Integrating Observations of the Boundary Current Flow around Sri Lanka

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LONG-TERM GOALS

The long-term goal is to investigate the boundary-current and inter-basin ocean circulation which governs the conditions and variability in Bay of Bengal. For this, the flow around Sri Lanka is critical since it exchanges salt and freshwater between the Bay of Bengal and the Arabian Sea.

OBJECTIVES

In-situ continuous observations of the boundary current flow around Sri Lanka will be collected over a period of several years. In order to assess potential bifurcations or merging of current branches coming from the north and from the east, two sections will be occupied – one on the east side of Sri Lanka, and one south of Sri Lanka. These will complement satellite altimetry information, as well as sporadic glider and drifter observations in the boundary current.

APPROACH

The approach chosen consists of deploying and operating two seafloor instruments called PIES (pressure-sensing inverted echo sounders) on each of the sections (east and south). The PIES instruments are installed on the seafloor and measure bottom pressure and the travel time of an acoustic signal between the seafloor and the surface. Together, these measurements represent the integrated mass content and an integral of sound slowness (which depends on integrated heat and salt) of the water column. Pairing such measurements at the end points of a section allows an estimate of the geostrophic currents, given sufficient a-priori information. The instruments can remain deployed for up to four years, but carry acoustic modems which allow the data to be retrieved each time local ship passes by, e.g. during a routine CTD section.

WORK COMPLETED

Much of the work presented here was carried out by graduate student A.Anutaliya at SIO (Scripps Institution of Oceanography).

Two PIES instruments were deployed on a section east of Sri Lanka in November 2014. The locations are along latitude 8°N and at approximate water depths of 600 and 3800 m, respectively. Figure 1 shows the location of the section and of the instruments deployed, as well as future deployment sites in the south. In order to find the best locations for these deployments, satellite altimetry data were analyzed, identifying the expected location, strength, and variability of the boundary current, figure 2.

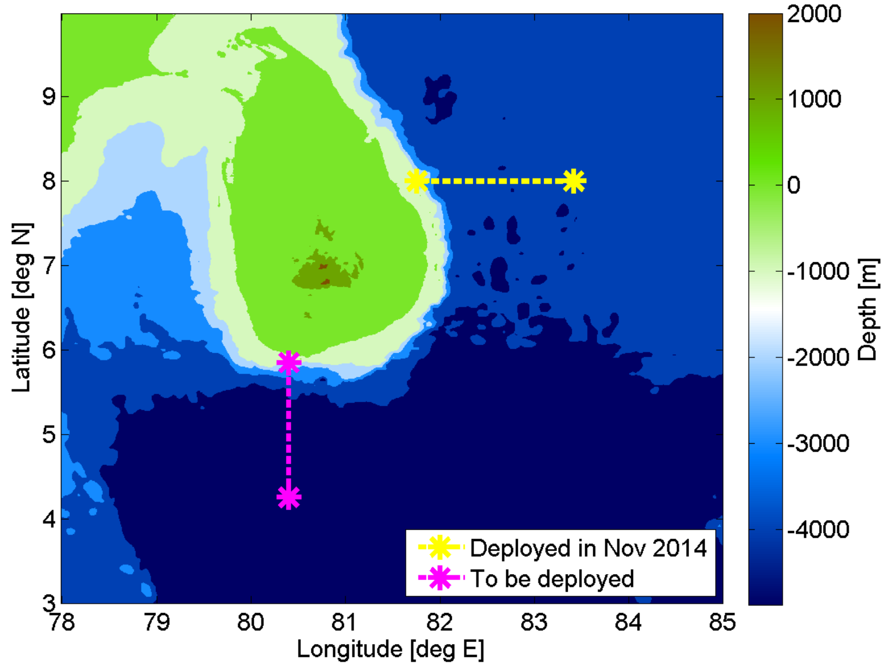


Figure 1: Map of Sri Lanka with the eastern and southern sections highlighted. The eastern section follows roughly 8°N, while the southern section is on 80.4°E. Deployment locations for the PIES are indicated as stars (actual on the eastern section, planned on the southern section).

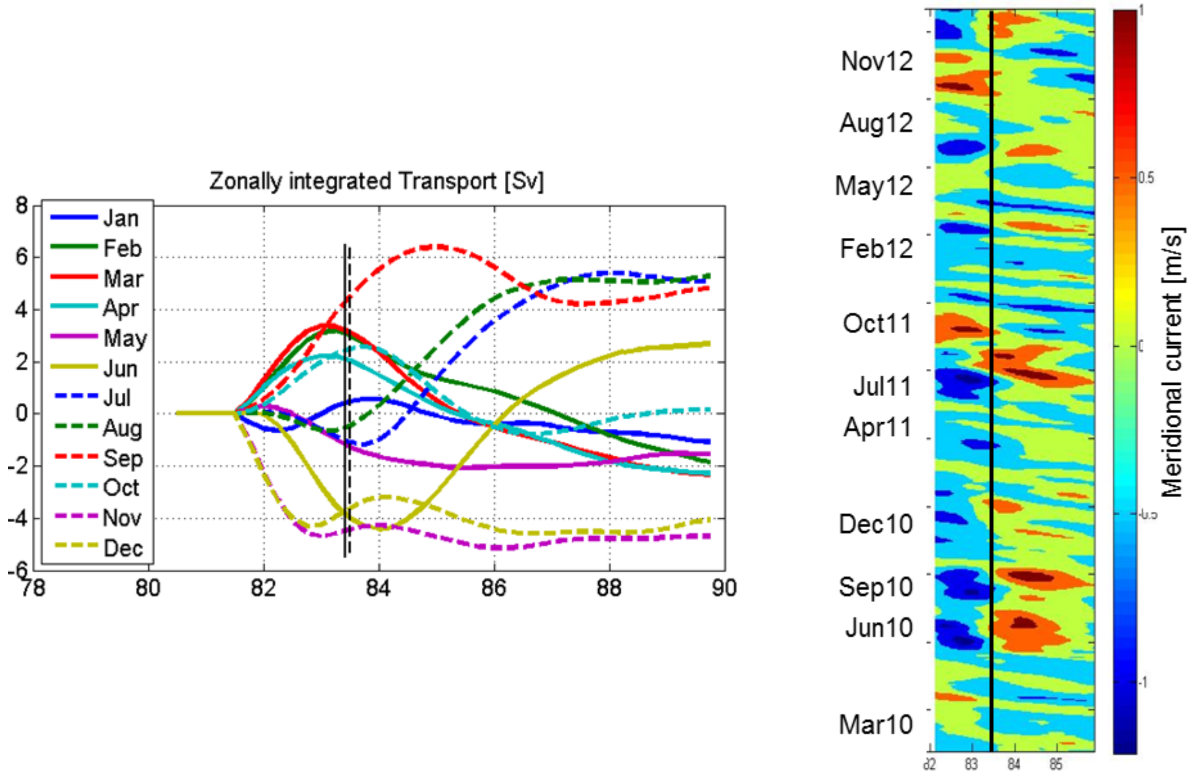


Figure 2: Flow through the eastern section at 8°N derived from satellite altimetry. Left: Cumulative mean transport for different months as a function of distance, assuming a vertical scale depth determined from CTD data. Right: Surface currents as a function of time and distance along the section. Both suggest that the boundary current regime extends to 83.5°E.

Both panels in figure 2 were used to define the lateral extent of the boundary current, by selecting a location at which the transport levels off and where the regime clearly changes character. Further refinement was done by spectral analysis (not shown here), which revealed that the time scales of variability in the boundary are notably different from those in the interior (semi-annual versus annual periodicity). Based on these analyses of the surface flow, the location of the offshore PIES deployment was chosen. For the inshore location, additional analyses and simulations shown below were used.

In order to assess the expected size of the signal (and to demonstrate that the PIES technique can in fact observe transports here), CTD data were analyzed to determine the depth scale of the boundary current, and altimetry provided the range of variability of the transports to be expected, once the length of the section to be occupied was chosen. Figure 3 shows the typical flow and transport variability expected from altimetry data. For validation, also a profile from an old ship-based study is shown.

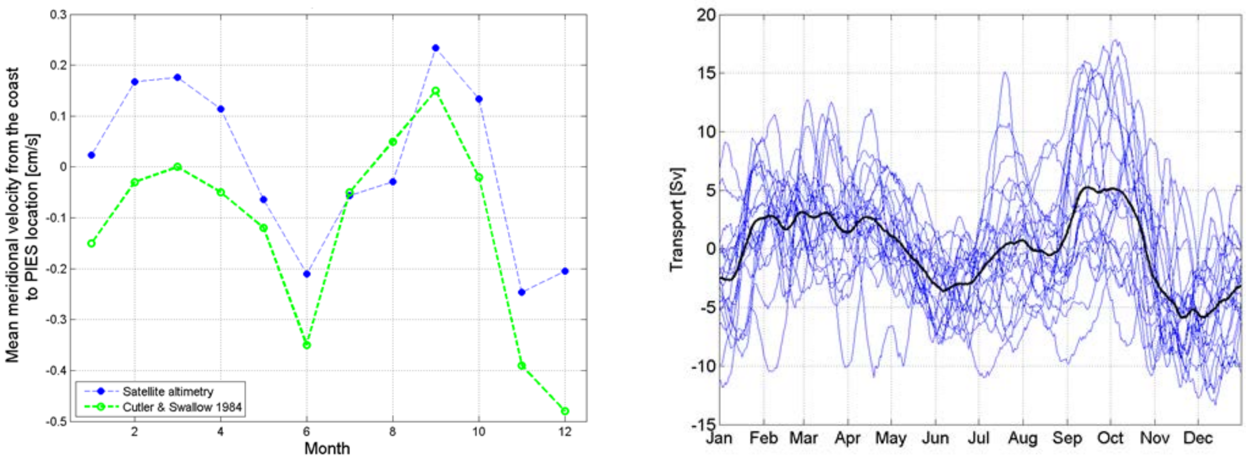


Figure 3: Typical flow and transport variability of the boundary current on the eastern section out to the offshore PIES deployment location chosen. The panel shows the mean seasonal variability of the mean surface flow, and the right panel shows transport timeseries assuming a 100m scale depth for individual years.

The typical transport variability found is +/-10Sv, and there is a clear semi-annual period visible.

In order to simulate the primary measurements of the PIES (we will use mainly the acoustic traveltime), all available CTD profiles were used to calculate the vertical acoustic traveltime (from the sound speed derived from the CTD data). We included a free surface which means that the surface deflection was taken into account assuming a mainly active surface layer (1-1/2 layer approximation). At the same time, pairing the CTD data with each other also allows an estimate of the transport resulting from each measurement assuming geostrophic flow relative to a deep reference level (here 1000m). These simulations gave rise to the results shown in figure 4. The transport amplitude is about +/-10Sv, very close to the altimetry signal but here derived from completely independent data (CTD). The acoustic traveltime signal corresponding to this is 4ms, which is well measurable given the expected accuracy of a fraction of a millisecond of the instrument (after daily averaging). These simulations were done for an instrument depth of 600m, which was the preferred choice for the depth of the inshore PIES as a compromise between capturing most of the flow and not saturating the acoustic signals by deploying the PIES too shallow. Figure 4 confirms that 600m is a workable depth for the inshore PIES, and we have other simulations which demonstrate that this is also representative of the upper layer flow (e.g. upper 200m) since that is where most of the signal originates.

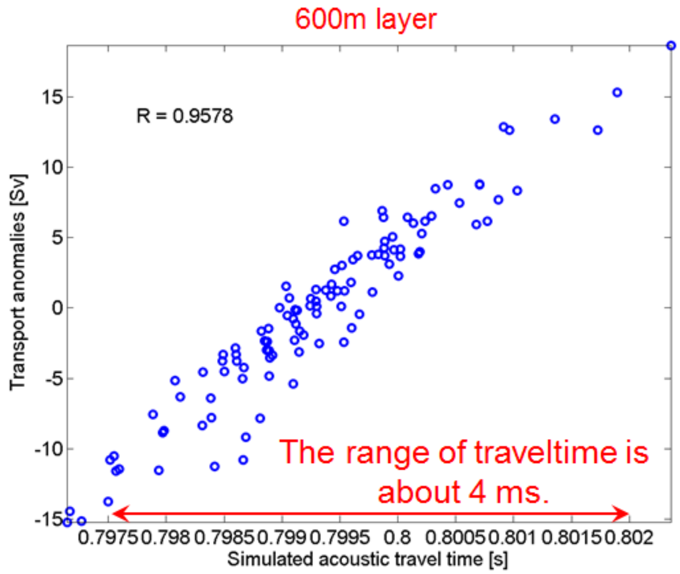


Figure 4: Simulations of PIES acoustic traveltime (x-axis) for pairs of CTD data, which can be translated into geostrophic transport relative to the lower depth of the CTD profiles (y-axis). The signal for a 600m deep PIES is about 4ms, which is well measurable, and corresponds to the +/- 10Sv already expected from altimetry data.

Additional estimates for the bottom pressure measurements of the PIES, which help to further constrain the transport estimates, showed that the expected accuracy of barotropic transport components (over a 100m layer) is 0.25 (0.5)Sv in the presence of 20 (40)Sv signals on the eastern (southern) section.

The entirety of the analyses summarized above lead to the deployment configuration of the PIES on the eastern section, i.e. offshore end of the section at 83.5°E, and the inshore PIES at a depth of 600m. The resulting section with the PIES locations and depths is shown in figure 5.

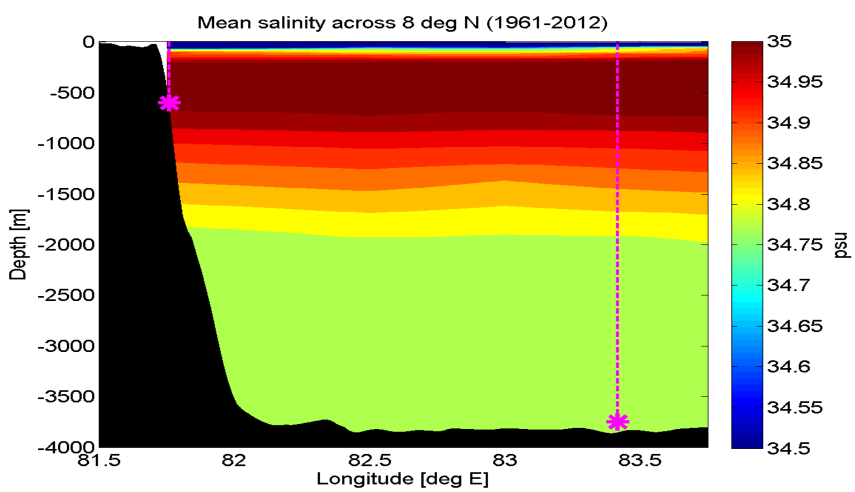


Figure 5: Section along 8°N showing the actual PIES deployment locations and depths, overlaid with a mean salinity field from historical CTD data. Note that the goal of the PIES measurements is measurement of the boundary current in the upper 100-200m, which dominated the vertical integral at both locations.

Similar analyses and simulations have by now been carried out for the southern section, leading to the planned PIES deployment locations shown in figure 1.

After extensive testing at SIO, the instruments and required deployment tools were shipped to NARA (National Aquatic Resources Agency) at Sri Lanka. The instruments were designed to record data internally at resolutions of 6 measurements per hour for seafloor pressure, and 24 measurements per hour for acoustic travel time. Acoustic data telemetry modems were integrated together with the PIES, and receive hourly subsets of the data. Figure 6(top) shows the equipment as it was being transported to the port of deployment. Logistics of such remote shipping have been challenging, especially with substantial amounts of lithium batteries, but were resolved in time. The instrumentation was then assembled on the deployment vessel (figure 6 left) and launched (figure 6 right). With the deployment in November 2014, the PIES array on the eastern section is complete. Endurance of the deployed instrumentation is expected to be close to 4 years. Acoustic communication with the instruments after deployment confirmed that they landed safely at the intended depths, and were recording data nominally.

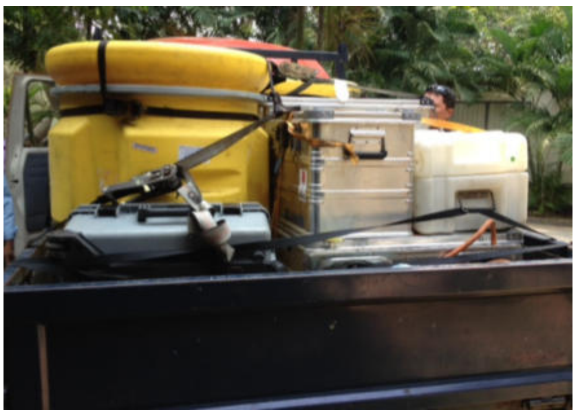
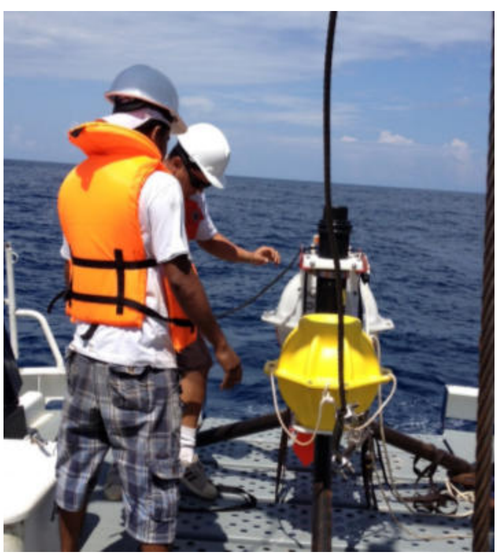
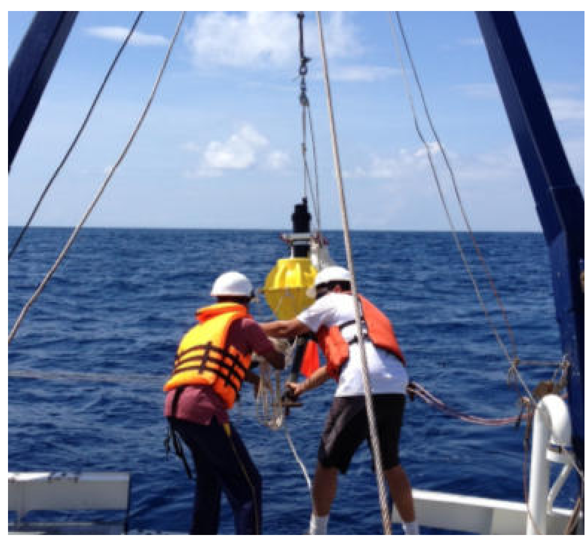


Figure 6: Shipping of equipment to Sri Lanka and internally to the port on the east coast (top), preparation of a PIES for deployment on the 8°N section (bottom left), and deployment of the PIES from the NARA research vessel (bottom right).





An attempt to deploy identical instrumentation on a section south of Sri Lanka (also shown in Figure 1) was made in May 2015. This was abandoned due to logistical problems. The instrumentation was then returned to storage in Sri Lanka and is deployment-ready.

Outlook: In the upcoming 12-month period, the intent is to do two field operations. Firstly, the eastern PIES sites will be visited during a NARA CTD section, and the data from the deployed instruments will be retrieved remotely. This is expected to return the first dataset of the project. Secondly, another attempt will be made to deploy the southern instruments.

RESULTS

Since there has been no recovery of data from the deployed PIES so far, there are no results to report from these data yet. We expect first such data to be available within 6 months.

However, extensive analyses of satellite and in-situ CTD data have been carried out to characterize the scales and variability of the boundary current as much as possible. A significant result is shown in figure 7 where the eastern section boundary current variability is plotted together with two ocean climate indices – the Oceanic Niño Index (ONI) and the Dipole Mode Index (DMI). The correlation with the DMI is 0.65, and the maximum correlation occurs if the boundary current is defined to extend to 83.4^{0}E, which again confirms the choice for the boundary current scale and the PIES deployment geometry. The high correlation with the DMI is surprising and points to a dynamical mechanism governing the boundary current circulation and thus the exchange between the Bay of Bengal and the Arabian Sea.

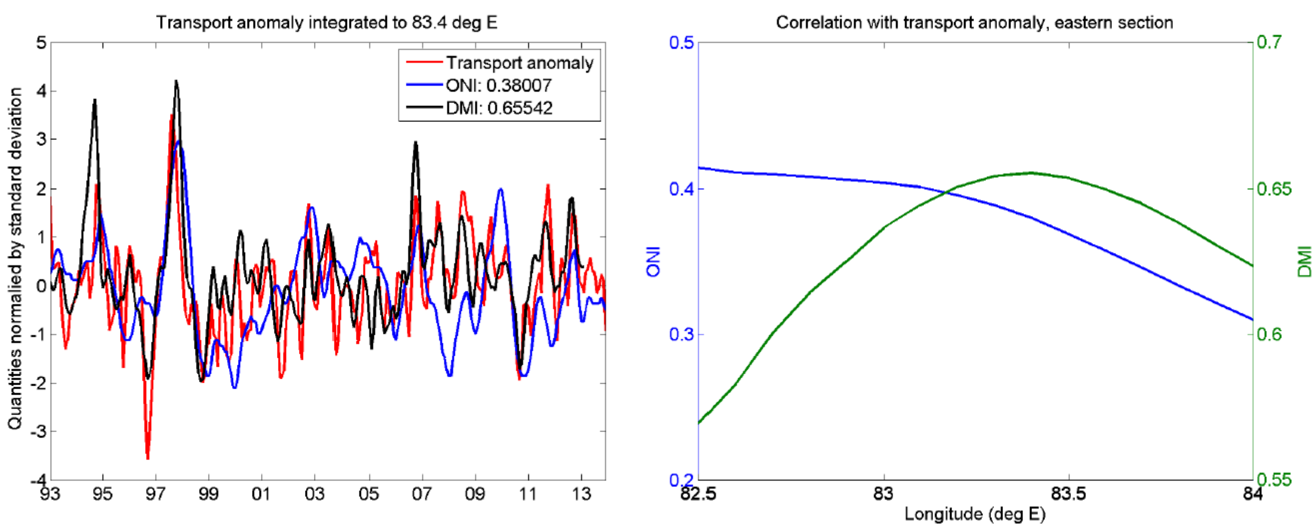


Figure 7: Left - Timeseries of altimetry derived eastern boundary section transport anomaly (red), ONI index (blue) and DMI index (black). The correlation of the indices with the transport are shown in the legend. Right – Longitude dependence of the correlation, showing the maximum correlation with the DMI at 83.4 ^{0}E.

In addition to CTD and altimetry analyses, comparisons with high-resolution ocean models have begun. For example a HYCOM simulation appears to capture the surface boundary current flow on the eastern section reasonably well (as judged by altimetry comparisons), figure 8. Work is under way to investigate the water mass properties and depth structure of the boundary current circulation in the models, as compared to observations. As soon as first observational results are in hand, these will be compared with altimetry and model results. One expectation is that combining the PIES observations with altimetry information (and projecting onto vertical EOFs from CTD data) will reveal a high-quality continuous quantification of the boundary current exchange flow around Sri Lanka.

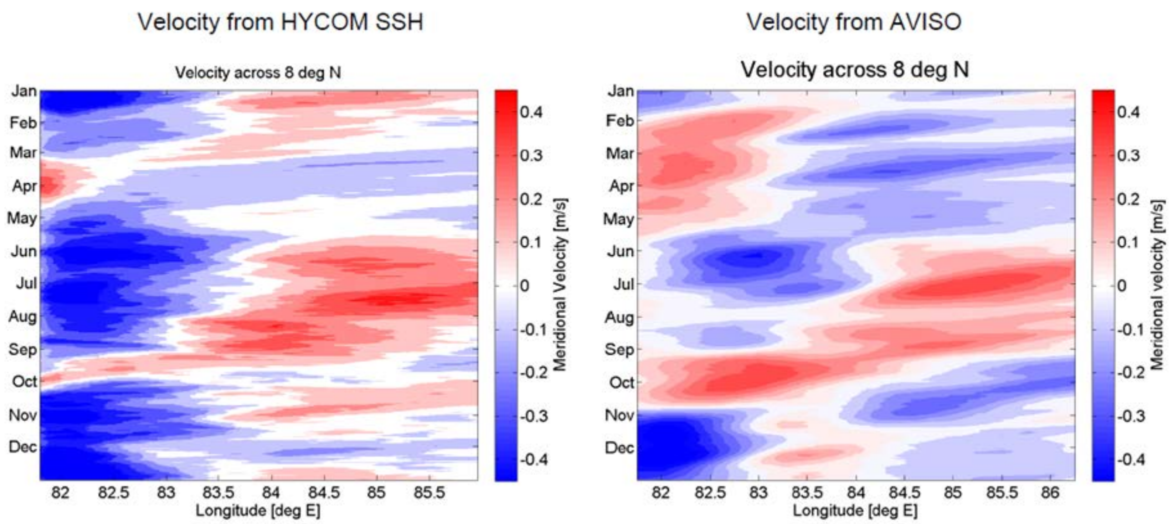


Figure 8: Hovmueller diagram of the mean seasonal surface geostrophic velocity across the eastern section, from the HYCOM model (left) and from the satellite altimetry AVISO product (right).

IMPACT/APPLICATIONS

The intended outcome of the measurements is an improved scientific understanding of the currents around Sri Lanka, including the role they play in transporting salt/fresh water and heat. These transports are an important component of the climate system in the Indian Ocean. Making direct observations in the ocean provides the necessary data to quantify the role of the ocean for these transports, the underlying mechanisms, allows testing of model fidelity, and enables the design of a potential sustained observing system for the boundary currents in the region.

RELATED PROJECTS

The project is embedded in the larger ASIRI initiative, as described by Wijesekera et al. (subm. 2015). In particular the glider observations supported by University of Washington (Craig Lee) and the drifter observations (Luca Centurioni, SIO) in the boundary current around Sri Lanka are important complements to our observations. Modelling work in the ASIRI and NASCar projects will also be relevant for the PIES observations, and NASCar in general has a focus on the inter-basin exchange to which our observations are expected to provide important insight.

PUBLICATIONS

Wijesekera, Hemantha W. et al.: **Decrypting a Mystery Bay – the ASIRI Ocean-Atmosphere Initiatives on Bay of Bengal**. *Bull. Am. Met. Soc.*, 2015 [submitted].

Acknowledgement: The altimeter products were produced by Ssalto/Duacs and distributed by Aviso with support from Cnes.