Large-Amplitude Internal Waves in the South China Sea

D.S. Ko,[1] P.J. Martin,[1] S.Y. Chao,[2] P.T. Shaw,[3]
and R.C. Lien[4]
[1]*Oceanography Division*
[2]*University of Maryland*
[3]*North Carolina State University*
[4]*University of Washington*

Prologue: One of the most spectacular phenomena recently discovered in the South China Sea is that of very large internal waves. Field observations and satellite images show that these internal waves are over 200 meters in amplitude and their crests extend more than 200 km (Fig. 3). These fast, transient, large-amplitude internal waves can push water up or down 200 meters in 10 minutes and seriously impact the safe operation of submerged vessels, particularly the less powerful unmanned undersea vessels, or UUVs. The large-amplitude internal waves can also have a strong effect on underwater sound propagation as reported by the Office of Naval Research (ONR) Asian Seas International Acoustics Experiment.[1] Several NRL scientists from the Acoustics and Oceanography Divisions participated in this experiment. In 2005, ONR launched the Nonlinear Internal Waves Initiative (NLIWI) to better understand the large-amplitude internal waves in the South China Sea. NRL teamed with university scientists to participate in the NLIWI to conduct internal wave studies using computer ocean models and observations.

Modeling Tools: We used a hydrostatic ocean model for the northern South China Sea and non-hydrostatic, process-oriented ocean models to study the large-amplitude internal waves. The hydrostatic model is the NRL Ocean Nowcast/Forecast System (ONFS).[2] The NRL ONFS was implemented using a nested grid system. The larger grid covers the East Asian Seas and provides boundary conditions for a higher-resolution grid that includes the Luzon Strait and northern South China Sea (Fig. 3). Tidal forcing is applied at the open boundary of the high-resolution grid. Temperature and salinity analyses generated from satellite altimeter and Multi-Channel Sea Surface Temperature (MCSST) data are assimilated into the model to produce a realistic stratification. Applying the NRL ONFS and non-hydrostatic models, numerical experiments were conducted and analyses were made to study the effects of bottom topography, tidal forcing, and stratification on the generation and propagation of the large-amplitude internal waves.

How Large-Amplitude Internal Waves are Generated: Figure 4 illustrates how the undersea ridges in the Luzon Strait transform the ocean tide into large-amplitude internal waves. Large amounts of water rush through the Luzon Strait pushed by the tide. The ridges first convert the barotropic tides to internal tides. Propagating away from the ridges, the internal tidal wave steepens, and transforms the internal tide to an internal bore. The internal bore evolves into a large-amplitude, internal solitary wave as it propagates further away from the ridges. If the tide is strong, the solitary wave may develop into a packet of internal solitary waves.

Where is the Source? The east ridge in the middle reaches of the Luzon Strait is the major internal wave generation site where the internal tidal energy flux diverges (Fig. 4). There is a secondary generation site at the northern shallow reaches of the west ridge south of Taiwan. The internal tidal energy generated at these two locations propagates westward into the deep northern South China Sea and dissipates on the shallow shelf. The west ridge in the middle portion of the Luzon Strait blocks part of the incoming internal tidal energy from the east ridge.[3]

Which Tide Generates the Internal Waves? The barotropic tides are the major forcing that generates internal waves in the South China Sea. Without the tide, internal energy can be generated by the frontal instability of the Kuroshio current or by Kuroshio-topography interaction, but this energy is much weaker than the internal energy produced by the tides. The semidiurnal tide is more effective than the diurnal tide in generating the large-amplitude internal waves (Fig. 5). Although the strength of the semidiurnal and diurnal tides are about equal in the South China Sea, the internal tides generated by the semidiurnal tides have a shorter wave length and more easily evolve into large-amplitude internal waves. Concurrent satellite synthetic aperture radar (SAR) images and shipboard observations suggest that this is the case.

Can We Predict Large-Amplitude Internal Waves? The model predictability of the large-amplitude internal waves in the South China Sea was validated by field observations and satellite remote sensing data. NLIWI field observations taken during the 2005, 2006, and 2007 cruises and at three moorings during 2007 were used. The satellite SAR and Moderate Resolution Imaging Spectroradiometer (MODIS) images of 2005 were also used. The validation suggests that the timing and relative amplitude of the large-amplitude internal waves in the South China Sea can be predicted accurately (Fig. 5). The results of this study were presented to the Naval Oceanographic Office. NRL is now in the process of transitioning an internal wave prediction capability for operational application.

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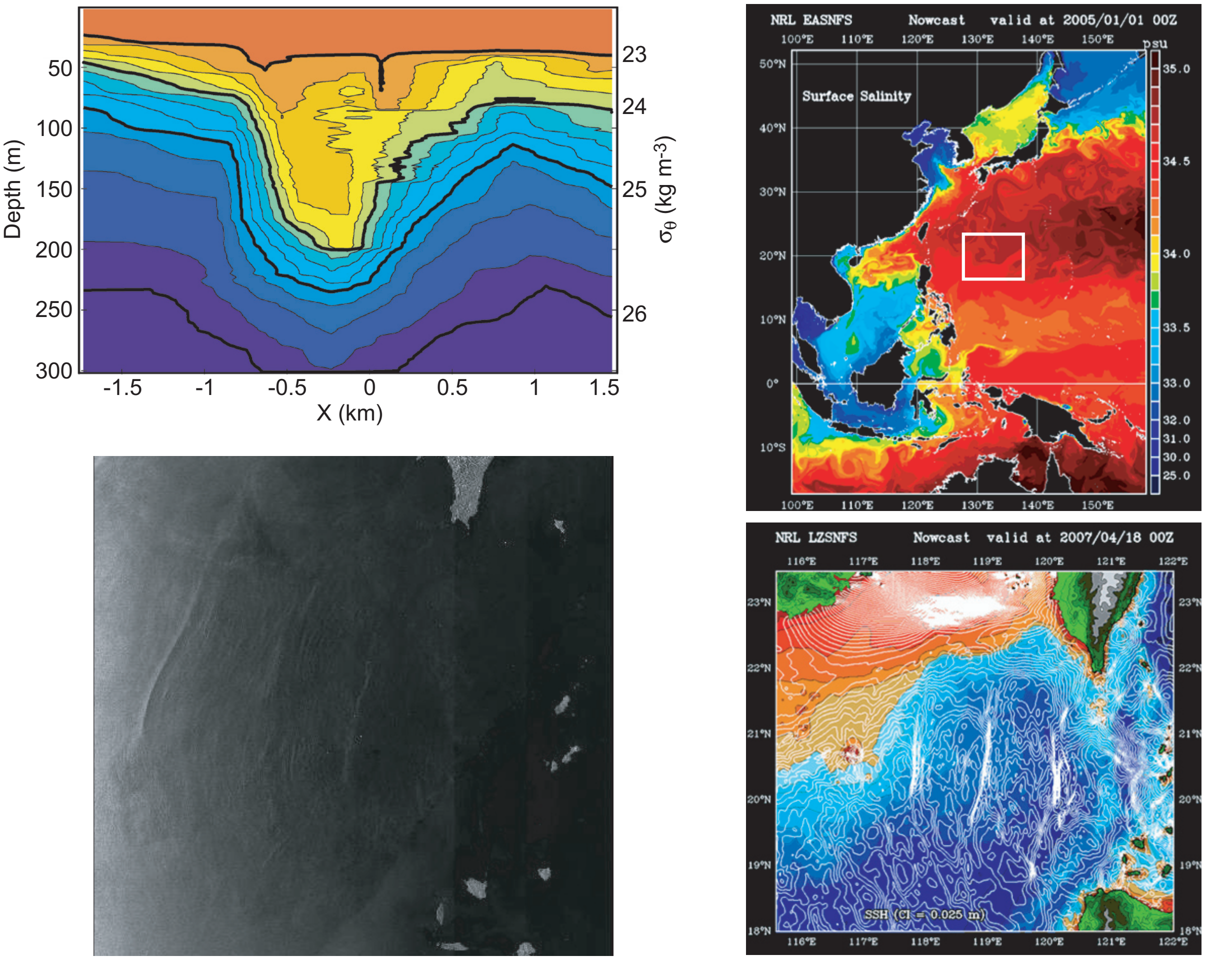

FIGURE 3
Internal waves in the South China Sea have amplitudes over 200 m (top left) and extend over 200 km (bottom left). A coupled NRL Ocean Nowcast/Forecast System with a nested grid (right) is used to study the internal waves.

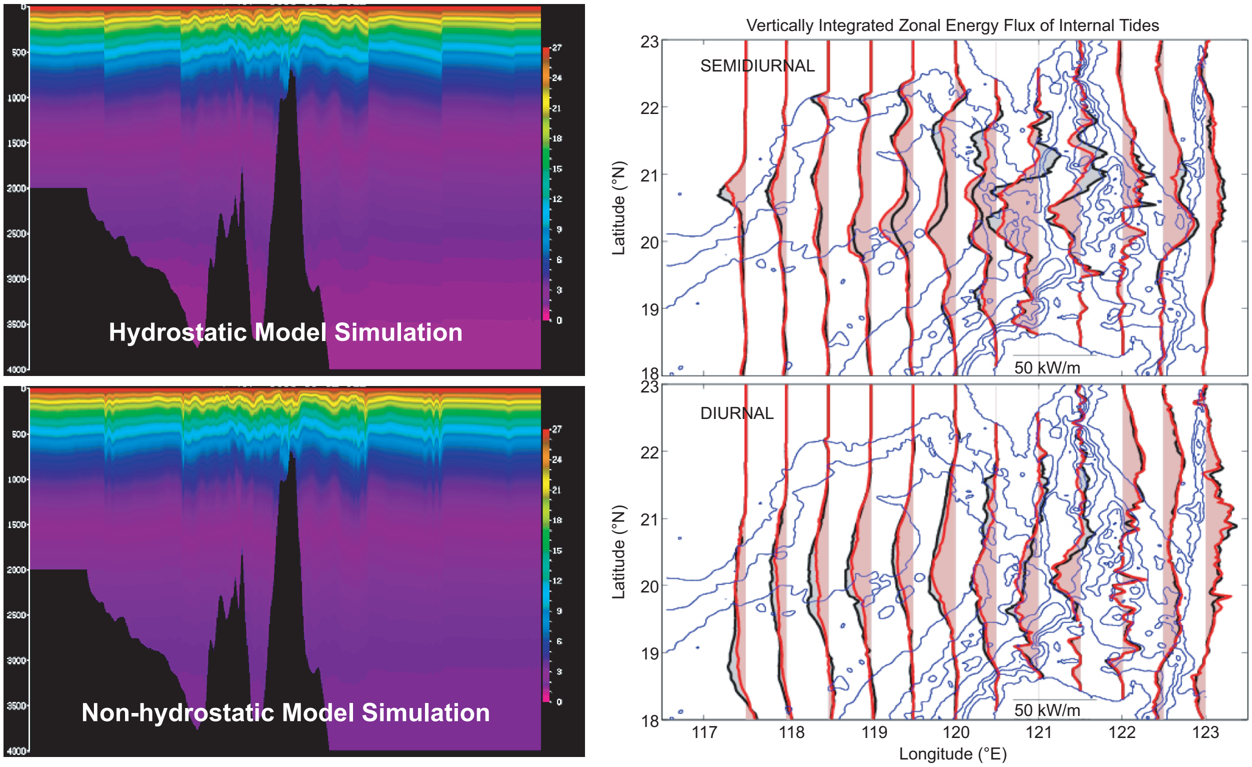

FIGURE 4
Simulations of the internal-wave generation and propagation with hydrostatic and non-hydrostatic models (left). The energy flux of the internal tides (right); red and black correspond to results with and without west ridge blocking, respectively.

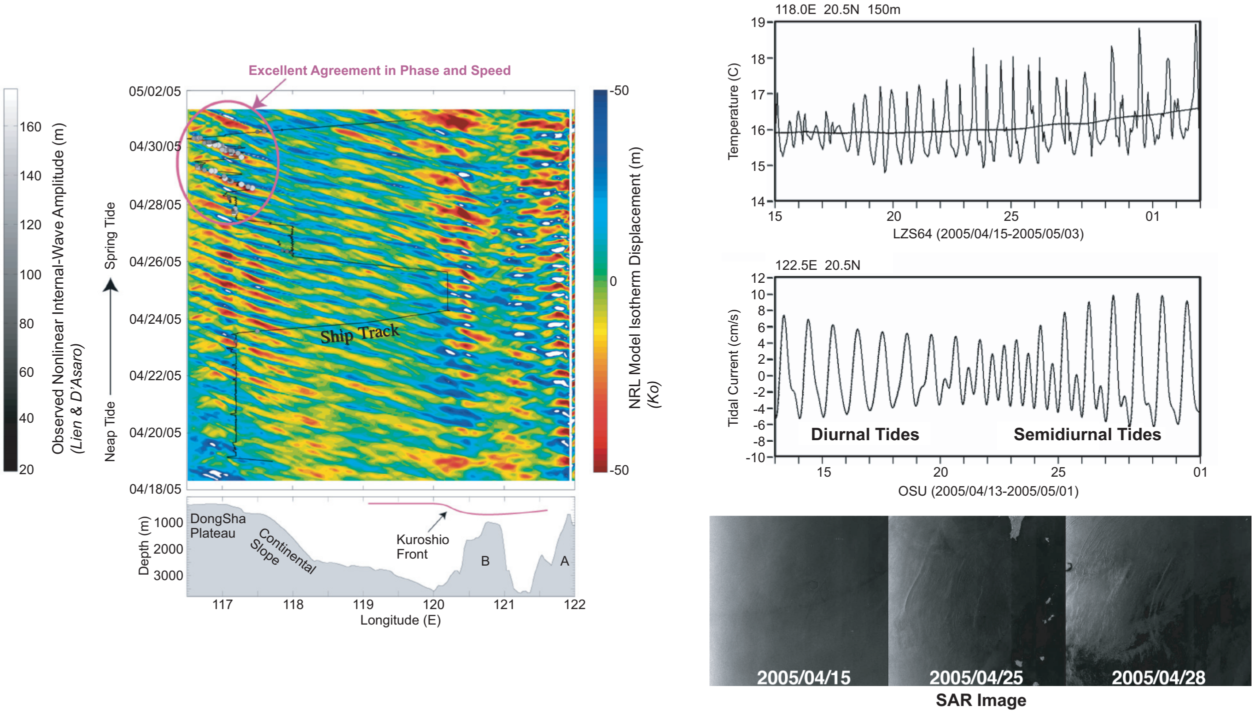

FIGURE 5
Comparison of predicted internal waves with shipboard observations (left). Comparison of model-predicted internal waves with corresponding tidal current and satellite synthetic aperture radar (SAR) images (right).

References

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Probabilistic Prediction for Improved Scientific Understanding and Improved Decision Making

J. Hansen, C. Bishop, J. Doyle, J.S. Goerss, T.R. Holt,
J. McLay, and C. Reynolds
Marine Meteorology Division

Introduction: In recognition of the importance of quantifying uncertainty in atmosphere-ocean forecasting for the purpose of managing operational risk, NRL-Monterey (MRY) is involved in several related efforts in support of the design, utility, and evaluation of forecasts that utilize and quantify uncertainty. NRL-MRY recently stood up the Probabilistic Prediction Research Office (PRO) to help facilitate and coordinate these efforts. The PRO also reaches out to users, decision makers, and funding agencies to better understand the environment in which meteorology and oceanography (METOC)-related decisions are made and to identify situations in which probabilistic environmental information can be utilized.

NRL-MRY research efforts that attempt to exploit uncertainty information for improved understanding and decision making include the following: research on the design of the global atmospheric ensemble forecast system; research in the use of stochastic parameterizations to account for model uncertainty, which holds promise for improved ensemble forecasting of tropical cyclone track forecasts; the design of a new mesoscale atmospheric ensemble forecasting system, which accounts for model uncertainty through varying parameters in the physical parameterization schemes and perturbing sea surface and land surface forcing; use of ensemble-based covariances for data assimilation and adaptive observing applications; use of ensemble forecasts at the urban scale to quantify risk in the event of a toxic release; and the use of ensembles to learn about and improve model parameterizations. Some of these efforts are described below.

Global Modeling: Ensemble forecasting attempts to quantify forecast uncertainty by running many realizations of a numerical weather prediction (NWP) model, each from a different initial condition and/or each being a different version of the forecast model. The research efforts on global atmospheric weather forecast model ensemble design have focused on both the initial uncertainty problem and the model uncertainty problem. The ensemble transform (ET) method combines flow-dependent information from short-term forecasts with error statistics from the data assimilation system to produce initial perturbations that are balanced and conditioned for growth. The ET scheme has been found superior to the current operational scheme under a variety of metrics, including lower ensemble mean rms errors and a stronger relationship between ensemble variance and forecast error variance.

In addition, a stochastic scheme has been developed to account for uncertainty in the physical parameterization of moist convection. Implementation of this scheme has led to improved ensemble performance in the tropics under a variety of measures. The stochastic convection ensemble also appears to provide useful information for 4- to 5-day tropical cyclone track forecasts, providing ensemble mean forecasts of comparable skill to the multi-model consensus forecast, averaged over the 2005 season (Fig. 6 shows one case).

High-Resolution Regional Modeling: One of the attractive features of the ET ensemble generation technique is that it enables uncertainty information to be sampled at the scale of the simulation model. This is critically important for applications such as characterizing the uncertainty in forecasts of toxic plume dispersion in urban areas. Figure 7 depicts an ensemble of plume forecasts from two distinct release sites near Tokyo, Japan. If civil protection agencies had access to only a single forecast (mbr000), there would be a danger that they would not be cognizant of the many other areas that might be affected (indicated by the plumes mbr001 through mbr010). Apart from accounting for uncertainties in initial conditions, the ensemble simulations also accounted for uncertainties in the representations of urban and sea surface temperature effects on the plumes.

Physical parameterizations for processes such as surface heat and moisture exchange, boundary layer mixing, clouds, and precipitation also have inherent uncertainties in their formulations. For example, parameterization coefficients, which are often derived for a specific circumstance and then applied to all meteorological conditions, should be represented by a wider spectrum of values or, more accurately, by a probability density function if it is known. Preliminary research is under way to gain a better understanding of how to represent these uncertainties within the COAMPS®* suite of physical parameterizations appropriate for the mesoscale. Our current method involves

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