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Ocean Turbulence and Mixing Around Sri Lanka and in Adjacent Waters of the Northern Bay of Bengal



By S.U.P. Jinadasa, Iossif Lozovatsky, Jesús Planella-Morató,
Jonathan D. Nash, Jennifer A. MacKinnon, Andrew J. Lucas,
Hemantha W. Wijesekera, and Harinda J.S. Fernando

ABSTRACT. As a part of the US Air-Sea Interactions Regional Initiative, the first extensive set of turbulent kinetic energy dissipation rate (ϵ) measurements from microstructure profilers were obtained in the Bay of Bengal (BoB) and around Sri Lanka during 2013–2015. The observations span almost 1,200 km meridionally, and capture the dynamics associated with a variety of mesoscale and submesoscale features. High freshwater input in the northern part of the basin leads to regions of intense near-surface stratification, which become weaker moving south. The thin layers trap mechanical energy input from the atmosphere, often confining turbulence to the surface boundary layer. These thin layers can form shallow fronts, which at times resemble turbulent gravity currents (Sarkar et al., 2016, in this issue), and are associated with high levels of mixing. Away from the local frontal zones, turbulence in the surface low-salinity layer appears to be decoupled from the underlying pycnocline, where turbulence occurs only in rare and sporadic breaking events. A striking feature common to all of the data acquired is a dearth of turbulent mixing at depth, a condition that appears to be pervasive throughout the basin except during the passage of tropical storms. It is likely that the strong near-surface stratification effectively isolates the deeper water column from mechanical penetration of atmospheric energy.

INTRODUCTION

The variability of key atmospheric and oceanic processes in the Bay of Bengal (BoB) over a range of scales—from monsoons to mixing—significantly affects regional (Indian Ocean) and global weather and climate. As a result of heavy rainfalls and enormous river discharge into the northern BoB, mainly during the summer monsoons, a very sharp density interface known as a barrier layer is formed between low-salinity surface waters and more saline deep-ocean waters (Girishkumar et al., 2011). The barrier layer is a very distinct feature of BoB stratification, and small-scale mixing across this layer is crucial for heat, mass, momentum, and biogeochemical fluxes in the bay (Venychandran et al., 2013; Akhil et al., 2014).

Large-scale currents along the BoB boundaries, as well as eddies propagating toward the center of the bay, transport the

fresher surface water. These eddies degenerate into smaller (submesoscale) features, forming sharp salinity fronts and filaments (Sengupta et al., 2016). Lateral mixing associated with submesoscale dynamics affects sea surface temperature (SST) and sea surface salinity (SSS), and hence the overlying convection and propagating disturbances in the atmosphere. Small-scale mixing is central to turbulence, which can be generated by wind stress, shear, collapsing fronts, baroclinic instabilities, convective overturning, and internal wave breaking. Integrative understanding of BoB dynamics from large to dissipative scales is a challenging puzzle. The smaller the scales of the processes, the more difficult they are to sample, observe, and interpret. Until now, no systematic measurements of turbulence in the northern Indian Ocean existed, and as a part of the US Air-Sea Interactions Regional Initiative (ASIRI), we had an opportunity to obtain turbulence measurements in the BoB and in the coastal waters of Sri Lanka. This paper describes the findings of this study.

During the boreal winter, the East India Coastal Current (EICC; Figure 1) develops under the influence of the northeastern monsoon and flows southward along the eastern and southern coasts of Sri Lanka (Shetye, 1993; Wijesekera et al., 2015). During the summer monsoon,

southwestern winds drive the Summer Monsoon Current (SMC; Figure 1), which is directed along the southern coast of Sri Lanka into the BoB. During transition periods (April–May and September–October), the EICC reverses or weakens along the Sri Lanka coast, and the SMC gradually reverses westward, becoming the winter monsoon current (WMC; de Vos et al., 2014). These current systems, and their interactions with nearby waters, initiate a rich variety of turbulence-generating processes, which cascade energy down to dissipation scales (Lee et al., 2016, in this issue). The convergence/divergence of currents, as well as their reversals during monsoon transitions, can be expected to produce remarkable spatial variability of mesoscale and small-scale phenomena near the eastern and southern coasts of Sri Lanka (Shetye et al., 1996; Mukherjee et al., 2014). However, despite their importance, very little information has been obtained about small-scale processes in the BoB (Kunze et al., 2006), and no direct measurements of small-scale turbulence there and in adjacent waters have been captured until now. Dissipation rates and vertical diffusivities inferred from Argo float strain profiles in the 250–500 m depth range indicate that the central and western parts of the BoB have anomalously low turbulence (Whalen et al., 2012).

The first direct microstructure data and associated hydrodynamic variables (stratification, currents) were collected in 2013–2015 in the BoB and to the south of Sri Lanka (Figure 1) during research cruises conducted onboard R/V *Roger Revelle* and R/V *Samuddrika* (a regional research vessel of the National Aquatic Resources Research and Development Agency of Sri Lanka). At many of the sites in 2013–2014, the duration of microstructure measurements was limited to no more than several hours at a time, so it was not possible to deduce details of turbulence generation and dissipation there; longer time series were obtained during 2015. Here, we present snapshots of the turbulent structure in a handful of

FACING PAGE. (inset) Oceanographers from Sri Lanka's National Aquatic Resources Research and Development Agency working aboard R/V *Samuddrika* launch a vertical microstructure profiler for turbulence and stratification measurements in the Bay of Bengal. Photo credit: B.M.D.H. Kumarasiri. (background) A US scientist deploying a smaller version of the same instrument off the back of R/V *Roger Revelle*, using a fishing reel and rod instead of the A-frame. Photo credit: Gualtiero Spiro Jaeger

regions, with a goal of providing a glimpse of BoB turbulence spanning a broad range of processes and locations at specific time periods. Several noteworthy themes can nevertheless be deduced, including the wind-induced turbulence above and below the shallow barrier layer; the turbulence affected by narrow, sharp baroclinic (salinity) fronts; and turbulence structure across the EICC and WMC. Weak mixing below the near-surface layer is also a recurring theme.

OBSERVATIONS

Turbulence observations in the BoB were acquired during four research cruises spanning winter and summer monsoons and the transition periods between them. Turbulence data were collected using loosely tethered Rockland Scientific

vertical microstructure profilers (VMPs) deployed in two different modes. The VMP-500 is a large profiler that records data internally but transmits real-time pressure through its tether. This device was deployed through the ship's A-frame using a large winch in 2013–2014 (see title page photo), and it obtained data down to 150 m depth. The smaller VMP-250 records data internally, and was deployed from the ship's starboard quarter and recovered using a thin, nonconducting tether and free-spooling electric fishing reel; its depth was limited to 100 m by spool capacity. Both VMPs carried two airfoil probes (to estimate the turbulent kinetic energy [TKE] dissipation rate ϵ), a three-component accelerometer, a pressure sensor (to calculate depth), and accurate temperature-conductivity sensors to

obtain precise estimates of temperature, salinity, and potential density. The data processing followed the methodology of Roget et al. (2006); additional information can be found in Liu et al. (2009) and Lozovatsky et al. (2015). Data above 5–10 m have been discarded due to the potential for ship-wake contamination.

The measurements discussed below were conducted at the locations indicated in Figure 1. Also shown are profiles of the time-average TKE dissipation rate and salinity at each location in order to give a broader flavor of the freshwater distribution across the BoB and its implications for mixing. These data are discussed in more detail below. In November 2013, 55 VMP-500 profiles were obtained along two mini-sections (November 18–19), across the head of a bore (two sections, November 21), and over a short (~25 km) mesoscale transect (November 23) in a region bounded by 15.95°N–16.25°N and 86.7°E–87.0°E. Similar measurements were taken by R/V *Samuddrika* across Sri Lankan coastal waters south of Weligama (Weligama section, WS, 80.4°E, 5.9°N–5.2°N; April 24–26, 2014) and east of Trincomalee (Trincomalee section, TS, 8.5°N–7.5°N, 81.5°E–83°E; September 10–11, 2014). The meridional WS section covered 11 stations with 17 VMP-500 casts over a distance of ~125 km. In addition to this

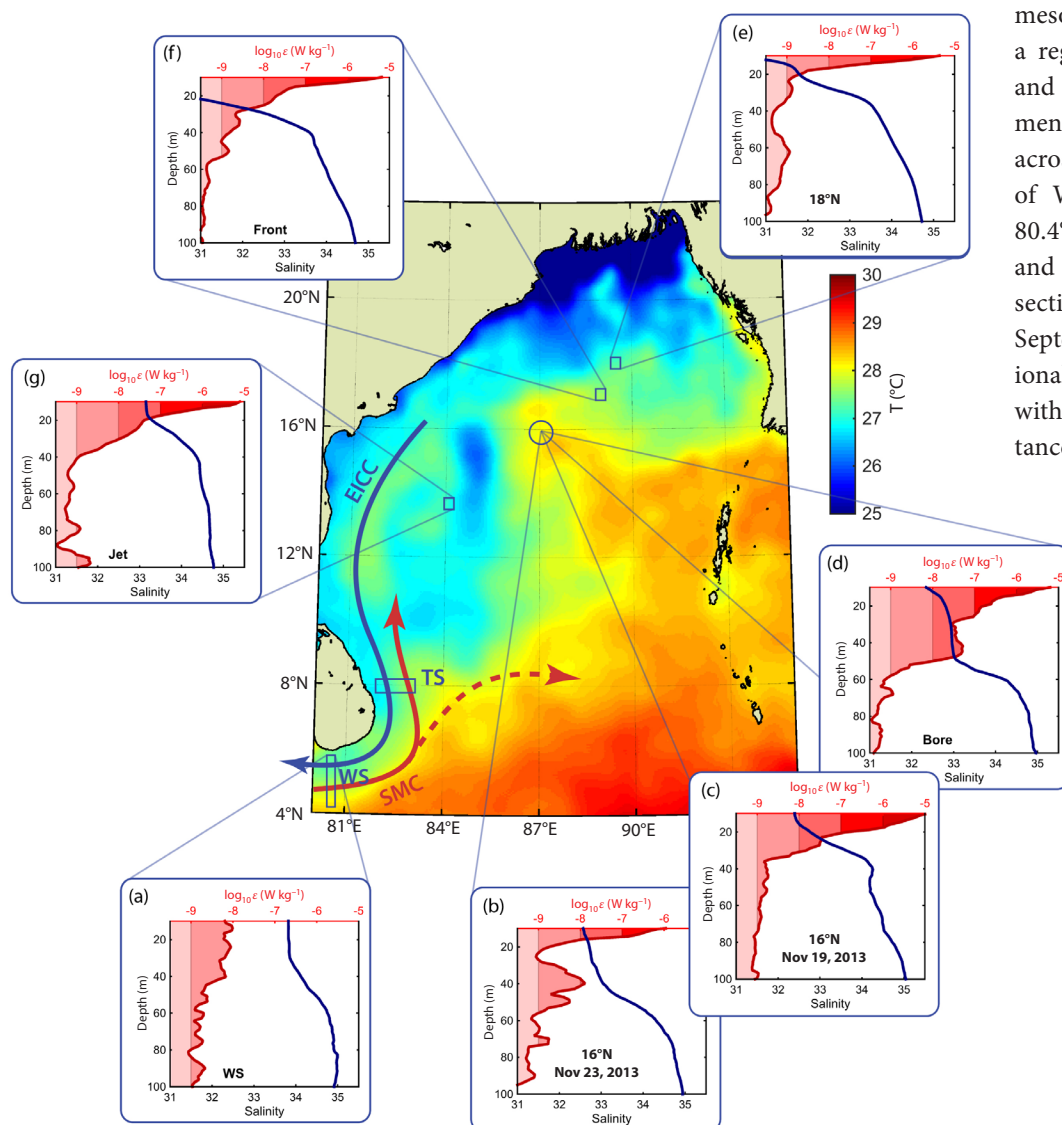


FIGURE 1. Summary of vertical microstructure profiler (VMP) measurements in the northern Bay of Bengal, with a sea surface temperature composite from December 14, 2013, shown in color. Counterclockwise from bottom left are average vertical profiles of dissipation (red shading) and salinity (solid line) from: (a) Weligama section (WS) from R/V *Samuddrika* (April 24, 2014), (b–d) 16°N for November 23, 16°N for November 19, and bore sections from R/V *Roger Revelle* (November 21, 2013), and (e–g) 18°N, “front” and “jet” sections from R/V *Roger Revelle* (August–September 2015). Not shown are the Trincomalee section (TS) data, which were not averaged because of substantial spatial variability.

transect, 14 VMP-500 profiles were obtained during a ~7 km long drift near the Weligama shelf break. Another nine VMP-500 casts were carried out in deep waters near the shelf break on February 3, 2014, allowing estimation of the mixed layer depth (MLD) in the WMC. A 130 km long TS zonal transect covered nine stations with 20 VMP-500 profiles. In addition to these 2013–2014 data, a VMP-250 was used to acquire turbulence profiles to 80–100 m depth from R/V *Roger Revelle* across a jet-like feature at 13°N on August 26, 2015 (“jet”; 309 profiles), across a submeso-scale front near 17°N on September 9, 2015 (“front”; 123 profiles), and near the 18°N moorings on September 12–14 (“18°N”; 699 profiles).

The TKE dissipation rate ε was calculated by fitting a Nasmyth benchmark spectrum to the measured spectra (e.g., Gregg, 1999) at consecutive two-second segments (1,024 points). As a result, vertical profiles of $\varepsilon(z)$ were obtained with a vertical spacing of ~1.4 m. The same spacing was adopted for temperature $T(z)$, salinity $S(z)$, potential density $\rho_\theta(z)$, and buoyancy frequency $N(z)$ profiles, where $N^2 = (g/\rho_\theta) \times (d\rho_\theta/dz)$. The squared shear $Sh^2 = (\Delta\bar{u}/\Delta z)^2 + (\Delta\bar{v}/\Delta z)^2$ and the gradient Richardson numbers $Ri = N^2/Sh^2$ were calculated by matching the vertical resolution of the calculations of temperature/salinity and dissipation profiles measured by the VMP sensors. Here, \bar{u} and \bar{v} are the zonal and meridional components of the mean currents, which were measured by a 150 kHz acoustic Doppler current profiler (ADCP) with vertical resolution of 8 m and then interpolated to a 5 m grid.

STRATIFICATION AND TURBULENCE IN THE NORTHERN BAY OF BENGAL

Surface Layer Turbulence and a Weak Interfacial Mixing

In this section, we compare two series of microstructure measurements collected in the same location in the BoB on

November 18 and 19 around noon local time. During the 23-hour time period of VMP measurements, the wind speed periodically changed from $W_a \sim 10 \text{ m s}^{-1}$ down to $\sim 4\text{--}8 \text{ m s}^{-1}$ and up to $\sim 14\text{--}16 \text{ m s}^{-1}$. Four periods of wind increase were registered, each lasting approximately two hours. The air temperature fluctuated between 27.5°C and 24°C.

Under moderate winds (November 18), a shallow ($z < 10\text{--}15 \text{ m}$) low-salinity (32.2–32.6 psu) surface mixed layer (Figure 2a) was effectively decoupled from the water below by a

sharp thermohalocline, where $N^2 > (6\text{--}8) \times 10^{-4} \text{ s}^{-2}$ (Figure 2c). Relatively small but distinguishable horizontal variability of T/S and specific potential density $\sigma_\theta = (\rho_\theta - 1,000)$ in the mixed surface layer (Figure 2a,c) indicate that the measurements were in an area of a weak local frontal zone. On November 19, after several relatively short periods of higher winds, the mixed layer deepened only slightly, still decoupled from the waters below by an even stronger barrier layer where $N^2 > 2 \times 10^{-3} \text{ s}^{-2}$ (Figure 2b,d). Wind mixing, however, erased the

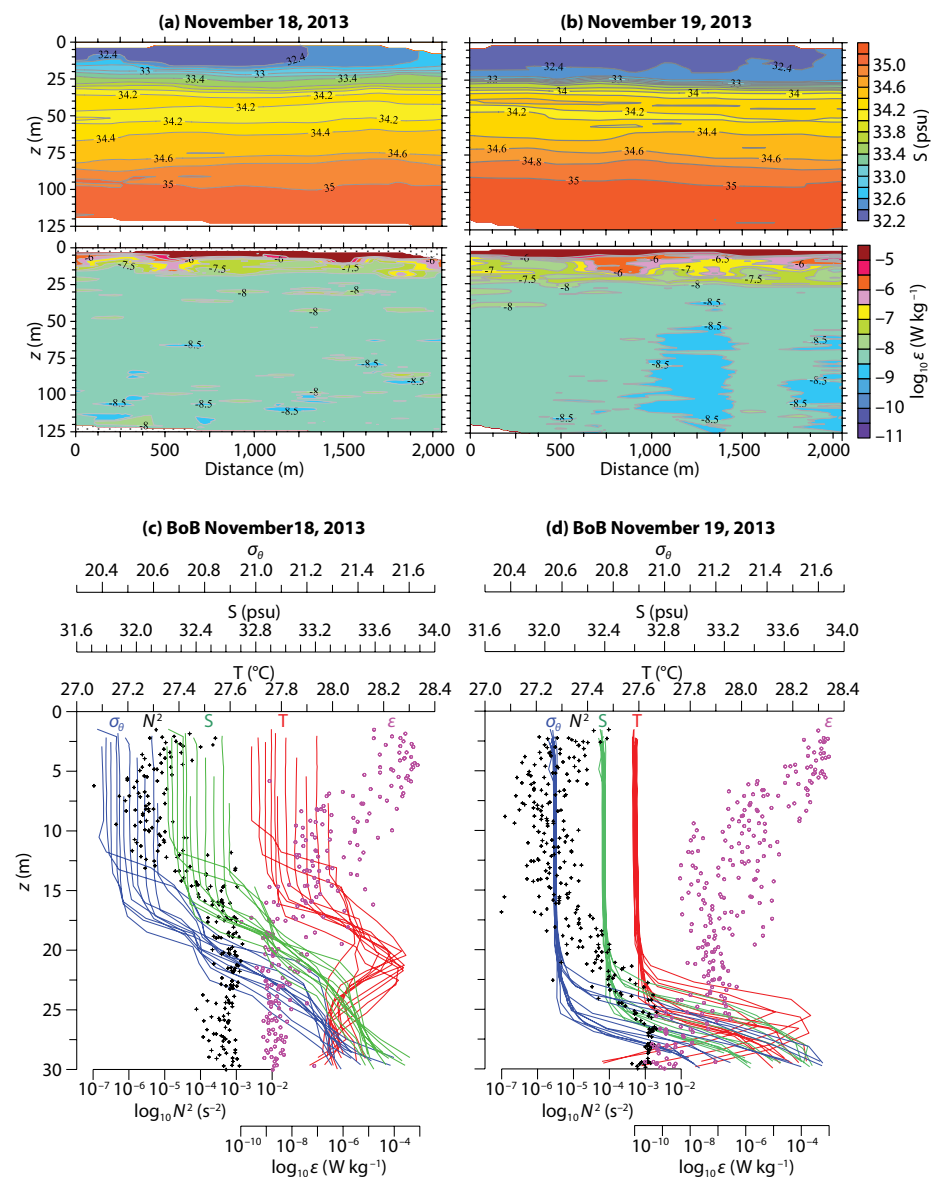


FIGURE 2. Salinity (upper) and the dissipation rate (lower) contour plots along two mini-sections taken in the Bay of Bengal on November 18 (a) and 19 (b) and the corresponding vertical profiles of $T(z)$, $S(z)$, $N^2(z)$, $\sigma_\theta(z)$, and $\varepsilon(z)$ in the upper 30 m layer (c) and (d), respectively.

horizontal thermohaline and density gradients in the surface layer almost completely, as Figure 2c,d, shows in detailed profiles of $T(z)$, $S(z)$, and $\sigma_\theta(z)$ and ε for the upper 30 m.

Under mild winds, the turbulence intensity, characterized here by ε , gradually decreased from $\varepsilon \sim (3 \times 10^{-5} - 10^{-3}) \text{ W kg}^{-1}$ at $z = 5 \text{ m}$ to $\varepsilon \sim (10^{-6} - 10^{-8}) \text{ W kg}^{-1}$ between $z = 10 \text{ m}$ and $z = 15 \text{ m}$. Thereafter, a sharp drop to $\varepsilon \sim 10^{-9} \text{ W kg}^{-1}$ was followed by an approximately constant value of $\varepsilon(z)$ with increasing depth. The horizontal differences of T , S , and σ_θ in the middle of the surface layer ($z = 7 \text{ m}$) were $\Delta_x T \approx 0.25^\circ\text{C}$, $\Delta_x S \approx 0.4 \text{ psu}$, and $\Delta_x \sigma_\theta \approx 0.22$, respectively, over a $\sim 2 \text{ km}$ separation (Figure 2a,c). An increase of the dissipation rate to $\varepsilon \approx (10^{-6} - 10^{-7}) \text{ W kg}^{-1}$ across the entire mixing layer at the second mini-transect most likely is associated with periodic, but short-lived,

segments of wind stress intensification up to $\sim 0.5 \text{ N m}^{-2}$. Thus, simple formulae for mixed layer deepening based on a constant friction velocity at the sea surface (e.g., Pollard et al., 1972; see the review by Zilitinkevich et al., 2007) is expected to fail in predicting the observed changes of MLD from 10–15 m on November 18 to 22–25 m on November 19.

The enhanced turbulence in the surface layer may also break down spatial gradients by lateral stirring, as the horizontal thermohaline differences along the second mini-section reduced to $\Delta_x T \approx 0.017^\circ\text{C}$, $\Delta_x S \approx 0.02 \text{ psu}$, and $\Delta_x \sigma_\theta \approx 0.008$ over approximately the same distance as they did in the first section. On the other hand, the observed increase of the mixed layer depth to $z \approx 22 \text{ m}$ could be associated not only with localized wind-induced mixing but also with lateral advection of a deeper mixed layer to the measurement site.

The observation that the surface layer and pycnocline were effectively decoupled from each other suggests that internal sources of turbulence in the interior ($z \approx 25 - 120 \text{ m}$) were weak ($\varepsilon < 10^{-8} \text{ W kg}^{-1}$; Figure 2a,b) under mild and even relatively strong sporadic winds observed before and on November 18 and 19. Internal wave radiation and breaking of the waves below the barrier layer appear to be damped, possibly due to local wave breaking in the pycnocline (where a slight increase of ε could be seen).

Upper-Ocean Response to a Moderate Storm

A 48-hour time series of almost 700 vertical profiles at 18°N , 89.5°E provides an opportunity to assess the BoB's upper-ocean turbulent response to a moderate wind event (Figure 3). Initially, winds were light (5 m s^{-1}) and the near-surface boundary layer was capped by a cooler, low-salinity layer about 5 m thick and delineated from the fluid below by stratification associated with both salinity and temperature steps. As the winds picked up to 10 m s^{-1} , the surface boundary layer gradually deepened, but remained less than 10 m thick. Mixing at the base of the surface boundary layer reached $10^{-6} \text{ W kg}^{-1}$, but such directly forced turbulence never penetrated deeper than 15 m, even during the peak of the wind forcing. Below this depth, significant mixing events were weaker ($10^{-8} - 10^{-7} \text{ W kg}^{-1}$) and relatively infrequent, presumably because the strong near-surface stratification limited downward energy transfer (see also MacKinnon et al., 2016, in this issue, for a discussion).

During this period, three notable patches of enhanced turbulence can be identified beneath the surface layer. One is a region of elevated mixing that occurred at 06:00 on September 13 at 20 m depth as the surface mixed layer deepened but was clearly distinct and separated from the surface mixed layer by a layer of weaker turbulence. The other two patches occurred around 12:00 on September 14 following an increase in wind speed at

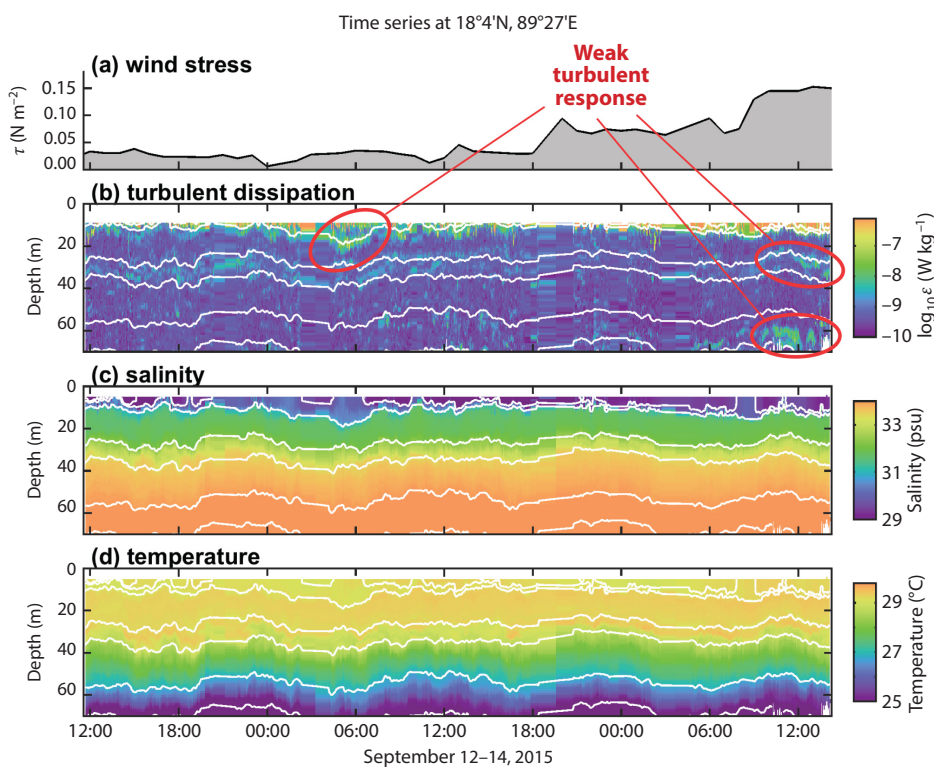


FIGURE 3. Upper-ocean response to a moderate strength wind event in the northern Bay of Bengal as captured by 699 vertical profiles spanning a 48-hour period near 18°N . (a) Wind stress from the Woods Hole Oceanographic Institution mooring at 18°N , (b) turbulent kinetic energy (TKE) dissipation rate, (c) salinity, and (d) temperature. Beneath the surface boundary layer, only a few patches of turbulence have dissipation rates approaching $10^{-8} \text{ W kg}^{-1}$ (circled in red); the time-averaged dissipation below 20 m is less than $10^{-9} \text{ W kg}^{-1}$, as summarized in Figure 1e.

about 09:00; any connection between this wind event and turbulence is speculative. However, neither of these patches significantly exceed $10^{-8} \text{ W kg}^{-1}$, such that the time-averaged deep dissipation is $10^{-9} \text{ W kg}^{-1}$ (Figure 1e), which is quite weak for upper-ocean turbulence. In addition to these localized events, there is also a notable band of slightly enhanced turbulence at 30 m depth that is persistent over the entire record and appears in conjunction with a thermal inversion there.

Surface-Layer Turbulence Affected by Strong Salinity Fronts

Frontal zones between saltier oceanic waters and lenses or filaments of fresher waters of riverine and/or rainfall origin strongly influence turbulence and mixing in the upper layer of the northern BoB. Horizontal dimensions of the low-saline features may vary from a few to tens and hundreds of kilometers. Many frontal zones were detected in the northern BoB during R/V *Roger Revelle* ASIRI cruises (Lucas et al., 2014; Wijesekera et al., in press). Turbulence measurements across one such front were made on November 21; this is the same front

shown in Figure B1c in Box 1 in Sarkar et al. (2016, in this issue). Two mini-sections (550 m and 720 m long, each with six and eight approximately equally distributed casts) were obtained while crossing approximately perpendicular to the front from saltier warmer ambient waters to the fresher colder side. The origin of this specific pool of low-salinity water is most likely an eddy or filament associated with southbound low-saline flow to the east (within the Sri Lankan Exclusive Economic Zone not sampled at that time). A very sharp salinity change ($\Delta_x S \sim 0.71 \text{ psu}$) was observed at the first crossing over a distance of $\sim 100 \text{ m}$ (Figure 4a); the temperature and density at the fresher side of the front (not shown here) decreased by $\Delta_x T \sim 0.52^\circ\text{C}$ and $\Delta \rho_x \sim 0.33 \text{ kg m}^{-3}$, respectively. Over the course of 10 hours, R/V *Roger Revelle* crossed the front 10 times while towing a thermistor chain from its bow. These data permit us to determine that the front was very sharp at times, dropping by as much as 0.5 psu in less than 5 m horizontal distance. These data also permit us to determine that the feature's propagation speed ($0.15\text{--}0.2 \text{ m s}^{-1}$

relative to the fluid ahead of it) was close to $\sqrt{g'H}$, consistent with internal gravity current speed (Turner, 1973). Here, $g' = g\Delta\rho/\rho = (3.2\text{--}3.5) \times 10^{-3} \text{ m s}^{-2}$ is reduced gravity and $H = 10 \text{ m}$ is the thickness of a colder, low-salinity layer. From the VMP-500 data, the feature appears turbulent, especially closer to the sea surface (compare the regions delimited by dashed lines in the upper and lower panels of Figure 4). Detailed inspection of T , S , and ρ_θ profiles closest to the front revealed many density inversions in the upper 10 m layer (not shown here), pointing to active turbulent mixing by the frontal flow. Below the low-salinity layer, turbulence was sharply reduced, with $\varepsilon < 10^{-8} \text{ W kg}^{-1}$, but only in a limited depth range ($\sim 25\text{--}35 \text{ m}$) shown by blue-green regions in the $\varepsilon(z, x)$ contour plots in the two lower panels of Figure 4. Strong stratification in the lower part of the frontal layer and immediately below could have provided this isolation. However, 20 m above the MLD, turbulence is not significantly influenced by the shielding effect of the front. In the depth range $\sim 40 < z < 60 \text{ m}$, the dissipation remained above $(3\text{--}5) \times 10^{-8} \text{ W kg}^{-1}$

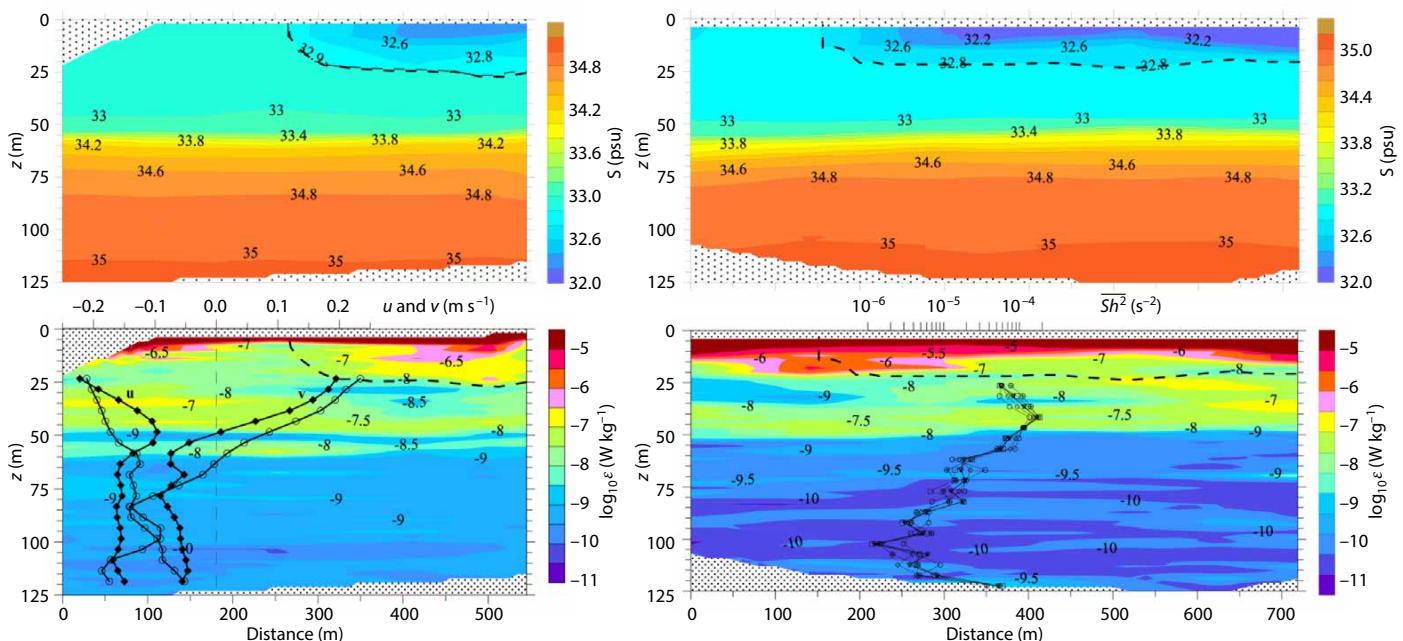


FIGURE 4. Salinity (upper) and TKE dissipation rate (lower) contour plots along two frontal cross sections with six (left) and eight (right) VMP profiles, respectively, taken on November 21, 2013. The heavy dashed lines are approximate lower boundaries of the low-salinity lenses. The $\varepsilon(z, x)$ plot on the left is overlaid by $u(z)$ and $v(z)$ current components measured in the front at the first (circles) and second (diamonds) sections. Examples of the mean squared shear profiles $\overline{Sh^2}(z)$ are in the lower right panel.

(yellow-green strips in the $\epsilon(z,x)$ plots) due to persistently high vertical shear. The squared shear was close or exceeded $Sh^2 \sim 10^{-4} \text{ s}^{-2}$, ensuring a Richardson number of the order 0.1 for $N^2 \sim 10^{-5} \text{ s}^{-2}$. Below the MLD, stratification increased in the pycnocline with $N^2 \sim 3 \times 10^{-4} \text{ s}^{-2}$ on average, while the mean shear substantially and continuously decreased to

less than $Sh^2 \sim 2 \times 10^{-6} \text{ s}^{-2}$, preventing shear-induced instability. As a result, the dissipation rate in the pycnocline drops below $10^{-10} \text{ W kg}^{-1}$ (Figure 4).

In addition to these 2013 observations associated with the propagation of a gravity current, regions of strong horizontal gradients were also sampled at two separate locations in 2015 and are

summarized in Figure 1f,g. In both cases, turbulence profiling spanned a region of strong horizontal velocity gradients that were associated with ageostrophic fronts, some of which were as sharp as those observed in 2013. While the strongest turbulence was confined to the surface boundary layer, in both of these cases, dissipation rates below the near surface were also enhanced, but not to the same extent as the 2013 event (compare Figure 1 panels f and g with d); dissipation rates below 40 m depth remained close to background levels.

STRATIFICATION, CURRENTS, AND TURBULENCE TO THE SOUTH AND EAST OF SRI LANKA IN THE SMC AND EICC

The VMP measurements to the south and east of Sri Lanka along the WS and TS lines (Figure 1) revealed substantial differences in stratification and turbulence between the EICC and SMC branches of the near-coastal currents that reflect seasonal and/or spatial variability. The TKE dissipation rate profiles along the WS and TS (color strips of $\log_{10}\epsilon$) are shown in Figure 5a,b overlaying the contour plots of potential density (the corresponding temperature and salinity panels are presented in Wijesekera et al., in press). During the intermonsoon season (April; Figure 5a), the depth of the relatively well-mixed surface layer in the blue water (>22 km from the coast) appears to be about 30–40 m across the entire southern branch of the current, deepening slightly toward the open sea. According to the VMP measurements made in February 2014 at two WS stations near the shelf break (not shown), the depth of the surface homogeneous layer was ~60 m, indicating the possibility of substantial convective cooling and/or strong wind mixing in the upper layer south of Sri Lanka during the winter monsoon, and gradually relaxing forcing toward the transition period. Lenses of slightly fresher and cooler water near the sea surface did not affect the near-surface density structure very much, as evidenced by

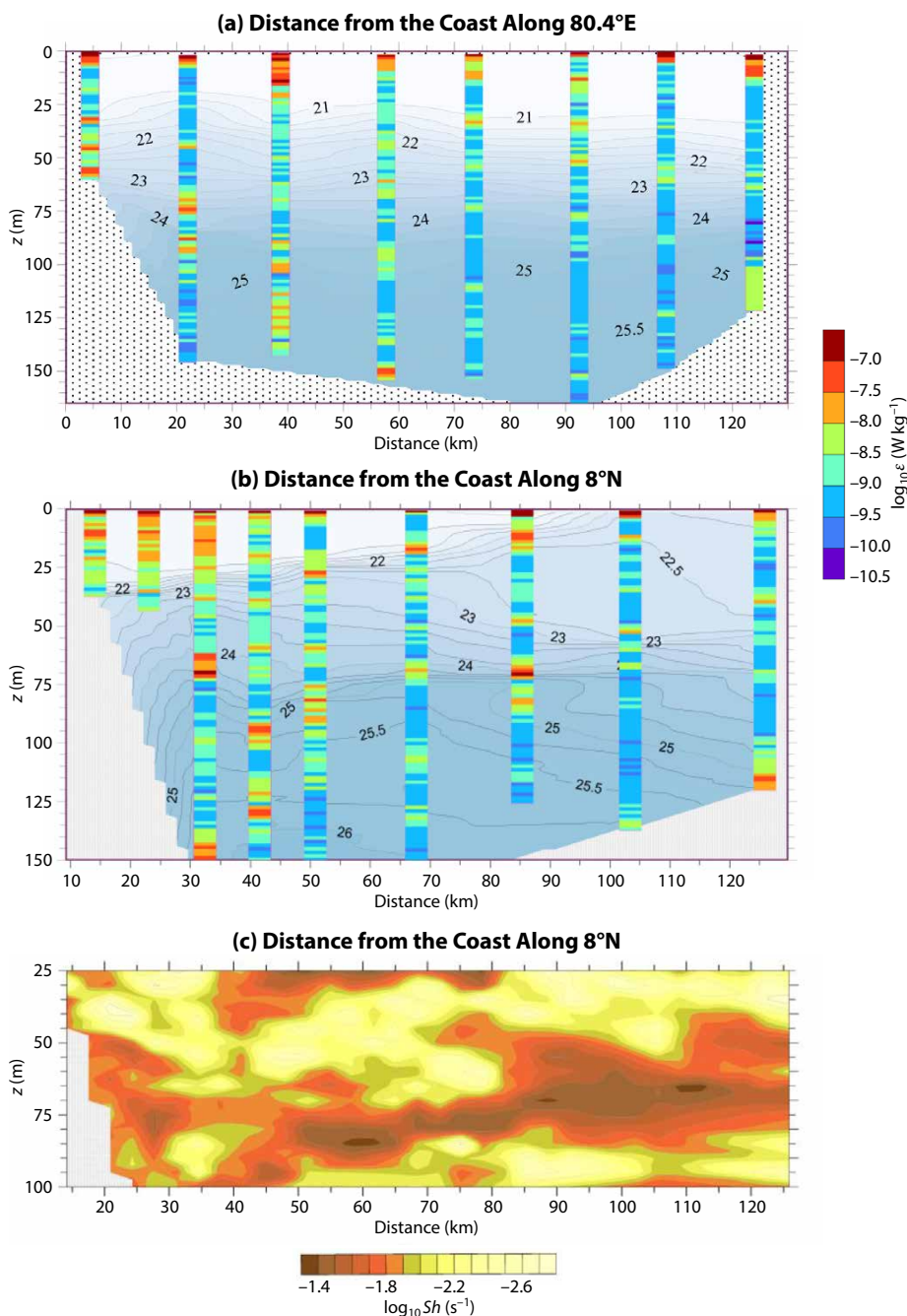


FIGURE 5. The TKE dissipation rate (ϵ , colored strips) overlaid on a background of specific potential density σ_θ along (a) the WS (80.4°E), and (b) the TS (8°N). The enhanced vertical shear (c) centered along $z = 75$ m coincides with the layer of high dissipation rate within the secondary pycnocline shown in (b).

the almost uniformly mixed upper layer and the sharp, but not very narrow, pycnocline. In general, the pycnocline deepens toward the south, suggesting predominantly eastward geostrophic transport at the end of April. This is well supported by the contour plot of geostrophic velocity (Figure 6a) calculated using deep-water Sea-Bird CTD profiles with a zero velocity reference level at 550 db. An interesting dynamical feature appears in Figure 6a closer to the Sri Lankan coast, where the eastward-directed along-slope current flows next to the westward-directed offshore current (dark blue contours). Although it is possible that the observed westward current is a remnant of the seasonal WMC during the transition season (April) between winter and summer monsoons, it is even more likely that we observed a well-developed (down to ~ 320 m) clockwise-rotating anticyclonic mesoscale eddy approximately 50 km in diameter with a core (\sim zero velocity) located about 45–48 km from the coast. Note that the regular SMC usually does not extend below ~ 200 m depth (Jensen, 2001). Sea surface elevation maps retrieved from the Aviso archive (http://eddy.colorado.edu/ccar/ssh/nrt_global_grid_viewer) show a mesoscale feature to the south of Sri Lanka, with a positive height (up to 6 cm max), which could be associated with an anticyclonic eddy that separated from westward flow near the Sri Lanka shelf break.

In September, toward the end of the summer monsoon, the thermohaline structure along the TS to the east of the Sri Lanka coast (Figure 5b) is much more complex than that of the WS. It exhibits a sharp thermohalocline in the depth range $z = 30$ – 40 m near the shelf break. However, approximately 80–90 km offshore, the pycnocline bends toward the sea surface, forming a striking baroclinic front that separates the fresher BoB surface water ($S < 33.8$ psu, $\sigma_\theta < 21.4$) moving southward along the Sri Lanka coast from the saltier water of Arabian Sea origin ($S > \sim 35.2$ – 35.4 psu at $z \approx 40$ – 50 m, corresponding to the specific density range

$\sigma_\theta \sim 22.4$ – 22.5 in Figure 5b) that is moving north-northeastward at the eastern end of the section. The calculation of geostrophic velocities across this section (Figure 6b) and ADCP measurements (Figure 6c) support this notion. Interestingly, in September, the southward-flowing branch of the EICC is present (green strip in the lower panel of Figure 6c), although it is quite narrow, extending from the coast only

~ 40 – 45 km offshore. It has two cores, at ~ 30 m and 90 m depths, with maximum velocity of about 0.4 m s^{-1} . Simulations by Jensen (2003) indicate that the southward branch is perennial in the northeastern part of Sri Lankan waters. On the contrary, the northward branch of the SMC is still a powerful current, with a maximum longitudinal velocity component v_{\max} of $\sim 1.5 \text{ m s}^{-1}$ in the mixed layer at a distance of 90–110 km from the coast (intense red

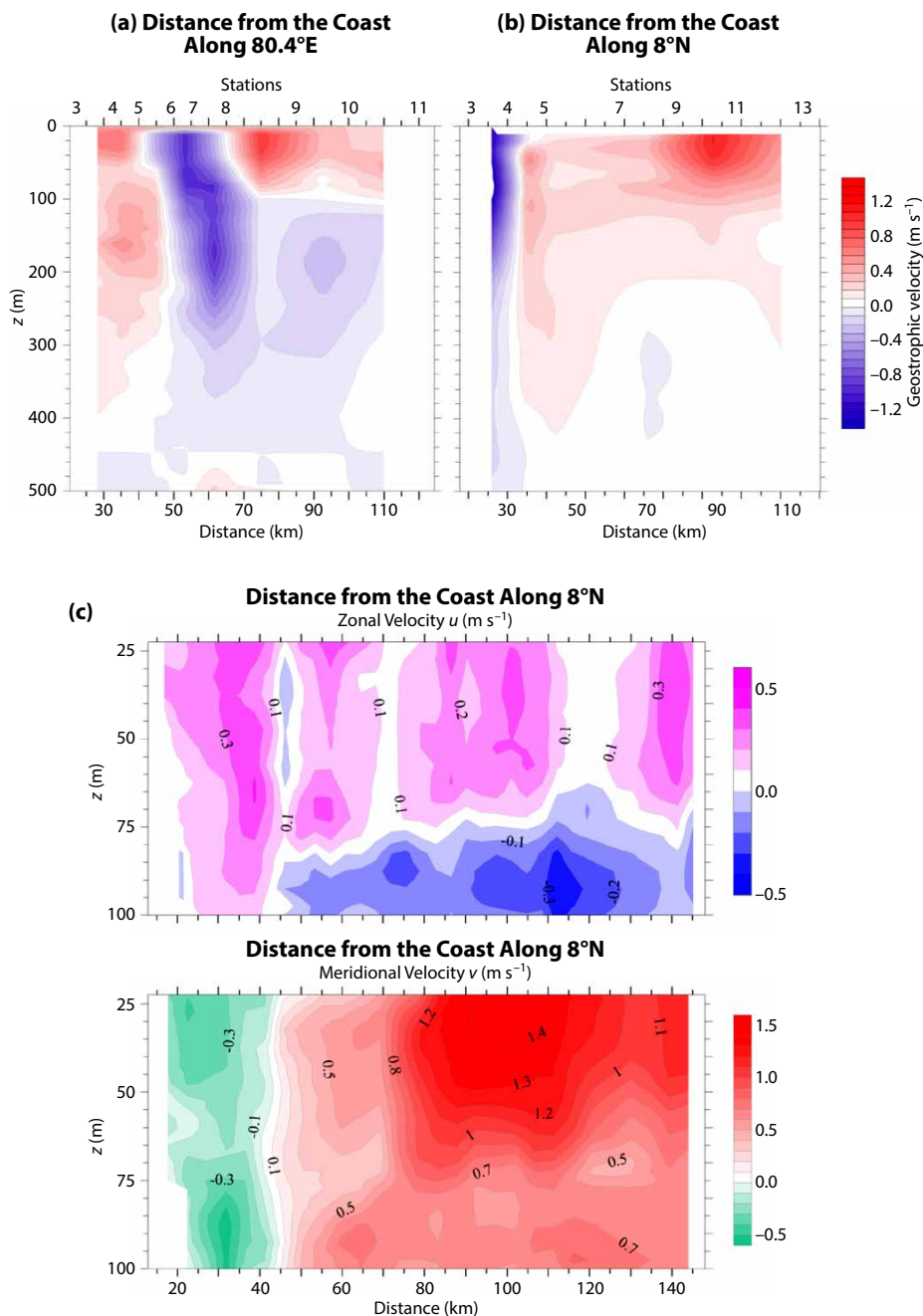


FIGURE 6. Geostrophic velocities (the reference level is 550 db) across the (a) WS and (b) TS. Positive velocities are to the (a) east and (b) north. (c) ADCP velocity components u and v along the TS.

area in Figure 6c). The zonal component u is much weaker ($u_{max} \sim 0.2 \text{ m s}^{-1}$) compared to v_{max} ; it is always directed eastward in the upper 75 m (pink segments in the upper panel of Figure 6c), showing oscillations with approximate wavelengths of $\sim 35\text{--}40 \text{ km}$. Below 75–80 m depth, the u component, which is still associated with the SMC because of the strong northward flow in the same depth range ($v \sim 0.5\text{--}0.7 \text{ m s}^{-1}$), is, however, directed westward (blue segments in the upper panel of Figure 6c), having approximately the same maximum value as its eastward counterpart. (Comparing Figure 6c and b, it is clear that the core of the SMC is composed of very salty Arabian Sea water [$S = 35.3\text{--}35.4 \text{ psu}$] and that the EICC water flowing along its east side originates in the BoB and exhibits its salinity as low as $33.7\text{--}33.8 \text{ psu}$.)

The main features of turbulence in the SMC somewhat resemble the observations in the northern BoB (Figures 2–4), where turbulence was mostly confined to the surface mixed layer, which is detached from interior water by a strong barrier layer. In the BoB pycnocline, however, only a small number of patches with ϵ exceeding $10^{-8} \text{ W kg}^{-1}$ were observed, but there was patchy intermittent turbulence in the pycnocline along the entire WS section above $z \sim 75 \text{ m}$ (Figure 5a). At distances of 20–40 km from the Sri Lankan coast, the dissipation patches were present at all depths where turbulence is likely to be sustained by the instability of radiative internal waves generated at the shelf break. In situ measurements of internal waves in Sri Lankan waters are currently underway (Wijesekera et al., in press). A more speculative possibility is that advection and regeneration of shear-induced turbulence in the interior water could also be in play. This is similar to the shelf-generated patches of turbulence as exemplified by Phillips et al. (1986) using laboratory experiments. Note that Lozovatsky et al. (2012) reported topographically induced turbulence at a distance greater than 15 km from the source; this turbulence was advected downstream by

strong currents and sustained along the way by shear instability (flow behind Baker Island in the western Pacific).

The spatial structure of the dissipation rate appears to be quite different along the TS (Figure 5b). The turbulent patches with $\epsilon > 10^{-8} \text{ W kg}^{-1}$ occupy the EICC at all depths (up to $\sim 40 \text{ km}$ from the coast). East of the EICC, the high turbulence is mostly confined within a very narrow and sharply sloping upper pycnocline, which starts 16 km from the coast at $z = 35\text{--}40 \text{ m}$ and crops out at the sea surface about 80 km offshore (Figure 5b), and in the lower secondary pycnocline at depths of $z = 70\text{--}80 \text{ m}$. The most probable source of this turbulence is strong shear instability at narrow interfaces (e.g., Strang and Fernando, 2001). Indeed, we detected a layer of strong shear (Figure 5c), $Sh > (2\text{--}3) \times 10^{-2} \text{ s}^{-1}$, that coincided with the secondary pycnocline centered at $z = 75 \text{ m}$, ensuring sporadic generation of the high-level of turbulence shown in Figure 5b.


CONCLUSIONS: SPATIAL PATTERNS OF MIXING IN THE BAY OF BENGAL

The first measurements of TKE dissipation rate ϵ in the northern BoB and adjacent waters around Sri Lanka provide an initial glimpse into mixing in the BoB. From these data, we gather a consistent picture of the patterns of mixing, as summarized by the profiles in Figure 1. Most striking is the general finding that the dissipation rate is extremely weak ($\sim 10^{-9} \text{ W kg}^{-1}$) below $\sim 20\text{--}30 \text{ m}$ depths, except during rare storm events. We also observe a general trend that the deep dissipation rates are weaker to the north, where surface stratification is strongest, and increases southward, where near-surface stratification is reduced. These observations lead to the general conclusion that turbulence in the northern BoB is largely influenced by details of the very thin, near-surface layer that is controlled by monsoon rainfall and river inflow and the complex meso- and submesoscale motions that advect it (MacKinnon et al.,

2016, in this issue). More specific conclusions of this study are:

1. Very strong stratification in the sharp BoB pycnocline can damp wind-induced mixing almost completely, preventing penetration of turbulence below a thin, lower-salinity mixed surface layer (MLD $< 15\text{--}20 \text{ m}$). Under moderate winds ($W_a \sim 11\text{--}12 \text{ m s}^{-1}$), the surface layer is effectively decoupled from the thermohalocline, but horizontal/temporal gradients of T and S still exist above the MLD. Under stronger winds ($W_a \sim 16\text{--}18 \text{ m s}^{-1}$), the homogeneous mixed layer deepens only slightly (Figure 1c), but is still largely decoupled from the pycnocline. The horizontal/temporal gradients of T , S , and specific potential density in the surface layer almost completely vanish, possibly due to enhanced wind stirring.
2. The northern BoB is characterized by shallow and very sharp density fronts, which at times resemble thin gravity currents with strongly turbulent heads. Turbulence observations across fronts made in both 2013 and 2015 indicate enhanced mixing associated directly with gravity current shear. Below the low-salinity near-surface frontal features, turbulence is enhanced, possibly as a result of strain induced by the overlying dynamics, leading to dissipation rates as high as $5 \times 10^{-8} \text{ W kg}^{-1}$ down to depths of almost 50 m in 2013. In the pycnocline, turbulence is sharply reduced, with ϵ reduced to less than $10^{-9} \text{ W kg}^{-1}$.
3. Substantial deepening of the surface layer south of Sri Lanka during the winter monsoon was detected (the MLD deepens to 60 m in February compared to $\sim 30\text{--}40 \text{ m}$ in April). The forcing gradually relaxes toward the transition period.
4. The spatial structure of the dissipation rate is quite different along meridional and zonal transects made to the south (WS) and to the east (TS) of Sri Lanka that cross the SMC and the EICC. The main features of turbulence

in the SMC resemble the observations in the northern BoB, where turbulence is mostly confined to the surface mixed layer, which is detached from waters below it by a strong pycnocline. However, coastal bathymetry influences pycnocline turbulence in the northern part of the WS, where turbulent patches may be related to internal waves generated at the shelf break.

5. In contrast to turbulence in the SMC, high-level dissipation that occurs along the TS (east of the EICC) is mostly confined within a very narrow and sharply sloping upper pycnocline, which starts at $z = 35\text{--}40$ m near the coast and crops out at the sea surface about 80 km offshore. The most probable source of such turbulence is strong shear instability at narrow interfaces, which is documented by ADCP data in the lower secondary pycnocline at the depths $z = 70\text{--}80$ m. 

REFERENCES

- Akhil, V.P., F. Durand, M. Lengaigne, J. Vialard, M.G. Keerthi, V.V. Gopalakrishna, C. Deltel, F. Papa, and C. de Boyer Montégut. 2014. A modeling study of the processes of surface salinity seasonal cycle in the Bay of Bengal. *Journal of Geophysical Research* 119(6):3,926–3,947, <http://dx.doi.org/10.1002/2013JC009632>.
- de Vos, A., C.B. Pattiaratchi, and E.M.S. Wijeratne. 2014. Surface circulation and upwelling patterns around Sri Lanka. *Biogeosciences* 11:5,909–5,930, <http://dx.doi.org/10.5194/bg-11-5909-2014>.
- Gregg, M.C. 1999. Uncertainties and limitations in measuring ϵ and χ_T . *Journal of Atmospheric and Oceanic Technology* 16:1483–1490, [http://dx.doi.org/10.1175/1520-0426\(1999\)016<1483:UALIMA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0426(1999)016<1483:UALIMA>2.0.CO;2).
- Girishkumar, M.S., M. Ravichandran, M.J. McPhaden, and R.R. Rao. 2011. Intraseasonal variability in barrier layer thickness in the south central Bay of Bengal. *Journal of Geophysical Research* 116, C03009, <http://dx.doi.org/10.1029/2010JC006657>.
- Jensen, T.G. 2001. Arabian Sea and Bay of Bengal exchange of salt and tracers in an ocean model. *Geophysical Research Letters* 28(20):3,967–3,970, <http://dx.doi.org/10.1029/2001GL013422>.
- Jensen, T.G. 2003. Cross-equatorial pathways of salt and tracers from the northern Indian Ocean: Modelling results. *Deep Sea Research Part II* 50(12):2,111–2,127, [http://dx.doi.org/10.1016/S0967-0645\(03\)00048-1](http://dx.doi.org/10.1016/S0967-0645(03)00048-1).
- Kunze, E., E. Firing, J.M. Hummon, T.K. Chereskin, and A.M. Thurnherr. 2006. Global abyssal mixing inferred from lowered ADCP shear and CTD strain profiles. *Journal of Physical Oceanography* 36(8):1,553–1,576, <http://dx.doi.org/10.1175/JPO2926.1>.
- Lee, C.M., S.U.P. Jinadasa, A. Anutaliya, L.R. Centurioni, H.J.S. Fernando, V. Hormann, M. Lankhorst, L. Rainville, U. Send, and H.W. Wijesekera. 2016. Collaborative observations of boundary currents, water mass variability, and monsoon response in the southern Bay of Bengal. *Oceanography* 29(2):102–111, <http://dx.doi.org/10.5670/oceanog.2016.43>.
- Liu, Z., H. Wei, I.D. Lozovatsky, and H.J.S. Fernando. 2009. Late summer stratification and turbulence in the Yellow Sea. *Journal of Marine Systems* 77:459–472, <http://dx.doi.org/10.1016/j.jmarsys.2008.11.001>.
- Lozovatsky, I., J.-H. Lee, H.J.S. Fernando, S.K. Kang, and S.U.P. Jinadasa. 2015. Turbulence in the East China Sea: The summertime stratification. *Journal of Geophysical Research* 120:1,856–1,871, <http://dx.doi.org/10.1002/2014JC010596>.
- Lozovatsky, I., Z. Liu, H.J.S. Fernando, J. Armengol, and E. Roget. 2012. Shallow water tidal currents in close proximity to the seafloor and boundary-induced turbulence. *Ocean Dynamics* 62:177–201, <http://dx.doi.org/10.1007/s10236-011-0495-3>.
- Lucas, A.J., E.L. Shroyer, H.W. Wijesekera, H.J.S. Fernando, E. D'Asaro, M. Ravichandran, S.U.P. Jinadasa, D. Sengupta, J.A. MacKinnon, J.D. Nash, and others. 2014. Mixing to monsoons: Air-sea interactions in the Bay of Bengal. *Eos, Transactions American Geophysical Union* 95:269–276, <http://dx.doi.org/10.1002/2014EO300001>.
- MacKinnon, J.A., J.D. Nash, M.H. Alford, A.J. Lucas, J.B. Mickett, E.L. Shroyer, A.F. Waterhouse, A. Tandon, D. Sengupta, A. Mahadevan, and others. 2016. A tale of two spicy seas. *Oceanography* 29(2):50–61, <http://dx.doi.org/10.5670/oceanog.2016.38>.
- Mukherjee, A., D. Shankar, V. Fernando, P. Amol, S.G. Aparna, R. Fernandes, G.S. Michael, S.T. Khalap, N.P. Satelkar, Y. Agarvadekar, and others. 2014. Observed seasonal and intraseasonal variability of the East India Coastal Current on the continental slope. *Journal of Earth System Science* 123(6):1,197–1,232, <http://dx.doi.org/10.1007/s12040-014-0471-7>.
- Phillips, O.M., J.H. Shyu, and H. Salmun. 1986. An experiment on boundary mixing: Mean circulation and transport rates. *Journal of Fluid Mechanics* 173:473–499, <http://dx.doi.org/10.1017/S0022112086001234>.
- Pollard, R.T., P.B. Rhines, and R. Thompson. 1972. The deepening of the wind-mixed layer. *Geophysical Fluid Dynamics* 4(1):381–404, <http://dx.doi.org/10.1080/03091927208236105>.
- Roget, E., I. Lozovatsky, X. Sanchez, and M. Figueroa. 2006. Microstructure measurements in natural waters: Methodology and applications. *Progress in Oceanography* 70:123–148, <http://dx.doi.org/10.1016/j.pocean.2006.07.003>.
- Sarkar, S., H.T. Pham, S. Ramachandran, J.D. Nash, A. Tandon, J. Buckley, A.A. Lotliker, and M.M. Omand. 2016. The interplay between submesoscale instabilities and turbulence in the surface layer of the Bay of Bengal. *Oceanography* 29(2):146–157, <http://dx.doi.org/10.5670/oceanog.2016.47>.
- Sengupta, D., G.N. Bharath Raj, M. Ravichandran, J. Sree Lekha, and F. Papa. 2016. Near-surface salinity and stratification in the north Bay of Bengal from moored observations. *Geophysical Research Letters* 43(8):1–9, <http://dx.doi.org/10.1002/2016GL068339>.
- Shetye, S.R. 1993. The movement and implications of the Ganges-Brahmaputra runoff on entering the Bay of Bengal. *Current Science* 64(1):32–38.
- Shetye, S.R., A.D. Gouveia, D. Shankar, S.S.C. Shenot, P.N. Vinayachandran, D. Sundar, G.S. Michael, and G. Nampoothiri. 1996. Hydrography and circulation in the western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research* 101:14,011–14,025, <http://dx.doi.org/10.1029/95JC03307>.
- Strang, E.J., and H.J.S. Fernando. 2001. Entrainment and mixing in stratified shear flows. *Journal of Fluid Mechanics* 428:349–386, <http://dx.doi.org/10.1017/S0022112000002706>.
- Turner, J.S. 1973. *Buoyancy Effects in Fluids*. Cambridge University Press, 368 p.
- Vinayachandran, P.N., D. Shankar, S. Vernekar, K.K. Sandeep, P. Amol, C.P. Neema, and A. Chatterjee. 2013. A summer monsoon pump

to keep the Bay of Bengal salty. *Geophysical Research Letters* 40:1,777–1,782, <http://dx.doi.org/10.1002/grl.50274>.

- Whalen, C.B., L.D. Talley, and J.A. MacKinnon. 2012. Spatial and temporal variability of global ocean mixing inferred from Argo profiles. *Geophysical Research Letters* 39(18), L18612, <http://dx.doi.org/10.1029/2012GL053196>.
- Wijesekera, H.W., T.G. Jensen, E. Jarosz, W.J. Teague, E.J. Metzger, D.W. Wang, S.U.P. Jinadasa, K. Arulananthan, L. Centurioni, and H.J.S. Fernando. 2015. Southern Bay of Bengal currents and salinity intrusions during a fall monsoon transition. *Journal of Geophysical Research: Oceans* 120(10):6,897–6,913, <http://dx.doi.org/10.1002/2015jc010744>.
- Wijesekera, H.W., E. Shroyer, A. Tandon, M. Ravichandran, D. Sengupta, S.U.P. Jinadasa, H.J.S. Fernando, N. Agrawal, K. Arulananthan, G.S. Bhat, and others. In press. ASIRI: An ocean-atmosphere initiative for Bay of Bengal. *Bulletin of the American Meteorological Society*, <http://dx.doi.org/10.1175/BAMS-D-14-00197.1>.
- Zilitinkevich, S., I. Esau, and A. Baklanov. 2007. Further comments on the equilibrium height of neutral and stable planetary boundary layers. *Quarterly Journal of the Royal Meteorological Society* 133:265–271, <http://dx.doi.org/10.1002/qj.27>.

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AUTHORS

S.U.P. Jinadasa is Head of Division and Principal Scientist, National Aquatic Resources Research and Development Agency, Crow Island, Colombo, Sri Lanka. **Iossif Lozovatsky** (i.lozovatsky@nd.edu) is Research Professor, Department of Civil & Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN, USA. **Jesús Planella-Morató** is Visiting Researcher, University of Notre Dame, Notre Dame, IN, USA, and Adjunct Professor, Department of Physics, University of Girona, Girona, Spain. **Jonathan D. Nash** is Professor, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. **Jennifer A. MacKinnon** is Professor, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA. **Andrew J. Lucas** is Assistant Research Oceanographer, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA. **Hemantha W. Wijesekera** is Oceanographer, US Naval Research Laboratory, Stennis Space Center, MS, USA. **Harinda J.S. Fernando** is the Wayne and Diana Murdy Endowed Professor, Department of Civil & Environmental Engineering & Earth Sciences, and Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN, USA.

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