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High-resolution quantification of turbulent mixing in the North Indian Ocean during the monsoons

Sutanu Sarkar
Department of Mechanical and Aerospace Engineering and Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0411
phone: (858) 534-8243 fax: (858) 534-7599 email: sarkar@ucsd.edu

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LONG-TERM GOALS

The overarching goals are to investigate the roles of vertical and lateral turbulent mixing processes in setting the spatial and temporal variability of temperature and salinity observed in the upper ocean surface of the Bay of Bengal. Understanding such processes will help improve the parametrization of momentum and heat fluxes across the air-sea interface in coupled circulation models as well as enhance the current capabilities of monsoon predictions.

OBJECTIVES

High-fidelity numerical simulations are used to understand and parametrize mixing processes in the upper ocean surface. Two canonical problems motivated by observational data collected in 2013 are targeted: (1) the erosion of a strongly stratified salinity barrier layer by wind including the influence of rotation; and (2) the vertical and lateral fluxes of momentum, heat and salinity associated with a nonlinear bore that propagates in an ambient with lateral buoyancy gradient.

APPROACH

Three-dimensional, nonlinear Navier-Stokes equations under the Boussinesq approximation are solved numerically. The code is non-hydrostatic and has capabilities to resolve turbulence through Large-eddy simulations (LES) in which advanced subgrid parameterizations such as the dynamic eddy-viscosity model and the dynamic mixed model are used. The model coefficients are not fixed but adapt locally to the development of resolved-scale instabilities. The solver is parallelized using MPI with 3-direction domain decomposition and is shown to scale well to billions of grid points providing capability for high resolution simulations on HPC resources.

The work is performed with postdoc Hieu Pham who also participated in the 2014 Bay of Bengal cruise. Parameters of the nonlinear bore simulations are set based on collaborative discussion with Jennifer McKinnon and Andrew Lucas from Scripps Institution of Oceanography and Jonathan Nash from Oregon State University in order to guide the analysis of nonlinear bore which was intensively

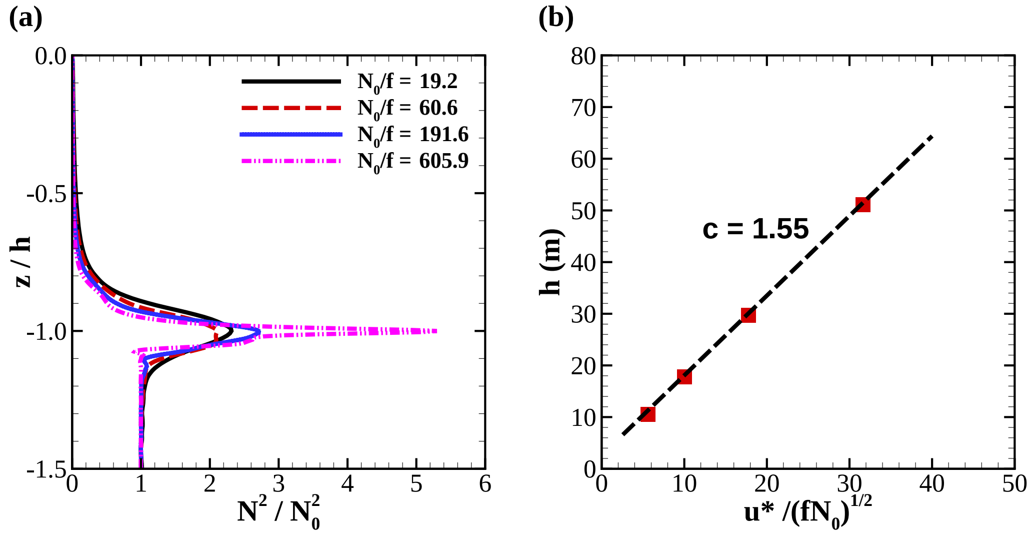

Figure 1: Scaling of the surface Ekman layer capped by the strong salinity gradient in the barrier layer: (a) Profiles of normalized squared buoyancy frequency N^2 as a function of vertical distance scaled with Ekman layer depth h; (b) the Ekman layer depth h (symbols) decreases according to $u^*/\sqrt{fN_0}$ (solid line) when the background stratification, N_0, increases.

surveyed during the 2013 pilot cruise.

WORK COMPLETED

Two sets of simulations have been completed. In the first set, a surface Ekman layer driven by wind is simulated to erode a barrier layer with various levels of stratification. The range of salinity gradient of the barrier layer covers four orders of magnitude from 0.0001 to $0.1 psu\, m^{-1}$ spanning the entire range of values observed in the Bay of Bengal. The simulations are being analyzed and a manuscript is being prepared for submission to Journal of Physical Oceanography.

In the second set of simulations, a nonlinear bore driven by a salinity difference is simulated to propagate into an ambient having a partially compensated lateral buoyancy gradient. Two simulations have been performed: one with the lateral gradient and one without the gradient for comparison. Results of the simulations have been shared with other ASIRI PI's for discussion and refinement.

RESULTS

a. Erosion of a barrier layer by a surface Ekman layer

When a surface Ekman layer driven by a wind stress with frictional velocity u^* and a Coriolis parameter f corresponding to $18^\circ N$ deepens to a barrier layer having a buoyancy frequency, N_0, its evolution is similar over a wide range of stratification N_0 *provided that* the proper scaling is used. As shown in Fig. 1, the profiles of the squared buoyancy frequency in cases with different N_0^2 are self-similar when scaled with the thickness of the Ekman layer h. As the stratification inside the barrier layer increases, the thickness of the surface mixed layer decreases following the relationship: $h = 1.55u^*/\sqrt{fN_0}$. The LES results are consistent with theoretical predictions, e.g. Pollard et al. (1973) who estimate the

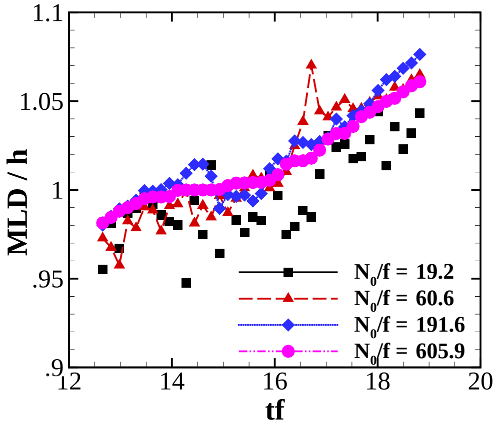

Figure 2: The surface mixed layer (MLD) deepens in cases with different stratifications. The entrainment rate depends on h and thus the background stratification N.

maximum thickness to be $h_{max} = 2^{3/4}u^*/\sqrt{fN_0}$.

Due to the constant momentum input from the wind stress, the Ekman layer continuously erodes the barrier layer by entraining saltier fluid from the barrier layer into the surface mixed layer as shown in Fig. 2. Quantifying the rate of entrainment u_e/u^* is important because it provides an estimate of the erosion rate of the barrier layer and the rate at which the cold water reservoir in the thermocline can cool the surface mixed layer. Mixed layer models often parametrize the entrainment rate as

$$\frac{u_e}{u^*} = a\,Ri_b^n, \tag{1}$$

where $Ri_b = gh\Delta\rho/\rho_0 u^{*2}$ is the bulk Richardson number, a and n are empirical constants. Previous observational and experimental studies indicate great variability in the value of the constants (Fernando, 1991). Application of mixed layer models often takes n to be -1 and a to be 0.25. We are currently analyzing the LES results to contrast the entrainment law with previous theoretical, experimental and numerical works.

b. Characteristics of a nonlinear bore

Observations from the 2013 pilot cruise reveals a nonlinear bore propagating in the surface mixed layer above the barrier layer. The bore transports cold fresh water over partially compensated warm salty water of the ambient. Velocity data shows flows in the surface mixed layer converge in the vicinity of the bore. As the bore propagates, the dissipation rate in the vicinity of the bore is elevated up to $10^{-6}\,m^2\,s^{-3}$ while its speed decreases in time. After the bore passes, the surface layer shows a compensated thermal inversion with cold fresh water laying on top of warm salty water.

The LES model of the nonlinear bore reveals the important role of lateral turbulent mixing in setting the vertical variability of temperature and salinity in the surface mixed layer in the Bay of Bengal. As shown in Fig. 3, the propagation of the bore is a highly nonlinear process which involves shear instabilities and turbulence. Kelvin-Helmholtz (KH) shear instabilities form along the density interface surrounding the bore. The KH instabilities generate isopycnal overturns with tens of meters vertical extent bringing warm fluid below the bore up to the surface. The shear instabilities reach to regions far behind the bore. The passing of the bore sets up a 25-m thick layer of thermal inversion with a

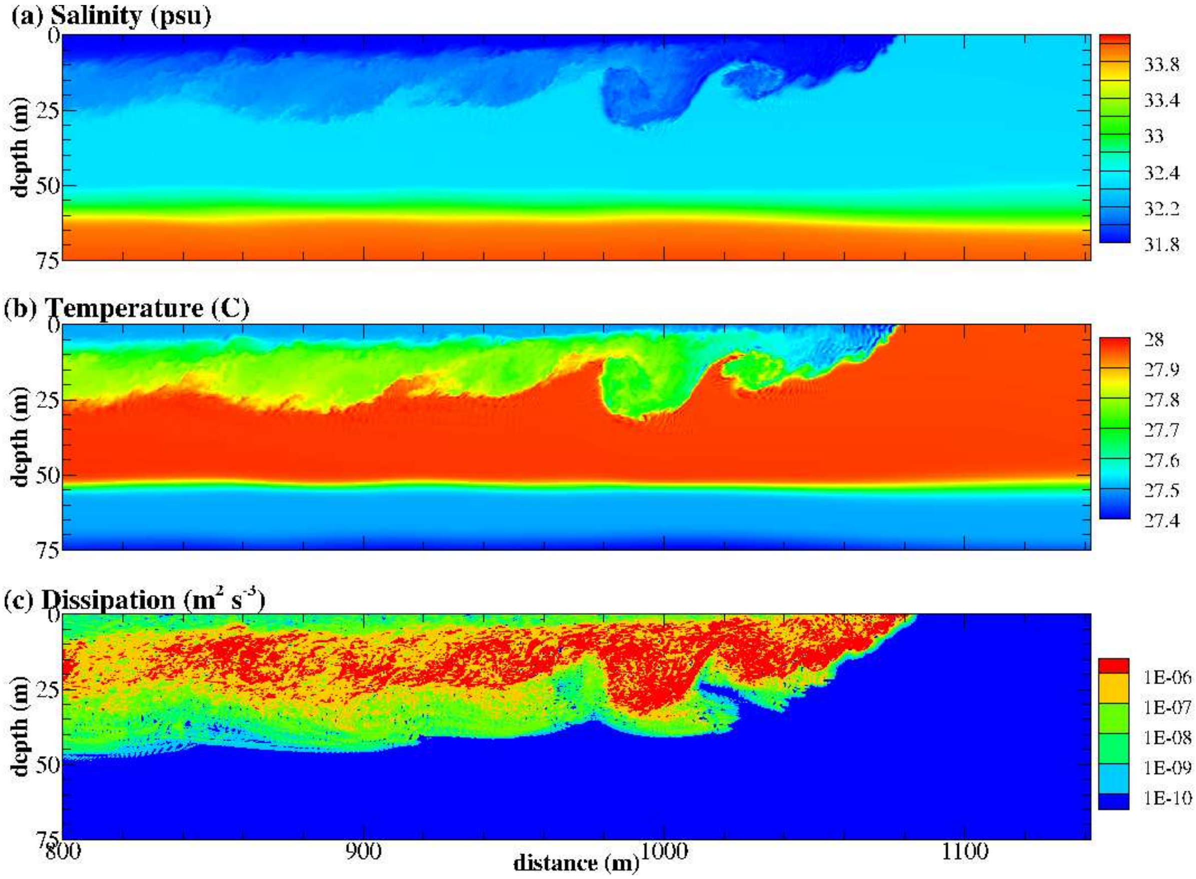

Figure 3: Structure of a nonlinear bore propagating into an ambient with lateral buoyancy gradient $M^2/f^2 = 3$: (a) the bore is driven by the salinity difference between cold fresh water on the left and warm salty water on the right; (b) Compensated thermal inversion is seen below the bore; and (c) Kelvin-Helmholtz shear instabilities cause strong turbulent mixing at the front as well as in regions trailing the bore.

temperature difference up to $0.3°C$ on top of the barrier layer. The turbulent dissipation rate, as a result of the shear instabilities in the vicinity of the bore, is elevated up to $10^{-6} m^2 s^{-3}$ comparable to the observations.

As the nonlinear bore propagates, its speed is found to *decrease* in the shipboard observations and it is of interest to identify the factors which slow down the bore. Results from the two LES simulations show that the speed of the bore also decreases similarly in the observations when the ambient has a lateral buoyancy gradient (as in the observations) as shown in Fig. 4. Without the lateral gradient, the bore propagates at a constant speed. Lateral buoyancy gradients are ubiquitous features of the surface mixed layer in the Bay of Bengal. It is well known that the speed of the bore is proportional to $\sqrt{\Delta\rho/\rho_0 gH}$ where g is gravity, H is the depth of the cold fresh water, and $\Delta\rho$ is the density difference which drives the bore. The presence of the lateral buoyancy gradient ahead of the propagating bore (background density decreases in the x-direction) reduces the speed of the bore in two ways: (1) it reduces the buoyancy difference across the bore; (2) the corresponding horizontal pressure gradient drives a counter gravity current which causes the bore to decelerate. The counter current also causes the flows in the surface mixed layer to converge. We are analyzing the LES results to see whether the speed

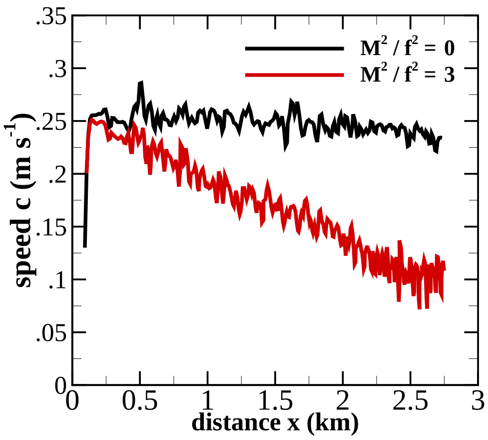

Figure 4: Propagation of the nonlinear bores: The speed decreases in the case with an ambient lateral buoyancy gradient ($M^2/f^2 = 3$) and is constant otherwise ($M^2/f^2 = 0$). Here, $M^2 = -(g/\rho_0)\partial\rho_b/\partial x$ is the lateral buoyancy gradient.

of the bore can be predicted by accounting for these two factors and what is the net mixing accomplished by the bore.

REFERENCES

H. J. S. Fernando. Turbulent mixing in stratified fluids. *Ann. Rev. Fluid Mech.*, 23.1:455–493, 1991.

R. T. Pollard, P. B. Rhines, and R. O. R. Y. Thompson. The deepening of the wind-mixed layer. *Geophys. Fluid Dyn.*, 4:381–404, 1973.