Analysis and Synthesis of Data From the WISE/VANS 2005-06 and NLIWI/SCOPE 2007 Field Experiments

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LONG-TERM GOAL

The long-term goal is to enhance our understanding of coastal oceanography by means of applying simple dynamical theories to high-quality observations obtained in the field. My primary area of expertise is physical oceanography, but I also enjoy collaborating with biological, chemical, acoustical, and optical oceanographers to work on interdisciplinary problems. I collaborate frequently with numerical modelers to improve predictive skill for Navy-relevant parameters in the littoral zone.

OBJECTIVES

The objective of this grant is to improve understanding of how the large-amplitude internal waves and tides in the northeastern South China Sea are generated via interaction of the barotropic tide with the ridges and islands in the Luzon Strait. In addition to the problem's inherent scientific interest, understanding the generation problem is essential for developing a forecast model to predict the wave characteristics in the deep basin and on the Chinese continental slope and shelf.

APPROACH

The approach is to analyze two data sets obtained in the South China Sea in the context of large-amplitude, nonlinear internal wave theory. The data sets were obtained during the Windy Islands Soliton Experiment / Variability Around the Northern South China Sea (WISE/VANS) experiment from April 2005 to June 2006 and the Nonlinear Internal Wave Investigation (NLIWI) from April to July 2007. Since the WISE/VANS data have been described in previous annual reports, this report focusses on the newer results from NLIWI. Two oceanographic moorings sensing current, temperature, and salinity, and four Inverted Echo Sounders with Pressure (PIES) were used to track the waves from the genration site to the western basin (Figure 1). Full-depth CTD casts were also done along the transect to map the ambient stratification in the water column. The observations are being used to test hypotheses for wave genration, and to initialize and verify several different numerical computations being run by collaborating investigators.

WORK COMPLETED

The NLIWI field work was successfully completed during two cruises on board the U.S. research vessel MELVILLE during April and July 2007. The work was staged out of National Sun Yat-sen University (NSYSU) in Kaohsiung, Taiwan, where the support for U.S. scientists was outstanding as

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14. ABSTRACT
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usual. Six Taiwanese graduate students from National Taiwan University (NTU) and NSYSU participated in both cruises. Two observers from the Taiwanese Navy also participated in the cruises. Initial data downloading, processing, and quality control has been accomplished. Since an accurate map of the bottom topography is critical to understanding the generation problem, multi-beam surveys of the region between Batan and Itbayat Island were also conducted. The multi-beam data were processed and maps made with assistance from the Monterey Bay Aquarium Research Institute (MBARI).

RESULTS

The NLIWI 2007 project succeeded in its goal of tracking ISWs unambiguously back to their source on a particular beat of the barotropic tide in the Luzon Strait. This was facilitated by having observations close enough together to follow the correct fluctuations, and by having an observation between the two ridges, which was previously lacking. The result (Figure 2) reveals several fascinating aspects of the wave generation and propagation problem.

- Where co-located data were available, the agreement between the temperature field and the acoustic travel time from the PIES was excellent (bottom panel). The two series are inversely related because the warmer water in the large thermocline depressions produces faster acoustic propagation speeds and shorter travel times.

- The ISWs can be easily tracked from site P2 to site P3. The waves were mostly solitary at P2 and formed packets by the time they reached P3.

- At site P1 located between the two ridges (see locator map, Figure 1) the internal tide was already quite nonlinear with a steeper leading edge than trailing edge, however no ISWs were observed there. This strongly suggests that the ISWs were not generated immediately across the sill, but rather required a finite amount of time to develop via nonlinear steepening of the internal tide.

- The thermal depressions which ultimately spawned the ISWs in the western basin passed mooring N2 a few hours after the peak flood tide, or about 14 hours after the tide turned from ebb to flood (Figure 2, top panel).

- The time-varying Froude number was calculated in the strait using a three-layer approach. The result showed the flow to be subcritical most of the time, but occasionally critical ($G^2 = 1$) for 4-5 days around the time of the strongest spring tides. This indicates a control point on the top of the sill on flood tide. Additional observations are needed in the lee of the sill.

IMPACT/APPLICATION

There are two primary candidates for non-linear wave generation in this region, namely lee waves forming behind the sill which are subsequently released when the tide turns, and non-linear steepening of the internal tide as it propagates WNW in the deep basin. The process is modulated by the stratification, which determines the strength of the initial interaction with topography and whether trapping of the energy can efficiently take place in the upper ocean. These observational results to date suggest multiple processes at work depending on the season and the strength of the rather complex barotropic tide in the Luzon Strait. These subjects will be further investigated during the upcoming Internal Waves in Straits Experiment (IWISE).

TRANSITIONS

The PI retains a courtesy appointment at the Naval Postgraduate School and has regular contact with the U.S. Navy via officer-students and faculty there. A tactical decision aid consisting of an empirical forecast model for wave arrivals has been developed (Jackson, Global Associates) and is being continually refined using our data to determine the positions and times of wave arrivals using realistic stratification along the propagation path. Transitions to SUBPACFLT are anticipated as they become available.

RELATED PROJECTS

A related study to model the SCS waves using primitive equation models is being conducted under NSF Combined Mathematics and Geophysics (CMG) funding. The lead PI on the grant is Prof. Woo-Young Choi, NJIT and it also includes S. R. Ramp (MBARI), D. Lyzenga (UMich) and R. Camassa (UNC). Nonlinear internal waves in the Monterey Bay were also observed during the Adaptive Sampling and Prediction (ASAP) program during August 2006, funded by a DoD MURI grant. These data will be analyzed during FY2007-2009.

PUBLICATIONS

Ramp, S. R., 2008: Models I'd Like to See. Presented at the second NSF CMG nonlinear internal waves workshop, Moss Landing, CA March 2008.

Ramp, S. R., 2008: Nonlinear internal waves in the South China Sea and a few words on where they are born. Stanford University, January 2008.

Li, Q., D. M. Farmer, T. F. Duda, and S. R. Ramp, 2008: Acoustical measurement of nonlinear internal waves using the inverted echo sounder. Submitted to *J. Atm. and Oc. Tech.*

Ramp, S. R., F. L. Bahr, T.-Y. Tang, and Y.-J. Yang, 2008: Seasonal variability of the nonlinear internal wave field in the northeastern South China Sea. AGU Ocean Sciences Meeting, Orlando, FL (prepared but not presented due to my wife's death).

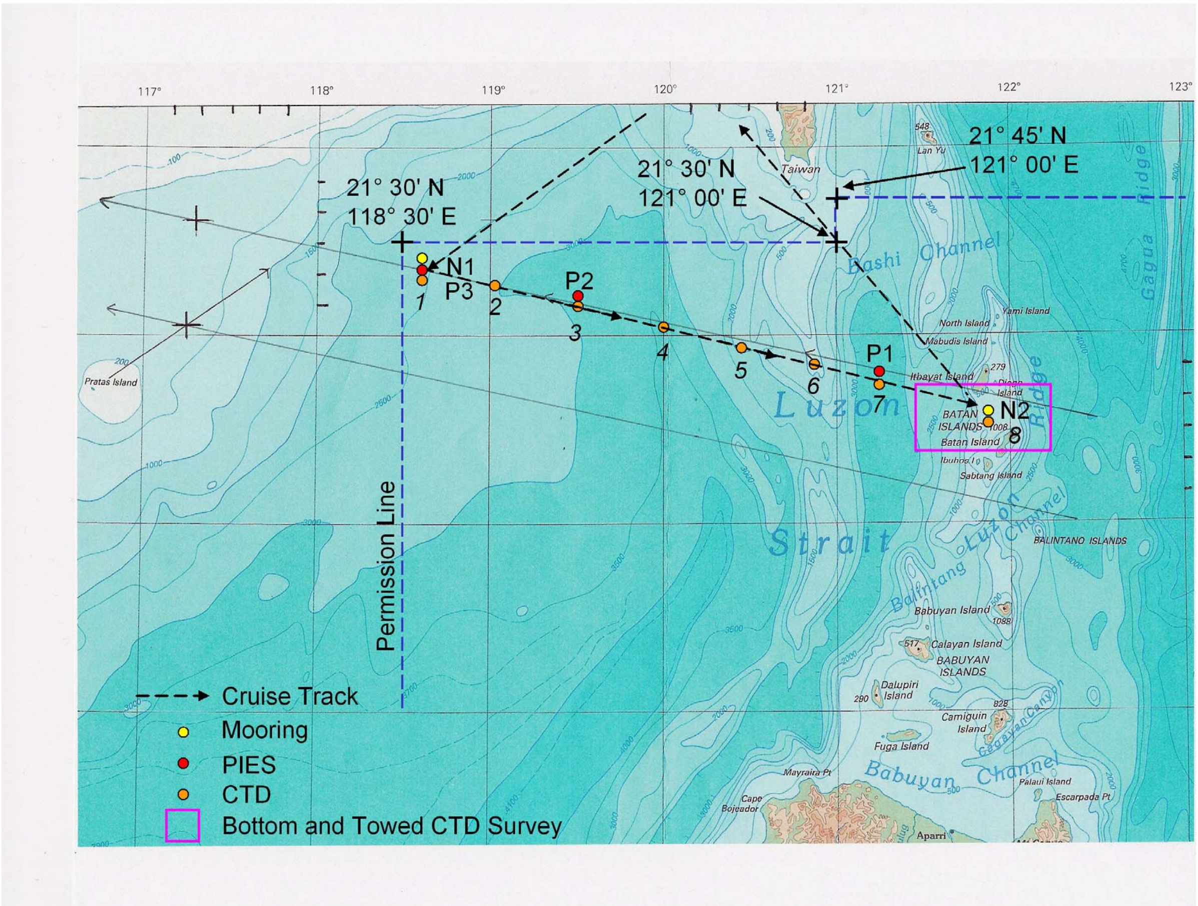

Figure 1. Locator map showing the NLIWI/SCOPE activity locations in the northeastern South China Sea. The yellow dots are moorings and the red dots are inverted echo sounders with pressure (PIES). CTDs are indicated by the orange dots.

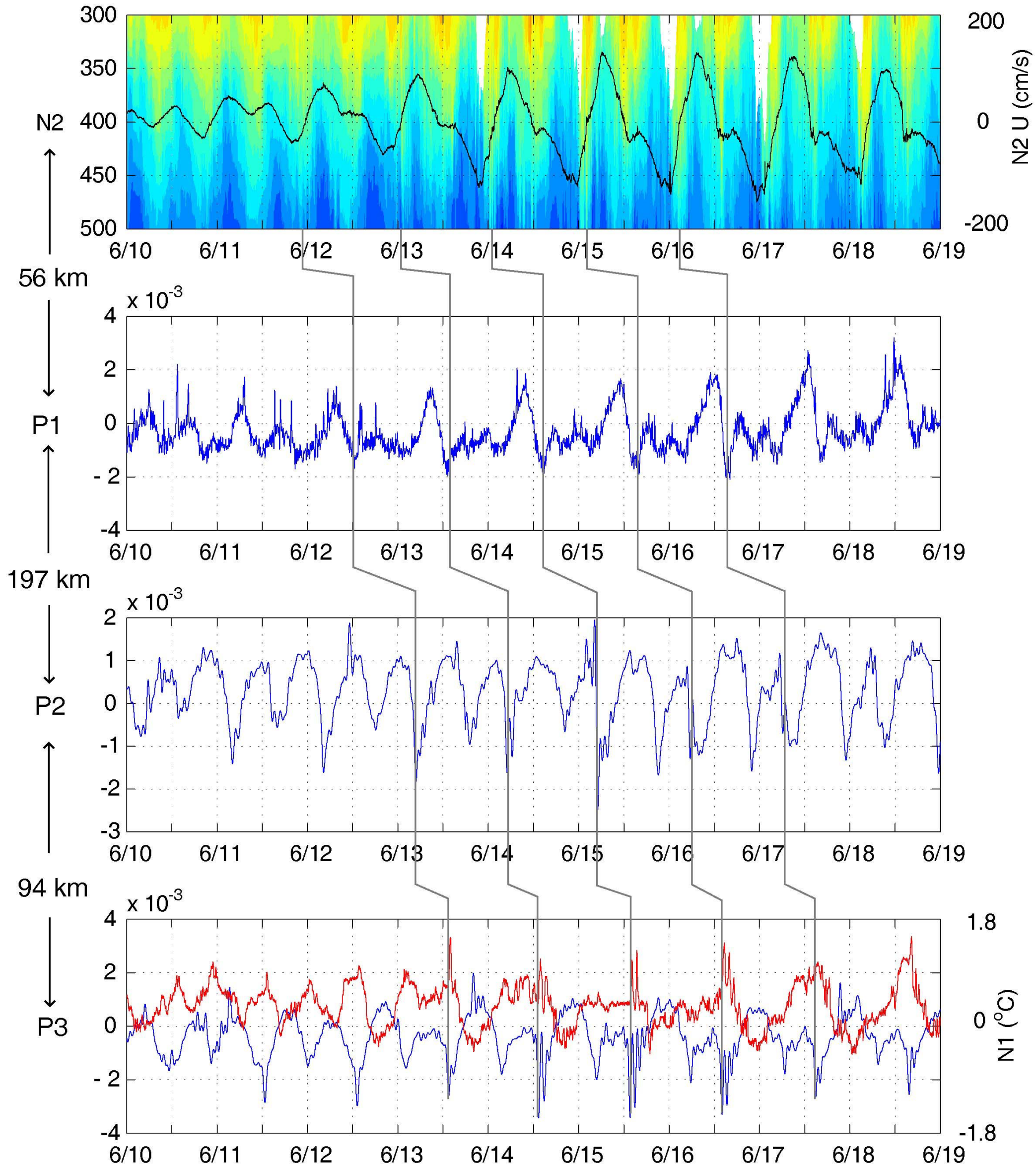

Figure 2. Stack plots of (from top to bottom) a) Temperature (color) at the Luzon Strait with vertically averaged zonal (u) velocity component overlain. Positive sign indicates an ebb (towards the Pacific) tide and a negative value indicates the flood (towards the SCS) tide. b) De-meaned acoustic travel time from the PIES located at P1 (see Figure 6 for locations). c) De-meaned travel time for the PIES located at P2. d) De-meaned travel time for the PIES located at P3 (blue) with the temperature data from the neighboring mooring N1 (red). The bottom panel serves as a verification that the PIES is effective at sampling the NLIWs. Note the increasing nonlinearity and number of waves per packet westward along the transect.