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# Issues and Progress in the Prediction of Ocean Submesoscale Features and Internal Waves

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*Abstract*— **Data-constrained dynamical ocean modeling for the purpose of detailed forecasting and prediction continues to evolve and improve in quality. Modeling methods and computational capabilities have each improved. The result is that mesoscale phenomena can be modeled with skill, given sufficient data. However, many submesoscale features are less well modeled and remain largely unpredicted from a deterministic event standpoint, and possibly also from a statistical property standpoint. A multi-institution project is underway with goals of uncovering more of the details of a few submesoscale processes, working toward better predictions of their occurrence and their variability. A further component of our project is application of the new ocean models to ocean acoustic modeling and prediction. This paper focuses on one portion of the ongoing work: Efforts to link nonhydrostatic-physics models of continental-shelf nonlinear internal wave evolution to data-driven regional models. Ocean front-related effects are also touched on.**

***Keywords—Ocean modeling, dynamical modeling, internal waves, internal tides, nonlinear waves, ocean prediction.***

## I. Introduction

The enterprise of data-driven dynamical ocean modeling is on a steady path of improvement. Methods of data collection, data assimilation, and subgrid physics parameterization have steadily evolved and improved over the recent decades. In addition, computational hardware, software, and inter-connection capabilities have allowed larger computational domains with greater dynamic range. The result is that mesoscale phenomena can be modeled with impressive accuracy, given that sufficient in situ information and boundary information are provided to the models. However, at scales smaller than the mesoscale, challenges related to stronger nonlinearity, a relative lack of detailed data, and increased sensitivity to subgrid-scale effects have slowed the progress compared with the larger scale phenomena. The challenges have long been recognized, and are now getting attention as the mesoscale modeling improves in quality.

The extension of data-driven ocean modeling to include smaller scale features reduces the number of subgrid-scale physical processes that must be parameterized, potentially improving model performance at all scales. This has been demonstrated with data-driven modeling done at Harvard and MIT of the conditions during the Office of Naval Research Shallow-Water 2006 (SW06) experiment [1], and has been shown by other ocean model testing studies [2]. There may never be a computationally solvable single equation-set model system spanning from molecular dissipation process scales to ocean eddy scales (or even turbulence processes outer-scales to eddy scales), so the method of making grids denser, as hardware improves, is not a probable ultimate solution. Therefore, alternative approaches to extend resolution to smaller scales may be more productive.

The underlying motivation for some of the work presented here derives from the fact that one family of small-scale dynamical ocean features, nonlinear internal gravity waves, can have strong influences on acoustic propagation. This has been found from both computed results (e.g. [3,4]) and measurements [5-7]. These waves can develop on their own from supercritical flow or from long-wavelength tidal-frequency internal waves (internal tides) [8]. Frontal boundaries also have important acoustics effects [9], and are regions of complex thermohaline circulation effects and small-scale mixing processes [10,11]. A critical need for such multi-

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resolution ocean modeling for acoustics use is the acquisition of in situ observations for accurate initialization and subsequent efficient adaptive sampling [12]. Such coupled ocean and acoustic forecasts with efficient initial and adaptive in situ sampling have been completed onboard ships [13,14], but over limited-area domains. Accurate predictions would also benefit from coupled physical-ocean and acoustics data assimilation [14]. In addition to deterministic field estimates, such efforts often require uncertainty predictions [15-17].

A multi-institution project is underway with goals of uncovering more of the details of these wave and frontal processes, working toward better prediction of their occurrence and variability. This paper will report on some of the issues related to modeling across the many scales, and on efforts on two topics: linking nonhydrostatic-physics models of continental-shelf nonlinear internal wave (NIW) evolution to data-driven regional models, and better modeling the frontal effects. This is part of a longer chain of linked models: ocean basin scale models providing boundary conditions to the regional models, the regional models driving the NIW models, and the NIW models providing input to 3D acoustic propagation models. Note that we sometimes expand our intended meaning of the term submesoscale to include internal gravity waves. We do this because they are have time and space scales shorter than mesoscale. This term has been used to refer to slower or balanced motions characterized by order-unity Rossby number dynamics.

The sections to follow will cover important issues in ocean modeling (II), progress in multi-resolution nested modeling (III), progress in nested models for internal wave study and prediction (IV), progress in frontal area modeling (V), and a summary.

## II. Issues

There are at least two ways that data-driven modeling is useful. One is to use a sparse data set to best map an ocean region in a dynamically consistent way. Another is to let the system run into the future to make predictions. Here is a list of issues related to these uses of dynamical ocean models:

- Data assimilation method.
- Data type and data coverage in time and space, including surface forcing data.
- Ocean model resolution.
- Boundary condition treatment, including non data-driven surface forcing (e.g. climate data base).
- Subgrid-scale process parameterization for resolved features.
- Subgrid-scale process parameterization for missing (small-scale) features.

There is a vibrant literature on many if not all of these topics. The intent here is not to summarize this entire body of work, and the reader is invited to explore each of these topics. There are also a few summary papers available from the 2009 OceanObs conference [18-21]. The vital process of optimally and consistently assimilating data into models for each of these purposes is an active area of research with significant progress

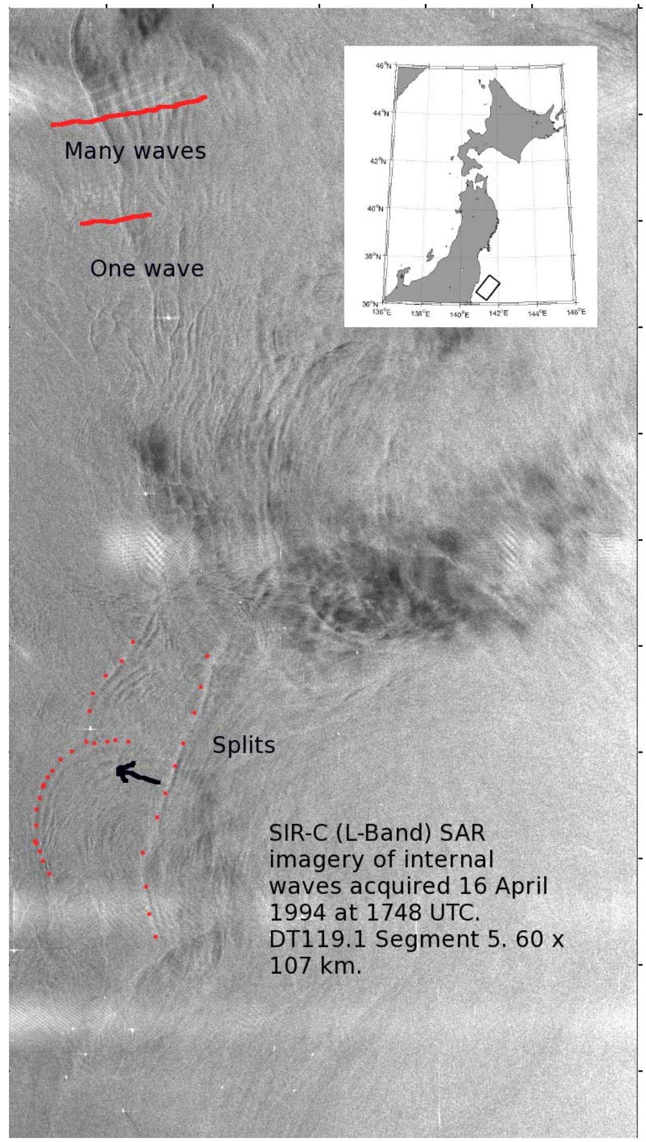


Fig. 1. A satellite synthetic aperture radar image of internal waves east of Honshu. The figure is adapted from a figure in Jackson's internal wave atlas [27].

over the last decade [22-25], and will not be addressed further here. Instead we move to the third, fifth and sixth bullets in the list above, relating to model resolution and the barely-resolved or unresolved submesoscale processes.

Efforts to address the mixing effects of subgrid processes, mostly internal waves, on the world's ocean, and modeling attempts to describe the ocean (fully computational, but also reduced-complexity), have been sustained, with steady progress [e.g. 26]. The goal of that work differs from our goal, which is to extend data-driven modeling to include these processes, rather than simply account for the effects of these processes on the larger scale. The small-scale processes may be fully described (deterministically modeled), they may be partially described, or they may be statistically described. For example, a partial description would be the location and travel

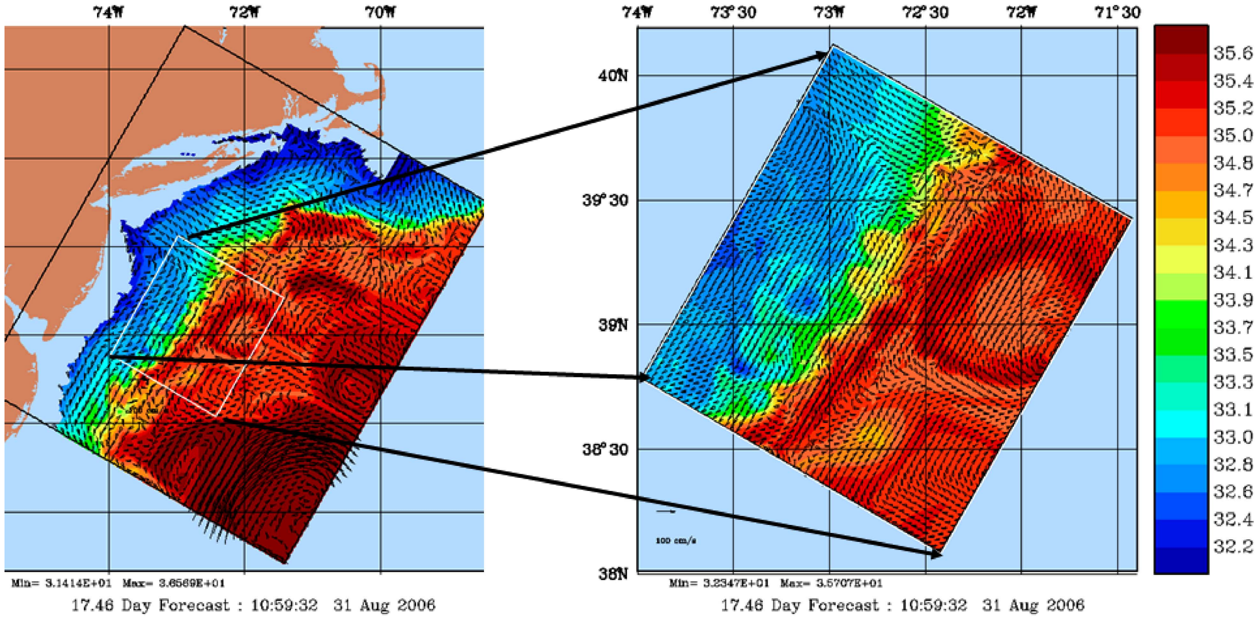


Fig. 2. Surface fields of a data-driven implicitly 2-way nested reanalysis simulation using the MSEAS modeling system in the Middle Atlantic Bight region during SW06. Show are 30m salinity fields overlaid with the 30m velocity vectors from that reanalysis of SW06 conditions, just prior to tropical storm Ernesto.

direction of internal wave packets, or the size of the largest wave in a packet. The exact number of nonlinear waves in a packet may be less reliably obtainable, due to inherent restricted predictability of nonlinear processes. Fig. 1 shows two examples of NIW packet variability. One wave packet at the lower end seems to split along its crest (under the assumption that that the waves to the left that are highlighted with dots are propagated versions of the highlighted waves to their right). At the top, a wave feature has a variable number of waves long its crest, with only one wave visible at one indicated location.

Before moving to small-scale feature modeling in the next sections, we can elaborate on the current paradigms regarding modeling and small-scale features. The small-scale processes of interest to us, which are so important to the fluid flows and structures in the ocean, are not fully resolved, and may never be, but their effects are critical, as is well known [26]. Two of these effects, isopycnal and diapycnal mixing of scalar properties (salt and heat, for example), and of momentum, are accounted for in models by so-called subgrid-scale parameterizations.

In flow-based parameterizations, aspects of the resolved flow field are inserted into formulas to compute the net effect on the field of the unresolved processes. This is fine when the resolution allows all types of motions into the computation. But this is rarely the case. For example, 100-m wavelength NIW, which exhibit nonhydrostatic pressure and which are common throughout the world and in particular on shelves [27], are not included in one-km resolution regional ocean models. Therefore, localized strong mixing effects confined to the locations of the waves [28] cannot be well accounted for.

In another type of parameterization, the subgrid phenomenon is dynamically independent of the model state, and is computed with a formula that may be only weakly dependent in the model state. This is one way to handle diapycnal mixing from ubiquitous weak ocean internal waves, (as opposed to strong NIW). Such formulas may depend on flow-field features such as vertical density gradient, and they also may depend on such parameters as seafloor roughness, height above seafloor, tide current strength (possibly applied off-line for a model not including ocean tides), and so on. Such a parameterization could be used to account for NIW-based mixing on the shelf. In the case that the spatial distribution of NIW waves and their sizes are known, it may be possible to effectively parameterize long-term average mixing rates, but this would be an unusually well-behaved situation for a nonlinear phenomenon.

Observations suggest that shelf NIW are more variable and unpredictable at many locations than the tides that produce them, with good evidence seen in satellite images of NIW ([27] and Fig. 1). The fact that these waves may not be distributed in known fashion means that feedback to the model flow-field evolution via a mixing parameterization is inexact. Whether it is might be good enough is a valid research question. In any event, one issue is whether we can localize NIW for the purpose of including their feedback mixing effect on the environment. In addition, motions at shelfbreak frontal boundaries (such as found south of New England) can influence nutrient transport upward into the euphotic zone [29] and into shelf waters [30], and may be very sensitive to the details of mixing in this complex region [31]. So we have two reasons for studying whether we can model in detail internal waves and fronts (which can meander due to instabilities, and spawn small-scale instabilities): (1) we wish to model and localize them for the purpose of pinpointing where and how they affect human activities (energy, industrial operations, acoustic surveillance); and (2) we wish to examine where and how their mixing and nonlinear transports impact the background conditions.

## III. Multi-Resolution Data-Driven Modeling

Accurate modeling, prediction and forecasting of small ocean features requires the best possible fields at the larger scales. Fortunately, accurate data-driven hydrostatic regional ocean modeling is an active area. One of the approach that can be followed to improve the predictive ocean-acoustic skill is to increase ocean modeling resolution where needed for underwater sound propagation modeling [12, 32, 16]. This is completed by the MSEAS group, using a hydrostatic primitive-equation modeling system [33] with a nonlinear free surface on implicit 2-way nested domains. This allows simulating the interactions of internal tides, sub-mesoscale eddies, fronts, currents and storm responses for the SW06 experiment. However, it does not simulate the non-hydrostatic nonlinear internal waves. The role of the multi-resolution data-driven modeling in our submesoscale modeling is explicitly stated here. These models must have sufficiently high resolution to provide faithful internal tide generation, from barotropic tide interaction with a sloping seabed, in the presence of density and current features inserted into the model via data assimilation. The internal tide and mesoscale fields from these models form the input parameters to our nested nonlinear/nonhydrostatic internal wave model, described in the next section. The model resolution must also be sufficient to accurately model frontal features.

To obtain multiscale re-analyses that are useful for acoustic studies, several improvements were completed. First, increased vertical (100 levels) and horizontal (1km) resolution were employed. The 100 levels were optimized to the thermocline structure. The atmospheric forcing applied to the ocean simulations were corrected, improving the merging of the WRF fields into the larger NOGAPS fields, and using corrected E-P and direct fluxes. The initial conditions were substantially upgraded. First, synoptic data and pseudo profiles were employed to bolster the front. Second, the World Ocean Atlas climatology was corrected to match 2006 slope conditions. Third, we employed a revised shelfbreak T/S front feature model, a Gulf Stream T/S feature model (based on synoptic data) and transport feature models for each of the Gulf Stream, slope recirculation gyre and shelfbreak front. Improved barotropic tidal forcing was obtained from OSU [34]. Focusing on the internal tides and open boundary conditions, a sponging scheme with a novel, efficient, time dependent sponging target field was designed to inhibit spurious reflections from open boundaries while preserving the incoming tidal forcing and permitting realistic subtidal dynamics (e.g. permitting the advection of eddies and upwelled water in and out of the computational domain). The temporal updating of the target field was also incorporated into the open boundary conditions. The data assimilation methodology was tuned for the front, and surface and internal tides through the use of shorter space scales and weaker, more frequent assimilation. Finally, model sub-grid scale parameters (vertical mixing, horizontal mixing and bottom friction) were also re-tuned. Overall, more than thousand data-driven simulations with varied numerical and physical parameters were completed. These re-analyses were inter-compared and also evaluated by quantitative comparisons with independent data, using a set of skill metrics.

Fig. 2 shows the 30 m depth salinity overlaid with the 30 m velocity vectors from the best 2013-reanalysis of the SW06 period, at a time just prior to tropical storm Ernesto. The new

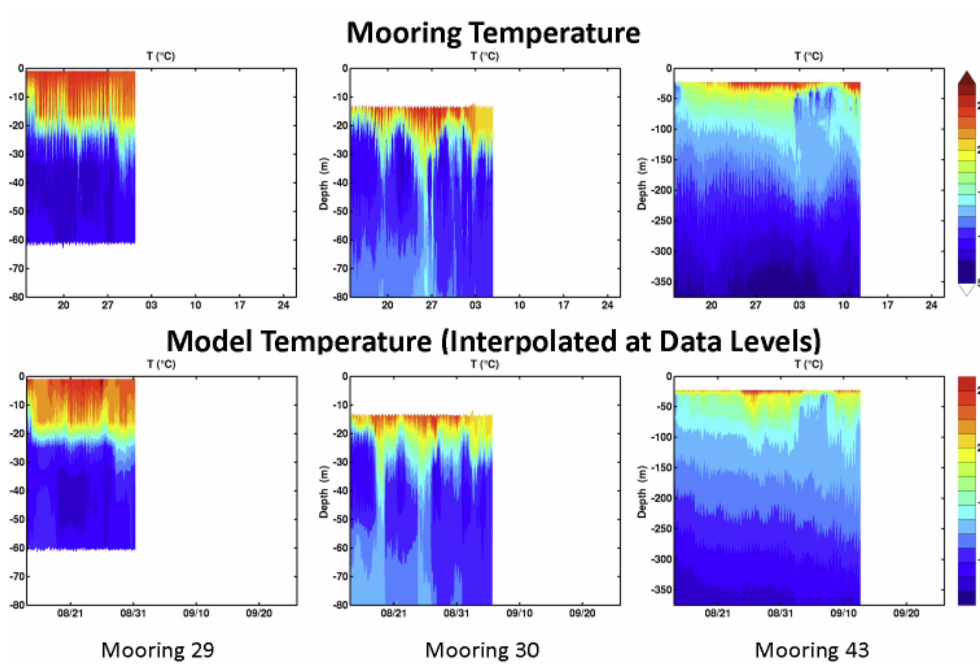


Fig. 3. Comparison of the MSEAS reanalysis with *independent* time-series of mooring temperature data. Shown from left-to-right: shallower 60m depth, shelfbreak 80m depth and slope 375m depth.

ocean SW06 reanalysis improved the frontal properties and especially the internal tide fields. Dynamical studies using the new simulation are underway including studies of the effects of the strong wind forcing, shelfbreak exchanges, subsurface intrusions, Gulf Stream and recirculation gyres.

Improvements to the ocean SW06 reanalysis directly led to increased fidelity of the simulations. For example, the thermocline and frontal intrusions were substantially improved, both in forecasts from the re-analysis (i.e. hindcasts) and in the re-analysis itself. This was evaluated by comparison with Scanfish data (the forecasts from the re-analysis do not assimilate that Scanfish data or any other data during the forecast period). For completely independent evaluation, the re-analyses were also compared to the mooring data which are not assimilated at all. These comparisons are illustrated for the best 2013 re-analysis in Fig. 3, considering three moorings (on the shelf, near the shelfbreak front and on the slope). The fit to that data was substantial improved compared to the previous re-analysis (not shown), with good agreement. The point-wise agreement of the re-analysis evaluated at mooring data locations with that independent data is better than expected. Of course, the mooring data still shows several higher frequency features that are not forced on, nor resolved by, the hydrostatic modeling system.

For specific NIW-modeling studies (next section), three types of detided fields were employed from the MSEAS reanalysis: (i) fields filtered with a running average (ii) two-week simulations with no tidal forcing initialized at 10-day intervals from the tidally forced reanalysis and (iii) an identical twin simulation of the full reanalysis run but without tidal forcing. Each type of detiding results in a different subtidal mesoscale environment due to accumulated differences in their respective tidal histories. These detided fields were used, first as a baseline without IT/IW and secondly as an environment in which specific IT/IW signals can be introduced and their acoustic impacts assessed.

Similar nested model development is underway at Rutgers. High-resolution subdomains are being nested into the eastern-USA coastal ESPreSSO operational data-driven ocean model [35]. Work is underway toward two-way nesting subdomains having the scope and resolution required to effectively model internal tides and internal waves. Convergence testing related to our recently published internal-tide generation studies [36,37] suggests that 1-km horizontal resolution may provide accurate internal-tide predictions.

## IV. Nested internal wave model

Our model for prediction of NIW features inside the domain of a data-driven regional model, but not fully resolved by that regional model, is briefly described here. It is more fully described in a recent conference paper [38]. Important points are that the data-driven (or data assimilating, DA) regional model allows only hydrostatic pressure, whereas NIW exhibit nonhydrostatic pressure (NP) physics. The model has four components.

The ***first component*** is a regional model running in DA mode with tidal forcing, so that internal tides develop. The mechanism for internal tide generation is oscillating flow near a sloped seabed, so that conservation of mass boundary conditions induce oscillatory vertical flow [39].

The ***second component*** is a ray-tracing calculation describing the propagation of internal tide normal modes. This model requires the modal properties to be computed from the de-tided output of the regional model. Required are vertical structures of internal-wave modes (eigenfunctions), and *x-y* maps of phase speed ($c$) related to the eigenvalues. Internal-tide initial conditions such as waveforms at outer-continental shelf wave origin locations are also required from the regional model. There are a few choices for the mode eigenfunctions, which we discuss below. Fig. 4 shows a ray-trace solution example.

The ***third component*** is a nonlinear wave evolution model with NP dynamics that describes the NIW themselves. This model is a generalization of the two-dimensional (vertical slice) Korteweg-de Vries model, known as the extended KdV model with earth rotation [40], which we abbreviate as eKdVf. It is a cubic nonlinear equation for internal-wave mode amplitudes in a time-space domain. The model equation is

$$\frac{d}{ds}\left(\frac{\partial\eta}{\partial t}+\left(c+\alpha\eta+\alpha_1\eta^2\right)\frac{\partial\eta}{\partial s}+\beta\frac{\partial^3\eta}{\partial s^3}-\frac{c}{Q}\frac{dQ}{ds}\eta\right)=\frac{f^2}{2c}\eta \quad .1$$

where $\eta$ is the mode amplitude. The spatial dimension $s$ is along-ray distance in our scenario. The nonlinear-term coefficients ($\alpha$'s) and the NP dispersion-term coefficient ($\beta$) are specific to the mode being worked on; they are integrals involving the mode eigenfunctions. $Q$ is a related variable that allows slowly-varying depth. The speed $c$ is spatially variable. Rotation effects are imparted by $f$, equal to 2 times sin(latitude)

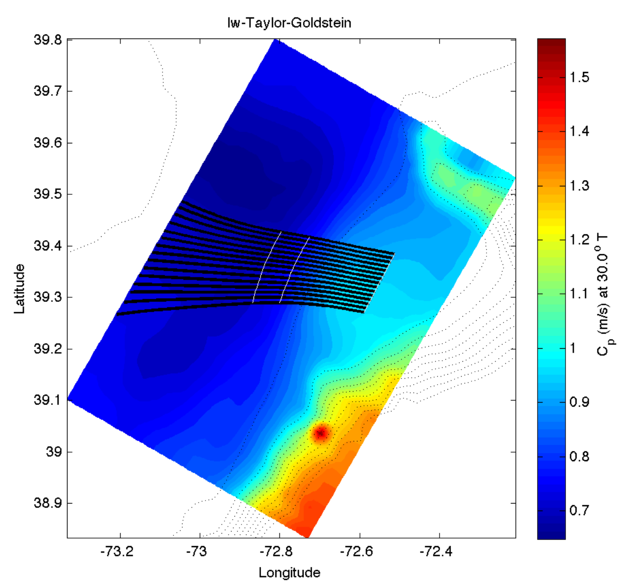


Fig. 4. Internal tide mode-one rays computed for a de-tided summer 2006 MSEAS field are shown. The color shows the approximate wave speed field used for the ray trace. The firtst mode at each location was found using the $k$=0 version of the Taylor-Goldstein equation, so the speed is a function of wave direction. We use "Anisotropic raytracing".

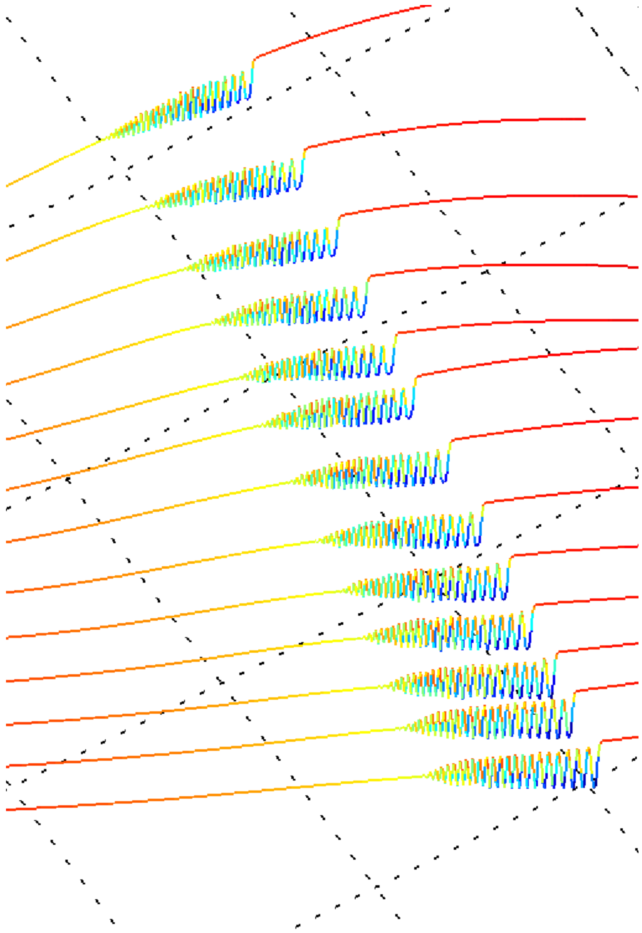

Fig. 5. A time snapshot of short internal wave shapes obtained by solving the eKdVf equation along rays are shown, supinposed on the rays. (See Fig. 4. for a picture of a related set of example rays.) The colors show the mode amplitude, closely reated to thermocline displacement for these mode-one waves. The initial conditions are M2 internal tide (period 12.42 hr) sine waves at the wave origin at the left (the right in Fig. 4.). Each simulated wave packet is about 6 km long.

times the earth rotation rate. The eKdVf is solved along internal-tide rays to give short-wavelength NIW along the rays. Mode one is the most energetic on the shelf, by far; the other modes are rarely modeled. Fig. 5 shows mode-one solutions along a set of closely-spaced rays.

The ***fourth component*** of the model is a 3D parabolic equation sound propagation code [41]. The acoustic effects of NIW are not the topic of this paper, and the interested reader is referred to the conference paper for more information.

The nested NIW model has not yet been proven to be sufficiently accurate to improve activities like sonar system performance prediction. Making this assessment is one of our research goals. To best formulate this model, basic research into IT formation and dynamics, NP wave dynamics, surface wave modelling, regional model development, statistical and computational acoustic propagation modelling, NP computational modelling, and efficient or optimal interfacing of ocean environment models and acoustic models (i.e. passing sufficiently but not unnecessarily detailed sound-speed structures to acoustic models).

There are some interesting technical issues related to linking these components, which have generally in the past been used independently. There are of course many issues, and choices to be made, in the implementation of the first component, the regional model. (See Section III.) Next, selection of the eigenvalue problem for the baroclinic wave modes has attracted our attention. Typically, the orthonormal set of long wave modes (with infinitesimal horizontal wavenumber *k*, and no rotation, $f = 0$), are considered. The technically sound way to apply the eKdVf equation is to use these modes to compute all of the needed parameters. The mode shapes in depth, mode speeds, and the eKdVf parameters vary with water depth and with the density profile. Waves will move faster than modal *c* when $f \neq 0$, and the eKdVf accounts for this. This method of ray tracing to find the paths for eKdVf implementation, and the eKdVf solution, can allow the local vertically-shear current parallel to the *k* vector to affect the wave speed, using the long wave version of the Taylor-Goldstein equation [42]. But normal currents are not allowed. Other modal computation methods will give different wave speeds and different rays. We are developing methods to allow the mesoscale flow to influence the internal tides (eigenvalue problem and ray trace) and obtain valid eKdVf solutions (i.e. properly accounting for the eigenvalue-obtained wave speed, rotational and NP dispersion, and nonlinearity) along these more realistic rays influenced by the 3D current field.

## V. Fronts and Intrusions

Other aspects of the coastal ocean that are challenging for ocean modeling are frontal geometries, frontal instabilities, and thermohaline intrusions. A measured example of an intrusion is shown in Fig. 6. Regional model resolution has a first-order

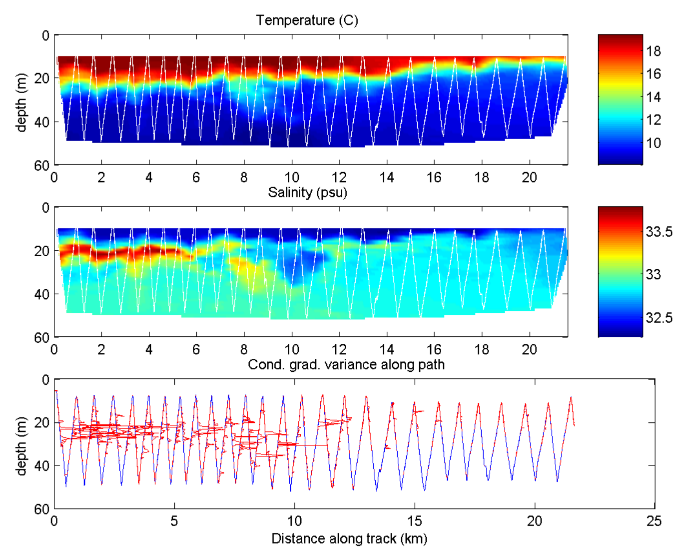


Fig. 6. A many-km long salty intrusion measured with an undulating platform on *RV Endeavor* Cruise 396 is shown. The lower panel shows conductivity gradient variance (microstructure related to mixing.)

effect on these processes, and the MSEAS model reanalysis described in Section III produced warm and salty intrusions extending westward toward New Jersey from the outer shelf, that are not always seen in model output for this area. Of note is that these thermohaline intrusions may be influenced by double-diffusive processes [31,43]. Because these processes are not explicitly applied to the resolved fields in computational models, is it unclear how accurately the models can portray them. To illustrate this, Fig. 7 shows data collected with a towed instrument [31] on a 2004 trip, where the data of Fig. 6 were also collected. The data strongly suggest (via the spectral properties of the microstructure, the Turner angles, and the step-like conductivity above the plume center) that diffusive layering instabilities, also called the diffusive regime [43], is (are) found above the intrusion, and salt-finger instabilities below. In this situation, heat flux would be high above the intrusion, making it heavier, and salt flux would be high below it, making it lighter. The dominance of one or the other of these would create density anomalies that can drive intrusion motion. Again, ocean models don't handle these distinct instability regimes very well, if at all, but they may be able to accurately model them nonetheless.

## VI. Summary

We are investigating improvements in ocean modeling with a goal in mind of increasing the use of models to study and predict the behaviour and properties of some of the smaller-scale motions that are seen on the continental shelf. Regional-model-driven NIW models are now being tested for their ability to produce short waves that arise from tidally-forced long-wavelength internal waves moving onto the shelf. Many factors control the long-wavelength waves, and the regional models may be able to predict these with moderate to good accuracy, if properly constrained by data. Using regional models to provide initial conditions for the NIW models, and also the NIW propagation conditions of the NIW models, NIW fields can in theory be predicted, although not in exactitude because of the nonlinearity. How well NIW can be predicted is an open question. It is likely that certain features of the NIW may be reasonably predicted, such as their existence at specific times and places (Are they there? Yes or no?), the direction of the waves, and wave packet energy. Other features such as the precise numbers of waves and wave shapes and sizes may not be as well modeled. Some of the tools used in this work have been described. Additionally, some provocative aspects of frontal-zone intrusions have been introduced.

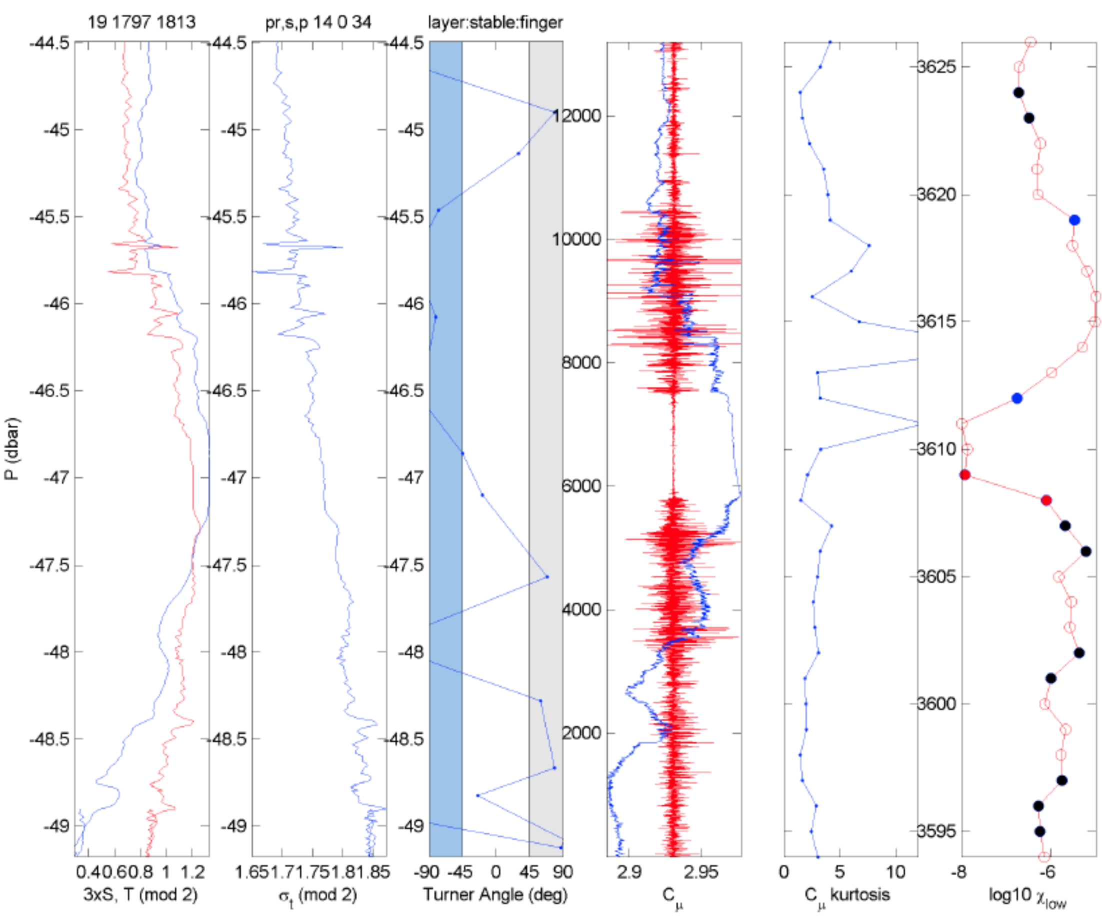


Fig. 7. Data collected at one intrusion on *Endeavor* cruise 396 are shown (transect 19). The sensors moved through the 5.5 m tall water volume in 33 s. Temperature and salinity (left panel) are both maximum at 47 dbar. The next panel shows a steady density increase with depth (and noise). The next panel shows the Turner angle [44], related to the salinity and temperature gradients, which determines doubly stable, diffusive layering, or salt finger regime. The next panel shows high-resolution (400 Hz) conductivity in blue and its gradient in red. There is no turbulence or microstructure in the plume center, only above and below. The next panel shows microscale conductivity kurtosis. The final panel shows estimated temperature gradient variance dissipation rate

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