Integrated Modeling and Analysis of Physical Oceanographic and Acoustic Processes

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Award Number: N00014-11-1-0701
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LONG TERM GOALS

The overarching long term goal is to improve ocean physical state and acoustic state predictive capabilities. The shorter-term goal fitting the scope of this project is to create a broadly applicable and portable continental shelf-area acoustic prediction capability that includes the effects of internal and surface gravity waves in addition to larger scale effects.

OBJECTIVES

Specific project objectives are completed 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 theoretical and computational tools for those physical processes identified to be important.

Specific studies include improvements to underwater acoustics models, including time-stepped three-dimensional models (3.5D) and true four-dimensional models, and to couple them with ocean flow models. Ocean flow modeling will be improved by coupling nonhydrostatic physics (NHP) models with data-driven regional hydrostatic physics (HP) models. Composite (or hybrid physics) models that used reduced-physics nonhydrostatic wave models nested within HP regional models will be created and tested for acoustic prediction effectiveness. Surface-wave models and moving-medium acoustic models will be developed and tested. Stochastic acoustic prediction models will be developed, applied, and tested. 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 that need to be better modeled, 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 understanding of the physics of coastal linear and nonlinear internal wave

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Integrated Modeling and Analysis of Physical Oceanographic and Acoustic Processes**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceanographic Institution,Applied Ocean Physics and Engineering Department, MS 11,Woods Hole,MA,02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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 project is split into seven tasks. The diverse skills required for this effort, and the base of developed codes and tools needed for the project, are spread across nine institutions, including MURI award grantee Woods Hole Oceanographic Institution (WHOI). The tasks are

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 4D acoustic models. (Also called composite flow model.)* Under this task, reduced-physics flow models capable of rapidly and efficiently modeling nonhydrostatic nonlinear internal waves will integrated with (nested within) regional flow models. These nested models can mode 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 deVries 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 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 spectral 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 two- and three-dimensional 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, 4D 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 total collection of 15 co-PI's. The co-PIs and institutional affiliations are listed here:

- WHOI: Jim 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 Woods Hole Oceanographic Institution, in the first month of the award. Ten PI-level personnel attended, with two phone participants and six other participants. At the meeting, linkages and 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.

Acoustic modeling (Tasks 3 and 5): Work has begun on a Padé expansion based solver for the 3D parabolic acoustic wave equation. The Fourier split-step method that we use requires a treatment of the density discontinuity at the water-seafloor interface that compromises accuracy at frequencies below 100 Hz. The new code will give better results at frequencies below this. Next, a cylindrical coordinate version of the Fourier split-step solver has been implemented. This code updates the azimuthal gridding to satisfy sampling criteria that are needed for accurate results, while also saving time. We typically use Cartesian coordinates for Fourier split-step implementations [1,2].

Unified waveguide model. (Task 4): The literature is being reviewed for non-hydrostatic modeling of internal ocean waves and ocean swells, and for interactions of waves with coastal flows. Two-dimensional time-dependent (x,z,t) simulations are being set-up using the MIT finite-volume code to investigate processes and impacts on sound propagation.

Internal-tide generation physics (Task 6): Internal-tide generation modeling with ROMS [3] for supercritical continental slope geometry has been performed. Figure 1 shows two snapshots of cross-slope velocity in cross-slope transects. The modeling is fully nonlinear but hydrostatic solving of the Boussinesq-equation based primitive equations. The fields show signatures of significant nonlinear effects, some of which have undergone limited prior study [4]. The nonlinear effects are being studied by switching off nonlinear terms in the equation set (equation of state, equation of motion, turbulence closure.) Internal-tide generation studies with the MIT MSEAS model [5] have begun with analysis of the real-time data-driven forecasts made during the SW06 field study [6,7]. Figure 2 shows signatures of internal tides in this model. A new version of this data-driven model, better optimized for internal-wave prediction, will be incorporated into the Hybrid Model (Task 2) and the Unified Model (Task 4). The Univ. of Texas wave physics group has worked to refine the mesh in the CDP code [8], to build a longer laboratory tank, and to improve laboratory diagnostic instrumentation.

Internal-wave propagation (Task 6): Dispersion relations 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, after making reasonable simplifying assumptions. 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 summer 2011 by a WHOI guest student 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. Figure 3 shows sound variations recorded at the WHOI HVLA system from a moving University of Delaware sound source. The source was towed along an approximately circular path around the receiver while a group of internal waves passed through the region. The position of the source was kept close to the front of the internal wave leading edge while the ship moved slowly with the advancing internal wave. This configuration provided geometries whereby the angle between the acoustic track and the internal wave front could be accurately measured during the IW propagation. The resulting acoustic intensity variation is due to azimuthally dependent propagation. Modeling and prediction of azimuthally and temporally variable acoustic effects such as these, and of probabilities of such events, and of acoustic parameter distribution functions, will be tested with additional data sets collected during the SW06 experiment.

RESULTS

The first few months of this project have yielded only initial results. Studies indicate strong sensitivity to density profiles of on-shelf internal tide energy flux, for fixed seafloor gemetry, as expected. Density gradient properties near the seafloor at the critical slope area appear to be important. These gradients are affected by mixing processes, creating the possibility of feedback. Internal-wave mode propagation speed predictions under conditions of rotation and realistic shear (drawn from models) have shown a high degree of variability. This variability is expected to have important dynamical ramifications, and thus to play a role in sound propagation variability and noise field variability.

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.

RELATED PROJECTS

There are many closely related projects among the many co-PI's. Many of the acoustic PI's have accompanying ONR projects 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.

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PUBLICATIONS

Duda, T. F., Y.-T. Lin and D. B Reeder, Observationally-constrained modeling of sound in curved ocean internal waves: Examination of deep ducting and surface ducting at short range, J. Acoust. Soc. Am., 130, 1173-1187, 2011. [Published, refereed]

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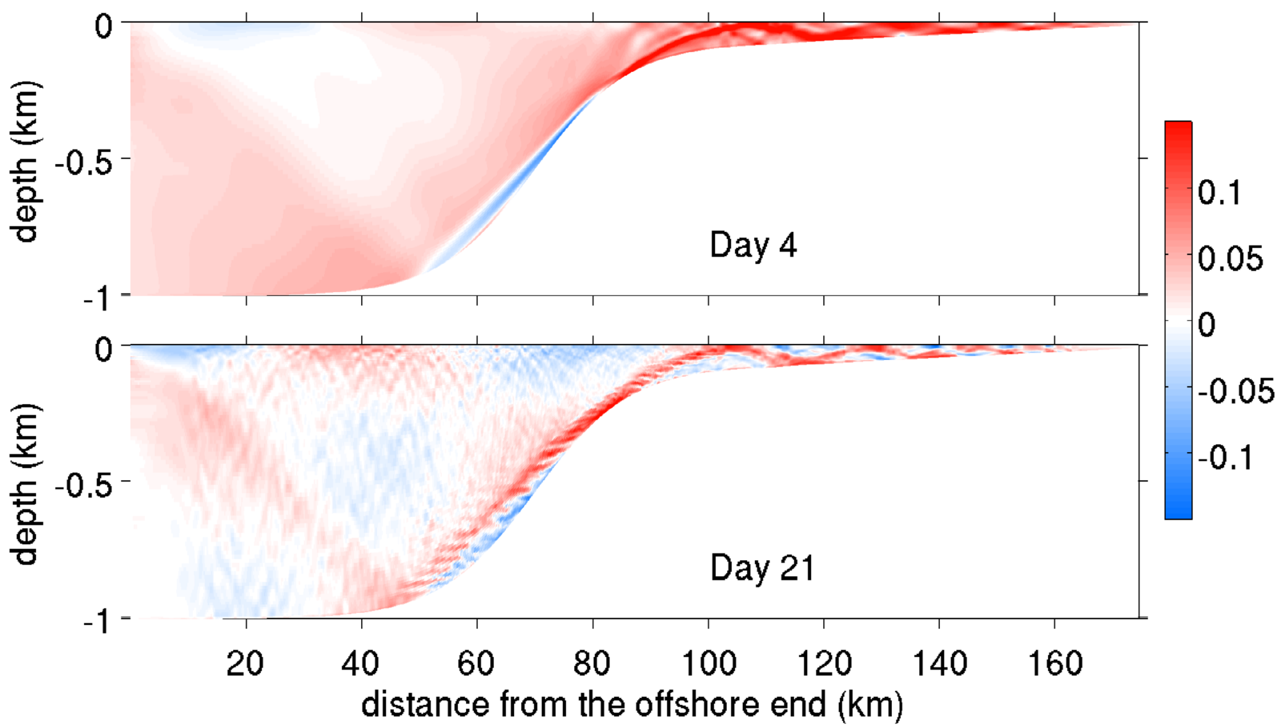

Figure 1. Cross-slope vertical sections of cross-slope velocity at two time steps in a hydrostatic ROMS [3] simulation of internal tide generation ata supercritical slope profile patterned after conditions at the Mid-Atlantic Bight. A barotropic M2-frequency tide wave travels along slope. There is no x-dependence (along slope) of the seafloor and forcing. (top) At day 4 the internal tide has spun up into simple energy beams following the characteristics of M2 internal waves. Internal tide energy flux diverges in the cross-shore direction from the critical slope location where beams are parallel with the seafloor. (bottom) At day 21 the pattern is significantly more complicated due to nonlinearities in the equation of state, the equation of motion, the conservation equations for temperature and salinity, the seafloor drag, and the turbulence closure method. The flattened stripes may be forced non-propagating subinertial disturbances related to a subharmonic instability. The beam reaching the surface at y=40 km is a nonlinear tidal harmonic.

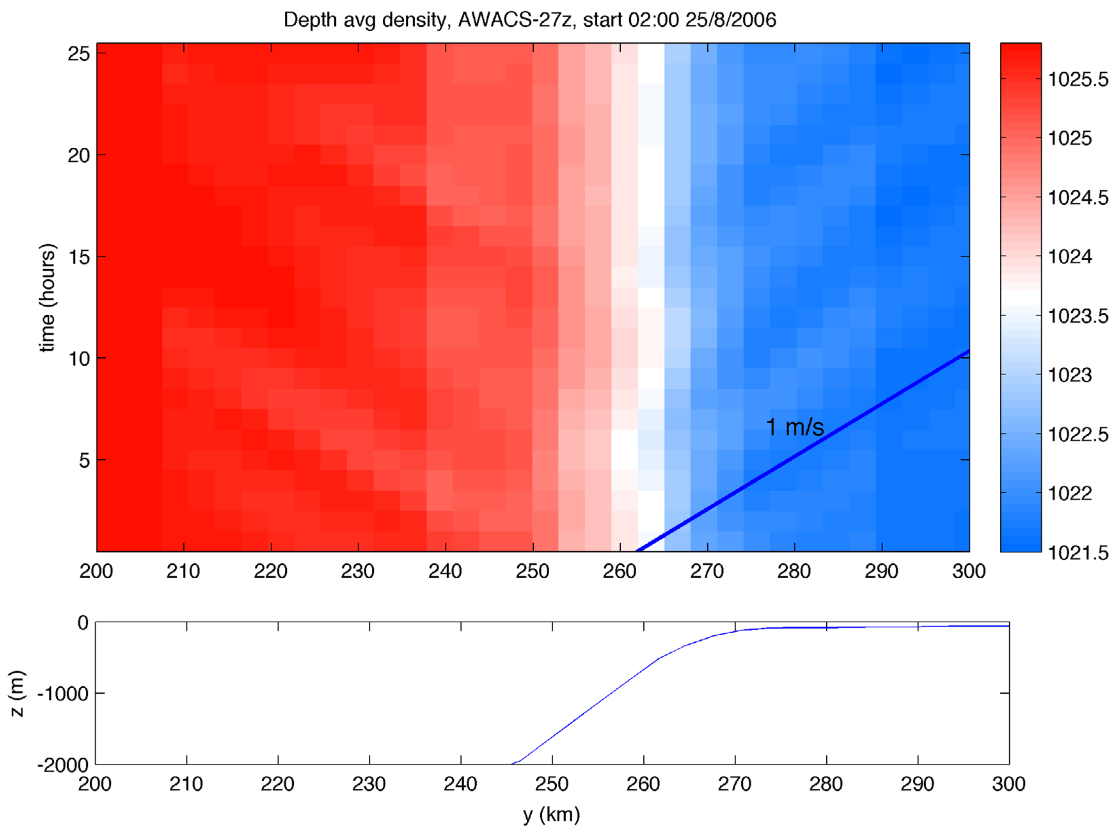

Figure 2. (top) A Hovmuller diagram of depth averaged water-column density is shown for a time series of cross-slope section output from the MIT-MSEAS primitive equation regional HP data-assimilative computations [5] made for the SW06 experiment [6]. The streaks of light color anomaly depict mode-one internal waves (internal tides) radiating towards both deep and shallow water from the region of 500-m depth. (bottom) The water depth along the section is shown.

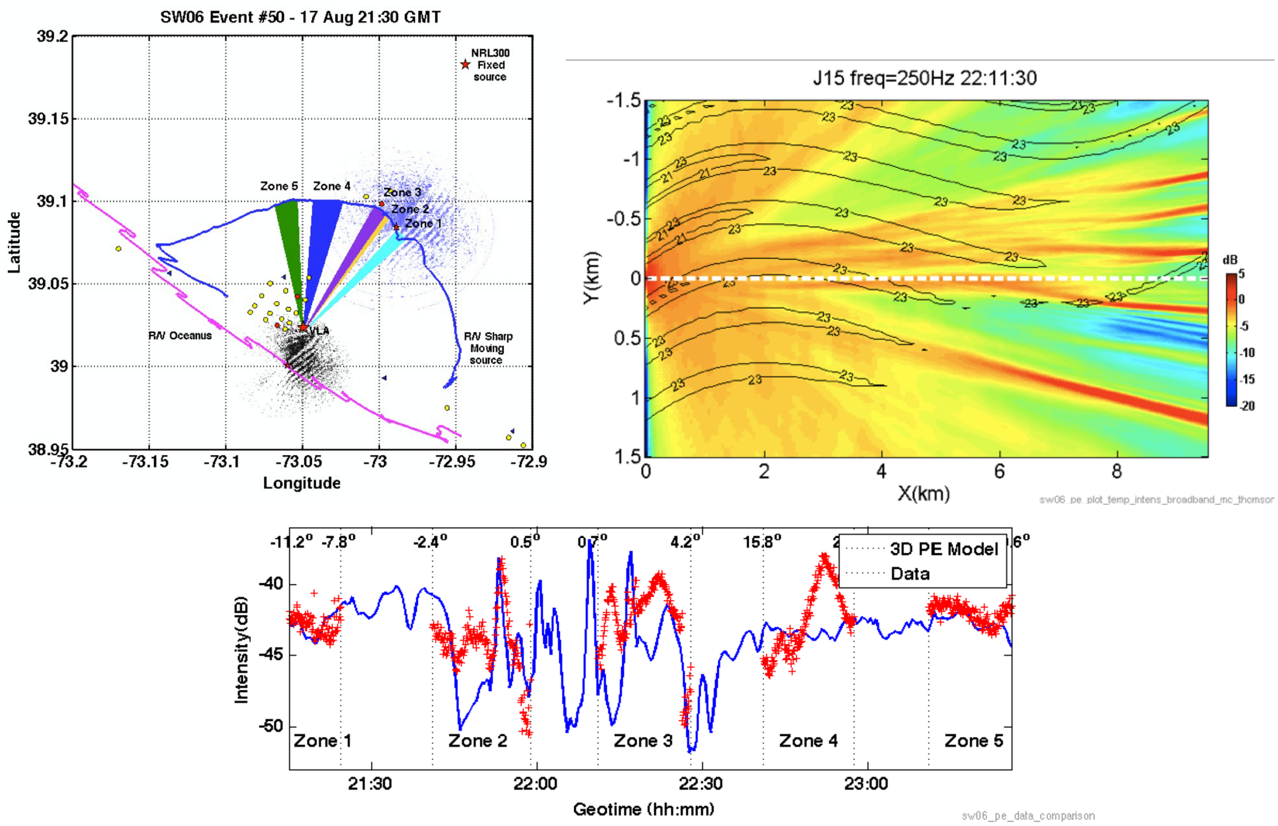

Figure 3. Model-data comparisons from the SW06 Experiment are shown. (top left) SW06 Experiment ship tracks of R/V Sharp (with acoustic source) and R/V Oceanus, location of VLA receiver, environmental moorings (red and yellow dots), radar images from R/V Sharp and R/V Oceanus at 21:30 GMT on August 17, 2006, and 5 acoustic zones of transmission. The colored pie slices show the direct acoustic paths for each time zone of transmission. (top right) U. of Delaware 3-D PE modeling results showing the acoustic intensity and the temperature contour at depth 20 m. Source is located at point (0,0) and the white dashed line shows the direct acoustic track. This is the beginning of the Zone 3 time period. (bottom) Model-data comparison of the depth-integrated intensity for transmissions of Zone 1 through Zone 5. At Zones 2 and 3 when the source locations were close to the thermistor strings, the model results (blue line) are in agreement with data (red x's). The model can't reproduce the Zone 4 peak intensity in the data due to lack of environmental data and existence of a possible secondary IW front at this geotime sample. The receiver is at y=34.