Internal Wave Generation in Straits

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LONG-TERM GOALS

The long term goals are to use observations and analysis of stratified flow past complex topography to understand how internal tidal interaction in straits is responsible for the generation of large amplitude high frequency internal waves.

OBJECTIVES

Our objectives were to deploy a 2-D array of pressure-sensor-equipped inverted echo sounders (PIESs) so as to observe the generation of internal waves by tidal interaction with topography in Luzon Strait (Fig. 1), and to interpret the results using appropriate models of internal wave formation and evolution.

APPROACH

Our approach required deployment of an array of Pressure sensor equipped Inverted Echo Sounders [PIES] (see Li et al. 2009). Five instruments were deployed in a pilot study and 13 were deployed at the end of the IWISE main experiment, with recovery in April 2012. Our approach has involved detailed analysis of wave amplitude and arrival times using the Hybrid Coordinate Ocean Model [HYCOM] simulations together with a hybrid linear internal tide generation and fully nonlinear propagation model. Our approach involved model evaluations of wave amplitudes and 2-dimensional ray-tracing to calculate wave arrival times.

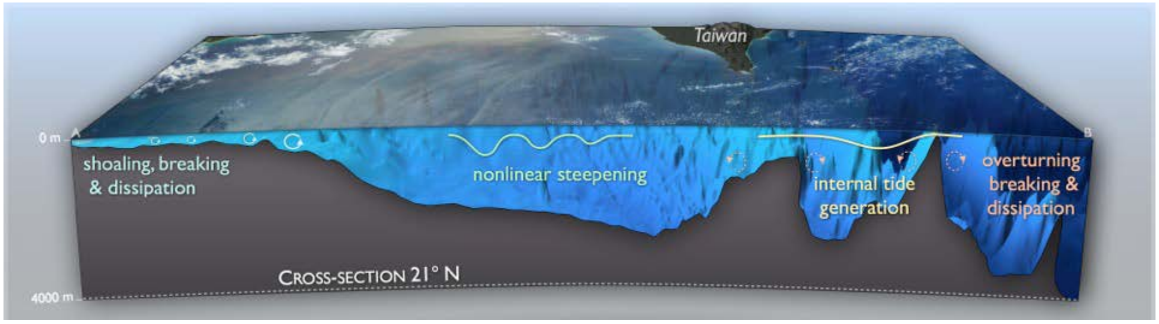

Fig. 1. This contribution to IWISE focused on the generation of internal tides through tidal forcing over the ridges in Luzon Strait and their subsequent nonlinear evolution as they propagate westwards across the deep basin of the South China Sea.

WORK COMPLETED

(1) Analysis of PIES ,easurements were carried out to search for and explain effects of a winter intrusion of the Kuroshio across Luzon Strait into the South China Sea. The potential for using HYCOM to provide a description of the 3-D velocity and density field was explored through comparison of HYCOM inferred fluctuations of sea surface slope in Luzon Strait with the corresponding time series derived from PIES deployments in the same location. Nominal nonlinear internal wave amplitude and arrival times in the South China Sea were then calculated using the Hibya-Helfrich model implemented by Li & Farmer (2011) that combines Hibya's (1986) linear internal tide generation with Helfrich's (2007) fully nonlinear evolution model, hereafter referred to as H-H.

RESULTS

Time series observations of amplitude and arrival times of nonlinear internal waves at station P05 in the deep basin of the South China Sea acquired with PIES were analyzed to examine the influence of Kuroshio intrusions across Luzon Strait. Time series simulations of the 3-dimensional distribution of density and velocity in Luzon Strait and the South China Sea for the winter of 2010-2011 were drawn from the HYCOM archive. The time series observations were compared with corresponding simulations generated by H-H, using TPXO global inverse tidal current simulations at Luzon Strait (21ºN, 122ºE) and a horizontally uniform stratification representative of winter conditions. The difference between the simulated and observed arrival times and amplitudes were then compared with changes in oceanographic conditions associated with Kuroshio intrusions for the same period simulated by HYCOM.

A check on the validity of the HYCOM simulations in the Luzon Strait area was carried out by using PIES observations at two locations within the strait (see Fig 4) to calculate fluctuations of the Sea Surface Slope [ΔSSH] and then calculating the cross-power spectral density of the observed time series with the corresponding HYCOM simulations or the 6 month period of the deployment. The results, shown in Figure 2, imply that useful predictions based on HYCOM should be limited to periods of 20 days and longer. Time series of the difference in amplitude (i.e. $\Delta\eta = \eta_{obs} - \eta_{model}$) and the difference in

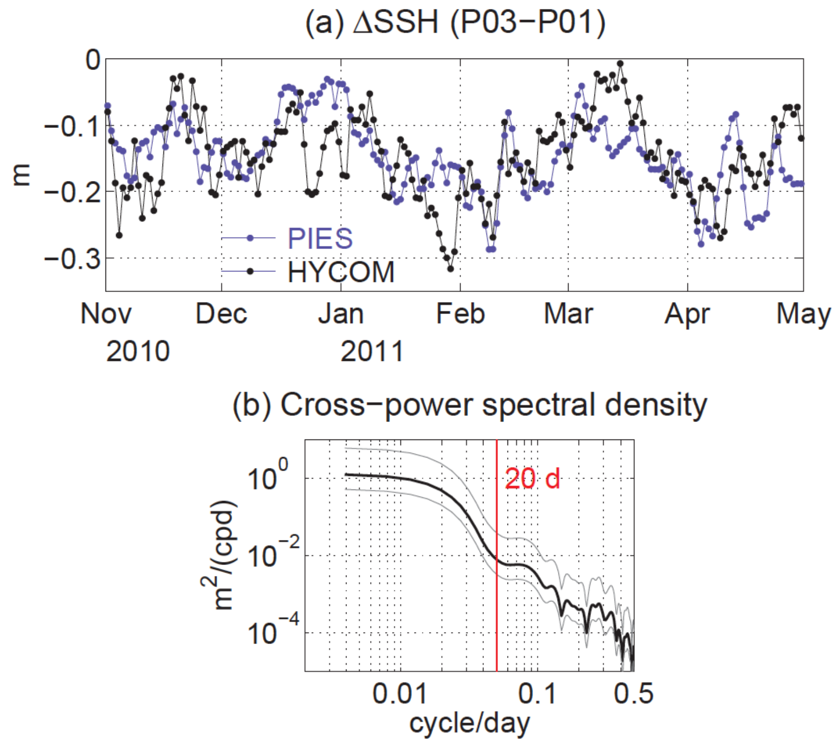

Fig. 2 (a) Comparison of observed fluctuations in sea surface slope ΔSSH (blue) with corresponding HYCOM simulation (black). (b): Cross-power spectral density between the observed and simulated time series.

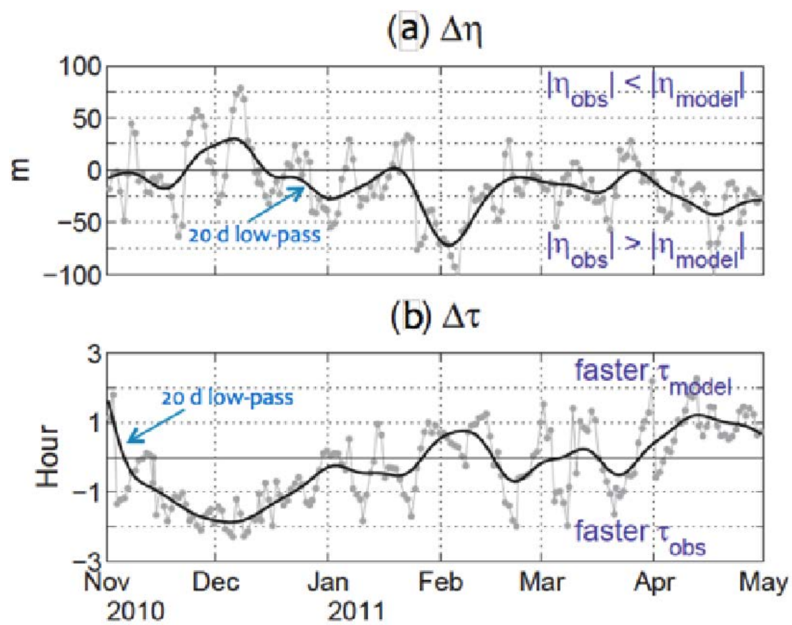

Fig. 3 Time series of the difference between simulated and observed (a) internal wave amplitude and (b) internal wave arrival time.

arrival time ($\tau_{obs} - \tau_{model} = \Delta\tau$) are shown in Figure 3; the daily values are in gray and the 20 d low-pass filtered time series in black. HYCOM simulations for the six month period, shown in Figure 4, illustrate a strong inflow in late November and December. During this period the waves arrived 1.5 h earlier than the average arrival time for the 6 month period and 1 h later than the average in April. The amplitude fluctuations appear less directly related to the inflows. Figure 4 shows the corresponding HYCOM simulations at 150 m.

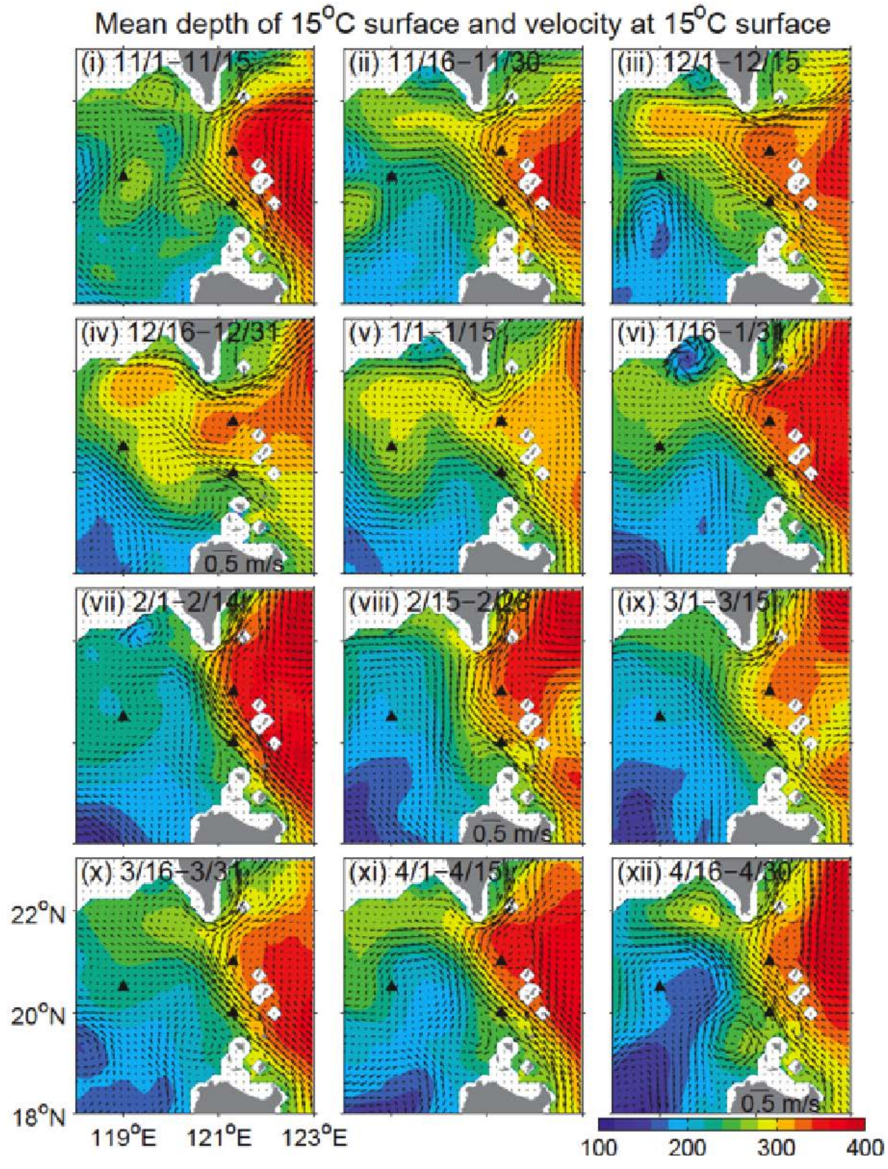

Fig. 4 Temperature at 150m and velocity vectors derived from data-assimilated HYCOM simulations for the 6 month period spanning the 2010-2011 winter. Solid black triangles show instrument locations: two in Luzon Str. and one in the deep basin.

Amplitude fluctuations were compared with different model predictions in Fig. 5: (a) the Soliton Amplitude Growth rate (Zheng et al.,2007), (b) vertical current shear (Choi, 2006), (c) barotropic forcing (Buijsman et al., 2010) and (d) stratification *N*. No single mechanism can fully explain the amplitude variability in terms of Kuroshio inflow, but the vertical shear exhibits the highest correlation (-0.39 with 95% confidence limit of -0.25). We anticipate that 3-D effects associated with oblique interaction of the Kuroshio with the two ridges, including the 3-D response within the strait would play a role.

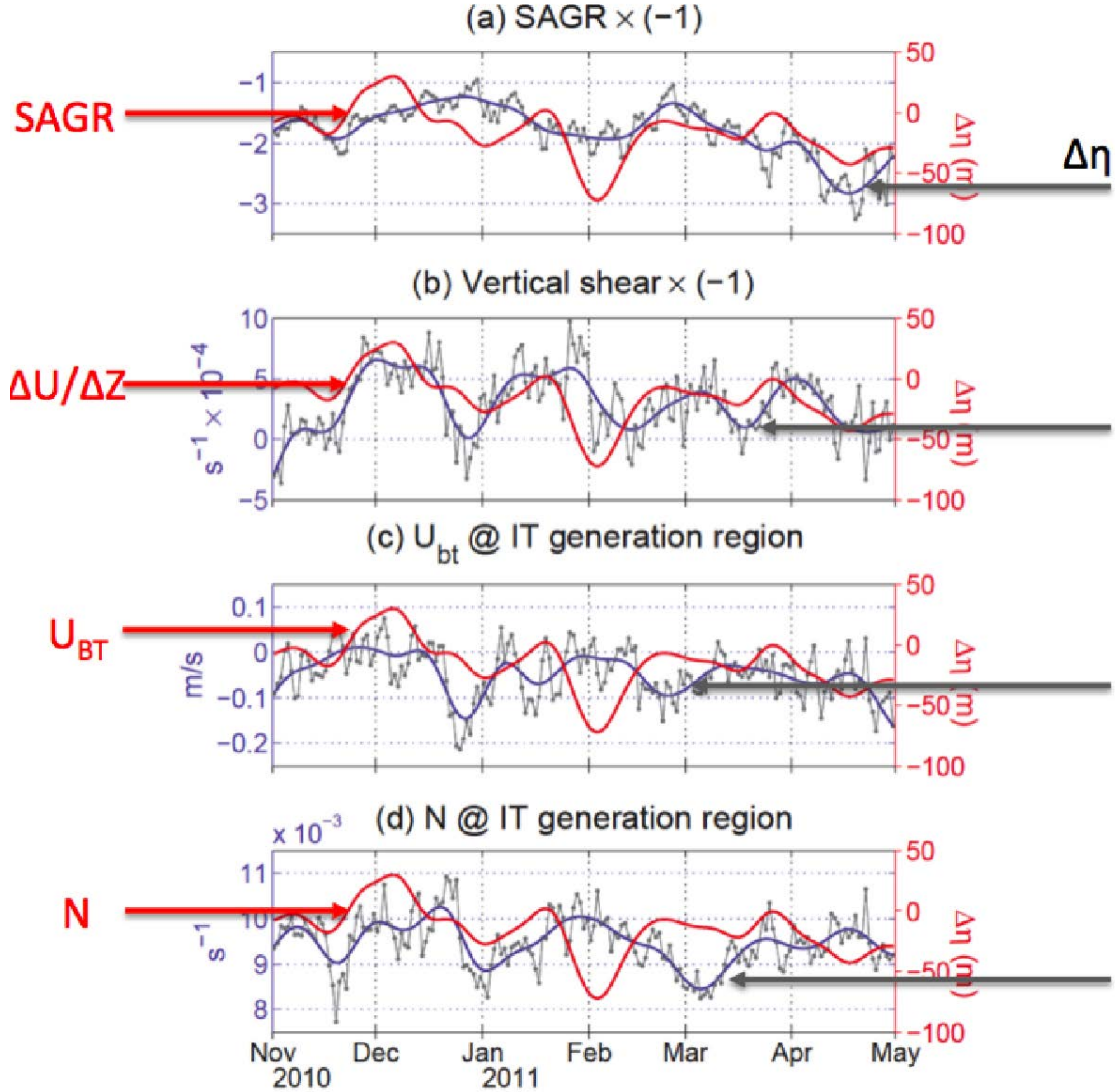

Fig. 5 Comparison of observed internal wave amplitude difference from H-H model simulation with different parameters: (a) Soliton Amplitude Growth Ratio, (b) vertical shear, (c) barotropic forcing, (d) stratification.

Variability in the wave arrival time was modelled using ray-tracing based on the 2-dimensional Taylor-Goldstein equation. The calculation was carried out with a 10 minute time step, starting from just west of the western ridge in Luzon Strait and incorporating vertical profiles of HYCOM simulated vector currents and the corresponding density profiles for each ray at each step. Variations in the wave arrival times $\delta\tau_R$ at P05 evaluated in this way are shown in Figure 6, together with the corresponding observed arrival times $\Delta\tau$. The ray-trace approach based on HYCOM stratification and velocity profiles is in quite good agreement with the observed time series. The ray trace results for the two periods identified by green arrows are shown in Figure 7. These results are described by Park & Farmer (2013).

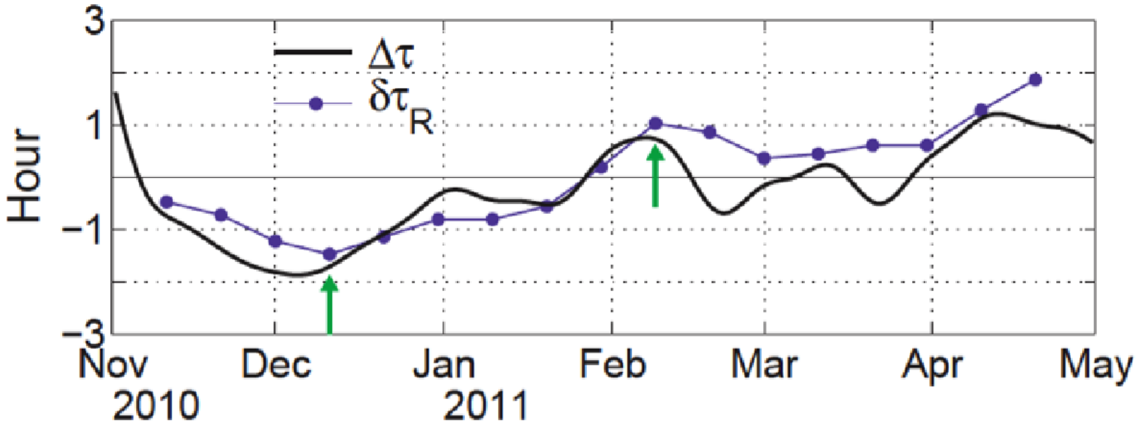

Fig. 6 Comparison of variability in observed wave arrival time ($\Delta\tau$) with predicted values ($\delta\tau_R$) based on ray-trace calculations for the HYCOM simulations.

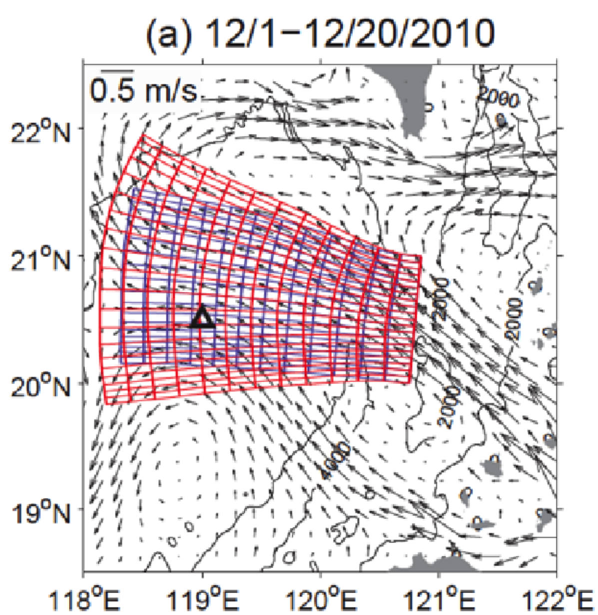

Fig. 7 Ray-trace calculations using the 2-dimensional Taylor-Goldstein equation for internal waves radiated from just west of Luzon Strait, with HYCOM simulated velocity and density fields for periods of (a) strong inflow and (b) weak currents in the deep basin. The Δ symbol indicates location of P05 PIES observations for the comparisons shown here.

IMPACT/APPLICATIONS

These results provide unambiguous evidence for the existence of nonlinear internal waves during winter and illustrates the way in which Kuroshio inflows can refract the waves due to changes in the velocity and density fields. The influence of these intrusions on amplitude of the waves is less clear and will most likely involve 3-dimensional effects.

RELATED PROJECTS

ONR project – Nonlinear Internal Wave Initiative

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PUBLICATIONS

Park, J-H & D. M. Farmer (2013), Effects of Kuroshio intrusions on nonlinear internal waves in the South China Sea during winter, *J. Geophys. Res.*.