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14. ABSTRACT
Our over-arching objective is to gain an understanding of upper ocean processes and air-sea interaction in the Bay of Bengal. This, in the long run, would contribute toward improving the intra-seasonal Monsoonal forecast in ocean-atmosphere coupled models. Major activities on this project provided results on barrier layer evolution, diel cycles in penetrative solar radiation and chlorophyll, kinematic properties from the deformation of a drifter swarm.

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Coastal and Submesoscale Process Studies for ASIRI

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This report supplements a comprehensive annual report submitted in June 2016 and represents only a small unexpended portion of the grant.

MAJOR GOALS

Our over-arching objective is to gain an understanding of upper ocean processes and air-sea interaction in the Bay of Bengal. This, in the long run, would contribute toward improving the intra-seasonal Monsoonal forecast in ocean-atmosphere coupled models. Several specific goals are listed below.

1. To determine the upper ocean structure of temperature and salinity at different times of year, and to understand its relationship with air-sea fluxes of heat and moisture in the Bay of Bengal.
2. To determine what processes control the surface temperature, the mixed layer depth, and the density stratification in the Bay.
3. To examine the influence of surface freshwater on the stratification, submesoscale dynamics, and mixing.
4. To examine the mechanisms by which the surface freshwater is dispersed.
5. To determine how one-dimensional and three-dimensional mixing and advective processes in the upper ocean influence the upper ocean temperature and air-sea fluxes.
6. Develop and foster collaboration with Indian scientists through ASIRI-OMM and offer training and educational opportunities as part of this collaboration.

ACCOMPLISHMENTS

Major Activities

1. Analyzed 2013 cruise profiles of salinity and temperature to assess the barrier layer's response to surface heat fluxes during winter.
2. Analyzed diel cycles in penetrative solar radiation and chlorophyll
3. Graduate student, Sebastian Essink, used drifter data from the 2015 Bay of Bengal experiment to diagnose vorticity, strain and divergence
4. Lectured and interacted with students at the winter workshop at IIT Madras, India
5. Participated in the ASIRI DRI meeting in Chennai (Jan 2017)

1. Barrier layer evolution

Melissa Omand, currently an Assistant Professor at the University of Rhode Island (URI), and formerly a Postdoctoral Investigator at WHOI and participant in the 2013 fieldwork with the PI, has examined the evolution of the barrier layer using cruise data and modeling. This was made possible through a subcontract to URI for Dr. Omand's summer salary.

Stable salinity stratification traps heat within subsurface layers. The oceans reluctance to release the heat trapped within these subsurface warm layers can contribute to delayed rise in surface temperature and heat loss from the ocean as winter progresses. In some cases, the barrier layer, stores heat from summer that is released after several days of surface cooling and wind-driven mixing in the winter. A stable salinity stratification resists mixing into the barrier layer until a point where further cooling

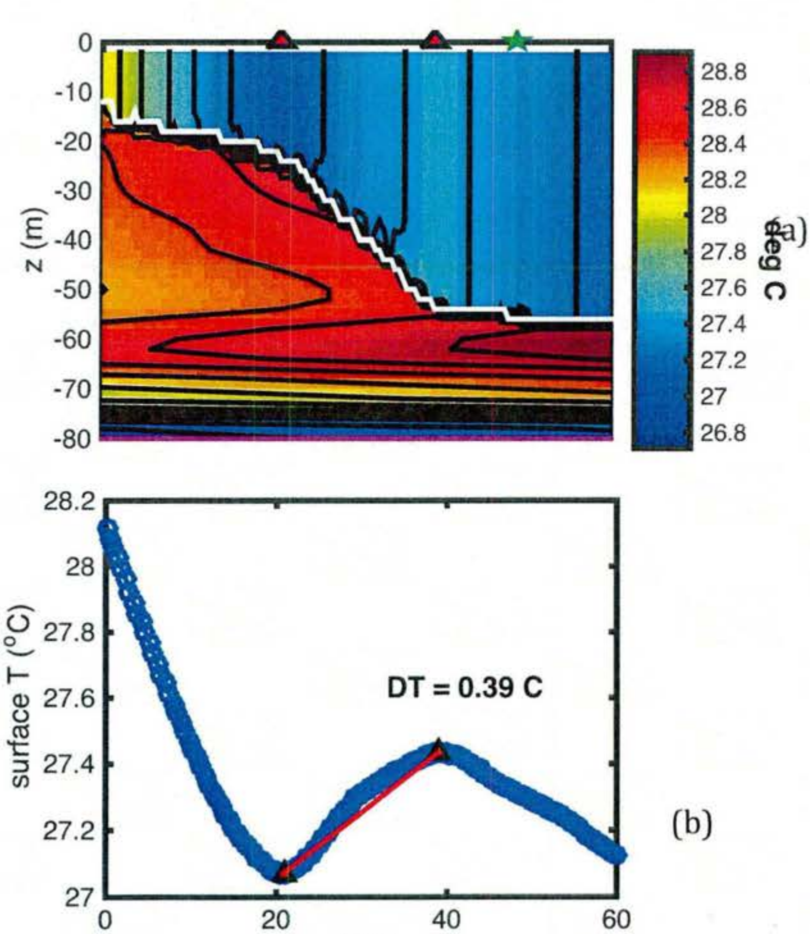

Fig. 1. Time evolution of a vertical profile of temperature forced by surface cooling. (a) The barrier layer, initially between 20 and 55 m, is destroyed as convection breaks down the salinity stratification. (b) SST falls initially, then rises as the collapse of the barrier layer releases heat from subsurface.

leads to a sudden collapse of the barrier layer, release of subsurface heat to the surface, and a warming of sea surface temperature. We use the one-dimensional PWP model on 2940 water column profiles collected throughout the BoB in winter 2013 to examine the conditions leading to a sudden collapse of the barrier layer. The model is forced with typical surface fluxes in December-January, and the evolution of the one-dimensional profiles of temperature and salinity is analyzed. Further, we propose a scaling that predicts the time to barrier layer collapse, depending on the summer and winter mixed layer temperature, salinity, and mixed layer depths.

2. Diel cycles in penetrative solar radiation and chlorophyll

A hyperspectral radiometer was deployed on the Wirewalker by Melissa Omand and Drew Lucas to measure the incoming shortwave radiation at multiple frequencies as a function of depth. The measurements were fitted with attenuation curves and the attenuation coefficients were calculated. An interesting finding was that the chlorophyll signal was quenched (non-photochemical quenching) in the upper 10 m of the water column during the daytime, and hence the near-surface chlorophyll-fluorescence was weaker at midday than during the night. Within the chlorophyll maximum, found at about 50 m depth, the chlorophyll-fluorescence increased during the daytime, indicating photosynthesis in response to light. These diel cycles in the chlorophyll can be taken in to account when including phytoplankton chlorophyll in the modeling of shortwave penetrative radiation.

3. Kinematic properties from the deformation of a drifter swarm

Sebastian Essink (PhD student and advisee of the PI), in collaboration with Verena Horman and Luca Centurioni, is analyzing the first 30 days in the time-evolution of the drifter swarm

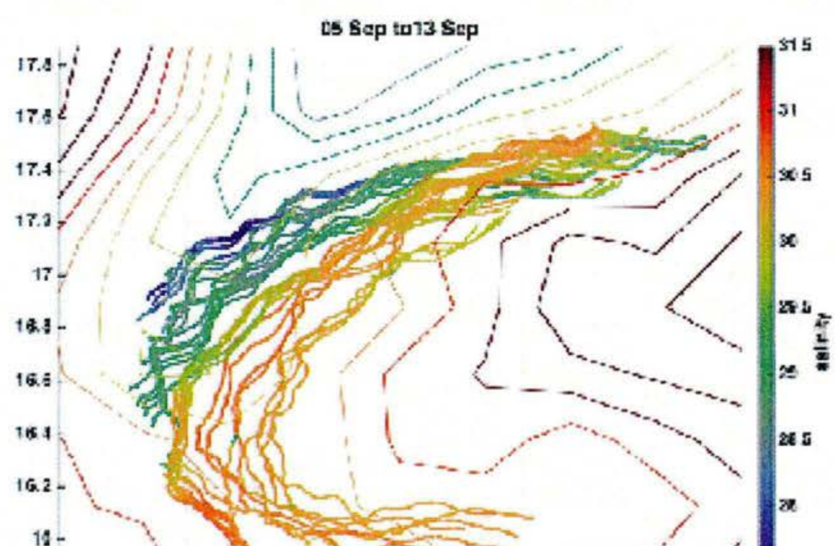

Fig. 2. Trajectories of drifters as they navigate a large mesoscale cyclonic eddy in the northern Bay of Bengal in 2015 Sept. Colors show surface salinity measured along the drifter tracks, overlaid with salinity contours from the SMAP satellite data. Since the drifters are drogued at 15 m, they cross fronts within the mixed layer as seen from their along-

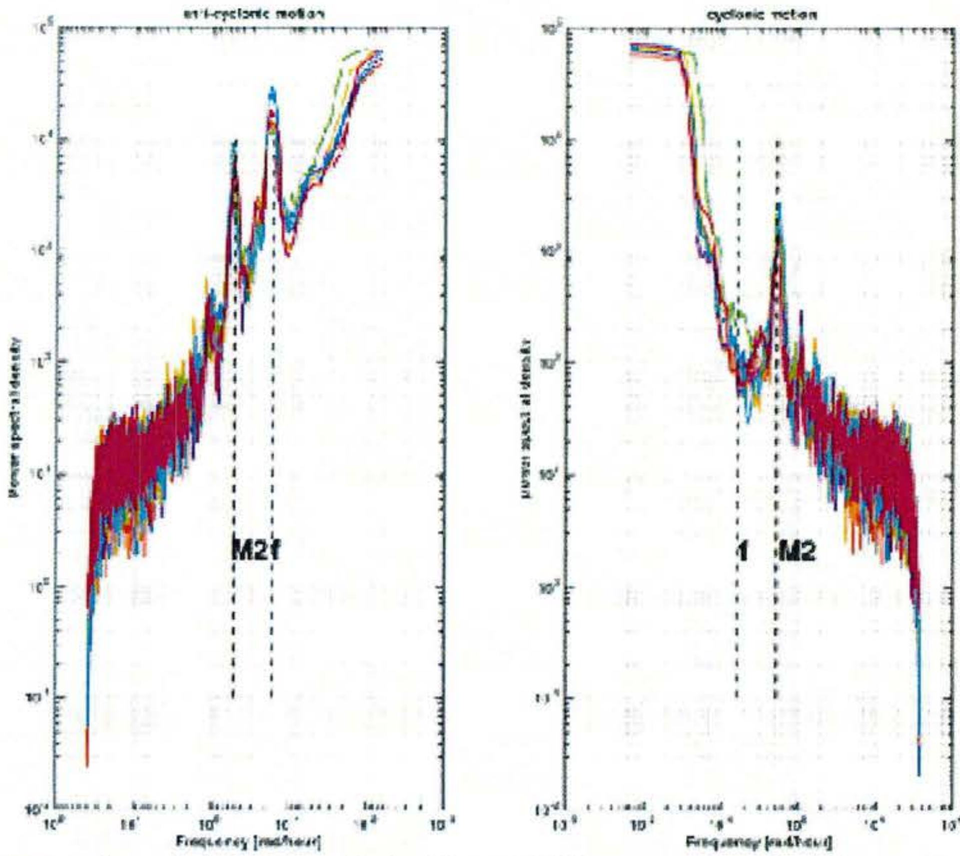

Fig. 3. Lagrangian velocity spectra calculated from 36 drifters shows how the drifter motion is dominated by tidal (M_2) and near-inertial (f) oscillations. The peaks at f and M_2 are less sharp than what might be obtained from a model because the drifters are sampling both space and time. This

Fig 4. Participants of the winter training workshop at IIT-Madras, India in January 2017.

consisting of 36 SVP-style drifters, with surface salinity and temperature sensors and drogues at 15 m (Fig. 2). By identifying polygon clusters (several thousand combinations are possible), we can examine the deformation of the polygons by the flow field and estimate the velocity gradients, and thereby the vorticity, strain and divergence. The properties are scale-dependent and we identify 2 regimes: At early times, we observe a "submesoscale" regime. During this time, the polygons are relatively small (tens of square kilometers in area), but get rapidly distorted (elongated) due to the high rates of shear, strain and vorticity that they sample. At later times (about 2 weeks after the release), which we term the "mesoscale regime", the polygons become larger (hundreds of square kilometers in area) and the strain and vorticity, as well as the rate of distortion of the polygons, is weaker. These regimes are also seen in the dispersion characteristics of the drifters. The 2-particle dispersion rates shows a clear change in behavior from an exponential spreading regime (at early times) to a (slightly super-) diffusive regime at later times.

The drifter swarm offers the unique opportunity to use multiple drifters to calculate the kinematic properties. One of the difficulties with the analysis has been the strong presence of near-inertial and tidal oscillations (**Fig. 3**), which are not easy to filter in the Lagrangian frame.

4. Winter training workshop

At a workshop hosted by Prof. Mani Mathur, IIT-Madras (Fig. 4), several PIs form the US and India (Drew Lucas, Eric D'Asaro, Tom Farrar, Craig Lee and Rama Govindarajan) gave tutorial style lectures, interacted with students and discussed the projects that they are working on as part of the Indian Ocean Mixing and Monsoons (OMM) collaboration with ASIRI. Two Ph.D. students from the US, Gualtiero Spiro Jaeger (MIT/WHOI) and Jared Buckley (UMassD) also participated.

Fig. 5. Participants of the science discussion meeting in India (January 2017) included ASIRI PIs from the US and Indian collaborators from various institutions and universities.

5. ASIRI DRI meeting and planning of future activities with India

Following the workshop, we had a DRI meeting in Chennai, where US and Indian PIs presented the ongoing work. Discussions were held with Indian scientists, and in particular, atmospheric modelers, about planning activities to study the Monsoon Intra-seasonal Oscillation.

Personnel

In addition to the PI, Melissa Omand (URI, Asst. Prof) contributed to the research (# 1,2 above). Sebastian Essink (WHOI/MIT Ph.D. Student) worked on the analysis of drifter data in collaboration with Verena Horman and Luca Centuroni (#3 above). Gualtiero Spiro Jaeger (WHOI/MIT Ph.D. Student), participated in the DRI meeting and workshop (# 4,5) and continues his Ph.D. research on the Bay of Bengal. The PI works closely with Prof. Amit Tandon (UMassD) and his research group consisting of Sanjiv Ramachandran and Jared Buckley.

Manuscripts in Preparation

- Essink, Sebastian, Verena Horman, Luca Centurioni and Amala Mahadevan
  Vorticity, strain and divergence from the deformation of a drifter swarm.
- Spiro Jaeger, Gualtiero and Amala Mahadevan
  Submeso-scale selective compensation of fronts in a salinity stratified ocean
- Omand, Melissa, Emily Shroyer and Amala Mahadevan
  Barrier layer collapse in the Bay of Bengal
- Shroyer, Emily, Melissa Omand, Amy Waterhouse, Arnold Gordon, J. Thomas Farrar, Robert Weller, Gualtiero Spiro Jaeger, Mara Freilich and Amala Mahadevan
  Upper ocean structure and variability in the Bay of Bengal
- Spiro-Jaeger, Gualtiero, Emily Shroyer and Amala Mahadevan
  Sharp, coherent layers of stratification and spice in the Bay of Bengal

Manuscripts Submitted

Ramachandran, S., A. Tandon, J. MacKinnon, A. Waterhouse, A. Lucas, R. Pinkel, J. Nash, E. Shroyer, A. Mahadevan, R. Weller, J.T. Farrar, Submesoscale processes at shallow salinity fronts: Observations from the Bay of Bengal during the winter Monsoon, Submitted to *J. Phys. Oceanogr*

Several manuscripts published in a special issue of Oceanography Magazine (June 2016) "From Monsoons to Mixing in the Bay of Bengal" were in the previous report.

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[bestAccomplishment] Collaborative fieldwork with India in Bay of Bengal, Special issue of Oceanography Magazine published June 2016
[comments] Amala Mahadevan 1994 PhD