SST Control by Subsurface Mixing during Indian Ocean Monsoons

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Award Number: N00014-14-1-0236

LONG-TERM GOALS

We seek to understand the detailed evolution of heat and freshwater distributions in the Bay of Bengal, given large-scale gradients associated with forcing (e.g., large source of freshwater input, heat fluxes, and wind forcing) and small-scale mixing processes. Since sea surface temperature variations are broad spatially and vary over long time scales, we are using extended time series at a variety of locations to directly measure and assess SST modification by turbulent mixing over the broad expanse of international waters in the Bay of Bengal on diurnal to seasonal time scales.

OBJECTIVES

Our specific objectives are to:

1. quantify the variability in upper ocean mixing associated with changes in barrier layer thickness and strength across the BoB and under different forcing conditions,
2. quantify the subsurface heat flux divergence across the thermocline and through the barrier layer that contributes to changes in SST, and
3. contrast barrier layer character (e.g., maintenance, turbulent mixing, strength) associated with relatively weak but uniform freshwater pools (e.g., originating from distant storms and/or riverine sources) to that of strong, patchy pools created through local precipitation.

These objectives directly target the fundamental role that upper ocean dynamics play in the complex air-sea interactions of the northern Indian Ocean.

APPROACH

In short, our approach has been to augment as many platforms as possible with additional turbulence sensors (*χpods*) for the purpose of acquiring long-term, spatially spread mixing measurements. Specifically, we have

1) deployed and recovered 10 *χpod*s on NRL moorings in the BoB,
2) augmented the 12N RAMA mooring with *χpods* at 15 and 30 m depth,
3) equipped Revelle and Sagar Nidhi CTDs with self-contained *χpods* during survey work in winter 2013,
4) deployed 9 *χpods* for deployment at 15, 30, and 45 meters on each of the 8, 12, and 15 N RAMA moorings for deployment fall 2014 (to be recovered fall 2015),
5) deployed 6 *χpods* for deployment on the WHOI air-sea interaction mooring at 18 N in fall 2014 (to be recovered fall 2015), and
6) in collabortion with Rudnick (Scripps) two SOLO profiling floats were augmented with *χpods* and deployed during the 2015 ASIRI cruise.

PI Shroyer has taken part in all three field seasons through cruise participation. Analysis from these efforts is underway. The first moored data were recovered last summer; initial processing of units from the NRL moored array has started. RAMA *χpods* are in return shipment, but both units were successfully recovered.

WORK COMPLETED

All *χpods* are either currently in the water (RAMA and 18N moorings) or recently recovered (initial RAMA deployment and NRL array). A map summarizing moored mixing measurements is shown in Figure 1.

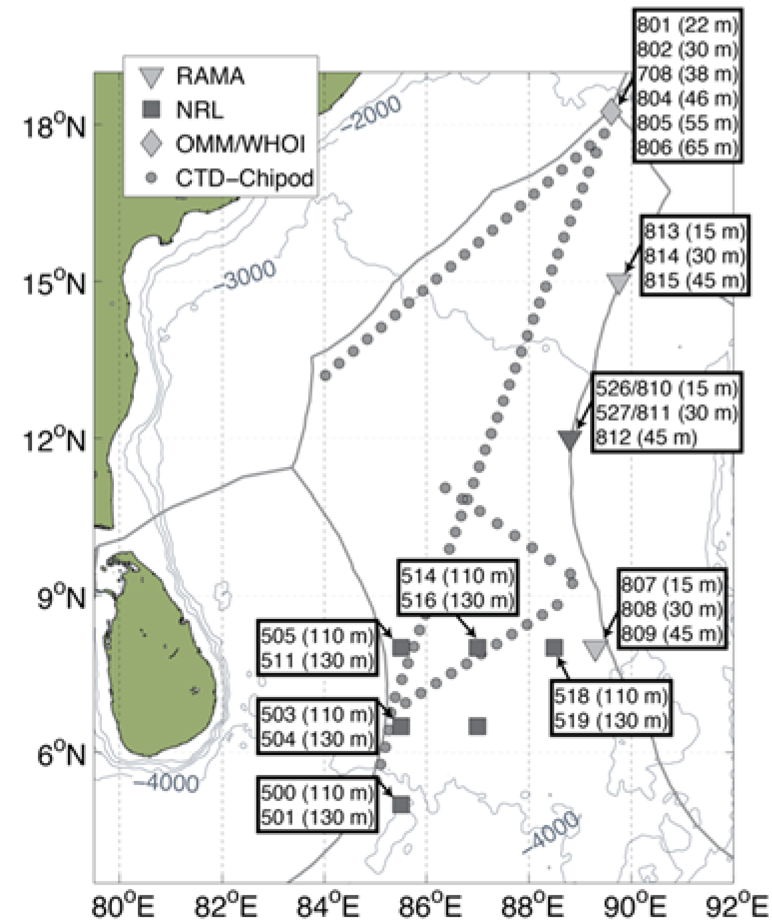

Figure 1: Map of existing (dark grey) and upcoming (light grey) χpod deployments on moorings (RAMA-triangles, NRL-squares, and WHOI/OMM-diamond). CTD-χpod stations that were collected during the 2013 pilot are indicated by circles. The RAMA mooring at 12N will collect a two-year data record with turn-around this fall. All other locations will span periods of 12-18 months.

The PI has participated in two ASIRI field cruises— November-December 2013, June 2014, and August-September 2015. She was the lead Chief Scientist for the winter cruise and assisted in the summer 2014 cruise. CTD-χpod measurements were acquired throughout the 2013 cruise; and χpods were added to wirewalkers for the summer 2014 and 2015 work.

RESULTS

The basin-scale survey results from the 2013 fieldwork are currently being summarized for a manuscript in preparation (Fig. 2). General characteristics of the vertical stratification and horizontal gradients have been quantified. While occasional intense fronts were observed, the majority of the basin has a similar distribution of salinity-dominated lateral density gradients (Fig. 3). The extreme southern range of the survey sampled at the end of the cruise is in contrast to this tenedency with relative weak, temperature dominated fronts (Fig. 3). The transition in frontal characteristics was coincident with the passage of Cyclone Madi, a very severe cyclone that intensified during the cruise duration. Breakdown of frontal characteristics by time (Fig. 4) suggests this regimme shift may be related to passage of the storm rather than a dependency solely on spatial location.

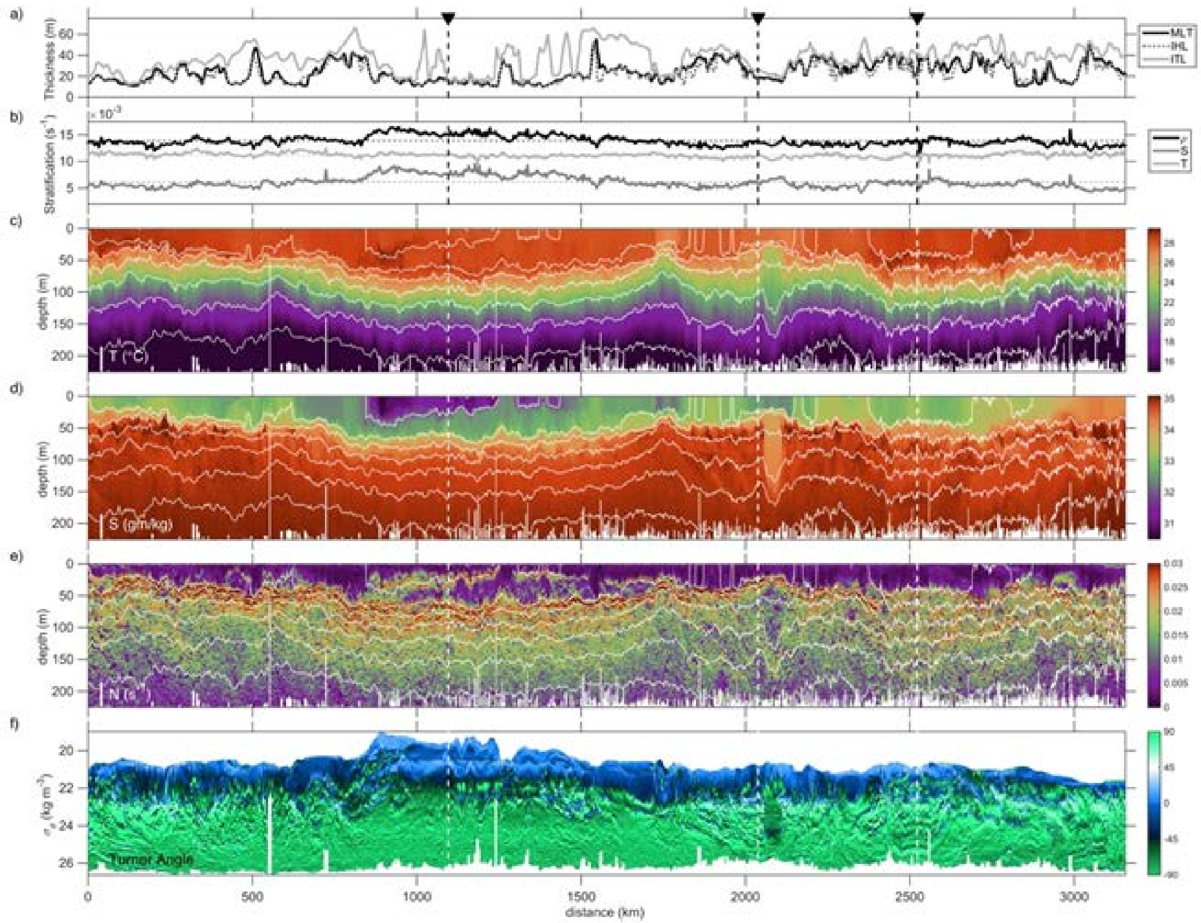

Figure 2: Summary of a) mixed, isohaline, and isothermal layer thickness, b) profile-mean density, salinity, and temperature stratification, c) temperature, d) salinity, e) stratification, and f) vertical Turner angle. Isopycnals 20--26 kg/m^3 are contoured every 1 kg/m^3 in white. Layer depths were smoothed with a 3-point running average. Vertical lines mark survey turns.

CTD-χpod data and turbulence glider measurements (Louis St. Laurent, WHOI) are being used to assess the mixing footprint of Cyclone Madi, a storm that developed and intensified during the 2013 cruise. Mixing within the thermocline was relatively weak during the northward transit, and began to intensify (along with winds) during the southwest transit outside the Indian EEZ. Wind and wave conditions over the northern portion of the southeast leg along with increasing urgency to recover a turbulence glider, prohibited additional CTD profiling during the first portion of the southeast leg. The maximum mixing was observed more than 500 km from the center of the storm during its peak intensity. We are in the process of anlalyzing the inertial wave response using shipboard ADCP data and the local mixing response using turbulence glider data in conjunction with Louis St. Laurent (WHOI) and Amy Waterhouse (Scripps).

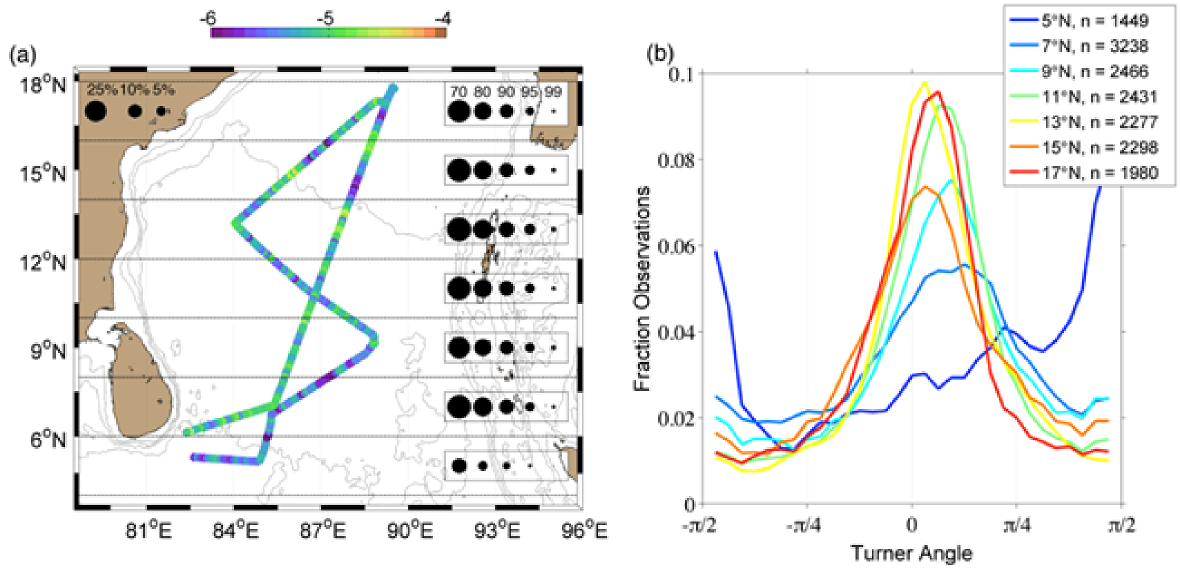

Figure 3: a) Geographic distributions of ∂ρ/∂x. Size of circles represents the percentage of observations in latitude bands (dashed horizontal lines) that exceed 70, 80, 90, 95, and 99\% of the observed ∂ρ/∂x. b) Distributions of the horizontal Turner angle by latitude bands (indicated by dashed horizontal lines in panel a).

Using the recently returned moored data we plan on assessing the monsoonal mixing signals and implication for upper ocean heat budget/air-sea fluxes. We will also look at the higher wavenumber and frequency mixing signals using χpods deployed on the NRL mooring array, (e.g., internal wave signals and dynamics associated with the Sri Lanka Dome). OSU graduate student, Kerstin Cullen, has been actively involved with this project, and is working on assessing the structure and variability of the Sri Lanka Dome (see annual report from N00014-15-1-2121).

IMPACT/APPLICATIONS

Within the Bay of Bengal high freshwater input creates salt-stratification that can form a barrier layer, dynamically isolating the thermocline from the surface mixed layer and trapping atmospheric heat and momentum fluxes near the surface. This buoyancy flux further stabilizes near-surface layers, therby requiring an increase in the energy needed to mix cool fluid up from the thermocline. Our work seeks to understand the time-evolving contribution of mixing to the upper ocean heat budget and sea surface temperature under the influence of strong freshwater buoyancy forcing and monsoonal winds.

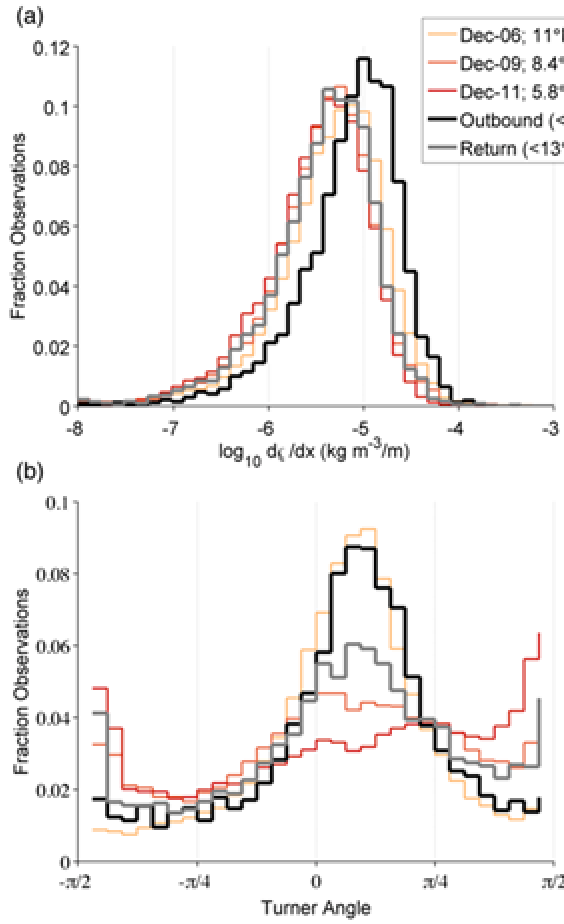

Figure 4: Distributions of a) $\partial\rho/\partial x$ and b) horizontal Turner Angle sorted by outbound (black) and return (grey) legs south of 13N, corresponding to the period prior to and during development of Cyclone Madi. Distributions along the return leg are further binned by latitude (red shades). Outbound and return histograms are significantly different from one another at the 99.5% level.

PUBLICATIONS

A. J. Lucas and E. L. Shroyer and H. W. Wijesekera and H. J. S. Fernando and E. D'Asaro and M. Ravichandran and S. U. P. Jinadasa and J. A. MacKinnon and J. D. Nash and R. Sharma and L. Centurioni and J. T. Farrar and R. Weller and R. Pinkel and A. Mahadevan and D. Sengupta and A. Tandon, *Eos, Transactions American Geophysical Union* 95 269--270 (2014)

RELATED PROJECTS

N00014-13-1-0357 funded the pilot work for this project.

N00014-15-1-2121 supports a graduate student under this project.