Mixing, Internal Waves and Mesoscale Dynamics in the East China Sea

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Grant Number: N00014-05-1-0245

LONG TERM GOAL

The long-term goal of our research program is to better understand and quantify the relationships between mesoscale dynamics, internal waves, turbulence and topographic features of shallow, tidally-affected seas.

OBJECTIVES

The objectives of the project during 2008 were:

(i) to analyze the microstructure and velocity structure of the bottom boundary layer in the western (Chinese) sector of the East China Sea (ECS), focusing on the area influenced by Changjiang (Yangtze River) Diluted Water (CDW); continuing investigations on shear instability that leads to the generation of internal waves and turbulence in ECS. and

(ii) to conduct further observations and analysis on the genesis of high-frequency non-linear internal waves packets and associated turbulence in the south-eastern part of ECS near the ocean shelf break.

APPROACH

1. Analysis of field data collected in 2006 in ECS during research cruises of the Ocean University of China (OUC).

2. Conduct of a new field campaign, led by the Korean Ocean Research and Development Institute (KORDI) in ECS, between the Cheju Island and the ocean shelf break.

WORK COMPLETED

Field Campaigns

The new research cruise of KORDI was conducted during August 20 – 31, 2008 in the same region of ECS as the August 2007 cruise (Fig. 1). A CTD survey and microstructure measurements were carried out using a SeaBird instrument and TurboMAP microstructure profiler at the hydrographic stations

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2008**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Mixing, Internal Waves And Mesoscale Dynamics In The East China Sea

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)
Ira Fulton School of Engineering at Arizona State University,Center for Environmental Fluid Dynamics,Tempe,AZ,85287-9809

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
code 1 only

14. ABSTRACT
The long-term goal of our research program is to better understand and quantify the relationships between mesoscale dynamics, internal waves, turbulence and topographic features of shallow, tidallyaffected seas.

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)**	**9**	

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

shown in Fig. 1. During this cruise, an ADCP (RD 350 kHz) and two temperature-salinity mooring chains (CTR7 with five T/C sensors) were also deployed in the survey area.

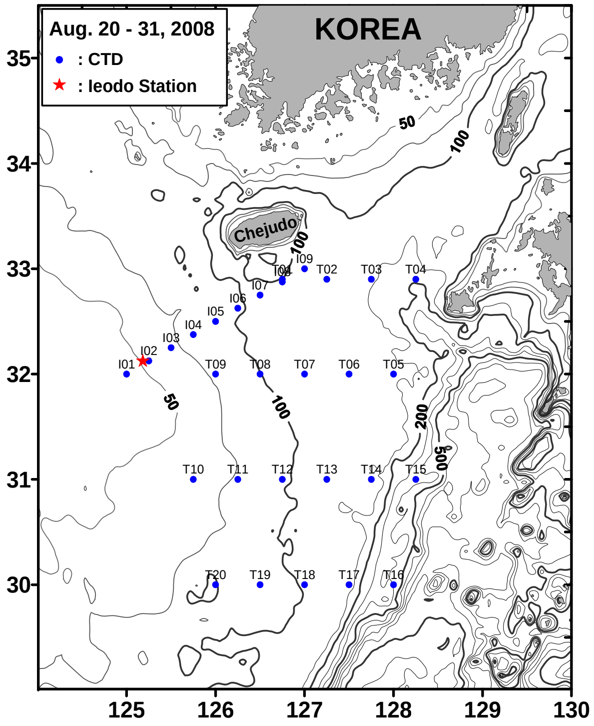


Fig. 1: The 2008 cruise of KORDI, August 20-31. The CTD stations were accompanied by TurboMap microstructure measurements.

The newly obtained data are now being processed and quality assured, and will be available for formal analysis shortly.

RESULTS

A. MICROSTRUCTURE IN THE CHANGJIANG (YANGTZE RIVER) DILUTED WATER

As has already been reported (Lozovatsky, I.D. and H.J.S. Fernando, Mixing, internal waves and mesoscale dynamics in the East China Sea, N00014-05-1-0245, *ONR Annual Report*, 2006: http://www.onr.navy.mil/ sci_tech/32/reports/po_06.asp), our subcontractor, OUC, conducted CTD, ADCP, ADV, and microstructure (MSS-60) measurements in ECS at a station in CDW (marked by a star in Fig. 2; λ = 30°49'N, φ = 122°56'E; the mean depth H_B = 38 m). Two successful periods of measurements that lasted 25 hours each (two semidiurnal tidal cycles) were completed during September 3 – 4 and September 7 – 8. On September 5 - 6, a tropical depression with winds up to 15 m/s interrupted the ship-based observations.

The barotropic tidal range during the first observational period was 1.5 m, increasing to 4 m during the second one. The barotropic tidal ellipses calculated using the OTIS software available through the Oregon State University website (http://www.oce.orst.edu/research/po/research /tide/ index.html) show a substantial increase of tidal flow amplitude during the second period of observations (see Fig. 3).

This led to an increase of turbulence, specifically in the bottom boundary layer (BBL), by more than an order of magnitude.

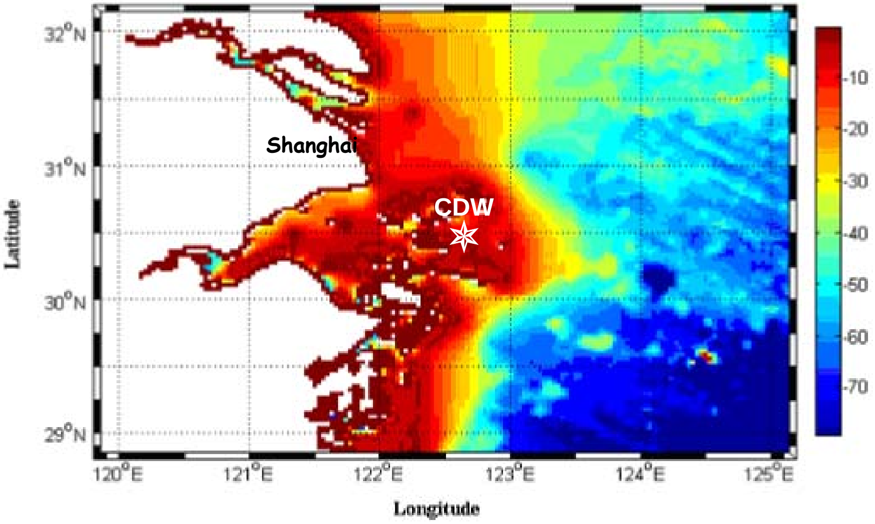


Fig. 2: The measurement test site (CDW) of the 2006 OUC cruise (September 3 - 8).

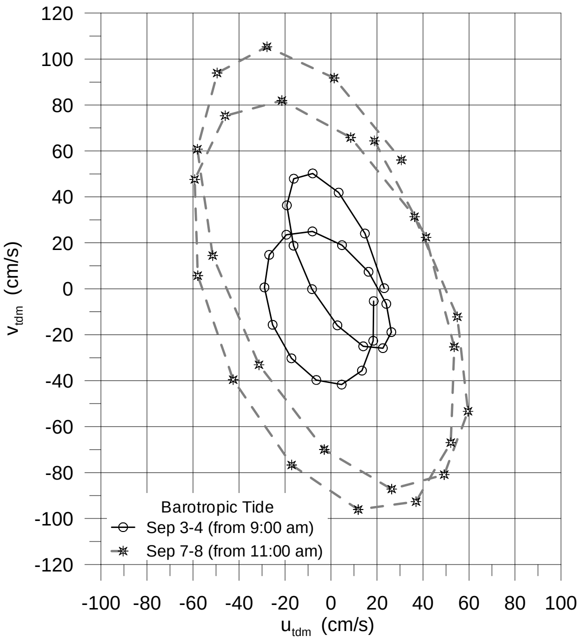
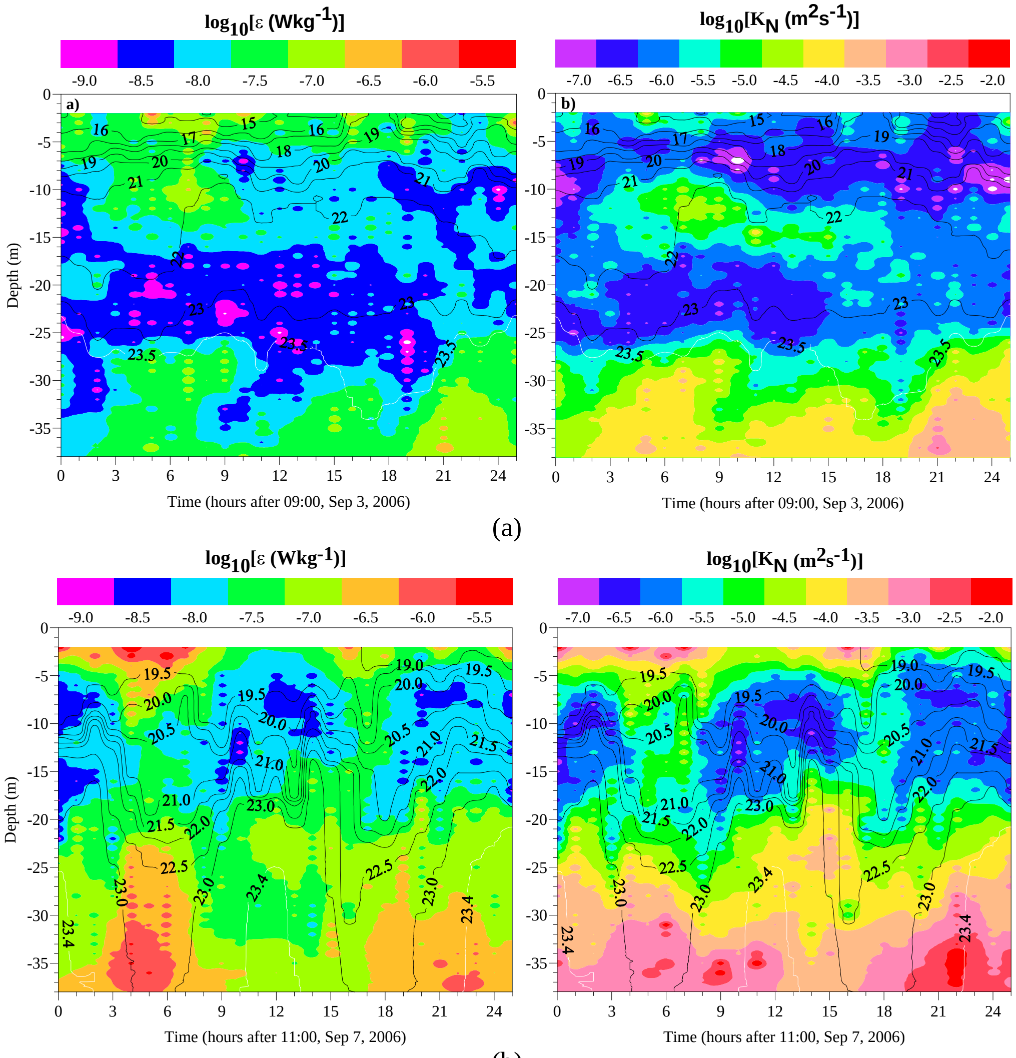


Fig. 3: Barotropic tidal ellipses for two periods of microstructure measurements.

The contour plots of the kinetic energy dissipation rate ε and eddy diffusivity $K_N = \gamma\varepsilon/N^2$ (Fig. 4), where $\gamma = 0.2$ is the mixing efficiency and N^2 the squared buoyancy frequency, show a turbulent BBL with a characteristic ε of about ~ 10^{-7} W/kg over ~ 10 meters above the bottom (mab) during the near-neap phase of the barotropic tide (September 3-4, Fig. 4a). There is a pronounced phase lag in ε with the distance from the seafloor, which has also been observed in a rotating tidal flow in the north-eastern sector of ECS (Lozovatsky et al. 2008a).

The height of the turbulent layer (where $\varepsilon > 10^{-7}$ W/kg) increased twice (~ 20 mab) and the dissipation in the lower 10 mab exceeded 10^{-6} W/kg on September 7-8 (Fig. 4b) closer to the near-spring tidal phase. The observed increase of BBL dissipation is in line with the increase of the magnitude of tidal currents U_{td}. In fact, according to the law-of-the-wall, $\varepsilon = Au_*^3/\kappa\zeta$ at a specific height ζ above the bottom; here $u_*^2 = C_d U_{td}^2$, where u_* and C_d are the friction velocity and drag coefficient, respectively, $A = 1.5$ in a rotating tidal flow (Lozovatsky et al. 2008b) and $\kappa = 0.41$ is the Karman constant. The correlation between the dissipation rate and mean velocity near the bottom was analyzed using the ADV data obtained at the test site (see Fig. 5a).

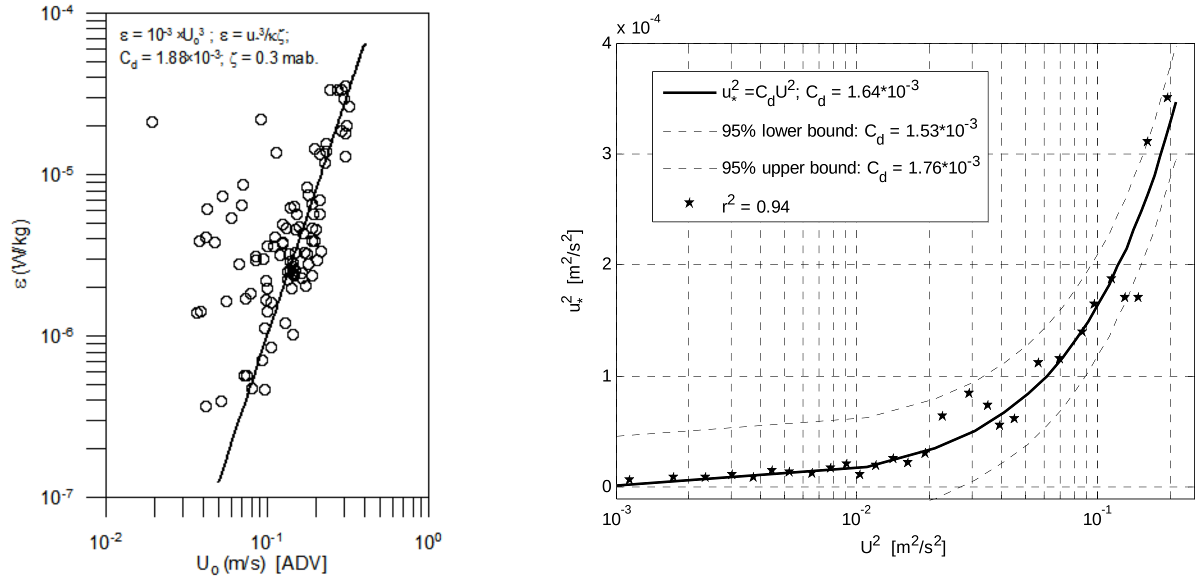


(a)

(b)

Fig. 4: The kinetic energy dissipation rate* ε *and eddy diffusivity* K_N *during the 25-hr period of measurement on September 3 – 4 (a) and September 7 -8 (b). Contours of a specific potential density are overlaid the color plots to show the variation of stratification.

The cubic power approximation, which is shown in the plot, implies that the mean value of C_d was about 1.9×10^{-3}. Conversely, the calculation of the drag coefficient based on the quadratic drag law, is shown in Fig. 5b. The ADV data obtained in the 2005 OUC cruise in a reversing tidal flow of ECS where used for this analysis with $A = 1$ (Lozovatsky et al. 2008b). A high correlation between the friction and mean velocities near the bottom gives $C_d = 1.64\times10^{-3}$, which is in good agreement with the above estimate obtained for rotating tidal flow in the CDW region. Thus, the amplification of U_{td} by a factor 2.2 between September 3-4 and September 7-8 could have caused the observed increase of ε by about an order of magnitude.



(a) (b)

Fig 5: (a) - The dissipation rate vs. mean velocity at ζ = 0.3 mab (rotating tidal flow in a CDW area of ECS, September 3-4 2006); (b) - The friction velocity vs. mean velocity at ζ = 0.45 mab (reversing tidal flow near the northeastern coast of China in December 2005).

The amplification of diffusivities K_N in the BBL was even more dramatic (from ~ 10^{-4} to ~ 10^{-2} m^2/s) due to the combined effects of an increase of ε and decrease of N^2. Because the intensification of turbulence in BBL and in the entire water column below the pycnocline was strongly correlated with the tidal cycle, we suggest that the influence of a mild storm that passed the observational area on September 5-6 was only short lived. The stratification in the pycnocline was quickly reestablished by advection in the CDW area. The influence of tidally-induced advection is demonstrated in Fig. 6 by the depth averaged records of $T(t)$, $S(t)$, and $\sigma_\theta(t)$. For example, colder and higher-salinity dense water (Δt ~ 6 – 11 hr and Δt ~ 15 - 20 hr in Fig. 6a) was advected to the test site primarily by the northwest directed flow from the open sea, while warmer lighter diluted water (Δt ~ 1 – 6 hr and Δt ~ 11 - 15 hr in Fig. 6a) was associated with the tidal phase when the flow was directed from the northwest (Yangtze River Delta). The amplitudes of advective variations of T and S on September 7-8 (Fig. 6b) were as twice as large as that on September 3-4 (~ 1.4^{o}C vs. ~ 0.5^{o}C and ~ 0.9 psu vs. 0.4-0.5 psu, respectively) due to a longer excursion of the near-spring tidal current compared to the weaker flow associated with near-neap tide (see Fig. 3).

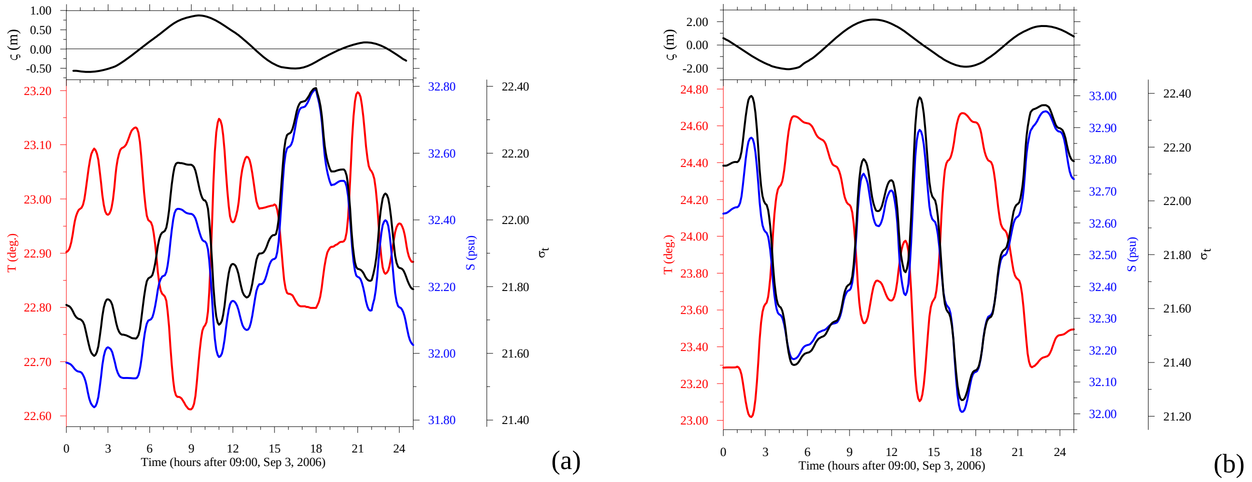


Fig. 6: Time variations of the water elevation, ζ and the depth-averaged temperature, salinity, and specific potential density over the 25-hr period of September 3 – 4 (a) and 7 – 8 (b).

Intense tidal internal waves affected the small-scale dynamics in the CDW area during the second observational period (see the ~ 10-15 meter displacements of the isopycnal surfaces in the middle of the water column in Fig. 4b). Smaller scale internal waves are also evident in this plot, but they could not be resolved by profiling measurements. An untimely malfunction of the upward looking ADCP prevented detailed analysis of internal-wave activity in the region, and thus our research was focused more on turbulence and currents specifically near the seafloor.

The downward looking high-resolution (dz = 2 cm) ADCP allowed to obtain unique velocity profiles in the lower 0.5 mab with the lowest level at 0.02 mab. During the 25-hour period of measurements (September 3-4), a very fine logarithmic layer was observed specifically at the segments with an increased amplitude of the tidal flow. In Fig. 7, two examples of $U(\zeta)$ (an hourly averaged data) that exhibit the log-layers with a high confidence fits (R^2 = 0.98 and 0.99, respectively) are shown. The friction velocities for these profiles ($u_{\bullet} = 0.41$ and 0.49 cm/s) were used to calculate the dissipation profiles $\varepsilon = Au_*^3/\kappa\zeta$ for ζ = 0.02 – 6 mab with A = 1.5, which are shown in Fig. 7 c,d by continuous lines that intersect or coincide with the lower ends of the MSS dissipation profiles (dotted dash lines). The almost perfect match between $\varepsilon_{\mathrm{MSS}}$ and $\varepsilon_{\mathrm{ADCP}}$ assures the applicability of the law-of-the-wall with A = 1.5 to the lower ~ 5 m of the water column in ECS (for $u_{\bullet} = 0.4 - 0.5$ cm/s). When the flow magnitude $U(\zeta)$ at ζ = 0.5 mab dropped during the tidal cycle below 5 cm/s, the skin log-layer approximation failed. The height of the mixed BBL here is controlled by a characteristic lengthscale $L_* = u_*/N$, which is about 4 - 5 m for $N \sim 10^{-3}$ s^{-1}.

An interesting example of the dissipation profile is shown in Fig. 7.

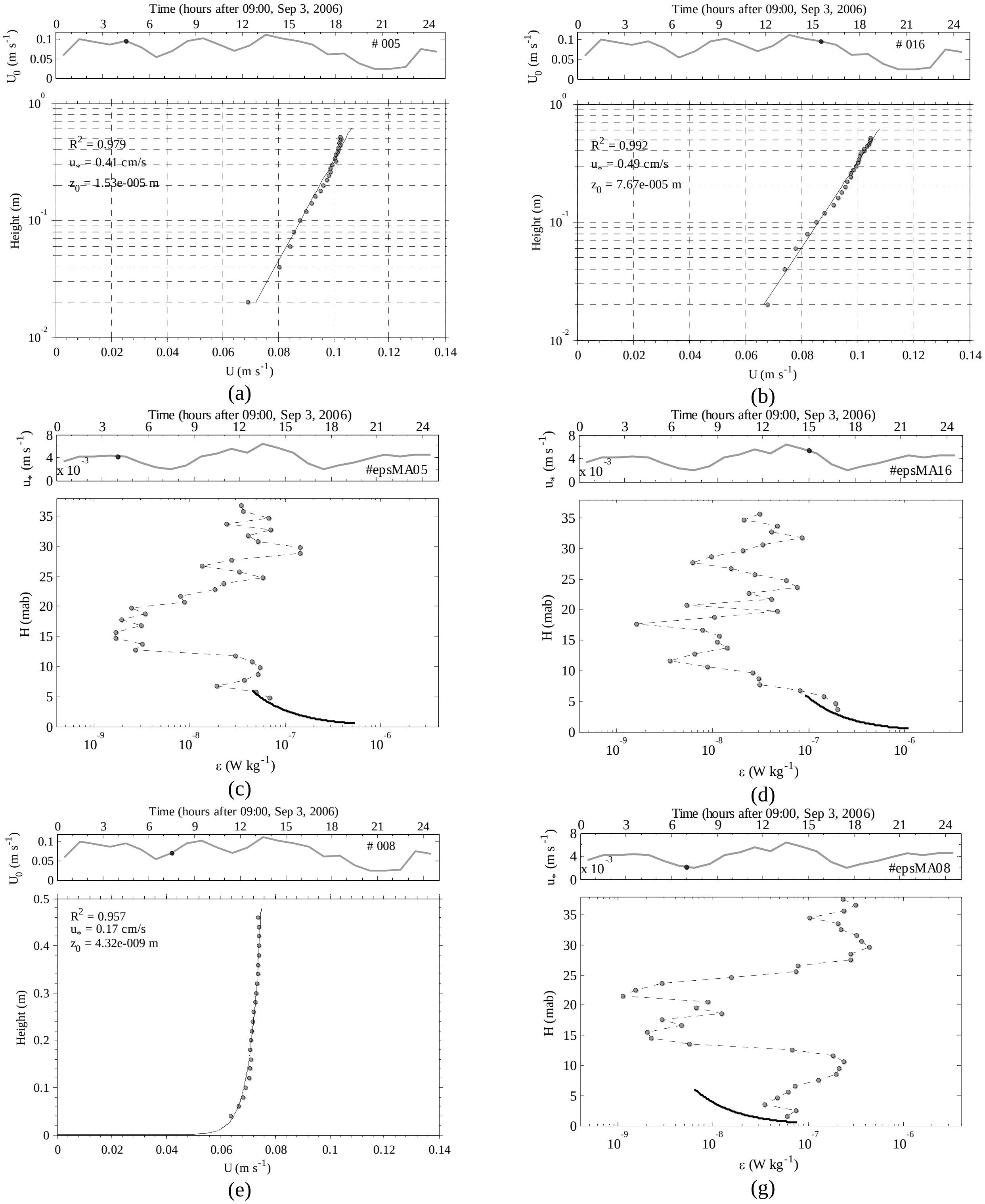


Fig: 7. Examples of the log-layer profiles (a: t = 5 hr) and (b: t = 16 hr) and the corresponding profiles of ε obtained by the MSS profiling measurements (dotted dash lines) and the law-of-the-wall calculation using the ADCP data and log-layer approximations. A distortion of the decrease of the dissipation rate upwards from the skin bottom turbulent layer (g) and the corresponding U(ζ) on linear scale (e).

The lowest point of the MSS profile at $\zeta = 1.5$ mab coincided with the law-of-the-wall dissipation rate, but an internal source of turbulence at ~ 10 mab (presumably due to shear instability) “erased” the expected decrease of near-bottom generated turbulence upwards to the middle of the water column.

B. SHEAR INSTABILITY NEAR A LOCAL SHELF BREAK IN THE YELLOW SEA

The study of flow instabilities and associated turbulence intermittency in ECS has been started (Liu et al. 2008) and will be continued in 2009. As a preliminary result, the cumulative probability distribution of the gradient Richardson number *Ri* above the turbulent BBL using the 2006 OUC measurements near a local shelf in the Yellow Sea (Liu et al. 2008) is shown in Fig. 8. The generation of turbulence in the lower part of water column was mostly driven by shear instability of tidal currents. The effectiveness of this process at different heights from the bottom can be characterized by the probability distributions of *Ri*. Above the turbulent BBL, sporadically the Richardson number fell below its critical value. In the upper part of the logarithmic layer ($\zeta = 3 – 8$ mab), the probability of occurring pure Kelvin-Helmholtz (K-H) instabilities was 0.32 (see the cumulative distribution function *F*(*Ri*) in Fig. 8).

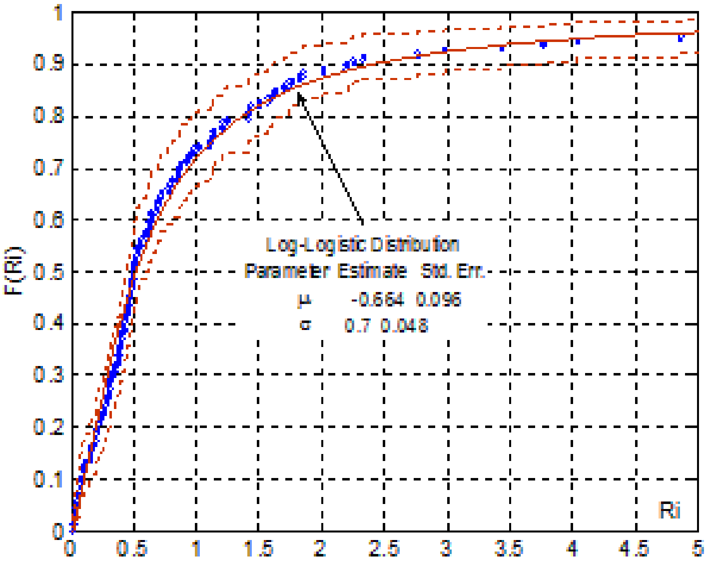


Fig. 8. The cumulative distribution of the Richardson number in the depth rang $\zeta = 3 – 8$ mab.

According to Strang and Fernando (JFM, 428, 349-386, 2001), in the range $0.36 < Ri < 1$, the turbulence is dominated by a combination of K–H instabilities and breaking asymmetric internal wave. In our case, $F(Ri < 1) = 0.73$. Away from the log-layer ($\zeta = 9 – 14$ mab), the probability of $Ri < 0.36$ drastically decreases to 0.1, but $F(Ri < 1)$, = 0.68, did not change much. In the pycnocline ($\zeta = 15 – 20$ mab), $F(Ri < 0.36)$ for the occurrence of K-H instabilities increased to 0.15 but $F(Ri < 1)$ decreased to 0.35. Below the pycnocline, the *F*(*Ri*) values were well approximated by the log-logistic distribution (see the example in Fig. 8), with parameters μ and σ dependent on the height from the seafloor. Statistical analyses of instabilities as well as the dissipation rate are continuing based on the ADCP, CTD, and microstructure (Turbomap) data obtained in the summer pycnocline of ECS during the recent cruises of KORDI.

IMPACT/APPLICATION

Our research program has been strengthened by the international collaboration with Korean and Chinese oceanographers. Two joint papers with the OUC colleagues have been published in 2008 in the Journal of Continental Shelf Research and another paper was accepted for publication in the Journal of Marine Systems. The PIs are planning to make a presentation at the 2nd International Symposium on Shallow Flows (ISSF-2008) in December, Honk Kong and th eco-PI J.-H. Lee presented two talks at the 5th Asia Oceania Geosciences Society Meeting in Busan, Korea. A paper on a new BBL mixing parameterization that depends on the bottom roughness was published in 2008 in the Journal of Deep Sea Research. This research was supported by a previous grant awarded to the PIs by ONR.

TRANSITIONS

None

RELATED PROJECTS

The Co-P.I. Fernando is involved in another ONR funded project dealing with laboratory investigations of surface waves in coastal zone, their breaking and interactions with solid objects. This project is funded by the Coastal Geosciences Program of the ONR.

PUBLICATIONS

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