Proposal title:

Integrated Modeling and Analysis of Physical Oceanographic and Acoustic Processes

Project title, upon award:

Integrated Ocean Dynamics and Acoustics (IODA)

Program affiliation: ONR Ocean Acoustics

Timothy F. Duda
Woods Hole Oceanographic Institution (WHOI)

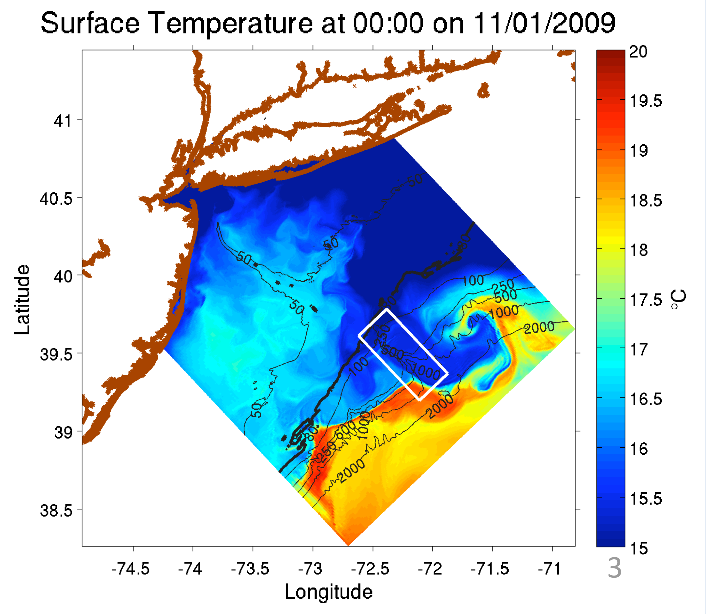
Multidisciplinary University Research Initiative (MURI) Program Review
17 Dec 2013

What we are trying to do

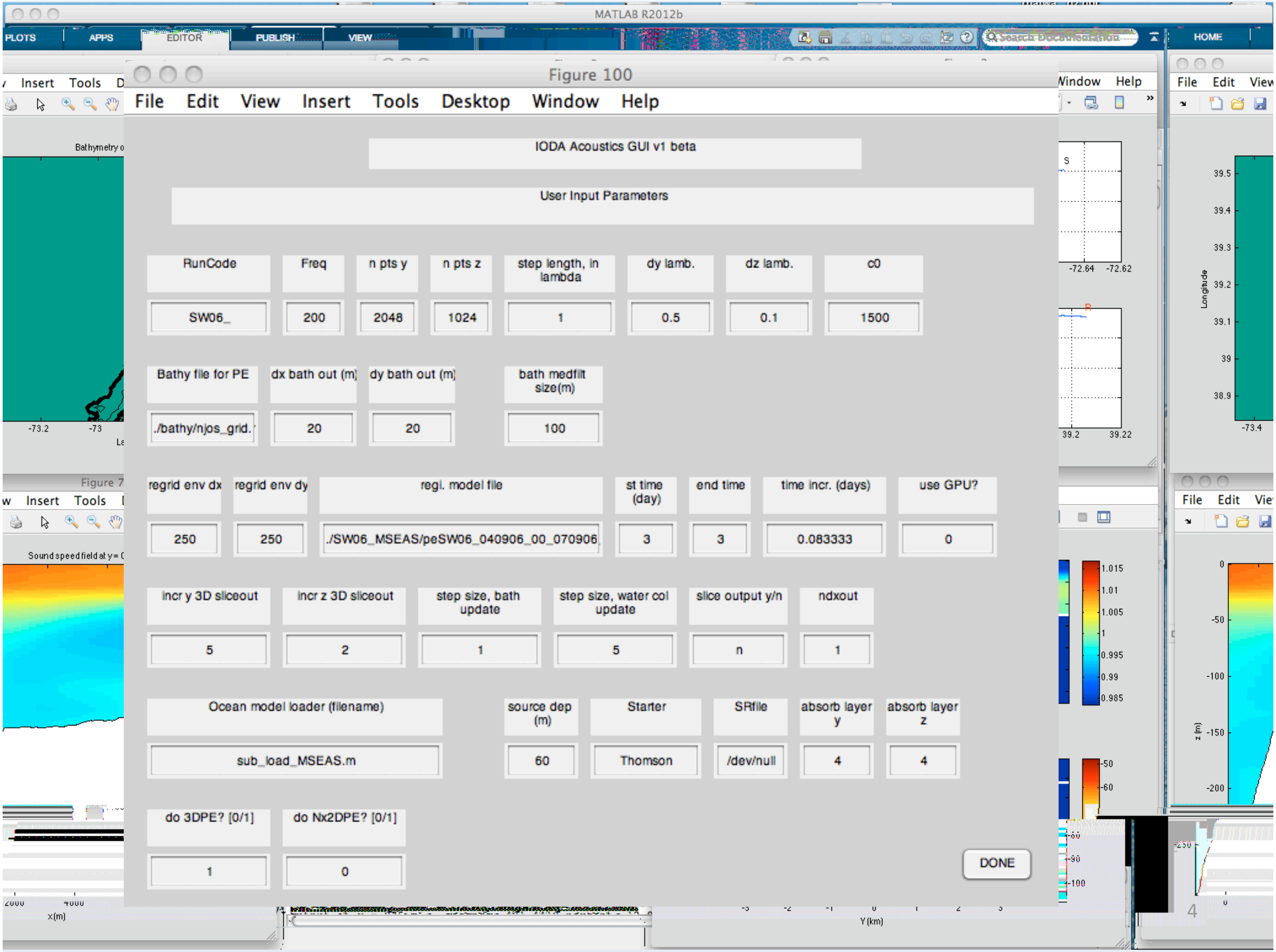
- Answer questions about variability in the ocean acoustic environment:
    - Which features/processes have important acoustic effects?
    - Do we understand these features well enough?
    - Can we sequentially predict the feature behavior and the acoustic effects, and to what degree of accuracy?
    - When should statistical and/or deterministic modeling and prediction frameworks be used?

The project we devised:
Integrated Ocean Dynamics and Acoustics (IODA)

- **Overall objective**:
  - To accurately model acoustic propagation behavior and sonar performance in ocean environments that include internal waves and other submesoscale features
- **Project goals**
  - To improve computational ocean dynamical model accuracy for acoustically relevant features such as internal waves and fronts
  - To refine our understanding of internal wave generation, propagation, and dissipation dynamics. (Required for above)
  - To develop and integrate a phase-resolving surface/internal wave model
  - To improve 4-dimensional acoustic propagation models (xyz and time)
  - To research optimal interfacing of acoustic models and ocean models



(Data-driven) Hudson Canyon Model snapshot. *WG Zhang, WHOI.*



IODA Acoustics GUI v1 beta

User Input Parameters

RunCode	Freq	n pts y	n pts z	step length, in lambda	dy lamb.	dz lamb.	c0
SW06_	200	2048	1024	1	0.5	0.1	1500

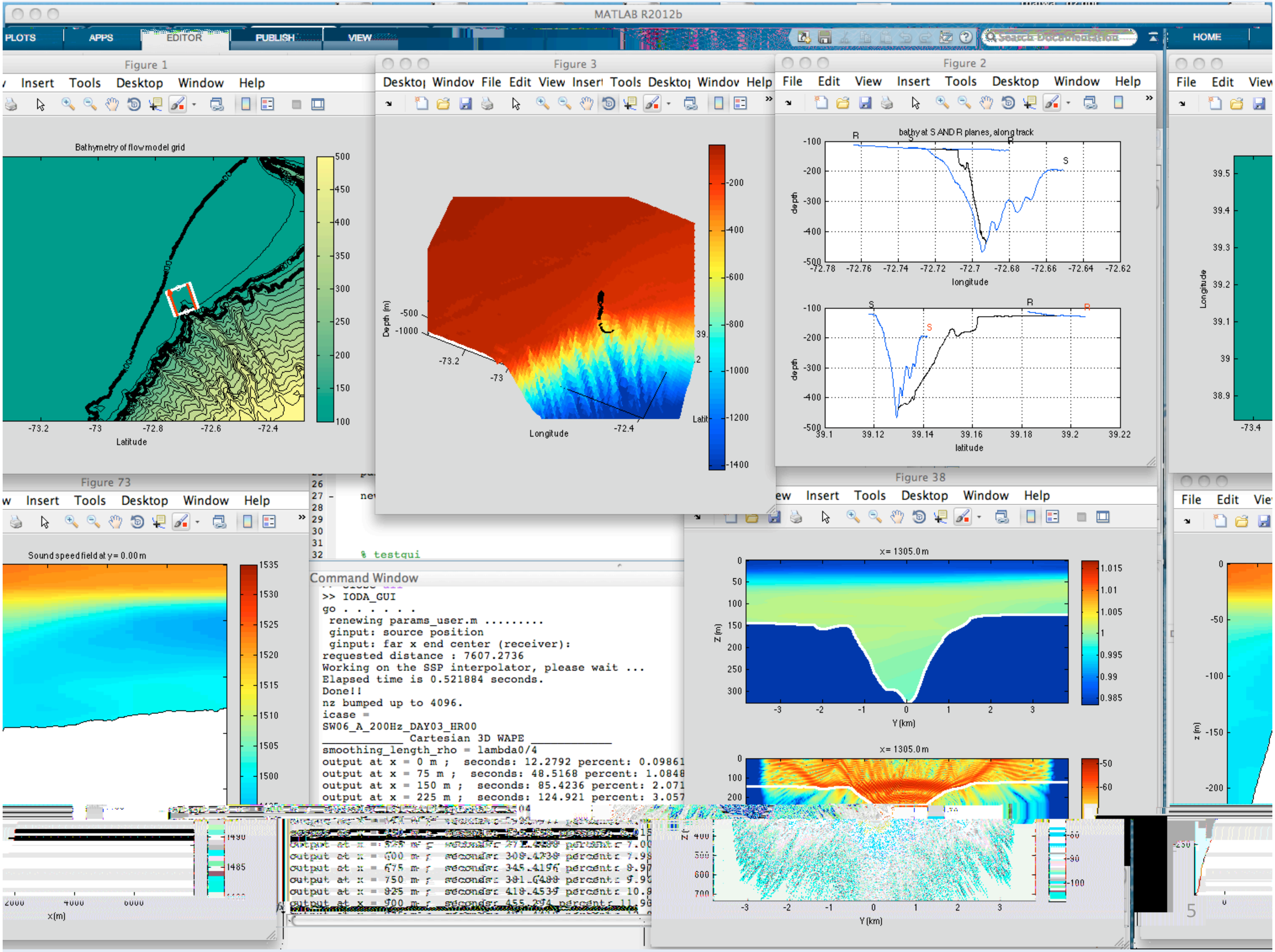
Bathy file for PE	dx bath out (m)	dy bath out (m)	bath medfilt size(m)
./bathy/njos_grid.	20	20	100

regrid env dx	regrid env dy	regl. model file	st time (day)	end time	time incr. (days)	use GPU?
250	250	./SW06_MSEAS/peSW06_040906_00_070906	3	3	0.083333	0

incr y 3D sliceout	incr z 3D sliceout	step size, bath update	step size, water col update	slice output y/n	ndxout
5	2	1	5	n	1

Ocean model loader (filename)	source dep (m)	Starter	SRfile	absorb layer y	absorb layer z
sub_load_MSEAS.m	60	Thomson	/dev/null	4	4

do 3DPE? [0/1]	do Nx2DPE? [0/1]
1	0



```
>> IODA_GUI
go . . . . . . .
 renewing params_user.m .........
 ginput: source position
 ginput: far x end center (receiver):
requested distance : 7607.2736
Working on the SSP interpolator, please wait ...
Elapsed time is 0.521884 seconds.
Done!!
nz bumped up to 4096.
icase =
SW06_A_200Hz_DAY03_HR00
____________ Cartesian 3D WAPE ____________
smoothing_length_rho = lambda0/4
output at x = 0 m ;  seconds: 12.2792 percent: 0.09861
output at x = 75 m ;  seconds: 48.5168 percent: 1.0848
output at x = 150 m ;  seconds: 85.4236 percent: 2.071
output at x = 225 m ;  seconds: 124.921 percent: 3.057
output at x = 525 m ;  seconds: 271.4488 percent: 7.00
output at x = 600 m ;  seconds: 308.4238 percent: 7.9
output at x = 675 m ;  seconds: 345.4196 percent: 8.9
output at x = 750 m ;  seconds: 381.6488 percent: 9.9
output at x = 825 m ;  seconds: 418.4539 percent: 10.9
output at x = 900 m ;  seconds: 455.294 percent: 11.9
```

Linked data-driven ocean dynamical simulation and 3D acoustic simulation is potentially a great tool,

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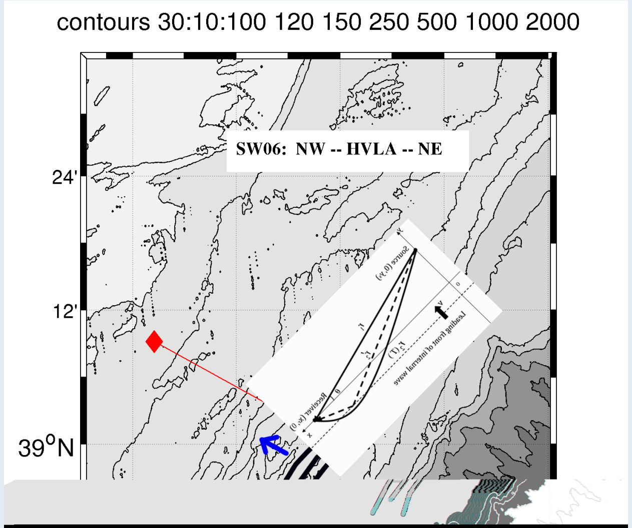
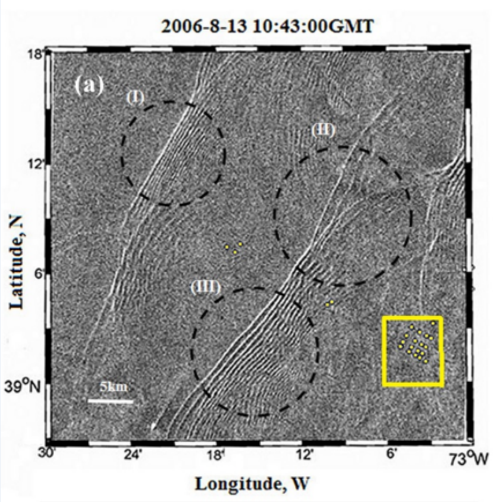
But

- The internal tides are known to be difficult to model realistically (i.e. to get right)
- Short nonlinear internal waves (solitary-type waves) are not allowed by the hydrostatic-pressure dynamics
- Surface waves are not included.
- Submesoscale features like fronts and salty intrusions are pushing the model capabilities.

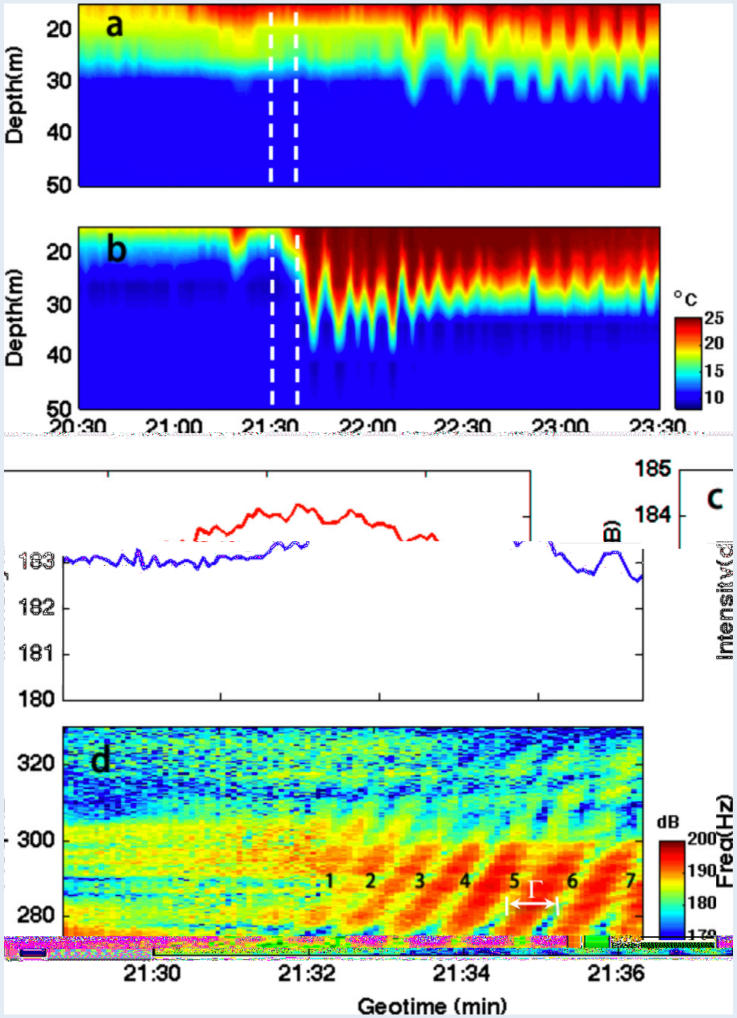
Internal wave (IW) groups and surface waves (SW) affect sound propagation.

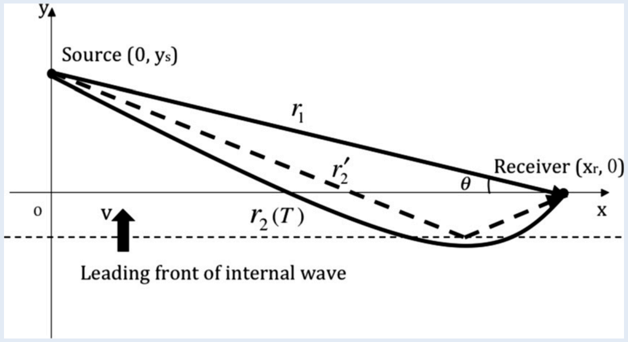
IW effects on sound intensity, along-crest SW06 path





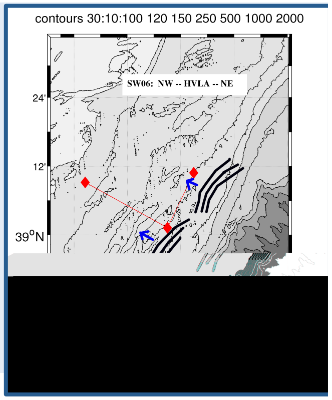
Satellite SAR image 4 days prior to wave/acoustics at right





Luo and Badiey, JASA, 2012.

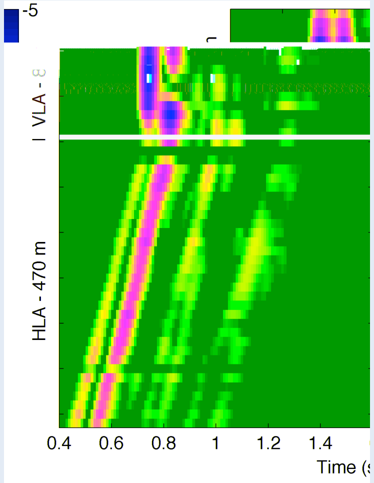
Measured environmental effects: Horizontal coherence, SW06 data, 20-km propagation path. Bottom-mounted 465 m array.

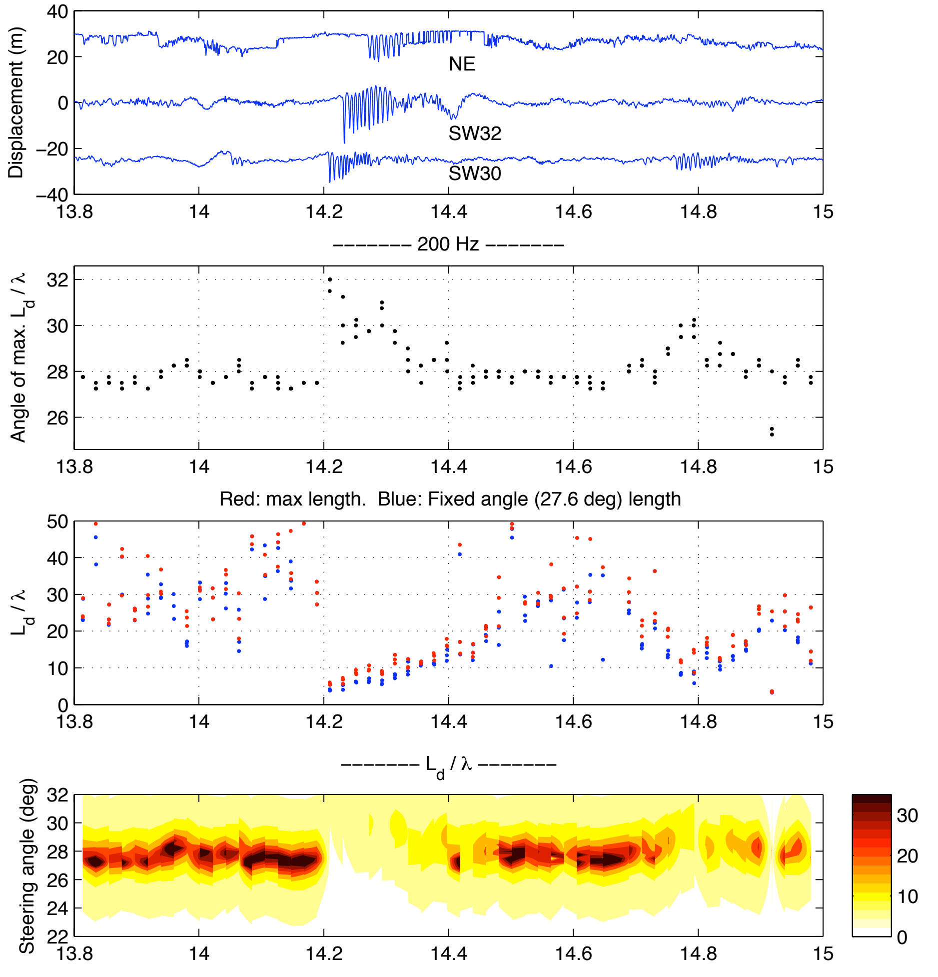


$$R_N(x) = \frac{\left\langle \Psi^*(x_0)\Psi(x_0+x)\right\rangle}{\left\langle \Psi(x_0)^2\right\rangle^{1/2}\left\langle \Psi(x_0+x)^2\right\rangle^{1/2}} \qquad R_N(0)=1$$

Field $\Psi = A\exp(i\phi)$
after beam steering at
angle θ from broadside

Phase (not shown)
dominates $R(x)$



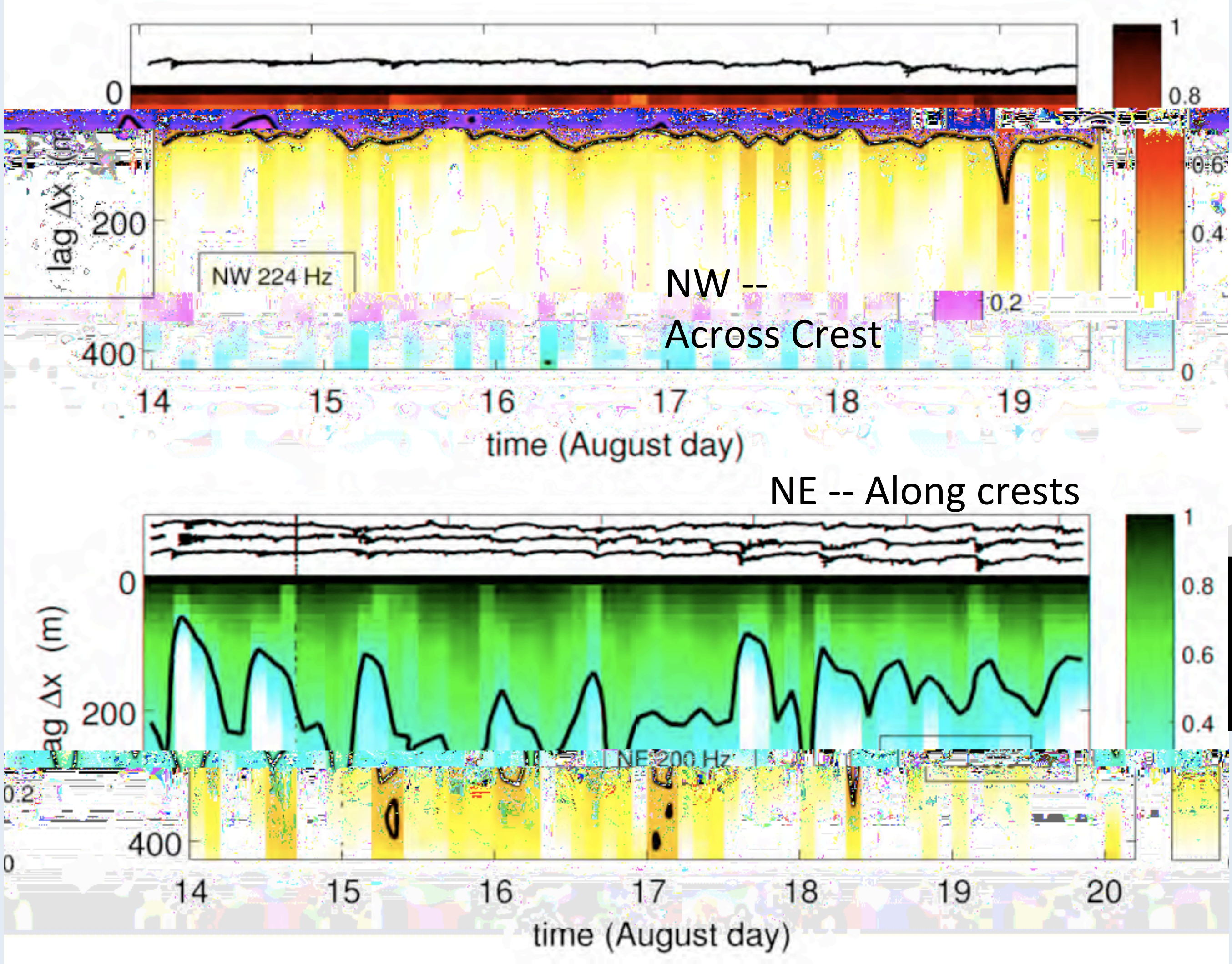


1/*e* point of declining *R(x)* defines coherence length *L*

Duda et al., JASA 2012

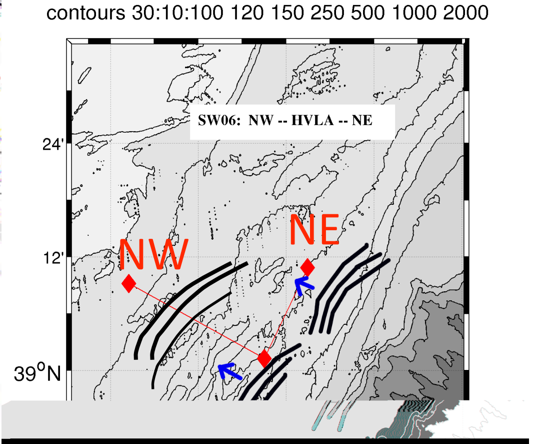
Time-dependent horizontal correlation functions, two SW06 paths.

1/e contour shown in black; color shows *R*(*Δx*)



NW -- Across Crest

NE -- Along crests



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More formal underlying scientific principles for moving forward

- Submesoscale ocean features such as internal gravity waves and fronts have profound effects on underwater sound propagation, particularly in shallow water [continental shelf, basically].
- These features have complex nonlinear dynamics, with the Navier-Stokes fluid equations used as a starting point to explain the behavior.
- Ocean acoustic effects are governed by the wave equation for a heterogeneous medium in three spatial dimensions.
- When sound is influenced by motions in an elastic seabed or elastic ice cover, an expanded set of equations of motion must be solved.

◆ **We seek to understand which features are acoustically relevant, and how they develop and evolve**, working toward useful prediction of the features *and* their acoustic effects.

Why is this an important area of research?

- Underwater acoustics is a primary technology of the US Navy. (And others on, or in, the sea.)
- Ocean data are precious and need to be leveraged in every possible way (e.g. model an area surrounding some sensors).
- Ocean dynamical models, underwater acoustics models, and sonar performance models will be more useful operating together with consistent and inclusive dynamics rather than separately or with restricted dynamics.
- Pushing ocean models to smaller scales will improve their usefulness.

Prior state-of-the-art advances that support a multidisciplinary approach (Why tackle this now?)

- **Rapid recent maturing of**
  - Computational ocean flow modeling methods
  - Computational ocean acoustic modeling methods
  - Computational phase-resolved surface-wave modeling
  - The field of nonlinear ocean wave dynamics
  - The field of ocean internal tide physics (baroclinic tides)
  - The field of sound propagation complexity in dynamic 3D environments
- **New computing capabilities**
  - Reduced cost for fast processors and memory
  - Parallel implementations (clusters and graphics processors)
- **Our multiple disciplines:**

  Computational fluid dynamics
  Applied mathematics
  Ocean dynamics
  Underwater acoustics
  Nonlinear dynamics

Scientific barriers/challenges

- Fundamental unpredictability of many nonlinear processes. Roots in geophysical fluid dynamics, e.g. Lorenz's work.
- The features that ARE fundamentally predictable and trackable may NOT be so with the typical (small) amount of available ocean data at a time/place of interest. (More data would constrain the models.)
- Many details of the nonlinear internal-tide generation process are unknown, so proper model set-up is a challenge.
- The process of short nonlinear internal-wave development from the long internal tide is only partially understood.
- Full numerical models that resolve short nonlinear internal waves are computationally expensive.
- Present acoustic models have limitations: seafloor slope, surface, seabed.
- Unmodeled ocean processes will always remain, e.g. subgridscale motions, dissipation, biota.

The IODA project goals and structure

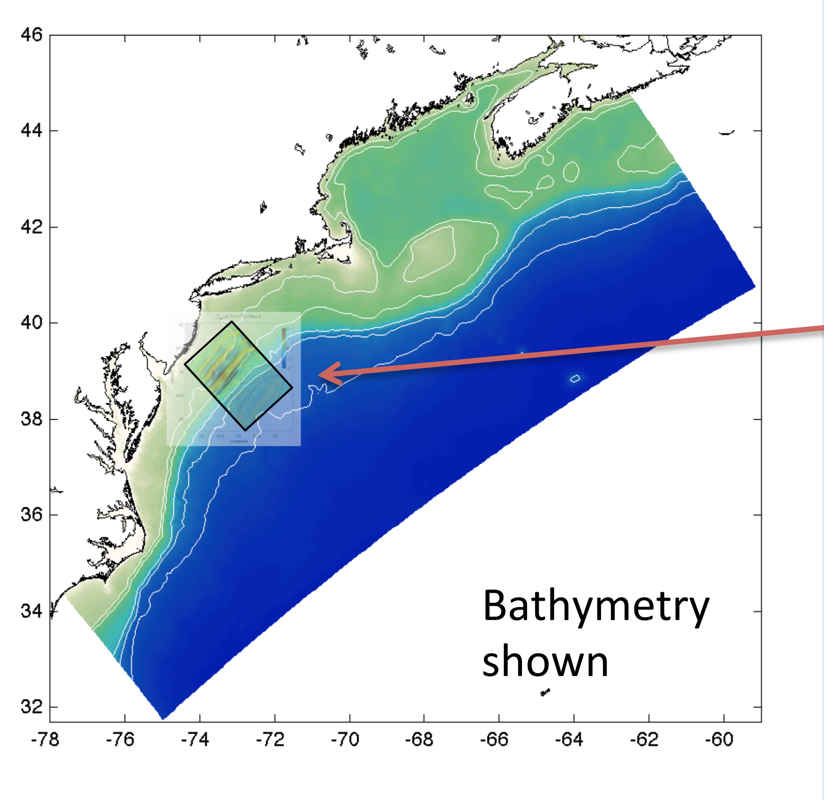
Goal 1 tasks: Modeling tools

- NHP ocean model nested within data-driven HP model, tied to 4D acoustic models (3.5D)
- Hybrid model: Hierarchical internal-wave models nested within HP model, tied to 4D acoustic models (3.5D)
- Improved 4D deterministic and stochastic acoustic modeling (3.5D)
- Unified waveguide model (4D)
- Integration work necessary for the above

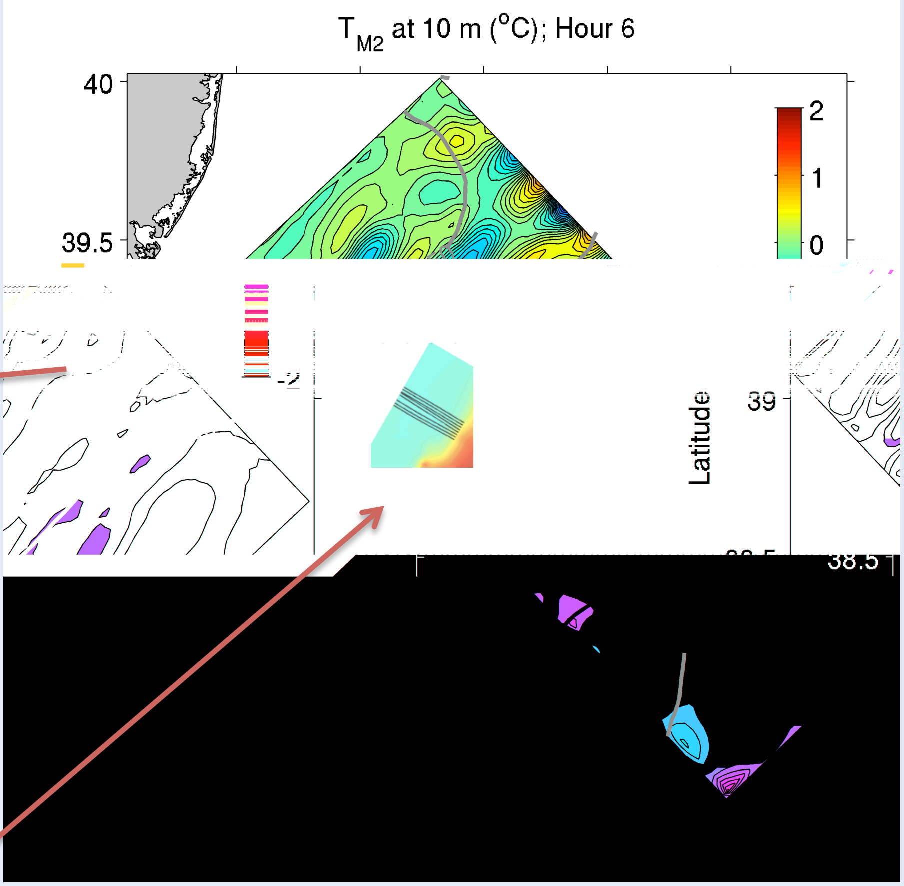
Goal 2 tasks: Physics studies and model verification

- Spatially 3D internal-wave physics studies
- Comparison of outputs and predictions with ground-truth field and lab data

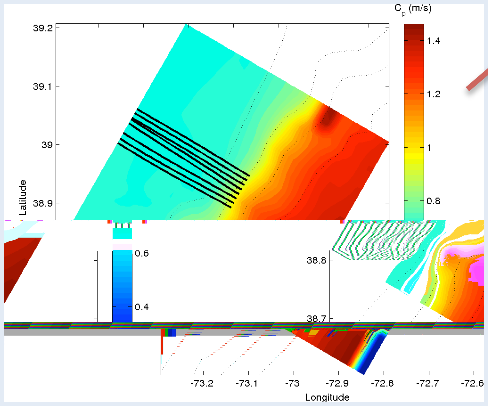
Test bed for research results: A hierarchical model: Outer-domain model is new Rutgers data-driven regional ROMS model *Doppio* (enlarged *Espresso* model) *



Bathymetry shown



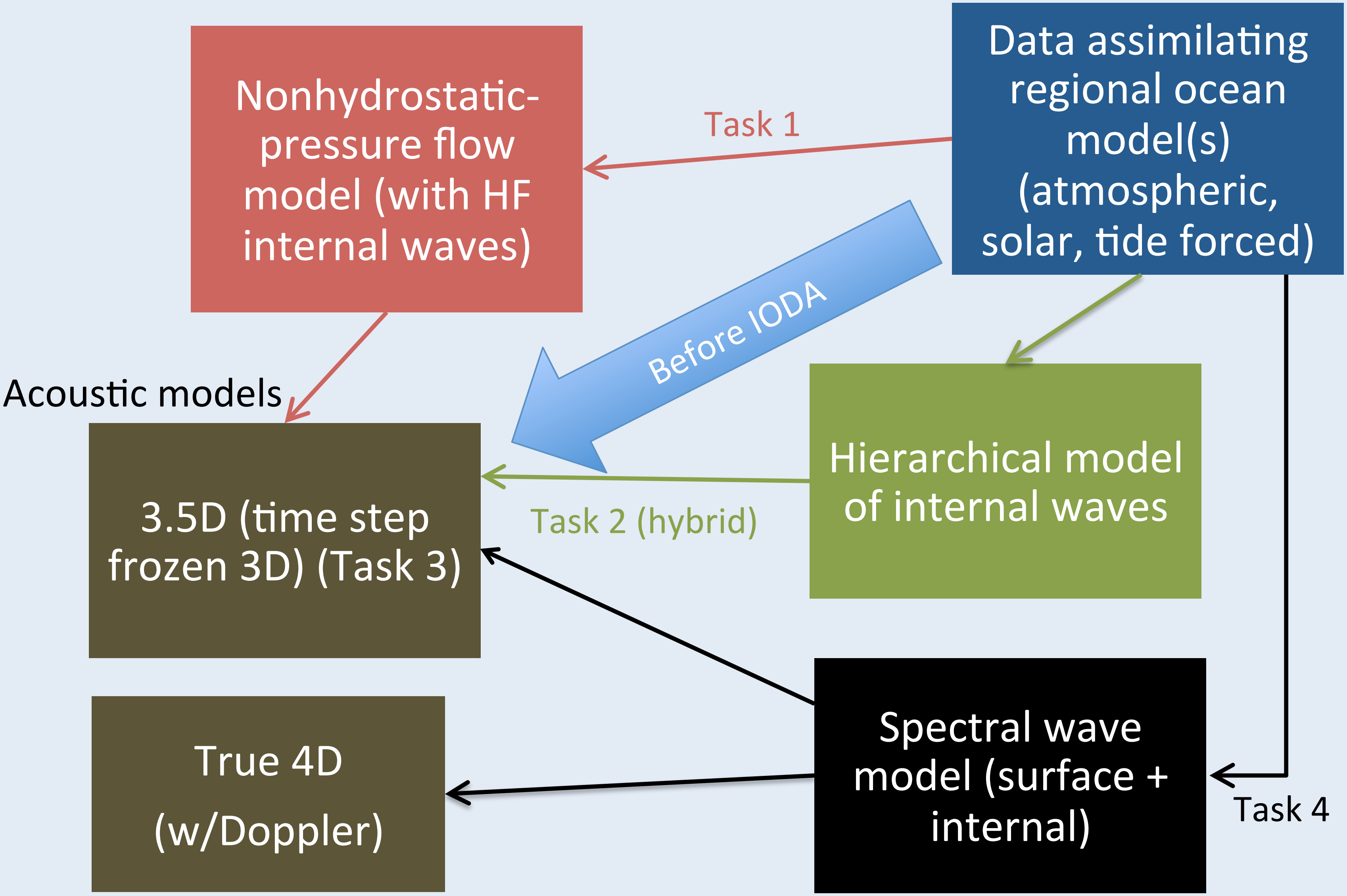
Nested non-assimilating 2-km grid domain;
Resolved internal tides.



* MIT models anchor another test bed

Reduced-physics nonhydrostatic **wave evolution model *AND/OR* 3D computational nonhydrostatic model** nested into 2-km grid model, providing input to **3D acoustic propagation model**.

IODA modeling tasks. *Additional physics theory, lab, and field comparison tasks will be used to "tune" the models and interfaces.*



15 IODA PIs and 3 *team members; 9 institutions.*

WHOI	**Timothy F. Duda** Senior Scientist, Applied Ocean Physics and Eng. (AOPE)
	James F. Lynch Senior Scientist, AOPE
	Karl R. Helfrich Senior Scientist, Physical Oceanography
	Ying-Tsong Lin Associate Scientist, AOPE
	Weifeng Gordon Zhang Assistant Scientist, AOPE
	Arthur Newhall Research Specialist, AOPE
Univ. of Texas at Austin	**Harry L. Swinney** Sid W. Richardson Found. Regents Chair and Prof. of Physics
Rutgers University	**John L. Wilkin** Professor; Director, Graduate Program in Oceanography
	Julia Levin Associate Research Professor, Inst. Marine and Coastal Sciences
Mass. Inst. of Technology	**Pierre F. J. Lermusiaux** Doherty Assoc. Prof. in Ocean Utilization, Mech. Eng.
	Nicholas C. Makris Professor, ME
	Dick K.-P. Yue Philip J. Solondz Professor of Engineering; Director Intl. Progs., ME
	Yuming Liu Principal Research Scientist, ME
University of Delaware	**Mohsen Badiey** Professor, Phys. Ocean Sci. and Eng ; Civil and Env. Eng.
Rennselaer Polytech. Inst.	**William L. Siegmann**, Prof., Math. Sci.; Assoc. Dean of Science for Grad. Edu.
Colorado School of Mines	**Jon M. Collis** Asst. Professor, Applied Mathematics and Statistics
Naval Postgrad. School	**John A. Colosi** Professor, Oceanography
Florida Inst. of Technol.	**Steven M. Jachec** Assistant Professor, Marine and Environmental Systems

IODA PIs and *team members by* primary discipline (some of my choices are debatable)

Underwater acoustics	**Timothy F. Duda**	WHOI
	James F. Lynch	WHOI
	Mohsen Badiey	UD
	Ying-Tsong Lin	WHOI
	Nicholas C. Makris	MIT
	John A. Colosi	NPS
	Arthur Newhall	WHOI
Computational fluids:	**Pierre F. J. Lermusiaux**	MIT
	Julia Levin	Rutgers
	Steven M. Jachec	FIT
	Dick K.-P. Yue	MIT
	Yuming Liu	MIT
Ocean dynamics:	**John L. Wilkin**	Rutgers
	Karl R. Helfrich	WHOI
	Weifeng Gordon Zhang	WHOI
Applied math:	**William L. Siegmann**	RPI
	Jon M. Collis	CSM
Nonlinear dynamics:	**Harry L. Swinney**	UT

Wave physics contributions

- Requirement of nonlinear dynamics to get the phase and amplitude of internal tide (IT) correct (W. Zhang and Duda pub.)
- Effective height (or virtual canyon floor) reduction of IT generation response. (L. Zhang and Swinney sub. pub.)
- Multiple-scatter analysis of asymmetric IT generation and propagation away from a canyon. (Zhang, Duda, Udovydchenkov, pub.)
- Breaking criterion for IT (conversion to short internal waves) and wave fission at a shelf break (Helfrich and Grimshaw sub. pub.)

Acoustic propagation modeling contributions

- New 3D standard order (wide-angle) Fourier split-step parabolic equation solvers (Lin, Duda, Newhall pub.)
  - Cartesian
  - Cylindrical, radial grid (zero-pad grid refinement)
  - Cylindrical, constant arc-length grid increment (unrolling, "nautilus")
- New higher-order (2nd-order) parabolic equation operator expansion (Lin and Duda pub.)
  - Fourier split-step 3D codes, cylindrical and Cartesian
  - Alternating direction implicit (ADI) 3D Pade' code (Lin, Collis and Duda pub.)
  - Standard direct Pade' (memory intensive) code (Lin, Collis and Duda pub.)
- New rough-surface 3D Pade' PE (Lin)

Regional ocean dynamical modeling contributions

- ***Doppio:*** New data-driven east-coast USA/Canada Regional Ocean Modeling System (ROMS) implementation (Wilkin and Levin)

- Detailed hi-resolution MSEAS ensemble Kalman filter type (ESSE) simulations, which are beginning to have realistic frontal intrusions (Lermusiaux)

Small-scale nonlinear* wave modeling contributions

- A dimensional form of the pseudospectal solver for the regularized form of the rotation-modified extended Korteweg-deVries equation (eKdVf) is in place, taking environmental conditions and initial conditions from regional models or *in situ* instrumentation.

* A framework that handles the effects of nonhydrostatic pressure is needed. (Linked to vertical acceleration of water)

Integration contributions

- Linked regional models and 3D PE models, GUI or data-file initiated.
  - MSEAS SW06 New Jersey Shelf (Lermusiaux and Haley)
  - Southern California MITgcm internal-tide model (Ponte and Cornuelle)
  - Nat. Taiwan Univ. South China sea model (Prof. Sen Jan)
  - WHOI Hudson Canyon ROMS model (Weifeng Gordon Zhang)

- Linked regional model and eKdVf nonlinear wave solver.
  - Internal-tide rays are computed in the regional model environment.
  - Coefficients of the nonlinear equation along the rays are calculated from the regional model environment.
- Experimental data base
  - Mapping SW06 internal waves, SW06 internal waves statistics and SW06 internal wave database for model validation (Badiey and Lynch

Statistical acoustic modeling contributions

- Temporal coherence model for broadband signals (Gong, Makris et al. Pub.)
  - A potential to include spatially variable internal wave fields

- Transport theory model for mean fields (Colosi)
  - Spatially variable internal wave fields
  - Spatially variable surface wave fields.
  - Internal waves and surface waves together.

IODA project meetings

- Kickoff Workshop, 13-14 June 2011
  - At WHOI
  - Ten PIs and seven other personnel
  - Group leaders assigned
- IODA Acoustics Meeting, 12-13 June 2012
  - At the University of Delaware
  - Seven PIs and nine other personnel
  - Results shared. Intercomparisons planned.
- IODA Physical Oceanography Meeting, 13-14 March 2013
  - At WHOI
  - Ten PIs and ten other personnel
  - Results shared. Acoustic PI viewpoint explained to PO PI's.
- Presentations, videos, and documents online for team
  http://www.whoi.edu/sites/IODA

8 Graduate students and 7 postdocs (some partially MURI funded)

- **University of Texas at Austin** (Prof. Swinney)
  Ruy Amador, undergraduate student in physics
  Amadeus Dettner, awarded MS in Physics (U Texas at Austin), Dec. 2012
  Matthew Drake, awarded MS in Physics (U Texas at Austin), Dec. 2012
  Santiago Jose Benavides (Schlumberger Undergraduate Research Fellowship, starting soon)
  Likun Zhang, postdoc, PhD Physics (acoustics), Washington State U (2012) (ASA fellowship funded)
  Matthew Paoletti, postdoc, PhD Physics, University of Maryland (2010)
- **MIT** (Profs. Lermusiaux, Makris and Yue)
  Akash Phadnis, graduate student (Masters expected soon)
  Yulin Pan, PhD student (degree expected in 2 years)
  Chris Mirabito, postdoc, PhD U Texas at Austin (10% support)
  Zheng (Roger) Gong, postdoc, PhD Northeastern U.
  Areti Kiara, postdoc, PhD MIT (partial support)
- **Rensselaer Polytechnic Inst.** (Prof. Siegmann)
  Brendan deCourcy, PhD student (partial support)
  John Brimlow, PhD student (partial support)
- **Naval Postgraduate School** (Prof. Colosi)
  Kaustubha Raghukumar, postdoc, PhD UC San Diego
- **University of Delaware** (Prof. Badiey)
  Lin Wan, postdoc.PhD Georgia Tech.
- **WHOI** (Drs. Duda, Lin, Lynch, Zhang and Helfrich)
  Odile Hebert, Guest Masters level student, summer 2012 (ENSTA ParisTech, Engineering)

Refereed publications

1. Badiey, M., L. Wan and A. Song, Three-dimensional mapping of internal waves during the Shallow Water 2006 experiment, J. Acoust. Soc. Am., 134, EL7-EL13, dx.doi.org/10.1121/1.4804945, 2013.
2. 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, dx.doi.org/10.1121/1.3605565, 2011.
3. Gong, Z., T. Chen, P. Ratilal, and N. C. Makris, Temporal coherence of the acoustic field forward propagated through a continental shelf with random internal waves, J. Acoust. Soc. Am., 134, 3476-3485, 2013. [published, refereed]
4. Grimshaw, R., C. Guo, K. Helfrich, and V. Vlasenko, Combined effect of rotation and topography on shoaling internal solitary waves, J. Phys. Oceanogr., submitted, 2013 [submitted]
5. Haley, P. J. Jr., A. Agarwal, and P. F. J. Lermusiaux, Optimizing velocities and transports for complex coastal regions and archipelago. Ocean Modeling, submitted, 2013. [submitted]
6. Kiara, A., K. Hendrickson and D. K. P. Yue, SPH for incompressible free-surface flows. Part II: Performance of a modified SPH method, Computers and Fluids, 86: 510-536, dx.doi.org/10.1016/j.compfluid.2013.07.016, 2013.
7. King, B., M. Stone, H. P. Zhang, T. Gerkema, M. Marder, R. B. Scott, and H. L. Swinney, Buoyancy frequency profiles and internal semidiurnal tide turning depths in the oceans, J. Geophys. Res. (Oceans) 117, C04008, dx.doi.org/10.1029/2011JC007681, 2012. [published, refereed]
8. Lin, Y.-T. and T. F. Duda, A higher-order split-step Fourier parabolic-equation sound propagation solution scheme, J. Acoust. Soc. Am., 132, EL61-EL67, 2012.
9. Lin, Y.-T., J. M. Collis, and T. F. Duda, A three-dimensional parabolic equation model of sound propagation using higher-order operator splitting and Padé approximants, J. Acoust. Soc. Am., 132, EL364-370, dx.doi.org/10.1121/1.4754421, 2012.
10. Lin, Y.-T., T. F. Duda, and A. E. Newhall, Three-dimensional sound propagation models using the parabolic-equation approximation and the split-step Fourier method, J. Comput. Acoust., 21, 1250018, dx.doi.org/10.1142/S0218396X1250018X, 2013.
11. Lin, Y.-T, K. G. McMahon, J. F. Lynch, and W. L. Siegmann, Horizontal ducting of sound by curved nonlinear internal gravity waves in the continental shelf areas, J. Acoust. Soc. Am., 133, 37-49, dx.doi.org/10.1121/1.4770240, 2013.
12. Nash, J. D., S. M. Kelly, E. L. Shroyer, J. N. Moum, and T. F. Duda, The unpredictable nature of internal tides and nonlinear waves on the continental shelf, J. Phys. Oceangr., 42, 1981-2000, dx.doi.org/10.1175/JPO-D-12-028.1, 2012.
13. Nash, J. D., E. L. Shroyer, S. M. Kelly, M. E. Inall, T. F. Duda, M. D. Levine, N. L. Jones, and R. C. Musgrave, Are any coastal internal tides predictable? Oceanography, 25, 80-95, http://dx.doi.org/10.5670/oceanog.2012.44, 2012.
14. Paoletti, M. S., and H. L. Swinney, Propagating and evanescent internal waves in a deep ocean model, J. Fluid Mech., 108, 148101, dx.doi.org/10.1017/jfm.2012.284, 2012.
15. Tran, D. D., M. Andrews, and P. Ratilal, Probability distribution for energy of saturated broadband ocean acoustic transmission: Results from Gulf of Maine 2006 Experiment, J. Acoust. Soc. Am., 132, 3659-3672, 2012.
16. Xiao, W., Y. Liu, G. Wu and D. K. P Yue, Rogue wave occurrence and dynamics by direct simulations of nonlinear wave-field evolution, J. Fluid Mech., 720, 357-392, 2013.
17. Zhang, W. G. and T. F. Duda, Intrinsic nonlinearity and spectral structure of internal tides at an idealized Mid-Atlantic Bight shelfbreak, J. Phys. Oceanogr., 43, 2641-2660, 2013.
18. Zhang, W. G., T. F. Duda, and I. A. Udovydchenkov, Modeling and analysis of internal-tide generation and beam-like onshore propagation in the vicinity of shelfbreak canyons, J. Phys. Oceanogr., in press, 2013.
19. Raghukumar, K. and J. Colosi, High frequency normal mode statistics in a shallow water waveguide: The effect of random linear internal waves,. JASA, submitted, 2013. [submitted]

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