensors (i.e., scanning Doppler LiDAR, microwave radiometer, and ceilometer) were deployed in the southern Arabian Sea (Seychelles), the western Bay of Bengal (Sri Lanka), and the eastern equatorial Indian Ocean (Singapore) between February 1 and March 15, 2015, with the goal of resolving intraseasonal (i.e., 10–45 day) and faster oscillations. These observations will aid in understanding the spatial extent and implications for SST of anomalous (downward) air-sea heat fluxes (Bhat and Fernando, 2016) in the northern Arabian Sea under high-wind conditions, and they will also provide valuable data for the validation of the numerical models used in NASCar (Box 2).

NASCar PRELIMINARY FINDINGS

NASCar's autonomous data collection and modeling are currently underway (Figure 3). Some early results are described here.

Region 1. The Somali Boundary Current System

The northern Arabian Sea boundary current system, including the Somali Current, varies greatly with latitude. Sea level anomaly observations reveal that the mean width of the boundary current system decreases from about 300 km at 17°N at the coast of Oman to 60 km at the Somali coastline near 4°N. Ongoing drifter releases targeting the Somali boundary current system will define the spatial structure of the surface flow and the timing of the seasonal reversal of the surface flow.

The Somali Current between the equator and 10°N is dynamically divided into three regions: equatorial, central, and northern. Models (i.e., eddy-active ocean general circulation models) suggest that the reversal processes and timing vary

with regions. The flow in the northern part (6°N–10°N) is the first to reverse from equatorward to poleward during early boreal spring, due to the arrival of a downwelling Rossby wave propagating from the tip of India, and may reverse even earlier than this due to northward shear persisting from the previous season. South of about 2°N, the flow also reverses earlier than the local wind, whereas it closely matches the timing of the wind reversal in the central region between 2°N and 6°N. HR-XBT temperature profiles are revealing new fine-scale subsurface currents near the Somali coast. The precursor of the strong northward Somali Current observed in April has a significant subsurface southward countercurrent at depth. Model results also show a system of strong seasonal subsurface countercurrents, depending on their Somali Current region.

Regional coupled models indicate that currents and SSTs in the western part of the northern Arabian Sea are dynamically coupled to the atmosphere at distinct spatial scales (Seo et al., 2008; Seo,

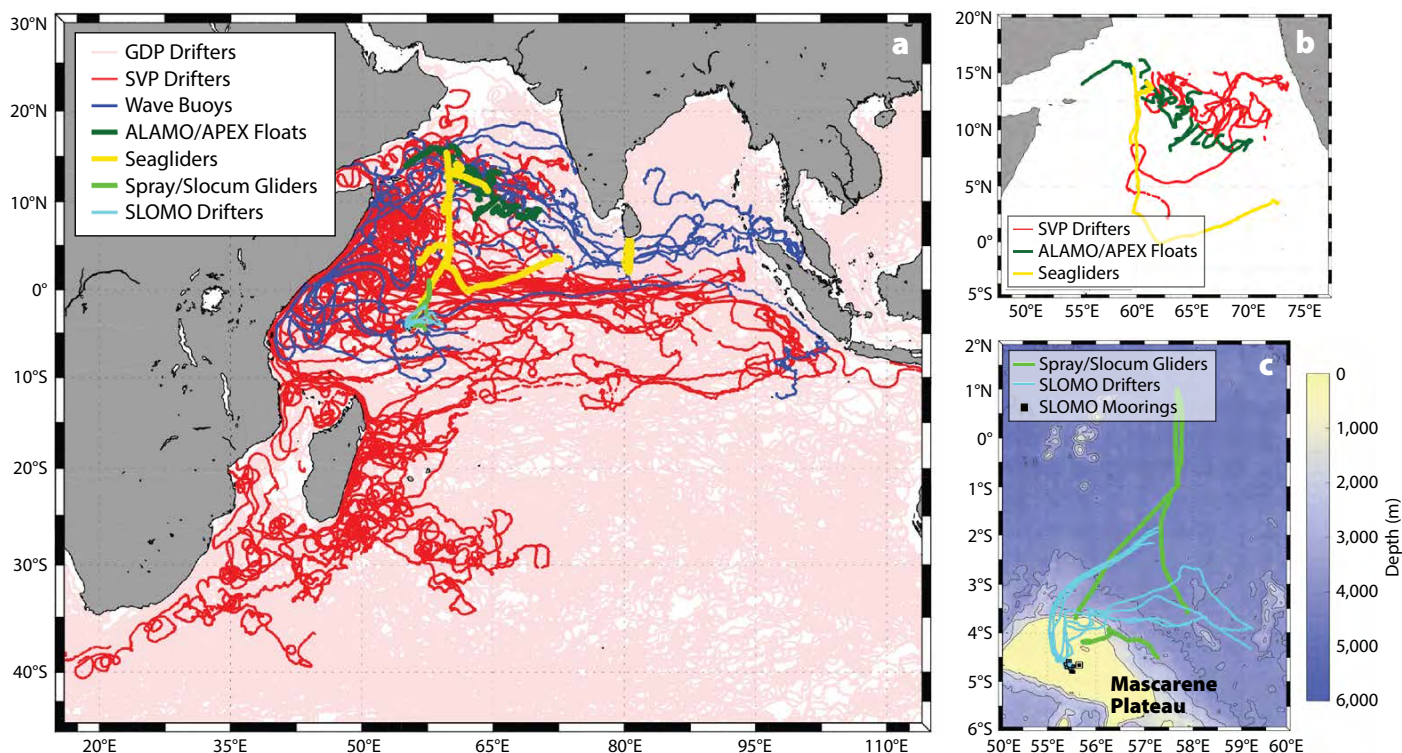


FIGURE 3. (a) Tracks and locations of NASCar autonomous assets. Details are shown of (b) the coordinated multi-platform Lagrangian drift (Region 2, and Box 3), and (c) Seychelles Local Ocean Modeling and Observations (SLOMO; Region 3).

in press). SST-wind coupling is strong on the oceanic mesoscale, affecting the position of the Great Whirl and the separation latitude of the Somali Current, while current-wind coupling attenuates the monsoon circulation and eddy activity. Furthermore, the moisture transport by the Findlater Jet is enhanced due to the current-wind coupling, suggesting that the current-induced air-sea interaction is important for simulation and prediction of monsoon rainfall over India. In situ surface current data from surface drifters will help to constrain the energetics of the surface flow to realistic estimates.

Further evidence of strong regional ocean-atmosphere coupling is provided by wind stress curl computed from the SAR data (Horstmann and Koch, 2005; Hersbach, 2010), showing strong positive curl associated with SST fronts. Bands of positive and negative wind stress curl, indicating organized large atmospheric eddies that arise from turbulent processes associated with a moderately unstable marine planetary boundary layer and aligned with the monsoon jet, occur over the southeastern part of the Somali Current region.

Region 2. Interior Dynamics of the Northern Arabian Sea (“Mixing Processes”)

The coordinated multi-platform Lagrangian drift experiment (Box 3) has revealed rich, vertical thermohaline interleaving structures in the upper 200 m. The numerous persistent thin layers support the strong tendency for salt fingering in the transition zone underlying the well-mixed surface layer. The observed fine-scale thermohaline structures suggest double-diffusive mixing, with uniform thermohaline gradients beneath warm, salty intrusions, and nearly isothermal haloclines above them (Figure 4). To support the Lagrangian experiment, multi-resolution ensemble ocean simulations (Lermusiaux, 2007; Haley et al., 2015) downscaled from HYCOM were run in real time. Forecasts showed that high-resolution (e.g., $1/75^\circ$ in the horizontal

with 70 or more optimized levels) were needed to develop and maintain such layered features.

On the larger scale, historical Argo data indicate salt-fingering-favorable conditions throughout the northwestern part of the northern Arabian Sea, both at the base of the saline surface layer and below, with the exception of the fresh Bay of Bengal inflow region. A quantitative index of active salt fingering, computed from historical Argo data and preliminary NASCar observations, shows that the layers are poised just below the critical value, with random, scattered forays into strong salt fingering, suggesting double diffusion is influencing vertical stratification.

Near the surface, preliminary results from Large Eddy Simulations (LES) of northern Arabian Sea diurnal cycling do not strongly support a significant role for wave breaking in setting near-surface vertical temperature gradients. Instead, it was found that including Langmuir turbulence in the LES accounts for most of the observed near-surface mixing attributable to waves. NASCar will elucidate the relative importance of turbulent mixing processes that set the regional SST properties.

Region 3. The Equatorial Region and the Mascarene Plateau

Observations from four glider surveys across the equator between 57.5°E and 62°E provide new insights into the seasonal evolution that occurs near the

equator (Figure 5). Water mass properties within 1° of the equator varied significantly during the eight-month period from August 2016 to May 2017, particularly shallower than the 26.0 kg m^{-3} isopycnal ($\sim 150 \text{ m}$, Figure 5a–i). A well-developed mixed layer with a thickness of about 50 m was present near the end of the southwest monsoon when the freshest near-surface waters were observed (Figure 5a,e,i). By January 2017, near-surface waters had become cooler and saltier, resulting in a surface density increase of nearly 1 kg m^{-3} and shoaling of the 24.0 kg m^{-3} isopycnal by about 50 m (Figure 5b,f,i).

During boreal spring, near-surface warming led to the warmest observed waters ($>30^\circ\text{C}$ by May 2017; Figure 5c,d,i). The saltiest waters observed within 1° of the equator were found at 50–100 m depth in April 2017 (Figure 5g,i). This salty layer thickened and spread southward in May 2017 (Figure 5h). The back-to-back transects across the equator between March and May 2017 highlight how quickly water mass properties can change as the southwest monsoon sets in. The density of the subsurface salinity maximum near 0.5°N decreased by 1 kg m^{-3} in 11 days (Figure 5i), while the high-salinity layer spread southward and upward between the two transects (Figure 5g,h). Absolute velocity profiles from the Spray glider (Todd et al., 2017) captured the shift in the equatorial circulation coincident with the abrupt shift

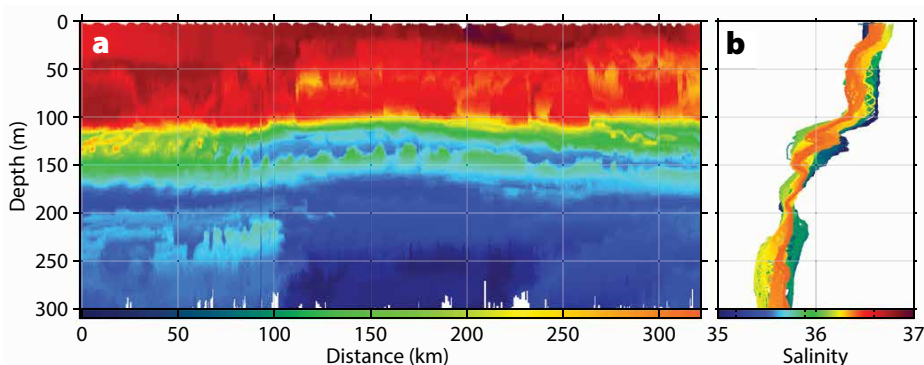


FIGURE 4. Salinity observations from an ALAMO float deployed during the coordinated multi-platform Lagrangian experiment reveal fine-scale interleaving of water masses. (a) Salinity profiles are shown along the track of the float, and (b) individual salinity profiles are color-coded by along-track distance.

in water mass properties during March–May 2017. The Equatorial Undercurrent, which carried high-salinity waters eastward, weakened from April to May. At the surface, currents south of the equator switched from westward to eastward, presumably as a Wyrtki jet developed.

The 2016 SLOMO observations highlight strong seasonal currents on the Mascarene Plateau, with variability dominated by near-inertial currents and not by tides, which are only a weak influence. The stratification varies semi-annually, as does the low-pass filtered

sea surface height. It is hypothesized that these semi-annual signals are tied to the monsoonal changes in the equatorial circulation. Local processes, such as high-frequency internal waves, are likely modulated by the monsoons with remote processes driving the stratification. CODE

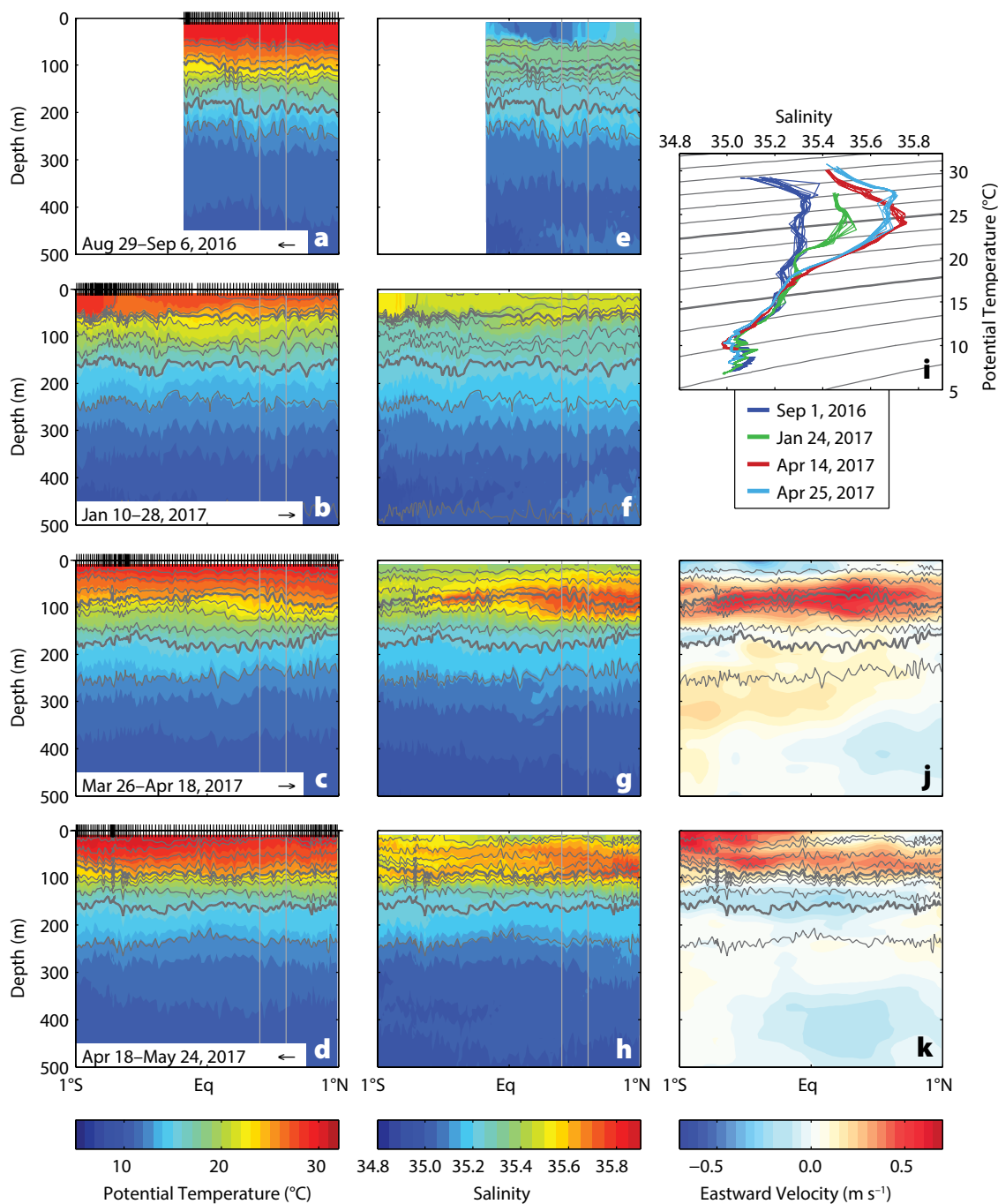


FIGURE 5. Equatorial observations collected by NASCar gliders. Transects of (a–d) potential temperature and (e–h) salinity in the upper 500 m are shown for four successive equator crossings, with dates and directions of glider transits denoted in a–d. (i) Potential temperature–salinity curves between 0.4°N and 0.6°N (vertical gray lines in a–h) from each glider transect with approximate dates indicated. (j–k) Eastward velocity measured by the Spray glider. In all panels, contours of potential density are drawn every 0.5 kg m⁻³ with the 24.0 kg m⁻³ and 26.0 kg m⁻³ isopycnals marked bold. Locations of individual profiles are denoted by tick marks at the top of panels a–d.

drifters released at the Seychelles further demonstrate connectivity between the plateau and the equatorial currents of the order of days (Figure 3c).

Region 4. Northern Arabian Sea/ Bay of Bengal Interbasin Exchanges and Connectivity

Exchanges and connectivity between the Arabian Sea and Bay of Bengal are being analyzed observationally using Argo floats, drifters, gliders, remote sensing of surface salinity and winds, moored arrays south of Sri Lanka, and in models using Lagrangian particle tracking. The observations show the spread of fresh Bay of Bengal waters along the two pathways into the Arabian Sea, as described in the program design section above.

Monthly releases of virtual surface drifters in near-surface velocity fields from HYCOM and advected for two years (2013–2015) suggest residence times for the Bay of Bengal and the northern Arabian Sea waters of about one month during boreal summer. Some of the exported waters return to the release regions in fall, and the sustained residence times based on the annual cycle are closer to a year. Waters originating in the Bay of Bengal reach the northern Arabian Sea between January and May in the year after seeding, whereas waters from the 2013 northern Arabian Sea release reached the Bay of Bengal from September 2013 to March 2014. In both cases, the drifter trajectories varied strongly with the timing of their release, thus confirming the importance of seasonal variability in the regional ocean circulation.

The connectivity between the Somali Current and the interior Arabian Sea, the tropical gyre south of the equator, and the Bay of Bengal is also studied with simulated surface drifter trajectories using the Lagrangian Tool Connectivity Modeling System (Paris et al., 2013) and monthly near-surface velocity fields from historical GDP data (Laurindo et al., 2017). A preliminary analysis of the simulations suggests little connectivity between the Somali Current

and the interior circulation (cf. Figure 3a) and confirms the occurrence of two distinct cross-equatorial gyres (see Schott and McCreary, 2001, or Schott et al., 2009, for schematics of the monsoon circulation). The first gyre results from surface waters branching eastward at about 3°N after crossing the equator in April and May and feeding into the South Equatorial Countercurrent, which is also reflected in the drifter trajectories shown in Figure 3a. Subsequently, these waters are driven southward by local winds and return to the western boundary via the South Equatorial Current after about one year. The second gyre results from surface waters crossing the equator from April to August and continuing north to feed into the Somali Current and the Great Whirl. From June to October, these waters flow southeastward and into the Bay of Bengal along the equator, recirculating via the North Monsoon Current. Eventually, the southwest monsoon drives these waters southward back across the equator. The return path to the western boundary is similar to that for the first gyre, with the whole circulation taking about two years.

SUMMARY

The NASCar initiative investigates complex oceanographic processes that contribute to the modulation of air-sea fluxes in the northern Arabian Sea and the associated impacts on the monsoon evolution and feedbacks. The observational program covers a wide range of spatial and temporal scales with in situ observations from autonomous instruments, and operates in an area where in situ observations have been sparse for the past two decades due to piracy concerns. NASCar is rapidly filling this notable data gap with a multi-pronged approach that merges autonomous ocean observations with ocean and coupled climate models, conceptual models, remote sensing, and meteorological observations. Optimal Planning Systems (Box 2) are used to assist the deployment and recovery of several autonomous assets and were also used for planning and guiding the coordinated Lagrangian

drift (Box 3; Lermusiaux et al., 2017, in this issue). Such an approach is becoming increasingly important as the use of autonomous platforms gains traction as a powerful and comprehensive alternative, as discussed here, to more traditional ship-based research programs. International collaborations and the use of Voluntary Observing Ships for deployments are key elements for maintaining multiyear time series at both basin and global scales. NASCar benefits from the decades of experience of programs such as the GDP that developed a global network of international partners based on the collaboration between oceanographers and meteorologists (Niiler, 2001; Centurioni et al., 2017) under the Data Buoy Cooperation Panel of the World Meteorological Organization as well as on the established tradition of international collaborations that are central to the success of several ONR programs.

Early results support the efficacy of the novel NASCar approach. For instance, the observations of thermohaline interleaving in the northern Arabian Sea are providing new insights into the importance of barrier layers and double diffusion in setting the vertical stratification and in influencing SST. Sustained glider and float measurements in the region will further elucidate the role of barrier layers and lateral mesoscale stirring/advection in creating SST anomalies.

Interbasin glider, wave buoy, and Wirewalker observations are complemented by larger-scale drifter and float data as well as remote-sensing products to establish a new baseline for elucidating the role of ocean-atmosphere processes in modulating and pre-conditioning the reversing monsoon circulation of the Arabian Sea and of the equatorial region, and for determining how mesoscale SST properties and energetics affect regional air-sea fluxes. Various numerical models will not only allow for a detailed and validated assessment of small-scale coupling in the circulation of the Arabian Sea and air-sea flux modulation but will also provide a detailed dynamical view

of the regional circulation that cannot be fully resolved by the NASCAR observations alone. A joint analysis of models and observations will thus be central to enhancing forecasting skills for this complicated region. 

SUPPLEMENTAL MATERIALS

YouTube video of coordinated drift during the NASCAR experiment can be viewed at <https://youtu.be/WveJDHaIS3g>.

REFERENCES

- Beal, L.M., V. Hormann, R. Lumpkin, and G.R. Foltz. 2013. The response of the surface circulation of the Arabian Sea to monsoonal forcing. *Journal of Physical Oceanography* 43(9):2,008–2,022, <https://doi.org/10.1175/JPO-D-13-0331>.
- Bhat, G., and H.J. Fernando. 2016. Remotely driven anomalous sea-air heat flux over the North Indian Ocean during the summer monsoon season. *Oceanography* 29(2):232–241, <https://doi.org/10.5670/oceanog.2016.55>.
- Centurioni, L., A. Horányi, C. Cardinali, E. Charpentier, and R. Lumpkin. 2017. A global ocean observing system for measuring sea level atmospheric pressure: Effects and impacts on numerical weather prediction. *Bulletin of the American Meteorological Society* 98(2):231–238, <https://doi.org/10.1175/bams-d-15-00080.1>.
- Cronin, M.F., and M.J. McPhaden. 2002. Barrier layer formation during westerly wind bursts. *Journal of Geophysical Research* 107(C12), 8020, <https://doi.org/10.1029/2001JC001171>.
- Davis, R.E. 1985. Drifter observations of coastal surface currents during CODE: The method and descriptive view. *Journal of Geophysical Research* 90(C3):4,741–4,755, <https://doi.org/10.1029/JC090iC03p04741>.
- de Boyer Montégut, C., F. Durand, R. Bourdallé-Badie, and B. Blanke. 2014. Role of fronts in the formation of Arabian Sea barrier layers during summer monsoon. *Ocean Dynamics* 64(6):809–822, <https://doi.org/10.1007/s10236-014-0716-7>.
- Döös, K., J. Kjellsson, and B. Jönsson. 2013. TRACMASS: A Lagrangian trajectory model. Pp. 225–249 in *Preventive Methods for Coastal Protection*. T. Soomere and E. Quak, eds, Springer, Heidelberg.
- Eriksen, C.C., T.J. Osse, R.D. Light, T. Wen, T.W. Lehman, P.L. Sabin, J.W. Ballard, and A.M. Chiodi. 2001. Seaglider: A long-range autonomous underwater vehicle for oceanographic research. *IEEE Journal of Oceanic Engineering* 26(4):424–436, <https://doi.org/10.1109/48.972073>.
- Fer, I., A.K. Peterson, and J.E. Ullgren. 2014. Microstructure measurements from an underwater glider in the turbulent Faroe Bank Channel overflow. *Journal of Atmospheric and Oceanic Technology* 31:1,128–1,150, <https://doi.org/10.1175/JTECH-D-13-00221.1>.
- Findlater, J. 1969. A major low-level air current near the Indian Ocean during the northern summer. *Quarterly Journal of the Royal Meteorological Society* 95(404):362–380, <https://doi.org/10.1002/qj.49709540409>.
- Gordon, A.L., E.L. Shroyer, A. Mahadevan, D. Sengupta, and M. Freilich. 2016. Bay of Bengal: 2013 northeast monsoon upper-ocean circulation. *Oceanography* 29(2):82–91, <https://doi.org/10.5670/oceanog.2016.41>.
- Haley, P.J., A. Agarwal, and P.F.J. Lermusiaux. 2015. Optimizing velocities and transports for complex coastal regions and archipelagos. *Ocean Modelling* 89:1–28, <https://doi.org/10.1016/j.ocemod.2015.02.005>.
- Haley, P.J., and P.F.J. Lermusiaux. 2010. Multiscale two-way embedding schemes for free-surface primitive equations in the “Multidisciplinary Simulation, Estimation and Assimilation System.” *Ocean Dynamics* 60(6):1,497–1,537, <https://doi.org/10.1007/s10236-010-0349-4>.
- Hersbach, H. 2010. Comparison of C-band scatterometer CMOD5.N equivalent neutral winds with ECMWF. *Journal of Atmospheric and Oceanic Technology* 27(4):721–736, <https://doi.org/10.1175/2009JTECH0698.1>.
- Horstmann, J., and W. Koch. 2005. Measurement of ocean surface winds using synthetic aperture radars. *IEEE Journal of Oceanic Engineering* 30(3):508–515, <https://doi.org/10.1109/JOE.2005.857514>.
- Izumo, T., C. de Boyer Montégut, J.-J. Luo, S.K. Behera, S. Masson, and T. Yamagata. 2008. The role of the western Arabian Sea upwelling in Indian monsoon rainfall variability. *Journal of Climate* 21(21):5,603–5,623, <https://doi.org/10.1175/2008jcli2158.1>.
- Jayne, S.R., and N.M. Bogue. 2017. Air-deployable profiling floats. *Oceanography* 30(2):29–31, <https://doi.org/10.5670/oceanog.2017.214>.
- Jayne, S.R., D. Roemmich, N. Zilberman, S.C. Riser, K.S. Johnson, G.C. Johnson, and S.R. Piotrowicz. 2017. The Argo Program: Present and future. *Oceanography* 30(2):18–28, <https://doi.org/10.5670/oceanog.2017.213>.
- Jensen, T.G., H.W. Wijesekera, E.S. Nyadjro, P.G. Thoppil, J.F. Shriver, K. Sandeep, and V. Pant. 2016. Modeling salinity exchanges between the equatorial Indian Ocean and the Bay of Bengal. *Oceanography* 29(2):92–101, <https://doi.org/10.5670/oceanog.2016.42>.
- Laurindo, L.C., A.J. Mariano, and R. Lumpkin. 2017. An improved near-surface velocity climatology for the global ocean from drifter observations. *Deep Sea Research Part I* 124:73–92, <https://doi.org/10.1016/j.dsr.2017.04.009>.
- Lee, C.M., B.H. Jones, K.H. Brink, and A.S. Fischer. 2000. The upper-ocean response to monsoonal forcing in the Arabian Sea: Seasonal and spatial variability. *Deep Sea Research Part II* 47(7–8):1,177–1,226, [https://doi.org/10.1016/S0967-0645\(99\)00141-1](https://doi.org/10.1016/S0967-0645(99)00141-1).
- Lee, T., G. Lagerloef, M.M. Gierach, H.Y. Kao, S. Yueh, and K. Dohan. 2012. Aquarius reveals salinity structure of tropical instability waves. *Geophysical Research Letters* 39, L12610, <https://doi.org/10.1029/2012GL052232>.
- Leetmaa, A. 1972. The response of the Somali Current to the southwest monsoon of 1970. *Deep Sea Research and Oceanographic Abstracts* 19:319–325, [https://doi.org/10.1016/0011-7471\(72\)90025-3](https://doi.org/10.1016/0011-7471(72)90025-3).
- Lermusiaux, P.F.J. 2007. Adaptive modeling, adaptive data assimilation and adaptive sampling. *Physica D: Nonlinear Phenomena* 230(1):172–196, <https://doi.org/10.1016/j.physd.2007.02.014>.
- Lermusiaux, P.F.J., P.J. Haley Jr., S. Jana, A. Gupta, C.S. Kulkarni, C. Mirabito, W.H. Ali, D.N. Subramani, A. Dutt, J. Lin, and others. 2017. Optimal planning and sampling predictions for autonomous and Lagrangian platforms and sensors in the northern Arabian Sea. *Oceanography* 30(2):172–185, <https://doi.org/10.5670/oceanog.2017.242>.
- Lermusiaux, P.F.J., T. Lolla, P.J. Haley Jr., K. Yigit, M.P. Ueckermann, T. Sondergaard, and W.G. Leslie. 2016. Science of autonomy: Time-optimal path planning and adaptive sampling for swarms of ocean vehicles. Pp. 481–498 in *Springer Handbook of Ocean Engineering*. M.R. Dhanak and N.I. Xiros, eds, Springer International Publishing.
- Lighthill, M.J. 1969. Dynamic response of the Indian Ocean to onset of the southwest monsoon. *Philosophical Transactions of the Royal Society of London A* 265(1159):45–92, <https://doi.org/10.1098/rsta.1969.0040>.
- Lucas, A.J., J.D. Nash, R. Pinkel, J.A. MacKinnon, A. Tandon, A. Mahadevan, M.M. Omand, M. Freilich, D. Sengupta, and M. Ravichandran. 2016. Adrift upon a salinity-stratified sea: A view of upper-ocean processes in the Bay of Bengal during the southwest monsoon. *Oceanography* 29(2):134–145, <https://doi.org/10.5670/oceanog.2016.46>.
- Lukas, R., and E. Lindstrom. 1991. The mixed layer of the western equatorial Pacific Ocean. *Journal of Geophysical Research* 96(S01):3,343–3,357, <https://doi.org/10.1029/90JC01951>.
- McPhaden, M.J., G. Meyers, K. Ando, Y. Masumoto, V.S.N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, and W. Yu. 2009. RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bulletin of the American Meteorological Society* 90(4):459–480, <https://doi.org/10.1175/2008BAMS2608.1>.
- Niiler, P.P. 2001. The world ocean surface circulation. Pp. 193–204 in *Ocean Circulation and Climate*. G. Sieglar, J. Church and J. Gould, eds, Academic Press.
- Paris, C.B., J. Helgers, E. Van Sebille, and A. Srinivasan. 2013. Connectivity Modeling System: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. *Environmental Modelling & Software* 42:47–54, <https://doi.org/10.1016/j.envsoft.2012.12.006>.
- Pinkel, R., M.A. Goldin, J.A. Smith, O.M. Sun, A.A. Aja, M.N. Bui, and T. Hughen. 2011. The Wirewalker: A vertically profiling instrument carrier powered by ocean waves. *Journal of Atmospheric and Oceanic Technology* 28:426–435, <https://doi.org/10.1175/2010JTECH0805.1>.
- Rao, R.R., and R. Sivakumar. 1999. On the possible mechanisms of the evolution of a mini-warm pool during the pre-summer monsoon season and the genesis of onset vortex in the South-Eastern Arabian Sea. *Quarterly Journal of the Royal Meteorological Society* 125(555):787–809, <https://doi.org/10.1002/qj.49712555503>.
- Rudnick, D.L. 2016. Ocean research enabled by underwater gliders. *Annual Reviews of Marine Science* 8:519–541, <https://doi.org/10.1146/annurev-marine-122414-033913>.
- Rudnick, D.L., R.E. Davis, and J.T. Sherman. 2016. Spray underwater glider operations. *Journal of Atmospheric and Oceanic Technology* 33:1,113–1,122, <https://doi.org/10.1175/jtech-d-15-02521>.
- Schmidtko, S., G.C. Johnson, and J.M. Lyman. 2013. MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers. *Journal of Geophysical Research* 118(4):1,658–1,672, <https://doi.org/10.1002/jgrc.20122>.
- Schmitt, R.W. 1994. Double diffusion in oceanography. *Annual Review of Fluid Mechanics* 26(1):255–285, <https://doi.org/10.1146/annurev.fl.26.010194.001351>.
- Schott, F.A., and J.P. McCreary. 2001. The monsoon circulation of the Indian Ocean. *Progress in Oceanography* 51(1):1–123, [https://doi.org/10.1016/S0079-6611\(01\)00083-0](https://doi.org/10.1016/S0079-6611(01)00083-0).
- Schott, F.A., S.-P. Xie, and J.P. McCreary Jr. 2009. Indian Ocean circulation and climate variability. *Reviews of Geophysics* 47(1), RG1002, <https://doi.org/10.1029/2007rg000245>.

- Seo, H. In press. Distinct influence of air-sea interactions mediated by mesoscale sea surface temperature and surface current in the Arabian Sea. *Journal of Climate*, <https://doi.org/10.1175/jcli-d-16-0834.1>.
- Seo, H., A.J. Miller, and J.R. Norris. 2016. Eddy-wind interaction in the California Current System: Dynamics and impacts. *Journal of Physical Oceanography* 46(2):439–459, <https://doi.org/10.1175/JPO-D-15-0086.1>.
- Seo, H., R. Murtugudde, M. Jochum, and A.J. Miller. 2008. Modeling of mesoscale coupled ocean-atmosphere interaction and its feedback to ocean in the western Arabian Sea. *Ocean Modelling* 25:120–131, <https://doi.org/10.1016/j.ocemod.2008.07.003>.
- Seo, H., A.C. Subramanian, A.J. Miller, and N.R. Cavanaugh. 2014. Coupled impacts of the diurnal cycle of sea surface temperature on the Madden-Julian oscillation. *Journal of Climate* 27(22):8,422–8,443, <https://doi.org/10.1175/JCLI-D-14-00141.1>.
- Shcherbina, A.Y., M.C. Gregg, M.H. Alford, and R.R. Harcourt. 2009. Characterizing thermohaline intrusions in the North Pacific Subtropical Frontal Zone. *Journal of Physical Oceanography* 39(11):2,735–2,756, <https://doi.org/10.1175/2009jpo4190.1>.
- Shcherbina, A.Y., M.A. Sundemeyer, E. Kunze, E. D'Asaro, G. Badin, D. Birch, A.-M.E.G. Brunner-Suzuki, J. Callies, B.T. Kuebel Cervantes, M. Claret, and others. 2015. The LatMix summer campaign: Submesoscale stirring in the upper ocean. *Bulletin of the American Meteorological Society* 96(8):1,257–1,279, <https://doi.org/10.1175/bams-d-14-00015.1>.
- Sherman, J.T., R.E. Davis, W.B. Owens, and J. Valdes. 2001. The autonomous underwater glider "Spray." *IEEE Journal of Oceanic Engineering* 26(4):437–446, <http://doi.org/10.1109/48.972076>.
- Todd, R.E., D.L. Rudnick, J.T. Sherman, W.B. Owens, and L. George. 2017. Absolute velocity measurements from autonomous underwater gliders equipped with Doppler current profilers. *Journal of Atmospheric and Oceanic Technology* 34(2):309–333, <https://doi.org/10.1175/JTECH-D-16-0156.1>.
- Trott, C.B., B. Subrahmanyam, and V.S.N. Murty. 2017. Variability of the Somali Current and eddies during the southwest monsoon regimes. *Dynamics of Atmospheres and Oceans* 79:43–55, <https://doi.org/10.1016/j.dynatmoce.2017.07.002>.
- Vecchi, G.A., S.-P. Xie, and A.S. Fischer. 2004. Ocean-atmosphere covariability in the western Arabian Sea. *Journal of Climate* 17(6):1,213–1,224, [https://doi.org/10.1175/1520-0442\(2004\)017<1213:ocitwa>2.0.co;2](https://doi.org/10.1175/1520-0442(2004)017<1213:ocitwa>2.0.co;2).
- Wang, Y., and M.J. McPhaden. 2017. Seasonal cycle of cross-equatorial flow in the central Indian Ocean. *Journal of Geophysical Research* 122, <https://doi.org/10.1002/2016JC012537>.
- Wijesekera, H.W., T.G. Jensen, E. Jarosz, W.J. Teague, E.J. Metzger, D.W. Wang, S.U.P. Jinadasa, K. Arulanandhan, L.R. Centurioni, and H.J.S. Fernando. 2015. Southern Bay of Bengal currents and salinity intrusions during the northeast monsoon. *Journal of Geophysical Research* 120(10):6,897–6,913, <https://doi.org/10.1002/2015JC010744>.
- Wolk, F., R. Lueck, and L.C. St. Laurent. 2009. Turbulence measurements from a glider. In *OCEANS 2009, MTS/IEEE Biloxi - Marine Technology for Our Future: Global & Local Challenges*. October 26–29, 2009, Biloxi, Mississippi.
- Wyrtki, K. 1973. An equatorial jet in the Indian Ocean. *Science* 181(4096):262–264, <https://doi.org/10.1126/science.181.4096.262>.

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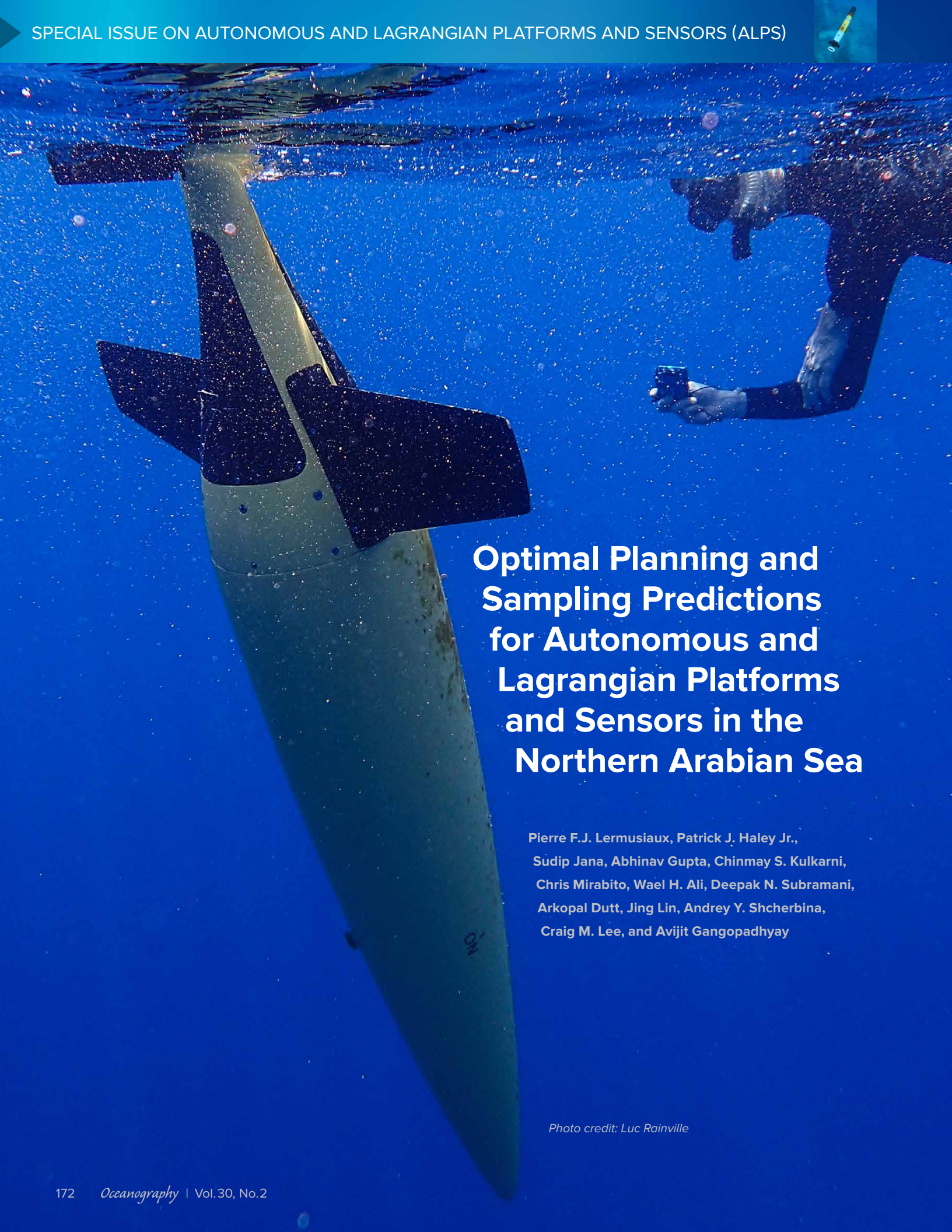
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Optimal Planning and Sampling Predictions for Autonomous and Lagrangian Platforms and Sensors in the Northern Arabian Sea

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ABSTRACT. Where, when, and what to sample, and how to optimally reach the sampling locations, are critical questions to be answered by autonomous and Lagrangian platforms and sensors. For a reproducible scientific sampling approach, answers should be quantitative and provided using fundamental principles. This article reviews concepts and recent progress toward this principled approach, focusing on reachability, path planning, and adaptive sampling, and presents results of a real-time forecasting and planning experiment completed during February–April 2017 for the Northern Arabian Sea Circulation-autonomous research program. The predictive skill, layered fields, and uncertainty estimates obtained using the MIT MSEAS multi-resolution ensemble ocean modeling system are first studied. With such inputs, deterministic and probabilistic three-dimensional reachability forecasts issued daily for gliders and floats are then showcased and validated. Finally, a Bayesian adaptive sampling framework is shown to forecast in real time the observations that are most informative for estimating classic ocean fields and also secondary variables such as Lagrangian coherent structures.

INTRODUCTION

Since the early days of ocean science, fixed platforms or expeditions with vessels have been used to collect varied observations (e.g., Stommel, 1989; Dickey, 2003; Schofield et al., 2010). In the past decade, adventurous research expeditions have been augmented with varied robotics-based platforms and sensors (e.g., Rudnick and Perry, 2003; Bellingham and Rajan, 2007; Nicholson and Healey, 2008). These include vehicles with a relative speed, such as propelled autonomous underwater vehicles (AUVs), underwater gliders, wave gliders, solar-powered vehicles, and surface craft. The experiments also involve vehicles with no or limited relative speeds such as autonomous drifters, floats, hybrid profilers, and semi-drifting surface craft.

A critical benefit of robotics platforms is that they reduce the undersampling of ocean surveys and augment satellite data. However, they are significantly affected by dynamic ocean motions, such as currents and waves. Their ocean measurements are thus a mixture of Eulerian (fixed or not affected by currents) and Lagrangian (current-following) observations. These facts are crystallized in the name “autonomous and Lagrangian platforms and sensors (ALPS),” introduced by

pioneering researchers (e.g., Rudnick and Perry, 2003; Dickey et al., 2008, and references therein). To best account for environmental effects, ALPS systems should become “expert systems” (e.g., Jackson, 1998) that plan and optimize their motions, using and integrating predictive models, control algorithms, uncertainty estimates, and data assimilation. Such integration of disciplines was initiated by the Autonomous Ocean Sampling Network (e.g., Curtin et al., 1993; Rudnick et al., 2004; Leonard et al., 2007, 2010; Lermusiaux, 2007; Ramp et al., 2009; Curtin and Bellingham, 2009), and it remains an area of active research.

For a reproducible scientific sampling approach, predicting where, when, and what to sample (i.e., optimal ocean sampling), and predicting which sampling locations can be reached and how to best reach them (i.e., reachability and optimal path planning), should be done quantitatively and using fundamental principles. Such principled autonomous sampling then becomes part of the emerging discipline of the “Science of Autonomy” (Steinberg, 2006; Lermusiaux et al., 2016). In simple terms, the Science of Autonomy is the systematic development of fundamental knowledge and reproducible methods about autonomy. This article

reviews concepts and illustrates some of our recent progress using this approach, based on real vehicles operating in a large open-ocean basin, within the context of the Northern Arabian Sea Circulation-autonomous research (NASCar) program. This US Office of Naval Research-funded program employs a variety of ALPS systems to investigate the dynamics of the northern Arabian Sea (Centurioni et al., 2017, in this issue). One of the goals of our NASCar contribution is to apply our theory and schemes for optimal path planning and optimal ocean sampling with swarms of autonomous vehicles. The collaborative applications that we describe are results toward this goal.

Effective predictive models of the relevant ocean dynamics and efficient uncertainty prediction and data assimilation schemes are crucial for quantitative optimal path planning and sampling. It is the advances in these disciplines that allow the present results, especially the progress in multiresolution numerical ocean modeling (Robinson et al., 2003; Deleersnijder and Lermusiaux, 2008; Deleersnijder et al., 2010; Haley and Lermusiaux, 2010; Cushman-Roisin and Beckers, 2011; Ringler et al., 2013; Haley et al., 2015; Burchard et al., 2017) and in ensemble uncertainty prediction and Bayesian data assimilation (Lermusiaux and Robinson, 1999; Lermusiaux et al., 2006a,b; Lermusiaux, 2006; Bocquet et al., 2010; Särkkä, 2013; Sondergaard and Lermusiaux, 2013a; Reich and Cotter, 2015; Lolli and Lermusiaux, 2017a). These advances will be employed next. We refer to the articles cited for the necessary details.

In this article, we first provide definitions and review fundamental equation-based results for reachability, path planning, and adaptive sampling. We then showcase results of the February–April 2017 real-time forecasting and

planning experiment in the interior northern Arabian Sea during which we predicted (1) high-resolution ocean fields and their probability; (2) reachable sets, reachability fronts, and time-optimal paths for underwater gliders and floats; and (3) the uncertainty of such reachability fields and optimal paths. Finally, we illustrate the use of our probabilistic modeling and Bayesian adaptive sampling theory to predict the locations that are most informative for estimating ocean fields or revealing coherent structures.

PLANNING FUNDAMENTALS FOR EXPERT ALPS SYSTEMS

We now review theories and methods for reachability, path planning, and adaptive sampling for expert ALPS systems operating in dynamic ocean currents. As schematized in Figure 1, quantitative planning for ALPS takes into account ocean currents and platform constraints (e.g., maximum speed, battery) and involves accurate predictions of the locations or regions that can be reached by the autonomous platforms (i.e., the reachable set), the optimal launch and recovery, the optimal observations to be collected to achieve the experiment's scientific goals, and the optimal paths for ocean vehicles to achieve these goals. Some key

questions are: (1) What are the locations that can be reached by an autonomous platform (i.e., reachability)? (2) What are the most informative locations and times at which measurements should be made to achieve the scientific goals (i.e., adaptive sampling)? (3) What are the optimal paths to reach these locations in desired times and in a safe fashion (i.e., path planning)? (4) Are the equations and methods answering these questions practical for real-time expert ALPS systems? In what follows, we focus on our own progress toward answering these questions by developing and using fundamental principles. Our quantitative planning utilizes prior knowledge in the form of simple fundamental relations, conservation laws, and mathematical models. This knowledge is combined with computational and decision-making capabilities, with the aim of obtaining expert systems (Jackson, 1998; Russell and Norvig, 2009). For reviews on marine path planning and adaptive sampling, we refer readers to Leonard et al. (2007), Lermusiaux (2007), Roy et al., (2007), Paley et al. (2008), Lermusiaux et al. (2016, and in press), and Subramani et al. (2017), and the references cited therein. Other results that are useful for marine autonomy but are not covered here include nested autonomy

(e.g., Schmidt et al., 2016); underwater navigation, communication, and motion control (e.g., Leonard and Bahr, 2016); and ocean sensing and underwater networks (e.g., Curtin and Bellingham, 2009; Venkatesan et al., 2017).

Path Planning

The prediction of paths along which specific criteria (e.g., time, energy, data collected, and/or safety) are optimized is called path planning. Traditionally, path planning has been developed for robots in complex but mostly static environments. Most planning methods are based on graphs and dynamic programming, fast marching schemes, wave front expansions, potential fields, nonlinear programming, nonlinear optimization, evolutionary algorithms, case-based reasoning, or dynamics-based approaches. Some of these methods consider uncertainties in the ocean estimates, usually by computing the deterministic plan for an ensemble of realizations. However, because ocean currents can be both highly dynamic and strong when compared to ALPS nominal speeds, many methods provide inaccurate solutions or are too expensive for real-time use with ALPS systems. Consequently, we developed theories and schemes that provide exact and practical solutions. They are reviewed next and will be exemplified later in this article (Applications section) by novel applications in the NASCAR region.

REACHABILITY

As schematized in Figure 1, we studied the problem of path planning through the fundamental concept of reachability (Lolla et al., 2014a,b, and references therein). The set of locations that can be reached is the reachable set, and its boundary is called the reachability front. The net motion of autonomous vehicles is the sum of the forward thrust and advection by dynamic currents. Based on these first principles, we developed a level-set partial differential equation (PDE) that governs the reachability front of a vehicle moving in strong and dynamic flows.

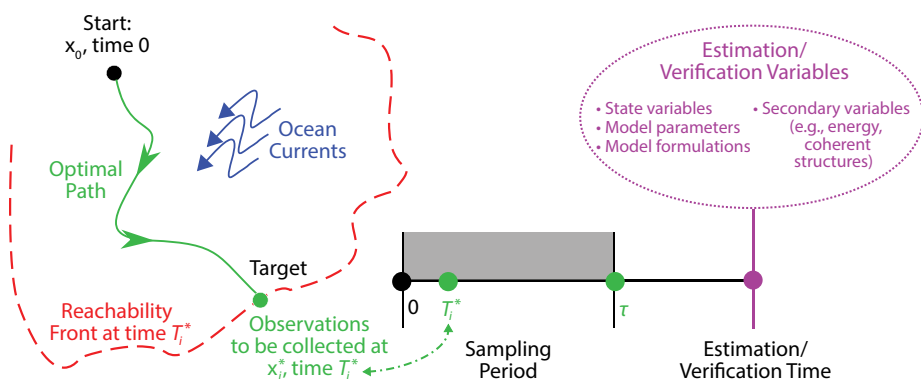


FIGURE 1. Schematic of reachability, path planning, and adaptive sampling. Reachability sets are predicted for a vehicle operating at nominal speed within dynamic currents. The total vehicle velocity is the vector sum of currents at that location and the nominal velocity. Optimal most informative measurements are taken at each optimal position x_i^* and time T_i^* . Predictions can be done in two or three dimensions, and for deterministic or stochastic currents. For stochastic currents, we employ ensembles or efficient dynamically orthogonal equations to evaluate distributions of reachable sets, fronts, and optimal paths. Adaptive sampling aims to predict the location x_i^* and time T_i^* of the observations to be collected over the sampling period $[0, \tau]$ that are most informative about the to-be-estimated/verification variables. Here, only a single future fixed verification time is sketched, but the estimation time(s) can be in the past or cover a period of time.

OPTIMAL LAUNCH, PICK-UP, AND INTERCEPTION

To save time and costs in ocean sampling, the launch, pick-up, and/or interception of autonomous platforms should be efficient. The use of dynamic reachable sets (Figure 1) is directly applicable to these problems. They provide exact solutions, and their utilization has been exemplified for time-optimal interceptions by surface craft, including natural and vessel wave effects (Mirabito et al., in press) and for pursuit-evasion problems (Sun et al., 2017a,b).

TIME- AND ENERGY-OPTIMAL PATHS

The first time at which the reachability front reaches the target end point or optimal sampling location is the fastest travel time (Figure 1). The time-optimal headings are normal to the reachability fronts. The corresponding time-optimal path can then be extracted from the dynamic reachability front prediction by solving a particle backtracking ordinary differential equation (ODE; Lolla et al., 2014b). These equations were applied to gliders and AUVs for reachability and path planning, and coordinated path planning of swarms, in realistic current simulations (Lolla et al., 2014a, 2015). They were theoretically extended to anisotropic motions and to fully three-dimensional paths, including planning for floats or other vehicles with constrained relative motions. They were also used successfully with real AUVs at sea (Subramani et al., in press; Edwards et al., in press) and extended to uncertain stochastic currents (Wei, 2015) and to energy-optimal path planning (Subramani and Lermusiaux, 2016; Subramani et al., 2017).

COMPUTATIONAL COSTS

The computational time for all above applications is much shorter than the mission time. For example, for reachability and time-optimal planning, the computations take seconds to minutes to plan missions that last days to weeks, and the cost only grows linearly with the spatial resolution. Even for large

stochastic energy-optimal planning run on a single CPU, the computational time is less than the time required to integrate modern numerical ocean modeling systems. Optimal paths can thus be recomputed multiple times as new observations arrive, hence allowing feedback and onboard routing.

Adaptive Sampling

Ocean science observation campaigns are designed based on hypotheses or questions to be answered. As schematized in Figure 1, observations are to be collected over a period of time, often referred to as the sampling period. The observational data should provide the most information about the chosen hypotheses or questions, at a fixed time or over a period of time. These data can be utilized on their own, but are in general combined with prior knowledge, including conservation laws and model equations. Observations are then utilized to improve state variable estimates or field predictions, to infer model parameters, to test model formulations, or to estimate secondary variables such as energy, enstrophy, spiciness, or coherent structures of the flow (Figure 1). Given that platforms and sensors at our disposal are limited, the goal of adaptive sampling is thus defined here as guiding the ALPS system optimally so as to collect the observations that are most informative about the scientific objectives.

Practical adaptive sampling is directly linked to path planning: adaptive sampling requires not only identifying the most informative data types, locations, and times but also planning feasible optimal paths. This latter path planning serves two purposes. First, it determines the reachable regions of the platforms that limit the set of possible candidate measurements. Second, after the most informative data are determined, path planning guides the platforms so that they navigate along the optimal paths to collect the desired data. Because each measurement will change both our ocean prediction and the expected information content in later candidate observations,

the planned paths and the computed information content should be updated as data are collected.

Previous results on ocean adaptive sampling include methods that involve some linearizations of the system dynamics, such as in the use of adjoint equations for sensitivity analysis or of optimal perturbations and singular vectors. Other methods with limited or no linearizations utilize breeding, ensemble subspaces, ensemble transforms, mixed-integer programming, potential functions, or genetic algorithms. Reviews are provided in Lermusiaux (2007) and Lermusiaux et al. (in press). Note that in their present usage, these methods neglect the non-Gaussian properties of the dynamics.

We recently formulated a novel and rigorous framework by combining uncertainty quantification, Bayesian data assimilation, and information theory. For uncertainty predictions, we employ the variance-optimal reduced-order stochastic dynamically orthogonal (DO) equations (Sapsis and Lermusiaux, 2009; Ueckermann et al., 2013; Feppon and Lermusiaux, in press). To exploit the non-Gaussian statistics, we utilize the Gaussian Mixture Model (GMM)-DO filter (Sondergaard and Lermusiaux, 2013a,b) and smoother (Lolla and Lermusiaux, 2017a,b). To rigorously measure the information content of varied observations in a principled way, we employ mutual information (Cover and Thomas, 1991). Mutual information quantifies the amount of information a variable has about another variable. For reachability computation and optimal navigation, we utilize the previously mentioned path planning equations. Finally, we use dynamic programming to solve the information content optimization problem exactly and so predict the optimal future sampling strategies (Lolla, 2016).

APPLICATIONS

We now illustrate some of the capabilities of the theory and methods reviewed in the last section for planning ALPS operations in the interior northern

Arabian Sea during February–April 2017, within the context of the NASCar program. We first describe results on predictive skill, dynamics, and uncertainty obtained using our real-time multi-resolution ensemble ocean modeling. The corresponding forecast fields and their probabilities were then input to our path planning and adaptive sampling studies (Figure 2). For the path planning, we exemplify our deterministic and probabilistic three-dimensional reachability forecasts issued daily for gliders and

floats as they operated in the region (see later section on Probabilistic Eulerian-Lagrangian Reachability for Gliders and Floats), using the level-set PDEs introduced in the Path Planning section. For the adaptive sampling, we showcase how computing machines using our Bayesian schemes can forecast in real time the observations that are most informative for estimating classic ocean fields and also secondary variables such as Lagrangian coherent structures (Bayesian Adaptive Sampling section).

Multiresolution Ensemble Ocean Forecasting and Dynamics

The MIT Multidisciplinary Simulation Estimation and Assimilation System (MSEAS) was utilized for three months for real-time multi-resolution simulations (Lermusiaux et al., 2017). Capabilities employed involved implicit two-way nesting for realistic tidal-to-mesoscale modeling with hydrostatic primitive equations (PEs) and a nonlinear free surface (Haley and Lermusiaux, 2010; Leslie et al., 2010; Haley et al., 2015) and Error Subspace Statistical Estimation (ESSE) for stochastic uncertainty predictions (Lermusiaux, 1999; Lermusiaux et al., 2002).

MODELING SETUP

The NASCar modeling domain (Figure 2a) in the northern Arabian Sea had a $1/60^\circ$ horizontal resolution and 70 vertical levels with optimized level depths (e.g., higher resolution near the surface or large vertical derivatives). The bathymetry was obtained from the 15 arc-seconds SRMT15 data (Smith and Sandwell, 1997). Initial conditions were downscaled from $1/12^\circ$ HYCOM (Hybrid Coordinate Ocean Model) analyses (Cummings and Smedstad, 2013) via optimization for our higher-resolution coastlines and bathymetry (Haley et al., 2015). Tidal forcing was computed from the high-resolution TPX08-Atlas from Oregon State University (Egbert and Erofeeva, 2002, 2013), again with adjustments to our higher-resolution geometry and quadratic bottom drag. For atmospheric forcing, we employed the wind stress and surface freshwater flux from $1/4^\circ$ NCEP GFS (National Centers for Environmental Prediction Global Forecast System) one-hourly forecasts (Environmental Modeling Center, 2003) and the net heat flux from $1/2^\circ$ NAVGEM (Navy Global Environmental Model) three-hourly forecasts (Hogan et al., 2014).

DYNAMICS AND FORECAST SKILL

The MSEAS PE modeling system and its physical and numerical parameters were calibrated for the regional dynamics

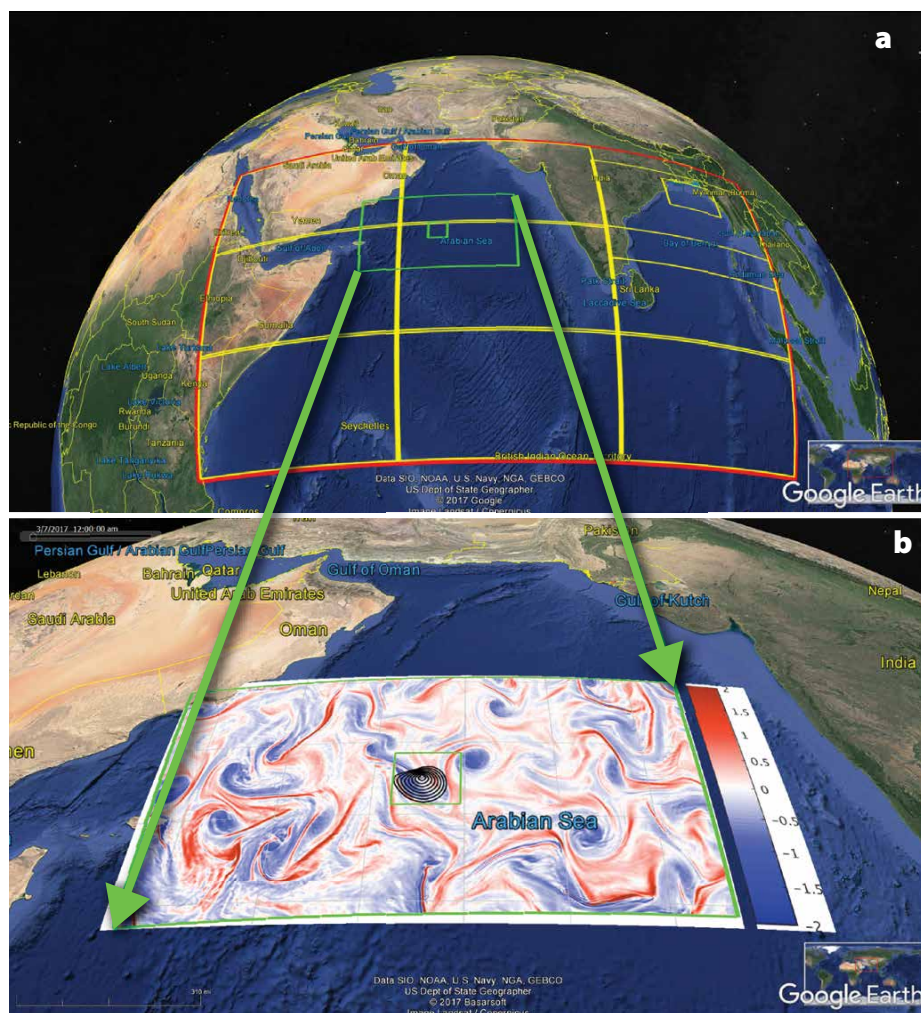


FIGURE 2. (a) Our multi-resolution computational domains in the northern Indian Ocean. The domain bounded by the green outer box (53.66°E – 69.18°E ; 9.38°N – 17.83°N) is the main domain used for real-time forecasts to support Northern Arabian Sea Circulation-autonomous research (NASCar) operations. (b) Three-day forecast of the vorticity field at 2 m depth, issued by the MIT Multidisciplinary Simulation Estimation and Assimilation System primitive-equation (MSEAS PE) modeling system for March 7, 2017, 00Z (middle time for the March 5–9, 2017 forecast period for Seaglider SG137). A smaller moving domain (green inner box) surrounds the initial position of Seaglider SG137 on March 5, 2017, 00Z. The black contours are four days of reachability front forecasts, at 12-hour intervals (12 h to 96 h forecasts). The reachability front is the boundary of the largest set (the reachability set) that the glider can reach within that duration. It was forecast by integrating its exact governing level-set partial differential equation.

using more than 600 deterministic simulations and data-model comparisons. Once calibrated, three- to four-day forecasts were issued daily for three months. As we will illustrate, we found that the higher resolution and tides in our calibrated system resolved additional processes and improved the skill of lower-resolution ocean fields. This result is not direct because increasing resolution and adding dynamics can easily increase uncertainties and reduce the skill of deterministic forecasts.

One such example of additional dynamics is the formation of layering in upper-ocean salinity in the form of interleaving subsurface layers of high and low salinity, as observed by Seaglider SG133 during March 4–7 (Figure 3c). This layering was largely absent in the initial conditions from HYCOM (Figure 3a); however,

it was created within the higher-resolution MSEAS PE as the forecast simulation progressed (Figure 3b). Similar findings were also obtained by comparisons of model forecasts to another Seaglider (SG137; not shown in figure). This indicates that the MSEAS-PE additional dynamics and increased resolution ($1/60^\circ$ and 70 optimized levels) were likely needed to develop and maintain the complex layered features observed in the region. The addition of tidal forcing also generated internal tides and waves in the western part of the domain at Socotra Island, as well as on nearby ridges (not shown).

To evaluate the effect of model resolution on the forecast skill, Figure 4a–c compares the salinity profiles from the initial conditions for March 11 (Figure 4a) and the MSEAS PE three-day forecast for March 14 (without data assimilation;

Figure 4b) against in situ Argo profiles collected during March 14 in the region (Figure 4c). With the increased MSEAS PE resolution, the salinity forecast bias is reduced by 50% and the root mean square error (RMSE) by 25% when compared to the lower-resolution initial conditions. A significant improvement in the salinity is seen in the 100–300 m depth range (driven in part by the formation of the layering). Overall, forecasts showed that high resolution in the model was needed to develop and maintain such layered features. The assimilation of observations further improved the higher-resolution forecasts. Figure 4d–f shows this impact of assimilating the Argo profile data for one week prior to issuing forecasts. Specifically, we compare two higher-resolution MSEAS PE three-day salinity forecasts for March 10, one without

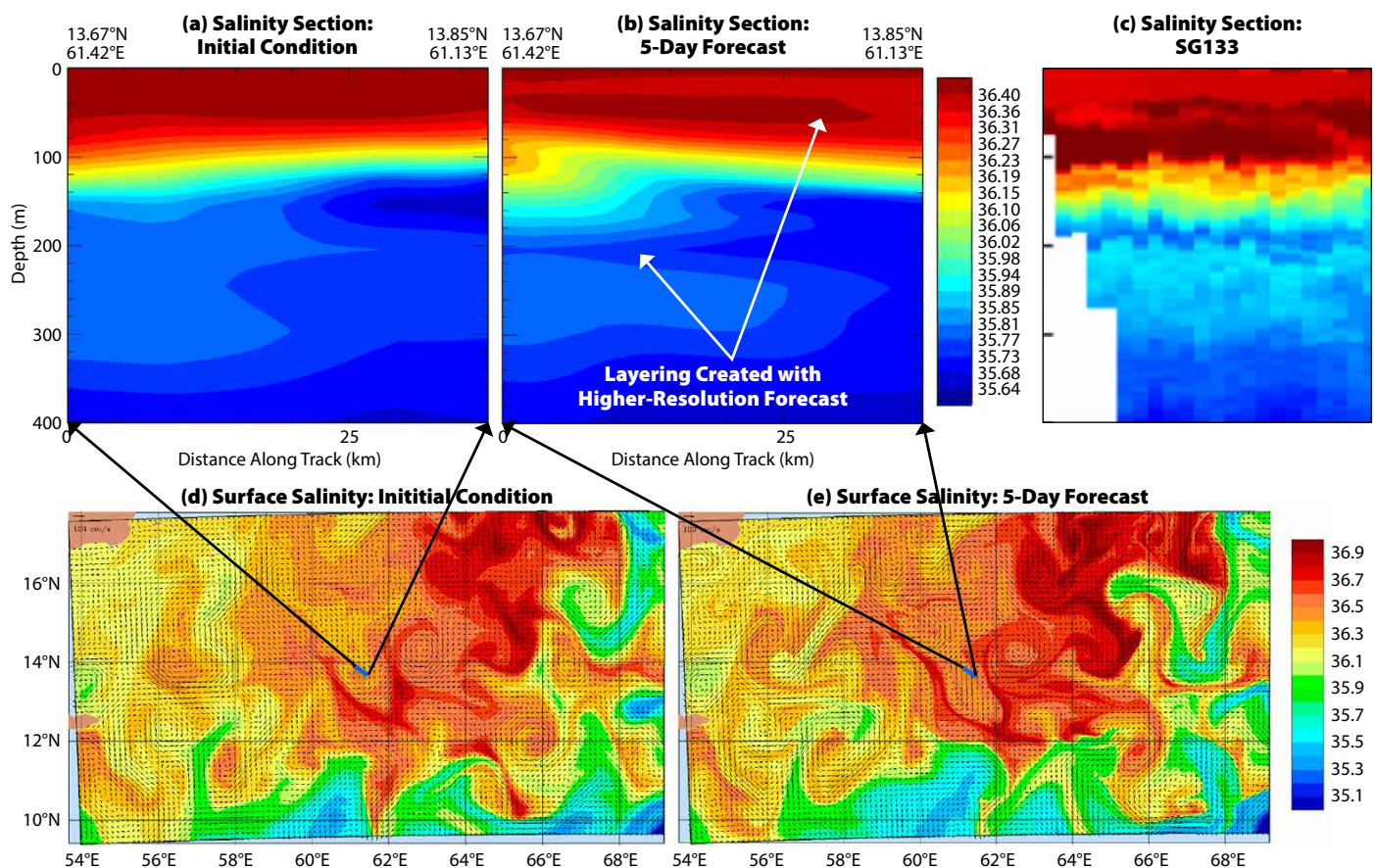


FIGURE 3. Additional processes arising from increased resolution and added dynamics. Simulated salinity is compared in the figure to observed salinity from March 4–7, 2017. No data were assimilated in this comparison. Seaglider SG133 data show salinity layering (e.g., high/low saline waters around 80 m/200 m) in the upper ocean (c). Over the exact same section location, this layering is largely absent from the initial conditions downscaled from a coarser model (a) but is created as the higher-resolution MSEAS-PE forecast proceeds (b). Similar results were observed with Seaglider SG137 (not shown). The location of the salinity sections are shown in surface maps of salinity from the initial conditions (d) and five-day forecast (e).

(Figure 4d) and one with (Figure 4e) Argo data assimilation, against the same independent verification Argo profile data of March 10. In the simulation with data assimilation (Figure 4e), we assimilated the Argo profiles from March 1–7 prior to the start of the forecast period. The assimilation corrected salinity features in the upper ocean and other ocean fields during that March 1–7 period, which led to a reduction of both the bias and the RMSE in the salinity forecast for March 10.

ESSE ENSEMBLE FOR UNCERTAINTY FORECASTING

Once the deterministic modeling system was calibrated, uncertainties were forecast. The ESSE uncertainty forecasts consisted of an ensemble of numerical simulations that were each set up by perturbing the initial and boundary conditions in accord with their

dominant uncertainties, and by adding stochastic forcing to the external forcing (i.e., uncertainties in the times/phases and amplitudes of the atmospheric fluxes and tides) and to the deterministic equations so as to represent modeling errors occurring during the time and space integrations of the MSEAS PE ocean modeling system. The result is an ensemble of forecasts from which statistics can be computed, including not only classic ensemble standard deviations but also histograms or probability density functions. In the present NASCar experiment, 50-member ensemble forecasts were issued daily using ESSE from mid-March to April. To initialize multiscale ensembles (Lermusiaux et al., 2000; Lermusiaux, 2002, 2007), historical CTD synoptic data for January, February, and March were used to create joint vertical EOFs (empirical orthogonal functions) for temperature (T) and salinity (S). To construct the

three-dimensional T and S perturbations, the joint EOFs were combined with an eigendecomposition of a horizontal correlation matrix defined by a Mexican hat correlation function of 25 km decay-scale and 75 km zero-crossing (these numbers were obtained from the calibration MSEAS-PE runs and the literature). These T and S perturbations were used to generate velocity perturbations in accordance with close-to-geostrophic PE balance. The MSEAS-PE model was integrated for four days for each ensemble member's initial conditions, including also novel stochastic error models for tides and atmospheric fields (Lermusiaux et al., 2017).

Figure 5 illustrates one of these ESSE uncertainty forecasts for March 27, at two days into the four-day forecast. The forecast shows significant uncertainties: at the surface, the average ensemble standard deviation forecasts for velocity, salinity, and temperature are about 18 cm s^{-1} , 0.14,

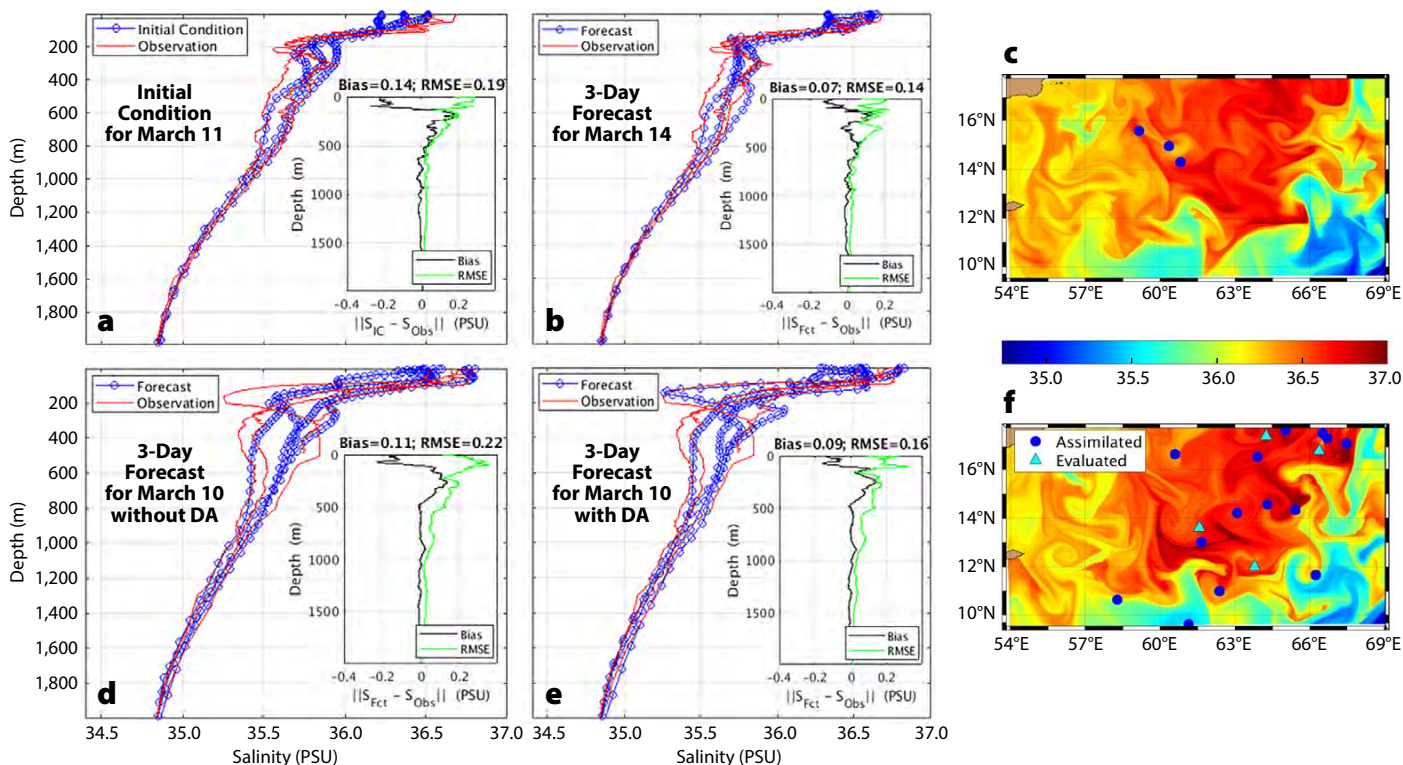


FIGURE 4. Effects of resolution and assimilation on the MSEAS-PE forecasts. (a–c) Impact of higher spatial resolution. Salinity profiles from the initial conditions for March 11 (a) and from the three-day higher-resolution forecast for March 14 (b) are compared to Argo profiles of March 14 (data not assimilated). Locations of the March 14 Argo profiles overlaid on the surface salinity forecast for March 14 00Z are shown in (c). Higher resolution enhanced the forecast skill. (d–f) Impact of data assimilation (DA). Salinity profiles from two three-day forecasts without (d) and with (e) DA compared to Argo profiles collected on March 10. The simulation with DA assimilates March 1–7 Argo data, prior to starting the forecast. This DA corrects the salinity features in the upper layers. Locations of the March 1–7 and March 10 Argo profiles overlaid on the surface salinity forecast for March 10 00Z are again shown in (f). For comparison with initial conditions, all profiles of the considered day are compared with the initial conditions regardless of the observation time. For forecast comparison, the Argo profiles are compared with the forecast profile at the data time and location.

and 0.4°C , respectively (not shown). As shown in Figure 5, at 100 m depth, these same average ensemble standard deviation forecasts are about 13 cm s^{-1} , 0.2, and 0.6°C , respectively. The uncertainties in T and S follow distinct features at different depths (due to layering) and are less uniform in space at 100 m, while the density (not shown) and velocity uncertainties at 100 m are much more uniform over the domain. In accord with the initialization, in the upper layers, this reflects an uncertain multiscale eddy field that is not far from geostrophic balance with density uncertainties, while T and S variabilities mostly compensate each other. The T and S uncertainties were higher on the eastern and southeastern sides (Figure 5a) of the modeling domain because of the presence of a tighter thermocline/halocline to the east. This is in part because the western side experienced higher vertical mixing due to past strong atmospheric forcing and internal tides. The uncertainty due to the multiscale eddy field dynamics (Figure 5b) is clearly more uniform, with standard deviations generally between 11 cm s^{-1} and 16 cm s^{-1} everywhere. The formation of distinct quasi-horizontal layers (e.g., isopycnals) led to a demarcation in the uncertainty contained in the upper layers (e.g., four layers in the upper 200 m in Figure 5c) with significant salinity uncertainty visible within the main halocline from about 150 m to 400 m. All of this is logical because unsampled variability is a strong contributor to uncertainty, especially when the variability is growing in time and space. As the simulations progress to the four-day forecast, advective stirring, instabilities, and vertical mixing spread the salinity uncertainty between the upper layers in about 60% of the domain (not shown). There was also significant growth in the uncertainty near the base of the main pycnocline (200–350 m) and near Socotra Island where internal tides were generated (not shown). Below 200 m depth, the T and S variations were compensated, leading to relatively smaller potential density uncertainties (not shown).

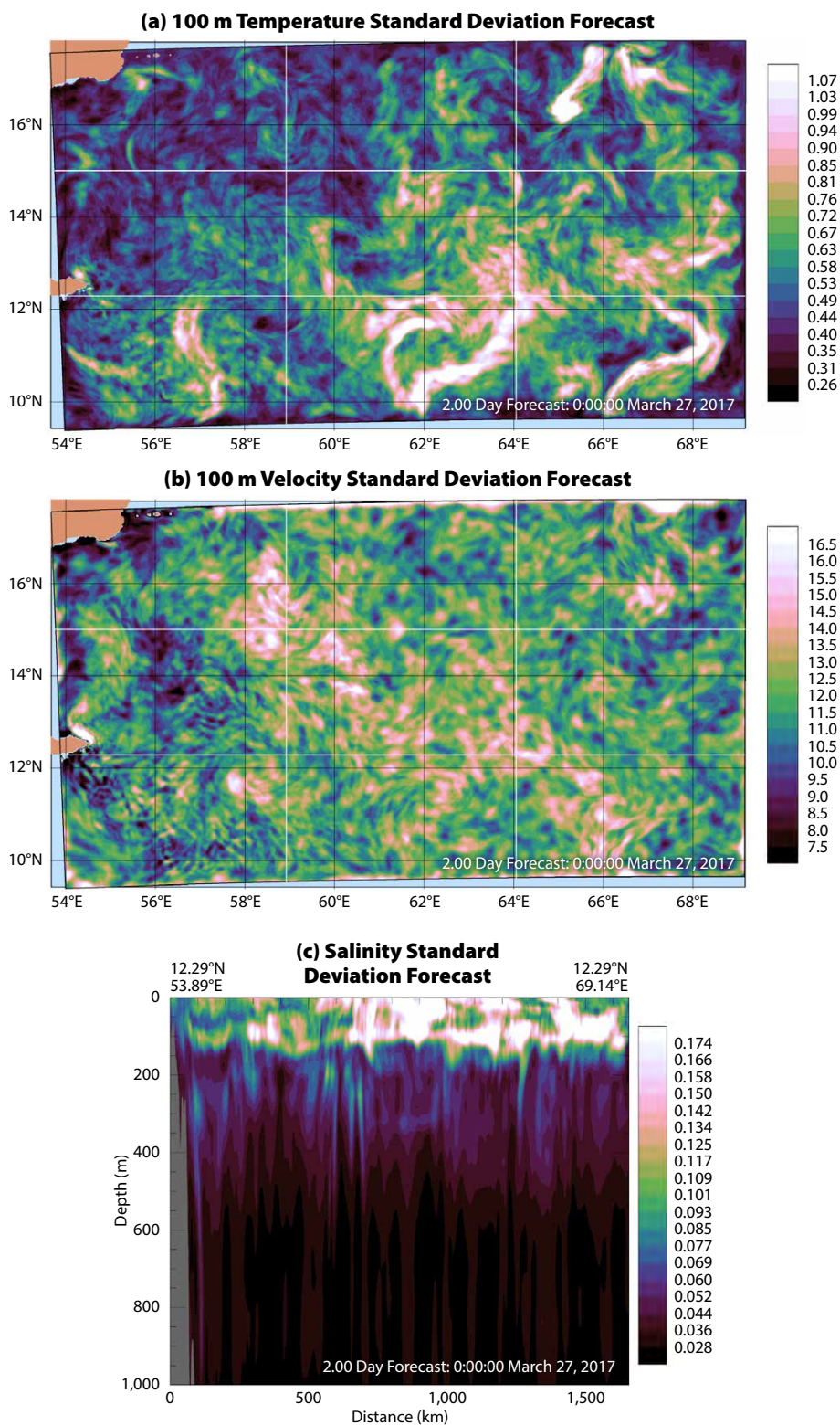


FIGURE 5. Real-time two-day Error Subspace Statistical Estimation (ESSE) ensemble forecast for March 27, 2017, from an ensemble of 50 members. (a) Forecast standard deviation in temperature at 100 m depth. At that depth, temperature (T) and salinity (S) uncertainties are higher on the eastern-southeastern sides of the Arabian Sea because of the presence of a tighter thermocline/halocline to the east. This is in part because the western side experiences higher vertical mixing due to past strong atmospheric forcing and recurring internal tides. (b) Magnitude of the forecast standard deviation in velocity at 100 m depth. (c) East-west vertical section of forecast standard deviation in salinity. The formation of distinct vertical layers leads to a demarcation in the uncertainty contained in the layers.

Probabilistic Eulerian-Lagrangian Reachability for Gliders and Floats

During February–April 2017, we forecasted the reachability fronts of Seagliders SG133 and SG137 and the dynamic probability of reachable points of ALAMO (Air-Launched Autonomous Micro-Observer) profiling float 9103. The Seagliders were navigating in a bow-tie pattern to track the ALAMO float (Centurioni et al., 2017, in this issue). The Seagliders dove to 1,000 m depth every four to five hours, and the float was profiling to roughly 300 m depth every two hours.

GLIDER REACHABILITY FORECASTS

To assist the Seaglider operations, daily four-day glider reachability forecasts for SG133 and SG137 were issued using our ocean forecasts. Gliders were piloted in a yo-yo pattern (1,000 m dives in four to five hours) and their reachability was computed accordingly (e.g., Lolla et al., 2014a). Figure 2b illustrates such a glider reachability forecast overlaid on a 2 m mesoscale vorticity forecast. In Figure 6, we study four such forecasts. Columns 1 and 2 correspond to Seaglider SG133, and columns 3 and 4 to SG137.

In each Figure 6 panel, the actual location of the glider at the beginning of the forecast window is shown as a gray point. The reachability fronts at every 12 hours are shown by black contour lines overlaid on a forecast of the 2 m vorticity (columns 1 and 3), and depth-averaged currents (columns 2 and 4) are at the midpoint of the forecast time window. As defined previously, the area within the reachability front can be visited by the gliders while the area outside cannot.

Overall, the growth and shape of the reachability fronts are set by the local

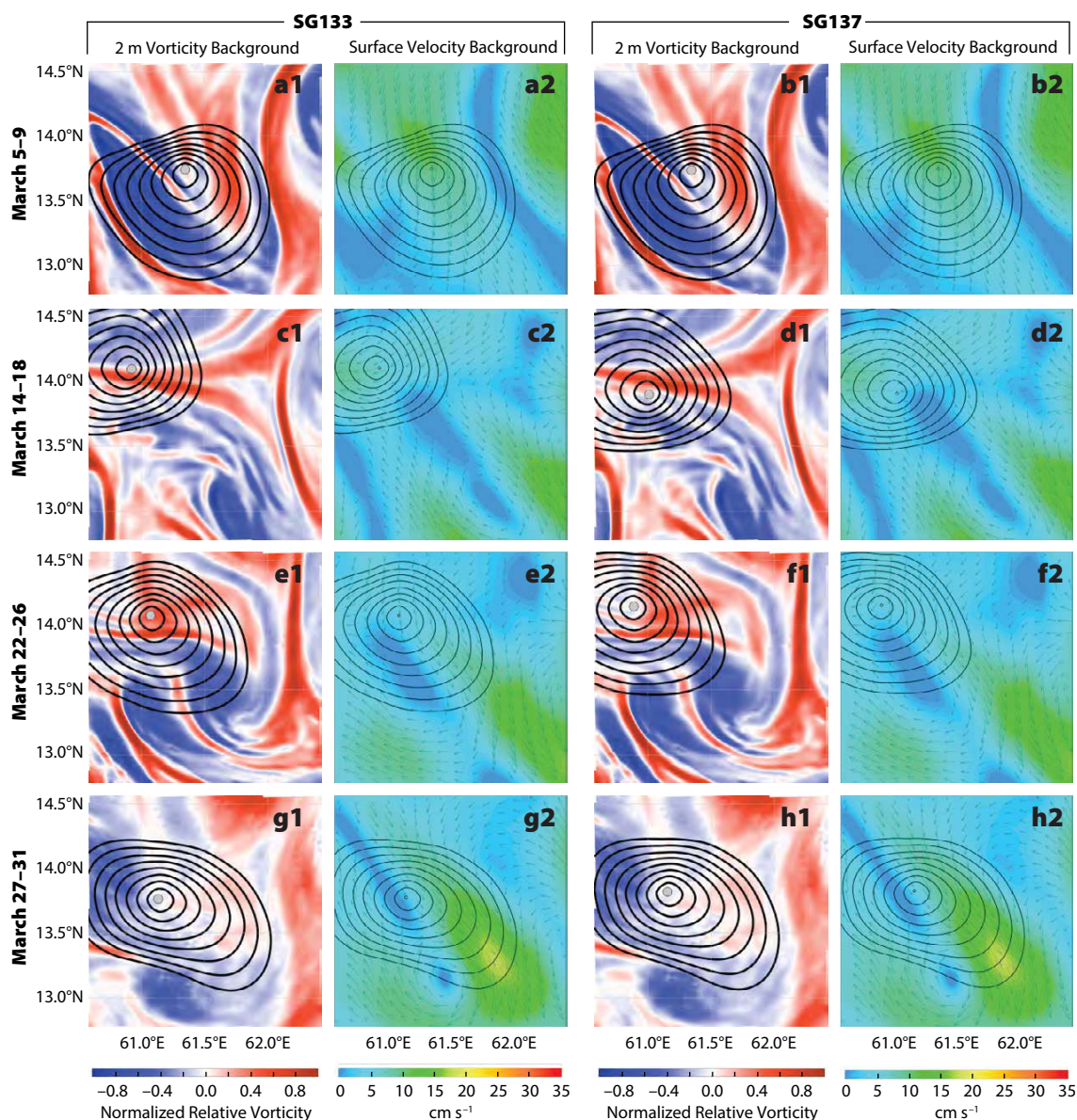


FIGURE 6. Reachability front forecasts for Seagliders SG133 (columns 1 and 2) and SG137 (columns 3 and 4) for March 5–9 (1st row), March 14–18 (2nd row), March 22–26 (3rd row), and March 27–31 (4th row) 2017. The actual locations of the gliders at the beginnings of the forecast windows are shown as gray points. The reachability fronts forecast at 12-hour intervals (12 h–96 h) are shown by black contour lines. The 48-hour forecasts of 2 m mesoscale vorticity (columns 1 and 3) and the 0–1,000 m depth-averaged flow magnitude overlaid with velocity vectors (columns 2 and 4) are shown in the backgrounds.

circulation and by the glider's propulsion (itself affected by buoyancy fields). For the period March 5 to March 9 (Figure 6, row 1), the integrated flows near both gliders are forecast to be predominantly to the south, and hence the reachability front grows farther to the south (where currents aid motion) than to the north (where currents oppose motion). The forecast mesoscale vorticity field (Figure 6a1,b1) is positive to the east of the gliders and negative to the west. As a result, the reachability forecasts develop a kidney bean-shaped pattern, with a bit more growth on the northeast and northwest extremes compared to the immediate north. For the period March 14 to 18 (Figure 6, row 2), the forecast flows around SG133 (Figure 6c2) are southwest in the north, east, and southeast, westward in the west, and northwest in the south. The maximum flow is to the east with magnitude of $\sim 15 \text{ cm s}^{-1}$. The flows around SG137

(Figure 6d2) are similar except they are nearly zero in the southeast. The growth of the reachability fronts is aided to the east but opposition in other directions is not as strong as from March 5 to March 9. The local shape of the reachability fronts is governed by the mesoscale flows and vorticity. For the periods March 22 to March 26 (Figure 6, row 3) and March 27 to March 31 (Figure 6, row 4), the flows are to the southeast, with stronger flows in the vicinity of the gliders for the latter period when compared to the former. The effect of the anticyclonic eddy in setting the shape of the reachability front during the March 27 to March 31 period is clearly visible in the last two forecasts.

ALAMO FLOAT POSITION PROBABILISTIC FORECASTS

Daily forecasts of four-day future float positions were also issued, with good accuracy. To account for uncertainties in

the initial float positions and initial flows around them, we first advected a dynamic set of possible reachable positions, starting from a small circle around the latest known position of each float. This reachable set then estimates the region of likely future locations (i.e., the regions outside of which the likelihood of finding the float is small). It is conceptually different than the reachable set of a glider because a float is assumed horizontally passive while a glider is not; the governing equation is nonetheless the same, up to the propulsion term. These sets were forecast from the latest known position of each float and issued in 12-hour intervals. Figure 7a1–a6 shows three examples of such forecasts issued on March 18, 21, and 26. They are overlaid on the 0–300 m averaged velocity forecast magnitude and vectors, again at the midpoint of the forecast time window. A plot of the real track of the float accompanies each forecast

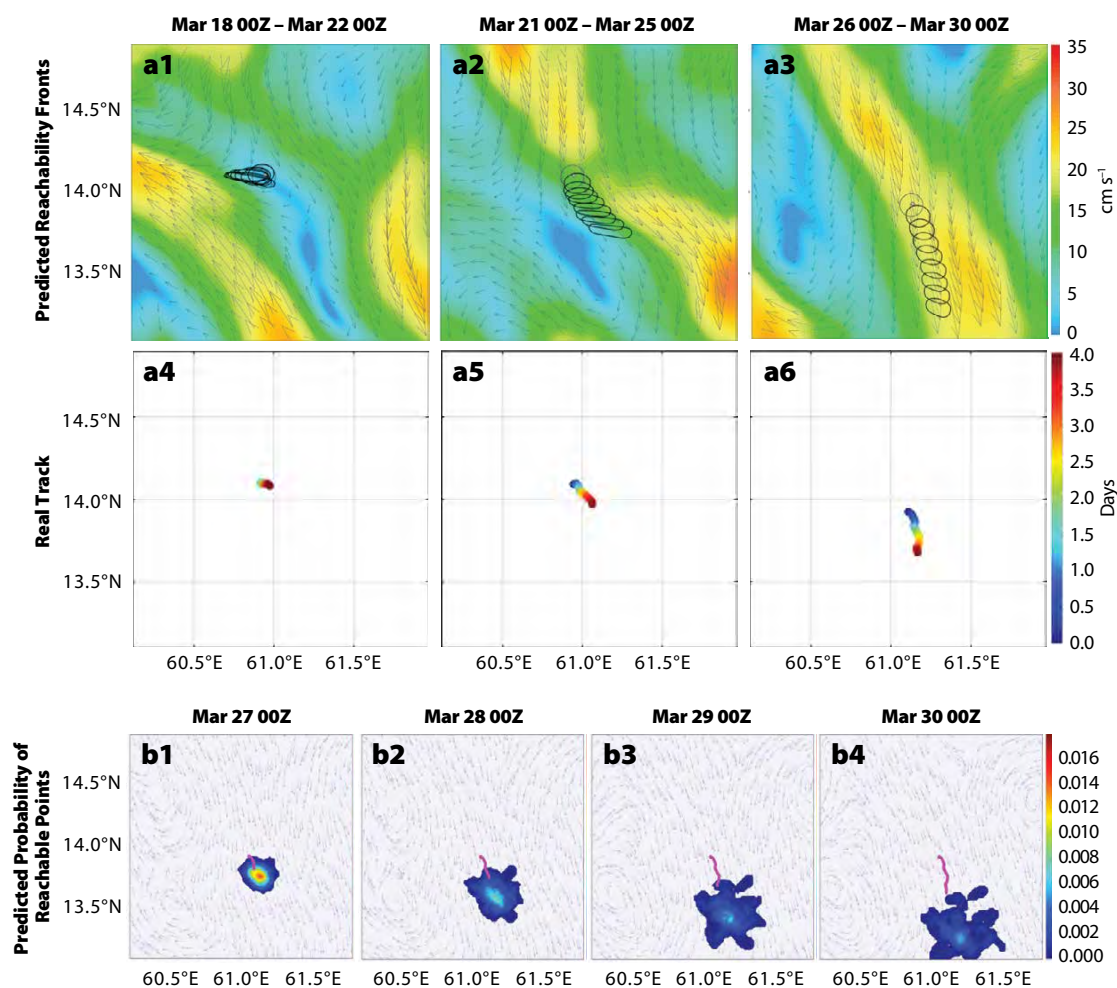


FIGURE 7. ALAMO float position probabilistic forecasts. (a1–a3) Reachability sets forecast from the latest known positions of each float and issued in 12-hour intervals, overlaid on the 0–300 m averaged velocity forecast magnitude and vectors, at the midpoint of the forecast time window. (a4–a6) Plots of the real float tracks during the forecast horizon. The real tracks (a4–a6) overall confirm their corresponding forecasts (a1–a3). (b1–b4) Probabilistic reachable set field forecast for the ALAMO float issued on March 26, 2017, 00Z for the four-day period March 26–30. Overlaid on the probability map are 0–300 m averaged current vectors from the central MSEAS PE forecast and the real track of the float from March 26 00Z to the time of the forecast of each panel. The Lagrangian probabilistic reachability planning system shows predictive skill for long periods of time.

during the forecast horizon.

On March 18 (Figure 7a1), the float is in a region of low velocity with east-west shears from adjacent stronger currents. The forecast reachable set initially advects westward but then elongates (due to the shear) both eastward and westward. This pattern was consistent with the actual float, which initially moved westward but then reversed and advected eastward. On March 21 (Figure 7a2), the float is positioned between weak and strong south-east flows. Hence, the eastern edge of the reachable set grows farther south than the western edge. In the above two sets, the shear in the forecast flows stretches the reachable set, thereby elongating the initial circle to ellipse shapes. The real float track (Figure 7a4,a5) is consistent with forecasts and improves with the strength of the flow near the float. In the March 26 forecast (Figure 7a3), the float is in the strong flow proper. It is thus predicted to move faster, which again agrees with the real float tracks (Figure 7a6).

The skill of the float's reachable set forecast was mostly governed and limited by the accuracy of the larger time-dependent mesoscale flow. To account for its complete dynamic uncertainty, we employed ESSE ensembles to predict the dynamic set of reachable positions for each ensemble member. A rigorous probability field of reachable float positions is then obtained through normalizing by area the union of each ensemble's set of reachable positions. Figure 7b1–b4 depicts such a probabilistic reachable set field forecast for the ALAMO float. It was issued on March 26, 2017, 00Z for the four-day period March 26–30. The four panels show the forecasts every 24 hours from day 1 to day 4 of the forecast (March 27 00Z to March 30 00Z). The color represents the quantitative probability that a location on the map is in the reachable set for the float. Overlaid on the probability map are 0–300 m averaged current vectors from the central MSEAS PE forecast and the real track of the float from the March 26 00Z to the time of the forecast of each panel. This

Lagrangian probabilistic reachability planning system shows predictive skill for long periods of time.

Bayesian Adaptive Sampling

We extended the Bayesian GMM-DO data assimilation for simultaneous estimation of Eulerian variables (e.g., velocity, temperature, salinity) and Lagrangian variables (e.g., drifter/float positions) and features derived from these variables (e.g., waves, fronts, eddies, and other coherent structures). Lagrangian coherent structures, or the most influential and persistent material surfaces in a flow (Haller, 2015), have gained prominence as a tool for studying fluid flow transport and particularly advection of hazardous material in environmental flows. A common approach to identifying Lagrangian coherent structures relies on finite-time Lyapunov exponent (FTLE).

In Figure 8, we illustrate how mutual information fields forecasts can be used to identify the locations for observing different types of data that would be most informative about the velocity field or Lagrangian coherent structures. A particular realization of the ensemble forecast of the forward-time FTLE field over an interval of three days (March 27 to March 30, 2017) is shown (Figure 8a). The ridges of the forward-time FTLE field correspond to repelling Lagrangian coherent structures (i.e., material lines from which parcel trajectories separate the most). The white box marks the region for which the zoomed-in FTLE field is shown on the right. Winds and upper-ocean dynamics lead to rapid variability in the surface velocity field (not shown). When the velocity field is rapidly varying, the features in the FTLE field cannot be identified with the velocity field at one particular time instance. In Figure 8c,d we show forecast mutual information fields between candidate observations of salinity anywhere in the small domain (white box in Figure 8a), and the verification variable, which is a field defined over the whole small domain. The mutual information field between salinity and the

scalar field of zonal velocity over the small domain indicates that the most informative salinity data locations are around 12.6°N, 58.2°E. The mutual information field between salinity and the FTLE field over the small domain (from which coherent structures can be estimated) indicates the most informative salinity data locations are around 12.5°N, 58.7°E. The informative locations in this field lie on the edge of a high-salinity intrusion (not shown here). We also note the differences in the locations of the most informative data in the two fields, confirming that observation data locations that are highly informative for one verification variable may not be so for another.

In Figure 8e–g we show forecast mutual information fields between velocity and the forward-time FTLE field. The mutual information field between zonal velocity and forward-time FTLE field indicates that the most informative locations are around 12.5°N, 58.8°E. In contrast, when meridional velocity is measured, the most informative data locations lie near 11.6°N, 59.2°E. Also, there are more candidate observation locations that are highly informative about coherent structures when measuring either velocity component than when measuring salinity. Furthermore, if we were to observe both zonal and meridional velocity, the mutual information about the coherent structures is logically higher than when we measure only one of the components. This full velocity mutual information is, however, maximized when the observation locations are around 12.3°N, 58.8°E and 11.7°N, 59.6°E.

CONCLUSIONS

Recent fundamental theories and methods for optimal planning and sampling predictions were reviewed and illustrated in real-time forecasting conditions in the northern Arabian Sea. The emphasis was on the concepts of reachability, path planning, and adaptive sampling. Reachability and path planning equations provide exact and practical solutions for time and energy optimal solutions, naturally

including coordination, obstacle avoidance, anisotropic motions, and uncertain flows. A novel and rigorous framework for adaptive sampling was also outlined, integrating uncertainty quantification, Bayesian data assimilation, and information theory.

For the real-time forecasting and planning experiment completed during February–April 2017 in the northern Arabian Sea, the predictive skill, layered fields, and uncertainty estimates obtained using our MIT MSEAS multiresolution ensemble ocean modeling system were studied and validated against independent in situ data. The higher resolution and inclusion of tides in our calibrated system resolved additional processes and improved the skill of lower-resolution

ocean fields. The ensemble ocean forecasts enabled probabilistic prediction of the reachable sets, reachability fronts, and time-optimal paths of underwater gliders and floats. These reachable sets and paths were verified by comparison to subsequent vehicle tracks, showing predictive skill for several weeks. The Bayesian adaptive sampling framework was shown to be capable of forecasting the information content of specific observation about different state or secondary variable fields. Specifically, it determined the future surface salinity and velocity observations that would be most informative about the surface velocity field and surface FTLE field (from which Lagrangian coherent structures are estimated).

We expect that the transfer of humans’

scientific predictive knowledge and decision-making capabilities to autonomous ocean sampling and computing machines will continue to increase, leading to expert ALPS systems and collaborative human-machine networks for ocean science. 

REFERENCES

- Bellingham, J.G., and K. Rajan. 2007. Robotics in remote and hostile environments. *Science* 318(5853):1,098–1,102, <https://doi.org/10.1126/science.1146230>.
- Bocquet, M., C.A. Pires, and L. Wu. 2010. Beyond Gaussian statistical modeling in geophysical data assimilation. *Monthly Weather Review* 138(8):2,997–3,023.
- Burchard, H., L. Debreu, K. Klingbeil, and F. Lemarié. 2017. The numerics of hydrostatic structured-grid coastal ocean models: State of the art and future perspectives. *HAL-Inria*, ID: hal-01443357.
- Centurioni, L.R., V. Hormann, L.D. Talley, I. Arzeno, L. Beal, M. Caruso, P. Conry, R. Echols, H.J.S. Fernando, S.N. Giddings, and others. 2017. Northern Arabian Sea Circulation-Autonomous

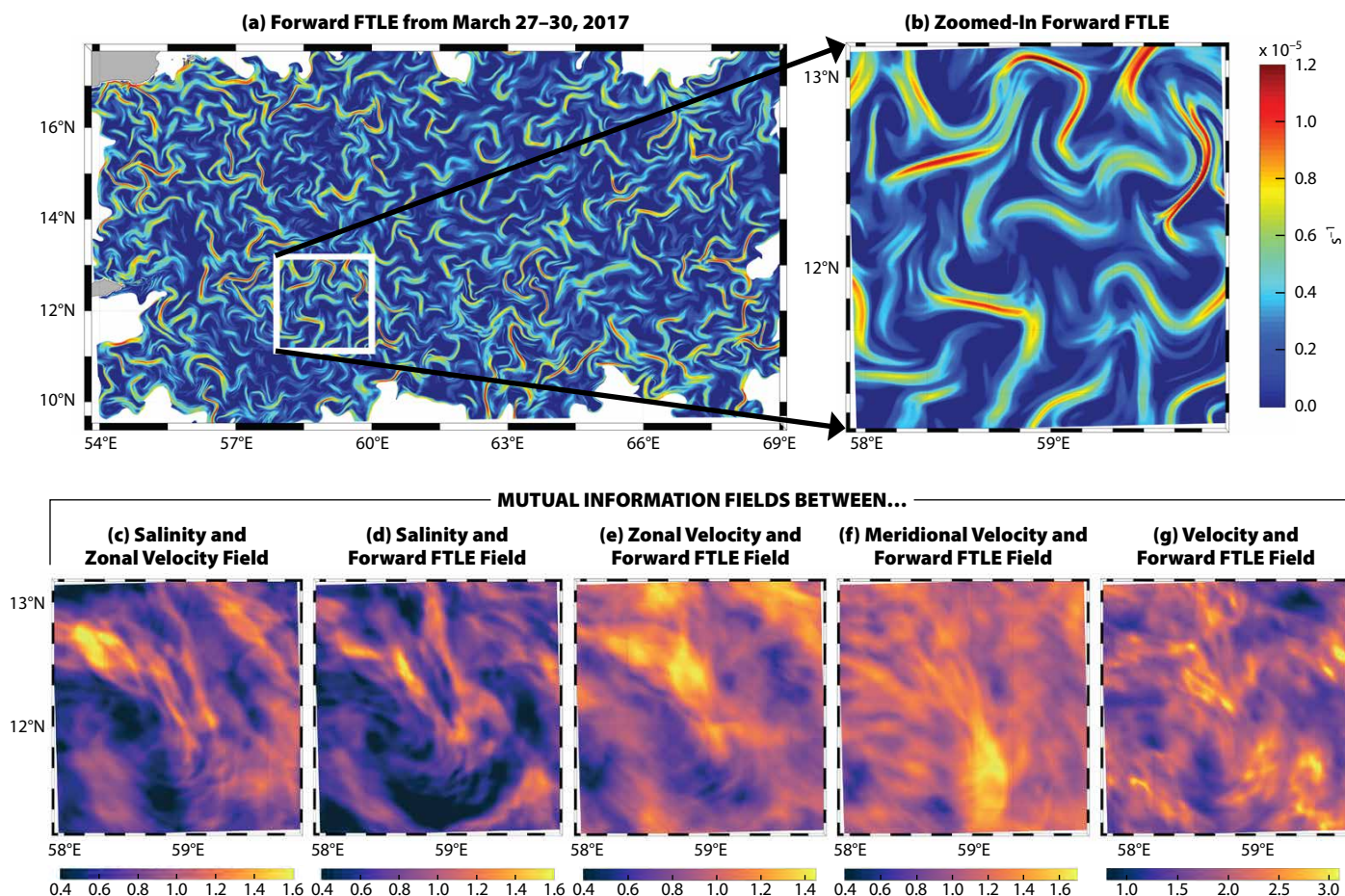


FIGURE 8. Adaptive sampling predictions for velocity or coherent structure fields. (a–b) Forecast realization of the forward-time finite-time Lyapunov exponent (FTLE) field (a) and of the same FTLE field but zoomed in a small domain (b), marked by the white box in (a). (c–g) Forecast mutual information fields within this small domain, between the observation variable at any location in the domain and the verification variable which is here always a field defined over that small domain. The five mutual information fields forecasts are between each of the following pairs of observation and verification variables: (c) salinity and zonal velocity field, (d) salinity and forward-time FTLE field, (e) zonal velocity and forward-time FTLE field, (f) meridional velocity and forward-time FTLE field, and (g) velocity (both components) and forward-time FTLE field. These mutual information fields forecast the most informative observation locations for estimating the verification variable over the small domain. Note that the color bars of panels (c–g) differ.

- Research (NASCar): A research initiative based on autonomous sensors. *Oceanography* 30(2):74–87, <https://doi.org/10.5670/oceanog.2017.224>.
- Cover, T.M., and J.A. Thomas. 1991. *Elements of Information Theory*. John Wiley & Sons, 576 pp.
- Cummings, J.A., and O.M. Smedstad. 2013. Variational data assimilation for the global ocean. Pp. 303–343 in *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, vol. II. Springer Berlin Heidelberg.
- Curtin, T.B., and J.G. Bellingham. 2009. Progress toward autonomous ocean sampling networks. *Deep Sea Research Part II* 56(3):62–67, <https://doi.org/10.1016/j.dsr2.2008.09.005>.
- Curtin, T.B., J.G. Bellingham, J. Catipovic, and D. Webb. 1993. Autonomous oceanographic sampling networks. *Oceanography* 6(3):86–94, <https://doi.org/10.5670/oceanog.1993.03>.
- Cushman-Roisin, B., and J.M. Beckers. 2013. *Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects*, vol. 101, 2nd ed. Academic Press, 875 pp.
- Deleersnijder, E., V. Legat, and P.F.J. Lermusiaux. 2010. Multi-scale modelling of coastal, shelf and global ocean dynamics. *Ocean Dynamics* 60:1,357–1,359, <https://doi.org/10.1007/s10236-010-0363-6>.
- Deleersnijder, E., and P.F.J. Lermusiaux. 2008. Multi-scale modelling: Nested grid and unstructured mesh approaches. *Ocean Dynamics* 58:335–336, <https://doi.org/10.1007/s10236-008-0170-5>.
- Dickey, T.D. 2003. Emerging ocean observations for interdisciplinary data assimilation systems. *Journal of Marine Systems* 40:5–48, [https://doi.org/10.1016/S0924-7963\(03\)00011-3](https://doi.org/10.1016/S0924-7963(03)00011-3).
- Dickey, T.D., E.C. Itsweire, M.A. Moline, and M.J. Perry. 2008. Introduction to the *Limnology and Oceanography* special issue on autonomous and Lagrangian platforms and sensors (ALPS). *Limnology and Oceanography* 53, https://doi.org/10.4319/lo.2008.53.5_part_2.2057.
- Edwards, J., J. Smith, A. Girard, D. Wickman, P.F.J. Lermusiaux, D.N. Subramani, P.J. Haley Jr., C. Mirabito, C.S. Kulkarni, and S. Jana. In press. Data-driven learning and modeling of AUV operational characteristics for optimal path planning. In *Oceans '17 MTS/IEEE*, Aberdeen, June 19–22, 2017.
- Egbert, G.D., and S.Y. Erofeeva. 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology* 19(2):183–204, [https://doi.org/10.1175/1520-0426\(2002\)019<0183:EIMOB>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOB>2.0.CO;2).
- Egbert, G.D., and S.Y. Erofeeva. 2013. *TPX08-Atlas*. OSU Tidal Data Inversion, http://volkov.oc.eorst.edu/tides/tpxo8_atlas.html.
- Environmental Modeling Center. 2003. The GFS Atmospheric Model. NCEP Office Note 442, Global Climate and Weather Modeling Branch, EMC, Camp Springs, Maryland.
- Fetton, F., and P.F.J. Lermusiaux. In press. Dynamically orthogonal numerical schemes for efficient stochastic advection and Lagrangian transport. *SIAM Review*.
- Haley, P.J. Jr., A. Agarwal, and P.F.J. Lermusiaux. 2015. Optimizing velocities and transports for complex coastal regions and archipelagos. *Ocean Modelling* 89:1–28, <https://doi.org/10.1016/j.ocemod.2015.02.005>.
- Haley, P.J. Jr., and P.F.J. Lermusiaux. 2010. Multiscale two-way embedding schemes for free-surface primitive-equations in the Multidisciplinary Simulation, Estimation and Assimilation System. *Ocean Dynamics* 60:1,497–1,537, <https://doi.org/10.1007/s10236-010-0349-4>.
- Haller, G. 2015. Lagrangian coherent structures. *Annual Review of Fluid Mechanics* 47:137–162, <https://doi.org/10.1146/annurev-fluid-010313-141322>.
- Hogan, T.F., M. Liu, J.A. Ridout, M.S. Peng, T.R. Whitcomb, B.C. Ruston, C.A. Reynolds, S.D. Eckermann, J.R. Moskatis, N.L. Baker, and others. 2014. The Navy Global Environmental Model. *Oceanography* 27(3):116–125, <https://doi.org/10.5670/oceanog.2014.73>.
- Jackson, P. 1998. *Introduction to Expert Systems*, 3rd ed. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 542 pp.
- Leonard, J.J., and A. Bahr. 2016. Autonomous underwater vehicle navigation. Pp. 341–358 in *Springer Handbook of Ocean Engineering*. Springer International Publishing.
- Leonard, N.E., D.A. Paley, R.E. Davis, D.M. Fratantoni, F. Lekien, and F. Zhang. 2010. Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in Monterey Bay. *Journal of Field Robotics* 27(6):718–740, <https://doi.org/10.1002/rob.20366>.
- Leonard, N.E., D.A. Paley, F. Lekien, R. Sepulchre, D.M. Fratantoni, and R.E. Davis. 2007. Collective motion, sensor networks, and ocean sampling. *Proceedings of the IEEE* 95(1):48–74, <https://doi.org/10.1109/JPROC.2006.887295>.
- Lermusiaux, P.F.J. 1999. Estimation and study of mesoscale variability in the Strait of Sicily. *Dynamics of Atmospheres and Oceans* 29(2):255–303, [https://doi.org/10.1016/S0377-0265\(99\)00008-1](https://doi.org/10.1016/S0377-0265(99)00008-1).
- Lermusiaux, P.F.J. 2002. On the mapping of multivariate geophysical fields: Sensitivity to size, scales and dynamics. *Journal of Atmospheric and Oceanic Technology* 19:1,602–1,637, [https://doi.org/10.1175/1520-0426\(2002\)019<1602:OTMOMG>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<1602:OTMOMG>2.0.CO;2).
- Lermusiaux, P.F.J. 2006. Uncertainty estimation and prediction for interdisciplinary ocean dynamics. *Journal of Computational Physics* 217:176–199, <https://doi.org/10.1016/j.jcp.2006.02.010>.
- Lermusiaux, P.F.J. 2007. Adaptive modeling, adaptive data assimilation and adaptive sampling. *Physica D* 230:172–196, <https://doi.org/10.1016/j.physd.2007.02.014>.
- Lermusiaux, P.F.J., D.G.M. Anderson, and C.J. Lozano. 2000. On the mapping of multivariate geophysical fields: Error and variability subspace estimates. *Quarterly Journal of the Royal Meteorological Society* 126:1,387–1,430, <https://doi.org/10.1002/qj.49712656510>.
- Lermusiaux, P.F.J., C.-S. Chiu, G.G. Gawarkiewicz, P. Abbot, A.R. Robinson, R.N. Miller, P.J. Haley, W.G. Leslie, S.J. Majumdar, A. Pang, and F. Lekien. 2006a. Quantifying uncertainties in ocean predictions. *Oceanography* 19(1):90–103, <https://doi.org/10.5670/oceanog.2006.93>.
- Lermusiaux, P.F.J., P.J. Haley Jr., S. Jana, A. Gupta, C. Kulkarni, C. Mirabito, W.H. Ali, and D. Subramani. 2017. NASCar-OPS Sea Exercise 17, Arabian Sea: February–March 2017, http://mseas.mit.edu/Sea_exercises/NASCar-OPS-17.
- Lermusiaux, P.F.J., T. Lolla, P.J. Haley Jr., K. Yigit, M.P. Ueckermann, T. Sondergaard, and W.G. Leslie. 2016. Science of Autonomy: Time-optimal path planning and adaptive sampling for swarms of ocean vehicles. Pp. 481–498 in *Springer Handbook of Ocean Engineering*. T. Curtin, ed., https://doi.org/10.1007/978-3-319-16649-0_21.
- Lermusiaux, P.F.J., P. Malanotte-Rizzoli, D. Stammer, J. Carton, J. Cummings, and A.M. Moore. 2006b. Progress and prospects of U.S. data assimilation in ocean research. *Oceanography* 19(1):172–183, <https://doi.org/10.5670/oceanog.2006.102>.
- Lermusiaux, P.F.J., and A.R. Robinson. 1999. Data assimilation via Error Subspace Statistical Estimation: Part I: Theory and schemes. *Monthly Weather Review* 127(7):1,385–1,407, [https://doi.org/10.1175/1520-0493\(1999\)127<1385:DAVESS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<1385:DAVESS>2.0.CO;2).
- Lermusiaux, P.F.J., A.R. Robinson, P.J. Haley, and W.G. Leslie. 2002. Advanced interdisciplinary data assimilation: Filtering and smoothing via error subspace statistical estimation. Pp. 795–802 in *Proceedings of OCEANS 2002 MTS/IEEE*, April 29, 2003. Holland Publications, <https://doi.org/10.1109/OCEANS.2002.1192071>.
- Lermusiaux, P.F.J., D.N. Subramani, J. Lin, C.S. Kulkarni, A. Gupta, A. Dutt, T. Lolla, P.J. Haley Jr., W.H. Ali, C. Mirabito, S. Jana. In press. A Future for Intelligent Autonomous Ocean Observing Systems. *The Sea*.
- Leslie, W.G., P.J. Haley Jr., P.F.J. Lermusiaux, M.P. Ueckermann, O. Logutov, and J. Xu. 2010. *MSEAS Manual*. MSEAS Report-06, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.
- Lolla, T. 2016. *Path Planning and Adaptive Sampling in the Coastal Ocean*. 2016. PhD Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering.
- Lolla, T., P.J. Haley Jr., and P.F.J. Lermusiaux. 2014a. Time-optimal path planning in dynamic flows using level set equations: Realistic applications. *Ocean Dynamics* 64(10):1,399–1,417, <https://doi.org/10.1007/s10236-014-0760-3>.
- Lolla, T., P.J. Haley Jr., and P.F.J. Lermusiaux. 2015. Path planning in multi-scale ocean flows: Coordination and dynamic obstacles. *Ocean Modelling* 94:46–66, <https://doi.org/10.1016/j.ocemod.2015.07.013>.
- Lolla, T., and P.F.J. Lermusiaux. 2017a. A Gaussian mixture model smoother for continuous nonlinear stochastic dynamical systems: Theory and scheme. *Monthly Weather Review* 145:2,743–2,761, <https://doi.org/10.1175/MWR-D-16-0064.1>.
- Lolla, T., and P.F.J. Lermusiaux. 2017b. A Gaussian mixture model smoother for continuous nonlinear stochastic dynamical systems: Applications. *Monthly Weather Review* 145:2,763–2,790, <https://doi.org/10.1175/MWR-D-16-0065.1>.
- Lolla, T., P.F.J. Lermusiaux, M.P. Ueckermann, and P.J. Haley Jr. 2014b. Time-optimal path planning in dynamic flows using level set equations: Theory and schemes. *Ocean Dynamics* 64(10):1,373–1,397, <https://doi.org/10.1007/s10236-014-0757-y>.
- Mirabito, C., D.N. Subramani, T. Lolla, P.J. Haley Jr., A. Jain, P.F.J. Lermusiaux, C. Li, D.K.P. Yue, Y. Liu, F.S. Hover, and others. In press. Autonomy for surface ship interception. In *Oceans '17 MTS/IEEE*. Aberdeen, June 19–22, 2017.
- Nicholson, J.W., and A.J. Healey. 2008. The present state of autonomous underwater vehicle (AUV) applications and technologies. *Marine Technology Society Journal* 42(1):44–51, <https://doi.org/10.4031/002533208786861272>.
- Paley, D.A., F. Zhang, and N.E. Leonard. 2008. Cooperative control for ocean sampling: The glider coordinated control system. *IEEE Transactions on Control Systems Technology* 16(4):735–744, <https://doi.org/10.1109/TCST.2007.912238>.
- Ramp, S.R., R.E. Davis, N.E. Leonard, I. Shulman, Y. Chao, A.R. Robinson, J. Marsden, P.F.J. Lermusiaux, D. Fratantoni, J.D. Paduan, and others. 2009. Preparing to predict: The second Autonomous Ocean Sampling Network (AOSN-II) Experiment in the Monterey Bay. *Deep Sea Research Part II* 56:68–86, <https://doi.org/10.1016/j.dsr2.2008.08.013>.
- Reich, S., and C. Cotter. 2015. *Probabilistic Forecasting and Bayesian Data Assimilation*. Cambridge University Press, 308 pp.
- Ringler, T., M. Petersen, R.L. Higdon, D. Jacobsen, P.W. Jones, and M. Maltrud. 2013. A multi-resolution approach to global ocean modeling. *Ocean Modelling* 69:211–232, <https://doi.org/10.1016/j.ocemod.2013.04.010>.

- Robinson, A.R., J. Sellschopp, W.G. Leslie, A. Alvarez, G. Baldasserini, P.J. Haley, P.F.J. Lermusiaux, C.J. Lozano, E. Nacini, R. Onken, and others. 2003. Forecasting synoptic transients in the Eastern Ligurian Sea. In *Rapid Environmental Assessment*. E. Bovio, R. Tyce, and H. Schmidt, eds, SACLANTCEN Conference Proceedings Series CP-46, Saclantcen, La Spezia, Italy.
- Roy, N., H.L. Choi, D. Gombos, J. Hansen, J. How, and S. Park. 2007. Adaptive observation strategies for forecast error minimization. Pp. 1,138–1,146 in *Computational Science—ICCS 2007*. Y. Shi, G.D. van Albada, J. Dongarra, and P.M.A. Sloot, eds, https://doi.org/10.1007/978-3-540-72584-8_149.
- Rudnick, D.L., R.E. Davis, C.C. Eriksen, D.M. Fratantoni, and M.J. Perry. 2004. Underwater gliders for ocean research. *Marine Technology Society Journal* 38:73–84, <https://doi.org/10.4031/002533204787522703>.
- Rudnick, D.L., and M.J. Perry, eds. 2003. *ALPS: Autonomous and Lagrangian Platforms and Sensors*. Report of the Workshop held March 31–April 2, 2003, 64 pp, https://geo-prose.com/pdfs/alps_report.pdf.
- Russell, S., and P. Norvig. 2009. *Artificial Intelligence: A Modern Approach*. Prentice Hall, Upper Saddle River, NJ, 1,152 pp.
- Sapsis, T.P., and P.F.J. Lermusiaux. 2009. Dynamically orthogonal field equations for continuous stochastic dynamical systems. *Physica D* 238:2,347–2,360, <https://doi.org/10.1016/j.physd.2009.09.017>.
- Särkkä, S. 2013. *Bayesian Filtering and Smoothing*. Volume 3 of Institute of Mathematical Statistics Textbooks, Cambridge University Press, 232 pp.
- Schmidt, H., M.R. Benjamin, S.M. Petillo, and R. Lum. 2016. Nested autonomy for distributed ocean sensing. Pp. 459–480 in *Springer Handbook of Ocean Engineering*. Springer International Publishing.
- Schofield, O., S. Glenn, J. Orcutt, M. Arrott, M. Meisinger, A. Gangopadhyay, W. Brown, R. Signell, M. Moline, Y. Chao, and others. 2010. Automated sensor networks to advance ocean science. *Eos Transactions, American Geophysical Union* 91(39):345–346, <https://doi.org/10.1029/2010EO390001>.
- Smith, W.H., and D.T. Sandwell. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277(5334):1,956–1,962, <https://doi.org/10.1126/science.277.5334.1956>.
- Sondergaard, T., and P.F.J. Lermusiaux. 2013a. Data assimilation with Gaussian mixture models using the dynamically orthogonal field equations: Part I. Theory and scheme. *Monthly Weather Review* 141(6):1,737–1,760, <https://doi.org/10.1175/MWR-D-11-00295.1>.
- Sondergaard, T., and P.F.J. Lermusiaux. 2013b. Data assimilation with Gaussian mixture models using the dynamically orthogonal field equations: Part II. Applications. *Monthly Weather Review* 141(6):1,761–1,785, <https://doi.org/10.1175/MWR-D-11-00296.1>.
- Steinberg, M. 2006. Intelligent autonomy for unmanned naval vehicles. In *Proceedings of SPIE 6230, Unmanned Systems Technology VIII*. 623013, May 9, 2006, <https://doi.org/10.1117/12.665870>.
- Stommel, H. 1989. The Slocum mission. *Oceanography* 2(1):22–25, <https://doi.org/10.5670/oceanog.1989.26>.
- Subramani, D.N., P.J. Haley Jr., and P.F.J. Lermusiaux. 2017. Energy-optimal path planning in the coastal ocean. *Journal of Geophysical Research* 122:3,981–4,003, <https://doi.org/10.1002/2016JC012231>.
- Subramani, D.N., and P.F.J. Lermusiaux. 2016. Energy-optimal path planning by stochastic dynamically orthogonal level-set optimization. *Ocean Modelling* 100:57–77, <https://doi.org/10.1016/j.ocemod.2016.01.006>.
- Subramani, D.N., P.F.J. Lermusiaux, P.J. Haley Jr., C. Mirabito, S. Jana, C.S. Kulkarni, A. Girard, D. Wickman, J. Edwards, and J. Smith. In press. Time-optimal path planning: Real-time sea exercises. In *Oceans '17 MTS/IEEE*. Aberdeen, June, 19–22 2017.
- Sun, W., P. Tsiotras, T. Lolla, D.N. Subramani, and P.J.F. Lermusiaux. 2017a. Pursuit-evasion games in dynamic flow fields via reachability set analysis. Pp. 4,595–4,600 in *American Control Conference (ACC)*. 2017. May 24–26, 2017, Seattle, Washington, IEEE, <https://doi.org/10.23919/ACC.2017.7963664>.
- Sun, W., P. Tsiotras, T. Lolla, D.N. Subramani, and P.F.J. Lermusiaux. 2017b. Multiple-pursuer/one-evader pursuit-evasion game in dynamic flow fields. *Journal of Guidance, Control and Dynamics* 40(7):1,627–1,637, <https://doi.org/10.2514/1.G002125>.
- Ueckermann, M.P., P.F.J. Lermusiaux, and T.P. Sapsis. 2013. Numerical schemes for dynamically orthogonal equations of stochastic fluid and ocean flows. *Journal of Computational Physics* 233:272–294, <https://doi.org/10.1016/j.jcp.2012.08.041>.
- Venkatesan R., A. Tandon, E. D'Asaro, and M.A. Atmanand, eds. 2017. *Observing the Oceans in Real Time*. Springer International Publishing, 400 pp.
- Wei, Q.J. 2015. *Time-Optimal Path Planning in Uncertain Flow Fields Using Stochastic Dynamically Orthogonal Level Set Equations*. B.S. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.
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An undercurrent off the east coast of Sri Lanka

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Abstract. The existence of a seasonally varying undercurrent along 8° N off the east coast of Sri Lanka is inferred from shipboard hydrography, Argo floats, glider measurements, and two ocean general circulation model simulations. Together, they reveal an undercurrent below 100–200 m flowing in the opposite direction to the surface current, which is most pronounced during boreal spring and summer and switches direction between these two seasons. The volume transport of the undercurrent (200–1000 m layer) can be more than 10 Sv in either direction, exceeding the transport of 1–6 Sv carried by the surface current (0–200 m layer). The undercurrent transports relatively fresher water southward during spring, while it advects more saline water northward along the east coast of Sri Lanka during summer. Although the undercurrent is potentially a pathway of salt exchange between the Arabian Sea and the Bay of Bengal, the observations and the ocean general circulation models suggest that the salinity contrast between seasons and between the boundary current and interior is less than 0.09 in the subsurface layer, suggesting a small salt transport by the undercurrent of less than 4 % of the salinity deficit in the Bay of Bengal.

firmed the role of the surface current along the Sri Lankan east coast in distributing mass and salt between the AS and the BoB. Drifters indicate that a strong surface-intensified current to the east of Sri Lanka during the northeast monsoon (November–January) transports low-salinity water out of the BoB toward the AS around the south coast of Sri Lanka (Wijesekera et al., 2015). An ocean general circulation model (OGCM) study also shows that significant mass and salt transport occur between the AS and the BoB along the eastern and southern coast of Sri Lanka (Jensen et al., 2016).

The surface current to the east of Sri Lanka is influenced by local alongshore winds, remote winds in the vicinity of the northern and eastern boundaries of the BoB, equatorial waves, and interior Ekman pumping (Yu et al., 1991; Shetye et al., 1993; McCreary et al., 1996; Shankar et al., 1996; Vinayachandran and Yamagata, 1997). This current has a strong seasonal pattern (Shankar et al., 2002; Lee et al., 2016) with recirculation loops that are highly variable in time and space (Durand et al., 2009). Some of the recirculations appear seasonally, such as the Sri Lanka Dome (SLD), a cyclonic eddy that is well developed in July (Vinayachandran and Yamagata, 1997). The SLD is driven by Rossby waves radiating from the eastern boundary and intensified Ekman pumping inside the BoB (Vinayachandran et al., 1999; Shankar et al., 2002; de Vos et al., 2014). The SLD propagates westward (Wijesekera et al., 2016b) toward the east coast of Sri Lanka, resulting in a southward coastal surface flow during early summer. In October, the prevailing wind in the BoB starts reversing direction and blows south-

1 Introduction

Knowledge of the circulation in the southern Bay of Bengal (BoB) is crucial to understanding the contrasting salinity distributions of the Arabian Sea (AS) and the BoB since it controls the amount of water and salt exchanged between the two ocean basins. Observations and modeling studies have con-

westward. This marks the start of the northeast monsoon when the local wind along the east coast of India drives the East India Coastal Current (EICC) southward with speeds exceeding 1 m s^{-1} extending from the east coast of India southward to the southern tip of Sri Lanka (Shetye et al., 1996; Wijesekera et al., 2015).

The subsurface circulation in this region is also potentially important, as high-salinity water from the AS can be subducted beneath the fresher surface water originating from river runoff and precipitation in the northern BoB (Rao and Sivakumar, 2003; Sengupta et al., 2006; Vinayachandran et al., 2013; Gordon et al., 2016; Jensen et al., 2016); this is evident in observations and model studies both during the northeast (Wijesekera et al., 2015) and southwest monsoons (June–August) (Wijesekera et al., 2016b). Little is known about the subsurface structure of the boundary current along the east coast of Sri Lanka. Mooring observations show a reversing subsurface current occurring off the southern coast of Sri Lanka; it is most distinct during boreal spring and summer (Schott et al., 1994). In addition, a reversal of the EICC along the east coast of India is observed below 100 m that is southward during the southwest monsoon and northward during the northeast monsoon, with the winter undercurrent being a more permanent feature (Mukherjee et al., 2014). The direction of this undercurrent is in good agreement with findings from a continuously stratified linear ocean model (SLM) (McCreary et al., 1996). The SLM also suggests the presence of an undercurrent along the Sri Lankan east coast (centered at 8° N) that reverses its direction twice a year, with model speeds ranging from 6 cm s^{-1} equatorward during boreal spring to 8 cm s^{-1} poleward during summer. This undercurrent has not been observed before and will be the focus of this study. We will investigate the vertical structure and seasonal variability of subsurface flows in the boundary current system off the eastern coast of Sri Lanka using OGCMs as well as observations from shipboard hydrography, Argo floats, and glider measurements. Knowledge of the vertical structure, variability, and associated dynamics of the boundary current will contribute to a better understanding of mass and salt exchanges in the northern Indian Ocean.

2 Data and methodology

Shipboard hydrography and Argo conductivity–temperature–depth (CTD) profiles, together with satellite altimeter-derived surface absolute dynamic topography (ADT), were used to determine the vertical structure of the current east of Sri Lanka. There were 13 shipboard hydrography and 116 Argo profiles available between 7 and 9° N and within 130 km of the Sri Lankan east coast that sampled to at least 1000 m depth (Fig. 1a). The hydrographic profiles were collected over the period of 2008–2017 while the Argo profiles were collected over 2007–2017. The gridded delayed-time ADT products were derived from Archiving,

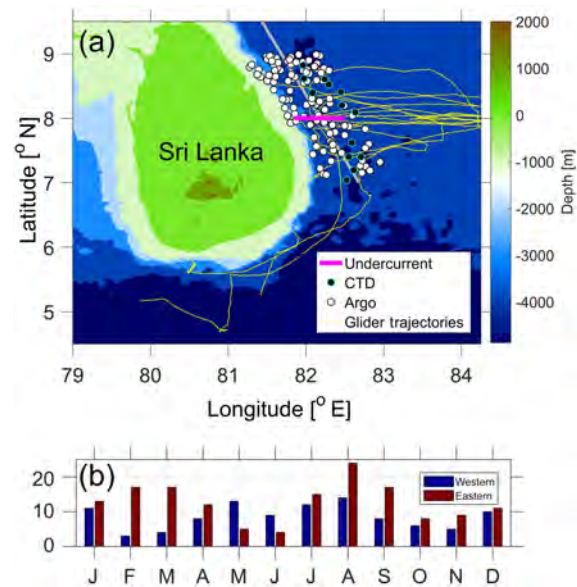


Figure 1. Bathymetry around Sri Lanka (a) with the location of the shipboard hydrography measurements (black dots), Argo profiles (white dots), and glider measurement transects (yellow lines). The grey line divides hydrography and Argo measurements into the eastern and western sectors used in the seasonal mean dynamic height calculation. The OGCM outputs are interpolated along 8° N (magenta line). The number of hydrography and Argo profiles available in the mean dynamic height calculation for each month for the eastern (red) and western (blue) sectors are shown in (b).

Validation, and Interpretation of Satellite Oceanographic (AVISO) Data (Ducet et al., 2000) which are available over the period of 1993–2016 with spatial and temporal resolutions of $1/4^\circ$ latitude $\times$ $1/4^\circ$ longitude and 7 days, respectively.

The hydrography–Argo-based mean seasonal absolute geostrophic meridional velocity profiles were calculated by combining sheared velocity profiles from hydrography and Argo measurements and surface velocity from the ADT products. The number of hydrography and Argo profiles available were too few to calculate robust estimates of monthly meridional geostrophic velocity. Hence, to derive the seasonal sheared velocity profiles, we used sliding mean dynamic heights calculated from hydrography–Argo profiles located to the west and east of the central position of the boundary current (Fig. 1a), measured every 2 months (hereafter denoted as bimonthly); the position of the boundary current was determined from a longitude–depth velocity transect along 8° N derived from glider measurements and OGCMs (e.g., Fig. 2). The low-pass-filtered geostrophic meridional sheared velocity profile is thus proportional to the corresponding difference between the eastern and western filtered dynamic heights. The number of hydrography and Argo profiles available in each bimonthly period varied from 3 to 14 in the western region and from 4 to 24 in the eastern region

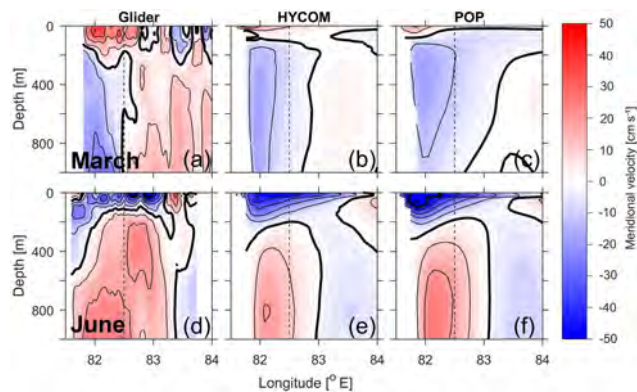


Figure 2. Geostrophic meridional velocity referenced to the depth-averaged velocity across 8° N from glider measurements during 18–30 March 2014 (a) and 24 May–8 June 2014 (d), the mean total meridional velocity from HYCOM (b and e) and POP (c and f) in March and June over 2003–2012 and 1995–2007 periods, respectively. The black dashed line marks the typical eastern extent of the undercurrent core; the region bounded to its west is used for a subsequent averaging in Fig. 3. Thin black lines are plotted every 10 cm s^{-1} , and thick black lines are plotted every 50 cm s^{-1} .

(Fig. 1b). The equally low-pass-filtered surface meridional velocity from the satellite ADT along 8° N between 81.75° and 82.5° E was added to the sheared profiles to yield absolute geostrophic meridional velocity profiles.

Glider measurements were deployed to the east of Sri Lanka between 7° and 9° N to collect salinity and temperature profiles from the surface to 1000 m depth during February 2014–January 2016 (Lee et al., 2016) (Fig. 1a). The geostrophic velocities from the glider measurements are referenced in two ways. Glider temperature and salinity profiles are used to calculate geostrophic velocity across 8° N referenced to the glider depth-averaged velocity to examine the vertical structure of the undercurrent (e.g., Fig. 2). Note that profiles sampled by the gliders were sporadic in time; the gliders took approximately 2–7 days to complete the transect and then could take 5–30 days until the same transect was repeated. Thus, the glider velocity referenced to the depth-averaged current is less suitable to estimate the seasonal evolution of the circulation along Sri Lankan east coast (i.e., Fig. 3). Instead, temperature and salinity profiles were used in the same way as the hydrography and Argo profiles to calculate bimonthly geostrophic meridional velocity.

Two global, strongly eddy-active OGCMs were used to study the vertical structure and seasonal variation of the boundary current, as well as its associated dynamics: 0.1° Parallel Ocean Program (POP) and 0.08° Hybrid Coordinate Ocean Model (HYCOM). Their horizontal resolutions correspond to 11 and 9 km at 8° N, respectively. POP is a three-dimensional, z -level, primitive equation model (Smith et al., 2010). It was configured on a global tripole grid with 42 vertical levels and partial bottom cells. Its vertical grid spacing

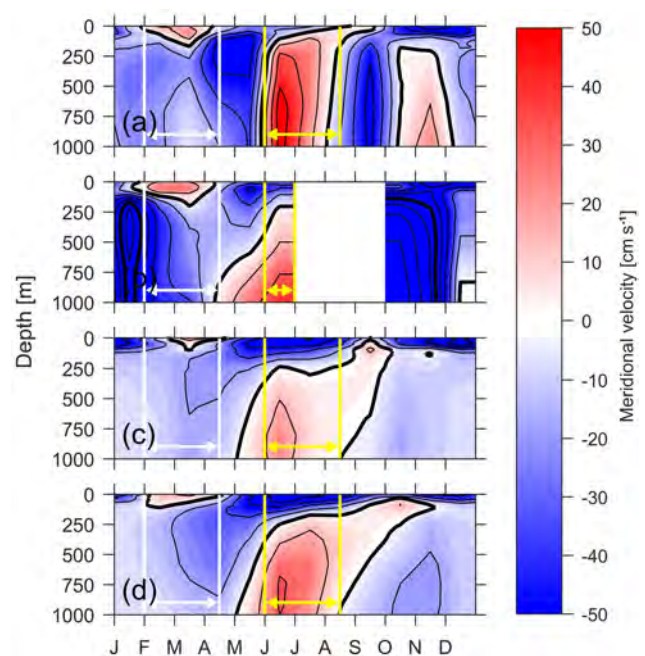


Figure 3. Bimonthly-mean seasonal variation of the meridional geostrophic velocity referenced to the surface satellite ADT across the magenta transect in Fig. 1 from hydrography and Argo measurements (a), glider measurements (b), monthly-mean meridional velocity profiles from HYCOM (c), and POP (d) output. Line contours are plotted in the same manner as in Fig. 2. White and yellow lines indicate periods when the undercurrent is most pronounced.

near the surface (top 50 m) is roughly 10 m. The POP simulation was initialized from year 30 of an earlier POP run that used the same set-up but was driven by a monthly climatology of Co-ordinated Ocean Reference Experiments (CORE) atmospheric surface fluxes (Maltrud et al., 2010). The subsequent POP simulation was forced by interannually varying CORE-II fluxes for 1990–2007 (Delman et al., 2015). The POP output analyzed here consists of three-dimensional daily-averaged velocities and salinity for 1995–2007. HYCOM has a hybrid vertical coordinate with isopycnal coordinates in the open stratified ocean, a terrain-following coordinate for coastal regions, and a z -level coordinate in the mixed layer (Metzger et al., 2010). It was configured on a global tripole grid with 41 vertical layers. Vertical grid spacing very close to the surface is roughly 1 m, increasing to 8 m over 36–85 m. The simulation was forced by 3-hourly Navy Operational Global Atmospheric Prediction System (NOGAPS) fields (Rosmond et al., 2002). However, the archived velocity fields used here are monthly and cover a shorter period compared to POP of 2003–2012.

Table 1. Statistics of the undercurrent across 8° N in March from the glider geostrophic velocity as presented in Fig. 2 and mean total velocity from HYCOM and POP. Here, $v_{\max}$ represents maximum meridional velocity; depth of reversal is defined as the depth of the zero meridional velocity at the location of the maximum velocity; width of the undercurrent is defined as the distance from the coast at the depth of maximum velocity to the location where the meridional velocity is zero.

	$v_{\max}$ (cm s ⁻¹)	Depth of $v_{\max}$ (m)	Position of $v_{\max}$ (° E)	Depth of reversal (m)	Width (km)
Glider	-25.3	1000.0	82.06	232.0	107.8
HYCOM	-16.2	570.4	82.00	83.3	151.9
POP	-18.9	268.5	81.95	77.4	209.1

Table 2. Same as Table 1 but for June.

	$v_{\max}$ (cm s ⁻¹)	Depth of $v_{\max}$ (m)	Position of $v_{\max}$ (° E)	Depth of reversal (m)	Width (km)
Glider	29.6	1000.0	81.90–82.40	117.3–300.0	206.9
HYCOM	20.6	800.8	82.08	244.8	165.1
POP	27.6	918.4	82.15	244.1	172.8

3 The circulation east of Sri Lanka

3.1 Vertical structure

A zonal transect along 8° N is used to examine the circulation off the eastern coast of Sri Lanka. Both observations and OGCMs show a seasonally reversing surface current confined to the upper 100–200 m of the water column (Figs. 2, 3). A subsurface current that flows in the opposite direction to that of the surface water, defined here as an undercurrent, is observed from glider measurements and the OGCMs particularly in March and June (Fig. 2). As noted above, geostrophic velocities derived from glider measurements, during 18–30 March 2014 (Fig. 2a) and 28 May–8 June 2014 (Fig. 2d), are referenced to the depth-averaged velocity measured directly by the gliders. Velocity transects from HYCOM (Fig. 2b, e) and POP (Fig. 2c, f) were constructed from monthly averages of total velocity in March and June for the periods of 2003–2012 and 1995–2007, respectively.

The model transects show reasonable agreement with that from the gliders in regard to the vertical structure of both the surface current and undercurrent. In March, the core of the observed undercurrent is located about 55 km from the coast and has a maximum speed of 16–25 cm s⁻¹ southward (Table 1). HYCOM and POP have maximum flows in the reverse direction to the surface, i.e., southward, at 570 and 268 m, respectively (Fig. 2a–b) while glider measurements show maximum subsurface flow at the deepest measured depth of 1000 m (Fig. 2c). In June, a northward undercurrent is observed below approximately 250 m with a maximum speed greater than 20 cm s⁻¹ at about 900 m (Fig. 2d–f; Table 2). The summer undercurrent is approximately 165 km wide in the OGCMs. The velocity section derived from gliders shows a wider undercurrent of 210 km with two cores: a deep core that is approximately 100 km wide centered at 82.2° E and a

shallow core at 400 m near 82.75° E (Fig. 2d). This double-core feature is also evident in some individual model years, but is not present in the multiyear mean (Fig. 2e, f).

Investigation of individual years of HYCOM and POP velocity fields reveals that, although the location of the undercurrent core varies in depth and longitude, it is nearly always confined to the west of 82.5° E. Thus, this longitude limit will be used in subsequent averages over the undercurrent regime, and is indicated by the dashed line in Fig. 2. The spring undercurrent exists in all years in the model simulations except for in 2007 and 2011 in HYCOM when an El Niño occurs in the preceding year. POP also shows a weakening of the spring undercurrent following an El Niño event, except in 1998 when the northward-flowing surface current is absent and the southward current extends from the surface to approximately 550 m depth.

3.2 Seasonal variation

Bimonthly-mean meridional velocities computed from hydrography and Argo profiles and glider measurements are shown in Fig. 3a and b respectively. These observed geostrophic velocities are all referenced to surface velocity from the ADT. The model monthly-mean total meridional velocities (Fig. 3c, d) were constructed from the OGCMs by averaging the monthly-mean velocity across 8° N along the transect from the eastern coast of Sri Lanka to 82.5° E (depicted by the magenta transect in Fig. 1), which captures most of the undercurrent signal (Fig. 2; Tables 1, 2).

3.2.1 Surface circulation

Both surface and subsurface currents have strong seasonal variability (Fig. 3). The surface current reverses its direction twice a year, in agreement with previous studies (Yu et al., 1991; McCreary et al., 1996; Shetye et al., 1996; Vinay-

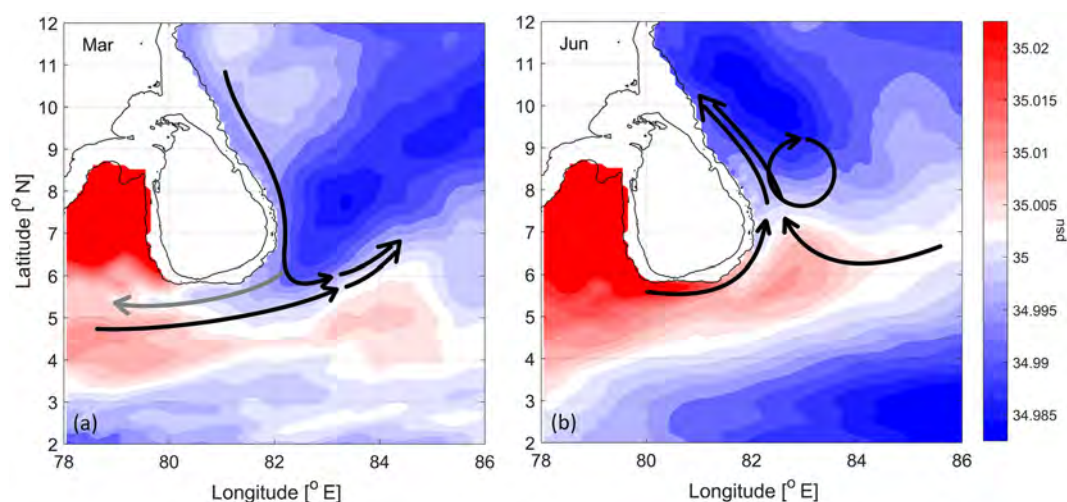


Figure 4. Simplified schematic of the undercurrent along the east and south coast of Sri Lanka at 729 m depth based on POP outputs in March (a) and June (b) plotted over the corresponding POP monthly-mean salinity. The black arrows represent the annual current patterns at 729 m, and the gray arrow shows circulation that is observed occasionally. The 0 and 1000 m bathymetry contours are plotted as thin black lines.

achandran and Yamagata, 1997; Vinayachandran et al., 1999; Eigenheer and Quadfasel, 2000; Durand et al., 2009; de Vos et al., 2014; Wijesekera et al., 2015; Lee et al., 2016). The mean meridional surface current is northward during boreal spring (Figs. 2a–c, 3) as the westward flowing North Equatorial Current often bifurcates at the east coast of Sri Lanka at approximately 7.5° N, splitting into a northward and southward branch (Shetye et al., 1993; Hacker et al., 1998). The SLD emerges during the southwest monsoon. Its western branch is responsible for the observed southward flow along the eastern coast of Sri Lanka in that season (Figs. 2d–f, 3). During boreal fall, the surface current is northward. Similarly, northward surface flow was also observed in mooring measurements in the southern BoB in late July of 2015 at 85.5° E (Wijesekera et al., 2016b). During the winter, the southward-flowing EICC extends from the Indian east coast to the southern tip of Sri Lanka (Schott et al., 1994; Wijesekera et al., 2015), resulting in strong southward flow at 8° N (Fig. 3).

3.2.2 Subsurface circulation

An undercurrent flowing in the opposing direction to the surface current is a prominent and consistent feature among the observations and OGCMs in boreal spring (beginning of February to mid-April) and summer (beginning of June to mid-August) (Fig. 3). In boreal spring, the southward-flowing undercurrent extends from approximately 200–900 m depth with a velocity maximum core in the range of 300–600 m depth. The velocities derived from hydrography and Argo profiles and glider measurements confirm the existence of the undercurrent below 150–250 m, although the magnitudes are not consistent (Fig. 3). This may be due to

interannual variation in intensity and position of the subsurface reversed flow, combined with the sporadic sampling of the hydrography and Argo data.

During the southwest monsoon, the northward-flowing undercurrent is apparent in both observations and the OGCMs (Fig. 3). The undercurrent starts developing in May and reaches its maximum speed in June. The OGCMs also suggest an upward phase propagation during summer and early fall (May–October), with a speed of approximately 1.5 m day^{-1} in the upper 200 m of the water column (Fig. 3c, d). This feature is also evident in the geostrophic velocity derived from hydrography–Argo profiles in the upper 100 m of the water column (Fig. 3a).

To gain a better understanding of the subsurface circulation, we examine the POP velocity fields at 729 m (Movie S1 in the Supplement), which encompasses the depth location of the undercurrent core in boreal spring and summer (Figs. 2, 3; Tables 1, 2). In March, the undercurrent is strong and confined to 82.5° E along the entire Sri Lankan east coast (Movie S1). The undercurrent usually turns eastward around 6° N to combine with an eastward-flowing current along the Sri Lankan south coast, as shown in the simplified schematic derived from the POP 729 m velocity fields (Fig. 4a). However, in some years (e.g., 1995, 1999, 2005, and 2007), the undercurrent turns westward around the southern coast of Sri Lanka and forms a narrow current, about 50–70 km wide, on the northern side of the eastward flow (Movie S1; Fig. 4a). Note that a similar circulation is observed in the POP velocity fields at 318 m in March, although the flow is stronger. In boreal summer, there is a convergence of the eastward-flowing current along the south coast of Sri Lanka and a westward-flowing current in the southwestern BoB at approximately 7° N, 82.25° E (Movie S1), which is also shown in the simpli-

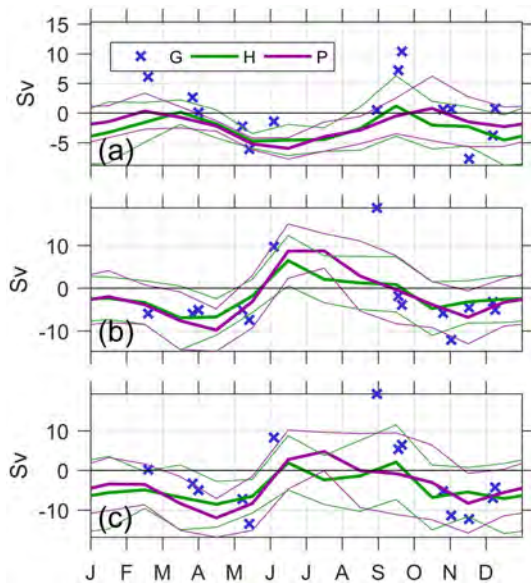


Figure 5. Meridional volume transport across 8° N from the Sri Lankan east coast to 82.5° E (dashed line in Fig. 2) calculated from glider geostrophic velocity referenced to the depth-averaged velocity (G; blue cross) and total velocity fields from HYCOM (H; thick green line) and POP (P; thick purple line) over the 0–200 m (a), 200–1000 m (b), and 0–1000 m (c) layers. Thin lines designate the mean value ± 1 standard deviation.

fied schematic (Fig. 4b). Both OGCMs agree that the convergence produces the undercurrent flowing north along the east coast of Sri Lanka that injects relatively saline water into the BoB. In addition, an anticyclonic eddy often develops along the east coast, trapping local saline water inside, which is then propagated northward with the eddy (Movie S1).

During boreal fall (mid-August to end of October) and winter (beginning of November to end of January), flows in the subsurface layer are less consistent between the observations and the OGCMs (Fig. 3). The models suggest that the subsurface current is not persistent across the years during fall and winter (Movie S1). Longitude–depth transects of meridional velocity across 8° N from POP and HYCOM (not shown) do not show a well-defined undercurrent near the east coast of Sri Lanka in the top 1000 m of the water column during these seasons.

3.3 Depth-integrated volume transport

Monthly volume transports computed from the OGCMs and volume transport computed from the discrete glider sections (referenced to depth-averaged velocity; e.g., Fig. 2) across the 8° N transect between the eastern coast of Sri Lanka and 82.5° E (Fig. 1a) over the upper (0–200 m) and lower (200–1000 m) layers are presented in Fig. 5. The seasonal variation from HYCOM, POP, and glider measurements agree well, especially in the subsurface layer. Mean volume transport in the upper layer (0–200 m) has a semiannual cycle that ranges

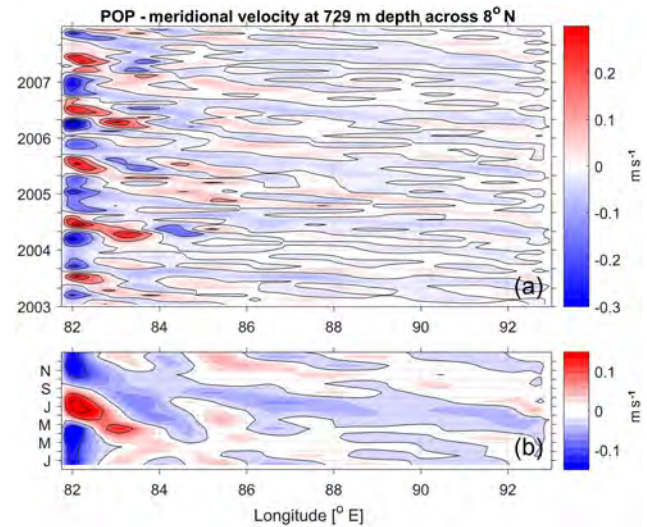


Figure 6. Time–longitude plots of monthly meridional velocity (a) and seasonal mean velocity (b) over 2003–2007 across 8° N at 729 m from POP. Note the difference in color scale.

from 1 to 6 Sv into and out of the BoB (Fig. 5a). Southward flows are observed in the surface layer during boreal summer and winter. The flows are weakly northward during boreal spring and fall.

Depth-integrated transport in the subsurface layer is southward throughout the year except during the summer when the northward-flowing undercurrent is present (Figs. 3, 5b). The undercurrent volume transport is approximately 5–7 Sv out of the BoB during boreal spring and 3–11 Sv into the BoB during boreal summer (Table 3). Moreover, the OGCMs suggest only a small mean volume transport of the subsurface current during fall and winter compared to its standard deviation (Fig. 5b), implying that the fall and winter undercurrent is not well defined in these seasons and indeed can flow northward in some years. Volume transport over the 0–1000 m layer ranges from -12 to 5 Sv and exhibits an annual cycle similar to that in the lower (200–1000 m) layer (Fig. 5c).

4 Discussion

The circulation in the southern BoB is complex as it is controlled by various forcings, such as local winds, Ekman pumping, and equatorial waves, which impact the region in different seasons. The mechanisms driving the undercurrent remain unclear and, although these are beyond the scope of this study, we put forward some informed hypotheses based on previous studies and our observations. The Rossby waves, equatorial waves, and Ekman pumping are likely to be important for producing the undercurrent: a Hovmöller diagram of POP meridional velocity across 8° N (Fig. 6) shows the westward propagation of the velocity signal at 729 m depth, origi-

Table 3. Mean transport and seasonal salinity range of the undercurrent (200–1000 m) across 8° N in boreal spring (February to mid-April as highlighted by white lines in Fig. 3) and summer (June to mid-August as highlighted by yellow lines in Fig. 3) from hydrography–Argo profiles, glider measurements, HYCOM, and POP. Seasonal salinity range is the approximate difference between boreal spring and summer extremes in average seasonal cycle. Note that the statistics representing glider measurements are derived from gridded velocity referenced to its depth-averaged velocity (e.g., Fig. 2) and salinity interpolated onto 8° N.

	Mean transport (Sv)		Seasonal salinity range
	Spring	Summer	
Hydrography–Argo	−6.9	9.7	0.09
Glider	−5.7	11.4	0.04
HYCOM	−4.6	3.0	0.01
POP	−5.7	6.8	0.01

nating from the eastern boundary of the BoB, that takes about 4 months to cross the southern BoB. It has a propagation speed of 12 cm s^{-1} , in good agreement with the phase speed of a mode 2 baroclinic Rossby wave in this region (Shankar et al., 1996; Killworth and Blundell, 2003; Wijesekera et al., 2016a). A westward-propagating signal first develops at the eastern boundary of the BoB in April–May at the same time that the Wyrski Jet, a surface-intensified eastward-flowing current observed in the equatorial Indian Ocean during the monsoon transitions (Wyrski, 1973), reaches this eastern boundary. The westward-propagating signal reaches the east coast of Sri Lanka in September contributing to the southward-flowing subsurface current (Fig. 3); this is consistent with findings from the SLM study (McCreary et al., 1996). In April, the westward-propagating meridional flows originating at 83–85° E (Fig. 6b) are associated with the subsurface anticyclonic eddy observed along the east coast of Sri Lanka during the summer (Fig. 4b). The influence of equatorial waves on the undercurrent is still unclear and more studies are needed. Upward phase propagation is present during summer and early fall (Fig. 3) implying the influence of equatorial waves on the subsurface flow during this time (Luyten and Roemmick, 1982). Equatorial waves are also known to impact currents along the Indian east coast (Mukherjee et al., 2014) and Sri Lankan south coast (Schott et al., 1994; Shankar et al., 2002).

Ekman pumping can also significantly impact the circulation along the eastern coast of Sri Lanka (McCreary et al., 1996; Vinayachandran et al., 1999). The SLM study of McCreary et al. (1996) suggested that Ekman pumping drives the undercurrent east of Sri Lanka from April to December. The model undercurrent has a core at 400–500 m that can reach a maximum speed of 10 cm s^{-1} southward and northward in March–April and August, respectively. Although this value agrees quite well with that of the spring undercurrent

observed in the observations and OGCMs, the magnitude given by the SLM during the summer is about half that shown in this study (Fig. 3). During the winter, the mean subsurface current of the observations and OGCMs agrees with the results from the SLM (McCreary et al., 1996) within 1 standard deviation. This implies that a combination of local along-shore winds, Ekman pumping, and equatorial waves, which are the main mechanisms driving the subsurface current during the winter in the SLM, is important in producing the subsurface current in only some years.

Circulation in the subsurface layer along the Sri Lankan east coast is characterized by reversed flows relative to the surface during boreal spring and summer, similar to the subsurface circulation along the Indian east coast and Sri Lankan south coast described by previous studies (Schott et al., 1994; McCreary et al., 1996; Mukherjee et al., 2014). During the southwest monsoon, the current along the Sri Lankan south coast (Schott et al., 1994), Sri Lankan east coast (Fig. 2d–f; Table 2), and Indian east coast (Mukherjee et al., 2014) reverses its direction below approximately 100–150 m. The subsurface current flows eastward along the southern coast of Sri Lanka (Schott et al., 1994), in agreement with the circulation pattern derived from the POP velocity fields (Fig. 4b) and poleward along the Sri Lankan and the Indian east coast (McCreary et al., 1996; Mukherjee et al., 2014). This suggests the possibility of a subsurface conduit connecting the region off the Sri Lankan south coast to the northern BoB. However, the subsurface poleward current along the Indian east coast is not always apparent (Mukherjee et al., 2014), although it is also possible that the undercurrent during this season occurs below the deepest measurement, at 300 m, from the Mukherjee et al. (2014) study. In boreal spring, mooring measurements along the Sri Lankan south coast (Schott et al., 1994) verifies the existence of the eastward-flowing subsurface current observed in the POP velocity fields (Fig. 4a). The subsurface current extends from approximately 250 to 1010 m (Schott et al., 1994). Unlike the summer subsurface circulation, flow at and north of 12° N is poleward over 0–300 m (Mukherjee et al., 2014), in the opposite direction to the undercurrent off the Sri Lankan east coast (Figs. 2a–c, 3). However, since the core location of the spring undercurrent is highly variable from year to year, direct velocity measurements in the deeper layer would help foster a better understanding of the pathways of the subsurface circulation along the western boundary of the BoB during boreal spring.

Although velocity and salinity fields from POP suggest the possibility of significant salt exchange between the AS and the BoB, the estimated salt transport via the undercurrent is small based on the data and models we have available. POP velocity fields show that the summer undercurrent injects relatively saline water into the western boundary of the BoB that can be trapped in a northward-propagating seasonal anticyclonic eddy (Fig. 4b). The source of the saline water is mostly from the southwest of Sri Lanka, although some-

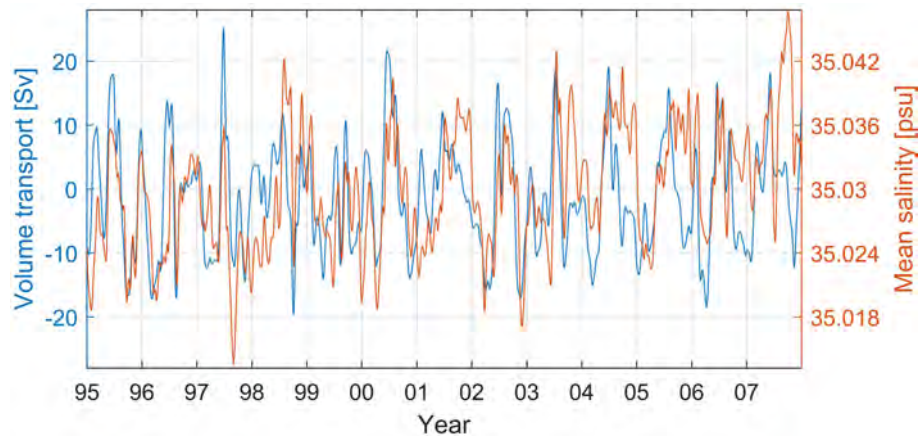


Figure 7. Time series of volume transport (blue) and mean salinity (orange) between 81.5 and 82.5° E over the 200–1000 m layer from POP.

times, such as in 1998, it originates from the eastern BoB (Movie S1). Relatively fresher water is transported southward along the east coast of Sri Lanka in the subsurface layer in spring (Figs. 4a, 7). It can be advected westward along the Sri Lankan south coast in some years, depending on the strength and location of the deep eastward-flowing Wyrtki jet (Reppin et al., 1999; Movie S1). The time series of salinity averaged over the width of the undercurrent (from the east coast of Sri Lanka to 82.5° E) and the volume transport of the POP undercurrent (over 200–1000 m) along 8° N clearly show a positive correlation, i.e., the undercurrent tends to export freshwater from the BoB and import saline water into the BoB (Fig. 7). The hydrography–Argo profiles, glider measurements, and HYCOM also show that poleward subsurface transport is associated with relatively saline water and vice versa (not shown). The correlation coefficient between the subsurface transport and salinity computed from POP is 0.50, significant at the 95 % confidence level. The salt flux due to the fluctuations of the flow and of the salinity (departures from the 13-year climatology) in the 200–1000 m layer from POP is $0.04 \times 10^6 \text{ kg s}^{-1}$ (Fig. 7), while the estimated salt flux from the hydrography–Argo profiles and glider measurements are 0.19×10^6 and $0.09 \times 10^6 \text{ kg s}^{-1}$, respectively. The difference between the observational and POP salt fluxes arises from the smaller salinity range of the model compared to the observations (Table 3). The estimated salt input is up to 4 % of the total expected salt transport into the BoB of $4.5\text{--}4.9 \times 10^6 \text{ kg s}^{-1}$, which is estimated from the annual freshwater input of 0.13–0.14 Sv (Rao and Sivakumar, 2003; Sengupta et al., 2006; Wilson and Riser, 2016). Note that the total net salt transported by POP into the BoB across 8° N is $4.3 \times 10^6 \text{ kg s}^{-1}$; this value is in good agreement with the expected salt transport discussed above. Estimates of salt flux by the *mean* flow over the same depth layer from POP and HYCOM are even smaller: the mean undercurrent transport of 1.5–2 Sv in the OGCMs is fresher than the interior northward flow, as judged from HYCOM and sparse hydrogra-

phy and Argo profiles (not shown), but the salinity contrast at this depth layer is smaller than 0.01. In addition, the small salt transport from the mean flow in the 200–1000 m layer might be due to the core of the undercurrent moving vertically such that this layer may sometimes include opposite flows or smaller salinity contrasts with the interior (Figs. 2, 3; Tables 1, 2).

An alternative interbasin-exchange pathway is through the interior of the BoB, particularly during the southwest and northeast monsoon (Vinayachandran et al., 1999; Wijesekera et al., 2015, 2016b). Observations indicate that the eastward-flowing southwest monsoon current (SMC) has a role in the injection of saline water, originating in the AS, into the southern central BoB during early summer. As the summer progresses, the seasonal cyclonic (i.e., the SLD) and anticyclonic eddies influence the pathway of the SMC (Vinayachandran and Yamagata, 1997; Vinayachandran et al., 1999). Mooring observations at 85.5° E from 5–8° N reveal a northward-flowing subsurface SMC that is associated with high salinity water (Wijesekera et al., 2016a, b). During the northwest monsoon, mass and salt exchange between the AS and the BoB is also observed in the interior over the 50–75 m layer in the southern BoB, approximately between 82.5 and 85° E (Wijesekera et al., 2015).

5 Summary

The velocity fields derived from hydrography and Argo profiles, glider measurements, POP, and HYCOM reveal the presence of an undercurrent off the east coast of Sri Lanka during boreal spring and summer, which has opposite direction to the seasonally reversing surface flow. The location and width of the core of the undercurrent change seasonally. The undercurrent shows the greatest interannual variability during spring, which is likely due to the influence of El Niño events. The observations and OGCMs suggest that the undercurrent over the 200–1000 m layer transports more water

than the surface current over the 0–200 m layer. The mechanisms driving the undercurrent are still unclear, though Ekman pumping is likely to affect the undercurrent especially during the boreal spring (McCreary et al., 1996; Vinayachandran et al., 1999). Upward phase propagation is distinct during the summer, suggesting the influence of equatorial forcing on the circulation across 8° N. Our analyses do not observe the direct influence of Rossby waves on the modification of the spring and summer undercurrent. Although the POP velocity fields suggest a potential pathway in salt exchange between the AS and the BoB, salt transport across 8° N by the undercurrent, estimated from POP and the observations, is expected to be less than 4 % of the total salt input into the BoB required to balance the freshwater sources. More studies are needed to determine the mechanisms driving the undercurrent and its role in interbasin salt and mass exchange. In turn, this knowledge will lead to a better understanding of property exchanges in the northern Indian Ocean.

Data availability. Hydrographic profiles are from the National Center of Environmental Information (Boyer et al., 2013) (<https://www.nodc.noaa.gov/access/index.html>). Argo data were collected and made freely available by the International Argo Program and the national programs that contribute to it (<http://www.argo.ucsd.edu>, <http://argo.jcommops.org>). The Argo Program is part of the Global Ocean Observing System (Argo, 2000). The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (<http://www.aviso.altimetry.fr/duacs/>). The HYCOM simulation is contributed by Naval Research Laboratory (NRL) and is approved for public release and unlimited distribution. POP output is available from the Extreme Science and Engineering Discovery Environment (XSEDE).

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References

- Argo: Argo float data and metadata from Global Data Assembly Centre (Argo GDAC), <https://doi.org/10.17882/42182>, 2000.
- Boyer, T. P., Antonov, J. I., Baranova, O. K., Coleman, C., Garcia, H. E., Grodsky, A., Johnson, D. R., Locarnini, R. A., Mishonov, A. V., O'Brien, T. D., Paver, C. R., Reagan, J. R., Seidov, D., Smolyar, I. V., and Zweng, M. M.: World Ocean Database 2013, NOAA Atlas NESDIS 72, edited by: Levitus, S. and Mishonov, A., Silver Spring, MD, 209 pp., <https://doi.org/10.7289/V5NZ85MT>, 2013.
- Delman, S. A., McClean, J. L., Sprintall, J., Talley, L. D., Yulaeva, E., and Jayne, S. R.: Effects of Eddy Vorticity Forcing on the Mean State of the Kuroshio Extension, *J. Phys. Oceanogr.*, 45, 1356–1375, 2015.
- de Vos, A., Pattiaratchi, C. B., and Wijeratne, E. M. S.: Surface circulation and upwelling patterns around Sri Lanka, *Biogeosciences*, 11, 5909–5930, <https://doi.org/10.5194/bg-11-5909-2014>, 2014.
- Ducet, N., Traon, P. Y. L., and Reverdin, G.: Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2, *J. Geophys. Res.*, 105, 19477–19498, 2000.
- Durand, F., Shankar, D., Birol, F., and Shenoi, S. S. C.: Spatiotemporal structure of the East India Coastal Current from satellite altimetry, *J. Geophys. Res.*, 114, C02013, <https://doi.org/10.1029/2008JC004807>, 2009.
- Eigenheer, A. and Quadfasel, D.: Seasonal variability of the Bay of Bengal circulation inferred from TOPEX/Poseidon altimetry, *J. Geophys. Res.*, 105, 3243–3252, <https://doi.org/10.1029/1999JC900291>, 2000.
- Gordon, A. L., Shroyer, E. L., Mahadevan, A., Sengupta, D., and Freilich, M.: Bay of Bengal: 2013 northeast monsoon upper-ocean circulation, *Oceanography*, 29, 82–91, <https://doi.org/10.5670/oceanog.2016.41>, 2016.
- Hacker, P., Firing, E., and Hummon, J.: Bay of Bengal currents during the northeast monsoon, *Geophys. Res. Lett.*, 25, 2769–2772, <https://doi.org/10.1029/98GL52115>, 1998.
- Jensen, T. G., Wijesekera, H. W., Nyadjro, E. S., Thoppil, P. G., Shriver, J. F., Sandeep, K. K., and Pant, V.: Modeling salinity exchanges between the equatorial Indian Ocean and the Bay of Bengal, *Oceanography*, 29, 92–101, <https://doi.org/10.5670/oceanog.2016.42>, 2016.
- Killworth, P. D. and Blundell, J. R.: Long extratropical planetary wave propagation in the presence of slowly varying mean flow and bottom topography, Part I: The local problem, *J. Phys. Oceanogr.*, 33, 784–801, 2003.

- Lee, C. M., Jinadasa, S. U. P., Anutaliya, A., Centurioni, L. R., Fernando, H. J. S., Hormann, V., Lankhorst, M., Rainville, L., Send, U., and Wijesekera, H. W.: Collaborative observations of boundary currents, water mass variability, and monsoon response in the southern Bay of Bengal, *Oceanography*, 29, 102–111, <https://doi.org/10.5670/oceanog.2016.43>, 2016.
- Luyten, J. R. and Roemmick, D. H.: Equatorial currents at semian-
nual period in the Indian Ocean, *J. Phys. Oceanogr.*, 12, 406–413, 1982.
- Maltrud, M. E., Bryan, F. O., and Peacock, S.: Bound-
ary impulse response functions in a century-long eddying
global ocean simulation, *Environ. Fluid Mech.*, 10, 275–295,
<https://doi.org/10.1007/s10652-009-9154-3>, 2010.
- McCreary, J. P., Han, W., Shankar, D., and Shetye, S.
R.: Dynamics of the East India Coastal Current 2. Nu-
merical solutions, *J. Geophys. Res.*, 101, 13993–14010,
<https://doi.org/10.1029/96JC00560>, 1996.
- Metzger, E. J., Hurlburt, H. E., Xu, X., Shriver, J. F., Gordon, A. L.,
Sprintall, J., Susanto, R. D., and van Aken, H. M.: Simulated and
observed circulation in the Indonesian Seas: 1/12° global HY-
COM and the INSTANT observations, *Dynam. Atmos. Oceans*,
50, 275–300, <https://doi.org/10.1016/j.dynatmoce.2010.04.002>,
2010.
- Mukherjee, A., Shankar, D., Fernando, V., Amol, P., Aparna, S.
G., Fernandes, R., Michael, G. S., Khalap, S. T., Satelkar, N. P.,
Agarvadekar, Y., Gaonkar, M. G., Tari, A. P., Kankonkar, A., and
Vernekar, S.: Observed seasonal and intraseasonal variability of
the East India Coastal Current on the continental slope, *J. Earth
Syst. Sci.*, 123, 1197–1232, [https://doi.org/10.1007/s12040-014-
0471-7](https://doi.org/10.1007/s12040-014-
0471-7), 2014.
- Rao, R. R. and Sivakumar, R.: Seasonal variability of sea sur-
face salinity and salt budget of the mixed layer of the
north Indian Ocean, *J. Geophys. Res.-Oceans*, 108, 9-1–9-14,
<https://doi.org/10.1029/2001JC000907>, 2003.
- Reppin, J., Schott, F. A., and Fischer, J.: Equatorial currents and
transports in the upper central Indian Ocean: Annual cycle and
interannual variability, *J. Geophys. Res.*, 104, 15495–15514,
1999.
- Rosmond, T. E., Teixeira, J., Peng, M., Hogan, T. F., and Pauley, R.:
Navy Operational Global Atmospheric Prediction System (NO-
GAPS): forcing for ocean models, *Oceanography*, 15, 99–108,
2002.
- Schott, F. A., Reppin, J., and Fischer, J.: Currents and transports of
the Monsoon Current south of Sri Lanka, *J. Geophys. Res.*, 99,
25127–25141, 1994.
- Sengupta, D., Bhsrath Raj, G. N., and Shenoi, S. S. C.: Surface
freshwater from Bay of Bengal runoff and Indonesian Through-
flow in the tropical Indian Ocean, *Geophys. Res. Lett.*, 33,
L22609, <https://doi.org/10.1029/2006GL027573>, 2006.
- Shankar, D., McCreary, J. P., and Han, W.: Dynamics of the East
India Coastal Current 1. Analytic solutions forced by interior Ek-
man pumping and local alongshore winds, *J. Geophys. Res.*, 101,
13975–13991, 1996.
- Shankar, D., Vinayachandran, P. N., and Unnikrishnan, A. S.: The
monsoon currents in the north Indian Ocean, *Prog. Oceanogr.*,
52, 63–120, [https://doi.org/10.1016/S0079-6611\(02\)00024-1](https://doi.org/10.1016/S0079-6611(02)00024-1),
2002.
- Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael,
G. S., and Nampoothiri, G.: The western boundary current of the
seasonal subtropical gyre in the Bay of Bengal, *J. Geophys. Res.*,
98, 945–954, 1993.
- Shetye, S. R., Gouveia, A. D., Shankar, D., Shenoi, S. S. C., Vinay-
achandran, P. N., Sundar, D., Michael, G. S., and Nampoothiri,
G.: Hydrography and circulation in the western Bay of Bengal
during the northeast monsoon, *J. Geophys. Res.*, 101, 14011–
14025, 1996.
- Smith, R., Jones, P., Briegleb, B., Bryan, F., Danabasoglu, G., Den-
nis, J., Dukowicz, J., Eden, C., Fox-Kemper, B., Gent, P., Hecht,
M., Jayne, S., Jochum, M., Large, W., Linday, K., Maltrud, M.,
Norton, N., Peacock, S., Vertenstein, M., and Yeager, S.: The
Parallel Ocean Program (POP) reference manual, LANL/NCAR
Tech. Rep. LAUR-10-01853, 140 pp., 2010.
- Vinayachandran, P. N. and Yamagata, T.: Monsoon response of the
sea around Sri Lanka: generation of thermal domes and anticy-
clonic vortices, *J. Phys. Oceanogr.*, 28, 1946–1960, 1997.
- Vinayachandran, P. N., Masumoto, Y., Mikawa, T., and Yamagata,
T.: Intrusion of the southwest monsoon current into the Bay of
Bengal, *J. Geophys. Res.*, 104, 11077–11085, 1999.
- Vinayachandran, P. N., Shankar, D., Vernekar, S., Sandeep, K. K.,
Amol, P., Neema, C. P., and Chatterjee, A.: A summer monsoon
pump to keep the Bay of Bengal salty, *Geophys. Res. Lett.*, 40,
1777–1782, <https://doi.org/10.1002/grl.50274>, 2013.
- Wijesekera, H. W., Jensen, T. G., Jarosz, E., Teague, W. J.,
Metzger, E. J., Wang, D. W., Jinadasa, S. U. P., Arulanan-
than, K., Centurioni, L. R., and Fernando, H. J. S.: South-
ern Bay of Bengal currents and salinity intrusions during the
northeast monsoon, *J. Geophys. Res.-Oceans*, 120, 6897–6913,
<https://doi.org/10.1002/2015JC010744>, 2015.
- Wijesekera, H. W., Teague, W. J., Jarosz, E., Wang, D. W.,
Jensen, T. G., Jinadasa, S. U. P., Fernando, H. J. S., Cen-
turioni, L. R., Hallock, Z. R., Shroyer, E. L., and Moum,
J. N.: Observations of currents over the deep southern Bay
of Bengal – With a little luck, *Oceanography*, 29, 112–123,
<https://doi.org/10.5670/oceanog.2016.44>, 2016a.
- Wijesekera, H. W., Teague, W. J., Wang, D. W., Jarosz, E., and
Jensen, T. G.: Low-Frequency Currents from Deep Moorings in
the Southern Bay of Bengal, *J. Phys. Oceanogr.*, 46, 3209–3238,
<https://doi.org/10.1175/JPO-D-16-0113.1>, 2016b.
- Wilson, E. A. and Riser, S. C.: An Assessment of the Seasonal
Salinity Budget for the Upper Bay of Bengal, *J. Phys. Oceanogr.*,
46, 1361–1376, 2016.
- Wyrtki, K.: An Equatorial Jet in the Indian Ocean, *Science*, 181,
262–264, 1973.
- Yu, L., O'Brien, J. J., and Yang, J.: On the Remote Forcing of the
Circulation in the Bay of Bengal, *J. Geophys. Res.*, 96, 20449–
20454, 1991.