PREDICTING INTERNAL WAVE PACKET CHARACTERISTICS AND ACOUSTIC SIGNAL COHERENCE

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Abstract: *A handful of experiments, theoretical studies and simulation studies have shown that packets of nonlinear internal waves, which are commonly found in shallow water areas, can have strong impacts on propagating sound. Impacts include rapid changes in the temporal and spatial coherence of the sound, and the occurrence of strongly focused sound accompanied by shadow zones with little or no sound energy. Moreover, the acoustic effects can be anisotropic, so that sound traveling in one direction geographically will have different characteristics than sound traveling another direction (for instance, along and across internal wave crests). To better apply this knowledge to the use of sound, we have developed a system of linked models to study our ability to predict the appearance of the internal wave packets, and to predict characteristics such as packet speed and direction, wave size, and wave shape. The model system links three fluid models: a primitive equation model, an internal tide model, and a nonhydrostatic internal wave model. These are linked in turn to a 3D acoustic propagation model. Output from the model system will be shown, including comparison with experimental data from the Shallow Water 2006 program. Acoustic field and acoustic parameter predictions from the system will also be shown and will be compared with experimental results.*

Keywords: *Nonlinear internal waves, ocean dynamical modeling, three-dimensional underwater acoustic propagation, acoustic field coherence*

INTRODUCTION

Nonlinear internal waves with strong currents and dramatic vertical displacements have been found to impact many oceanographic processes, and have been given a great deal of attention. Because they move stratified water vertically they create large and moving sound-speed anomalies centered at the pycnocline, and thus impact propagating sound. Many studies have shown the effects, through both theory (for example [1,2]) and experiment (for example [3-6]). In many situations, the three-dimensional (3D) nature of the internal waves is key to the acoustic effects [2-5].

The processes by which the waves affect sound are now well understood. However, ultimate impacts on the sound field vary widely depending on many parameters. These include the angle between the internal wave direction and the sound propagation direction, the amplitude (vertical excursion) of the internal waves, the wavelength, and whether the waves appear in isolation or in groups. Therefore, to predict the general patterns of internal wave effects on underwater sound in any given area, some basic properties of the waves at that location would need to be known, starting with such basic things as wave presence or absence, and wave direction. Moving beyond general patterns, specific acoustic effects at a given time and place might be predictable in detail if the waves could be predicted in detail.

Here, we review the basics of a system to study factors controlling the detailed behavior of the waves, to quantify their predictability. The system can also provide wave predictions given enough input data to drive the system towards a reliable state estimate that can run forward in time. The ability of the system to make predictions of sound field properties such as intensity level and coherence will be demonstrated but not tested directly against data for accuracy. Thus far, the major recent contributions from this research may be quantification of the internal tides and the nonlinear wave formation variability. The pronounced acoustic effects that the waves have, once they are formed, have been studied in the past few years and this part of the research effort may be further along.

LINKED MULTIPHYSICS MODELS

The system links three physical oceanographic models, each valid within a specific dynamic range and under a specific set of dynamical approximations. These are (1) a primitive equation computational flow model, (2) a ray-based model of internal tide modal propagation, and (3) a mode-based model of nonlinear nonhydrostatic wave evolution. When the models are linked, the system embeds packets of nonlinear nonhydrostatic internal waves (NNIW) into large-scale ocean flow fields. Internal tides are simply internal gravity waves of tidal frequency, which appear where tidal flows efficiently provide energy to the vertical oscillations of internal waves. The system can be considered a hybrid physical model; the term hybrid been used for models of processed like El Nino/Southern Oscillation (ENSO) but the term is not rigorous. The merged environmental fields (background and NNIW) are then processed to form a simulated environment for 3D acoustic modeling; and the acoustic simulation is the final step. The basics of the system are described in a paper written for the 2014 Underwater Acoustics Conference [7] and a recent paper gives a more complete explanation [8]. Our name for the system is the IODA-A model, because it is the main system put together under the Integrated Ocean Dynamics and Acoustics Project [7].

The modeling rests on 3D ocean fields of eddies, fronts, other mesoscale features simulated with tidal forcing included. The tides are necessary because they force the features that can be transformed dynamically into predicted NNIW.

The ocean fields from model (1), calculated using the nonlinear primitive equations with hydrostatic pressure, can be either constrained by data and meant to be predictive, or fully idealized with analytic boundary and flow descriptions, or somewhere between these. Certain features of the large-scale flow known to be important to NNIW formation and propagation are extracted from the flow fields to take the next steps to compute and then embed the NNIW.

There are six families of operations involved in linking the component models and then computing the sound field. (1) Regional modeling must be performed. Fields from a regional model with surface tides and internal tides are needed. (2) Estimation of a background state (with no internal waves) in a region of interest for internal-wave modeling is required. This required separation of internal waves from a background state suffers because of entangled time and spatial scales. An isopycnal surface tracking method is adopted for this operation. (3) Internal tides in the regional model must be characterized. Internal-tide signals must be extracted from the full field of isopycnal displacements (position differences from the estimated background state) at critical locations, and their properties tabulated. This forms input for internal tide and NNIW propagation analysis. Internal tide propagation trajectories (rays of mode-one waves) are computed at this time. (4) The extended rotation-modified Korteweg-de Vries nonhydrostatic wave model (eKdVf model) is run along the internal-tide modal rays. It is initialized and constrained by the background state and the characterized internal tides. (5) The regional model and eKdVf fields are merged into a set of volumetric ocean state snapshots. (6) Lastly, 3D acoustic simulations are run with the split-step Fourier parabolic equation (PE) method [9].

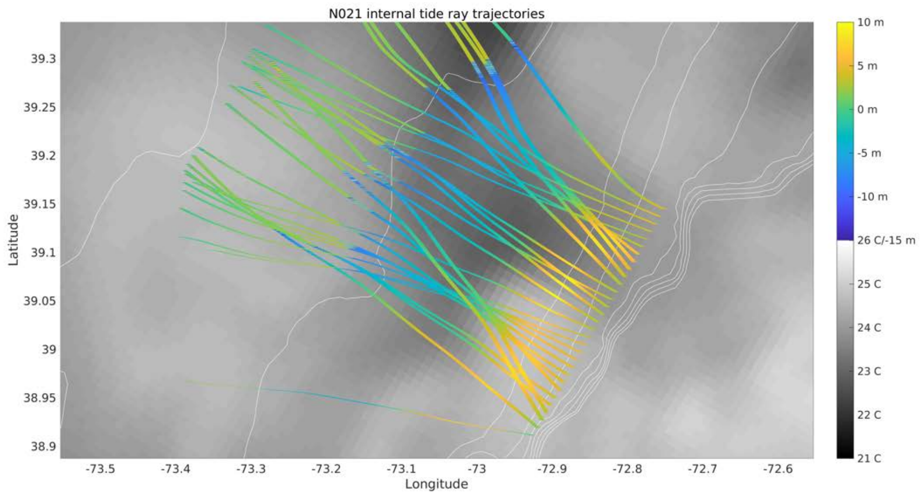

Fig. 1: Internal-tide mode-one rays computed from the model are plotted. The background field that is shown is the surface temperature of the MIT-MSEAS model. The color along the rays shows mode amplitude from the eKdVf model. Bathymetry in shallow water is contoured, none are shown in the rapidly deepening water to the southeast.

Fig. 1 shows mode-one internal tide rays initiated at the outer continental shelf, at the site of the ONR Shallow-Water 2006 experiment [10] and traced shoreward with refraction determined by the mode-one phase velocity field. The regional model used for this ray calculation is the MIT MSEAS data-assimilating model [11]. The area is east of New Jersey and Delaware Bay, USA. Mode-one internal waves have vertical displacement that are of uniform sign at all depths, appear to be an oscillation of the main thermocline, and are also similar to interfacial waves in a two-layer system. The rays are started in a cross-shelf zone where internal tides show flux divergence. This is the so-called critical zone where bathymetric slope transitions from low and *subcritical* in the shallow water to the northwest, to steep and *supercritical* to the southeast. Here, critical means that the near-seabed internal tide energy flux direction, in a vertical plane, is parallel to the seafloor. This is where internal tides are formed via barotropic tidal motion. Not all continental shelf edges and slopes exhibit this transcritical slope behavior, but most do, so the model had good applicability. The rays in Fig. 1, which model wave energy moving inshore to the northwest of the critical slope, are initiated at horizontal angles determined by a beamforming-type examination of internal tide motions in the area. Mode-one rays are shown and used exclusively in this modeling because a large fraction of internal-wave energy on continental shelves is mode-one, usually more than 50 percent, and often much more than that.

Fig. 2 shows a snapshot of internal tides and NNIW computed along the rays of Fig. 1 with the eKdVf model and then interpolated to fill more of the area. The 3D sound-speed field with wave perturbations can be built from this wave-amplitude field $\eta(x,y,t)$ via

$$c(x,y,z,t) = c_B\big(x,y,z-\varsigma(x,y,z,t)\big) \quad (1)$$

where the modeled internal-tide and displacement at each location is given by

$$\varsigma(x,y,z,t) = \eta(x,y,t)\phi_{\boldsymbol{B}}(x,y,z) \quad (2)$$

Here, c_B is the background sound-speed structure for a time window of the regional model determined by an averaging process that removes internal tides and gives background temperature (T) and salinity (S), η is the mode-one internal wave field snapshot from eKdVf (includes both internal tides and NNIW), and ϕ_B are the mode-one internal wave normal modes from the background T and S. The subtidal time-dependence of c_B and ϕ_B are suppressed.

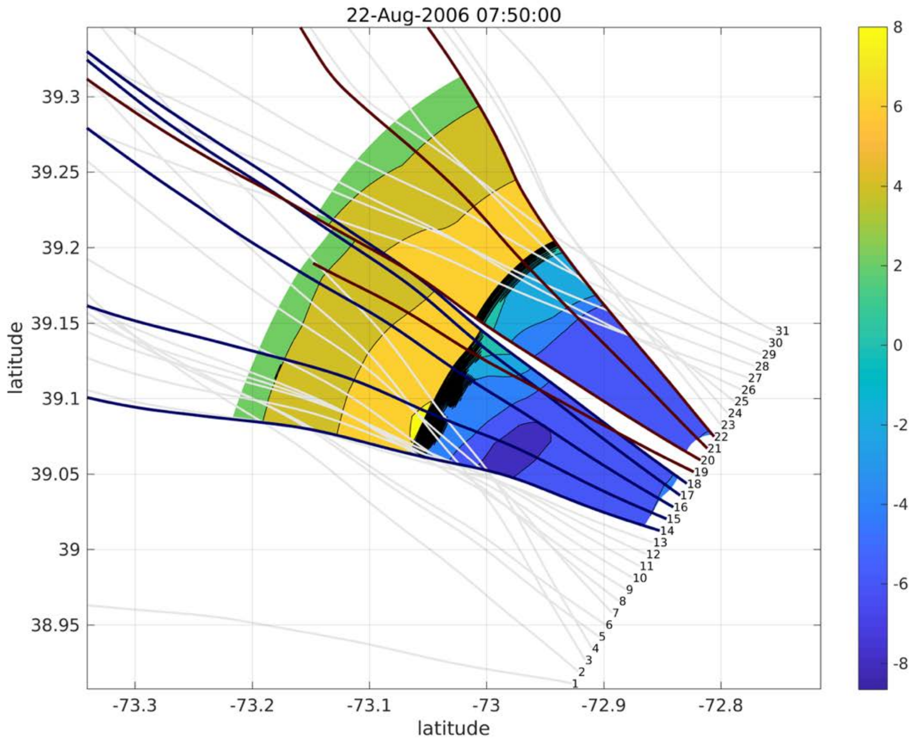

Fig. 2: Internal tides of order 30-km wavelength and short NNIW of order 300-m wavelength computed using the eKdVf model are shown. The model is run independently along each ray, then the results are examined to find wave crests common across rays and can be grouped to form wave crests similar to what is seen in nature. After the crests are identified, 3D sound-speed fields can be built from this. Many rays do not show NNIW development (not shown).

ACOUSTIC MODELING

The final step of the joint ocean/acoustic estimation procedure is to run the 3D acoustic simulation. Fig. 3 shows a rectangular domain for the Cartesian 3D PE for a packet of NNIW from the area depicted in Fig. 2, although for a different time. The figure also shows the intensity of the simulated 1000-Hz field at one depth, and the incoherent depth average intensity that shows sound refraction in the NNIW.

The acoustic field from the PE is now analyzed to show the effects of the NNIW on horizontal coherence. The correlation length L is derived from the correlation function

$$C(\Delta y; x, y, z) = \left. \langle \psi(x,y)\psi^*(x,y+\Delta y)\rangle \middle/ \langle \psi(x,y)\psi^*(x,y)\rangle \right. \tag{3}$$

for the acoustic field ψ by determining the spatial lag Δy where C drops to exp(-1) from a value of unity at zero lag. The correlation length in the y direction is shown in Fig. 4. This is computed by using 50-m long groups of data, so L longer than 50 m is not computed. Values of 50 m indicate full field coherence in the y direction. In the NNIW, L drops to order 5 or 10 meters, only a few wavelengths. The figure also shows signal strength (upper right) and signal strength after coherent field summation by plane-wave beamforming in the direction to the source. The beamforming is not fully effective in the NNIW, and is even less effective in an area in the NNIW "shadow". At the lower right the figure shows the gain from the coherent summation beamforming, measured with respect to the theoretical gain of 10 log10(N) where N is 66 elements in each 50-m array. Fig 5. Shows statistics of horizontal array gain degradation in selected portions of the modeled region, namely away from, within, and in the shadow of NNIW,

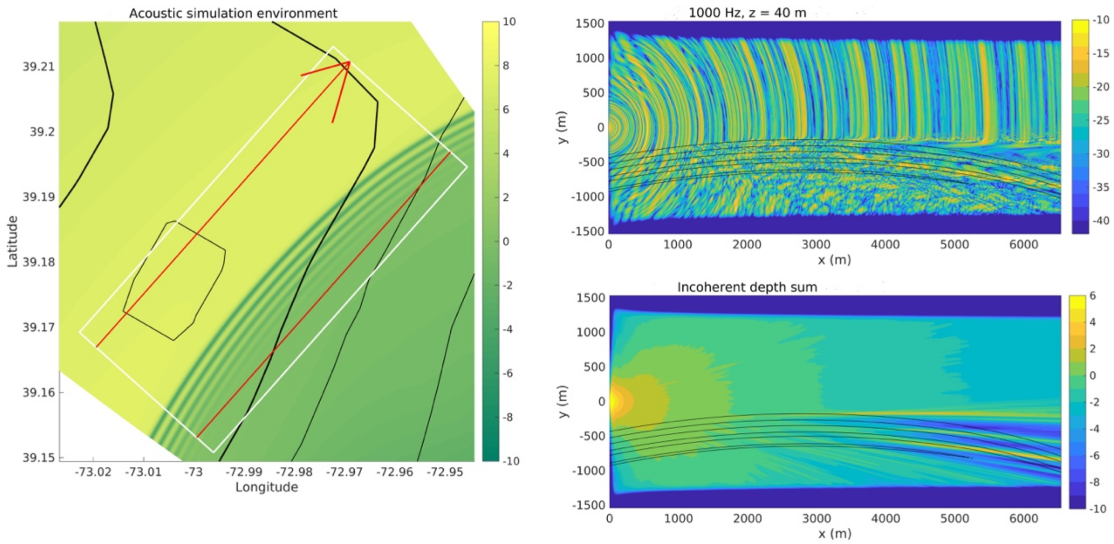

Fig. 3: Left: the rectangle shows the domain for a 1000-Hz PE simulation. The color shows the wave amplitude field η(x,y,t). The NNIW are waves of depression with downward displacements (dark color, green). Bathymetry is contoured; a closed 62-m contour (mound is shown, along with the thicker 74-m contour, and deeper 76 and 78 m contours. Upper right: The sound field intensity at 40-m depth is shown. Lower right: The depth-averaged intensity in the water is shown. Source is 60-m deep at (0,0).

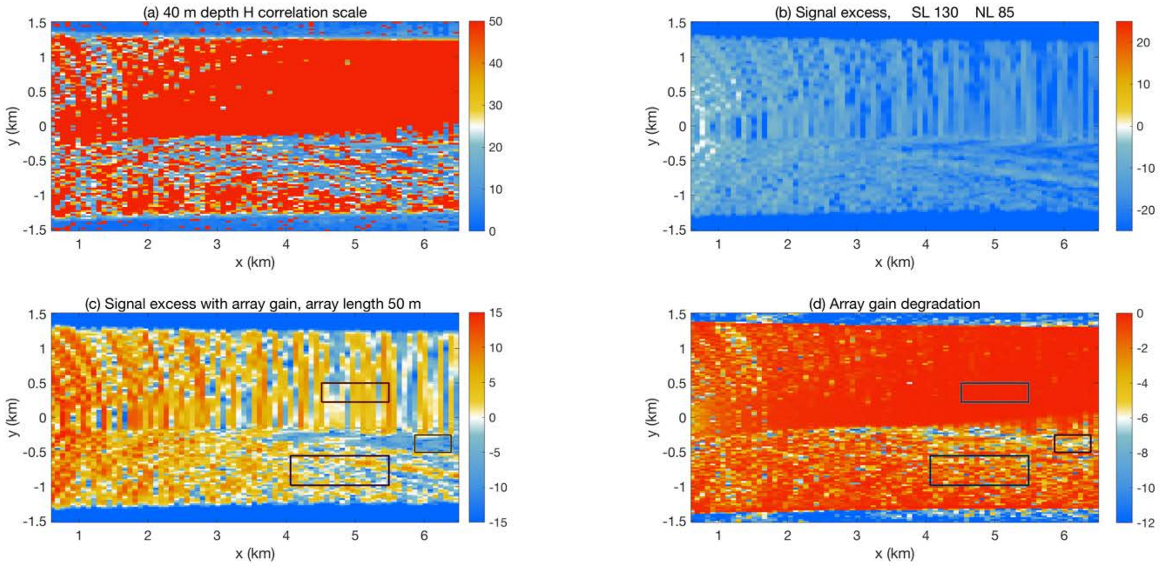

Fig. 4: Upper left: For 1000-Hz sound at 40-m depth in the simulation (Fig, 3), the field correlation length in the y-direction is plotted for the domain. 50-m long groups of points (synthetic arrays) are used. Upper right: The mean sound intensity in each synthetic array is shown. This is a scaled version of intensity, signal excess SE=SL-TL-NL. Lower left: Signal excess after beamforming is shown, SEB=SL-TL-NL+AG, where AG is the achieved array gain. Lower right: The array gain degradation is shown, AG-TG where TG is theoretical gain.

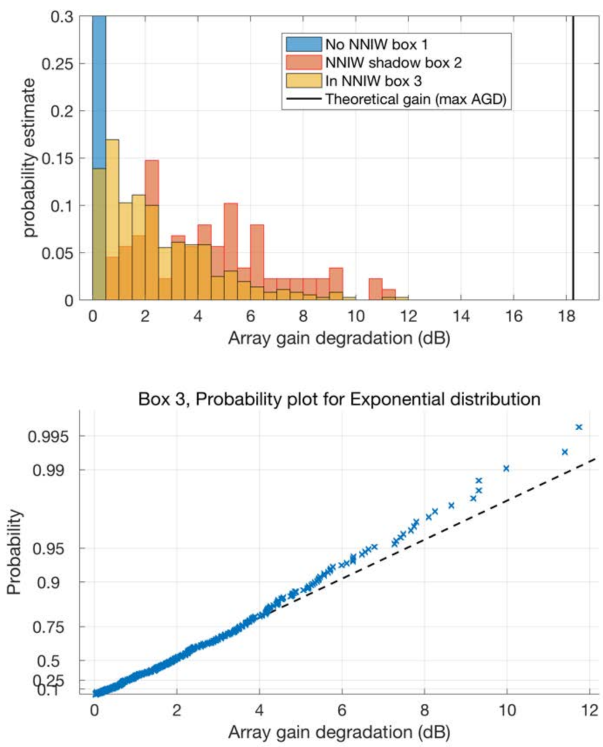

Fig. 5: Statistics of the array gain degradations shown in Fig. 4d are shown, with AGD= TG-AG. Histograms of AGD in three domain boxes are shown at the top, with the boxes shown in Fig. 4. One box shows AG within 0.5 dB of TG always, away from the NNIW. The other two boxes show significant AGD very often. At the bottom, the cumulative distribution of the AGD in box 3 (in NNIW) exceed 4 dB 25 percent of the time, and 5 dB 10 percent of the time.

DISCUSSION AND SUMMARY

A number of questions have arisen from this work. One is that NNIW form on some rays and not others, although the environmental conditions only vary slightly. The eKdVf partial differential equation model (can be used for any mode, mode one modeled here) has many parameters that are complicated functions of the environment, including the quadratic nonlinear term, the cubic nonlinear tern, and the dispersion term, and it would be informative to study the relationship between wave formation and the parameters with the parameters linked in the way that they are for data-constrained modeled ocean environments.

In addition, the initial conditions of the eKdVf, which are the internal-wave displacements at the ray origins, have been calculated to be consistent with internal-tide waves forces locally by barotropic tidal currents. Field observations strongly suggest that these local barotropic tidal currents are not the only source of internal tides and the NNIW they spawn in the SW06 area, and probably other areas [12]. The tidally-forced internal waves are beams in the vertical, and are made of many vertical modes. The beam moves shoreward and undergo mode coupling and loss in nature such that mainly mode one remains after less than a half wavelength or so of propagation, so the energy scaling of the eKdVf initial conditions is *ad hoc*. The other probable sources of mode-one shelf internal tidal energy are mode-one incident internal waves arriving from the deep ocean, known to occur from field studies, and virtually certain to form NNIW packets on the shelf [12]. These are not included in the eKdVf initialization. A scheme would be needed to extract these from the regional model fields and then include them into the eKdVf wave simulations. These are already mode one, and may nonlinearly combine with the multi-mode internal tides converting to mode-one waves just inshore of the critical-zone ray origins, so some research may be necessary to consistently drive the eKdVf with these two classes of onshore-directed wave energy.

The main purpose of the model system is to locate NNIW, determine their amplitudes, packet parameters, propagation direction, and speed. If this were possible to do reliably, then the acoustic effects of NNIW known from previous work and amenable to PE simulation can be incorporated into detailed high-resolution acoustic condition predictions in shallow water areas of interest.

ACKNOWLEDGEMENTS

This work was supported by Department of Defense Multidisciplinary University Initiative (MURI) grant N00014-11-1-0701, managed by the Office of Naval Research Ocean Acoustics Program, and National Science Foundation Grant OCE-1060430. Manuscript preparation was supported by ONR Ocean Acoustics grants N00014-17-1-2624 and N00014-17-1-2692. PFJL also thanks ONR and NSF for research support under grants N00014-13-1-0518 and OCE-1061160.

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