ASIRI 2014 Cruise–Bay of Bengal

Leg-I: R/V Roger Revelle Cruise RR 1405

17-28 June 2014

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1 Overview and Objectives

1.1 Overview

The second of three scheduled ASIRI multi-leg cruises in the Bay of Bengal (BOB) took place in June and July 2014. The 2014 field effort was split into two legs: a process study in and out of Chennai, India, and a survey study around the NRL moorings in the south-central BOB. The Leg-1 portion of the 2014 cruise (17 – 28, June, 2014; Lucas and Shroyer, Chief Scientists) was designed to sample during the early stages of the monsoon to contrast pilot work undertaken in winter 2013. The oceanographic and forcing conditions differed significantly from those measured in the previous year, providing a valuable point for comparison. Sampling within India's exclusive economic zone was fully restricted, and a 20h commute to/from international water was required at the beginning and end of the cruise, yielding close to 9 days of dedicated science time.

Prior to departing, a brief welcome ceremony was held on the R/V Roger Revelle. Acting Consul General Nicholas Manring from the U.S. Consulate General (Chennai) welcomed scientists, Indian dignitaries, and U.S. consular officials. Attendees included Dr. R. R. Rao (National Monsoon Mission), Dr. M.A. Atmanand (Director, National Institute of OceanTechnology), and Dr. Ramesh Kolar (ONR International). Following the ceremony on the fantail, a reception was held in the main lab. The atmosphere was festive and welcoming thanks to a wonderful effort by the Revelle's Master and crew.

1.2 Objectives

The cruise consisted of two major components: 1) a large-scale rapid survey and 2) two smaller scale high-resolution surveys involving autonomous (Wirewalkers (WW) and a Slocum-Turbulence glider) and shipboard assets. During that time we employed a variety of observational techniques to 1) map the large-scale ($\gtrsim$ 100 km) physical context and 2) record the evolution of the upwind and

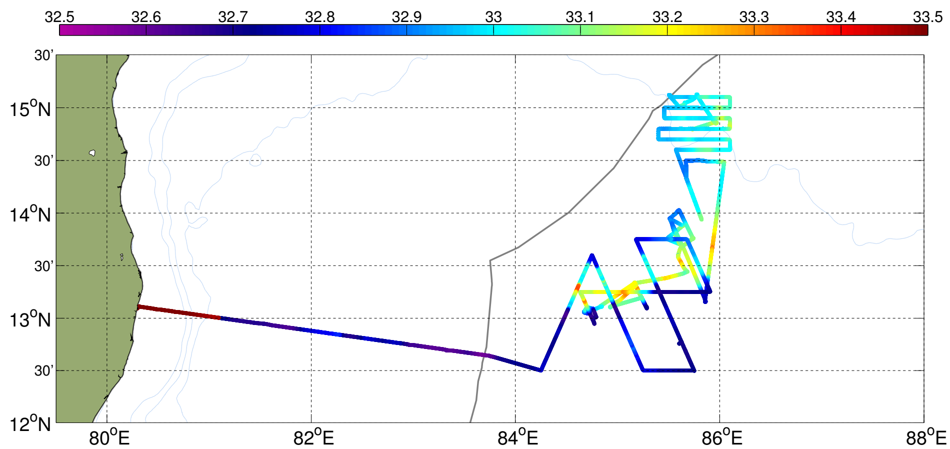

Figure 1: Cruise track with SSS shaded.

downwind edges of a salty filament. Training of Indian and US students, who comprised a majority of the science crew, was one of the primary missions of the cruise.

The specific objectives of the cruise were:

1. Utilize remote sensing products to plan an effective use of the shipboard and autonomous assets, focusing on small lateral-scale features in the surface ocean.
2. Determine the relevant dynamical scales and gradients during the (early) southwest monsoon.
3. Investigate the mesoscale conditions in the identified study area.
4. Map the evolution of a salty filament in time and space in both a drifting and survey mode.
5. Assess the dynamics that result in stirring and mixing of frontal features under forcing conditions that differed from those of the 2013 pilot cruise.
6. Provide for collaborative and training opportunities between scientists, students, and technical staff between Indian and US personnel.

1.3 Personnel

Personnel included the Chief Scientist, Andrew Lucas (Scripps, University of California San Diego) and co-Chief Scientist, Emily Shroyer (Oregon State University), postdoctoral researchers– Melissa Omand (Woods Hole Oceanographic Institution), Amy Waterhouse (UCSD), Hieu Pham (UCSD) and Sanjiv Ramachandran (University of Massachusetts, Dartmouth), and research engineers– Ben Hodges (WHOI), Tyler Hughen (UCSD), and Jonathan Ladner (UCSD). Graduate students and research scientists from both US and Indian institutions, made up the remainder of the 25-person science crew: Effie Fine (UCSD), Atul Laxmikant (OSU), Gualtiero Rudi (WHOI), Amrapalli

Table 1: List of science personnel, role during cruise, and watch. Those not specifically listed in this table participated in general operations and stood watches with the UCTD.

Name	Role	Watch
Lucas	Chief Scientist	
Shroyer	Co-Chief Scientist	
Waterhouse	Night Shift Lead	Midnight-to-Noon
Hughen	Wirewalker Ops	
Ladner	Wirewalker Ops	
Hodges	UCTD Lead	Noon-to-Midnight
Shivaprasad	UCTD Lead	Midnight-to-Noon
Rao	Water Sampling	Noon-to-Midnight
Sherin	Water Sampling	Midnight-to-Noon
Omand	Data Analysis and Training	Noon-to-Midnight
Laxmikant	Data Analysis and Training	Noon-to-Midnight
Whalen	Data Analysis and Training	Midnight-to-Noon
Ramachandran	Data Analysis and Training	Midnight-to-Noon

Garanaik (University of Colorado), Caitlin Whalen (UCSD), Manita Chouskey (India Institute of Technology), Bhaskar Rao (National Institute of Oceanography), CK Sherin (NIO), Prakash Thanga (Indian National Center for Ocean Information Services), Shiva Shivaprasad (INCOIS), Vijay Pottapinjara (INCOIS), Murugesh Pathikasalam (National Institute of Ocean Technology), Dheeraj Varma, (IIT), Kumar Yadav (IIT) Ganga Prasath (TIFR), and Aditya Chaudhary (SAC). Matt Durham and Brent de Vries provided support as the R/V Revelle research and computer technicians, respectively.

2 Observational Tools and Methods

Operational procedures closely resembled those used during the 2013 pilot work. A combination of shipboard assets that included additional pole- and hull-mounted Doppler profilers; underway-CTD; bow chain (temperature and conductivity sensors); ship-maintained CTD, underway themosalinograph, and Doppler profilers; and water sampling were used to map large-scale (at speeds of 10-12 knots) and small-scale (at speeds of 4-5 knots) features. Autonomous assets (wirewalkers and Slocum-tglider) were deployed for two drift periods, accompanied with high-resolution (slower speeds) sampling. A long-range sea glider was recovered and its replacement was redeployed.

2.1 Wirewalker Operations

Wirewalker (WW) operations consisted of the deployment of 4 units on two multi-day drifts. The WW profilers were deployed on 100m wires, and completed a round-trip profile once per $\sim$10 min on average. WWs were deployed with CTD, current meters (both on the profiler and, at depth, an upward-looking ADCP), χ-pods, and optical instruments. One WW was also equipped with an oxygen sensor. Final vertical resolution after averaging to improve signal to noise ratio was 0.25m in CTD, optical, and processed χ products. Initial processed velocity resolution was 1m, although further averaging and smoothing is likely to be necessary as analysis continues. One of the four WWs were equipped for real-time telemetry via inductive modem, connecting the profiler with the surface buoy, and Iridium communications for buoy to shore communications.

The first WW deployment bracketed a salty filament between two mesoscale eddies. Remote sensing indicated, and the drift showed, a strong eastward velocity. The positions of the WW cluster shifted little relative to one another, indicating the mixed-layer velocities were coherent over the size of the array. However, WW operations were compromised in the first deployment. WW-1 was ballasted heavy and stuck after very few profiles on the bottom. WW-2 also profiled erratically during the first deployment, in the end surfacing with a broken fin. The first drift lasted $\sim$ 2d.

The second WW drift array was deployed in the eddy outflow to the east-north-east of the deployment 1 location. Again there was only weak spreading and rotation of the cluster (Figure 2), indicating that the average velocity over 100m was relatively coherent in the eddy outflow. All WWs had excellent profiling performance. WW1 and WW3 gathered χ data. On the second drift, the WW cluster indicated a ML that was gradually warming to the north (presented in time here). The cluster was also embedded in a west/east temperature gradient. The ML was $\sim$25m deep, and the pycnocline was approximately 50m thick. Strong temperature/salinity interleaving was present in the pycnocline, in particular during the first half of the drift.

Dissolved oxygen was characterized by a very strong gradient in percent saturation at the base of the pycnocline (and coincident with the deep fluorescence maximum). The bulk of the pycnocline was consisted of oxygen concentrations higher than 100% saturation, while the mixed layer hovered near $\sim$100% saturation, indicating ventilation. The cause of the super-saturation is unknown, but the super-saturation was also evident in the shipboard CTD (all casts). χ_T was elevated at the base of the mixed layer (an area of strong T gradient), and intermittently at depth (between roughly 80 and 100 m). For example, during the second drift WW1 showed elevated χ_T at depth starting around 24 June 2014 (Fig. 4). Temperature, salinity, dissolved oxygen, and chlorophyll fluorescence also showed a shift in structure at this depth during this period (Fig. 3).

A summary of the Wirewalker deployments can be found in Table 2. In all, 2,904 WW profiles were collected over the $\sim$9 sampling days.

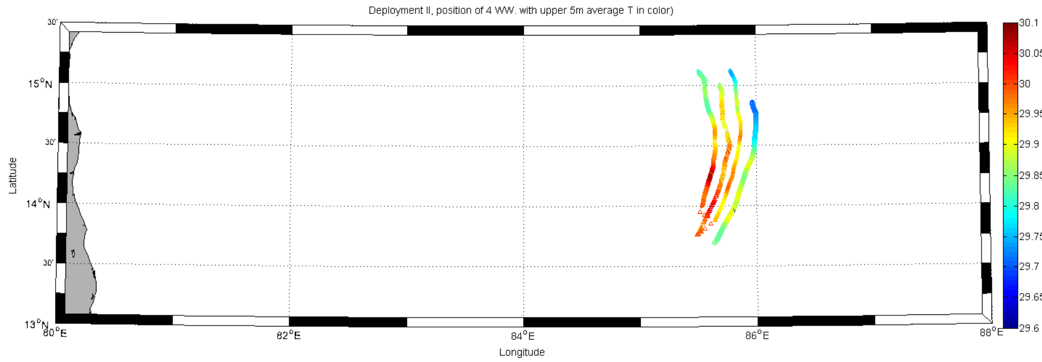

Figure 2: The second WW drift. The lateral variability of temperature is evident from the drifting array. This variability is essentially compensated by salinity changes over the length of the drift; nevertheless the spice variance is high on short time and space scales in the mixed layer.

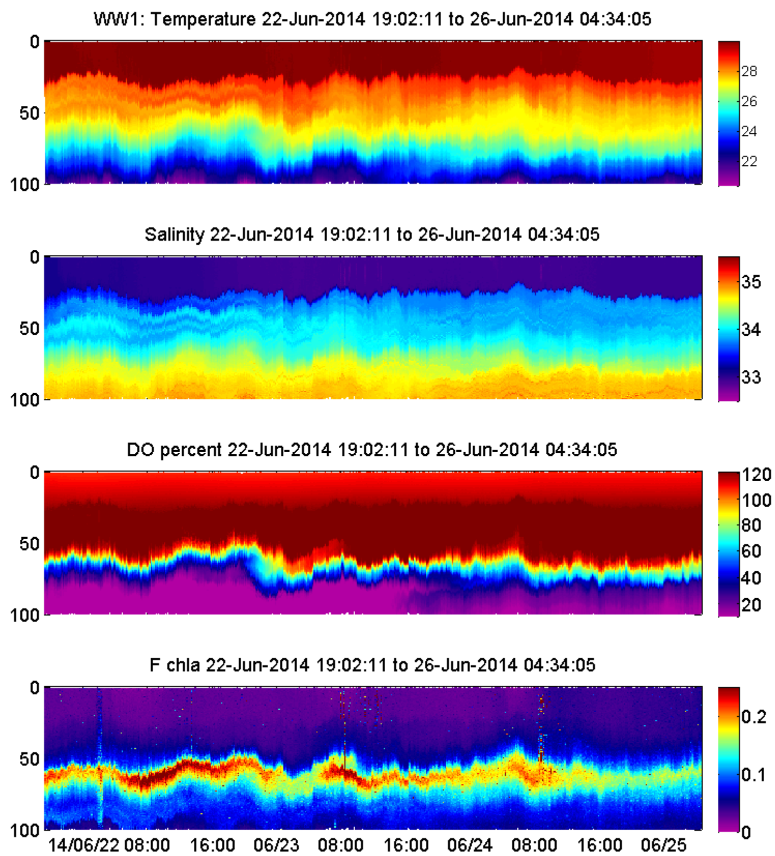

Figure 3: The second WW drift. WW-1. Temperature, salinity, disolved oxygen and chlorophyll fluorescence.

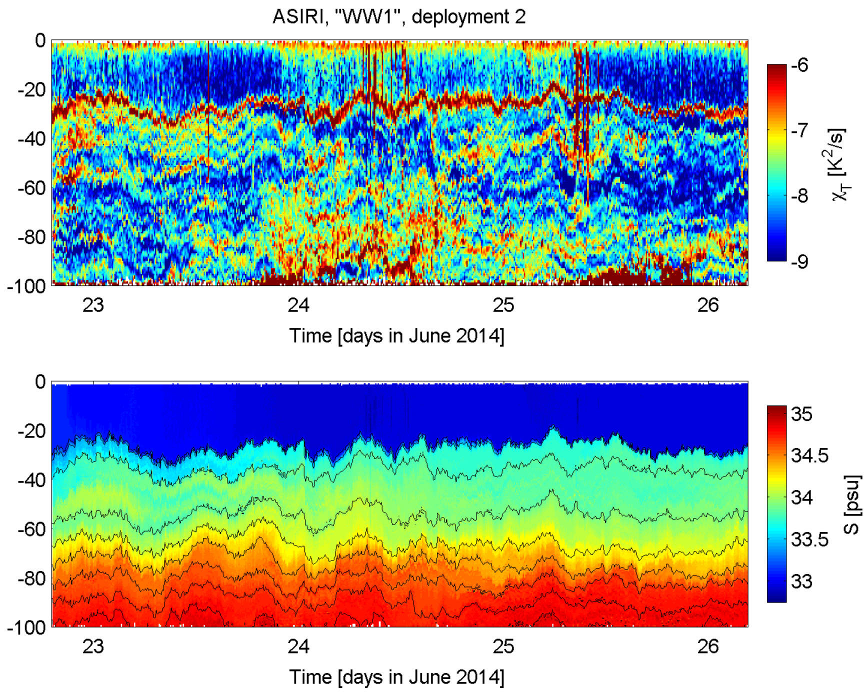

Figure 4: The second WW drift. WW-1. Salinity and χ.

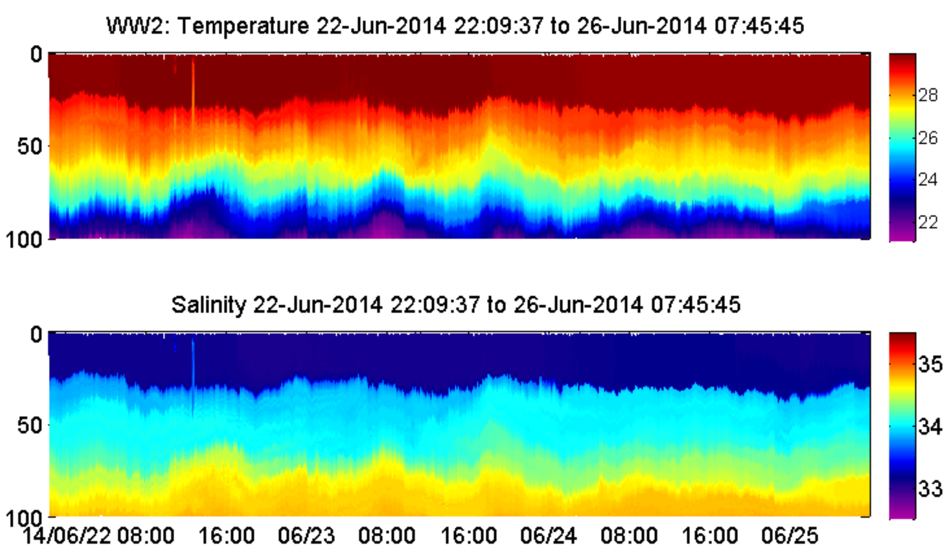

Figure 5: The second WW drift. WW-2. Temperature, salinity, disolved oxygen and chlorophyll fluorescence.

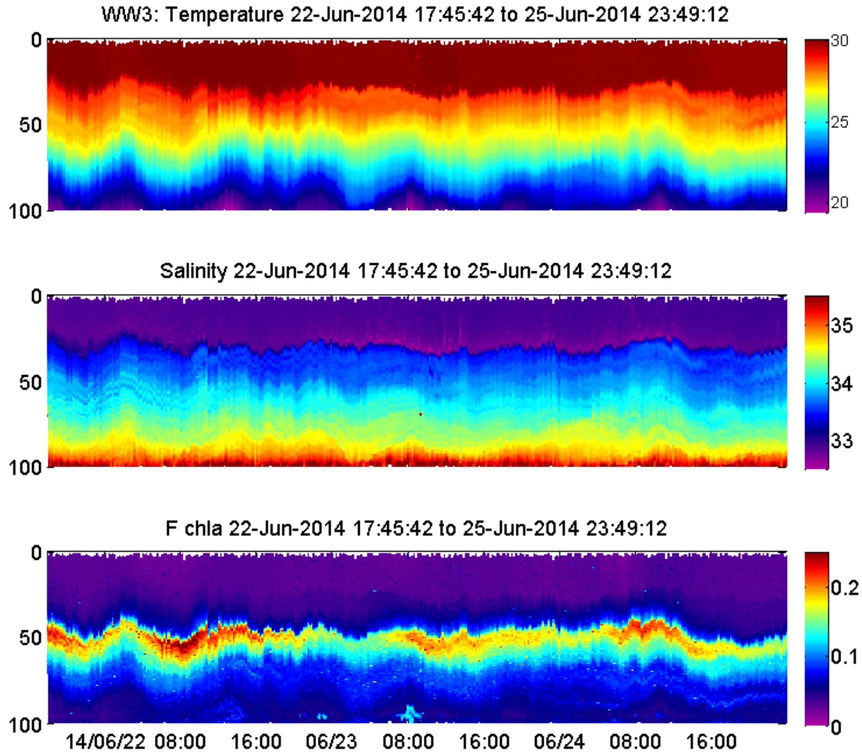

Figure 6: The second WW drift. WW-3. Temperature, salinity, disolved oxygen and chlorophyll fluorescence.

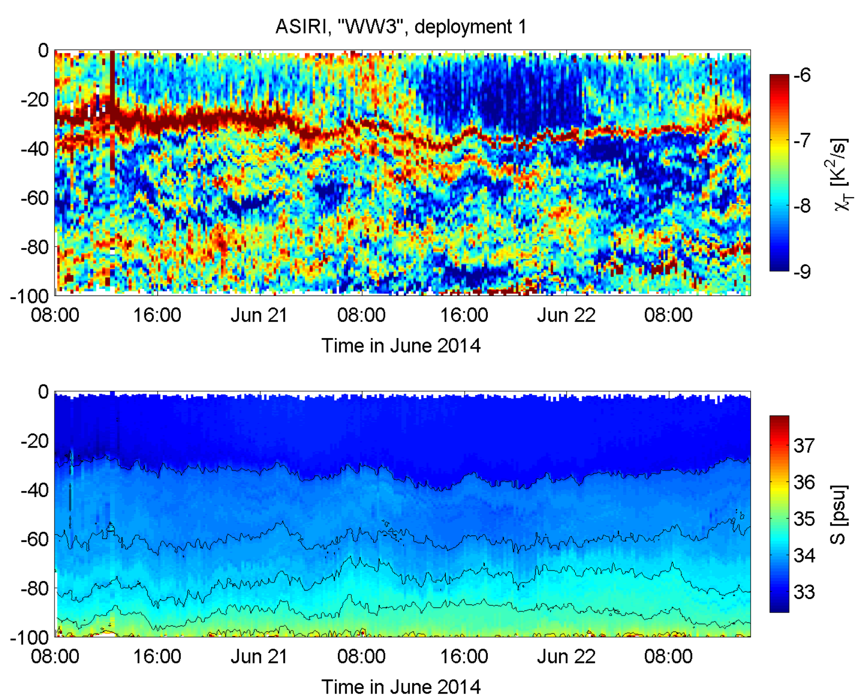

Figure 7: The second WW drift. WW-3. Salinity and χ.

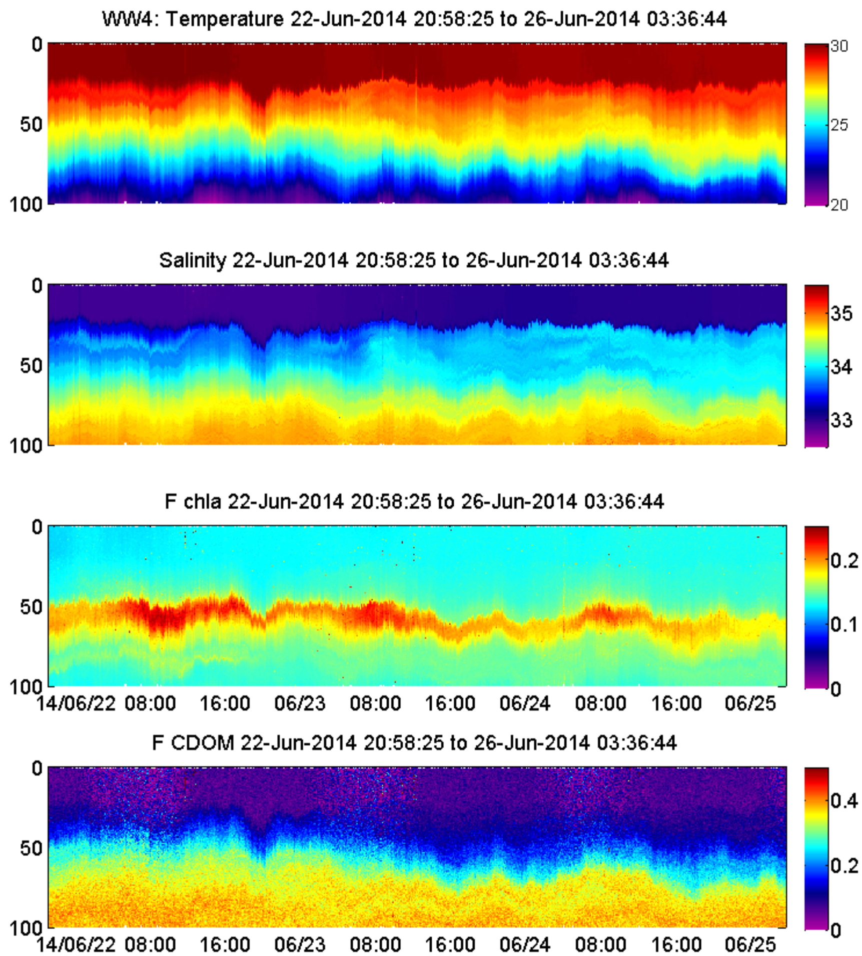

Figure 8: The second WW drift. WW-4. Temperature, salinity, disolved oxygen and chlorophyll fluorescence.

Table 2: **Wirewalker Operational Details**

Name	Instrumentation	Deploy. Pos.	Dates	Profiles
WW-1	RBR CTD, Nortek HR current profiler, RINKO DO, CDOM, Chl a F, PAR, χ-pod, 300 kHz upward-looking ADCP	1: 13.12N 84.956E 2: 13.88N 85.65E	06/20/14 - 06/22/14 06/22/14 - 06/26/14	48 539
WW-2	SBE CTD, Nortek HR current profiler, Chl a F, χ-pod, PAR	1: 13.12N 84.956E 2: 13.69N 85.63E	06/20/14 - 06/22/14 06/22/14 - 06/26/14	42 619
WW-3	SBE CTD, Nortek HR current profiler, CDOM, Chl a F, PAR,Turbidity, χ-pod, 300 kHz upward-looking ADCP	1: 13.09N 84.75E 2: 13.94N 85.51E	06/20/14 - 06/22/14 06/22/14 - 06/26/14	287 357
WW-4	RBR CTD, Chl a F, RAMES Hyperspectral Irradiance Sensor, PAR, 300 kHz upward-looking ADCP	1: 13.05N 84.67E 2: 13.76N 85.48E	06/20/14 - 06/22/14 06/22/14 - 06/26/14	400 612

2.2 UCTD Operations

Benjamin Hodges (WHOI) served as the lead UCTD technician during the cruise with most students taking an active role in UCTD operations. Hodges held training sessions during the commute to international waters on 17 June 2014, using a dummy probe. All science personnel were trained in the deployment and recovery of the probe, operation of the winch, downloading of the data, and initialization of the probes.

We opted for two modes of UCTD profiling: 1) full steam profiling with traditional Seabird probes targeted for mapping the large-scale field and 2) relatively slow tow-yoing with a RBR Concerto profiler during autonomous drift periods. Nominal horizontal resolution was just under 10 km for underway sampling and 1 km during tow-yoing; profile limits were roughly 250 m and 200 m for the two methods, respectively. Tow-yo lines were run from 21 June 2014 0145 to 22 June 2014 0310 and 23 June 2014 1625 to 24 June 2014 1340. A map of profile locations is shown in Fig. 9. In total, 218 underway casts and 375 tow-yo casts were completed.

Two probes were damaged during recovery operations, one on 18 June 2014 (cast 9) and one on 19 June 2014 (cast 40). Both probes hit the ship when being recovered with the winch; both probes showed a similar conductivity drift that progressively worsened after impact. The remaining probe lasted the duration of the cruise after implementing a hand-over-hand recovery policy.

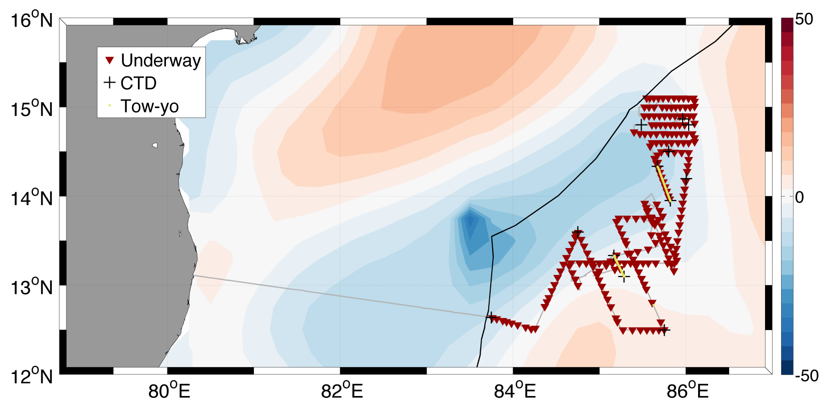

Figure 9: Locations of underway and tow-yo CTD stations along with CTD-water sampling stations. Sea surface height anomaly (cm) from June 16 is contoured in red-blue.

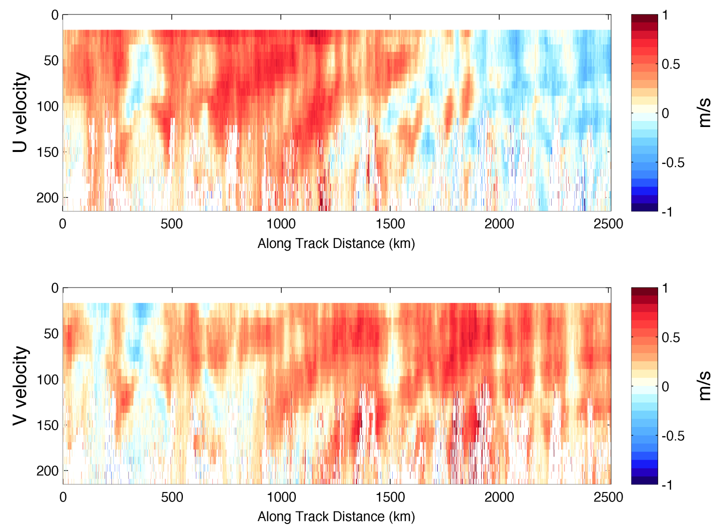

Figure 10: Along-track summary of velocity data from the 150 kHz ADCP.

2.3 Acoustic Doppler Measurements

The three Revelle-maintained Doppler sonars, the HDSS (140 and 50 kHz), a 75 kHz ADCP, and a 150-kHz ADCP (Fig. 10), were supplemented with a well-mounted 300 kHz ADCP (Fig. 11) and pole-mounted five beam Sentinel V (500 kHz). The additional systems allowed for improved resolution near the surface. Configurations were similar to those used during the pilot. The well-mounted system was configured to sample as rapidly as possible (1 Hz) in 2 m bins. Its vertical range extended to roughly 100 m. The pole-mounted sonar was deployed off the port side of the ship during times of relatively slow transits (4–6 knots), and was configured to sample in 1 m bins at 2 Hz. The instrument was mounted at a 15-degree angle pointed away from the hull of the ship.

2.4 TSG and Met Sensors

The Revelle underway TSG and meteorological sensors were operated throughout the cruise. All sensors appeared to be functioning properly. TSG data was used as an in situ calibration and quality check for UCTD data. TSG salinity was used to map the salty filament that formed the focus of this study (Fig. 1). Meteorological data are shown in Fig. 12. Apart from a cool front that the ship passed through on 23 June 2014, atmospheric conditions were stable. Winds were steady from the southeast at roughly 12 m/s, cloud cover and precipitation were minimal, and air temperatures hovered above 30 °C.

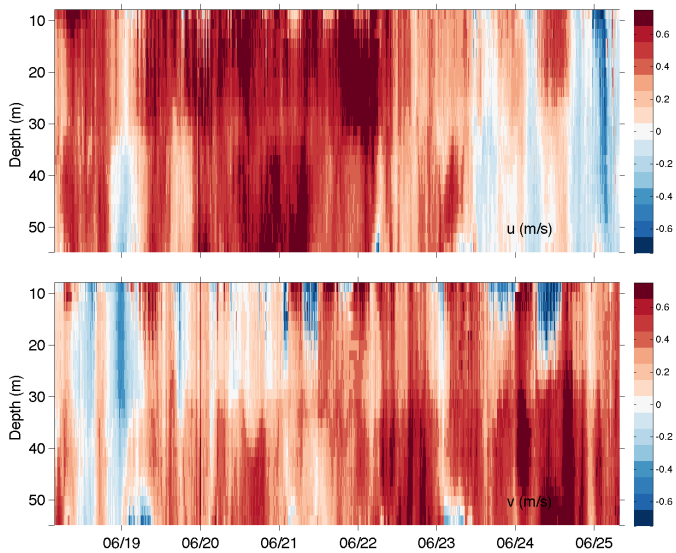

Figure 11: Same as Fig. 10 but for the hull mounted 300 kHz ADCP.

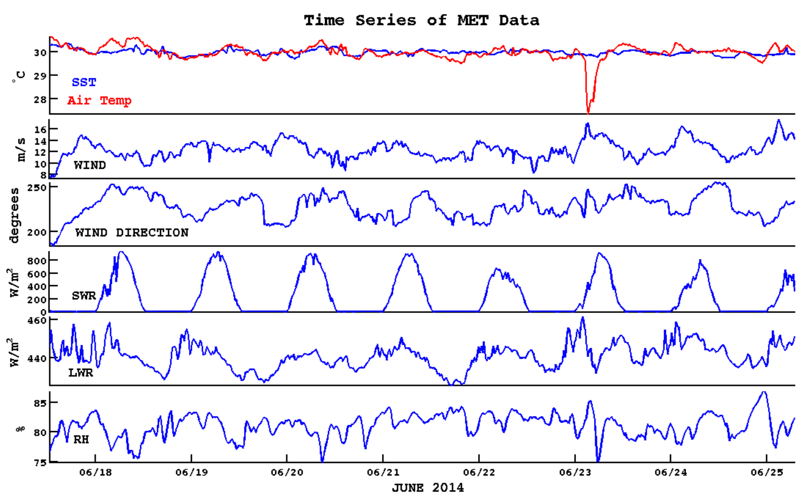

Figure 12: Summary of temperature (TSG-blue and air-red), wind speed, wind direction, incoming short wave radiation, outgoing long wave radiation, and relative humidity from mast meteorological sensors.

2.5 Bow Chain

A bow chain equipped with several CTDs and SBE56 thermistors was deployed during the two autonomous drift periods. During the first deployment (deployed at 20 Jun 2014 1600 UTC, retrieved at 20 Jun 2014 1826 UTC), two RBR Concertos (5.5 and 9.5 m), 3 Microcats (1.5, 3.5, 7.0 m), and 15 SBE56s were secured to the bow chain line (nominal spacing at 0.5 m). Regular visual inspections of the bow chain showed that the upper most Microcat had slipped. When the bow chain was recovered, it was clear that all Microcats had moved on the line, shifting some of the lighter SBE56 sensors with them. Microcats were re-secured, and the bow chain was turned around quickly for the second deployment (deployed at 21 Jun 2014 0040 UTC, retrieved at 21 Jun 2014 1250 UTC). These initial two deployments showed little to no vertical gradients over the upper 10 meters of the ocean. Sensor load during the third and fourth deployments was therefore reduced (RBR Concerto located at 7.25 m, SBE56 at nominal 1 m spacing from 1-10 m depth). Third and fourth deployments of the bow chain spanned 21 Jun 2014 0036 UTC – 22 Jun 2014 0329 UTC and 23 Jun 2014 1548 UTC – 24 Jun 2014 1459 UTC, respectively. Despite the lack of vertical gradients the bow-chain sensors recorded the fine horizontal scale variability across the filament, not detectable in other shipboard platforms.

2.6 Turbulence Glider

A Slocum glider equipped with a full turbulence suite (Rockland Scientific Microrider) was contributed and operated by Lou St. Laurent, WHOI. The glider was first deployed on 20 June 2014 during the first autonomous drift surveying. Deployment was conducted off the starboard-side of the Revelle. A buoy was attached for the initial test dive and communications check. Once the buoy was removed the Slocum was left in a mooring 'mode' outside the salty filament. Through the course of this first deployment the Slocum began to have trouble navigating due to an unresponsive fin. We broke away from survey ops to recover the Slocum at 1000 IST 22 June 2014. Recovery was also staged on the starboard side using the crane. The initial approach of the Revelle was clean, but the nose of the glider hit the side of the ship (low in the water) on recovery, breaking the shear probes and thermistors. B. Hodges ran diagnostics on the glider and prepped the glider for a re-deployment on 23 June 2014. The glider was recovered on 25 June 2014. The Revelle needed to make multiple passes for a successful hook and the sensors were again damaged, this time while still in the water. On inspection of the glider significant corrosion was evident near the probes, further investigation showed that the nose cone had flooded likely due to damage sustained during the first recovery.

2.7 Water Sampling

In order to study the biogeochemical processes in the water column, Investigators Bhaskara Rao Dokala and Sherin C K (NIO) collected water samples for analysis for the following parameters:

- Dissolved Gases (Nitrous oxide, Methane)

- Inorganic carbon Components (pH, Total Alkalinity)
- Dissolved inorganic carbon
- Dissolved organic carbon
- Nutrients (Nitrate, Nitrite, Phosphate, Silicate, Ammonia)
- Suspended particulate organic matter
- Phytoplankton pigments

Samples were collected from 12 stations between 15 and 28 June, 2014 in the International waters of Bay of Bengal. Water samples were collected at around 9 predetermined depths (near surface, 5m, 10 m, 25 m, 50 m, 75m, 100 m, 200 m and 500m depth). Temperature, salinity, fluorescence and dissolved oxygen data were collected from the shipboard CTD. Water samples for nitrous oxide, methane, dissolved inorganic carbon, PH, alkalinity and nutrients were poisoned with mercuric chloride solution and stored for off board analysis. Dissolved organic carbon samples collected in glass vials were then stored with few drops of phosphoric acid. Water samples for biological pigments and suspended particulate organic matter were collected in 20 litre plastic carboys and filtered immediately through GF/F filters (Pre-combusted filters are used for suspended particulate matter samples). Filtered Pigment samples are stored in liquid nitrogen and suspended particulate organic matter samples in deep freezer.

3 Preliminary Findings

3.1 Remote sensing, numerical modeling, and operational planning

Our in-cruise operational decisions were informed by a steady-stream of remote sensing products and numerical model results. A. Tandon and graduate student Jared Buckley (UMass-Dartmouth) provided a synthesis of Aquarius, CCAR, and HYCOM products, updated daily. Rashmi Sharma and the group from the Space Application Centre of the Indian Space Research Organization provided additional satellite-based imagery as well as 72-hr WRF forecasts at 5-km resolution. UMass-Dartmouth Post Doc S. Ramachandran was responsible for collating and preliminary interpretation of the remote sensing and numerical modeling products onboard. This information (and post-cruise analysis) provided mesoscale synoptic oceanic and atmospheric conditions. The initial survey showed that the ocean models and satellite products were accurate in representing the mesoscale conditions. Our drifting observations will supply a view of the small-scale spatiotemporal evolution of the upper ocean via mesoscale stirring, an especially interesting problem given the extremely rich T/S variability in the basin.

3.2 Large-scale survey

Prior to departing Chennai the study area was identified using available remote imagery and model products. Waypoints for the large scale survey were set to span a region of confluence between two eddies, primarily across sea surface height contours (Fig. 9). Prior to embarking we made the decision to limit the large-scale survey to less than two days of cruise time, with the caveat that we could break away early if a feature of interest was identified quickly.

Selected waypoints follow:

- WP1: 12.64N, 83.75E
- WP2: 12.5N, 84.25E
- WP3: 13.6N, 84.75E
- WP4: 12.5N, 85.25E
- WP5: 12.5N, 85.75E
- WP6: 13.6N, 85.25E
- WP7: 13.6N, 85.75E
- WP8: 12.5N, 86.25E
- WP9: 12.5N, 86.75E
- WP10: 13.6N, 86.25E

During the large-scale survey the Revelle maintained an underway speed of roughly 10 knots. The pole-mounted ADCP and bow chain were not deployed during this mode of sampling, and the UCTD was operated using Seabird probes that were pre-wound for each cast (as compared to a tow-yo mode). The in situ structure agreed remarkably well with sea surface height contours. While some high-frequency upward phase propagation is apparent, the predominant velocity signature is generally along SSH contours consistent with a geostrophic balance (Figs. 10 and 11). A salty filament, which roughly lay between the high and low SSH regions, was identified on the first southwest-northeast transect line (between WP2 and WP3). The feature was repeatedly observed on each subsequent line with a north-south component. The large-scale survey was cut short between WP7 and WP8 in order to prepare and deploy the first drift and high-resolution feature tracking across the southern flank of the filament.

3.3 Preliminary feature-tracking and survey results

The first drift tracked the evolution of the southward edge of the salty filament. Repeat UCTD sections and CTD stations documented the cross-filament distribution of mass, tracers, and velocity.

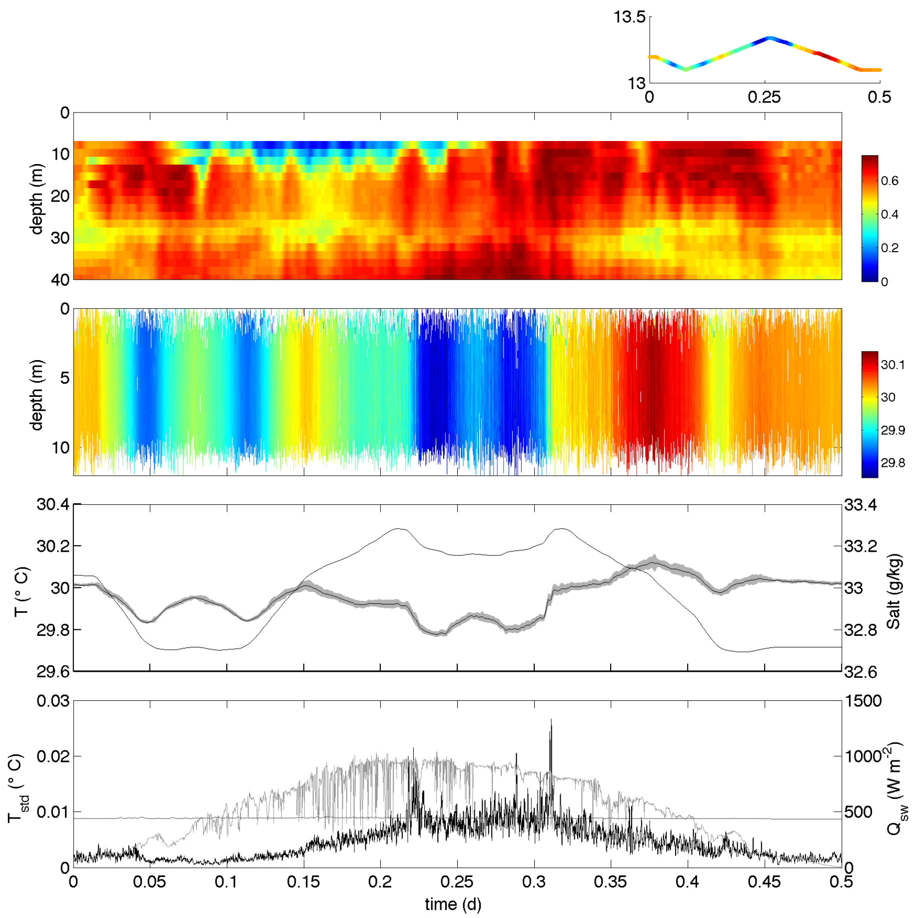

Figure 13: Summary of across-track velocity (upper panel), bowchain temperature (second panel), bowchain temperature (grey) and salinity (black) (third panel), and temperature variance (black) with incoming shortwave radiation (grey) (bottom panel) for one back and forth crossing of the salty side of the filament (upper inset shows temperature from TSG).

The WW pair that had good profiling performance provided detailed vertical information in time in a stream-wise sense. Velocity showed very little shear over the upper 100m, such that the profiler drifts were approximately Lagrangian. The mesoscale flow field appears to have been the primary driver of the drift trajectory and velocity fields. The distribution of spice, however, showed that the mesoscale density gradients arose from waters with differing T/S characteristics in an on-isopycnal frame of reference. Representative transects of bow chain data collected during the southern drift are shown in Fig. 13. Temperature was homogeneous over the upper ocean. (The MLD was nominally 30 m deep.) However, horizontally temperature and salinity did not vary in unison even over the short transects that spanned the southward edge of the filament. High vertical variance in bow chain temperature sensors accompanied sharp lateral gradients in mixed layer temperature, particularly near edges of the filament (Fig. 13). It remains to be determined whether this signal is associated with daytime heating and sampling or if it is representative of mixing processes at the front.

The second drift was positioned at the northern edge of the filament, which generally had weaker lateral gradients in temperature and salinity (Fig. 1). However, wind forcing and direction were relatively steady over the cruise duration (Fig. 12), so that collectively the two drifts sampled fronts oriented in both the downwind and upwind directions. After a day of sampling in our high-resolution mode, we were no longer able to detect a clear signature associated with the front. We therefore transitioned back into an underway mode in order to cover more ground and re-map this edge of the filament (see east-west lines at the northern extent of the study area; Fig. 1).

3.4 Training activities

Training activities comprised a major component of this cruise. These activities, aimed at the US and Indian students, combined gaining hands-on experience with all the instrumentation used during the cruise, a seminar-style series of talks, and daily data analysis workshops. Daily talks covered topics ranging from ongoing cruise planning and data collection to operational principals of acoustic Doppler profilers to UCTD data handling and calibration. Daily workshops on data processing, using data collected during the cruise, were held separately for day and night shifts. During these sessions students were trained in the basics of Matlab processing and display, and more senior students and scientists were available for hands on feedback and training. The students interacted amongst themselves and with the more senior scientific personnel outside of this dedicated time, completing data-processing activities that were self-directed. Indian engineers from INCIOS and NIOT were exposed to the Wirewalker profiling technology, as well as the more commonly utilized long-range and Slocum gliders. It was by all accounts a fruitful experience for everyone from both Indian and US institutions, and we look forward to continued collaboration with students as the ASIRI DRI progresses.

4 Conclusions

The 2014 Leg-1 ASIRI process cruise used a combination of autonomous assets and shipboard sampling to investigate the evolution of a salty filament under the influence of mesoscale and atmospheric forcing. A large-scale survey documented the mesoscale variability, while a pair of drifts and high-resolution surveys investigated small-scale dynamics. In addition to purely physical parameters, we gathered a wealth of optical information. Shipboard CTD rosette based sampling provided basic biogeochemical information and indicated that the physical dynamics where reflected in those quantities. Although analysis is ongoing, we appear to have a very detailed dataset, likely valuable for both basic questions regarding upper ocean dynamics as well as a comparison point for the previous and upcoming ASIRI cruises.