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14. ABSTRACT

This program funded by the Office of Naval Research under grant N00014-05-1-0140 is a 2005 field program (SCS05), where our primary challenge was to see if the waves arriving at the western slopes of the South China Sea were in fact, propagating trans-basin from generating sites to the east.

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Non-linear Internal Wave Evolution in the South China Sea: 2005 Field Program

Final Report: N00014-05-1-0140

Robert Pinkel
Marine Physical Laboratory
Scripps Institution of Oceanography

Background:

The ONR NLIWI program was conceived in the early years of this decade to investigate the phenomenology of non-linear internal waves. One of the focus areas was the South China Sea (SCS). At that time, large-scale solitary waves were known to shoal on the western shelves of the SCS. Solitons were also seen in satellite photos on the western slopes & shelves, as well as in the Luzon Strait, a potential generating site for the waves. There were no observations of non-linear waves in the deep central SCS and satellite evidence was inconclusive.

We proposed to joint a 2005 field program (SCS05), where our primary challenge was to see if the waves arriving at the western slopes of the SCS were in fact, propagating trans-basin from generating sites to the east. The U.S. Department of State restricted use of the R/V Revelle westward of 119 E, to avoid angering the Chinese. Thus, we were gambling that solitons would indeed be traversing the central SCS and that they would already be well formed before reaching our approved western boundary.

Our experiment had two science thrusts. The first was to document the form of the solitary wave packet as it evolves. The KdV equation had traditionally been used to describe this evolution. However, it was thought that the waves are too non-linear to satisfy the approximations that go into KdV. More realistic equations were being explored (numerically) by Kevin Lamb, Theo Gerkema and others. It was of value to compare these new evolution models with the real ocean.

The second thrust was to understand the source of the turbulence that is often found in the wake of nonlinear wave trains. Coastal nonlinear waves often propagate in an effective two-layer ocean, with strong shears generated at the interface by the passing waves. Jim Moum and colleagues had documented the development of small-scale instabilities on "density steps" on the leading edge of the first crest in a wave packet.

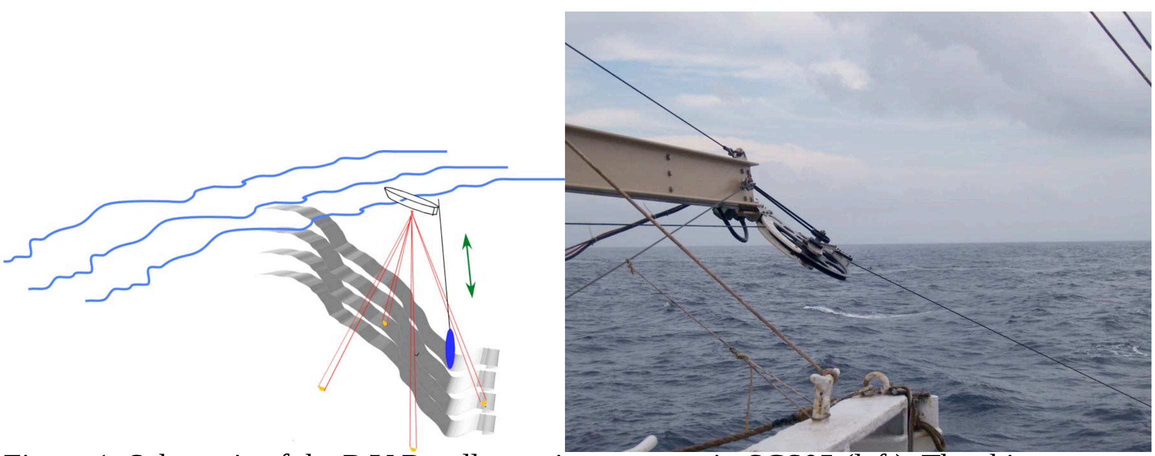

Figure 1. Schematic of the R/V Revelle sensing systems in SCS05 (left). The ship was equipped with downward profiling 140 and 50 kHz Doppler Sonars. A CTD was profiled at 4 m/s from the surface to ~700m. A custom winch and motorized sheave enabled the CTD to operate at extreme wire angles (right).

Observations of deep-water equatorial nonlinear waves suggest that the large-scale Richardson number is NOT close to critical in a wave train. We have seen turbulence, however. The solitons can trigger instabilities on the pre-existing shear, when it is already close to critical.

Our approach was to use the RV Revelle, with its deep profiling (50 kHz) and high-resolution (140 kHz) Doppler sonar system (HDSS Figure 1). We developed a fast-profiling CTD (F-CTD) to augment the velocity data with matching density observations. The key technical advances of the F-CTD included use of a thin, low-drag spectra cable suspended from a very high-speed digitally controlled permanent magnet winch motor. The Seabird SBE49 CTD and the added micro-conductivity sensor were driven at speeds exceeding 8 kts, roughly a vertical equivalent of Sea Soar. The system profiled to ~700 m every ~10 minutes.

The NLIWI field experiment took place in April-May 2005. In spite of having teething problems in its first deployment, an excellent F-CTD data record was achieved. The new winch proved to provide breakthrough capability, and the accompanying motorized sheave (Figure 1, right) allowed high-speed operation even at extreme wire-angles. Subsequent refinement of the system in IWAP (NSF), AESOP, SCS07, and in the Indian Ocean (NSF) has lead to a doubling of capability and a significant increase in reliability. Coupled with the HDSS, we were able to field a measurement system capable of resolving the baroclinic tides and solitons, and of discovering accompanying finer-scale phenomena (Figure 2).

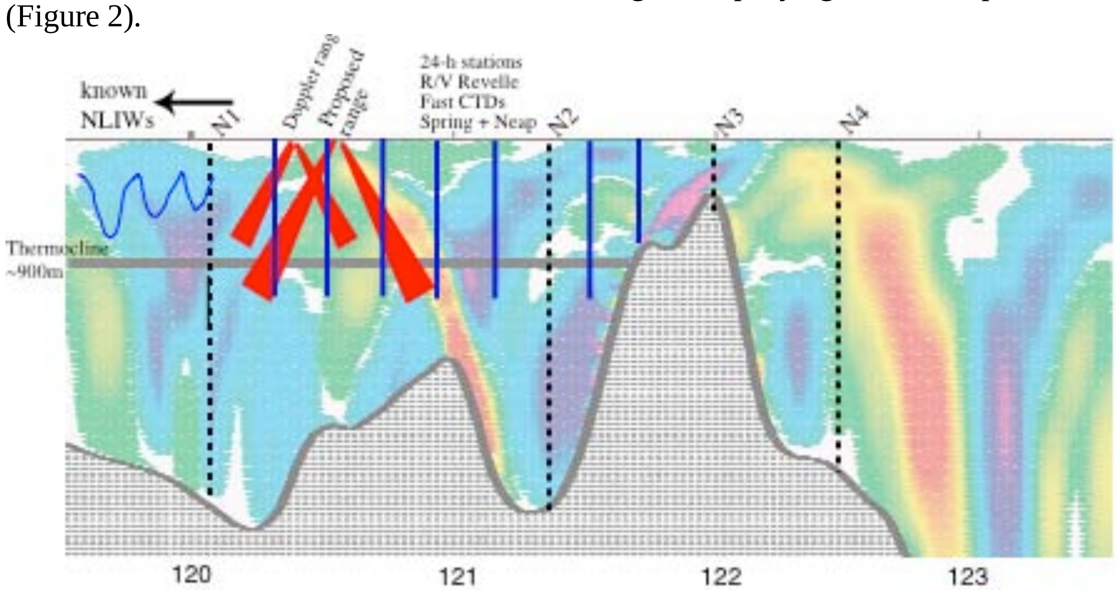

Figure 2. A cross section of the SCS, showing an instantaneous velocity pattern from the baroclinic tide, as generated by barotropic flow over the topography. The reach of the Revelle FCTD and sonar is shown to approximate scale. The depth-time reach of the system was appropriate to the scale of the phenomenon studied.

Results:

The fundamental discovery of the experiment is that huge internal solitary waves indeed traverse the deep central SCS, during periods of spring tide. A summary of soliton encounters in SCS05 is presented in Figure 3. The Revelle was operated in leapfrog mode. The ship would initially be stationed to the east, near 120 20’ East. After a “young” soliton completely passed by, the ship would steam westward. When ahead of the soliton, the ship would stop and collect a second record of the maturing soliton. This process was repeated, with the final record obtained with the ship stationed at our mandated western boundary.

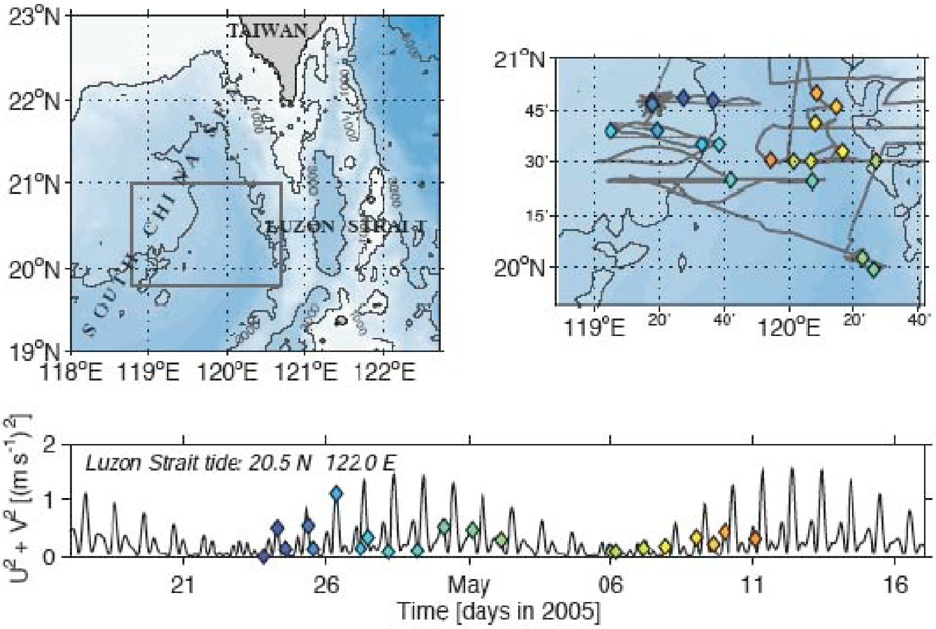

Figure 3. A chart of the NLIWI study area (left). The track of the Revelle in SCS05 (right). Soliton sightings from late April (dark blue), early May (light blue) and mid May (yellow orange) are shown geographically (right), and relative to the combined diurnal and semi-diurnal tides at the Luzon Strait (bottom).

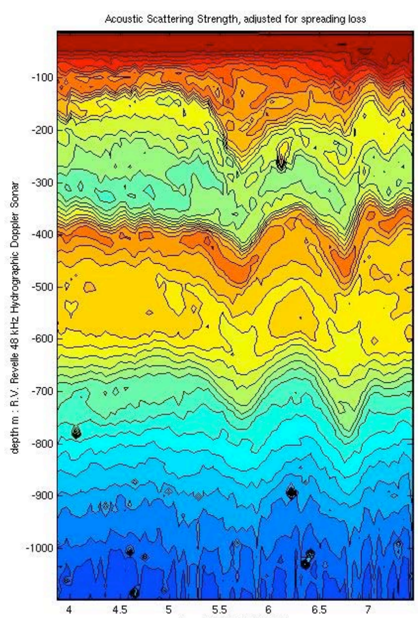

Figure 4. An acoustic scattering record from the HDSS 50 kHz sonar showing the passage of a large non-linear wave packet. The record is corrected for spreading and attenuation loss. Vertical excursions exceed 100 m at 700 m depth.

While the waves are larger than any previously observed (Figure 4), in the deep SCS, they are only weakly non-linear. Their form is well described by the classical Korteweg-deVris equation. While expected, the Richardson's Number associated with the soliton was large. Sonar intensity records displayed the vertical displacement of pre-existing scattering layers rather than the creation of fresh scattering signals (Figure 4).
The magnitude of modulation of ambient surface waves was surprisingly large. Apparent standing-wave patterns were seen in the leading edge of the soliton, with the breaking of 1-5 m waves producing vertical squirts of water with an associated “musical” sound that could heard over the noise of the ship in calm conditions.

The evolution of solitary waveform or packet structure followed no conclusive pattern. We concluded that the lateral variation in the propagation environment led to along wave-front variability in the signals. We followed the packets in the direction that we thought they were propagating, but 10^{o} errors could be expected.

Funds for subsequent data analysis were received in follow-on proposal 20044010R2 funded under the grant N00014-07-1-0236.