

# REPORT DOCUMENTATION PAGE

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| 6. AUTHOR(S)<br>Dr. Amala Mahadevan                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |             |                         |                               | 5e. TASK NUMBER<br>N/A                                |                                                           |
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| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |             |                         |                               |                                                       |                                                           |
| 14. ABSTRACT This project supports the research in physical oceanography of a Ph.D. student in the MIT/WHOI Joint Program. The project benefited from, and complemented, ONR's Air-Sea Interaction Regional Initiative (ASIRI) DRI, in which the PI has been involved. There are two themes to the student's research. (1) Submesoscale processes in a freshwater influenced region – the Bay of Bengal. The vorticity, strain rate and divergence of the upper ocean circulation were analyzed through a cluster of drifters deployed from an ASIRI cruise on board the R/V Revelle. The analyses examined the impact of these processes on the dispersal of freshwater estimated from surface salinity. (2) The role of physical processes on the patchiness of biological distributions. The distribution of reactive tracers was examined in a numerical model, subject to different degrees of turbulence. The Ph.D. student, Sebastian Essink, benefitted from participation in the ASIRI research cruises. He has acquired skills in both numerical modeling and observational oceanography and has presented his work at meetings and conferences. He is working on manuscripts for publication and expects to complete his Ph.D. in 2018. |             |                         |                               |                                                       |                                                           |
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| U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | U           | U                       | U                             | 6                                                     | 19b. TELEPHONE NUMBER (Include area code)<br>508-289-3440 |

ONR REPORT  
Early Student Support  
Process Studies of Surface Freshwater Dispersal

June 24, 2016

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**Abstract**

This project supports the research in physical oceanography of a Ph.D. student in the MIT/WHOI Joint Program. The project benefited from, and complemented, ONR's Air-Sea Interaction Regional Initiative (ASIRI) DRI, in which the PI has been involved. There are two themes to the student's research. (1) Submesoscale processes in a freshwater influenced region – the Bay of Bengal. The vorticity, strain rate and divergence of the upper ocean circulation were analyzed through a cluster of drifters deployed from an ASIRI cruise on board the R/V Revelle. The analyses examined the impact of these processes on the dispersal of freshwater estimated from surface salinity. (2) The role of physical processes on the patchiness of biological distributions. The distribution of reactive tracers was examined in a numerical model, subject to different degrees of turbulence.

The Ph.D. student, Sebastian Essink, benefitted from participation in the ASIRI research cruises. He has acquired skills in both numerical modeling and observational oceanography and has presented his work at meetings and conferences. He is working on manuscripts for publication and expects to complete his Ph.D. in 2018.

**MAJOR GOALS**

1. Examine the influence of freshwater on the structure of salinity and temperature in the upper ocean of the Bay of Bengal at kilometer scales in the horizontal, and meter scales in the vertical.
2. Study submesoscale processes that cause the dispersal and mixing of freshwater through vertical and horizontal processes in the Bay of Bengal.

3. Support, mentor and nurture a student through a Ph.D. in the MIT/WHOI Joint Program in Physical Oceanography.

## **ACCOMPLISHMENTS**

This grant supported MIT/WHOI Joint Program student, Sebastian Essink, toward a Ph.D.

### **Major Activities**

1. Performed modeling studies to examine the distributions of passive (and reactive) tracers in a flow field under different conditions.
2. Participated in the 2015 field campaign of the ASIRI DRI in the Bay of Bengal.
3. Analyzed drifter data from 2015 deployment to examine the change in surface salinity and its relationship to submesoscale processes in the Bay of Bengal.
4. Analyzed cruise data to examine influence of freshwater on T-S structure.

### **1. Modeling Process Studies**

*Distributions of passive and reactive tracers.* Motivated by wanting to understand the differences in observed distributions of temperature and chlorophyll, a number of idealized modeling studies were conducted in which synthetic turbulence was used to advect a tracer field that was capable of growth and decay. The synthetic turbulence model is forced with a kinetic energy spectrum, with energy distributed over a range of scales. A tracer, with a gradient is then advected with the turbulent field. To model chlorophyll, the tracer has a light-dependent growth rate, and the light field is varied to decay exponentially with depth. The spectra of tracer variance are computed for different growth rates and related to the turbulence spectrum.

*Lagrangian motion of active particles.* The Lagrangian motion of particles is studied with the same flow field. Particles, introduced in the flow, are given behaviors (e.g. biased random walk, and chemotactic behaviors based on the tracer field) and the consequent distributions (aggregations) of the particles is quantified using measures for patchiness.

These modeling studies constitute the first chapter of Sebastian Essink's Ph.D. A manuscript on the spatial heterogeneity of reactive tracers is under preparation.

### **2. Research cruise in the Bay of Bengal**

The PI, as well as Ph.D. student, Sebastian Essink, participated in a 4 week research cruise on board the R/V Roger Revelle during August-September of 2015. The cruise was part of the ASIRI DRI and was used to examine the upper ocean structure and processes in the Bay of Bengal. A FastCTD was deployed as the ship was underway at 4 knots to obtain vertical profiles of temperature and salinity at a horizontal spacing of approximately 300 m. Several other autonomous instruments were used such as wire walkers, floats, and the remotely operated surface sampler. About 40 drifters with 15 m drogues, the majority having salinity and temperature sensors at the surface, were deployed in a tight array. The drifters transmitted their position every 5 minutes, and their locations were used to estimate their drift velocity and

vorticity, as described below. The drifters were from Luca Centurioni and Verena Horman and we worked in collaboration with them for the following analysis.

### **3. Analysis of drifter data set**

The drifter deployment in clusters allows for insights into the kinematic properties contributing to the observed Lagrangian velocities. Estimates of the vertical component of the vorticity vector, the horizontal divergence, and lateral strain rate were derived from triads of drifters (e.g., Saucier, 1955; Molinari and Kirwan, 1975). The spatiotemporal distributions of the kinematic properties cast light on the processes that govern the dynamics in the BoB, which were characterized by a strong mesoscale eddy, pronounced fronts and shallow salinity stratification during the deployment period.

The divergence of the velocity field can be interpreted as the time rate of change of the area enclosed by three drifters. Through a linear transformation of the velocity components, the vorticity can also be derived in terms of the transformed area of the drifter triad calculated with the mapped velocity components. Similarly, the shearing and stretching deformations can be estimated by evaluating the divergence of the rotated velocity fields in the same manner as the divergence and vorticity. The magnitude of the lateral strain rate  $\alpha$  is computed from the stretching rate and the shearing rate.

We exploit the scale-dependence of the area-averages in order to separate processes at different scales (Figure 1). When averaging over large areas ( $A > 100\text{km}^2$ ), small-scale variability is smoothed and the strong mesoscale eddy dominates the vorticity, strain and divergence. Vorticity and strain are in the same order of magnitude with about  $0.5f$ . At intermediate scales ( $10 \leq A \leq 100\text{km}^2$ ), a range of processes including the mesoscale affect the distribution of kinematic properties. Besides the mesoscale circulation, submesoscale dynamics tend to cause regions of high vorticity and strain to co-occur (e.g., Shcherbina et al, 2013). Since anti-cyclonic features become unstable faster than cyclonic features, the vorticity distribution is skewed with longer tails in the distribution of cyclonic vorticity. Furthermore, we expect frontogenesis to have a signature in the horizontal divergence. At small scales ( $A < 10\text{km}^2$ ), small cluster areas lead to large values in the kinematic properties. These results are in an Oceanography paper that is in press.

Kinematic properties from clusters of drifters complement the information we gain from the drifters' temperature and salinity measurements at the surface. More work is needed to link the observed submesoscale variability in the kinematic properties to the observed salinity and temperature at the surface.

### **4. Analysis of cruise data**

#### **Personnel**

This grant supported WHOI/MIT Ph.D. Student Sebastian Essink, and provided some support to the PI. It also benefitted another Ph.D. student Gualtiero Spiro Jaeger, who is involved in ASIRI.

#### **Publications and Manuscripts (accepted or in review)**

- Horman, Verena, Luca R. Centurioni, Amala Mahadevan, Sebastian Essink, Eric D'Asaro, and B. Praveen Kumar, Meso- to submesoscale near-surface circulation and sea surface salinity observed from Lagrangian drifters in the Bay of Bengal during the waning 2015 southwest monsoon, in press *Oceanography*, 2016
- Mahadevan, A., Gualtiero Spiro-Jaeger, Mara Freilich, Melissa Omand, Emily Shroyer, Debasis Sengupta, Freshwater in the Bay of Bengal: Its fate and role in air-sea heat exchange, 2016, in press *Oceanography*.
- Wijesekara, H.W. and 20 co-authors, ASIRI An ocean-atmosphere initiative for Bay of Bengal, 2016, *Bull. Amer. Met. Soc.* doi:10.1175/BAMS-D-14-00197.1

## FIGURES

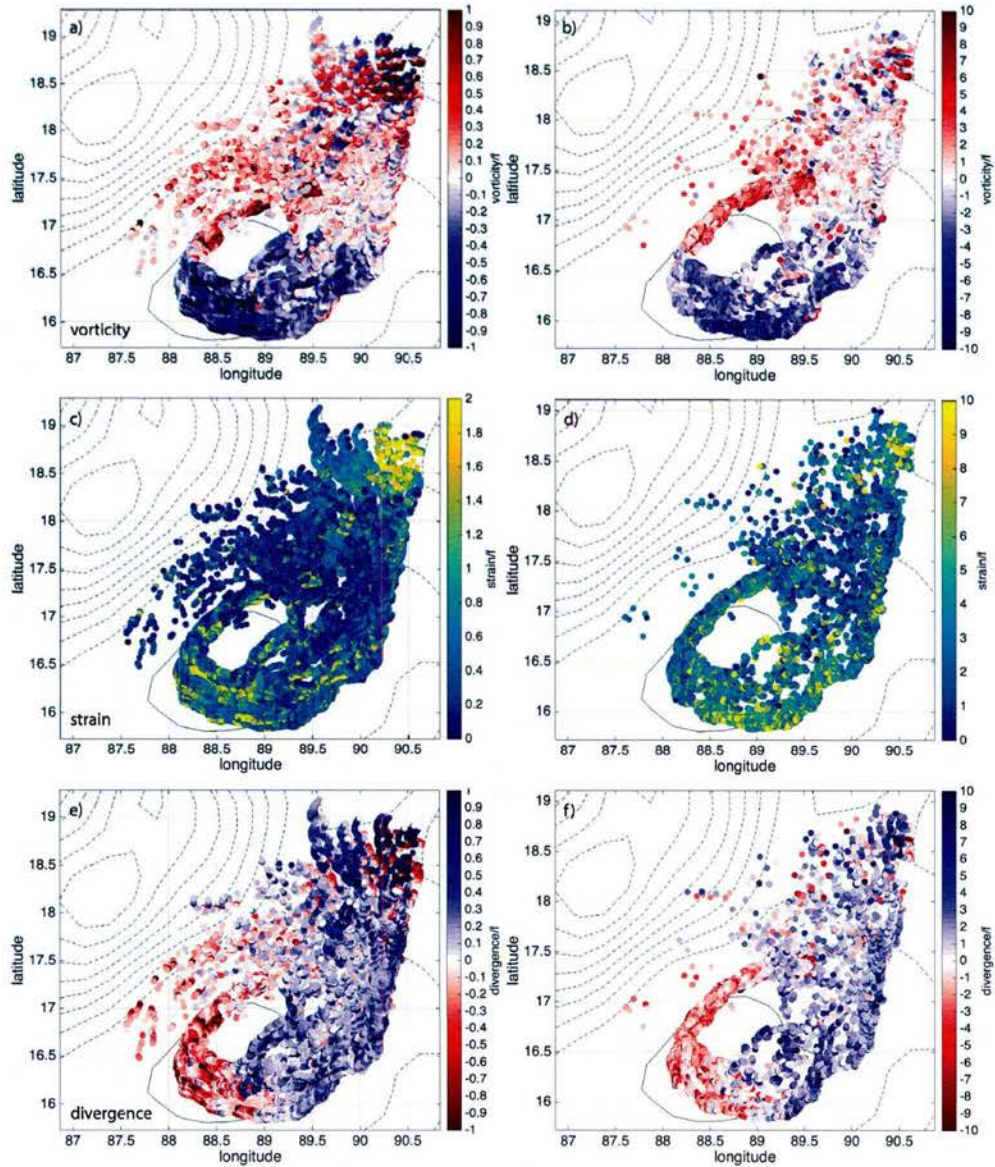


Figure 1. Maps of vorticity  $\zeta$  (a, b), lateral strain rate  $\alpha$  (c, d), and horizontal divergence  $\delta$  (e, f), all normalized by  $f$ , averaged over two different area ranges during the first month of drifter deployment. The left column (a, c, e) shows kinematic properties averaged over an area  $10 \leq A \leq 100 \text{ km}^2$ , the right column (b, d, f) is averaged over an area of  $1 < A < 10 \text{ km}^2$ . Sea-level anomaly contours are in the background, negative anomaly (dashed) and positive anomaly (solid). Analysis by Sebastian Essink.

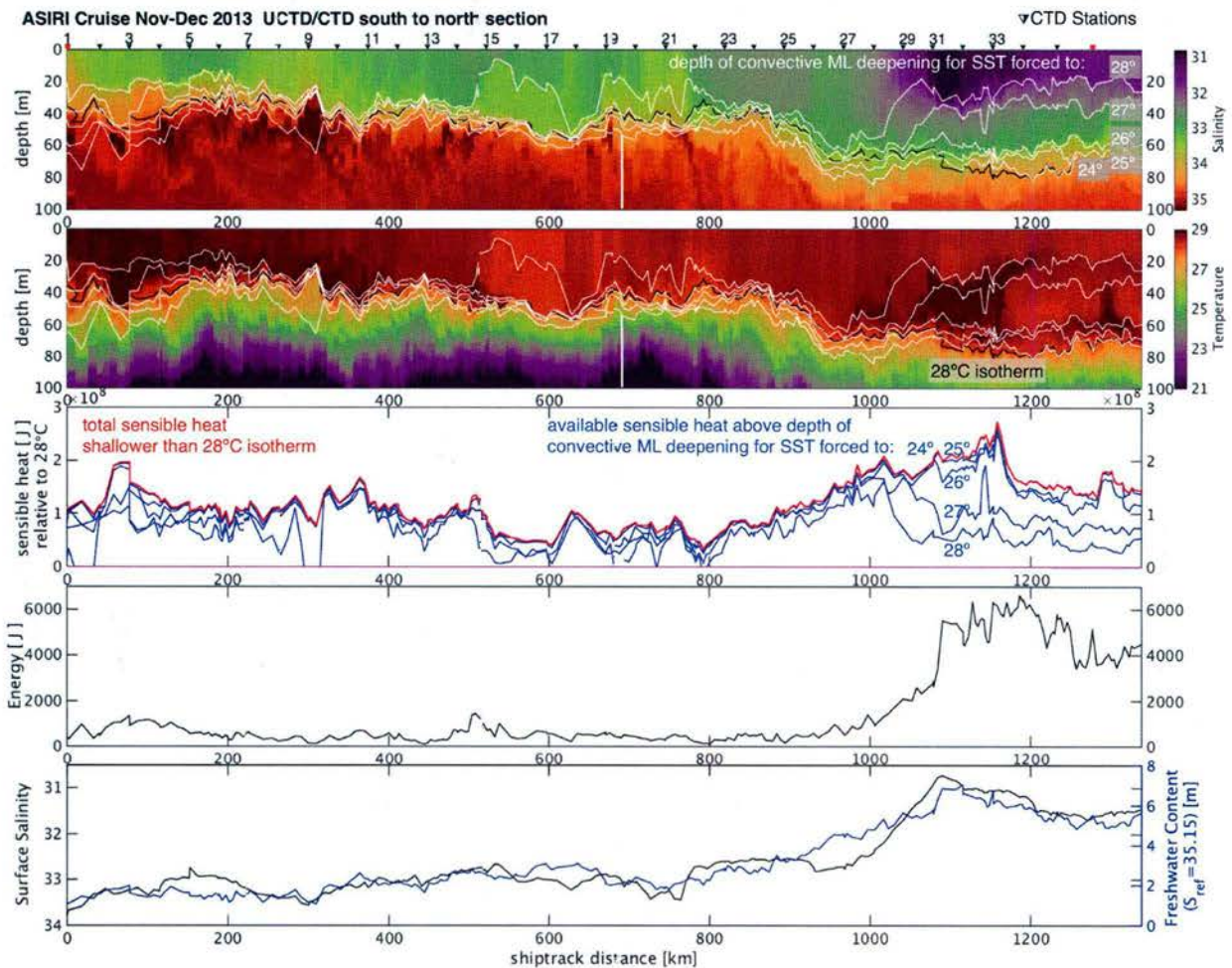


Figure 2. Section of the cruise showing (a) Salinity, and (b) Temperature, measured with an Underway-CTD system on board the R/V Revelle in November-December 2013. The data consists of profiles to a depth of 200 m (only the upper 100 m are shown) at a spacing of approximately 3 km along-track. The data are binned in to 1 m bins in the vertical. Fresher water, originating from river runoff, can be seen at the surface in the northern part of the section. Temperature inversions, with warm subsurface layers, are seen in the salinity stratified region to the north, and intrusions of saline water are seen subsurface in the southern part of the section. (c) Black: Amount of heat contained above the 28 degC isotherm (indicated by the black contour in b). Blue: the amount of heat extracted when the SST is held at 28 degC. The depth to which convective mixing would occur is indicated by the blue line in b. (d) The difference in potential energy of the density profiles, and the vertically mixed state, from the surface to the depth of the 28 degC isotherm. (e) Black: sea surface salinity and Blue: freshwater content. The two are strongly correlated. Analysis by Gualtiero Spiro Jaeger.