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Ocean Acoustic Propagation: Fluctuations and Coherence in Dynamically Active Shallow-Water Regions

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LONG TERM GOALS

The goals are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment (i.e. the physical mechanisms). This may enhance prediction of acoustic system performance and enable exploitation of oceanographic variability and signal features. Here, signal means any identifiable acoustic reception, including sounds of unknown origin, identifiable signals from discrete sources, and intentional signals.

OBJECTIVES

An objective is to explain sound fluctuation behavior in shallow-water environments with three-dimensional structure at all significant scales. A second objective is to classify acoustic stability and fluctuation using signal and/or oceanographic parameters. We are also investigating the time scales over which the often-invoked assumption of stationary conditions is valid. A noise prediction study not limited to shallow water was added this year.

APPROACH

To understand and predict shallow-water acoustic conditions we have been analyzing experimental data, performing theoretical analysis, and implementing computational propagation modeling. Three-dimensional (3D) acoustic effects arising from 3D aspects of the environment are an important class of effects that we focus on. The effort is aimed primarily at summer conditions in the temperate ocean (an approximate two-layer system), but also includes conditions found just inshore of shelfbreak fronts. We have focused on the Mid-Atlantic Bight and the northeastern South China Sea, two locations with available field data. The Mid-Atlantic Bight has warm water offshore and winter-cooled water on the shelf. In this particular frontal zone there can be a thin deep warm salty layer, capped by an inverted thermocline, on the near-edge section of the shelf. The South China Sea area has multiple types of large nonlinear internal waves. Internal tides and nonlinear mode-one internal gravity waves are known to often dominate acoustic variability in these (and other) regimes, and the acoustic effects of these waves are the main subjects of our research. Such waves at the location of a sound source would control acoustic mode excitation, and thus the effects of mode-stripping on long propagation paths.

Such waves along a sound propagation path can cause mode coupling (altering mode-stripping effects) and mode refraction. Long internal waves (having wavelengths tens of kilometers), including internal tides, can alter mode shapes and mode stripping, and can alter source excitation, but probably do not cause mode coupling.

The basic physics of sound propagation within ocean volumes with highly variable sound speed (variable in four dimensions) is well known. However, the sound speed (refractive index) is highly variable, causing complicated propagation and interference effects of unlimited variety. To quantify effects that occur in the real ocean we examine, as ground truth, field observations from four experiments, and compare them with theoretically based ideas and computationally derived results. The first experiment is the ONR ASIAEX South China Sea study. This study yielded four papers in 2004 containing analysis of acoustic signals at 250-450 Hz from sources at ranges of 21 and 32 kilometers: Orr et al. [2004], Mignerey and Orr [2004], Chiu *et al*. [2004], and Duda *et al*. [2004]. The next experiment is the Littoral Environmental Acoustics Research (LEAR) portion of the ONR Shallow-Water 2006 experiment (SW06). This experiment was on the shelf in the Mid-Atlantic Bight east of New Jersey, and took place July-September 2006 [Tang *et al*., 2007]. The third experiment is the spring 2007 ONR/Taiwan NLIWI acoustics experiment in the ASIAEX area of the South China Sea [Reeder *et al*., 2008]. The fourth is the ONR Quantifying, Predicting and Exploiting Uncertainty experiment (QPE), with major observations made in the East China Sea in Sept. 2009.

To better investigate horizontal refraction we have moved into 3D parabolic equation (PE) computational acoustic modeling. This tool is essential in sloped environments and where high lateral sound-speed gradients are found, such as in nonlinear internal waves, where the modal refractive index has been observed to vary up to one-half percent, and acoustic mode critical angles (related to ducting) can exceed five degrees.

The goal of the classification work is to identify unique shallow-water fluctuation regimes, classified in terms of fluctuation parameter state vectors received by an array, and relate them to their causes (large internal waves, small internal waves, focusing by alignment with internal wave crests, etc.). The ability to classify the propagation domain (i.e. identify the cause of dominating fluctuations) would enable modeling, prediction, and extrapolation. If received data alone could be used to identify the fluctuation regime, this would be a through-the-sensor technique.

WORK COMPLETED

A large number of LEAR/SW06 pulses transmitted from moored sources to the WHOI L-array (co-located HLA/VLA) have been analyzed. Figure 1 shows the experimental arrangement. Figure 2 shows coherence length estimates, obtained with a broadband method, and other parameters obtained from analysis of HLA signals after array shape correction and beam steering. Figure 2 shows that the sound arrival angle is altered and coherence length is diminished by the presence of internal waves between the source and receiver. The coherence length at fixed steering angle fluctuates greatly because of sound refraction and waveform interference. The time series of maximum observed coherence length is slightly more regular and reaches very long lengths because refraction is adaptively corrected for, but the maximum coherence length is not always long, with low values at times of wave activity. A manuscript describing the one-month time series of observations along the two paths is in progress, building on our published paper [Collis *et al*., 2008]. Figure 3 shows characteristics of some SW06 internal wave sound ducts in terms of normal-mode wave number perturbations (modal phase velocity perturbations). The figure is from a paper published this year [Lynch *et al.,* 2010].

Our Cartesian coordinate 3-D parabolic equation (PE) code has been incorporated extensively into our work. The model has been used to model environments built algorithmically and built from field measurements. This fiscal year a paper that used the code was published [Lin *et al.,* 2009]. The paper shows how an internal wave duct that fades (lengthwise) into the background state can emit highly variable beams of sound. At frequencies of a few hundred hertz, each acoustic mode has its own structure, evolving in time as the wave or sound source moves, so that receivers past the end of the duct see rapid variations of mode content and of overall sound level. Another paper was published having the topic of sound in curved internal waves [Lynch *et al.,* 2010]. This paper included 3-D PE modeling of sound through realistic internal waves. Further modeling was applied to the 2007 South China Sea experiment. Figure 4 shows the experiment region. Next, the conditions measured by the 2007 South China Sea PI's were used to model sound propagation. Initial results obtained with 3D propagation modeling through 2D (artificially straightened) internal waves showed promising agreement with measurements [Reeder *et al.,* 2008]. The next step was to fully model the propagation through the 3D internal waves, Figure 5. The simulations fully mimic the propagation along the curved waves. The simulations provide results at many angles besides those measured in the field, so other effects may be discovered. This fully-4D work has yielded a journal article submitted in September 2010 with authors Duda, Lin and Reeder. The paper covers deep and shallow ducting of sound in the large internal waves, and includes good data/model comparisons; the comparisons imply that insight taken from the model results can be trusted.

More coastal data have recently been obtained from QPE PI's. The predicted and observed acoustic propagation effects in this area will be compared against those tabulated in the earlier studies mentioned above.

RESULTS

SW06/LEAR: This year saw the publication of the previously mentioned paper covering propagation down an internal wave duct that fades away, as observed a few times in SW06 [Lin *et al.,* 2009]. The results show that a highly time-dependent mix of acoustic mode beams can emerge from the duct, with the beams of each mode appearing to be independent, or at least weakly coupled. A manuscript on the topic of propagation through curves internal waves was published [Lynch *et al.,* 2010]. The paper draws heavily on information from the SW06 experiment (internal wave shapes, ducting parameters, etc.)

A further analysis of the SW06 HVLA fluctuation data set that was partially analyzed and published [Collis *et al.,* 2008] puts the preliminary results into context. The highly variable horizontal array gain and coherence length variability for along-internal wave duct propagation in SW06 is now tabulated for many paths (both along-shelf and across-shelf) for the entire experiment. The manuscript is in preparation.

SCS/NLIWI: Sound refraction effects measured at the South China Sea site were found to be consistent with model results, with initial results appearing earlier [Reeder *et al*., 2008]. The paper reports mode refractive indices and critical angles of the internal waves present during the experiment. The 3D acoustic effects were replicated with propagation through straight internal waves using the 3-D propagation code. The good comparison between the experiment and the initial model output suggests that behavior at source-receiver geometries other than that of the experiment (down the internal wave duct, Figure 4) can be examined. This year, propagation through curved internal waves more consistent with the observations showed very similar results, with the addition of a new effect: surface ducting at

different azimuth angles than low-mode deep ducting. In the curved-wave situation, critical mode refraction effects evolve as the sound moves along the curved duct, rather than being constant. As a result, the internal waves may behave like prisms, separating modes. A journal paper was submitted.

Noise: A study of North Pacific Ocean noise levels at 100 to 1000 Hz was completed this year under a grant expansion. Contemporary noise, noise in 2050, and noise in 2100 was estimated at multiple locations using ocean sound absorption values derived from ocean acid levels computed in a state-of-the-art climate model. The results showing a small effect on noise level were published in a journal (Udovydchenkov *et al.,* 2010).

IMPACT/APPLICATIONS

The results may be useful in the signal processing domain. Algorithms may be developed by others that are robust to signal fluctuations, or which may exploit them. For example, processing might exploit fluctuations by utilizing intermittent but strong signal peaks, by predicting time limits for coherent analysis, or by predicting wait-time intervals before signals are reacquired after fade-outs.

RELATED PROJECTS

For SW06/LEAR the PI is working with Drs. J. Collis (Colorado School of Mines), H. DeFerrari (U. Miami), J. Lynch (WHOI) M. Badiey (U. Delaware), and J. Nash (Oregon State U.). The PI collaborates with Dr. Y.-T. Lin of WHOI on computational efforts. The PI is working with other ONR PI's analyzing data from the SW06, 2007 South China Sea, and QPE experiment sites. Dr. Ilya Udovydchenkov is supervised by the PI as a postdoc with ONR funding, and is working on coupled-mode long-distance deep-water acoustics. This year am ONR funded 3D sound modeling study joint with the Scripps Institution of Oceanography was initiated.

REFERENCES

Chiu, C.-S., S. R. Ramp, C. W. Miller, J. F. Lynch, T. F. Duda, and T. Y. Tang, Acoustic intensity fluctuations induced by South China Sea internal tides and solitons, *IEEE J. Oceanic Eng., 29,* 1249-1263, 2004.

Duda, T. F., J. F. Lynch, A. E. Newhall, L. Wu, and C.-S. Chiu, Fluctuation of 400-Hz sound intensity in the 2001 ASIAEX South China Sea Experiment, *IEEE J. Oceanic Eng., 29*, 1264-1279, 2004.

Mignerey, P. C. and M. H. Orr, Observations of matched-field autocorrelation time in the South China Sea, *IEEE J. Oceanic. Eng., 29*, 1280-1291, 2004.

Orr, M. H., B. H. Pasewark, S. N. Wolf, J. F. Lynch, T. Schroeder, and C. -S. Chiu, South China Sea internal tide/internal waves - Impact on the temporal variability of horizontal array gain at 276 Hz, *IEEE J. Oceanic. Eng., 29,* 1292-1307, 2004.

PUBLICATIONS 2008-2010

Reeder, D. B., T. F. Duda and B. Ma, Short-range acoustic propagation variability on a shelf area with strong nonlinear internal waves, *IEEE Oceans '08 Kobe Conference Proceedings*, April 2008. [published, not refereed]

Duda, T. F., and L. Rainville, Diurnal and semidiurnal internal tide energy flux at a continental slope in the South China Sea*, J. Geophys Res (C), 113*, C03025, doi:10.1029/2007JC004418, 2008. [published, refereed]

Duda, T. F. and A. D. Pierce, History of Environmental Acoustics, 1960's to 2000's*, MTS/IEEE Oceans '08 Quebec Conference Proceedings*, 2008. Invited paper. [published, not refereed].

Collis, J. M., T. F. Duda, J. F. Lynch, and H. A. Deferrari, Observed limiting cases of horizontal field coherence and array performance in a time-varying internal wavefield, *J. Acoust. Soc. Am., 124*, EL97, 2008. [published, refereed]

Li, Q., D. M. Farmer, T. F. Duda, and S. Ramp, Measurement of nonlinear internal waves using the inverted echo sounder, *J. Atmos Oceanic Technol., 26,* 2228-2242*,* 2009. [published, refereed]

Lin, Y.-T., T. F. Duda, and J. F. Lynch, Acoustic mode radiation from the termination of a truncated nonlinear internal gravity wave duct in a shallow ocean area, *J. Acoust. Soc. Am., 126,* 1752-1765, 2009. [published, refereed]

Lynch, J. F., T. F. Duda, Y.-T. Lin and A. E. Newhall, Nonlinear internal wave interactions with low frequency shallow water sound -- What is left to do?, in *Proceedings of the 2nd International Conference on Shallow Water Acoustics*, Sept. 16-20, 2009, Shanghai, China, 2009. [published, not refereed]

Lynch, J. F., Y.-T. Lin, T. F. Duda and A. E. Newhall, Acoustic ducting, reflection, refraction, and dispersion by curved nonlinear internal waves in shallow water, *IEEE J. Oceanic Engineering, 35,* 12-27, 2010. [published, refereed]

Udovydchenkov, I. A., T. F. Duda, S. C. Doney and I. D. Lima, Modeling deep ocean shipping noise in varying acidity conditions, *J. Acoust. Soc. Am., 128*, EL130-EL136, 2010. [published, refereed]

Duda, T.F., Y.-T. Lin, A. E. Newhall, W. Zhang and J. F. Lynch, Computational studies of time-varying three-dimensional acoustic propagation in canyon and slope regions, in *Oceans 2010 Seattle Conference Proceedings,* IEEE/MTS, 2010. [published, not refereed]

Newhall, A. E., G. G. Gawarkiewicz, J. F. Lynch, T. F. Duda, N. M. McPhee, F. B. Bahr, C. D. Marquette, Y.-T. Lin, S. Jan, J. Wang, C.-F. Chen, L. Y. S. Chiu, Y. J. Yang, R.-C. Wei, C. Emerson, D. Morton, T. Abbot, P. Abbot, B. Calder, L. Mayer, P. F.J. Lermusiaux, Acoustics and oceanographic observations collected during the QPE Experiment by Research Vessels *OR1, OR2* and *OR3* in the East China Sea in the summer of 2009, WHOI Technical Report WHOI -2010-06, 2010. [published, not refereed]

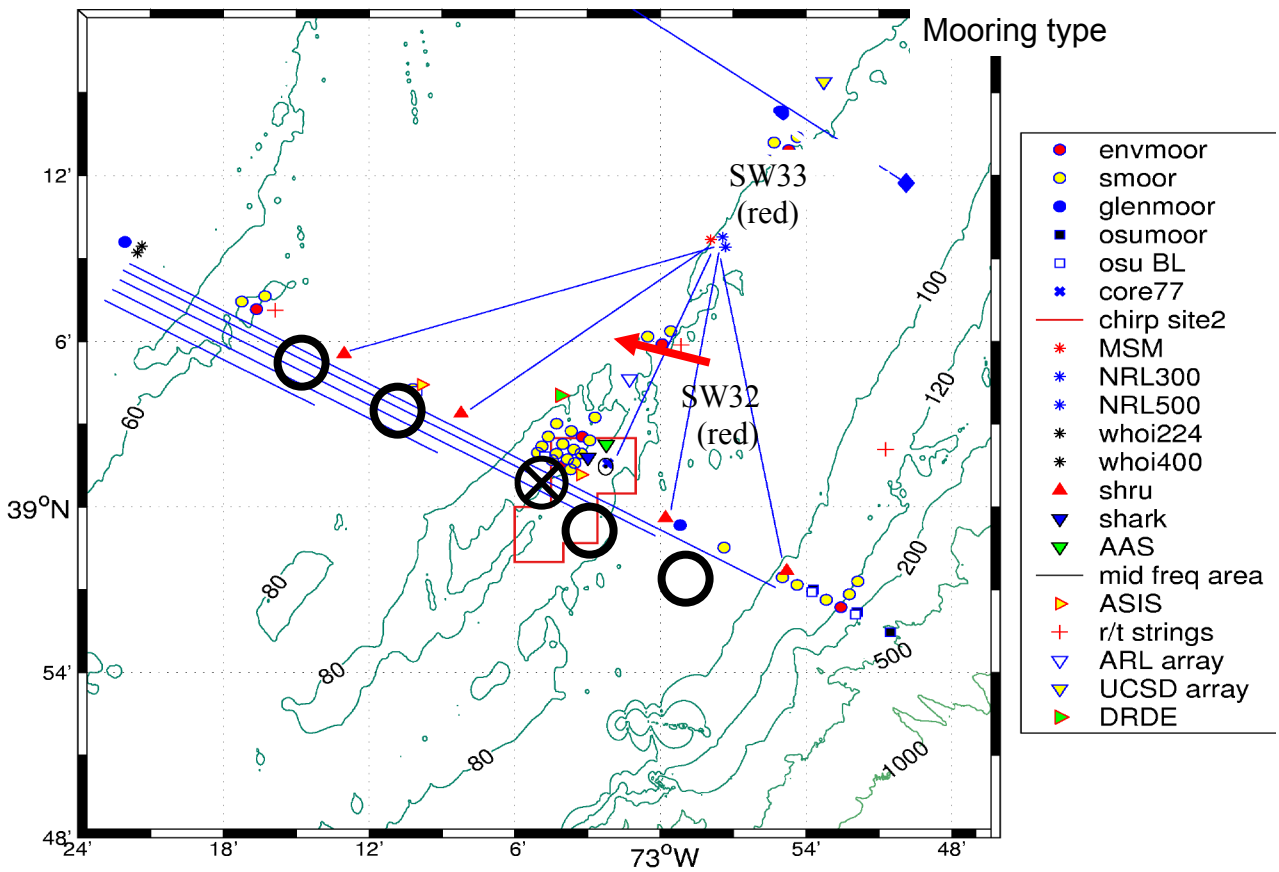

Figure 1. SW06 propagation paths from moored sources to moored receivers are shown with blue lines. The circles show single-phone SHRU receivers. The circle with the X shows the WHOI L-array (vertical line array (VLA) attached to horizontal line array (HLA) on the seafloor). The northwest (NW) site had 224 and 400 Hz sources. The northeast (NE) site had 100, 200, 300, 400, 800 and 1600 Hz sources. Environmental mooring SW32 whose data are shown in Fig. 2 is marked. Depths are contoured in meters.

[The L-array is near the center. At heading 30 (approx) are SW32 at 10 km distance and the northeast sources at 20 km. The four SHRUS are near a line of heading 300, two offshore of the L-array and two inshore. The northwest sources are 32 km from the L-array at heading 300 at about 60-m depth. The depth along the L-array to NE (heading 30) line is about 80 m.]

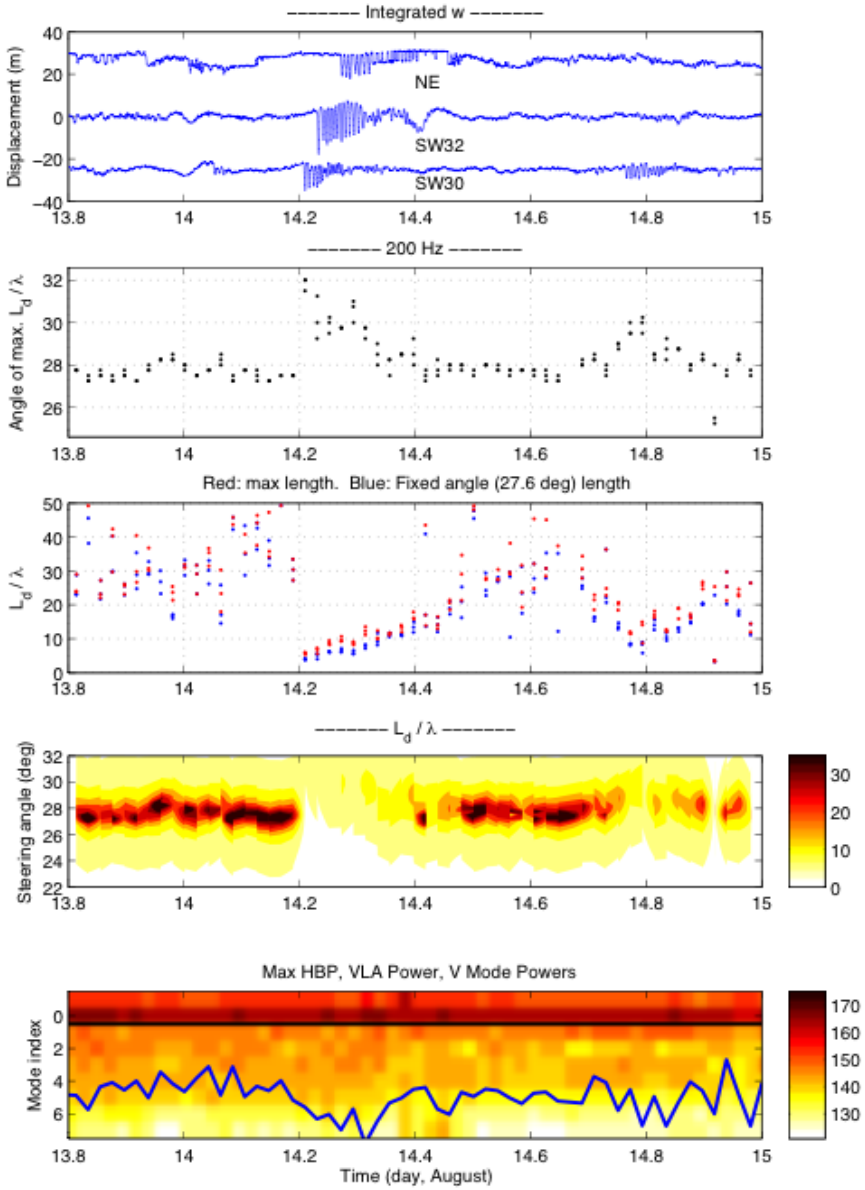

Figure 2. Wave and pulse parameters for the 200-Hz northeast source are shown for August 14, 2006. (a, top) Time series of thermocline displacements along the acoustic path, showing internal wave packets. (b) The HLA steering angle with maximum horizontal field coherence length is shown. (c) The coherence length divided by the acoustic wavelength is plotted. The red dots show the maximum coherence length as a function of time. The blue dots show the coherence length at the fixed angle of 28.2 degrees. (d) The coherence length is contoured versus steering angle and time. [Source of data shown in (b) and (c)]. (e) Mode content determined from VLA receptions. The blue line shows an ad hoc measure of mode width. Coupling evidence is seen at some of the times of waves and sound angular deflections.

[During two intervals of strong internal waves the acoustic parameters are altered, with beam angle changing from 28 to 30 degrees and coherence length falling from 40 to 7 wavelengths.]

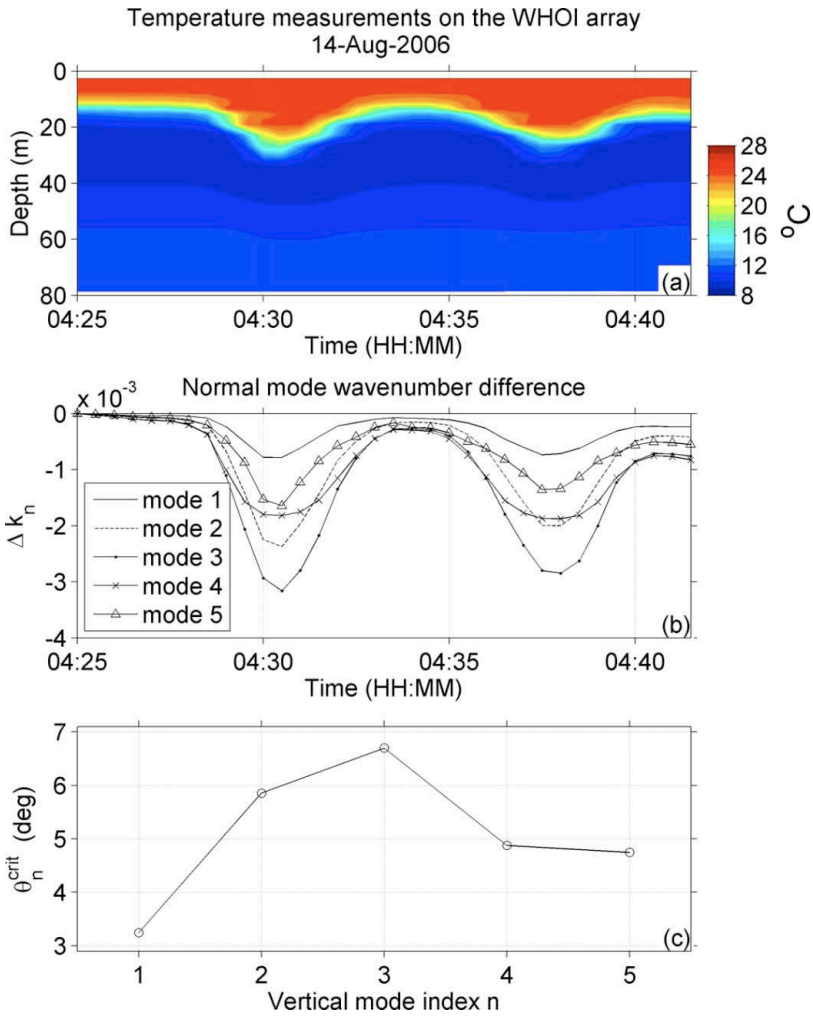

Figure 3. (a) Thermocline displacements from a portion of one internal-wave event measured at the SW06 WHOI L-array. (b) The perturbation of 100-Hz modal wavenumbers from background values prior to the wave event. (c) Critical angle for the early-time side of the acoustic mode duct existing between the two waves, 100 Hz. From Lynch et al., 2010.

[(a) Two internal waves of displacement are shown, one of amplitude 15 m at 0431 14 Aug 2006, and one of amplitude 10 m following at 0438. (b) Perturbation mode wavenumbers for 100 Hz (delta-k) peak at 3 x 10^{-3} rad/m in the first wave for mode 3, slightly less in the second wave. Mode-1 perturbations are the least. Modes 2, 4 and 5 have intermediate perturbations. (c) The critical angles for modes 1 through 5 are 3.2, 5.9, 6.7, 4.9 and 4.8 degrees, respectively.]

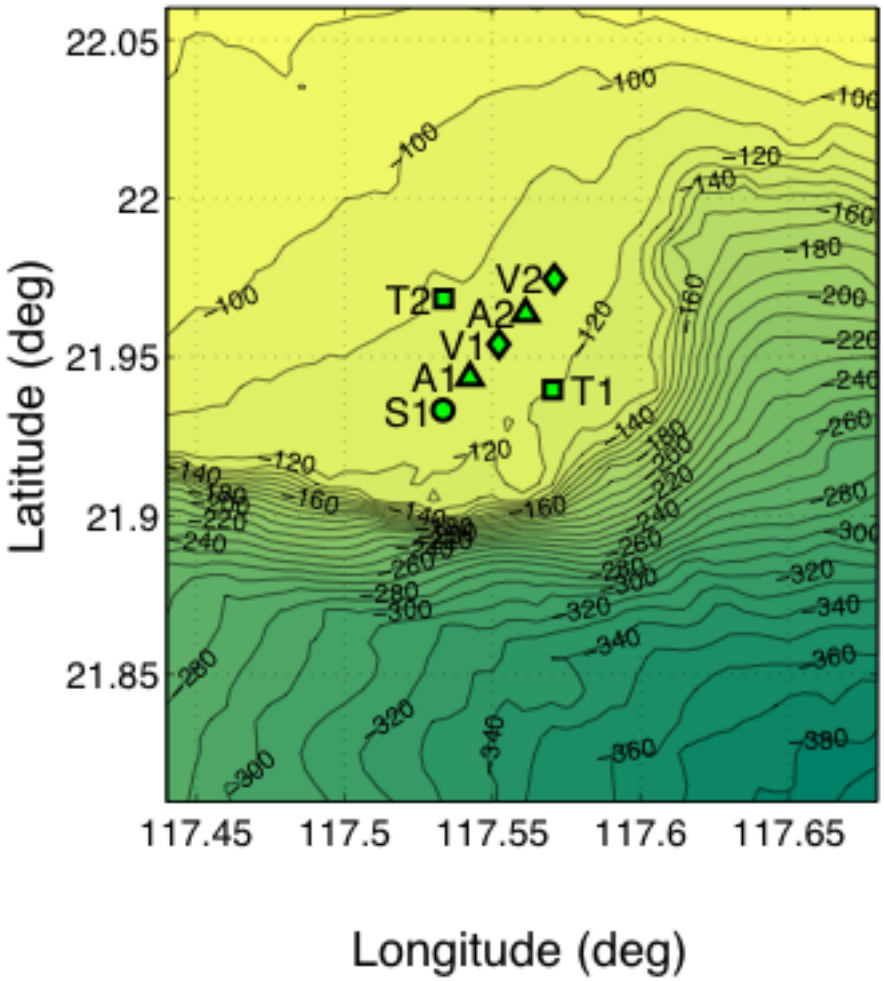

Figure 4. Bathymetric chart showing the 2007 NLIWI experiment area. Data from seven moorings were analyzed, shown in green. Five are along the acoustic propagation line: S1, 400-Hz acoustic source; A1 (ADCP) 1.48 km from S1; V1 (VLA) 3.00 km from S1; A2 (ADCP) 4.43 km from S1; and V2 (VLA) 6.01 km from S1. The heading along the mooring line is 40° True. Two additional thermometer array moorings were: T1, 2.45 km @ 130° from V1 and T2, 2.50 km @ 310° from V1. Internal waves arrived from the right (east) with crests approximately aligned with the main mooring line.

[The A1 to V2 mooring line (acoustic propagation line) is plotted. The depth in the mooring area is about 116 m. 4 km south and 4 km east of the moorings the shelf ends and the water becomes deeper, with the shelf edge having a curved shape.]

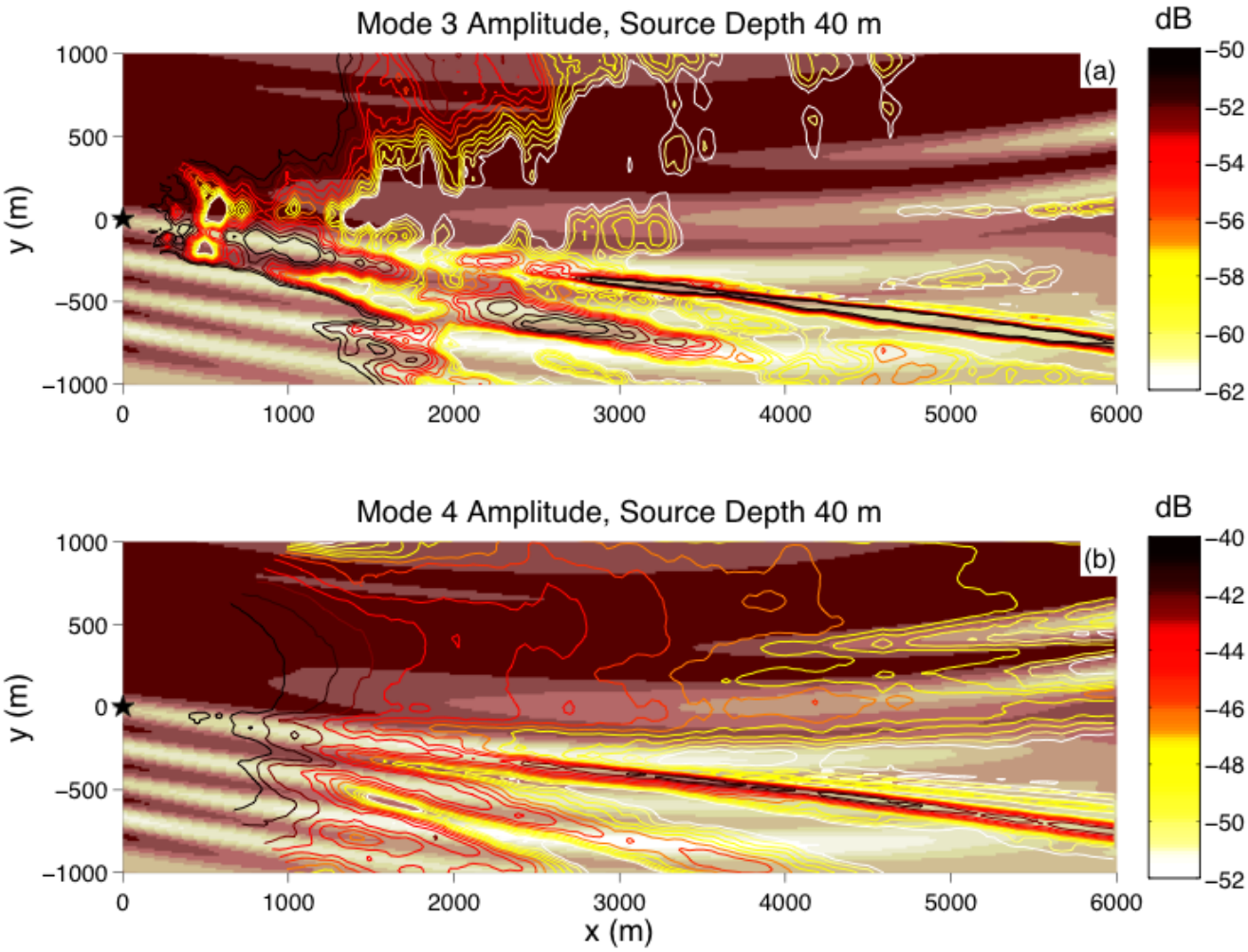

Figure 5. Two plots of 3D 400-Hz sound fields propagating through curved internal waves constructed from 2007 South China Sea NLIWI data. One time snapshot of 4D modeling is shown. The 3D fields are decomposed into normal mode constituents throughout the rectangular domain, with amplitude of mode 3 shown above and of mode 4 below with color contours. Sound is from a source at 40-m depth, which moves in and out of the warm upper layer as the waves pass. The light-to-dark color fill shows the thermocline heights in the internal waves, with dark showing depression and light showing elevation. Elevated zones are full-depth sound ducts (deep ducts, essentially) and the depressed zones are surface ducts. High mode-4 amplitude in the depression zone is a signature of enhances surface ducting. The sound source S1 is at the origin.

[The domain [0,-1000] < [x,y] < [6000,1000] (meters) is shown. Modes 3 and 4 are elevated by more than 10 dB in a deep beam extending from the origin to [6000,-700]. This sound originates in a curved internal wave duct but departs in a beam. Other beams are seen in lower-y areas. At y > 0 (upper half of plot), in a very wide depression wave, the mode 4 surface ducted sound propagates with little attenuation.]