

Integrated Modeling and Analysis of Physical Oceanographic and Acoustic Processes

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LONG TERM GOALS

The overarching long-term goal is to improve ocean physical state and acoustic state predictive capabilities. The goal fitting the scope of this project is the creation of broadly applicable and portable acoustic prediction capabilities that include the effects of internal and surface gravity waves, in addition to effects from larger scale features, with an emphasis on continental shelf and slope regions.

OBJECTIVES

Specific physics objectives are completion of targeted studies of the relevant oceanographic processes in a few environmental regimes, and of acoustic propagation and scattering processes in those regimes. An additional objective is the development of improved computational tools for acoustics and for physical processes identified to be important via the targeted studies.

Computational tool developments include work on underwater acoustic models and ocean flow models. Time-stepped three-dimensional (3.5D) and true four-dimensional (4D) acoustic models are to be improved, as well as the methods used to couple them with ocean flow models. Fully numerical ocean flow modeling will also be improved by coupling models having nonhydrostatic pressure (NHP) physics and data-driven regional models having hydrostatic pressure (HP) physics. Composite (hybrid physics) ocean models will be created that will nest reduced-physics models for NHP waves within HP regional models. Surface wave models and moving-medium acoustic models will be developed and tested. Stochastic acoustic prediction models will be developed. Models are to be tested for acoustic prediction effectiveness. Finally, internal-wave physics will be studied in detail in laboratory and direct numerical simulation settings to constrain and validate the other computational efforts.

APPROACH

The approach toward advancing the state of ocean modeling in support of acoustic systems and acoustic prediction is to identify acoustically relevant mesoscale, submesoscale, and NHP processes, and to improve computational models that include these processes. This approach can be broken into tasks directed toward two goals: (Goal #1) Development of fully integrated tools for joint oceanography/acoustic study and prediction, i.e. a modeling system; and (Goal #2) Development of an

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understanding of the physics of coastal linear and nonlinear internal wave generation and transformation, as observed in the model, lab and field-observed features, coupled with study of acoustical propagation in these features.

Achieving Goal #2 is intimately linked with the creation of a modeling system (satisfying Goal #1) because of the need to address, for our success, open questions on coastal internal wave physics, on coastal flow features, on details of NHP fluid computational modeling, and on coastal acoustic propagation effects.

The diverse skills, codes, and tools required for this effort are spread across nine institutions, including award grantee Woods Hole Oceanographic Institution (WHOI). The project is split into these seven tasks, already mentioned as objectives:

Goal 1: Modeling tools

1. *NHP ocean model nested within data-driven HP model, tied to 4D acoustic models.* Under this task a nonhydrostatic physics computational flow model will be nested numerically within a spatial subdomain of data-assimilative hydrostatic physics regional flow model.
2. *Hybrid model: Hierarchical internal-wave models nested within HP model, tied to 3.5D acoustic models. (Also called composite flow model.)* Under this task, reduced-physics flow models capable of rapidly and efficiently modeling NHP nonlinear internal waves will be integrated with (nested within) regional flow models. These nested models can more rapidly compute internal wave positions and sizes than the full NHP model (task 1), but may sacrifice detail and accuracy. Candidate models include those based on Korteweg-de Vries type wave evolution equations and 2D NHP numerical models.
3. *Improved 4D deterministic and stochastic acoustic modeling.* Improvements to time-stepped 3D (3.5D) and 4D acoustic models will be made to increase speed and accuracy. A transport equation model for mean fields and higher order statistics will also be improved. The models will be coupled with the task 1 and 2 modes (i.e. will use output of those models as environmental condition input.)
4. *Unified waveguide model.* A prototype acoustic waveguide model solving for acoustic conditions in areas of rough seabed, internal fluid motions (including the nonlinear waves that form our main emphasis), and atmospherically forced rough surface waves will be developed. This coordinated effort is an attempt towards fully integrated physics, studying and solving for the dynamics of the ocean, surface and internal waves, seabed and acoustics processes with atmospheric forcing, all in a fully synoptic and evolving fashion.
5. *Integration work necessary for the above.* Protocols for data output resolution, data format, metadata, and so on, will be developed. Protocols for physically correct nesting of the models with differing dynamics will be developed. Protocols for sufficient interpolation within the large gap separating flow model gridding and acoustic model gridding will be established.

Goal 2: Physics studies and model verification

6. *Spatially 3D internal-wave physics studies.* Basic research aimed at improving our knowledge of internal tide and nonlinear wave dynamics in 2D and 3D systems will be conducted using

laboratory, theoretical and numerical models as appropriate, on a parallel track with the modeling tool development. These results will guide model development, testing, and use.

7. *Comparison of outputs and predictions with ground-truth field and lab data.* To gain understanding and confidence in the model fields, the generation, propagation, and dissipation of internal waves will be studied using laboratory experiments and direct numerical simulations of fluid flow (DNS). Additionally, for both the NHP and hybrid models, 3.5D acoustic effects will be modeled, analyzed and compared to experiment and field observations.

Each of the seven tasks is handled by a subgroup of the 15 total PI's. The co-PIs and institutional affiliations are listed here:

- WHOI: James Lynch, Ying-Tsong Lin, Karl Helfrich, Weifeng Gordon Zhang
- University of Texas at Austin (UT): Harry Swinney
- Rutgers University (RU): John Wilkin
- Massachusetts Institute of Technology (MIT): Pierre Lermusiaux, Nick Makris, and Dick Yue
- University of Delaware (UDel): Mohsen Badiey
- Rennselaer Polytechnic Institute (RPI): Bill Siegmann
- Colorado School of Mines (CSM): Jon Collis
- Naval Postgraduate School (NPS): John Colosi
- Florida Institute of Technology (FIT): Steven Jachec

WORK COMPLETED

A project kickoff workshop was held 13-14 June 2011, at WHOI, in the first month of the award. Ten PI-level personnel attended, with two phone participants and six other participants. At the meeting, linkages between the distinct project goals were identified and agreed upon. Group leaders for each task were agreed upon, and 16-month project goals were developed. A website was built to support information exchange between PI's and institutions. The project was named "Integrated Ocean Dynamics and Acoustics" (IODA).

An IODA acoustics PI meeting was held 12-13 June 2012 at the University of Delaware. Seven PI's attended, along with nine other project personnel. Five topics were discussed: 3.5D and 4D acoustic model algorithms (Goal 3), the composite HP/NHP/acoustics hierarchical model (Goal 2), integration (Goal 5), and ground-truth work (Goal 7).

Acoustic modeling (Tasks 3 and 5): Five new three-dimensional acoustic propagation codes have been completed thus far. These are in the MATLAB[®] programming environment. Three of these are spilt-step Fourier (SSF) wide-angle codes at the typically used expansion order that is explained in papers by Thomson and Chapman [1] and Feit and Fleck [2]. These new codes are covered by an in-press journal article (Lin, Duda and Newhall, 2012), which illustrates their accuracy. The other codes are each unique, varying in expansion order and method from the three standard order SSF codes.

The first SSF code is the latest version of the Cartesian coordinate code. Next is our radial-grid 3D cylindrical coordinate code. This code marches in radius rather than the “ x ” marching of the Cartesian code. The transform coordinates are azimuthal and vertical wavenumbers, k_θ and k_z , as opposed to k_y and k_z for the Cartesian code. The code uses a zero-padding method (upsampling) to maintain azimuthal resolution while marching to larger radius. The third code uses cylindrical coordinates and involves a grid that, while marching, remains uniform in arc-length spacing in the azimuthal dimension. The transform variables are $k_s = k_\theta/r$ and k_z . This code retains spatial resolution while marching. If total arc length is fixed while marching, then the arc aperture is wrapped many times around a point source, giving 360-degree field calculation. At very long range this code asymptotically approaches the behavior of the Cartesian code. The paper (Lin, Duda and Newhall, 2012) compares the three codes; the agreement of results from the three codes implies that they are accurate because the details of their errors differ. Figure 1 shows the level of agreement among the three codes. The figure also shows that N×2D radial modeling is insufficient for this 3D propagation example.

The fourth new code solves a higher-order parabolic equation, but is similar to the three codes described above because the SSF algorithm is employed (Lin and Duda, 2012). This code can accurately model sound propagating at higher angle relative to the marching direction than can those three codes. The operators for the higher-order terms that are added to the first-order equation can be written so as to employ the numerical operators of the first-order equation, simplifying the coding. The higher-order terms must be computed to a desired convergence tolerance using an iterative scheme. Right now, the code uses twenty-two 2D Fourier transforms per marching step versus two for the standard first-order code, or eleven times the computing. We foresee the use for this code to be verification of the accuracy of production modeling runs using the standard order code (i.e. quantification of production model errors), where the production runs would be used to synthesize pulses or to study statistical variation of propagation.

The fifth new code uses the Padé expansion method, the alternating direction implicit (ADI) method, and 2D Galerkin discretization (Lin, Collis and Duda, 2012). The SSF method requires a smoothing of the density discontinuity at the water-seafloor interface, which compromises SSF accuracy at frequencies below 75 Hz. The Padé code can provide better results at frequencies below 75 Hz. The ADI method is implemented to reduce compute time compared to using a direct one-step Padé code, but the ADI solution of the first-order parabolic equation contains significant phase errors. The key to this code is the use of the new higher-order parabolic equation. Note that sixth new code was written also, a direct (non ADI) Padé code, but this is slow and impractical for general use.

Finally, trial protocols and code have been written to interpolate ocean sound-speed fields onto the acoustic model grids. The system has been used for three different regional ocean model domains. The ocean sound-speed is not interpolated at the acoustic model grid increment in the stepping direction (order one wavelength); instead, the resolution is three to six increments. This interpolation resolution needs to be examined for its effect on the simulated field output, along with the resolution in the other acoustic model grid dimensions.

Unified waveguide model (Task 4): Development work with the MIT MSEAS model [3] has continued. This year, a reanalysis of the conditions during the ONR SW06 field program [4] has been completed (http://mseas.mit.edu/Research/SW06/MSEAS_reanalysis/2012_Jun11_AW05/). The reanalysis uses a 100-level version of the data-driven model (compared to the 30 level version used previously), improved surface forcing fields, improved initial conditions, and modifications to sub-grid scale

parameterizations for bottom friction and mixing. A new version of this data-driven model, better optimized for internal-wave prediction, will be incorporated into the Hybrid Model (Task 2) as well as Task 4 efforts. To allow high-resolution ocean-acoustic modeling, a new portable, parallel, high-order finite-element non-hydrostatic ocean code with unstructured grids is developed. Software has also been developed to solve a generic system of differential equations forced by random correlated processes, both additive and multiplicative, and including uncertain initial and boundary conditions. The software is used to study the capabilities and performance of multiple uncertainty quantification schemes for idealized ocean-acoustic modeling. A set of 2D time-dependent (x, z, t) stochastic simulations are being set up to investigate processes and possible impacts on sound propagation.

Prof. Yue and Dr. Liu at MIT have developed and improved the direct wave field simulation capability for the prediction of large-scale phase-resolved ocean waves and flow fields by including nonlinear interactions among surface gravity waves, internal waves, variable current, and bottom topography. In particular, they developed and implemented an effective algorithm for accounting for nonlinear interactions of broadband waves in the flow fields. They also improved the capability of direct comparisons between the model prediction and in situ field measurements for phase-resolved wave field evolution. The developed wave model is ready to be integrated with the oceanographic and acoustic models to investigate the coupled acoustic-ocean-atmospheric dynamics.

Prof. Makris has developed an analytical model derived from the normal mode theory including the accumulated effects of range-dependent multiple forward scattering [5-7], and has applied the model to estimate the temporal coherence time scale of an acoustic field forward propagated through a ocean waveguide containing random three-dimensional (3D) internal waves. The inhomogeneous medium's scatter function density is modeled using Rayleigh-Born approximation to Green's theorem to account for random fluctuations in both density and compressibility caused by internal waves [6]. The generalized waveguide extinction theorem is applied to determine the attenuation due to scattering from internal wave inhomogeneities [8]. In a continental-shelf shallow water waveguide, the estimated coherence time scale of acoustic field fluctuations at tens of kilometer ranges is found to be (1) strongly dependent on the internal wave spectral energy, (2) consistent with the observed coherence time scales from several shallow water transmission experiments, and (3) much shorter than that of the deep ocean environments due to the significantly higher internal wave energies encountered in the shallow-water waveguides.

An analytical model to calculate the moments of forward scattered field that accounts for both the time-varying surface gravity waves and the random 3D internal waves in an ocean waveguide is also being developed also by Prof. Makris. Physical models previously developed for investigating the Doppler-shift scattered field by a moving object [9] and the moments of forward field propagated through a random 3D internal wave in a stratified ocean waveguide [5-6] will be combined. With the new model, the coupled effect of Doppler shift induced by the time-varying surface gravity and internal waves and the accumulated attenuation and dispersion due to the random internal wave inhomogeneities in the moments of forward scattered field will be investigated.

Hybrid model (Task 2): Nonlinear NHP internal wave evolution model codes have been put together by NPS (Prof. Colosi) and by WHOI (Dr. Helfrich). Figure 2 shows an example of wave evolution along a line, calculated with the cubic nonlinear “extended Korteweg-de Vries” equation with rotation [10] under time-average thermocline conditions extracted from the MIT MSEAS 100-layer reanalysis fields. Detailed realizations of 3D sound speed, driven by regional model initial conditions and local bathymetry, and assembled using the NHP tools, will form input to 3D acoustic propagation models.

Internal-tide generation physics (Task 6): Internal-tide generation modeling at WHOI with ROMS [11] for supercritical continental slope geometry has been performed. The work is described in an Oceans '12 conference paper (Duda, Zhang and Lin, 2012), and a manuscript is complete and nearly ready for journal submission. The modeling is fully nonlinear, using the Boussinesq-approximation based primitive equations, although the pressure is approximated as hydrostatic (NHP physics not allowed). The fields show signatures of significant nonlinear effects, some of which have undergone limited prior study [e.g. 12]. The nonlinear effects are being studied by switching off nonlinear terms in the equation set (equation of state, equation of motion, turbulence closure). Figure 3 shows a snapshot of the model output with full (although HP) physics included. The internal tide energy is higher if nonlinear advection is included in the model, approximately double that seen with this removed. The simulations show a rich field of harmonics, and tie-in well with the work of the UT wave physics group [13]. Under this project, the UT group has worked to refine the mesh in the CDP finite volume code [13], to build a longer laboratory tank, and to improve laboratory diagnostic instrumentation.

Internal-wave propagation (Task 6): Dispersion relations have been computed for internal wave modes under conditions of rotation and two-dimensional sheared background current. Specifically, an analog of the rotation-neglecting Taylor-Goldstein equation was solved, first after making reasonable simplifying assumptions, then in complete form. The results yield directionally varying (anisotropic) internal-wave mode wavenumbers, group velocities, and phase velocities for user-specified density profiles and current profiles. This work was performed in part by WHOI guest students in summers 2011 and 2012 under the supervision of WHOI PI's.

Ground-truth acoustic studies (Task 7): Combined analysis of acoustic data and environmental data collected by SW06 PI's has continued under this grant. Modeling and prediction of azimuthally and temporally variable acoustic effects, of probabilities of strong acoustic effects, and of acoustic parameter distribution functions, will be tested with data sets collected during the SW06 experiment.

RESULTS

Hybrid model (Task 2) and internal-wave physics (Task 6): After one year and few months, substantial progress has been made in many of the task areas. Studies have indicated strong sensitivity of on-shelf internal tide energy flux to density profiles, for fixed seafloor geometry, as expected, and strong importance of nonlinearity. Density gradient properties near the seafloor at the critical slope area appear to be important. These are controlled by mixing processes, which are nonlinear. Internal-wave mode propagation speed predictions under conditions of rotation and realistic shear (drawn from models) exhibit a high degree of variability. This variability is expected to have important dynamical ramifications, and thus to influence NHP wave energy and geometry, and subsequently to influence sound propagation and noise field variability.

Unified waveguide model (Task 4): The new SW06 MSEAS reanalysis improved the simulations, shown by comparison to independent data. For example, thermocline and frontal intrusions, internal tides, and wind responses were substantially improved, including in forecasts fields. Results of simulations with a hierarchy of nonlinear dynamical systems forced with random processes demonstrate that the Dynamically Orthogonal scheme can predict statistics efficiently, even in the case of multiplicative noise and time-dependent nonlinear systems. Other approaches (gPCE, TDgPC, etc) needed to be modified, and provided slow simulations. Manuscripts are in preparation.

The probability distribution of ocean-acoustic broadband signal energy resulting from saturated multipath propagation has been derived by the Makris (MIT) group using coherence theory (Tran et al., 2012). The frequency components obtained from Fourier decomposition of a broadband signal are each assumed to be fully saturated, with energy spectral densities that obey the exponential distribution with 5.6 dB standard deviation and unity scintillation index. When the signal bandwidth and measurement time are larger than the correlation bandwidth and correlation time, respectively, of its energy spectral density components, the broadband signal energy obtained by integrating the energy spectral density across the signal bandwidth then follows the Gamma distribution with standard deviation smaller than 5.6 dB and scintillation index less than unity. The theory is verified with broadband transmissions in the Gulf of Maine shallow water waveguide in the 300-1200 Hz frequency range. The standard deviations of received broadband signal energies range from 2.7 to 4.6 dB for effective bandwidths up to 42 Hz, while the standard deviations of individual energy spectral density components are roughly 5.6 dB. The energy spectral density correlation bandwidths of the received broadband signals are found to be larger for signals with higher center frequencies and are roughly 10% of each center frequency.

Wave physics (Task 6): The UT group has analyzed more than 18,000 data sets obtained in the World Ocean Circulation Experiment (WOCE) and have discovered many locations in the oceans where there exist “turning depths,” ocean depths below which internal gravity tides are exponentially damped. Below the turning depths, the rate of conversion of energy of the tides into internal gravity wave energy is less than that previously assumed. This discovery of turning depths has consequences for the energy budget of the oceans (King et al., 2012).

The discovery of the existence of turning depths motivated a computational and laboratory study of reflection and transmission of internal gravity waves in a stratified fluid with a turning depth. The UT measurements of the reflected and transmitted wave intensities were found to be in good quantitative agreement with recent predictions of theory (Paoletti and Swinney, 2012).

The next step in this research at the University of Texas will be to examine the effect of turning depths on acoustic propagation; this will be done in collaboration with the IODA collaborators at WHOI.

Ground-truth (Task 7): Using measured thermistor data, specifically using the thermistor farm data and combining them with the ship's radar data, the U. Delaware group has examined details of the internal propagation for a few events during SW06. In addition, they have used the extended KdV solution [10] to model internal wave events for paths between two points in the region. An example of this process is shown in Figure 4. The approach is to interpolate that measured thermistor data across a region, and to model it along one path.

IMPACT/APPLICATIONS

The creation of modeling suite that includes submesoscale features as well as data assimilation is expected to be a valuable asset to apply in numerous ocean regions. Identification of acoustic propagation and noise field features that are controlled by local oceanographic processes may allow exploitation or mitigation of the effects.

The MIT analytical model enables prediction of the temporal coherence time scale and Doppler spread of acoustic field fluctuations after propagating through random 3D internal waves in an ocean waveguide. The statistics of broadband ocean acoustics transmissions have been shown to follow a simple physical model.

RELATED PROJECTS

There are many closely related projects among the many co-PI's. Some of the acoustics PI's have ONR grants related to shallow-water acoustics. Several of the ocean-flow modeling PI's have closely related projects on data assimilation, dynamics, and model development funded by ONR and the National Science Foundation, including an ONR Young Investigator Grant to Prof. Jachec.

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HONORS

Recipient: Harry L. Swinney

Recipient's Institution: University of Texas at Austin

Award Name: Lewis Fry Richardson Medal of the *European Geosciences Union*

Date and Place of Award: 4 April 2012, Vienna, Austria

Award Citation: "*For his pioneering experiments on deterministic chaos and highly original models of geophysical flows*"

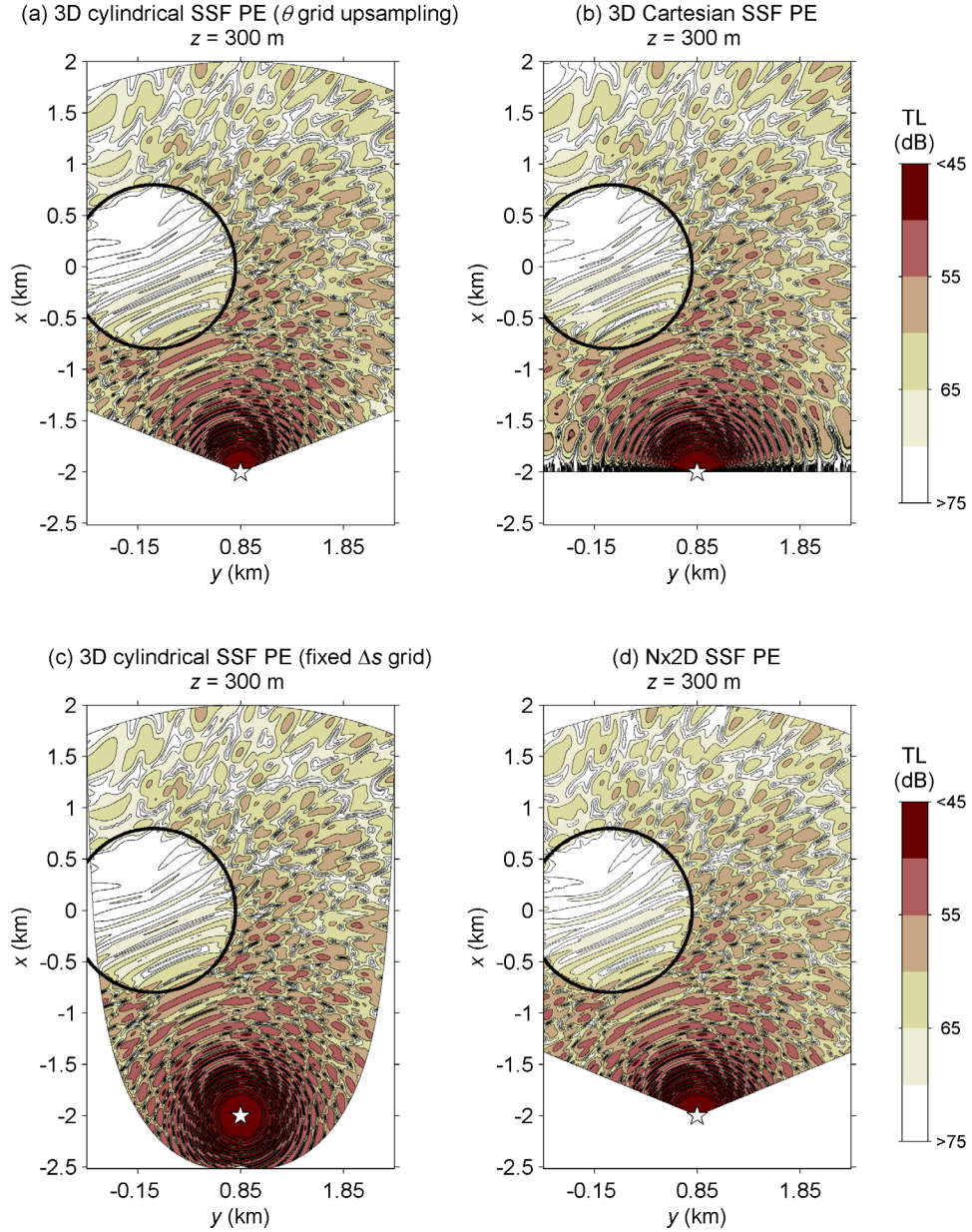


Figure 1. A comparison of transmission loss (TL) calculated with four different split-step Fourier (SSF) PE models is shown. A 100-Hz sound source (shown with star) is placed at 250 m depth a few km away from the tip of a seamount. The seamount summit is at depth $z = 200$ m. The TL in a plane at 300 m depth is plotted in the panels. The dark circles indicate the intersection of the seamount seabed with this plane. Panel (a) shows results from the upsampling radial grid cylindrical coordinate code. Panel (b) shows results from the Cartesian coordinate code. Panel (c) shows the fixed delta-s (arc length increment) cylindrical coordinate code. Panel (d) shows results from a radial N by 2D code.
[Panels (a) to (c) agree. Panel (d) shows a different result.]

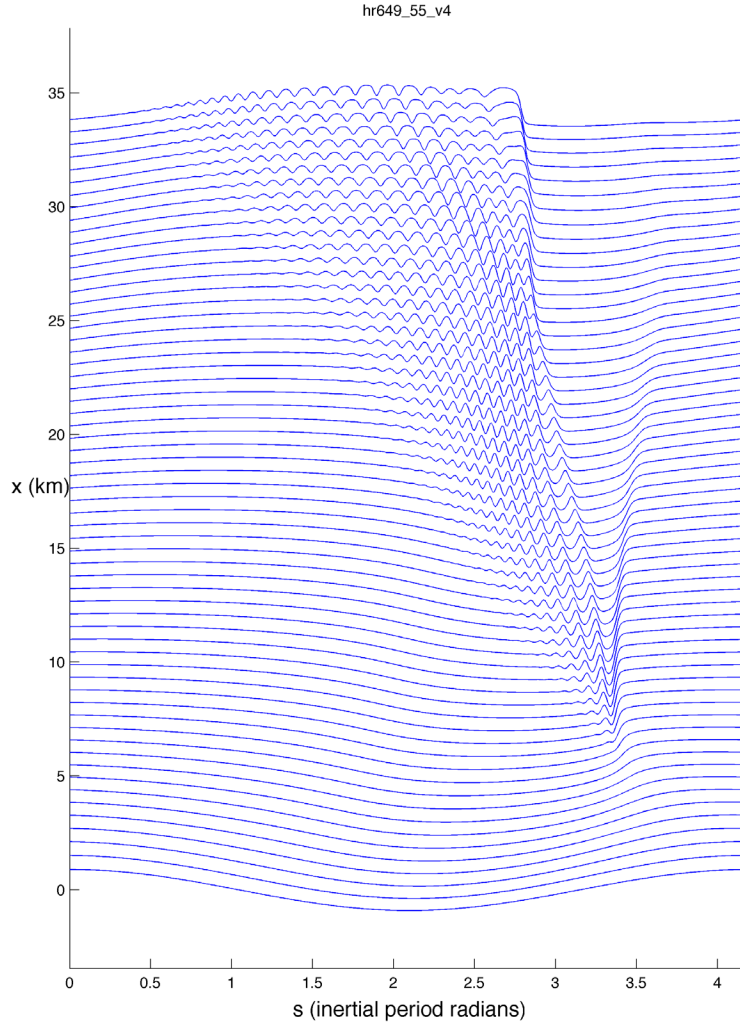


Figure 2. Time series of M2 tidal frequency internal-wave mode-one amplitude at many cross-slope locations (x) shoreward of an outer-shelf location, shown sequentially in distance (also time) along the vertical axis. The horizontal axis shows time, adjusted for each trace by the integrated spatially dependent shoreward linear long wave slowness, so that a simple linear sine wave would appear unchanged. The initial condition, at the bottom, is one cycle of an M2 tidal period sine wave. The corresponding maximum thermocline displacement is of order 10 meters.

[After about 8 km of propagation the sine wave changes into a steep bore, which moves faster than the benchmark wave speed (inverse of slowness), and a train of very short waves behind the bore, which move slower than the benchmark speed. The number of short waves increases from one at 8 km to about 15 after 35 km of propagation.]

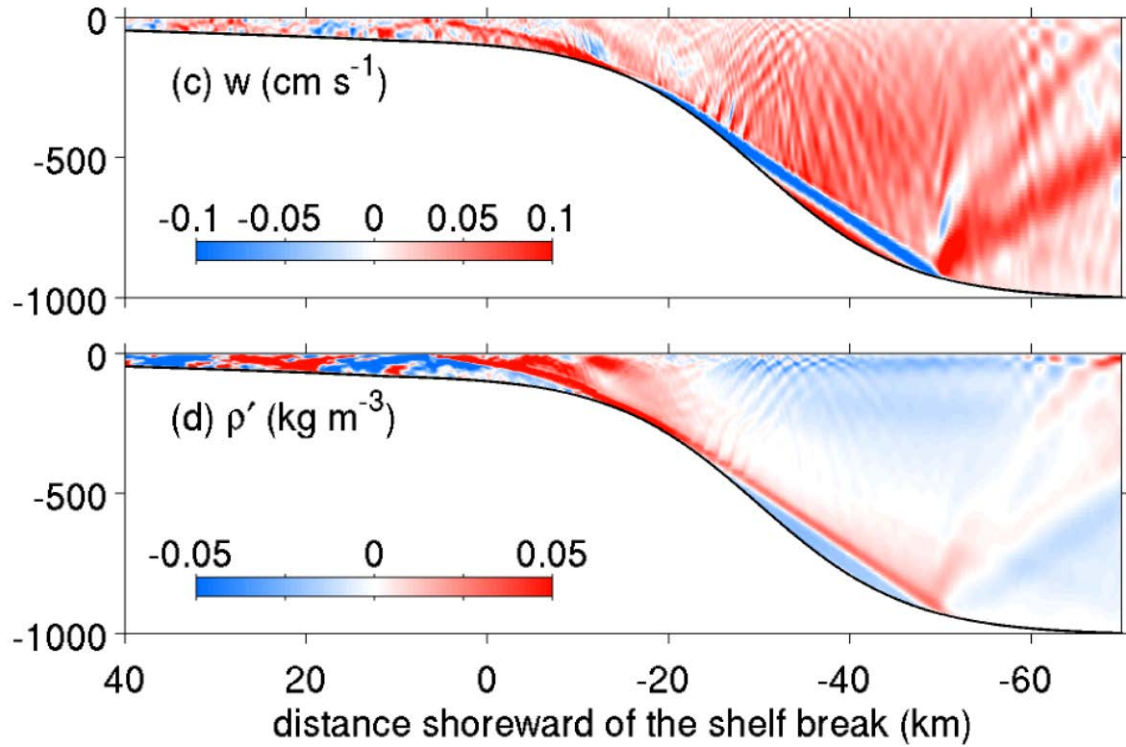


Figure 3. Cross-slope vertical section snapshots of vertical velocity (top) and density perturbation (bottom) in the quasi-2D HP ROMS output. The model run simulates internal-tide generation at a supercritical slope site patterned after conditions at the Mid-Atlantic Bight. A barotropic M2-frequency tide wave travels along slope, with no other forcing. The internal tide is strong in beams following the characteristics of M2 internal waves, with lesser intensity along steeper beams of M2 harmonic overtones caused by nonlinear effects. Internal-tide energy flux (not shown) diverges in the cross-shore direction from the critical slope location where beams are parallel with the seafloor (-15 km).

[(top) The strongest velocities are in a single beam extending onshore and offshore from the 200-m deep seafloor at the critical location. The beam is downward offshore, upward onshore, reflecting off the surface at location ~10 km. The remainder of the volume is filled with energy at many frequencies. (bottom) The density perturbation structure is similar to the velocity structure, with peak values of 0.05 kg per meter cubed versus 0.1 cm per second.]

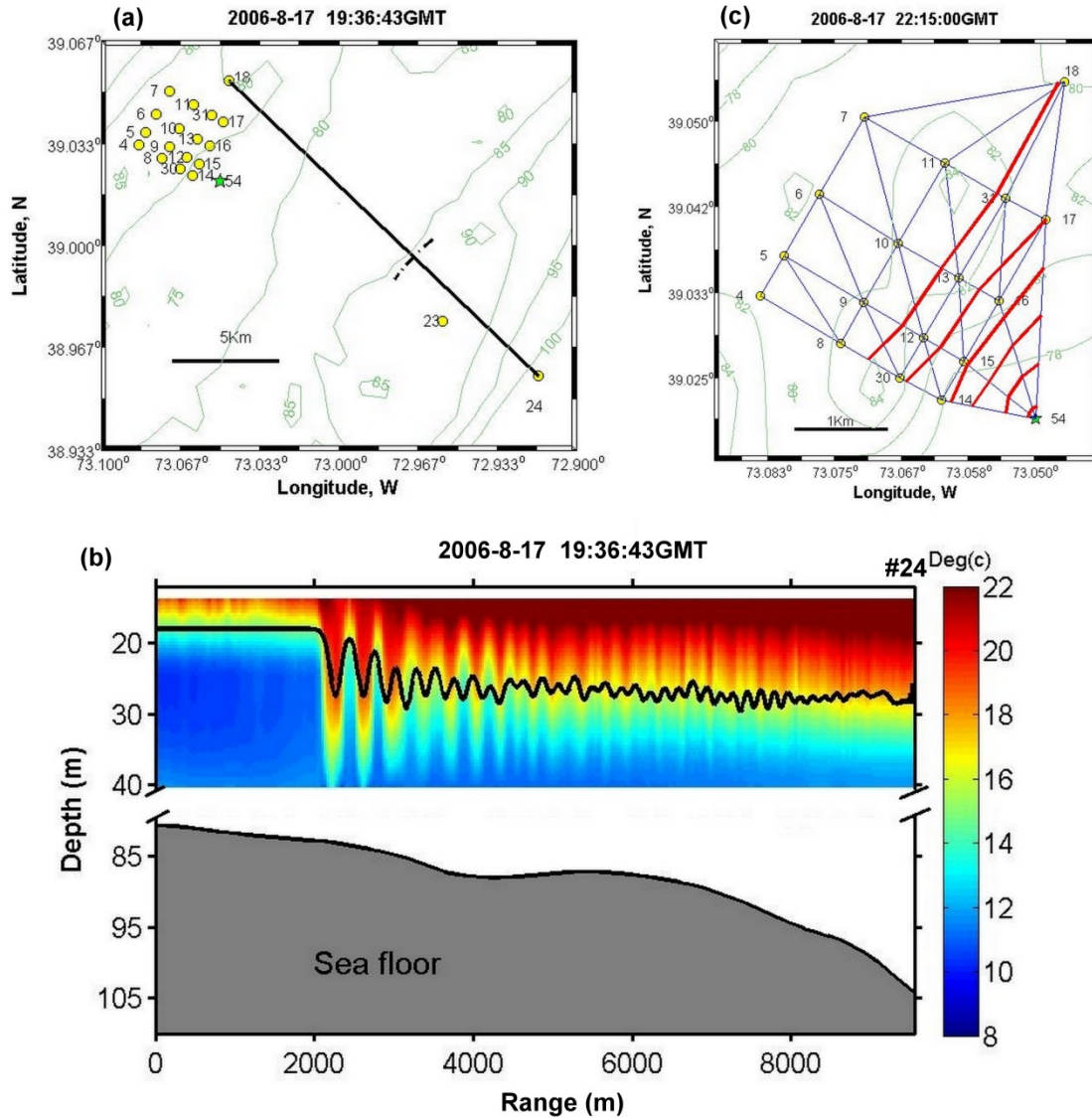


Figure 4. (a) A propagation track, shown by the solid line, connecting SW06 moorings #24 and #18. The dashed dot arc represents the location of the first wave front at 19:36:43 GMT on Aug. 17, 2006. (b) Interpolated temperature profiles and model outputs along the track #24–#18 at 19:36:43 GMT on Aug. 17, 2006. Note that temperature data were only measured for the upper water column, 15 to 40 m water depth. The right end of the horizontal axis of (b) represents mooring location #24. The internal wave propagated inshore, from right to left. The thick black line is the nonlinear eKdV prediction of the thermocline depths, assuming the internal waves were formed at the location #24. (c) Internal wave fronts identified from the interpolated temperature field at 22:15:00 GMT on Aug. 17, 2006.

[(a) The internal wave propagation track heads northwest toward the main field of moorings. (b) A packet of internal waves is shown that is approximately rank-ordered, and the model wave are similar to the measured waves. (c) The snapshot of internal wave crests in the center the 17 moorings shows five bent waves moving to the northwest.]