Wind-induced weakly penetrative mixing in the surface boundary layer in the Bay of Bengal

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Abstract

The current investigation was done under the Air Sea Interaction in the Northern Indian Ocean project. Objective of this study was to study wind induced mixing and stratification in surface boundary later. Vertical micro structure profile and conductivity temperature depth measurements were taken November 10-27, 2013 and meteorological measurements were coupled with oceanographic measurements. Very strong density stratification in the Bay of Bengal (BoB), principally governed by the fresh water influx at the sea surface, should suppress turbulence in the upper boundary layer. The microstructure measurements conducted in the BoB in 2013 confirmed this assumption for the first time ever, showing that the surface low-saline layer was effectively decoupled from the thermohalocline under moderate winds. The wind-induced turbulence did not penetrate below $z \sim 20 - 25$ m. Under higher winds the surface mixed layer deepened only slightly, but it is still decoupled from the thermohalocline. The horizontal/temporal gradients of temperature, salinity, and density in the surface layer almost completely vanished under the high wind conditions. Mesoscale lateral dynamics of the surface layer of BoB, being associated with filaments and lenses of diluted salinity water, led to active frontogenesis, which, along with atmospheric forcing, strongly influenced the turbulence and mixing in the entire upper oceanic layer. Front of high celerity associated with a low-salinity dynamical feature (lens or a filament) has been detected in the upper surface layer, resembling a gravity current with a highly turbulent core. Turbulence evanesced immediately below the low-salinity layer. However, turbulence in a stratified upper boundary layer was not affected by the front. Since observations of turbulence in BoB have started only recently, the origin, nature, spatial and temporal distribution and longevity of these lenses remain largely unknown, nor their role in air-sea interactions of the BOB.

Keywords: Turbulence, surface layer, mixing, stratification

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Introduction

Indian Ocean is the least explored Ocean among the three Oceans. The study of Bay of Bengal is complex and most of the studies have been based on the models. However, models do not represent the real world activities. Therefore, current effort was to validation of models and understanding the Oceanography of the Bay of Bengal through in-situ measurements.

These investigations were conducted as part of the Air Sea Interaction in the Northern Indian Ocean (ASIRI) as a collaborative project between NARA and University of Notre Dame. During the cruise various measurements have been taken and which were used to investigate the mixing and stratification status in the BoB. The cruise was conducted from November 10-27, 2014 and certain numbers of Vertical Micro-structure Profiler (VMP) and Conductivity Temperature Depth (CTD) profiling measurements (casts) were carried out.

Material and Methods

Measurements of turbulence and background thermohaline structure and stratification were taken using VMP produced by Rockland Scientific. The profiler carried two airfoil probes (measuring small-scale shear to infer the kinetic energy dissipation rate, ε), two fast thermistors (measuring microstructure gradients to estimate the temperature dissipation, χ), three-component accelerometer, pressure sensor (depth) and a Seabird CTD unit for precise measurements of temperature, salinity, and density. The deployment (down to ~ 120 – 140 m) of the instrument was done with a characteristic "free falling" velocity in the range 0.65-0.7 ms^{-1}. A comprehensive VMP measurement campaign was conducted on Nov 13, 15, and 16, under various stratifications and wind conditions. Starting from November 18, a high-quality dataset was collected at 4 mini sections analysed below.

Results

Wind-induced turbulence in the surface layer

Very strong density stratification, which was observed on November 18-19 just below a thin (less than 15-20 m deep) mixed surface layer (SL), almost completely suppressed the wind-induced turbulence, which does not penetrate below z ~ 20 - 25 m.

The surface low-saline layer was effectively decoupled from the thermohalocline under moderate winds, W_a ~ 11-12 ms^{-1}. Note the existence of horizontal/temporal gradients of T and S in the SL. Similar patterns of stratification and turbulence were also observed on November 19. Under higher winds, W_a ~ 16-18 ms^{-1}, the surface homogeneously mixed layer deepened only slightly, but it is still nominally decoupled from the pycnocline. The horizontal/temporal gradients of T, S, and σ_θ in the SL almost completely vanished.

Individual vertical profiles of T, S, σ_θ, N^2 and ε on November 18 show the upper boundary of the near-surface pycnocline was at z ~ 10 - 11 m and its lower boundary – at z ~ 15 m. Turbulence intensity, which can be roughly specified by ε for non-stratified flow, gradually decreases in the SL from ~ $3\times10^{-5} - \sim 10^{-3}$ Wkg^{-1} at z = 5 m to $10^{-6} - 10^{-8}$ Wkg^{-1} between z = 10 and z = 15 m. Below z ~ 15 m, the dissipation rate sharply decreased to ε ~ 10^{-9} Wkg-^{1}, remaining approximately constant downward.

The intensification of wind stress from ~ 0.16 on November 18 to ~ 0.5 Nm^{-2} on November 19, led to the increase of the dissipation rate $\varepsilon \approx 10^{-6} - 10^{-7}$ Wkg^{-1} across the entire mixing layer, deepening the homogeneous mixed layer to down to z ~ 22 m. The enhanced wind-induced turbulence not only produced 1D vertical mixing, but also initiated horizontal stirring dramatically reducing thermohaline differences in the mixed SL down to $\Delta_x T \approx 0.017$ C, $\Delta_x S \approx 0.02$ psu, and $\Delta_x \sigma_\theta \approx 0.008$, respectively, along almost the same distance (the section length ~ 2.4 km) as on November 18. However, very strong density stratification in the pycnocline just below the mixed SL suppressed the wind-induced turbulence, which does not penetrate below z ~ 22 - 25 m.

No internal sources of turbulence were evident in the water interior ($z \approx$ 22 - 120 m), suggesting that under mild and even relatively strong, but short-sustained winds dominated in the area before and on November 18-19, small-scale dynamics of the surface layer and that of the pycnocline were effectively detached from each other. Internal wave radiation and breaking below the pycnocline appear to be damped by activities of the pycnocline, possibly local breaking (see the slight increase of dissipation in the pycnocline region). This happened in the regions away from strong local frontal zones.

Surface-Layer Turbulence affected by a strong salinity front

Mesoscale lateral dynamics in the surface layer of BoB, being associated with filaments and lenses of diluted salinity, led to active frontogenesis, which, along with atmospheric forcing, immensely influenced turbulence and mixing in the entire upper oceanic layer. A very sharp "fresh water" front, where salinity is changed by more than 1 psu at a distance of ~100 m, is observed. This is one of the many fronts observed in the Revelle cruises.

This dynamical feature was moving northward with a speed of about 1 ms^{-1}, resembling a gravity current and being very turbulent inside. It is interesting that immediately below the "fresh water" layer, turbulence was almost completely blocked (ε reduced to less than 10^{-8} Wkg^{-1} – a yellow-green area in the depth range 25-40 m).Interestingly, turbulence in a stratified upper boundary layer at ~ 40 $<z<$ 60 m has not been affected by the front, a fascinating phenomenon that require further detailed analysis.

Discussion and Conclusion

Very strong density stratification in the BoB, principally governed by the fresh water influx at the sea surface, should suppress turbulence in the upper boundary layer. Our microstructure measurements conducted in the BoB in 2013 confirmed this assumption for the first time ever, showing that the surface low-saline layer was effectively decoupled from the thermohalocline under moderate winds, W_a ~ 11-12 ms^{-1}. The wind-induced turbulence did not penetrate below z ~ 20 - 25 m. Under higher winds, W_a ~ 16-18 ms^{-1}, the surface mixed layer deepened only slightly, but it is still decoupled from the thermohalocline. The horizontal/temporal gradients of temperature, salinity, and density in the surface layer almost completely vanished under the high wind conditions. No evidence of internal turbulence sources of turbulence were detected, suggesting that under mild and even relatively strong winds dominated in the BoB at the time of measurements, small-scale dynamics of the surface layer and that of the pycnocline were effectively detached from each other as a result of the strongly stratified pycnocline between them.

Mesoscale lateral dynamics of the surface layer of BoB, being associated with filaments and lenses of diluted salinity water, led to active frontogenesis, which, along with atmospheric forcing, strongly influenced the turbulence and mixing in the entire upper oceanic layer. Front of high celerity associated with a low-salinity dynamical feature (lens or a filament) has been detected in the upper surface layer, resembling a gravity current with a highly turbulent core. Turbulence evanesced immediately below the low-salinity layer. However, turbulence in a stratified upper boundary layer was not affected by the front. Since observations of turbulence in BoB have started only recently, the origin, nature, spatial and temporal distribution and longevity of these lenses remain largely unknown, nor their role in air-sea interactions of the BOB. The present work only provides support for their existence, and future field campaigns and theoretical studies will provide better understanding of the role of these small-scale features in regional and global oceanography.