Wind-driven circulation and freshwater fluxes off Sri Lanka: 4D-Sampling with Autonomous Gliders

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Monsoon response of the Bay of Bengal – Arabian Sea system.
- The processes that govern Indian Ocean circulation.
- How upper-ocean processes, in particular sub-mesoscale lateral stirring and diapycnal mixing contribute to water mass evolution and transformation.

OBJECTIVES

The Seaglider program focuses on understanding how riverine freshwater input, precipitation and atmospheric forcing act to govern Bay of Bengal upper ocean variability, water mass formation and export to the Arabian Sea. The glider measurements allow us to:

1. Characterize the annual cycle of lateral and vertical structure, water mass variability and mixing in the southern Bay of Bengal.
2. Understand how freshwater inflow, atmospheric forcing and the underlying mesoscale variability act to produce the observed contrasts (spatial and seasonal) in upper ocean structure and sea surface temperature.
3. Quantify the mid-basin processes (e.g., westward propagating Rossby waves) that modulate exchange between the Bay of Bengal and the Southeast Arabian Sea, and, in conjunction with nearshore measurements planned by NRL-SSC, characterize their impact on flushing of Bay of Bengal freshwater.

APPROACH

Seaglider surveys are used to address questions concerning Bay of Bengal freshwater transport pathways, the dynamics of air-sea interaction modulated by FW input, and the modification of upper ocean water masses. The glider sections provide data for:

1. Characterizing the properties of water masses exported from the Bay of Bengal into the Arabian Sea south of Sri Lanka, as they transit along different pathways setup by the seasonally varying circulation.

2. Estimating the dominant balance in the mixed layer heat and salt budgets over two annual cycles. In particular, the glider measurements will quantify the strength of the barrier layer as it forms and evolve, as well as its impact on mixed layer dynamics and air-sea fluxes.

The measurement program employs the latest generation of Seagliders, with a sensor suite that includes Seabird Electronics temperature and conductivity sensors, Aanderra optode dissolved oxygen sensor, and WET Labs BB2F (combination chlorophyll fluorometer, dual wavelength optical backscatter). The vehicles incorporate a new payload architecture that allows faster, 4 Hz sampling of the CTD, providing greatly increased resolution in critical regions such as thin, near-surface barrier layers. Numerous developments stemming from ONR-supported efforts provide extended endurance.

Continuously repeated survey lines, occupied at monthly timescales over a two-year span, aim to characterize large-scale variability in the southern Bay of Bengal over the course of two monsoon cycles.

WORK COMPLETED

Circulation on the Southern portion of the Bay of Bengal is complex and variable (Fig. 1). It carries important fresh and salty water masses in and out of the Bay, playing a major role in the Indian Ocean Circulation. The Seaglider surveys allow us to understand how freshwater inflow, atmospheric forcing and the underlying mesoscale variability act to produce the observed contrasts (spatial and seasonal) in upper ocean structure and sea surface temperature.

Through collaboration with Sri Lanka's National Aquatic Resources Research and Development Agency (NARA), 8 gliders have been deployed in joint operations conducted aboard R/V *Samuddrika* since December 2013. Fishing pressure and vessel traffic have forced an early end to some missions, and two Seagliders have been lost. The availability of R/V *Samuddrika* and its ability to accommodate foreign cruise participants has governed the tempo of Seaglider operations during this project.

To date, the program has collected over 1600 profiles of temperature, salinity, dissolved oxygen, and optical backscatter from the surface to 1000 m, completing about 12 sections along 8°N, from the shelf break on the west coast of Sri Lanka into international waters, 400 km offshore (Fig. 2). These sections have been obtained in roughly every month of the year, capturing the different monsoon phases and their transitions.

RESULTS

Gliders provide unprecedented sampling of the circulation in the Southern Bay of Bengal. The sections are obtained with enough regularity to capture the rapid evolution of the circulation (Fig. 3). Smooth sea-surface height estimated from satellite altimetry only marginally captures the observed currents.

Surface drifts, calculated from the position of the gliders during the ~20 min it takes to communicate with the base station and send data, are indicative of the near-surface currents. Even in strong currents, these are generally in a complete different direction than the 0-1000m depth-average currents, calculated over the course of the dive (comparing the actual end point with the expected position using a hydrodynamical flight model). Not only is the circulation highly variable in space, but it also has a strong baroclinic component.

Since gliders measure density along a zonal section and provide an estimate of absolute currents (depth-integrated current), absolute meridional geostrophic velocity can be estimated using the thermal wind equation (and applying adequate smoothing to limit the impact of non-geostrophic processes [e.g., internal waves]). The geometry of the glider sampling allows us to quantify the properties of the water masses moving in and out of the Bay of Bengal (Figs. 4 and 5). During the Winter Monsoon, a large fraction of the water moving through the section is going south, carrying freshwater out of the Bay of Bengal. Currents near the coast have the same direction (southward) at all depths. In the middle of the section below 200m, water is starting to move northward, caring salty water – this is the beginning of the transition phase.

During the Summer Monsoon, most of the water in the upper 100m along 8°N is moving northward, carrying salty Arabian Sea Water into the Bay of Bengal. Near the coast, fresh water is moving southward out of the Bay (Fig. 4). Currents are not uniform in depth, the velocity generally reverses below 200m, with distinct water masses overlapping in a complicated circulation evolving rapidly.

These patterns and the transport of freshwater from the Northern Bay of Bengal, as well of the import of salty Arabian Sea Water, are being investigated are using all the glider, remote sensing (SSH, SST, SSH, etc.), and additional ASIRI measurements. In particular, we are working with Luca Centurioni on a manuscript describing the freshwater pathways using the data shown here and surface drifters.

IMPACT/APPLICATION

N/A

RELATED PROJECTS

Multiple efforts within the Office of Naval Research ASIRI program. This includes projects directed by principal investigators Tandon, Mahadevan, Centurioni, D'Asaro, Send, Nash, Shroyer and McKinnon.

Our efforts in the Bay of Bengal are also directly related to the NASCar DRI, investigating upper ocean processes in the Arabian Sea. Results from the sections off Sri Lanka will contribute to understanding the role of exchanges between the two basins.

PUBLICATIONS

Wijesekera, H.W, E. Shroyer, A.Tandon, M Ravichandran, D. Sengupta, P. Jinadasa, H.J. S. Fernando, N. Agrawal, K Arulananthan, M. Baumgartner, J. Buckley, L. Centurioni, P. Conry, E.D'Asaro, J.T. Farrar, A.L Gordon, E. Jarosz, T. Jensen, S. Johnston, C.M Lee, L.S Leo, M. Lankhorst, I. Lozovatsky, A. Lucas, A. Mahadevan, J. Mackinnon, J. Moum, J. Nash, M. Omand, H. Pham, R. Pinkel, S. Ramachandran, L. Rainville, D.L Rudnick, S. Sarkar, U. Send, R. Sharma, H. Simmons, K. Stafford, L. St. Laurent, K. Venayagamoorthy, R Venkatesan, W.J Teague, A. Waterhouse, R. Weller, C.B Whalen. 2015. Decrypting a Mystery Bay - ASIRI Ocean-Atmosphere Initiatives on Bay of Bengal, Submitted to Bulletin of the American Meteorological Society.

FIGURES

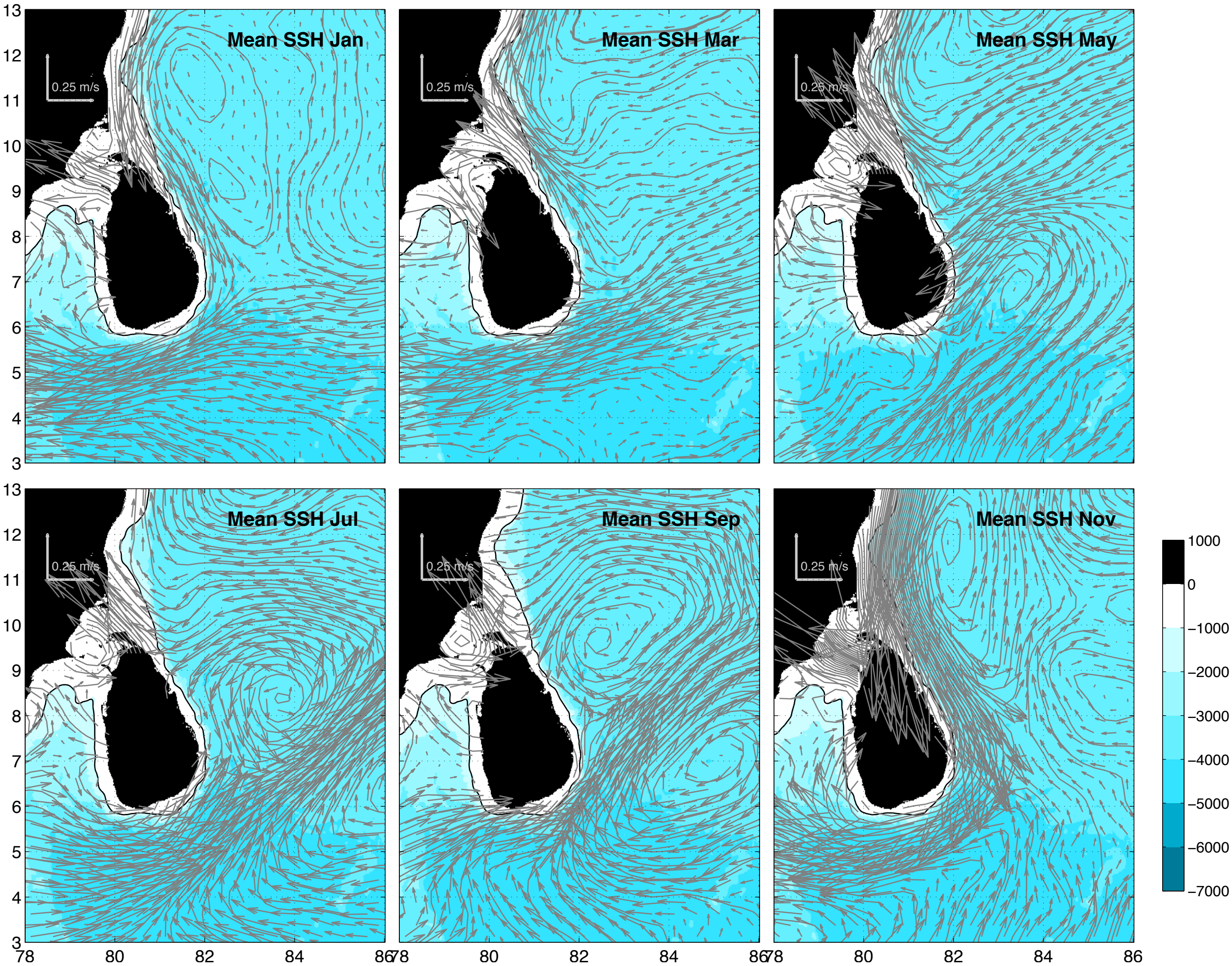

Figure 1. *Monthly climatology of sea surface height and geostrophic surface currents near Sri Lanka. The regional circulation is dominated by strong currents completely reversing during different phases of the monsoon.*

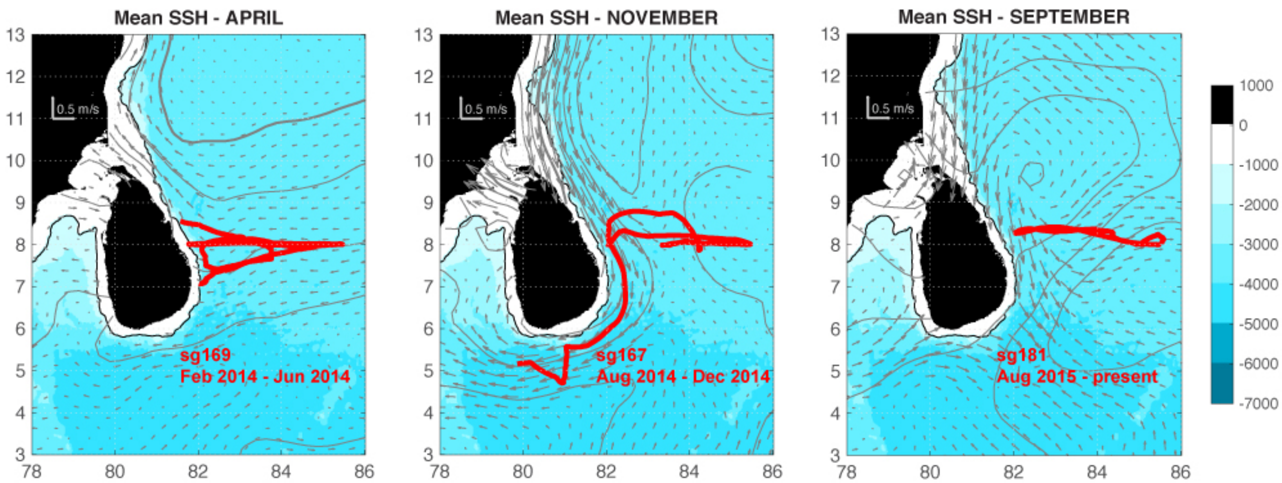

Figure 2. *Tracks of 3 long glider missions along 8°N, along with the monthly climatology of sea surface height and geostrophic surface currents during the middle month of each deployment. sg169 completed 779 dives during a 114 day mission, sg167 completed 481 dives during a 101-day mission, and sg181 was deployed in August 2015 and has done a little over 350 dives so far.*

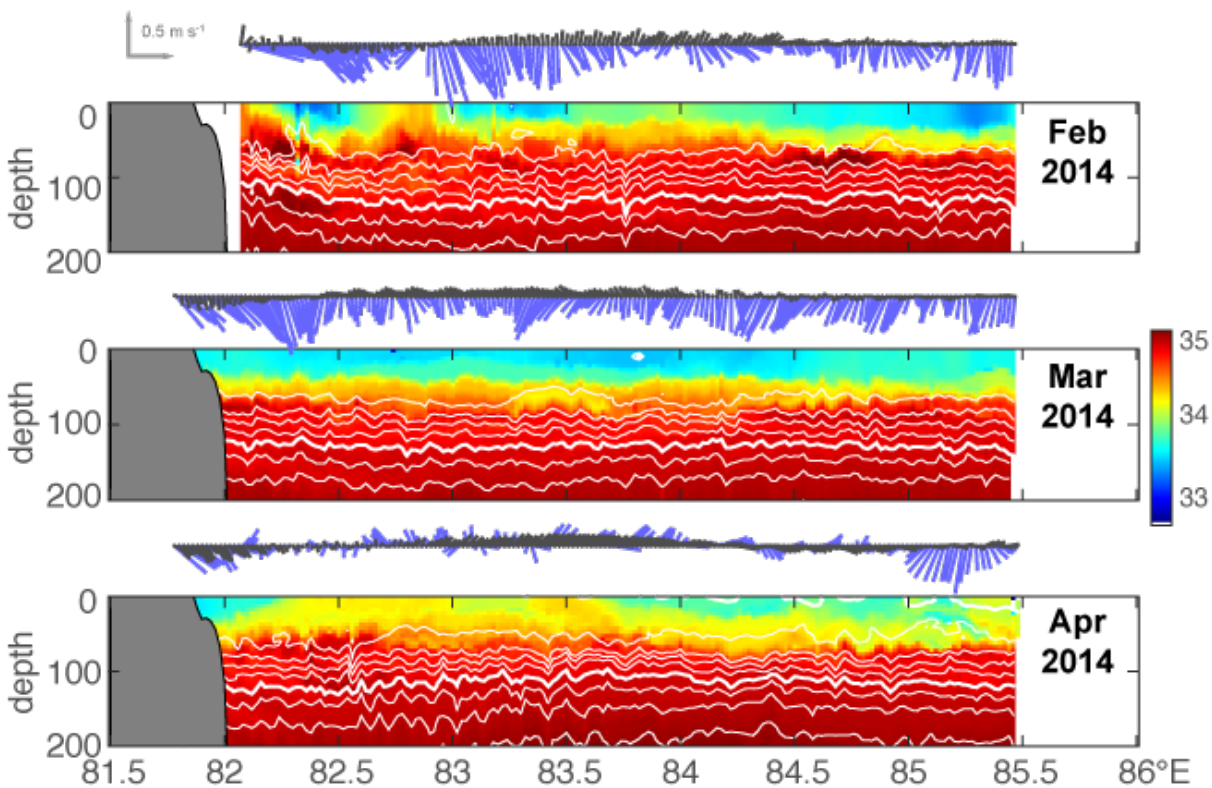

Figure 3. *Upper ocean portion of the salinity sections obtained in February, March, and April 2014 from sg169 along 8°N, as a function of longitude and depth. White contours show temperature (1°C intervals, 20°C contour is shown in bold around 120m). Depth-integrated currents from 0 to 1000 m (black vectors) and surface drifts (blue vectors, indicative of surface currents) are shown on top of each panel. Surface circulation is generally not in the same direction as the depth-integrated current.*

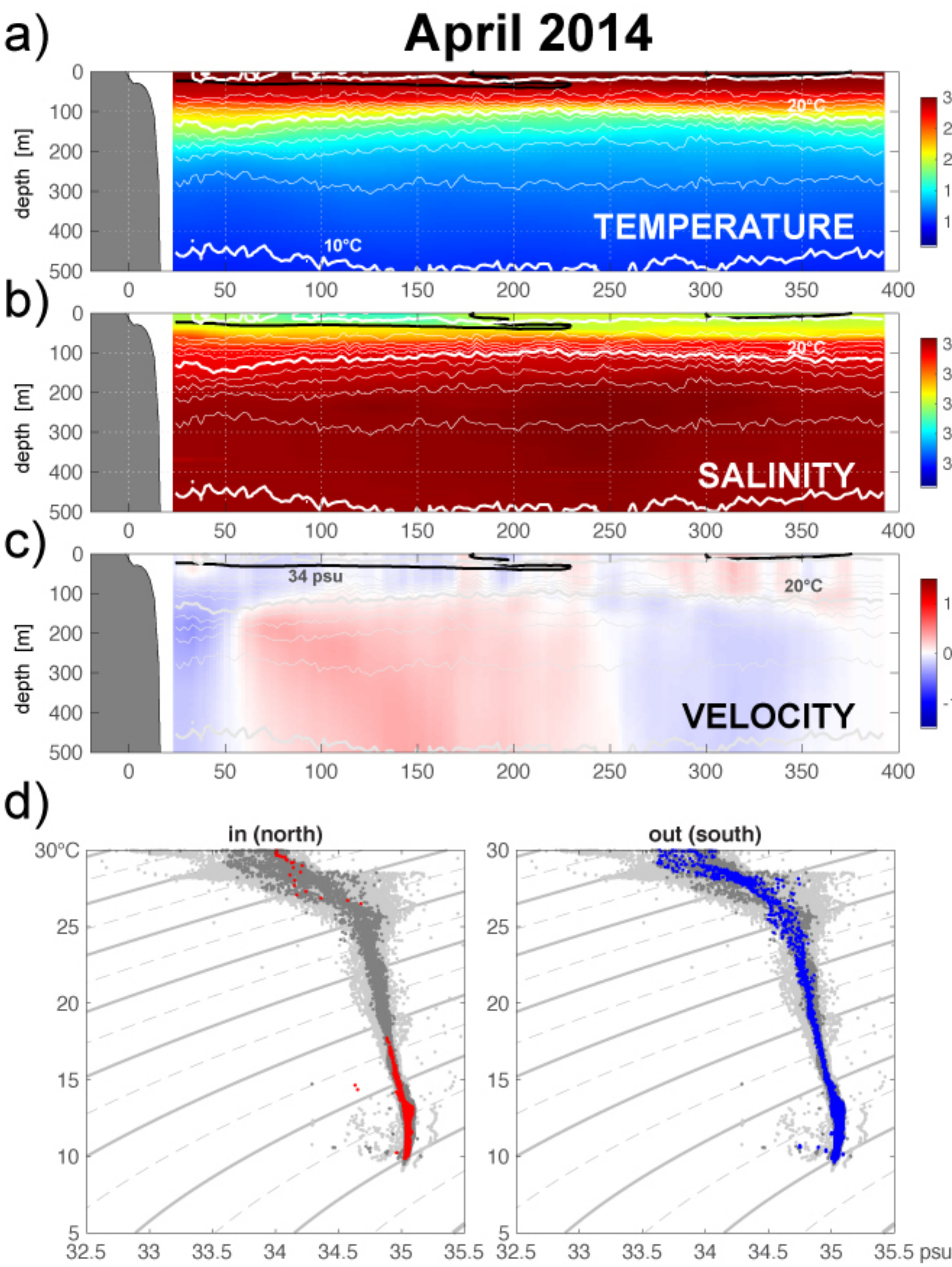

Figure 4. *(a) Temperature, (b) Salinity, and (c) northward geostrophic velocity estimated from glider measurements along 8°N in April 2014, during the Winter Monsoon. White contours show temperature, black line shows the 34 salinity contour. (d) Temperature-Salinity diagrams showing all of 2014 data (light gray), the data from this section (dark gray), and that of the waters moving northward at more than 0.1 m/s (red), and moving southward at more than 0.1 m/s (blue).*

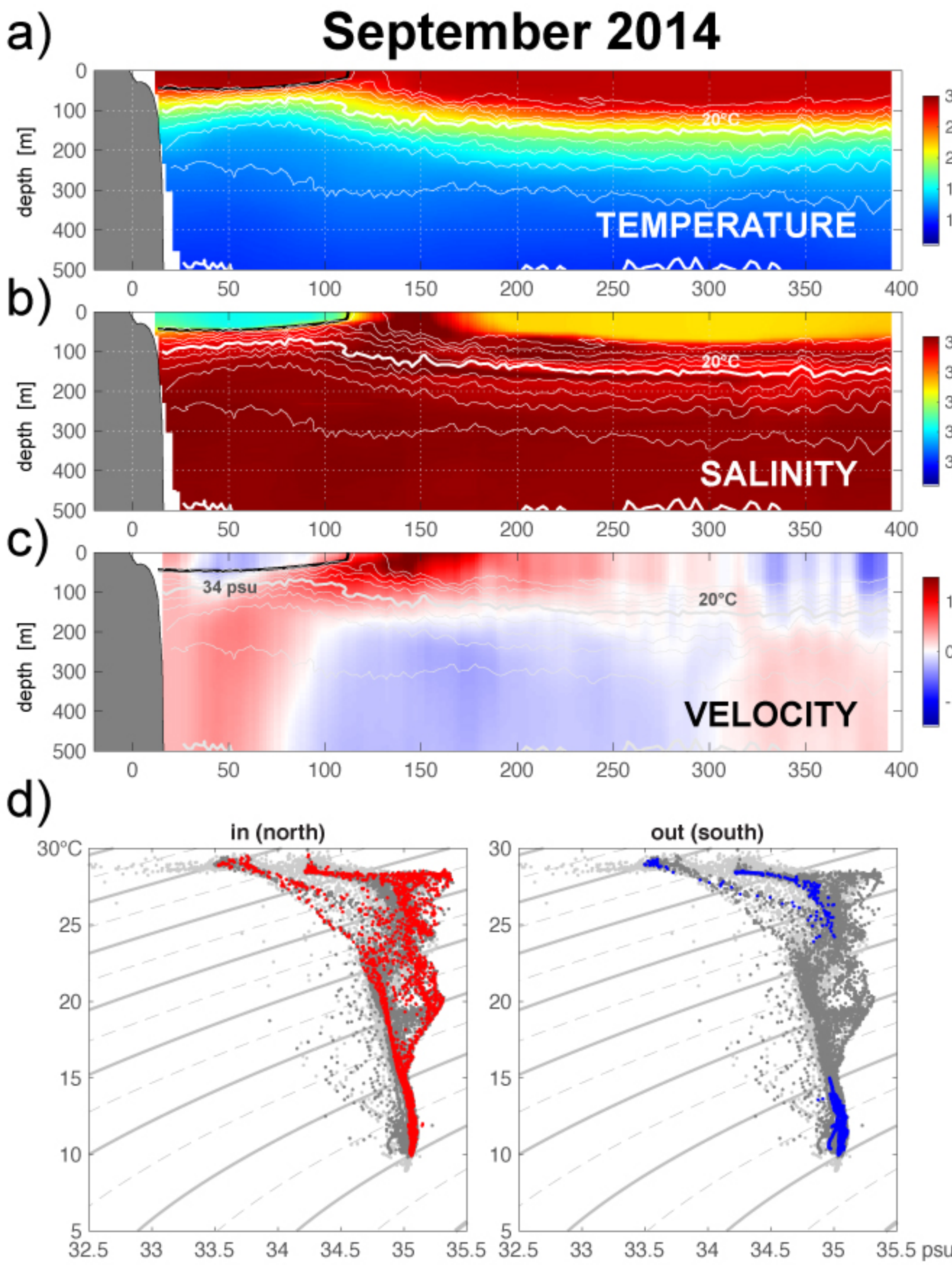

Figure 5. *As in Fig. 4, but for September 2014, during the Summer Moonsoon.*