ASIRI PILOT: Leg 1

R/V Roger Revelle cruise RR1316
Final Cruise Report

December 2013

1 Overview

The Air-Sea Interactions in the Northern Indian Ocean Regional Initiative (ASIRI) project is an ONR-funded experiment designed to: 1) understand and quantify dynamical processes and boundary transports that control fresh and salt water exchanges between the Northern Indian Ocean, the Bay of Bengal, and the Southeast Arabian Seas (SEAS), with particular emphasis on the relative contributions of air-sea interaction, mesoscale, and submesoscale processes; and 2) examine the relative roles and responses to buoyancy and wind stress forcing using both *in situ* observations and with high-resolution numerical models of both the process and forecast-types. These scientific interests motivate international partnerships with both India and Sri Lanka. The overall program is a 5-year project, with fieldwork in 2013, 2014 and 2015 using UNOLS, Sri Lankan, and Indian research vessels, as well as PIs from all three countries.

The fall 2013 ONR ASIRI Pilot cruise (10-November to 25-December 2013) was split into three legs. The legs were organized to include 1) a large-scale, high resolution survey of the N/S axis and N/S gradients of the upper ocean in the BoB (Leg 2), 2) an initial set of time-series observations of vertical variability in the southern BoB (Leg 2), 3) deployment of long range Spray glider, drifters, and SOLO floats (Leg 1) 4) a submesoscale experiment in the northern BoB (Leg 1), 5) joint ship operations between the R/V Revelle and the R/V Sagar Nidhi (Leg 1), 6) training opportunities for international (Sri Lankan and Indian) collaborators (Legs 1 and 2), and the deployment of moorings (Leg 3). This document describes the first leg of the pilot experiment (10 Nov - 27 Nov). Below we present details of our measurements, a basic survey of observational results, and a brief discussion of scientific hypotheses and questions.

By all measures, this was a successful cruise. We have managed to gather what we think will be a very interesting dataset characterizing small-scale lateral and vertical variability in the BoB. We deployed drifting assets in two regions of varying degrees of lateral mixed layer density gradients. We collected >2,400 wirewalker profiles to 150m (with a variety of sensors, including temperature microstructure), ∼1,500 UCTD + J-CTD casts, current data across a range of vertical scales including within the surface mixed layer, >50 VMP casts, and very high horizontal resolution T/S data from our bow chain. We also deployed surface drifters both in our process study area and on our steam to port, in addition to a long range glider and three Solo floats. Our two-ship operations with the R/V Nidhi will help to put our small-scale observations into a mesoscale context.

We had an excellent collaborative spirit among our US, Indian, and Sri Lankan groups, including the students. We believe all are excited about the work we have just embarked upon, and are all excited to dive into the data more thoroughly in the coming weeks and months.

2 Cruise track and summary

Leg-1 of the ASIRI Pilot cruise was primarily a small-scale (submesoscale) process study. The general sampling strategy was to utilize the Revelle's extended shipboard sampling capabilities to sample small lateral scale features in the context of drifting profiling assets. This approach allowed for repeated horizontal surveys of evolving submesoscale features gathered concurrently with high resolution time series observations from the drifting instruments. These complementary approaches provide the detailed horizontal, vertical, and temporal resolution necessary to examine submesoscale dynamical variability *in situ*,

We utilized remote sensing products and real-time shipboard data, particularly from the flow-through system and the underway CTD (UCTD), to target general areas and then hone in on small-scale dynamics of interest. Based on the remote sensing information shared by our Indian colleagues, we conducted sampling activities centered around 2 locations: 15°N 86°E (14-16 November, 2013) and 16°N 87°E (17-23 November, 2013). Upon arrival at both locations, we conducted a preliminary survey utilizing the shipboard sampling and UCTD. We subsequently deployed 3 Wirewalker (WW) wave-powered profilers (see below) and a densely instrumented spar buoy. Once the drifting assets were deployed, we typically lowered our over-the-side 500 kHz ADCP and instrumented bow-chain, and resumed horizontal survey activities, utilizing the drifting array as an anchor for our drifting surveys. During deployments of the over-the-side pole and bow chain, our forward speed was limited to ∼3 knots, leading to very fine spacing of UCTD casts during slow speed survey mode. We augmented these surveys with a series of sections and casts of a microstructure profiler (Rockland Scientific VMP-250) brought aboard and managed by Sri Lankan collaborators and Iossif Lozovatsky.

In what follows, we describe the details of the instruments used and deployment techniques. We then present a number of preliminary observations and initial scientific hypotheses.

3 Instrumentation and Field Methods

During the project we used a combination of autonomous assets and shipboard survey sampling. The primary operational aim was collecting data of high horizontal and vertical resolution. With the exception of the long-term glider and float deployments, the tools described below were utilized to this end.

Wirewalkers and Spar Buoy

The Wirewalker (WW) profilers were deployed on 150m wires, and completed a round-trip profile one ∼15 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.

Two of the three WWs were equipped for real-time telemetry via inductive modems, connecting the profiler with the surface buoy, and line-of-sight HF radio modems for buoy to ship communications. We achieved a range of ∼7-9km for uninterrupted line-of-sight radio modem connectivity, depending on sea state. The radio modem allowed us to observe profiling and instrument performance. The monitoring of these performance metrics led to three interventions due to lack of profiling performance and poor conductivity readings from a single CTD. Rapid assessment of problematic profiling or instrument performance allowed us to minimize gaps in data, and enhance data quality, thus maximizing the value of the funded ship time. After these very limited initial interruptions, WW performance was excellent.

The details of the Wirewalker and Spar buoy can be found in Table 1. In all, 2,459 WW profiles were collected over the ~9 sampling days. Figure 1 shows an example of a WW deployment using the Revelle's A-frame.

Table 1: **Wirewalker and Spar Buoy Operational Details**

Name	Instrumentation	Deploy. Pos.	Dates	Profiles
ASIRI-1	RBR CTD, Nortek HR current profiler, RINKO DO (Dep. 1-3), CDOM, Chl a F, PAR, χ-pod, 300 kHz upward-looking ADCP	1: 15 09.4N 86 06.16E 2: 15 58N 86 58E 3: 16 01N 86 58E 4: 16 10.8N 87E	11/14/13 - 11/16/13 11/17/13 - 11/20/13 11/20/13 - 11/22/13 11/22/13 - 11/23/13	190 291 204 172
ASIRI-2	RBR CTD, Nortek HR current profiler, RINKO DO (Dep. 3-5), Chl a F, χ-pod, 300 kHz upward-looking ADCP	1: 15 10N 86 06E 2: 15 58.3N 86 58.4E 3: 16 06.7N 87 00E 4: 16 10.6N 86 56.9E 5: 16 12.7N 87 02.7E	11/14/13 - 11/16/13 11/17/13 - 11/19/13 11/19/13 - 11/21/13 11/21/13 - 11/22/13 11/22/13 - 11/23/13	155 214 181 79 133
ASIRI-3	SBE CTD, Nortek HR current profiler, CDOM, Chl a F, Turbidity, χ-pod, 300 kHz upward-looking ADCP	1: 15 10.2N 86 05.4E 2: 15 58.2N 86 58.0E 3: 15 55.8N 86 52.2E	11/14/13 - 11/16/13 11/17/13 - 11/20/13 11/20/13 - 11/23/13	218 264 354
Spar Buoy	10 SBE 37s, 24 SBE 56s, 1200kHz RDI ADCP (at 20m) 300 kHz ADCP (at 140m)	1: 15 10.2N 86 05.4E 2: 15 58.2N 86 58.2E 3: 15 55.8N 86 52.2E	11/14/13 - 11/16/13 11/17/13 - 11/20/13 11/22/13 - 11/23/13	N/A

Underway CTD and J-CTD

The Underway CTD system (UCTD) is a free-falling CTD package designed to be deployed during transits or surveys. The system is comprised of a Seabird CTD probe, overboarding davit, and electrical winch. We utilized the UCTD system to conduct surveys around the drifting WW and spar buoys. Additionally, we utilized the UCTD system during transits to and between process study locations. The horizontal resolution of the UCTD sections depended on ship speed, deployment depth (typically 150 or 200m) and deployment mode (traditional, full recovery or toy-yo). During coincident surveys with the over-the-side ADCP and bow chain deployed, the ships speed was limited to ~3knots, and tow-yo mode UCTD operations led to horizontal spacing between casts of ~300m. During transits, the horizontal spacing between casts was between 6-7 km.

The operation of the UCTD entails inevitable risk to the probe. A common cause of failure is unintentional interaction between the probe and the side of the ship. In course of our UCTD operations, we damaged 3 probes. As our probe supplies dwindled, and our concern for the Leg-2 survey activities grew, we decided to rig a replacement probe using an RBR CTD brought aboard by J. Nash. The CTD

Figure 1: The deployment of a Wirewalker profiler from the R/V Revelle A-frame. The Wirewalker was equipped with CTD, current meter (both on the profiler and upward looking ADCP), χ-pod, and chlorophyll fluorometer. The Wirewalkers were deployed on a 150m wire, and performed a round-trip every 15min. Three such Wirewalkers were maintained during the two process experiments.

was secured in a pipe, fitted with a rope harness, and deployed utilizing the UCTD winch (Fig. 2). We referred to this as the J-CTD. The J-CTD was also equipped with a χ-pod to collect microstructure temperature information. We collected 847 profiles using the Seabird probe, and 641 profiles using the J-CTD.

Figure 2: UCTD probes (closest to camera) and JCTD probe (furthest from camera). The JCTD was rigged after we damaged a number of SBE UTCD probes. JCTD, in addition to measuring conductivity, temperature, and pressure, was also equipped with a χ-pod to measure temperature microstructure.

Bow Chain

To measure undisturbed near-surface density and turbulence and to capture finescale horizontal gradients of near surface features, we deployed a 20 element chain of T, CT and χ-pod sensors from the foremost opening on the Revelle's foredeck. Sensors were attached to a 10 m shot of 3/16" coated wire, which was kept close-to-vertical using a 220 lb depressor weight that looked like Starship Enterprise. The assembly was deployed using the knuckle crane, which lifted the top of the wire, all sensors, and weight over the Revelle's rail using a secondary lifting line (figure 3). Once lowered to the ocean surface, the load was transferred to a piece of 1/2" nylon, which was hauled in and made fast to a cleat.

The chain consisted of 20 sensors with 0.5 m nominal spacing. 5 RBR CTD sensors sampling at 6 Hz were distributed at 2 m intevals along the wire. Each sensor was customized by adding an OSU mini χ-pod internally into the RBR, which recorded fast temperature (at 100 Hz), its derivative, as well as 2 components of package acceleration. In between the RBRs were distributed 15 SBE-56 sensors sampling at 2 Hz. Pressure data from the RBR CTDs was used to determine instantaneous depths at 6 Hz, from which the SBE-56 pressures were inferred.

The system performed well at speeds of up to 5 knots. During periods of strong cross-winds or sharp turns, the chain occasionally hit the side of the ship, as evidenced by paint on the sensors. Although sensor damage was in general limited, some thermistor damage did occur when sensor stings vibrated to an extent that they broke off; in the future we will use the 5/8" diameter copper stings instead of the 1/8" stainless stings for the thermistor shafts.

ADCPs

To supplement sonars permanently installed in the ship hull, two additional ADCPs were utilized during this experiment. A 300-kHZ RDI ADCP was installed in an open well in the staging bay. This instrument was set to sample in 4-meter vertical bins with 1-second sampling. To acquire data even closer to the surface and additional ADCP was installed at the end of a pole mounted to the side of the ship. The instrument is a 'Sentinel V', a newly available instrument from RDI Teledyne (http://www.rdinstruments.com/followV.aspx). The instrument is still in the final stages of development at RDI Teledyne, and was loaned to us for the duration of the cruise to allow field-testing. In addition to a standard 4-beam Janus configuration it has a fifth vertically oriented beam. The addition of the fifth beam allows more accurate estimate of two-variable correlations such as Reynolds stresses. The instrument pings at 500 kHz, and was configured to record data in 1-meter bins every 0.5 seconds. In order to avoid one of the beams hitting the ship hull, the instrument was mounted at a 15 degree angle to the vertical, pointing away from the ship. Figure 4 shows both instrument deployments.

Throughflow thermosalinograph system and shipboard CTD

The Revelle's thermosalinograph (TSG) through-flow systems were very useful for adaptive management of the drifting assets and survey patterns. The TSG was set-up to record data in one minute intervals, leading to fine horizontal resolution in T and S in the upper 5m of the water column. Strong fronts in T and S were noted through-out the process experiment. For the deployment of the WW array across submesoscale fronts, we utilized the TSG data to assist with the difficult task of achieving small lateral separation in initial deployment location while bracketing the dynamics of interest. More broadly, the TSG gave us hints as to the strength and relative orientation of surface gradients to inform decision-making regarding the horizontal extent, orientation, and duration of the UCTD surveys. Finally, Nimit

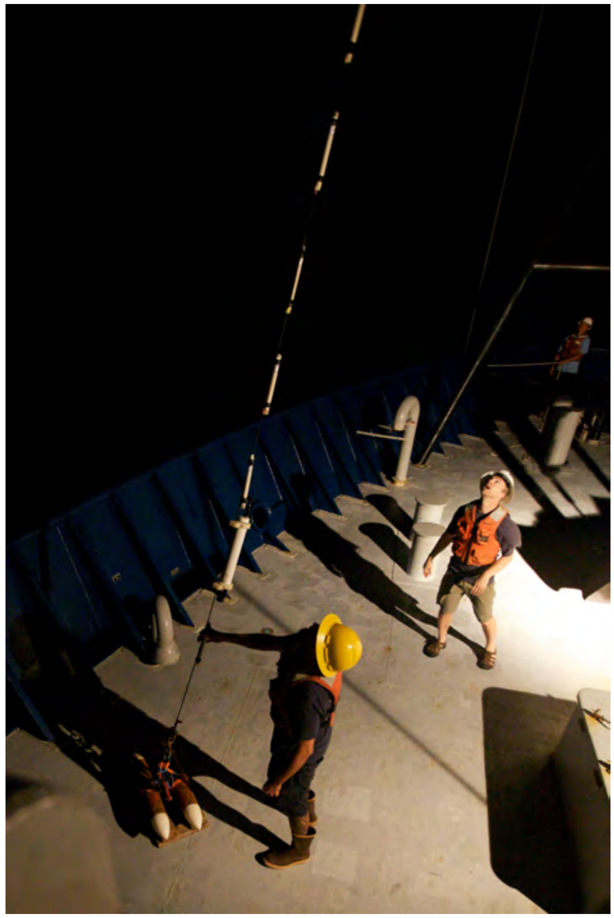

Figure 3: Nighttime deployment of the bow chain.

Diplikumar (INCOIS) collected water samples from the TSG system to perform stable isotope laboratory analyses.

Six irregularly spaced shipboard CTD casts were conducted. These shipboard CTDs were used primarily to provide calibration against UCTD probe drift. Water was collected via the rosette at various depths during those casts, again by Nimit Diplikumar (INCOIS), for stable isotope analysis. One deep CTD (to 1500 m) was performed to map the extent of the low oxygen distribution below the barrier layer (BL).

Rockland Scientific Vertical Microstructure Profiler

We augmented Thorpe and χ-pod-based dissipation measurements with direct shear microstructure measurements from the Rockland Vertical Microstructure Profiler (VMP), an effort led by Iossif Lozovatsky (Notre Dame) and Pryantha Jinadasa (NARA, Sri Lanka). The VMP is a loosely tethered instrument typically deployed from the stern with a small winch while steaming slowly (1-2 knot). In our case the

Figure 4: Left: "pipe string" system for installing an additional 300 kHZ ADCP in a well in the staging bay. Right: pole system for mounting the Sentinel V ADCP over aft port side of the deck. The instrument was approximately 1 meter below the surface.

Table 2: **Shipboard CTD operations**

CTD cast name	Deploy. Pos.	Date and time	Profile Depth
ASIRI-1-1	08 24.28 N 085 03.04 E	Nov 12 2013 11:32:31	300m
ASIRI-1-2	15 10.11 N 086 05.24 E	Nov 14 2013 16:39:36	300m
ASIRI-1-3	15 57.30 N 086 57.84 E	Nov 18 2013 07:27:07	300m
ASIRI-1-4	16 05.12 N 086 54.22 E	Nov 20 2013 10:01:40	300m
ASIRI-1-5	16 04.78 N 086 41.31 E	Nov 23 2013 17:13:16	300m
ASIRI-1-6	16 04.78 N 086 41.31 E	Nov 23 2013 18:29:55	1500m

winch malfunctioned, but the team rallied and we successfully deployed and recovered the instrument by hand for each cast (Fig. 5). We collected 55 VMP profiles during the science operations, as well as 17 test profiles early during the cruise. An example VMP section is presented below.

Autonomous asset deployments

We deployed a long-range Spray glider, 3 Solo II floats (including one conducting a rapid profiling mission plan, and 8 Niiler-type drifters. Three of those drifters, belonging to NARA, were deployed in the Sri Lankan EEZ. Table 3 contains the deployment specifics of the autonomous assets deployed on the pilot cruise.

4 International Collaboration

The US and Indian science teams began collaborating prior to the two legs by discussing remote sensing products, and the international collaboration was evident during both legs, as the scientists from US,

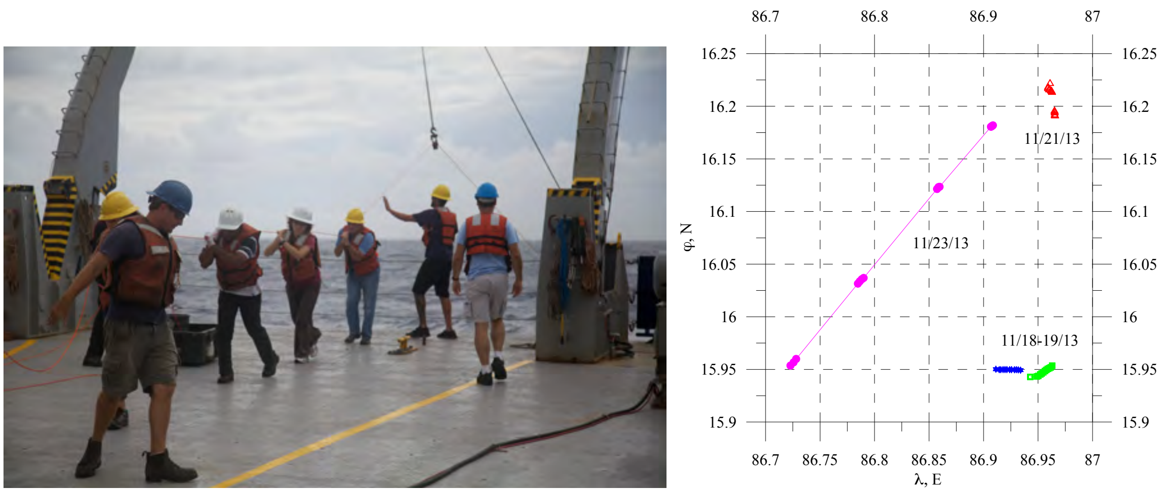

Figure 5: The "people-powered" VMP winch in action (left photo) and VMP deployment locations (right panel).

Table 3: **Long-term autonomous asset deployment details**

Name	Deploy. Pos.	Dates
SOLO II float 1	10 59.95N 85 25.85 E	11/13/2013 03:12
SOLO II float 2	13 02.5N 85 43.2 E	11/13/2013 15:19
Spray glider 024	15 10.752N 86 06.2925E	11/14/2013 12:42
SOLO II float 8119 (rapid profiling)	16 17.039N 86 58.432E	11/21/2013 11:01
Drifter 116181	16 13.174N 86 57.553E	11/21/2013 09:10
Drifter 109175	16 13.158N 86 57.549E	11/21/2013 09:21
Drifter 116182	16 13.079N 86 57.540E	11/21/2013 09:28
Drifter 116741	16 13.011N 86 57.602E	11/21/2013 09:39
Drifter 116006	16 12.996N 86 57.632E	11/21/2013 09:43
Sri Lanka Drifter 1	09 49.01N 83 40.238E	11/25/2013 09:28
Sri Lanka Drifter 2	08 44.712N 83 08.192E	11/25/2013 15:25
Sri Lanka Drifter 3	07 44.896N 82 37.796E	11/25/2013 20:45

India and Sri Lanka worked together on Revelle and scientists from India and US worked together on ORV Sagar Nidhi during these experiments.

The remote sensing group at Space Applications Center (SAC) Ahmedabad (OMM PI: Rashmi Sharma) and the group at Indian National Center for Ocean Information Systems (INCOIS) Hyderabad (OMM PI: M. Ravichandran) provided remote sensing images of SST, SSC and various other satellite products starting November 1st. The SRL SSH product was also made available by the SAC group. The

ASIRI mailing list was used for frequent collaborative emails prior to and during the experiment. The remote sensing groups also provided alert products for tropical cyclones in the area before the beginning of Leg-1.

As part of the collaboration, Eric D'Asaro (US ASIRI PI) and Michael Allen from University of Washington were on ORV Sagar Nidhi and provided much detailed training to young scientists on board. In addition, six early career scientists from Indian institutions - INCOIS Hyderabad, NIOT Chennai and IIT Bhubaneswar were on Revelle.

The international collaboration was further demonstrated during the two ship operations of Revelle and Sagar Nidhi. ORV Nidhi departed from Chennai on November 15th, and the two ships conducted joint work during November 17-19th for about 2.5 days. During this time the Nidhi conducted two outer surveys around the Revelle positions in square boxes of about 20 nautical miles (0.2 degree each side) at the second process study region near 16N, 87E. Revelle conducted finer scale detailed process studies inside this region. While the ADCP on the Nidhi did not work adequately and was used by Eric D'Asaro and Michael Allen primarily for training purposes, our collaborators on Nidhi were able to get more than 100 UCTD profiles in the outer box region during the joint experiment. Revelle and Nidhi were in frequent bridge-to-bridge radio contact during the joint experiment, and often within visual range during this phase.

5 Science Results

5.1 Mesoscale context

Remote sensing products from both countries (US and India) in advance of the collaborative experiments and Leg-1 process studies provided the mesoscale context for the experiment and helped inform site selections for the process study experiments. In particular, the remote sensing groups at two Indian collaborating institutions INCOIS Hyderabad and SAC Ahmedabad supported this Leg by providing many images on their ftp servers in support of Revelle and Nidhi operations. In addition, the processed data from Aquarius SSS and CCAR SSHA were combined with these products to provide a large scale context for this Leg. A combination of SSHA and SSS data for November 8th, 2013 is shown in Figure 6. The altimetry shows a cyclonic eddy centered at 16.4N, 86.4E, sandwiched between anticyclonic eddies to its North and South. All three features have length scales of O(400km) in the North-South direction, and further elongated in the zonal direction. The SSS features showed strong westward advection of the relatively fresher water from the Irrawaddy River discharge, which is stirred by the mesoscale eddy features. SST images also showed relatively cooler river water from the Ganges-Brahmaputra delta flowing westward along the Indian coast and separating rom the cost between 16N and 18N by the eddies. These are shown in Figure 7.

The remote sensing products were used to decide on some regions of potential interest for process studies. These were near 15N, 86-87E (near western edge of international waters) and 16-17N, 90.5E (near eastern edge), and 16.5N, 88.5E (SST fronts seen in remote sensing imagery). Since the SSH contours seemed to cross SSS contours near 15-16N, 86E, this was likely a region a mesoscale convergence and hence fronts. This indeed proved to be the case and we conducted process studies both near 15N, 86E and conducted a longer process study at 16N, 87E.

A composite of the Salinity measured by Aquarius, the CCAR Sea Surface Height Anomaly product and the thermograph salinity from Roger Revelle and Sagar Nidhi are shown in Figure 9. The Aquarius passes are shown in criss-cross patterns while the Revelle cruise track colored by its TSG salinity shows

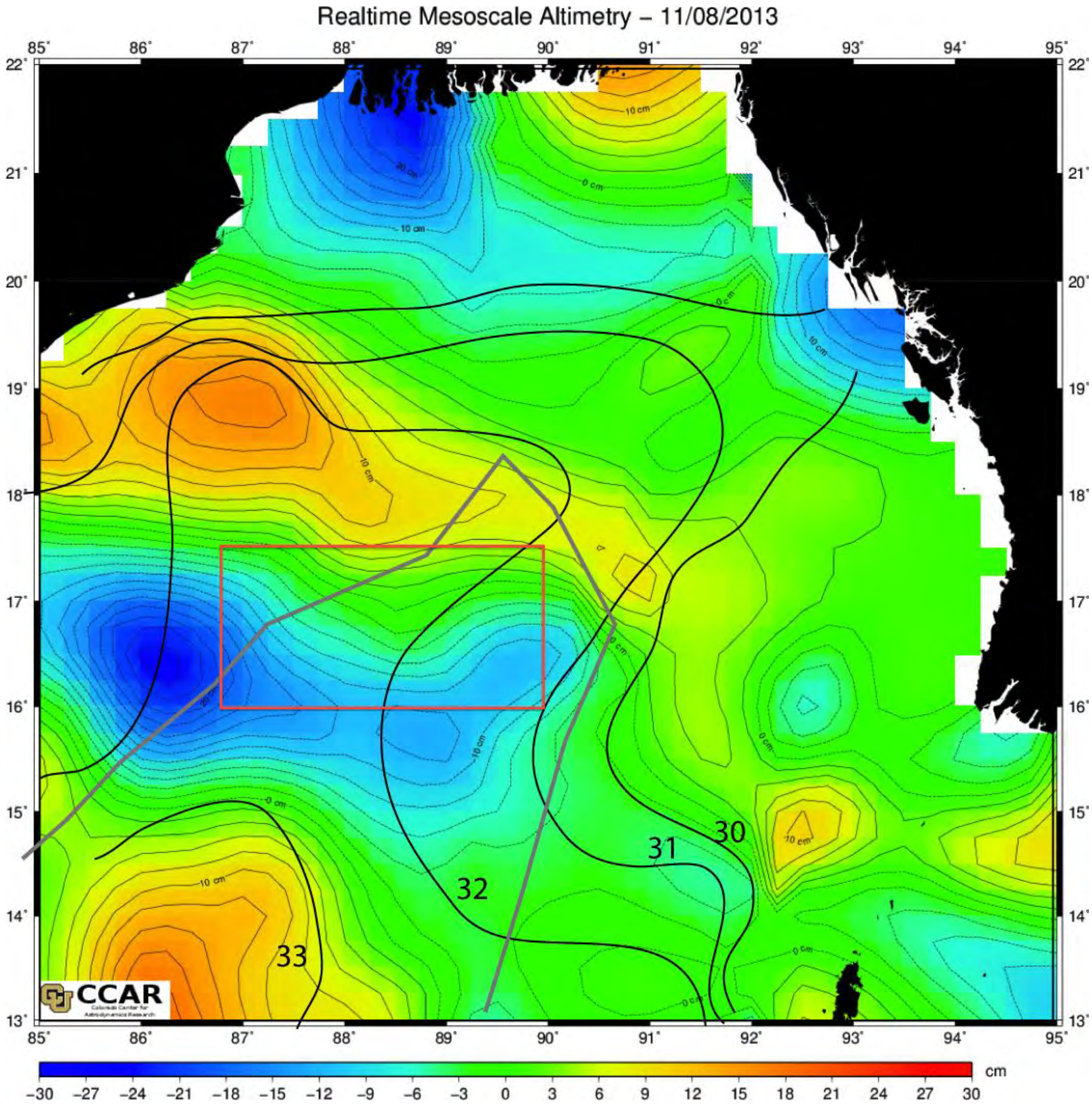

Figure 6: A remote sensing composite based on CCAR SSHA (colors show SSH anomalies contoured in thin lines, bold lines show SSS contours based on Aquarius data, EEZ boundaries are shown in gray. The blue shades show cyclonic mesoscale features while the red shades show anticyclonic features. Note the cylonic eddy centered at 16.4N, 86.4E.

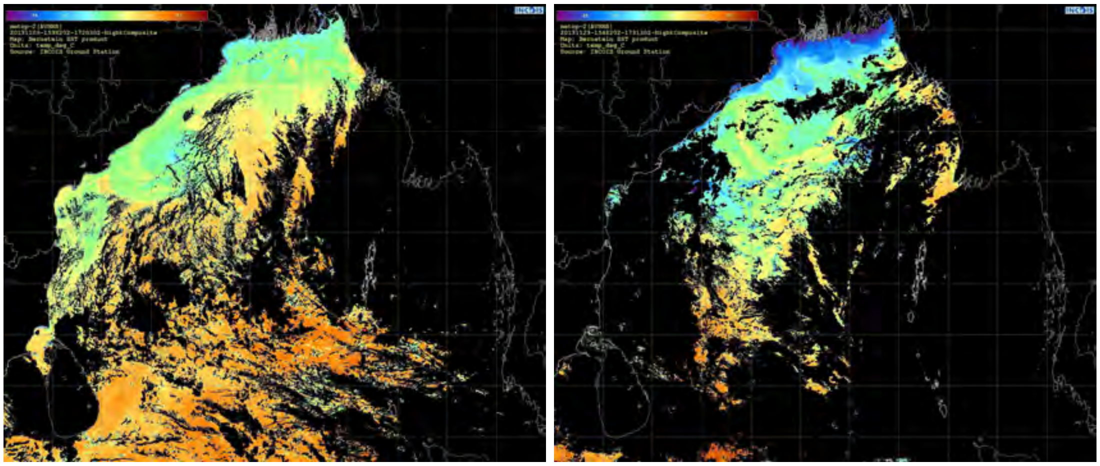

Figure 7: Night composite images processed by INCOIS collaborators showing remote sensing SST examples for November 9th and November 23rd. Note the cooler waters separating from the coast at 16N 82E due to the cyclonic feature shown in the previous figure. The figure on the right shows the cooler river water from the Ganges Brahmaputra delta flowing along the coast southwestwards.

two process study sites near 15N 86E, and near 16N 87E. Since both ships conducted joint experiment near 16N 87E, the salinity overlain ship tracks overlap in this region. This figure also hints at the time variability of surface salinity, as seen in the salinity difference between overlapping Aquarius tracks, as well as difference in salinity between overlapping ship tracks which are separated by a few days. The Bay of Bengal shows rich salinity gradients at many spatial and temporal scales.

As the figures 6 and 9 show, the region of 16N, 87E process study is on the eastward flank of the elongated cyclonic eddy with an implied north of northwestward flow at this location, and the mesoscale cyclonic feature implies eastward flow at the 15N, 86E process study location. The drifting assets in both legs showed that their drift directions were consistent with this mesoscale picture.

The spar buoy was densely instrument with temperature sensors and documented diurnal cycles and other variability of temperature within and below the surface layer (Fig. 8

Some aspects of submesoscale variability I: 1 - 5km scale salinity fronts observed by drifting assets

The second process experiment was centered on 16N 87E, a location which was characterized by much stronger horizontal variability in salinity (and density) than the first process study location. Wirewalker drifts crossed relatively strong salinity fronts (e.g. Deployment 2, ASIRI-3 Fig. 10) and so can be in some sense considered very slow cross-front sections. This is evident particularly during Deployment 2, see near-surface vertical and temporal (= temporal + horizontal) variability in density, salinity, and currents (particularly the meridional component, which is roughly along front; Figs. 11 and 12). The front was initially characterized by 0.7 PSU changes in surface salinity over <1 km (1200 UTC, Nov. 17 2013), with the along-front axis oriented approximately NNW/SSE. Rapid slumping of the front occurred over the following 24h, according to shipboard UCTD surveys and the WW time series. WWs ASIRI-2 and ASIRI-3 were primarily distributed on the fresh side of the salinity front, while WW ASIRI-1 was

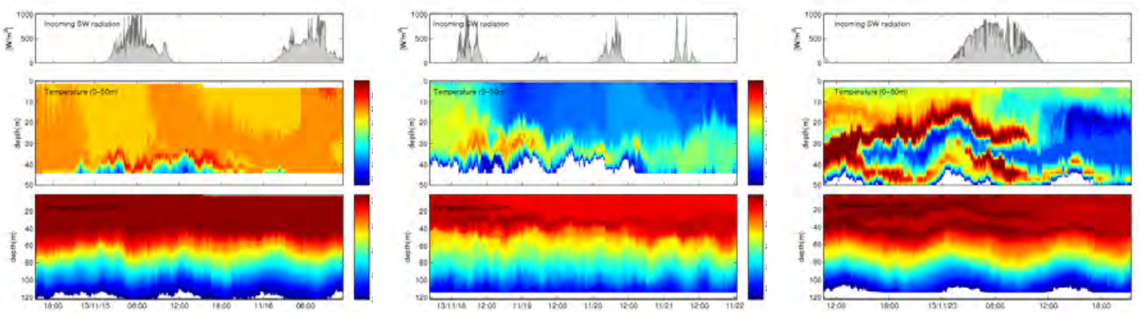

Figure 8: Example of temperature measurements from the spar buoy from 3 separate deployments. Top panels show the incoming shortwave radiation as an indicator of day/night cycling of heat flux. Middle panels show the temperature in the upper 50 m; lower panels show temperature over the entire length of the spar buoy. During deployment 1 (left), the surface layer was well mixing and exhibited strong nighttime convection. This contrasted deployment 3 (right), which was in region of much stronger horizontal gradients, leading to intense T-S finestructure and intrusive features.

primarily on the salty side. Future analysis will be focused on examining the lateral variability among the WW array. We focus what follows on the time-series record from ASIRI-3, in order to illustrate some basic features of the temporal and spatial variability we observed.

During the 6 d course of deployment 2 and 3, a strong barrier layer (BL) was found between 50 and 100 m depths. The BL was characterized by strong vertical gradients in compensated T/S variability (Fig. 11). Strong temporal, horizontal, and vertical variability characterized the upper layer. Initial surface mixed layer depths of 5m deepened by 20m over 24h (8km drift to the SW during this 24h period). Shear was strong at the base of the deepening surface mixed layer (Fig. 13). Preliminary Ri number analysis suggests that there was at times sufficient shear to overcome stratification at the base of the mixed layer, in particular during the the initial 24h. Shear/stratification and χ analyses demonstrated that mixing in the upper layers was in general constrained vertically by the BL. Mixing was deepest between 11/19-11/21, with weak restratification apparently inhibiting vertical exchange after 11/22 (with the exception of a limited area of high shear around 11/22 1200 UTC).

We expect that the instabilities demonstrated in other submesoscale process studies will be active in the Bay of Bengal (e.g. symmetric instabilities, mixed layer instabilities, etc.), in addition to other ageostrophic phenomena. Our analysis is not yet developed enough to assess established theoretical criteria for the existence of such dynamics from our field data. However, a some lines of evidence are apparent from our preliminary analysis. Perhaps the strongest is the distribution of optical variability in space and time (Fig. 15), and its relationship to physical variability. A clear signature of elevated chlorophyll is associated with the high shear layer at the base of the deepening mixed layer around 11/18 1200 UTC. Based on the change in the vertical strain of the isopycnals, the changing spice relationship (not shown), and high shear to stratification ratio during this period, mixing was most likely elevated at or just below this feature. Under the presumptions that phytoplankton concentration is nutrient limited, and nutrient fluxes are driven by vertical exchanges, this elevated optical signature provides another line of evidence that vertical exchange, either driven by 1-D mixing or 3-D ageostrophic processes, is active

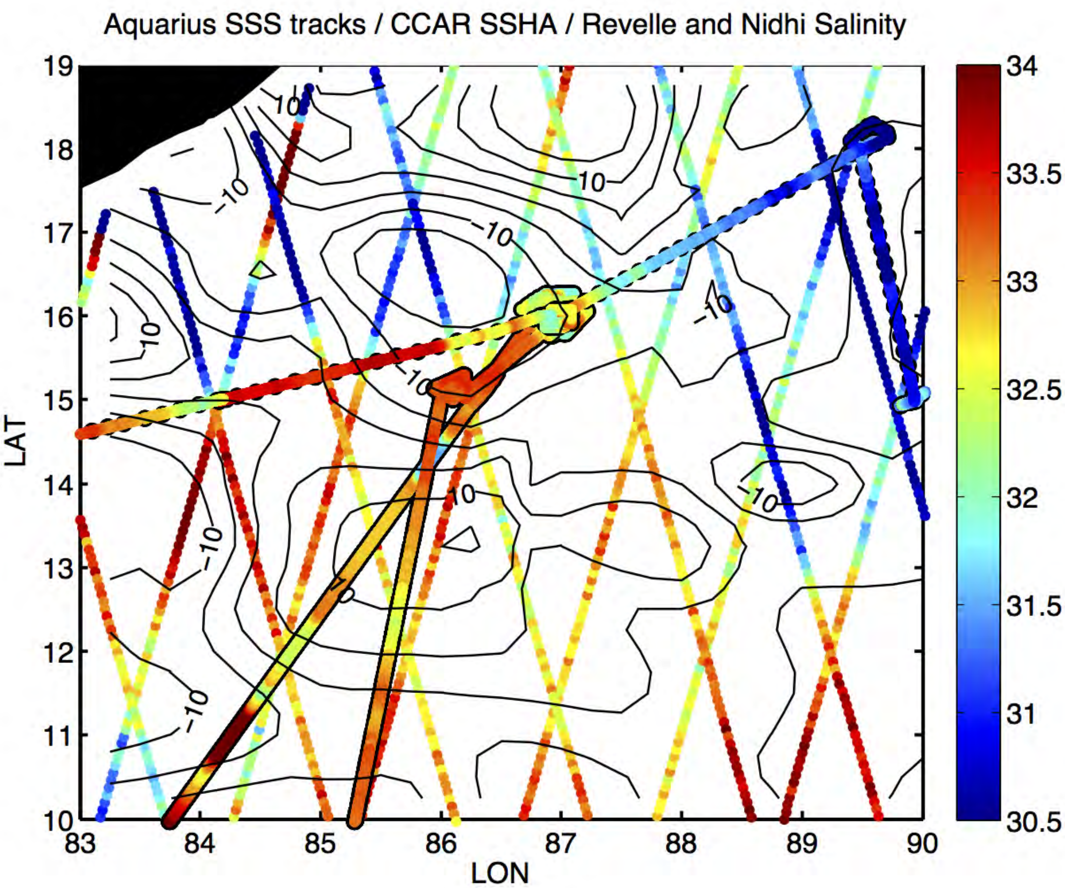

Figure 9: A remote sensing composite based on CCAR SSHA (black lines with contours every 10cm), Aquarius Salinity (criss-crossing tracks with smaller circles, color denotes salinity), and the Revelle and Sagar Nidhi thermosalinograph salinity. Larger circles are used for ship based salinity values. The ship track on the Northern side starting at 14.5N 83E and ending at 14.5N 90E is for Sagar Nidhi, while the track beginning at 10N, 83.8E and ending at 10N, 85.3E is for Revelle.

in this region during frontal slumping. Further evidence of the correlation between shear, mixing, and optical signatures can be seen shallower in the upper layers during restratification after 11/22. These results indicate that 1) productivity in the BoB may have a significant submesoscale component, 2) small patch size and high temporal variability challenges traditional shipboard productivity assessment, and 3) to the extent that surface heat flux depends on the optical character of the surface mixed layer in the BoB, parameterizing the physical influence on optical variability on small spatiotemporal scales is well justified.

Internal wave band variability was readily apparent in both currents and isopycnal depth (Fig. 10,Fig. 11). Further analysis will quantitatively asses the partitioning of current, shear, and isopycnal variance within the internal wave band. Qualitatively, the zonal component of velocity appears to more strongly modulated by semidiurnal variability than the meridional component. Inertial variability appears in upper layer isopycnal variability after 11/20, while the vertical variability in isopycnal displacement within the BL appears predominantly semidiurnal throughout the WW deployments. Shear was concentrated in layers 10-15m thick in the BL. Strong shear in the upper layers was well correlated with vertical position of the maximum density gradient. The velocity data indicate strong internal wave variability superimposed on the submesoscale lateral variability. The importance of internal wave dynamics to submesoscale dynamics is not well understood. The data collected during this Pilot Study may be useful in diagnosing the dynamical interaction between the two distinct sets of dynamics.

Instrument and vehicle performance appeared to be quite good. Shear and velocity was well correlated with the vertical distribution and time variability of isopycnals. Shear- and χ-based estimates of vertical mixing were in good qualitative agreement. Optical characteristics supported regions of mixing or ageostrophic vertical velocity within the evolving front. This represents a significant advance for the WW system, as accurate determination of currents had been in the past difficult to achieve.

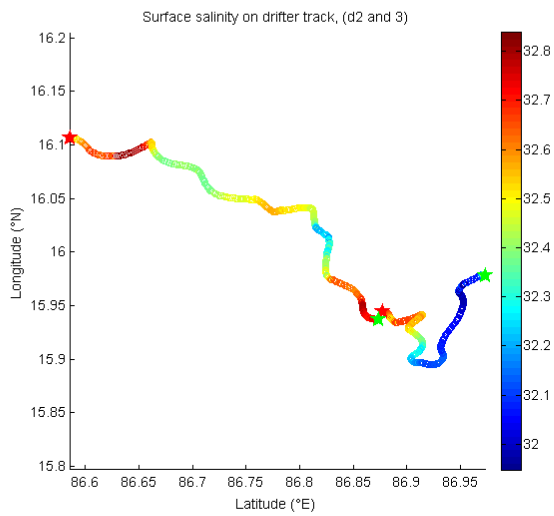

Figure 10: Drifting track, ASIRI-3 deployments 2 and 3 (Deployment 2 starts with the green star at 16N 87E, Fig. 10). Deployment 2 was 2.75d long. Following a brief turn around period (∼4h) ASIRI 3 was redeployed. The coherence in BL salinity structure between the end of deployment 2 and beginning of deployment 3 gives evidence that these two deployments may be viewed as relatively contiguous (Fig. 11, middle panel). Color scale is salinity averaged over the top 10m. Start locations are noted with green start, and end with red star.

Aspects of submesoscale variability II: Coherent freshwater filaments

Our UCTD/JCTD surveys provided a first look at order 5-10 km coherent interleaving fresh and salty filaments. Figure 16 shows our final survey near 16N. Surface salinity filaments are seen extending coherently across all 5 sections. In the 40 meter deep surface layer density is controlled by salinity,

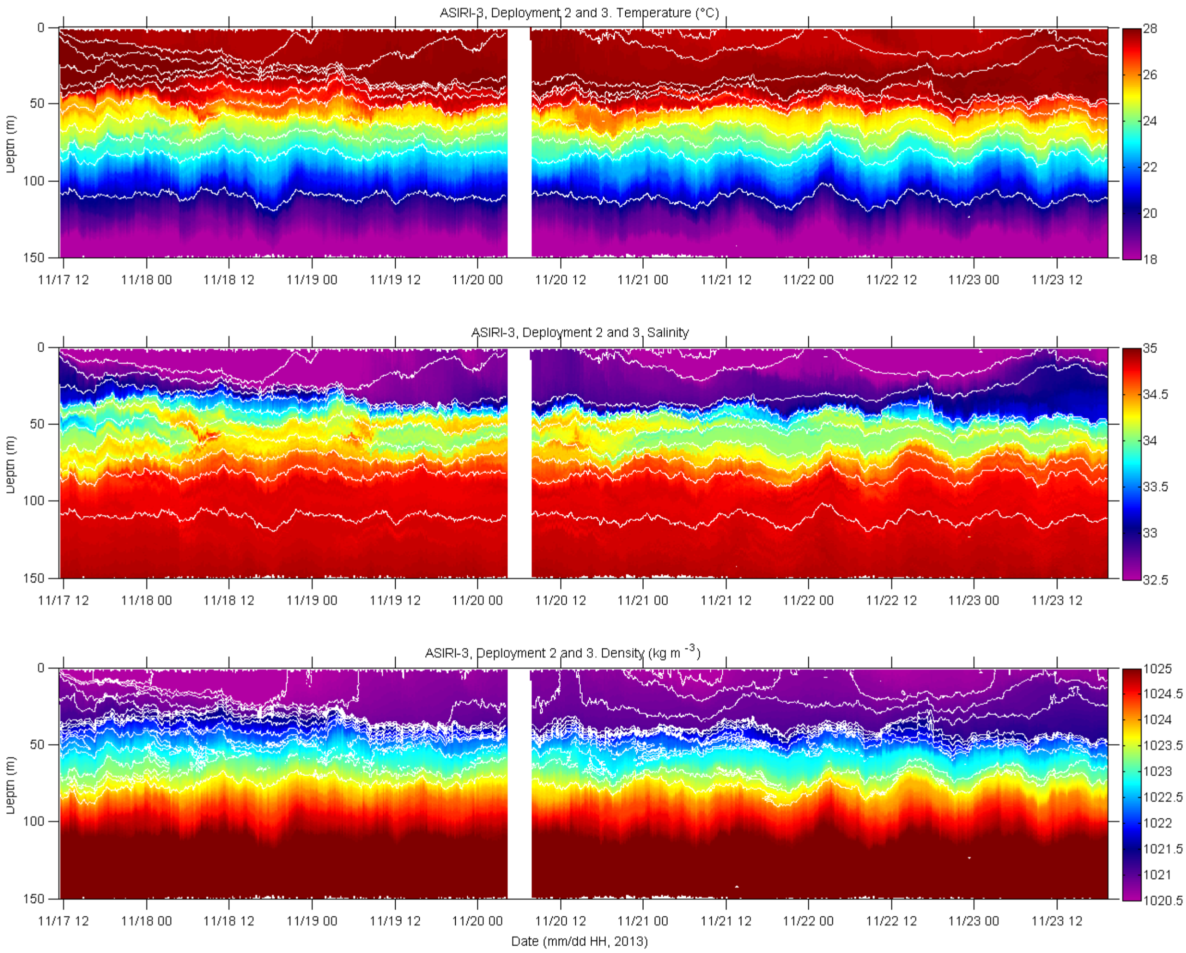

Figure 11: Temperature, salinity, and density (top to bottom) from deployment 1. White contours are density in the top two panels and salinity on the density colormap.

whereas it is controlled dominantly by temperature below. Strong spice variability is visible near the base of the surface layer, again extending coherently across all sections. N^2 highlights small-scale frontal features within the surface layer. These features appear upon first glance not to be as coherent across sections.

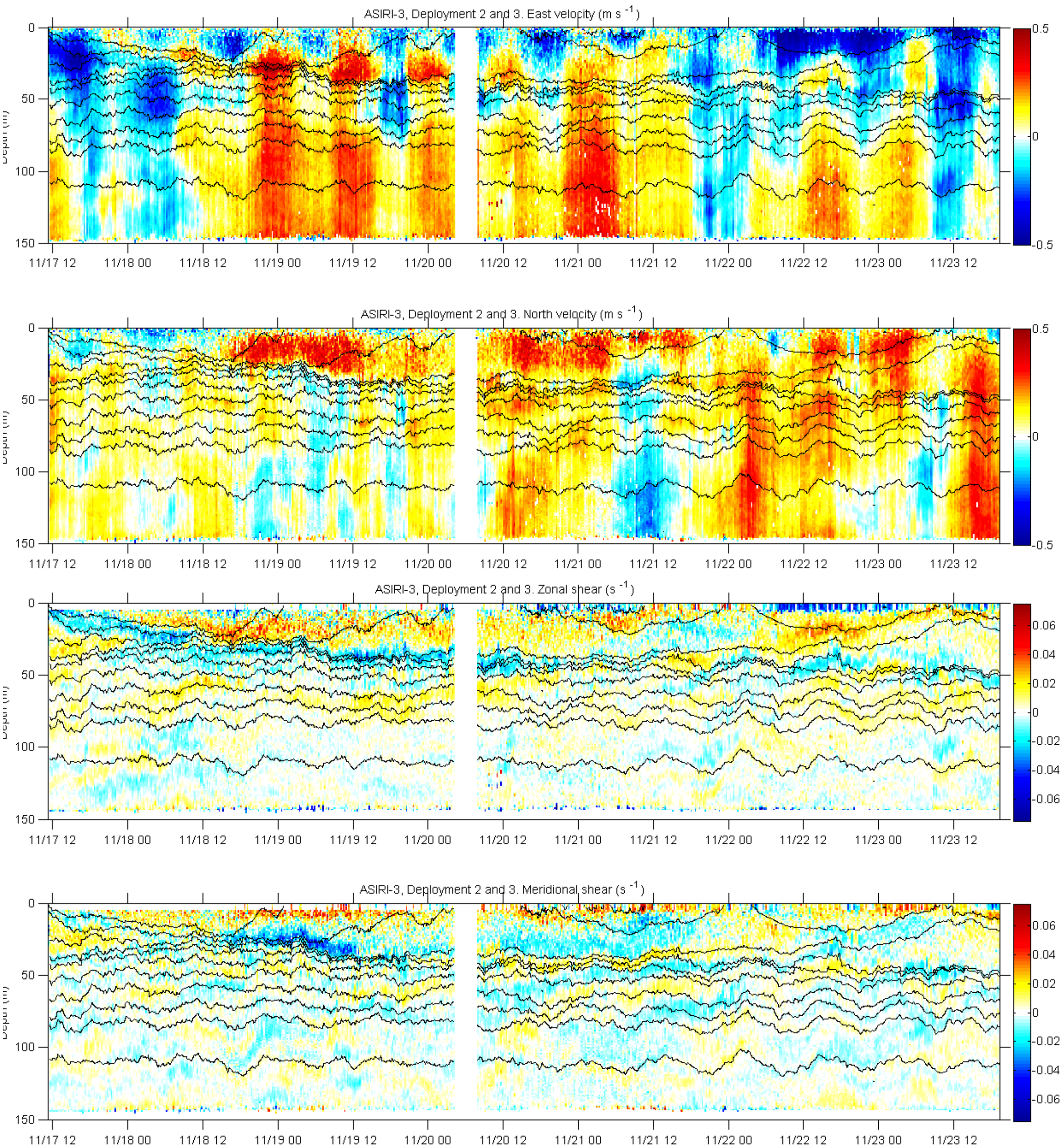

Figure 12: Zonal (positive eastward) and meridional (positive northward) velocity (upper two panels) and shear ($\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}$). Black contours are density.

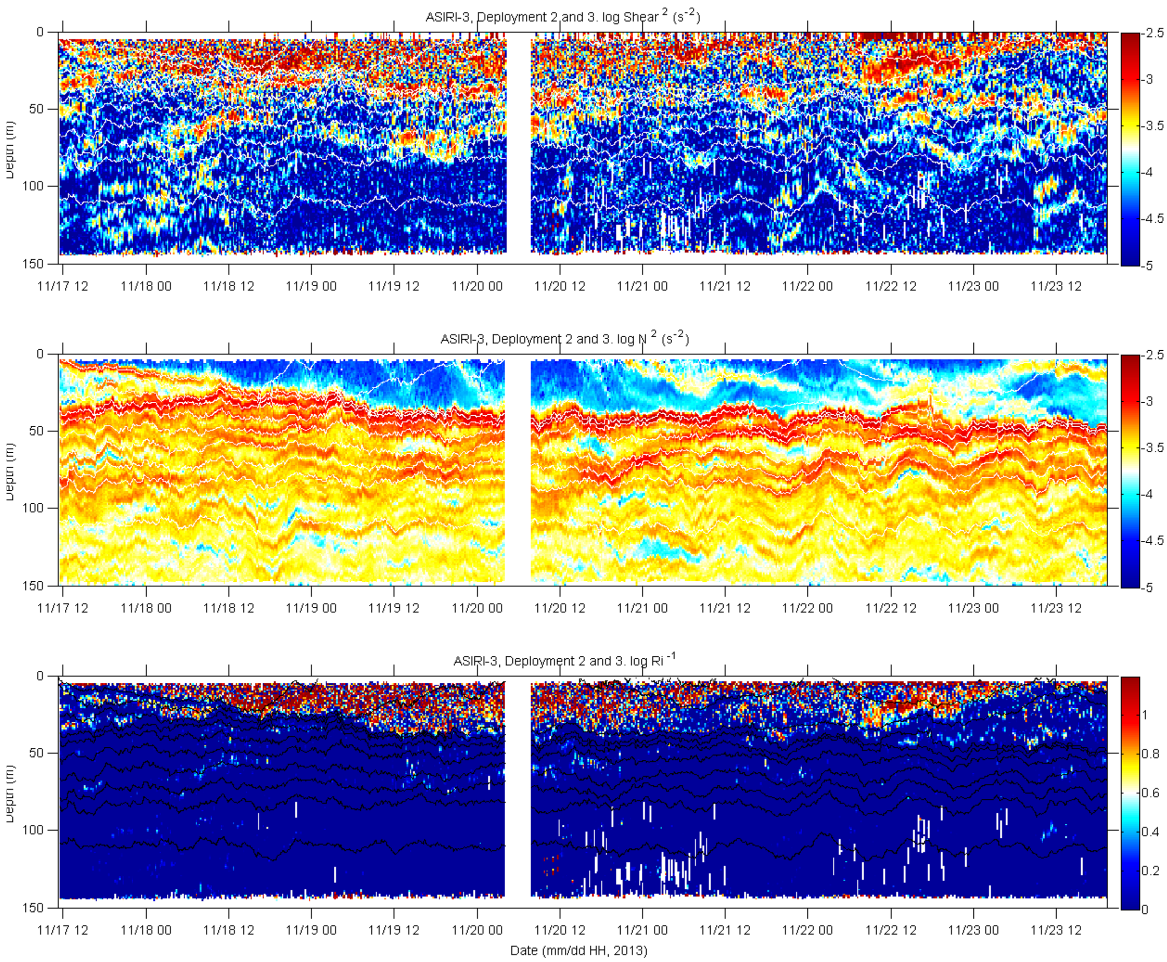

Figure 13: Shear squared (log $S^2 = \frac{\partial u}{\partial z}^2 + \frac{\partial v}{\partial z}^2$ [s^{-2}], top panel), buoyancy frequency (log N^2 [s^{-2}], middle panel), and inverse Richardson number (log $\frac{N^2}{S^2})^{-1}$, bottom panel) Color-scale on the bottom panel is values greater than the "critical" log inverse Ri number ($10^{0.605} = 4 = \frac{1}{0.25Ri}$) are warmer than white, and therefore indicate areas of "mixing."

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Aspects of submesoscale variability III: Sub-kilometer scale energetic nonlinear bores

We had several opportunities to observe strongly nonlinear bores. Figure 17 shows temperature from the ship through flow system during multiple bore crossings. There is a strong temperature jump visible

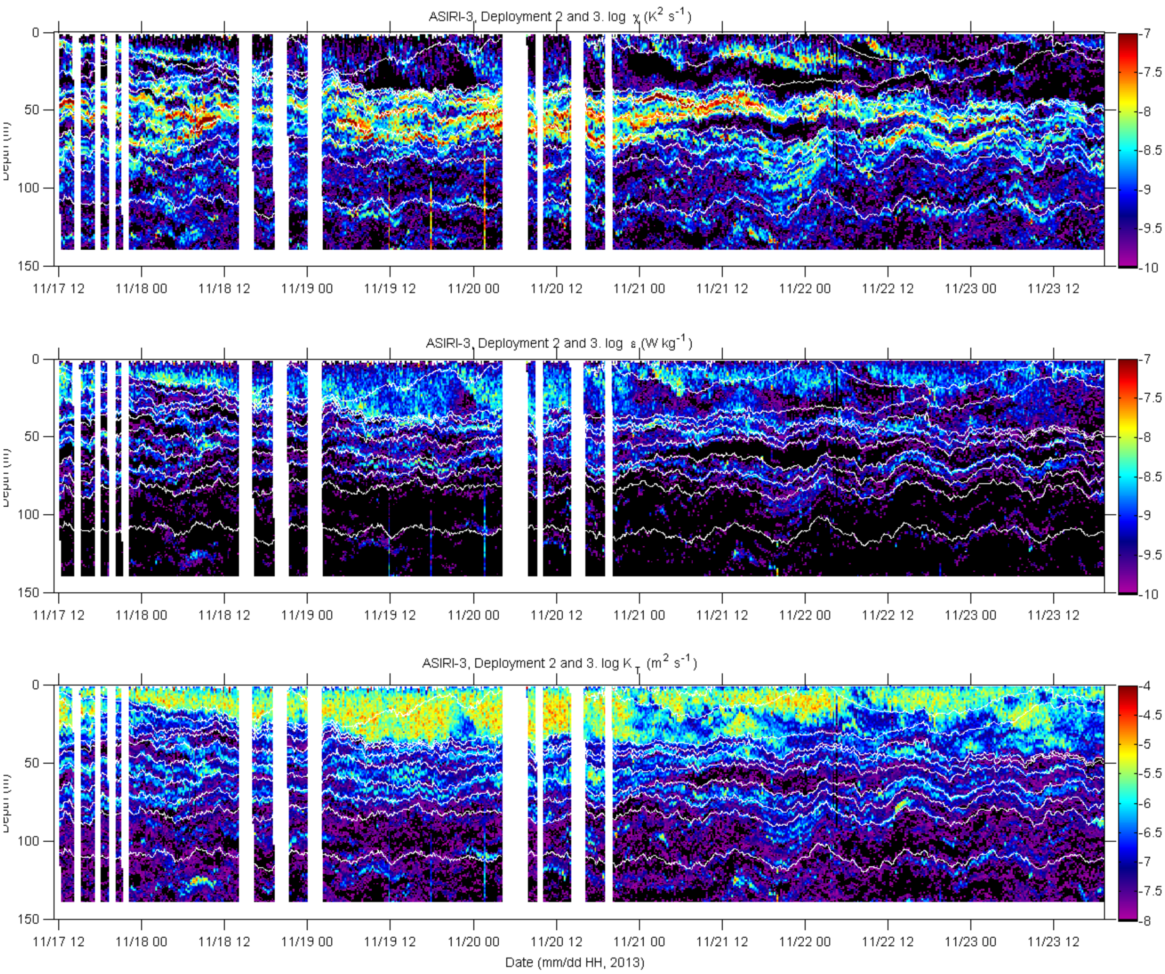

Figure 14: χ (log χ [K^2 s^{-1}], top panel), TKE dissipation rate (log ϵ [W kg^{-1}], middle panel), and the vertical diffusivity of heat (log κ_T [m^2 s^{-1}, bottom panel). Blank areas are due to periods of bad data recording.The patterns in these quantities echo the Ri patterns above, namely elevated diffusivity and dissipation in the deepening surface mixed layer. Again, reassuring that shear, stratification, and χ (i.e. three different instruments) seem to be telling the same story.

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in each of 8 crossings. During the several hours of this survey the front moved northward at a slowing rate. The temperature on the warm side of the front steadily decreased, which we interpret as a cold, freshwater layer propagating over a warmer, saltier water with an underlying N-S gradient. The front is starkly visible in the bow chain data, Figure 20. Velocity from the side pole mounted ADCP (Fig. 19) shows a strong convergence in surface velocity.

6 Personnel

Master: Tom Dejardins, Resident Technician: Matt Durham

Table 4: Science Personnel. US Team

Who	Role	Inst.
Andrew Lucas	Chief Scientist	SIO
Jennifer MacKinnon	Co-Chief Scientist	SIO
Jonathan Nash	PI	OSU
Amit Tandon	PI	U. Mass
Iossif Lozovatsky	PI	Notre Dame
Sanjiv Ramachandran	Post Doc	U. Mass
Caitlin Whalen	Grad. Student	SIO
Kelly McEnerney	Grad. Student	Norte Dame
Ben Mater	Grad. Student	Colorado State
Jeff Lord	Technician	WHOI
Ben Hodges	Technician	WHOI
Sebastian Bigorre	Technician	WHOI
Tyler Hughen	Technician	SIO
Jonathan Ladner	Technician	SIO
Paul Chua	Technician	SIO

Table 5: Science Personnel. Indian Team

Who	Role	Inst.
M. Girishkumar	Scientist	INCOIS
M. Dilipkumar	Scientist	INCOIS
M. Muthukumar	Engineer	NIOT
D. Gowthaman	Engineer	NIOT
SK. Mozamil	Scientist	IIT-BBS
Manita Chouksey	Grad. Student	IIT-BBS

Table 6: Science Personnel. Sri Lankan Team

Who	Role	Inst.
Pryantha Jinadasa	Scientist	NARA
Upul Adikari	Technician	NARA
Indika Weligamage	Technician	NARA

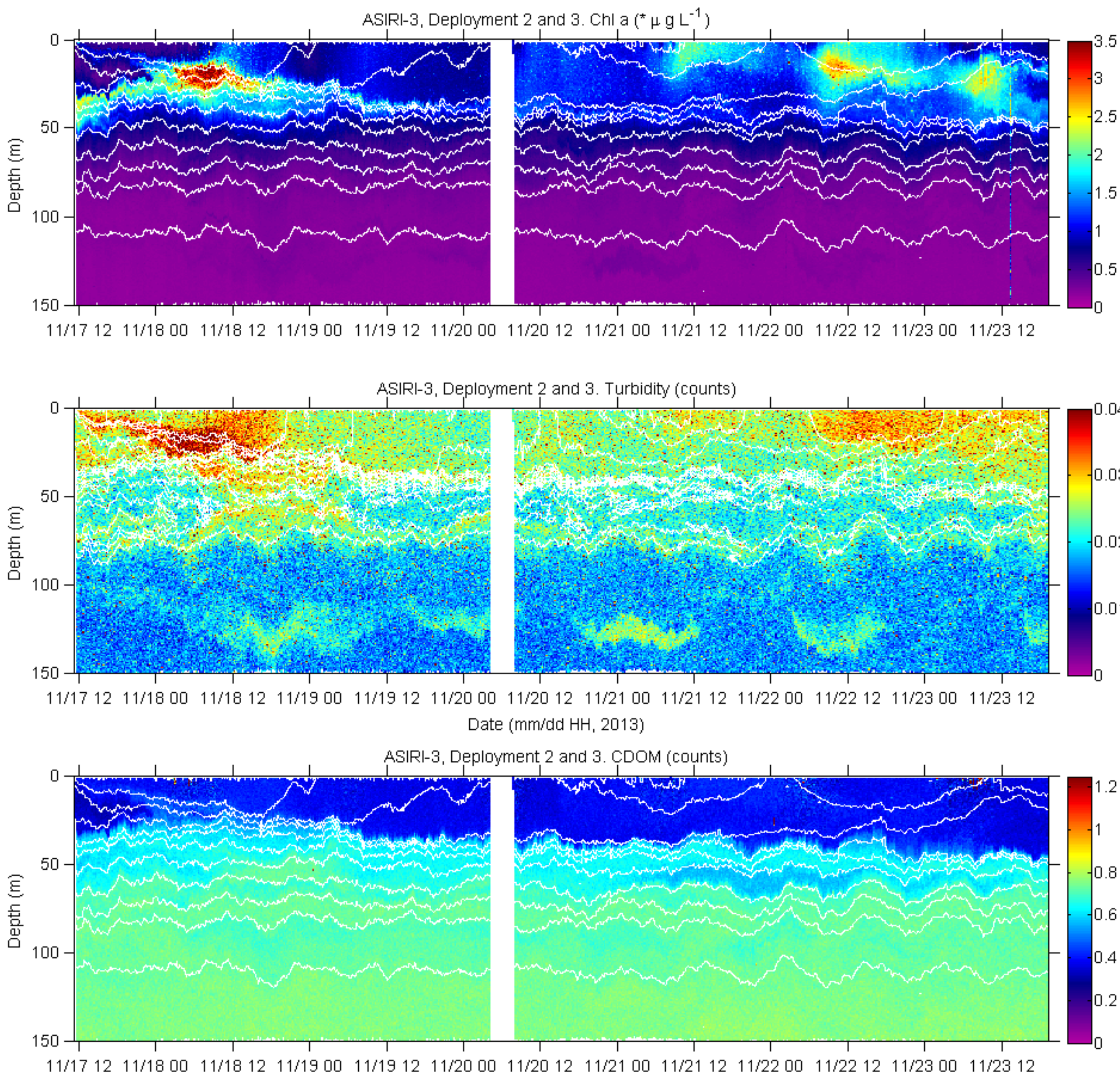

Figure 15: Optical variability (Chlorophyll fluorescence, CDOM fluorescence, and Turbidity. All quantities are expressed as uncalibrated values with the exception of chlorophyll, which has been converted to chlorophyll concentration using the factory calibration (likely to change after post-calibration of the sensor). Clear signatures of submesoscale optical variability associated with frontal dynamics is apparent in the chlorophyll and turbidity channels. These signatures likely demonstrate the activity of enhanced vertical circulation, perhaps due to ageostrophic processes.

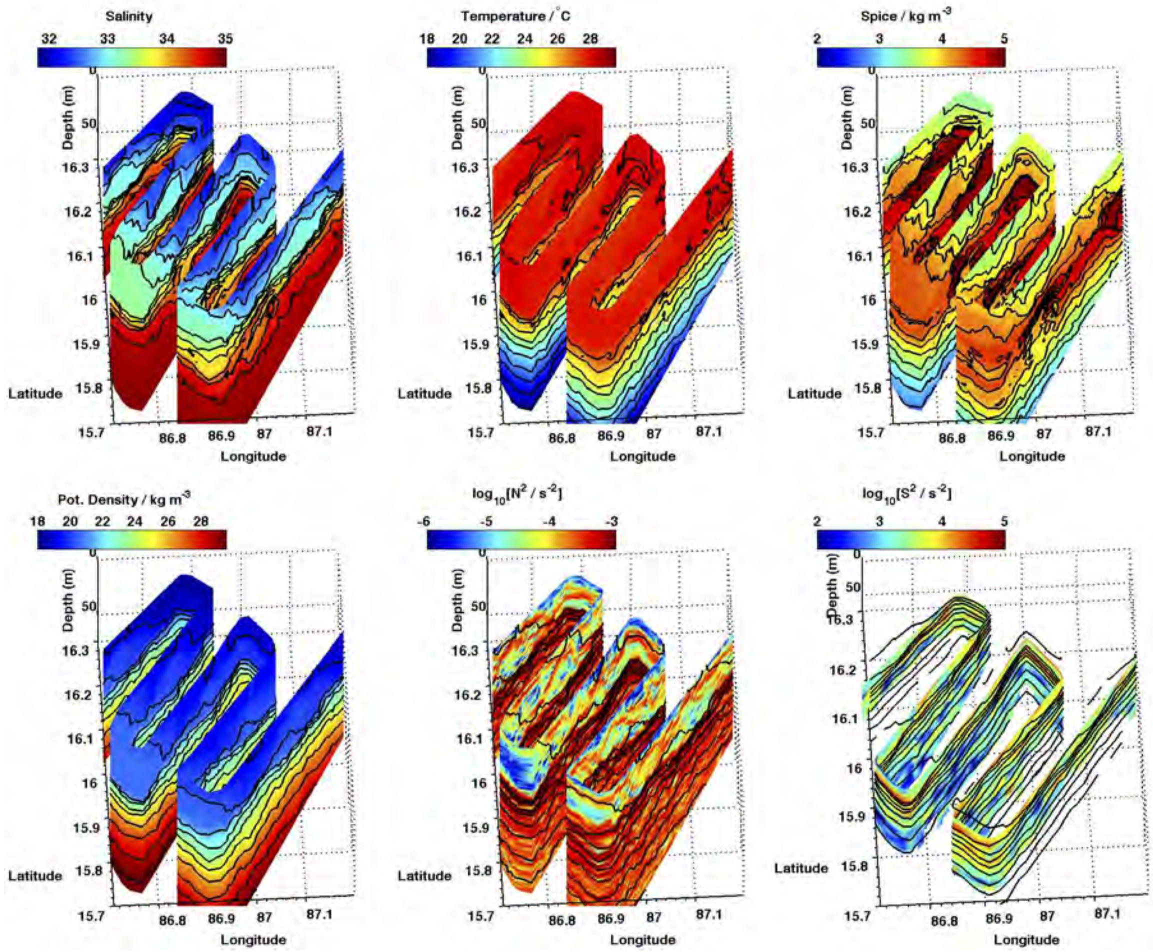

Figure 16: A survey. Each line is approximately 20 km in length, and lines are separated by 5 km. In all cases the black contours lines correspond to the variable being plotted, except for N^2 and S^2 in which cases the black contours are potential density.

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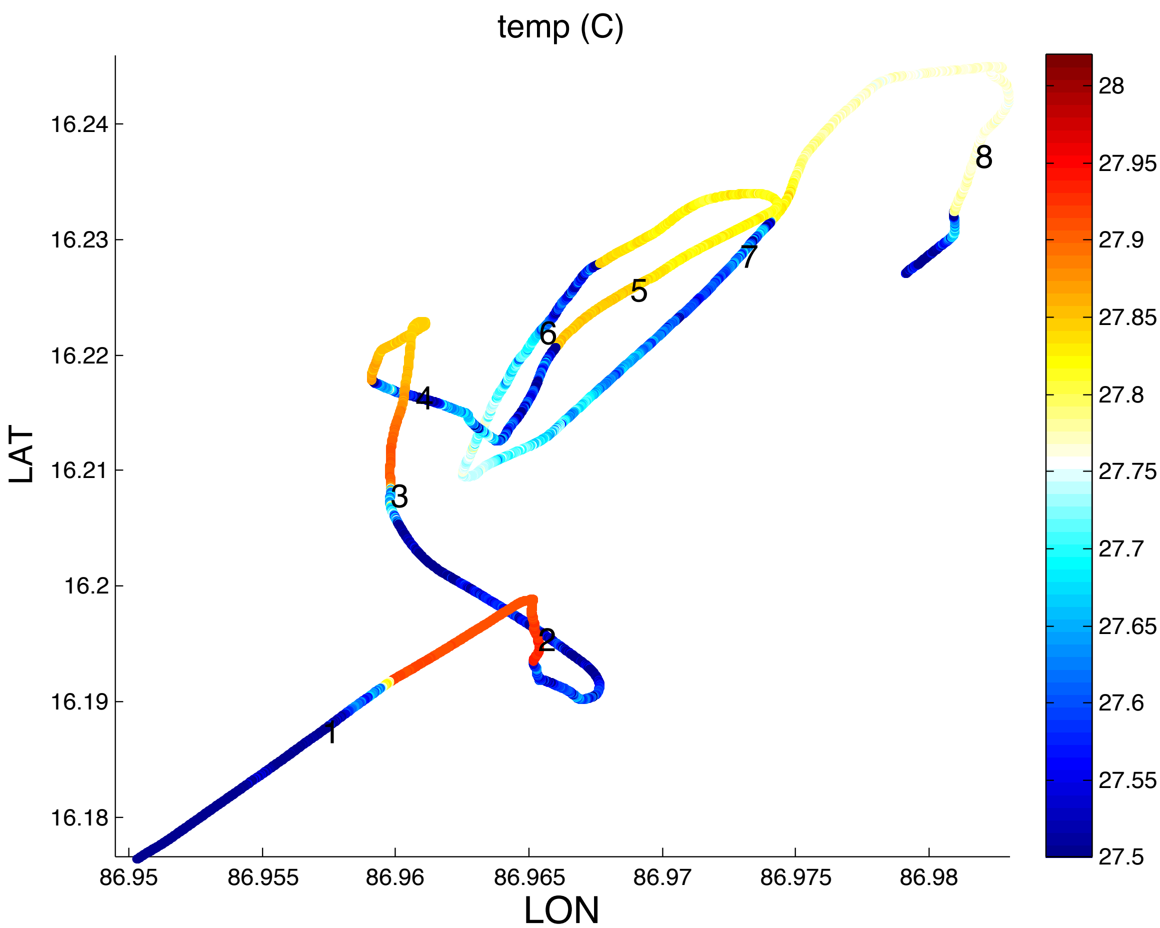

Figure 17: Surface temperature recorded from the through-flow system during the nonlinear bore survey
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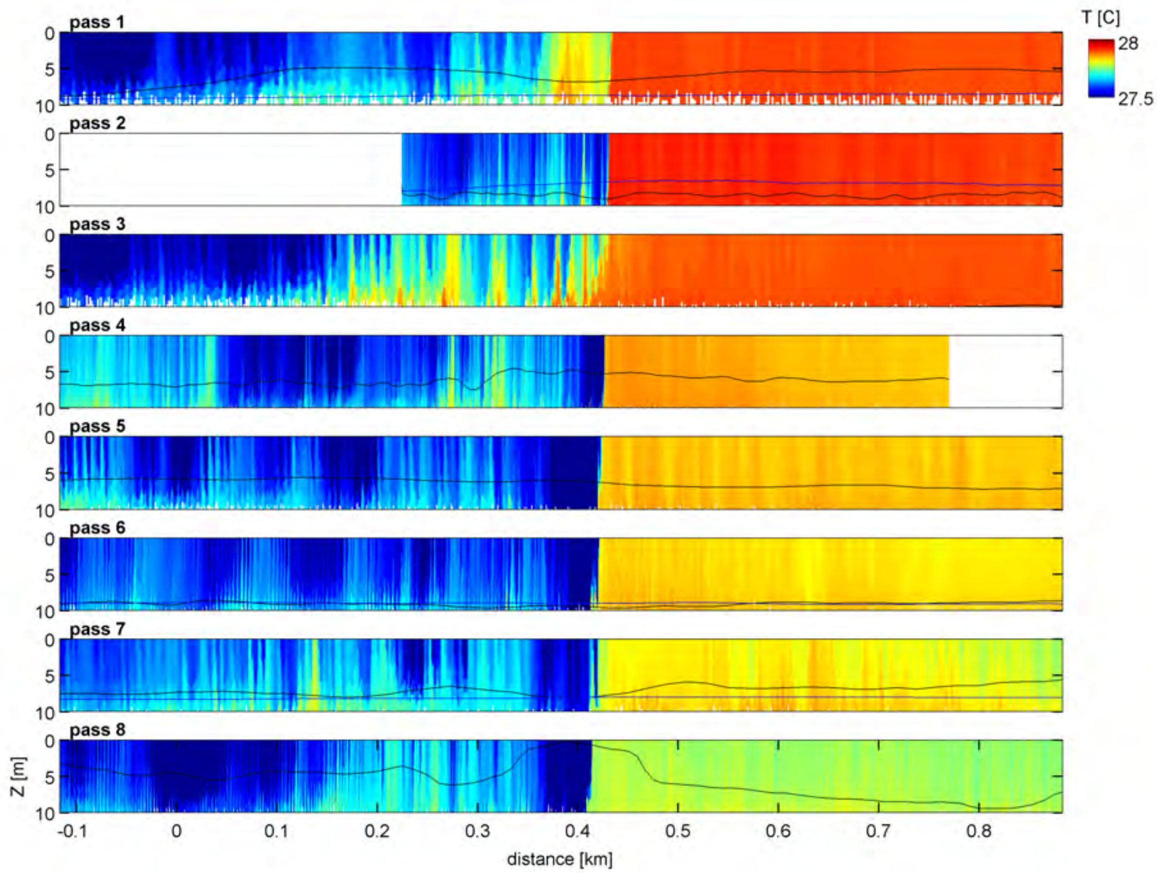

Figure 18: Bow-chain temperature during the nonlinear bore survey. Pass numbers refer to the surveys indicated in Fig. 17

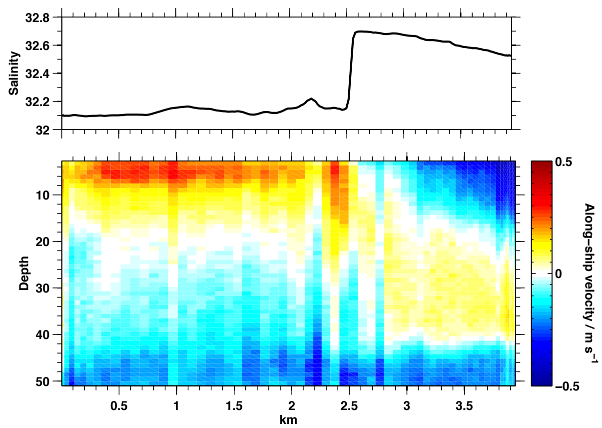

Figure 19: Upper: salinity from the ship through flow system during one bore crossing. Velocity from the side-mount Sentinel V ADCP in the along-ship direction (approximately perpendicular to the bore) during that same period.

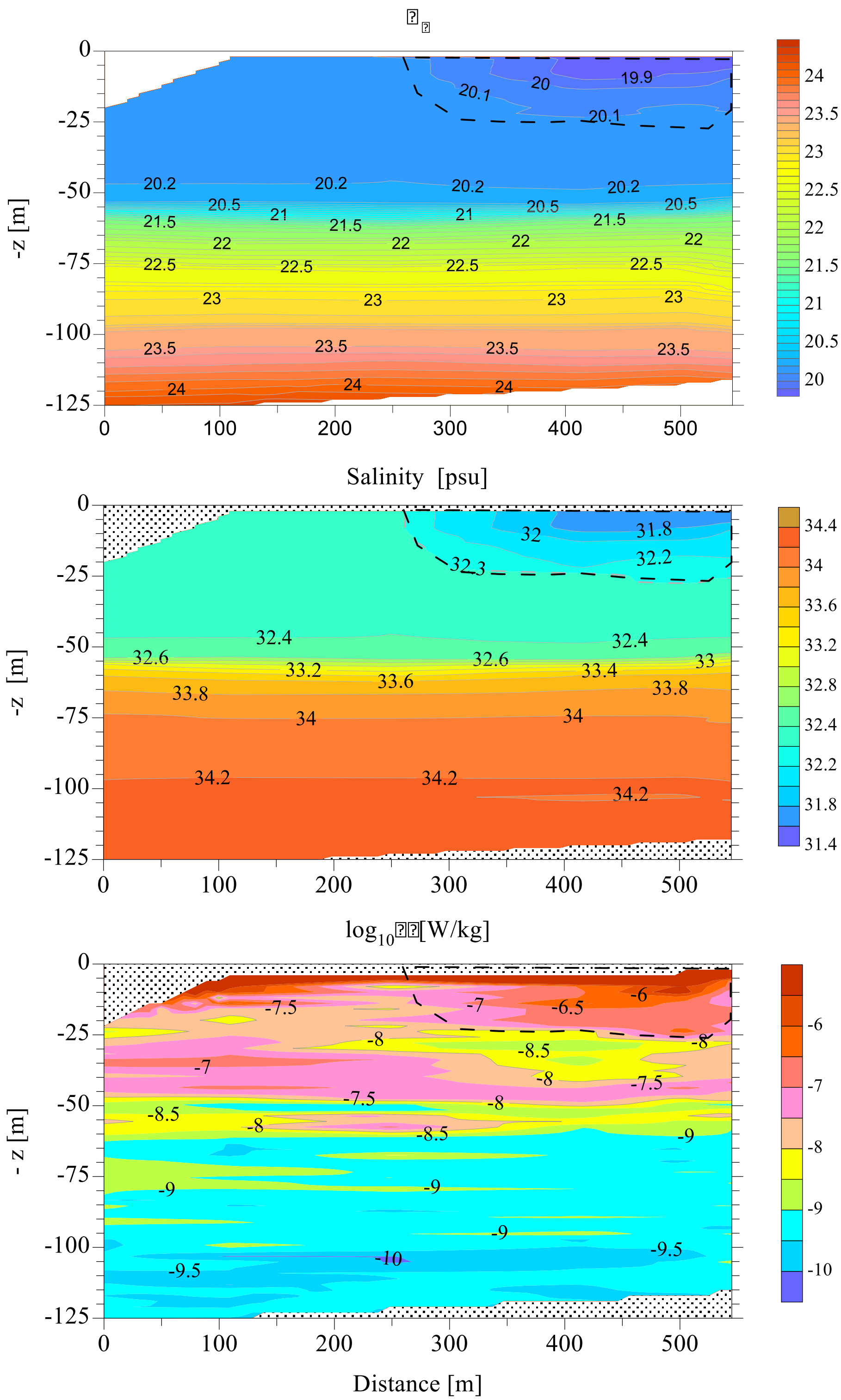

Figure 20: VMP section across the nonlinear bore. Elevated dissipation is apparent in the bore. The BL clearly inhibits mixing below 50m.