Mesoscale Dynamics, Lateral and Vertical Mixing in China Seas and Western Pacific

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LONG TERM GOAL

The long-term goal of our research program is to understand and parameterize links between background forcing and ensuing mesoscale and small-scale features of oceanic dynamics, with emphases on lateral and vertical mixing.

OBJECTIVES

The objectives of the project during 2010 (April 1 – September 30) were:

(i) to conduct measurements of turbulence in the Luzon Strait and adjacent waters of South China Sea (SCS),

(ii) to analyze the distribution of turbulent kinetic energy (TKE) dissipation rate in different areas of SCS and estimate the contributions of pycnocline and BBL to the dissipation on the shelf, and

(iii) to continue investigations on the dissipation rate very near the ocean floor, and in the region of Changjiang Diluted Water (CDW) of Yangtze River of the East China Sea.

APPROACH

Analysis of field data collected in previous years in ECS and SCS and obtaining of new data in the SCS during the 2010 research cruises of Xiamen University (China P.R.) with Dr. Hu as the Chief Scientist and Dr. Z. Liu (MSS measurements) as the Team Leader.

WORK COMPLETED

During the first 6 months of the project our collaborators at XMU conducted a research cruise in SCS, where 14 stations of microstructure measurements were taken along 3 meridianal transects (one section with 6 stations was taken across the Luzon Strait and two other transects were taken ~ 30 and 60 miles to the west (see Fig. 1).

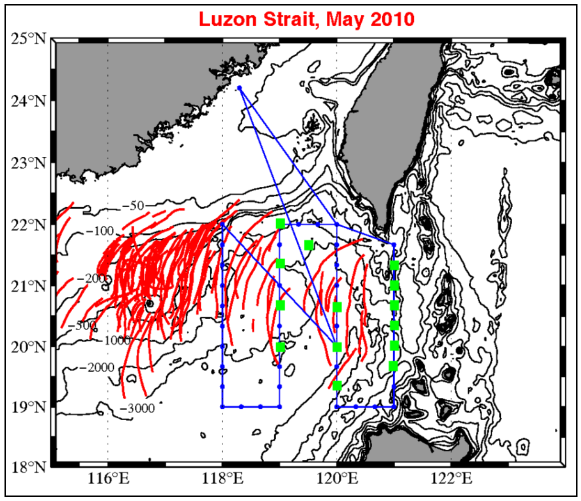

Fig. 1. Stations with MMS measurements (green circles) taken during the XMU cruise in May 2010. The distributions of internal wave signatures in SAR images for spring time is shown in the background by red lines [adopted from Huang et al. 2008].

The averaged dissipation rate in the upper pycnocline of SCS has been analyzed and compared with the potential energy content of internal waves (IW) on the shelf, in the central part of SCS and in the Luzon Strait.

The influence of a remote small seamount on the increase of turbulent dissipation in the BBL on the shelf was suggested and scrutinized.

RESULTS

A. Dissipation Rate in the Pycnocline and BBL of SCS

Using the microstructure data obtained by XMU in 2009 and 2010 cruises in SCS, the TKE dissipation rate ε was computed following a well-established procedure for MSS measurements [Liu et al. 2009]. Spectral densities of the denoised, interpolated small-scale shear signal of the airfoil probe were fitted with the Nasmyth spectrum at every 1-m segment of the vertical profile. The dissipation rate profiles $\varepsilon(z)$ along one of the year 2009 sections (yellow-dashed line in Fig. 2) are shown in Fig. 3. Note enhanced intermittent turbulence in the upper ~ 100 m, which is presumably linked to the interaction of tidally-induced IW with topography, extending ~ 300 km offshore. The corresponding level of vertical mixing over this distance, depicted in Fig. 3b based on the eddy diffusivity $K_N = 0.2(\varepsilon/N^2)$, is elevated by an order of magnitude compared to its background level ($\approx 10^{-5}$ m^2/s) of deep oceans and of the central basin of SCS (see S504 and S506).

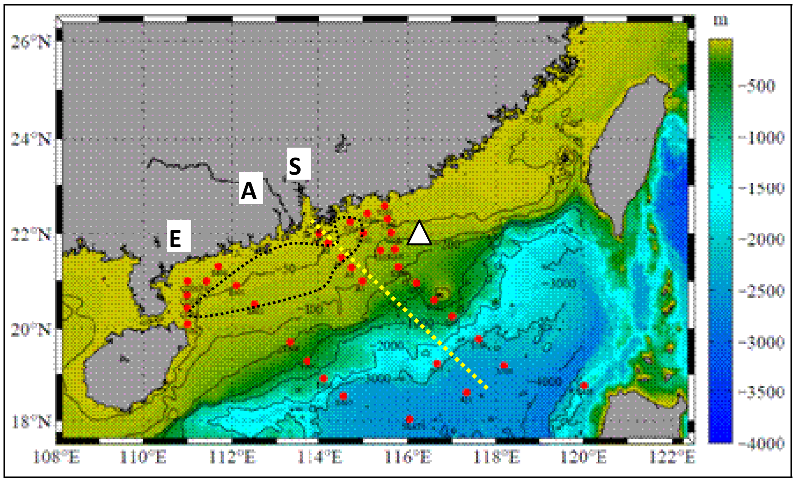

Fig.2. Stations of the XMU cruise taken in SCS in July 2009. Three longest across shelf sections are marked E, A, and S, and the triangle is the measurement site of St Laurent [2008].

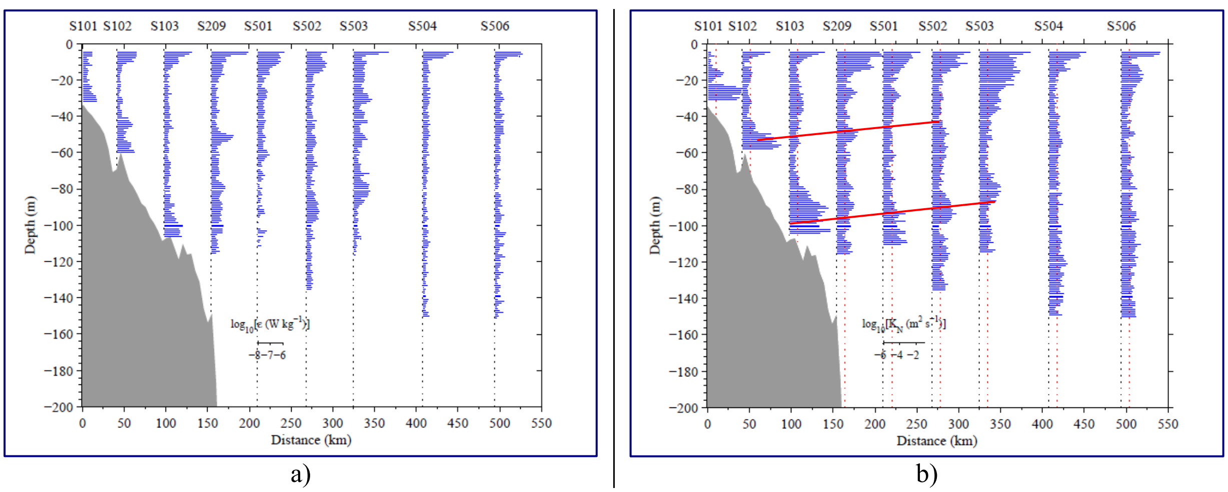

Fig.3.The dissipation rate $\varepsilon(z)$ (left) and the diffusivity $K_N(z)$ (right) profiles, respectively, along the section S highlighted in Fig. 2. The red lines in b) indicate enhanced mixing along a possible ray of internal waves reflected from the shelf break [Lien and Gregg 2001].

It has been shown [St Laurent 2008] that IW of various periods control the level of TKE dissipation rate on the SCS shelf margin north from the Dongsha Plateau (see Fig. 2). Our new measurements on the SCS shelf, in the deep basin, and in the Luzon Strait allowed analysis of dissipation rate over a vast area of the sea. Because the dissipation rate profiles were obtained in a limited depth range (z_{max} = 160 m), we calculated the averaged $\langle\varepsilon_p\rangle$ at a majority of the stations in the pycnocline (from the upper boundary of BBL up to the lower boundary of the upper mixed layer). The thickness of the pycnocline segments varied between 20 and 128 m, 72 m being the average). In addition, the integrated dissipation rate was calculated separately in the pycnocline and BBL at 7 relatively deep (z_B = 72 - 109 m) shelf stations encircled by the black-dashed line in Fig. 2. The map of $\langle\varepsilon_p\rangle$ (blue filled circles) is shown in Fig. 4.

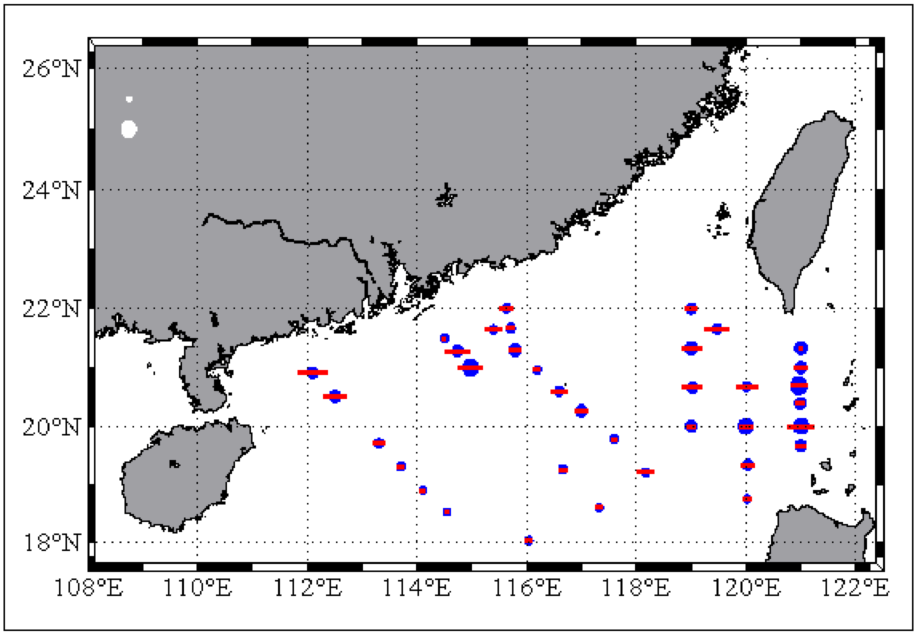

Fig. 4. The averaged dissipation rate <ε_p> (blue circles) and the estimates of APE of internal waves per unit mass (red horizontal bars) in the upper pycnocline of SCS. The dissipation rate is scaled between 2.4×10^{-8} ***and*** 1.3×10^{-7} ***m^2/s^3 and APE is between*** 1.3×10^{-4} ***and*** 10^{-3} ***m^2/s^2.***

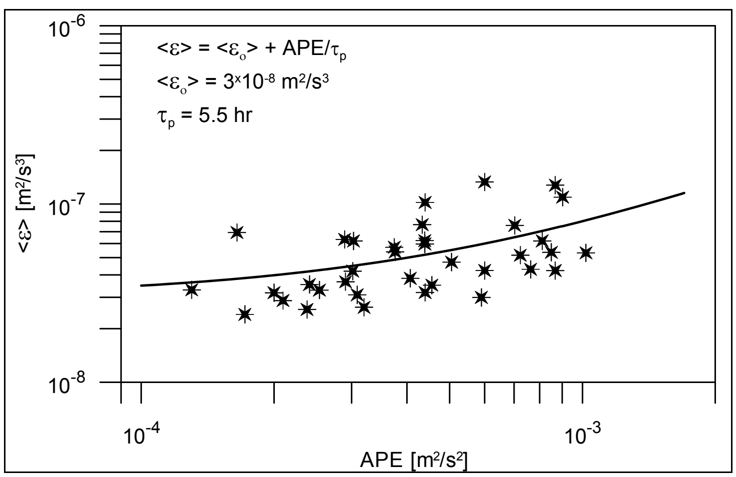

Fig. 5. The averaged dissipation rate in the pycnocline of SCS as a function of available potential energy; τ_p is a characteristic dissipation time of APE.

The enhanced level of dissipation in the pycnocline is observed in and near the Luzon Strait and at the shelf break. A comparison of <ε_p> with the rough estimates of the averaged Richardson numbers in the same layers (based on a shipboard ADCP shear at dz = 8 m) revealed a general trend of decreasing <ε_p> with increasing <Ri> but did not show a substantial correlation between the two variables, suggesting that relatively large scale shear instability may establish background turbulence in the SCS pycnocline but it may not generate powerful turbulent events. Degenerating internal waves of various scales appear to be a more dominant contributor of turbulent energy there. We calculated the available potential energy per unit mass APE = $0.5\widetilde{N}^2\eta^2$ based on linear IW theory, where $\widetilde{N}$ and $\eta = rms(\rho')/(\partial\widetilde{\rho}/\partial z)$ are the averaged buoyancy frequency and vertical *rms* displacements, respectively (density fluctuations ρ' were evaluated by high-pass filtering of individual density profiles). The larger circles in Fig. 4 (higher $<\varepsilon_p>$) generally coincide with larger values of APE (red bars). The regression of $<\varepsilon_p>$ with APE shown in Fig. 5 suggests that IW energy in the pycnocline may elevate the dissipation level above its background value of ~ 3×10^{-8} m^2/s^3. If the IW energy in SCS is approximately equi-partitioned between the potential and kinetic energies [St Laurent 2008], then the dissipation time scale τ_{IW} should be about $2\tau_p \approx$ 11-12 hrs, approaching a period of semidiurnal internal tide.

The ratio between integrated dissipation rate in the pycnocline on the shelf (a baroclinic source of TKE, most probably due to IW) and BBL (predominantly barotropic tide) varied between 0.6 and 2.5, with a mean value of 1.6 for six of the seven stations encircled in Fig. 2. This indicates that powerful internal waves arriving onshore from the deep basin (see Fig. 1) substantially contribute to the integrated dissipation rate of turbulent energy on the shelf of SCS. Detailed analysis of data are continuing.

B. The Influence of a Topographic Feature on the Near-Bottom Turbulence in the Far Field (CDW Shelf of the East China Sea)

In 2009 [Lozovatsky and Fernando 2009], we analyzed the profiles of TKE dissipation rate measured in the Changjiang (Yangtze River) Diluted Water of the East China Sea (CDW region: λ = 30°49'N, φ = 122°56'E; the mean depth H_B = 38 m).

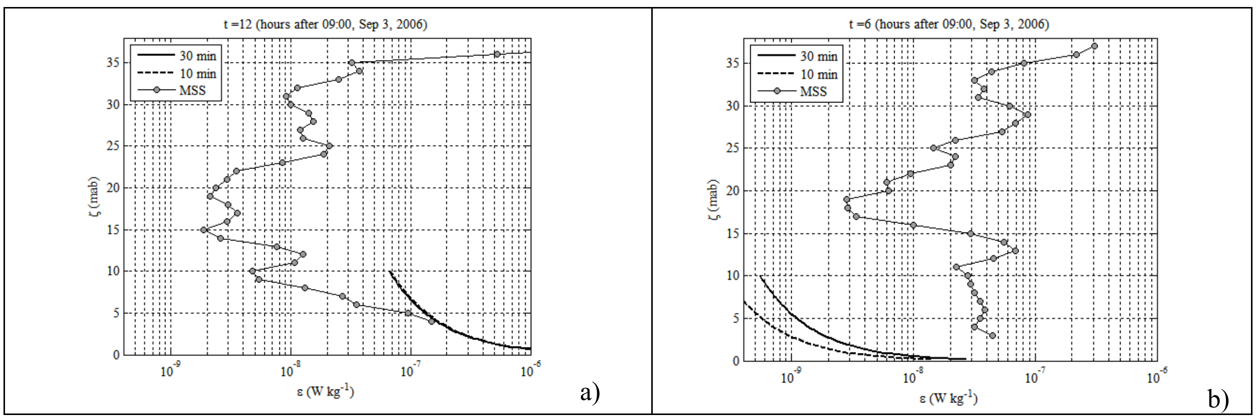

Fig. 6. The MMS dissipation profiles $\varepsilon_{mc}(\zeta)$ and the law-of-the-wall profiles $\varepsilon_b(\zeta)$ for the across-slope eastern (a) and western (b) flow (τ_{avr} = 30 and 10 min).

The microstructure (MSS) profiles $\varepsilon_{mc}(\zeta)$ were compared with those $\varepsilon_{wl}(\zeta)$ deduced from the law of the wall u_* estimates based on near-bottom ADCP data. It was found that in general, $\varepsilon_{wl}(\zeta)$ intersects with $\varepsilon_{mc}(\zeta)$ at ζ = 2 – 5 mab, suggesting the applicability of the law of the wall in shallow tidal-affected waters when averaged over about 30 min (see an example in Fig. 6a). However, when turbulence in the BBL is influenced by other external sources, in addition to local friction, the level of dissipation can be substantially higher compared to $\varepsilon_{wl}(\zeta)$; this was observed during the upslope phase of westerly directed tidal current (Fig. 6b). We hypothesized that internal waves and turbulence generated at the summit and flanks of a topographic rise to the east of the observational point may be responsible for the increased level of dissipation rate in the BBL ~ 15 km away on the shelf. For simplicity, we refer to this topographic rise as a small seamount (the summit is at 25 m in a 50 m deep water). To substantiate this hypothesis, the depth (*H*) integrated internal tide generating body force [Baines 1982] $F = \frac{\vec{Q}}{\omega_T} \nabla \frac{1}{H} \int_0^H N^2 z dz$ was calculated (ω_T is the tidal frequency and $\check{Q} = (hu_T, hv_T)$ the barotropic tidal transport); internal tides and non-linear internal waves can be actively generated in the areas where $\boldsymbol{F} > 0.25$ m^2/s^2 [da Silva et al. 2007; Green et al. 2008].

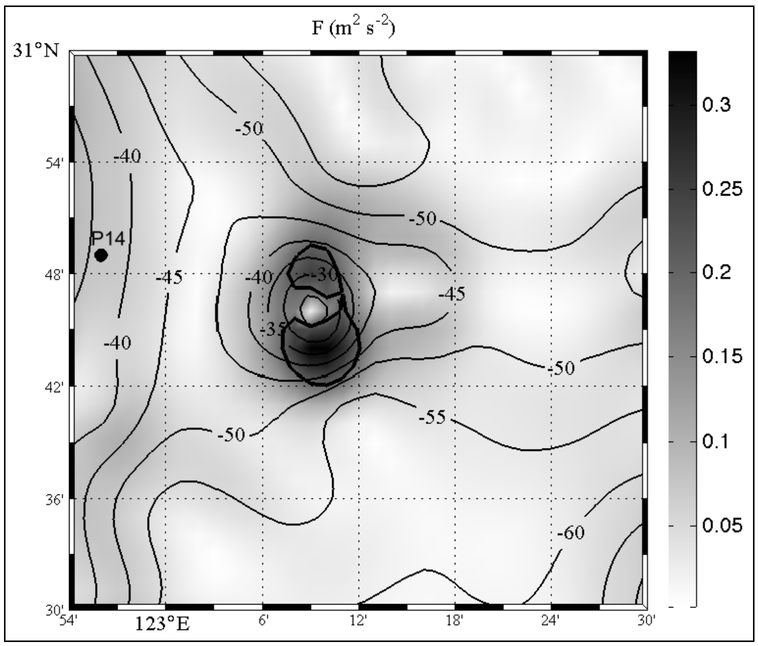

Fig. 7. Local bathymetry and the internal tide generating body force F near and to the east of the point of measurements (P14); F > 0.25 m^2/s^2 is encircles the small seamount.

As shown in Fig. 7, internal waves can be generated over the flanks of the seamount, advecting (together with the westward directed tidal current) topographically induced turbulence to the point of observations (P14) while generating new turbulence [Liu et al. 2009] by solitons and NLIW packets. This may explain enhanced dissipation (Fig. 6b) at the observational site during a specific phase [Lee et al. 2006] of the barotropic tide.

IMPACT/APPLICATION

Our research program involves fruitful collaboration between the US, Chinese and Korean scientists as well as other international groups. A joint paper on intermittency of turbulence was published in 2010 in the Journal of Geophysical Research, coauthored by our collaborators from Catalonia and China. Another paper on near-bottom turbulence in the CDW region of ECS is under revision for Continental Shelf Research. A paper on the study of turbulence in SCS is in preparation for submission to Journal of Oceanography. The co-PI Zhiyu Liu (China) visited University of Notre Dame in September and conducted joint work with PI Lozovatsky, who will be visiting Xiamen University later this year to arrange a field experiment in Xiamen Bay.

TRANSITIONS

None

RELATED PROJECTS

The Co-P.I. Fernando is involved in another ONR funded project dealing with laboratory investigations of submarine wakes in stratified fluids funded by the ONR turbulence program.

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