

# **Internal Wave Energy Budget Studies in the South China Sea**

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## **LONG-TERM GOALS**

We are focused on understanding small-scale processes that influence the ocean's thermodynamic and dynamic properties on the sub-mesoscale (scales less than 10 km). This includes the role of turbulence in modifying the upper ocean temperature and density structure. In the South China Sea, large-amplitude, nonlinear waves force turbulence in the seasonally variable continental shelf region. New observational data is sought for use in characterizing turbulence phenomena, and for parameterizing processes in models.

## **OBJECTIVES**

This program was focused on measuring the dissipation rate of mechanical energy on the shallow continental shelf and the Dongsha Plateau of the South China Sea. The measurements are being used to examine the energy dynamics of small-scale wave processes in relation to tidal forcing. The measurements are the first dissipation observations from a region where extreme-amplitude, nonlinear internal waves lose their energy in shallow water.

## **APPROACH**

During the NLIWI program, we conducted two turbulence surveys in the South China Sea (Figure 1). Our work in the South China Sea began in 2005 during the pilot phase of the program, when we conducted a survey on the continental shelf using a shallow water turbulence system. This survey was conducted from the OR1 during the period April 11-20 with Joe Wang (NTU), Glen Gawarkiewicz (WHOI), and Ching-Sang Chiu (NPS). Our work in 2005 was also coordinated with the acoustics effort being conducted by OASIS from the OR3. During 2007, we returned to the SCS to measure turbulence levels on the Dongsha Plateau. This survey was done from the OR3 during the period April 26 – May 4 with YuHuai Wang (NSYSU). Work focused on an intensive survey near Dongsha Island, extending out to the 900-m isobath. Our work was loosely collaborated with a simultaneous survey of the OR1, occupying the APL/UW mooring line along 21°N (Fig. 1).

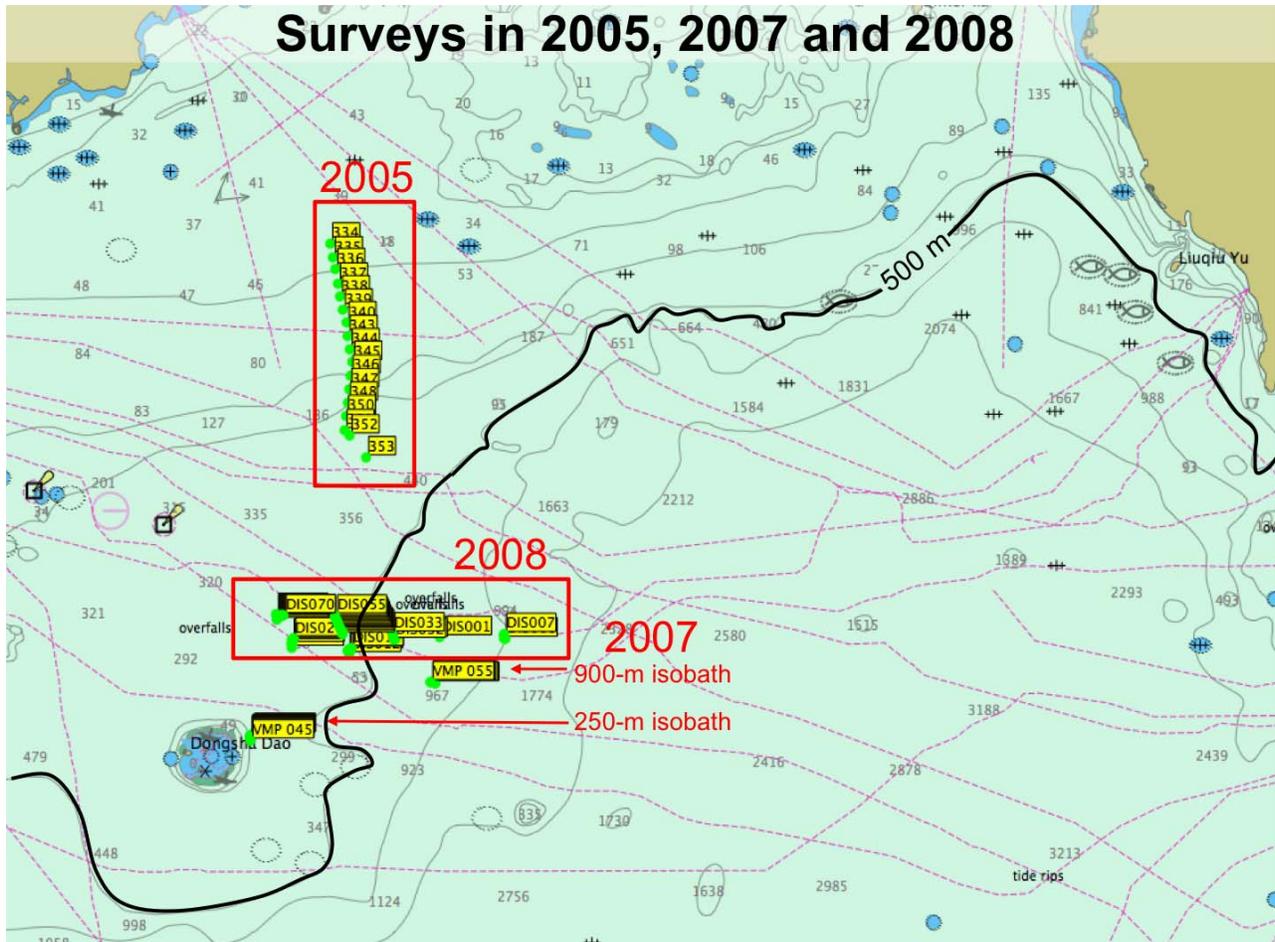
To date, our analysis of 2005 survey data has focused on quantifying the wave and turbulence conditions on the continental shelf to the shelf break, between the 40-m and 300-m isobaths (St. Laurent 2008). Our measurements of the in-situ density structure and turbulence energy provided the finest temporal and spatial resolution of any system used during the survey. We observed an abundance of nonlinear wave activity, but not the clear soliton-like waves of Luzon origin. We believe

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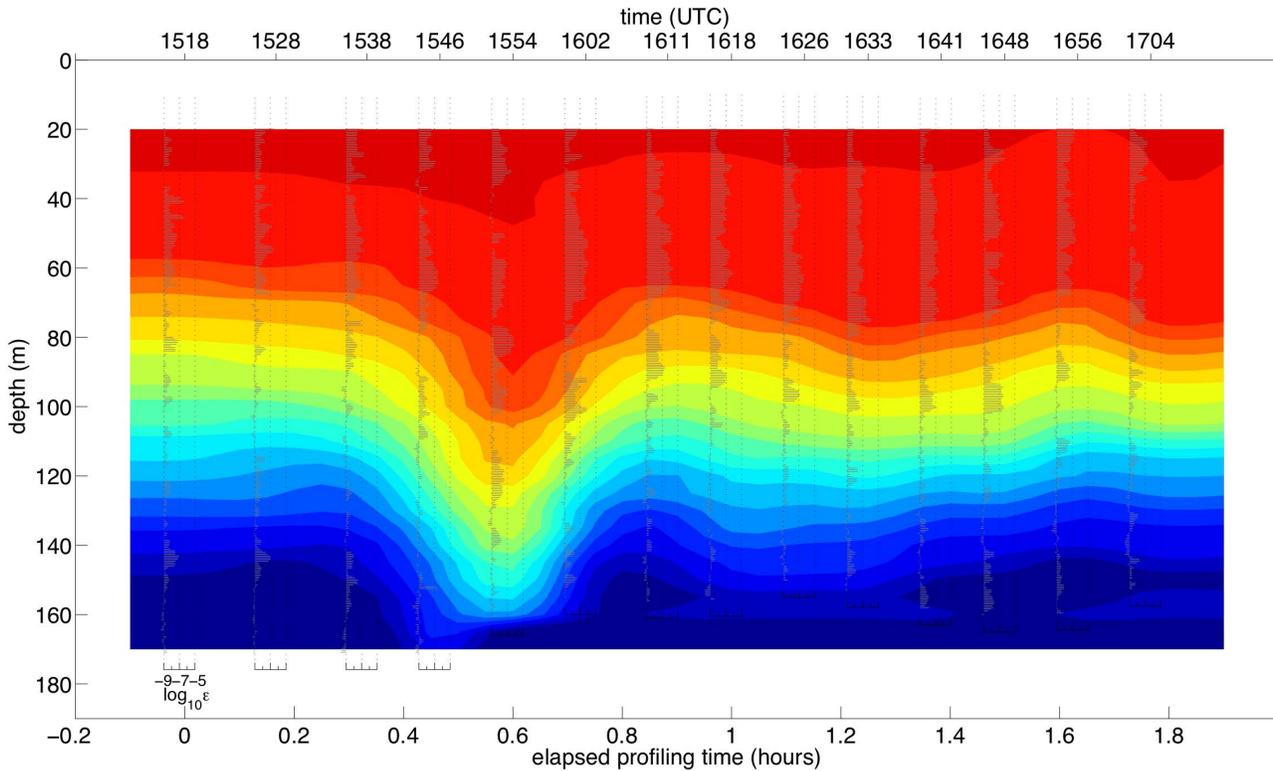
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**Figure 1.** Map showing the survey regions for FSU turbulence measurements in the South China Sea during 2005, 2007 and 2008. The 2005 survey to the north was located near the ASIA-EX study region, and focused on the shelfbreak. The 2007 and 2008 surveys were on the Dongsha Plateau to the northeast of Dongsha Reef. In 2007, observations of waves were limited to the 900-m isobath, and the 250-m isobath on the eastern side of the Reef. In 2008, we focused on shoaling waves between the 600-m and 300-m isobaths north of the Reef. In all, about 550 profiles of turbulence parameters were collected during 3 surveys.

that the environmental stratification clearly controlled the wave behavior we observed. Unlike the conditions documented during ASIAEX in 2000 (Gawarkiewicz et al 2004, Duda et al. 2004), we found that the on-shelf stratification in 2005 was considerably deeper. This allowed for the conversion of depression waves to elevation waves near the 100-m isobath. This further resulted in substantial conversion and dissipation of Luzon waves prior to their arrival on the shelf. Thus, soliton-like depression waves from the deep SCS basin were not being transmitted onto the shelf during 2005. We believe the observations in 2005 were the first to document the SCS shelf in this deep stratification state (St. Laurent 2008).

Despite the lack of observed soliton-like waves, we observed substantial baroclinic activity at all sites along our survey. Long trains of depression waves were observed shoaling at the shelf break. In at least one case, a large-amplitude depression had energy characteristics of a Luzon wave, suggesting

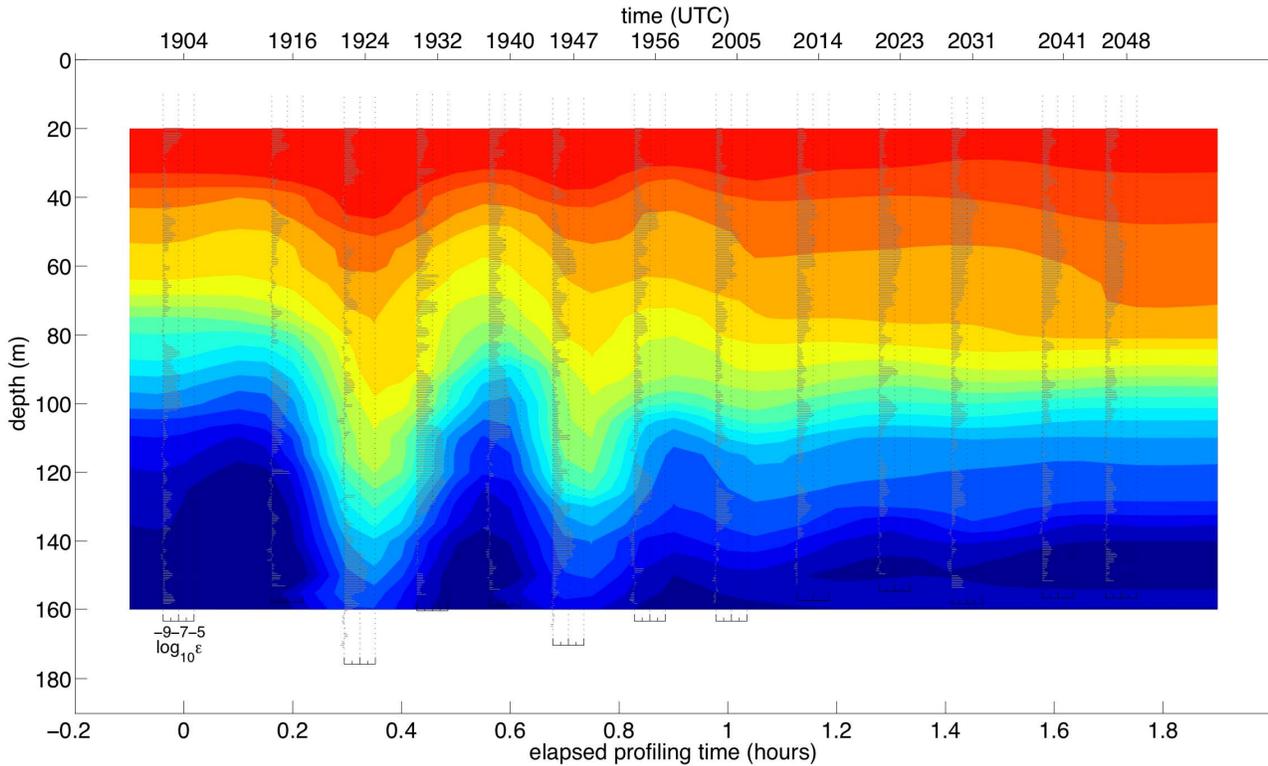


**Figure 2.** Section showing a wave along the 575-m isobath northeast of the Dongsha Reef. Data for the temperature isotherm structure is shown in color, with increments of 0.5°C between the 15°C isotherm (bottom) and 30°C isotherm (top). Turbulence dissipation levels are shown as profiles. The values are plotted using a logarithmic axis, as indicated by the left-most profile.

this pulse was the evolved remnant of a deep basin soliton. Near bottom elevation waves were also observed at the shelf break, in one case reaching 40-m amplitude, or roughly 1/3 of the water depth. Elevation waves were observed in water as shallow as 40-m, propagating along the buoyancy-gradient maximum as it shoaled toward the Chinese coast. It appears that much of the on-shelf baroclinic activity is the result of locally generated waves.

During 2007 and 2008, our work focused on observing wave activity on the Dongsha Plateau (Fig. 1). The study site was chosen based on modeling results that showed that Luzon waves focused a primary beam of baroclinic energy into this region. The Plateau region's bathymetry is in contrast to the shelf break. The region east of Dongsha Island slopes only gradually from 300-m to 500-m, but then steeply drops into the deep basin. Thus, Luzon waves abruptly shoal from the 3000-m isobath to the 500-m isobath, but then propagate along the plateau shoaling gradually to about 250-m depth

During 15-20 August 2008, we participated in an expedition to the waters of the South China Sea near the Dongsha Reef. This region experiences some of the most energetic high-frequency internal waves in the global ocean, and is hypothesized to be the site where much of the dissipation of these waves occurs. We observed several wave packets shoaling along the Dongsha Plateau. Most significantly, we were able to conduct in-situ sampling of a depression pulse of 50-m amplitude as it shoaled between the 600-m and 300-m isobaths. During this process, the original anomaly evolved into two prominent depressions with an increased turbulence level in the wake of the wave. These are the first



**Figure 3.** Section showing the same wave as in Fig. 2 as it passed the 375-m isobath two hours after the initial observation. Data for the temperature isotherm structure is shown in color, with increments of  $0.5^{\circ}\text{C}$  between the  $15^{\circ}\text{C}$  isotherm (bottom) and  $30^{\circ}\text{C}$  isotherm (top). Turbulence dissipation levels are shown as profiles. The values are plotted using a logarithmic axis, as indicated by the left-most profile.

measurements of energy dissipation made while through a wave at two locations during the shoaling process.

Our work in 2008 was a continuation of the study begun in 2005, and continued in 2007, sampling the dissipation levels directly along the margins of the S. China Sea. The work in 2008 allowed for the first time the sustained measurements of a wave pulse as it dissipated while shoaling. It also allowed for measurements in August, late in the typhoon season; when process-oriented observations have been scarce in the past.

## RESULTS

- The transmission of Luzon waves onto the shelf is sensitive to the depth of the primary stratification layer. The shelf break stratification in 2005 was deeper than in previous years, lead to a significant conversion of depression solitons into long dispersed trains of waves. These evolved Luzon waves have features similar to locally generated nonlinear waves originating from tidal forcing at the shelf break. A preliminary energy analysis suggests that wave packets of Luzon origin contain an order of magnitude more energy than the locally generate shelf waves.
- The Dongsha Plateau favors the preservation of soliton-like structure as the waves shoal up the continental slope. The initial shoaling past the 1000-m isobath clearly leads to significant dissipation throughout the wave structure, though this is not enough to destroy the solitons-like form of the waves. Shoreward of the 500-m isobath, the more gradual bottom slope of the plateau allows the remaining wave structure to propagate a considerable distance.
- No clear “graveyard” of nonlinear wave energy was found. Luzon waves shoaling past the shelf break are mixed with locally generated waves, all of which are acted on by dissipative drag with the surface and bottom boundary layers over the broad continental shelf off China. Luzon waves propagating along the Dongsha Plateau either collide with the Island, or dissipate over a considerable time and distance, loosing energy over the gradually sloping bathymetry.
- Our limited data suggests that the most significant sink in the Luzon wave energy budget occurs during the initial shoaling over the continental slope, between the 500-m to 1500-m isobaths.

## IMPACT/APPLICATIONS

The new data collected in the 2007 and 2008 observational program provides the first picture of the spatial and temporal signals of nonlinear internal wave fine- and microstructure on the Dongsh Plateau of the South China Sea. These measurements, in conjunction with model simulations and the efforts of other groups, will establish the basis for an internal-wave climatology of this important WestPac region.

## RELATED PROJECTS

The PI has worked closely with two other investigators modeling SCS waves. Harper Simmons (UAF) is a co-PI on the FSU South China Sea 2007 field effort. He has provided considerable modeling support for the overall SCS NLIWI program. Chris Jackson (GOA) has provided a model to wave-phase prediction, largely on remotely sensed imagery of the surface manifestation of the waves.

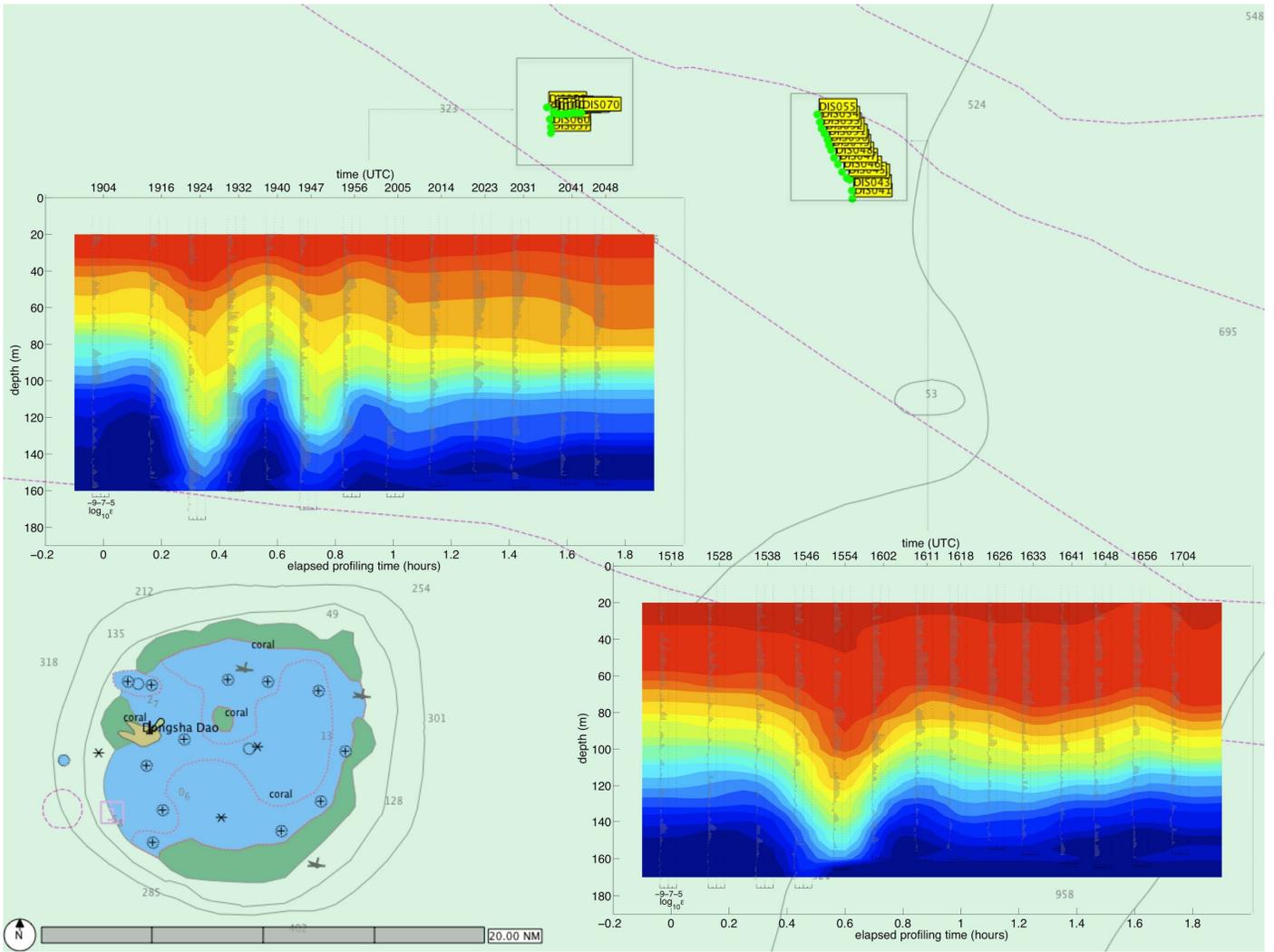
Both the UAF and GOA models were used extensively during the 2007 and 2008 field program for prediction of wave events, and both models proved to be excellent resources. In general, both models were accurate to within 30 to 90 minutes in phase prediction. Predictions for waves tended to lead observations for sites very close to Dongsha Island, but were otherwise very close for waves propagating in water deeper than 500 m.

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**Figure 4** Summary slide showing two snapshots of a wave pulse as it passed between the 575-m and 375-m isobaths northeast of the Dongsha. The locations of the observations are shown relative to the navigational chart of the Hong-Kong Hydrographic Office. Data for the temperature isotherm structure is shown in color, with increments of 0.5°C between the 15°C isotherm (bottom) and 30°C isotherm (top). Turbulence dissipation levels are show as profiles. The values are plotted using a logarithmic axis, as indicated by the left-most profile. The turbulence dissipation levels increased as the wave evolved from a single depression peak to two a two-peak depression.