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

Iossif Lozovatsky and H.J.S. Fernando
University of Notre Dame
Department of Civil Engineering and Geological Sciences,
Notre Dame, IN 46556
Tel: 574-631-3052, 574-631-5380;
e-mail: i.lozovatsky@nd.edu and Fernando.10@nd.edu

Grant Number: N00014-10-1-0738

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 2011 were:

(i) to study lateral variability of the turbulent kinetic energy (TKE) dissipation rate in the northern part of the South China Sea (SCS), particularly in relation to the characteristic of internal waves in the region, and

(ii) to conduct new measurements of turbulence and currents in shallow waters of SCS for the purposes of further studies on lateral mixing and to develop a comprehensive database for the region

APPROACH

Analysis of field data collected in 2009 and 2010 in SCS during the research cruises of Xiamen University (China P.R.), with Dr. Hu as the Chief Scientist and Dr. Z. Liu as the Team Leader and obtaining of new data in shallow waters during a special coastal experiment

WORK COMPLETED

A. Xiamen Bay Experiment

In March 2011, PI Lozovatsky visited Xiamen University (XMU) to work closely with our Chinese collaborators in analyzing data previously collected in SCS and to organize a pilot coastal experiment in Xiamen Bay. On March 17-19, the MSS-60 microstructure measurements were conducted for 50 hrs from an anchored small research vessel of XMU (Chief Scientist: Dr. Z. Liu) in conjunction with a

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Mesoscale Dynamics, Lateral and Vertical Mixing in China Seas and Western Pacific**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Notre Dame,Department of Civil Engineering and Geological Sciences,Notre Dame,IN,46556**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

shipboard mounted ADCP and three bottom-mounted ADCPs. The measurement sites S1, S2, S3 and S4 (Fig. 1) were setup within a circle ~ 600 m in diameter located about 200 m to the south of the Gulangyu Island, which is a small island (~ 1.78 km^2) at the southwest corner of the Xiamen Island. The mean water depth at the sites is about 20 m.

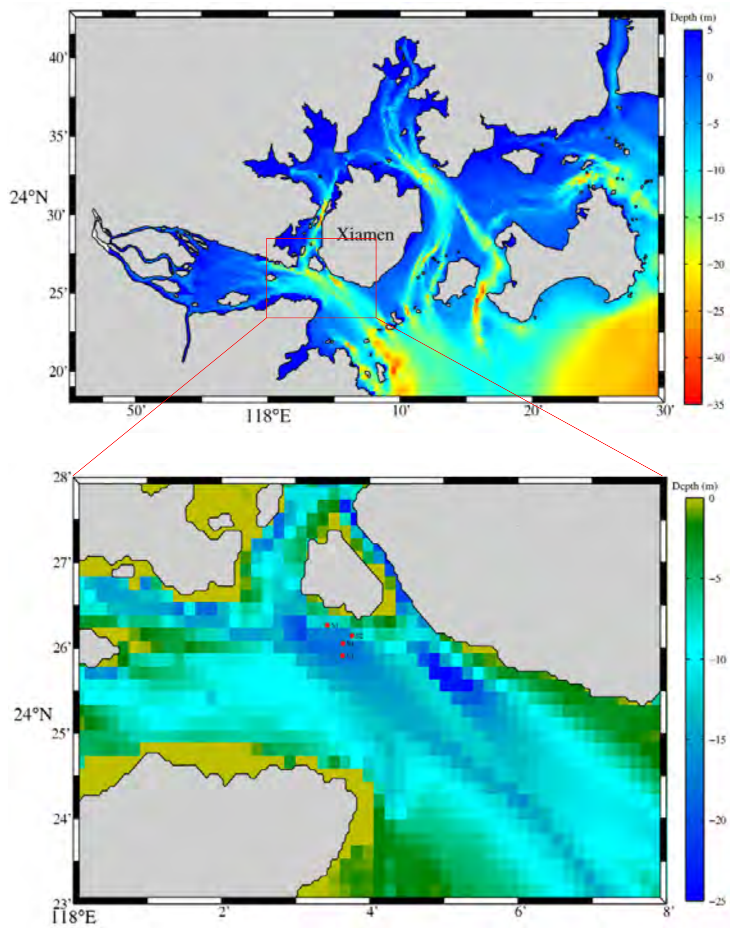

Fig. 1 Bathymetry around the Xiamen Island shown in meters above the theoretically lowest tide level. The measurement sites S1, S2, S3 and S4 are shown red bullets in the enlarged map. The measured mean water depths at S2, S3, and S4 are 19.4, 21.6 and 20.1 m.

At S4, the measurements were conducted using an MSS-60 microstructure profiler, while velocity vectors through the entire water column were measured by a 600 kHz shipboard ADCP. Mooring measurements were conducted at the other three sites, with along-beam velocity data collected by a 300 kHz (S1 and S2) and 600 kHz (S4) bottom-mounted ADCPs. The sampling intervals of the bottom-mounted and ship-mounted ADCPs were 2 s and 0.5 s, respectively. The vertical depth interval for the 600 kHz ADCPs is 0.5 m and for the 300 kHz ADCPs is 1 m.

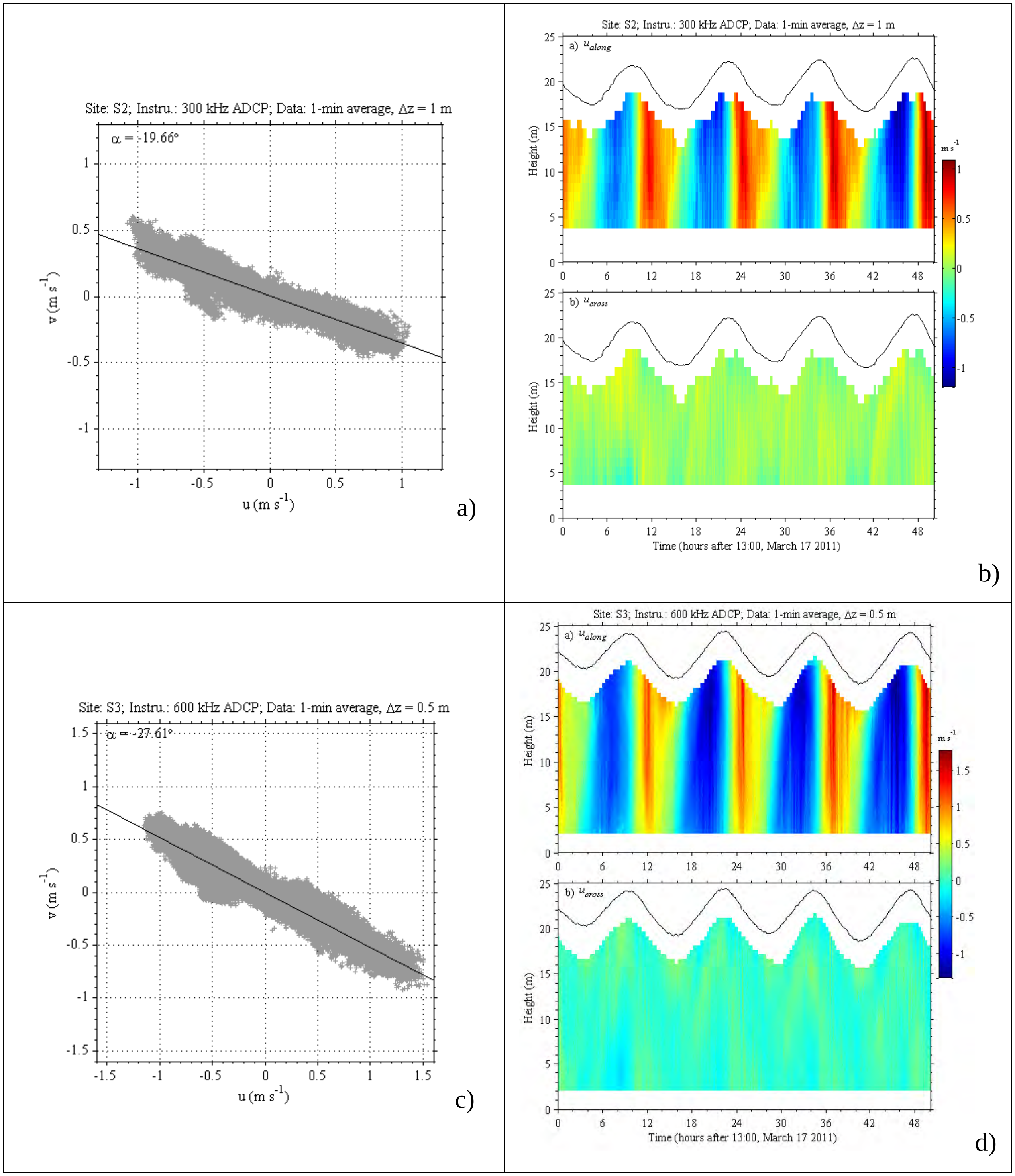

Fig. 2. Velocity measurements at S2 (a,b) and S3 (c,d). The "along channel" direction is determined by a best fit to the directions of the 1-min averaged velocity vector at all heights

Profiles of 1-min averaged ADCP velocity are shown in Fig. 2 for S2 and S3. The figure depicts a predominantly reversing tidal current (the range is 5.8 m) with northwest-southeast major axis approximately parallel to the isobaths and the southwestern coast of the Gulangyu Island. During the observational period, the tidal current amplitude exceeded 1 m s^{-1} at all sites. The tidal flow was almost symmetrical at S2 and S3, but at S3 a clear ebb-flood asymmetry was observed with amplitude up to1.5 m s^{-1}. Note that the 1-min averaged data obtained at S4 by the anchored ship-mounted 600 kHz ADCP are of the same high quality as the bottom-mounted ADCP data at the other two sites. This provides 50-hr continuous high-resolution velocity measurements at three closely located sites, with spacing between S2 and S4 and between S3 and S4 are almost identical ~ 260 m and between S2 and S3 is about 480 m, thus allowing analysis of lateral mixing at the scales of ~ 200 m. This work is in progress, and the results will be presented in a future report.

The tidal modulations of the dissipation rate ε at S4 are evident from Fig. 3.The high values of ε associated with near bottom-generated turbulence penetrate through the entire water column during the ebb and flood tides. During the observational period the barotropic tide transitioned from the neap to spring phase, showing an enhancement of ε over the transition period.

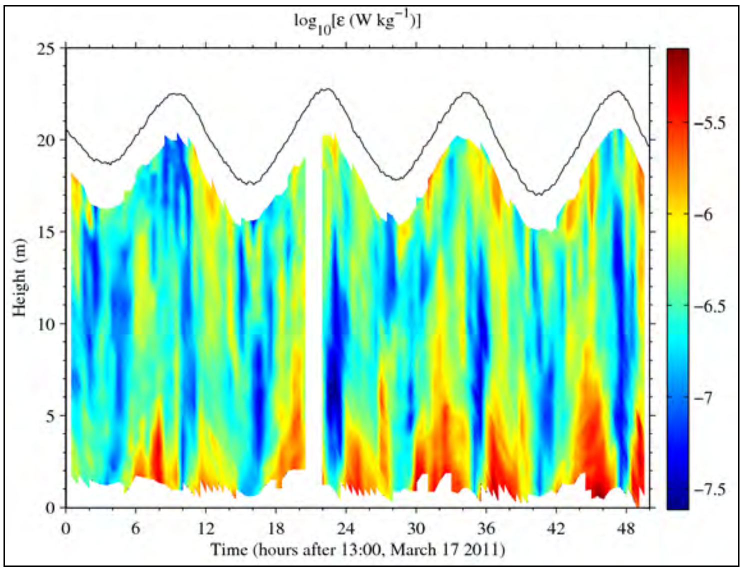

Fig. 3 The time-depth variation of the turbulent kinetic energy dissipation rate ε at S4.

During certain periods (e.g., t = 6 – 7 hrs) strong dissipation occurred in the mid-water column, possibly caused by shear instability of weakly stratified shear flow at the interface between the bottom and less saline surface waters. An analysis of the relationship between ε, buoyancy frequency and vertical and horizontal velocity shear is underway.

B. Dissipation in the Northern SCS

The averaged dissipation rates in the upper pycnocline of the northern SCS and the integrated dissipation on the Chinese shelf were analyzed and compared with the McKinnon and Gregg [2003] parameterization as well as local Richardson numbers. The energy dissipation of internal waves that propagate across the deep SCS basin west-northwest from the Luzon Strait creates regional asymmetry of the lateral distribution of ε. On the average, the dissipation rate in the upper pycnocline to the north of 20^{o}N is about two times larger than to the south of this latitude.

The influence of a remote bathymetric rise on the increase of turbulent dissipation in the BBL of the East China Sea shelf was also studied, and the results are now published in Lozovatsky et al. [2011].

RESULTS

The dissipation rate $\varepsilon(z)$ was measured at 38 stations in the northern SCS between 18^{o}N and 22.5^{o}N, and from the Luzon Strait to the eastern shelf of China using an MSS-60 microstructure profile during two research cruises of XMU. In 2009, the measurements were conducted at 24 stations in the western part of the basin and in 2010 at 14 stations in the eastern part of the northern SCS (see Fig. 4). The year 2009 data are supplemented by ship-board ADCP measurements with vertical resolution Δz = 8 m.

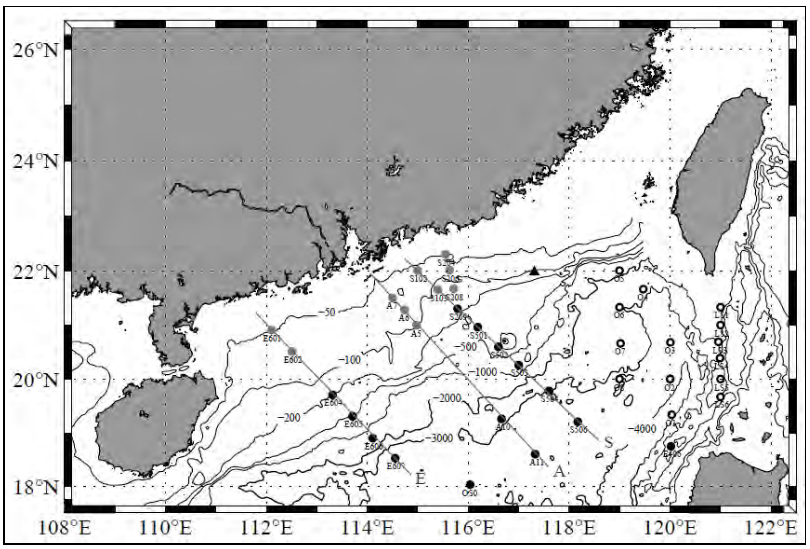

Fig.4. Stations of the year 2009 (July 25 – August 13, filled symbols) and 2010 (May 17 – 21, open symbols) cruises. Ten shelf stations that were selected to analyze the depth- integrated dissipation rate in the pycnocline and BBL are in grey.

The layer-averaged dissipation rate $\langle \varepsilon_p \rangle \triangleq \frac{1}{z_{end} - z_i} \int_{z_i}^{z_{end}} \varepsilon(z)dz$ were calculated in the upper pycnocline at the segments between z_i and z_{end} that specified the layers with approximately constant N^2. The length of these segments at the shallow shelf stations was prescribed to be at least 18 m; in deep waters it was about 100 m on the average because the ending depth of the casts did not exceed 160 m being limited by the length of tethered cable. In the Luzon Strait, we observed two major turbulent zones centered at $\varphi = 20.0^{o}$N and 20.7^{o}N that approximately coincided with the edges of a higher salinity lenses in the pycnocline. This points out on possible enhancement of lateral mixing in the vicinity of frontal zones between separate branches of the inflow of saline Pacific water through the Luzon Strait into SCS in the depth range ~ 80 - 120 m. The maximum averaged dissipation in the deep water pycnocline was observed in the center of the Luzon Strait, where $\langle \varepsilon_p \rangle^{max} = 1.3\times10^{-7}$ W/kg. Near the shelf break, the averaged dissipation $\langle \varepsilon_p \rangle$ was as high as 3×10^{-7} W/kg, which is several times larger than *in the pycnocline* on the shelf, where $\langle \varepsilon_p \rangle$ = $(3-6)\times10^{-8}$ W/kg.

It appears that the latitude 20^{o}N, which goes slightly to the south of the center of the Luzon Strait, roughly partitions the entire northern SCS basin to two regions with respect to the turbulence activity in the upper pycnocline. We found that at the deep-water stations, the averaged dissipation rate to the south of 20^{o}N was $\overline{\langle \varepsilon_p \rangle}^{south} = 3\times10^{-8}$ W/kg, but at 20^{o}N and to the north of it, the dissipation $\overline{\langle \varepsilon_p \rangle}^{north} = 6.7\times10^{-8}$ W/kg is more than two times larger.

The calculation of available potential energy of internal waves P_{IW} showed a positive linear correlation with $\langle \varepsilon_p \rangle$ of the same layers, and the characteristic dissipation time was $\tau_{IW} \sim P_{IW} / \langle \varepsilon_p \rangle$ about 5.5 hours. It is hypothesized that the observed disparities of the mean values of TKE dissipation in the upper pycnocline between the north and south of ~ 20^{o}N can be associated with the degeneration of internal waves originated in the Luzon Strait and propagated predominantly to the west-northwest.

The integrated pycnocline dissipation on the shelf $\hat{\varepsilon}_p$ contributes only 10-30% toward the total dissipation of the water interior below the surface layer (compare with St. Laurent [2008]), although we observed an episode with a total dissipation of 12 mW/m^2 equally partitioned between $\hat{\varepsilon}_p$ and $\hat{\varepsilon}_{BBL}$. It is hypothesized that this turbulence is induced by a solitary internal wave in the pycnocline. The dominant fraction of the tidal energy on SCS shelf dissipated in a 10 - 30 m height BBL, where $\hat{\varepsilon}_{BBL}$ was as high as 17-19 mW/m^2.

The estimated bin-averaged mean dissipation of upper pycnocline in the deep SCS basin showed a decreasing tendency with the Richardson number *Ri* as

$$\overline{\varepsilon} = \varepsilon_o + \frac{\varepsilon_m}{\left(1 + Ri/Ri_{cr}\right)^{1/2}} \quad . \tag{1}$$

Here $\varepsilon_o = 2.2\times10^{-8}$ W/kg is a relatively high background level of dissipation, which is not affected by the vertical scales of shear instability on the order of 8 m and larger, but most probably sustained by smaller scale processes. For this dataset, $\varepsilon_m = 7.8\times10^{-8}$ W/kg provides a maximum level of the dissipation $(\varepsilon_o + \varepsilon_m)$ in weakly $(Ri << Ri_{cr})$ stratified layers, where $Ri_{cr} = 0.25$ is a critical Richardson number. Note that Eq. (1) shows a relatively weak dependence of $\bar{\varepsilon}$ on *Ri* ($\sim Ri^{-1/2}$ at high *Ri*). As such $\bar{N}$ appears to play a dual role in the region, via large-scale internal waves and instabilities. This notion was checked using McKinnon-Gregg scaling

$$\varepsilon_{MG} = \varepsilon_o (N/N_o) \times (Sh/Sh_o), \qquad (2)$$

with application to pycnocline averaged dissipations $\langle \varepsilon_p \rangle$ and corresponding $\langle N_p \rangle$ and $\langle Sh_p \rangle$. It appears that for $\varepsilon < \sim 8 \times 10^{-8}$ W/kg, Eq. (2) does not contradict our data (see Fig. 5).

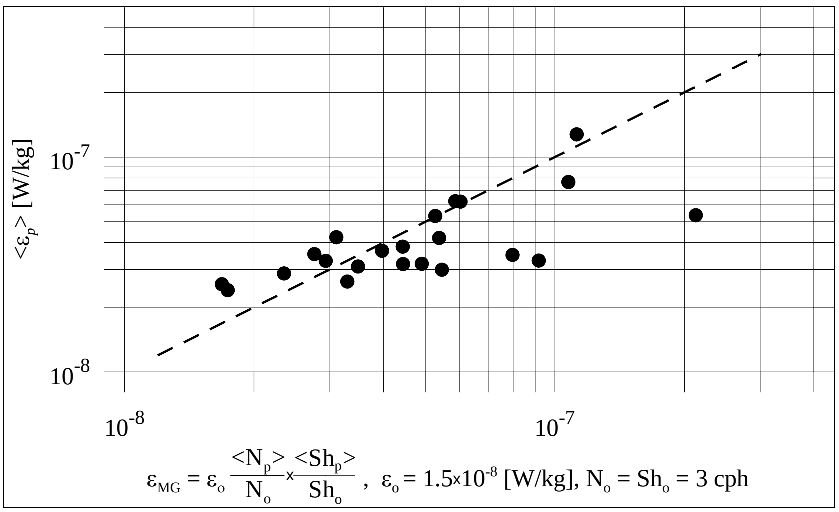

Fig. 5. The averaged dissipation rate in the pycnocline according to parameterization (2). The dashed line is for $\langle \varepsilon_p \rangle = \varepsilon_{MG}$ with the fitting parameter ε_o, which varies from the original formula. Here $\langle N_p \rangle$ and $\langle Sh_p \rangle$ are the averaged buoyancy frequency and low frequency shear.

It is suggested that in the SCS pycnocline, away from the Luzon Strait, a relatively high background level of turbulence on the order of 10^{-8} W/kg is generated by sustained internal-wave activity. The episodic dissipation rate enhancements can be associated with other processes such as solitary waves generated at the shelf brake.

IMPACT/APPLICATION

Our research program involves collaboration between the US, Chinese and Korean scientists as well as other international groups. A joint paper on turbulence patchiness is in press in the Journal of Geophysical Research and another paper on near-bottom turbulence in the CDW region of ECS is in press in the journal Ocean Dynamics, both co-authored by our Chinese and Catalonian collaborators. A paper on the study of turbulence in SCS is in preparation for submission to Journal of Marine Research. The PI Lozovatsky visited Xiamen University in March 2011 to conduct joint work with Dr. Zhiyu Liu (China).

TRANSITIONS

None

RELATED PROJECTS

The Co-P.I. Fernando is the PI of another ONR-PO funded project dealing with air-sea interactions in the Bay of Bengal during Indian Ocean Monsoons.

REFERENCES

Lozovatsky, I.D. and H.J.S. Fernando, "Mesoscale dynamics, lateral and vertical mixing in China Seas and Western Pacific", http://www.onr.navy.mil/reports/FY10/polozova.pdf, *ONR Annual Report* N00014-05-1-0245, 2010.

MacKinnon, J.A. and M.C. Gregg (2003): Mixing on the late-summer New England Shelf—solibores, shear, and stratification. *J. Phys. Oceanogr*., **33** (7), 1476-1492.

St. Laurent, L., "Turbulent dissipation on the margins of the South China Sea", *Geophys. Res. Lett*., **35**, L23615, doi:10.1029/2008GL035520, 2008.

PUBLICATIONS

Planella, J., E. Roget, ,and I. Lozovatsky,, "Statistics of microstructure patchiness in a stratified lake", *J. Geophys. Res*., 2011 (in press).

Lozovatsky, I., Z. Liu, H.J.S. Fernando, J. Armengol, and E. Roget, "Shallow water tidal currents in close proximity to the seafloor and boundary-induced turbulence". *Ocean Dynamics*. 2011 (in press).