ROMS and SUNTANS Continued Development and Support of AESOP and NLIWI

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LONG-TERM GOALS

Creation of a new generation of terrain-following, coordinate oceanic models capable of a wide range of applications — from high-resolution local domains to basin- and, potentially, global-scales. These new types of models should be capable of being a component in a multi-model coupled system.

OBJECTIVES

The specific objectives of this project include: the development of an ocean modeling code capable of producing high-resolution, realistic simulations for configuration of physical features directly related to our own research, as well as the generation of data to be used as input for side boundaries by our colleagues in the closely related SUNTANS project, which uses a finer-resolution, unstructured-grid, non-hydrostatic model focused on the simulation of internal waves. Another objective is the creation of our own non-hydrostatic, hydrodynamic kernel for ROMS; it will be to be used for process studies of nonlinear wave generation, interaction, and propagation with the prospect of simulation of such processes under realistic conditions. Finally, continuation of our revision of the Regional Oceanic Modeling System (ROMS) algorithms and physical parameterizations, including vertical mixing and surface/bottom boundary layer models; porting and optimization of the code toward new computer architectures; and adaptation of it for multi-disciplinary studies (biology, geochemistry, sediment transport, atmospheric model coupling).

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APPROACH

The UCLA ROMS research group is currently engaged in several related projects centered around common ROMS code, but dealing with very different physical problems. Consequently, the algorithm-development aspect plays an important coordination role in other projects, implying splitting tasks among different partners and a protocol for documenting and sharing experiences. We are trying to achieve optimum balance between realistic simulations, process studies, development of mathematical algorithms and computer science.

WORK COMPLETED

The nonhydrostatic version of ROMS has reached its maturity and an associated manuscript, Kanarska, *et al.*,2007, was published. The related continuing work now involves simulation of generation of internal waves by barotropic tide interaction with a topographic ridge, both in idealized configuration–with the emphasis on process studies, code validation and comparison of computational results with laboratory experiments (Thomas Peacock and Paula Echevierri, MIT)–and in a more realistic setup.

Recently we made several substantial developments in UCLA ROMS which affect virtually all our applications, infrastructure, and computational practices. At first, lateral open boundary condition algorithms were revisited mathematically. In doing so, we de-emphasize/limit the use of Orlanskii-type open boundary conditions combined with adaptive (depending on local inflow/outflow) nudging to external data (Marchesiello *et al.*,, 2001) in favor of a more straightforward algorithm based on upstream advection (in essence at the inflow side the external data is accepted at the rate controlled by local normal velocity, rather than a user-defined, empirically tuned parameter). This change affects boundary conditions for tracers and velocity components tangential to the boundary (both baroclinic and barotropic modes), and eliminates the use of user-defined parameters for these variables. The normal velocity component of the barotropic mode along with the free surface elevation use Flather-type boundary conditions based on characteristic variables (Blayo and Debreu, 2005), which are discretized taking into account the use of the staggered C-grid and the generalized forward-backward stepping of the barotropic mode. This results in a numerically clean radiation of outgoing surface gravity waves; no additional restriction of time-step size relative to the natural stability limit of barotropic mode; and connectivity between externally specified boundary values of the free surface and the model-generated field. Normal baroclinic velocities are treated using Orlanskii-type boundary condition with adaptive nudging. The use of different approaches to different variables is motivated by separation of physical processes into fast- (e.g., surface and internal gravity waves) and slow-motions (current and vortex dynamics that propagate with advection speed). Thus, boundary conditions for the free-surface and normal barotropic velocity component are motivated by fast dynamics, while tangential components (both barotropic and baroclinic) can be traced back to open boundary conditions for vorticity. Normal velocity for the baroclinic mode has contributions from both fast- and slow motions, which, in this case cannot be easily separated (hence this is the only place where Orlanskii-type conditions are still applied). The above revisions result in a much tighter control of the model solution through open boundaries, including the input of nontrivial signals (such as event simulation). It also leads to abandonment of the practice of climatological nudging within finite area bands near the boundaries inside the model domain, ultimately requiring much smaller data files (just one row of boundary values for each variables), and therefore making it practical to allow a much more frequent input of data.

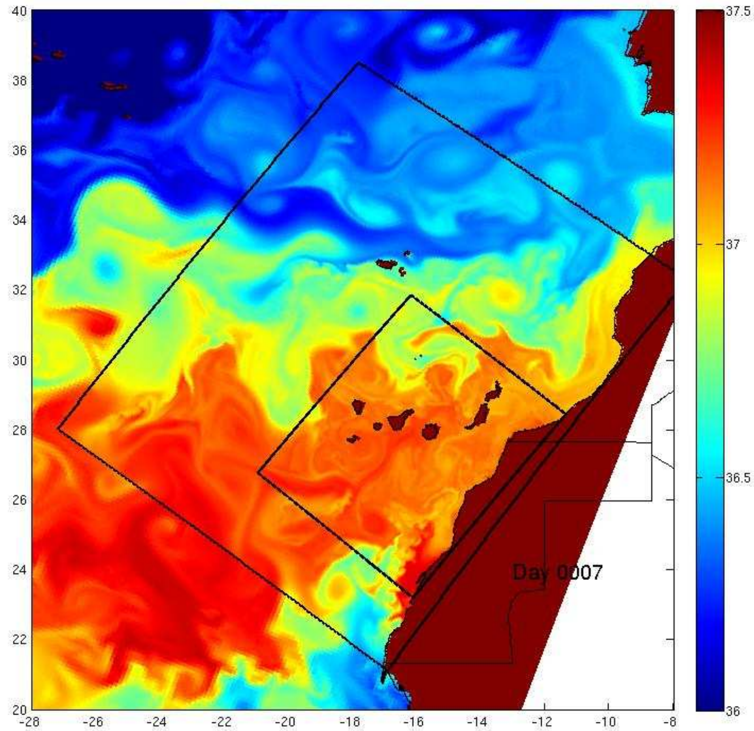

Figure 1: ***An example of continuity of model field (in this case nearsurface salinity) across the nested grid boundaries in 1-way off-line nesting. Three levels of resolution are shown. Note that orientation of each inner domain does not have to be the same for the outer domain, and the resolution ratio may be arbitrary as well.***

The second component of this effort is a major mathematical update of software that is used to generate side boundary condition data. These changes involve enforcement of strict conservation properties between data and model (or between parent and child grids), a better control of topographic consistency between the parent and the child grids near the boundaries (the two are different because of the necessity of satisfying topographic smoothness condition to avoid sigma errors on the two grids with different resolutions). There is also improvement in algorithms used to supply observational data in situations where an outer model solution is not available, for example Levitus data. This involves a better approach for the empirical correction of geostrophically balanced velocities with Ekman transport (computed from wind data) and the use of absolute free-surface elevation data (which recently has become available) to avoid the unreliable use of an arbitrarily chosen level of no motion. Overall the combination of these measures allow us to achieve

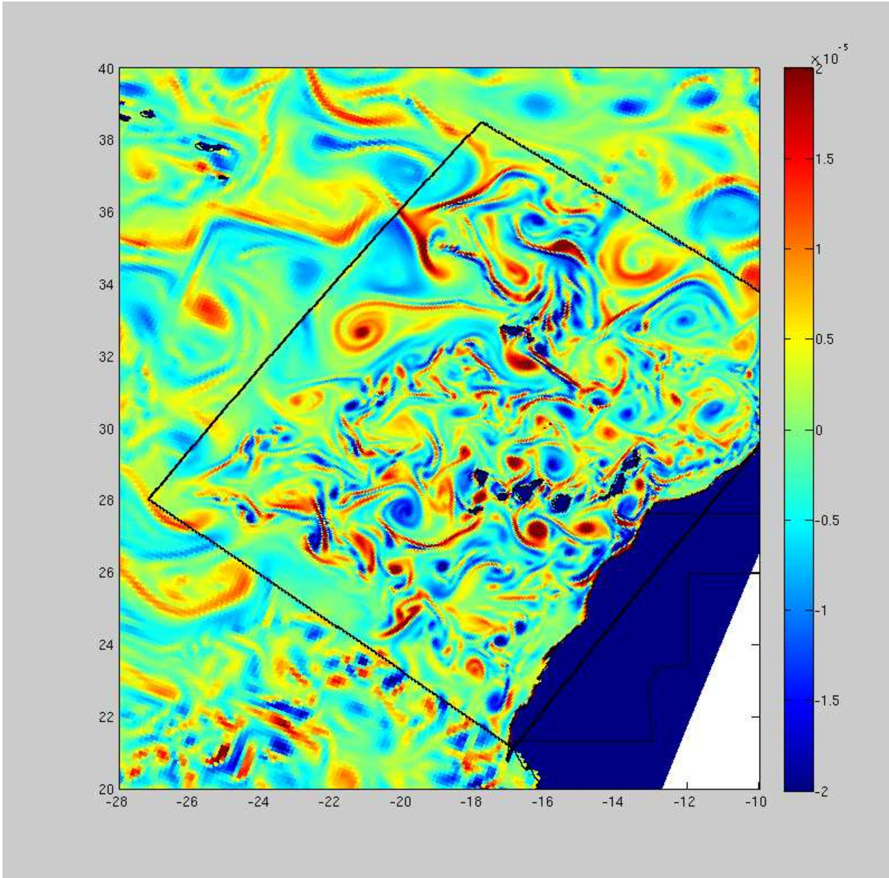

Figure 2: ***Continuity of relative vorticity field across nested boundaries for an off-line, 1-way nested solution.***

a better quality nested solution which is free of artifacts such as rim currents along open boundaries and has much a better continuity of model fields between different grid levels, Fig. 1. For the first time we can show the relative vorticity field free of artifacts associated with nesting, Fig. 2 (see also `http://www.atmos.ucla.edu/ nmolem/CB4.avi` for the corresponding motion picture).

Our work on the revision of the seawater Equation of State (EOS) for the Boussinesq model is now complete and an associated manuscript is being prepared for submission. In essence, the key result here is that if Boussinesq approximation is applied, it must also be applied to the EOS as well. This approach fully retains nonlinear effects in EOS, such as the thermobaric effect and cabbeling, but it also avoids internal inconsistencies associated with Boussinesq approximation, and the resultant acceleration due to the pressure gradient term (as a function of temperature, salinity, and depth(proxy for pressure in EOS)) is now closer to its non-Boussinesq counterpart. Overall our approach follows the guidelines of Dukowicz, 2001, but takes into account specific needs of the ROMS model — the need for reliable interpolation of density that guarantees monotonicity of stratification when density is not smooth on the grid scale and consideration of the interference of the compressible EOS with the ROMS mode splitting algorithm (the latter aspect is equally important for non-Boussinesq isopynnic models with a barotropic mode splitting, Dukowicz, 2006; Higdon & Bennett, 1996; Higdon, 2002, but was not analyzed in literature).

There are multiple updates for parts of the code associated with sub-models (parameterizations), forcing (both surface and open boundary), and parallel code infrastructure. Our work on parameterization of vertical mixing continues with the emphasis shifted from the mainly algorithmic aspect toward the achievement of well-behaved, multi-annual solutions (the main criterion is the correspondence of the modeled structure of 3D temperature and salinity fields to observed data). This work is closely tied to assessing the quality of the forcing fields — wind stress and heat/freshwater flux forcing. A closely related modeling development with the bottom boundary layer and sediment transport is now in an active phase (in part due to the recently funded Community Sediment Modeling project [NOPP] and also due to the UCLA ROMS group's interest in very shallow area coastal modeling).

Again, the increase in typical grid sizes, the usage of a larger number of CPUs, and the tendencies in computer hardware design necessitates modification of code for proper utilization of the resources. Linux cluster computing has became de-facto standard, and, in fact, with the scheduled decomission of the IBM p690 supercomputer at NCSA at the end of September, 2007, Linux clusters became the only supercomputing environment available to us. However, with the introduction and rapid proliferation of multi-core CPUs it became apparent that most current and near future cluster will consist of 4- to 8-way SMP nodes, and this 2-level hierarchy in machine architecture can no longer be ignored without sacrificing performance. In mid 2007, for the fist time, we are able to enable the use of multiple Open MP threads within each MPI process in ROMS. Originally this was motivated by the observation that within a single SMP node Open MP code has significantly better performance than MPI code, which treats an SMP node as multiple nodes. Also, because in ROMS code it is possible to select an number of Open MP subdomains (tiles) independent from the number of CPUs (hence reduce the subdomain size to fit into processor's cache), while MPI code sticks with one-subdomain-per-CPU policy (in practice, for our problems of interest the optimal Open MP partitioning may be very "sparse" — as many as 50...100 subdomains per each thread). General opinion among computer scientists is that hybrid code (multiple Open MP threads within MPI processes) better fits topology of a cluster made up of SMP nodes. However, in addition to that, our recent experience reveals that the use of multiple threads, and, more importantly, multiple subdomains-per-thread opens another resource for optimization — it provides a way to schedule MPI messages sent by different threads in such a way that it excludes/alleviates competition among multiple CPUs for access to network interface, which is unavoidably shared by the CPUs belonging to the same SMP node. To enable the use of multiple threads inside MPI processes we have to implement substantial revision of MPI halo exchange routines and ROMS Open MP tiling. Now UCLA ROMS uses 2-level hierarchial subdomain (each MPI subdomain is further partitioned into Open MP tiles), and it allows a *sparse* regime of computing in MPI mode. Sending halo-exchange messages takes place immediately after the processing of a particular tile is finished by the thread which that processes it, and only if the message is required, i.e., the tile is adjacent to the edge of MPI subdomain. Because of the sparse regime, one must ensure that on the neighboring subdomain there is a thread that works on an adjacent tile approximately at the same time, and which is ready to receive the message. This is achieved by “mirroring” the order of sequence of processing of tiles in adjacent MPI subdomains, Fig. 3. We combine this update with an evolution toward unstructured coverage of a computational domain with MPI subdomain patches. In doing so, we de-emphasize the notion of “processor grid” in favor of a more flexible processor mapping (this means that the use of variables associated with processor grid is now completely excluded within the physical parts of the code). This modification is also accompanied by eliminating the restriction that the dimensions of model physical grid must be evenly divisible by the number of MPI subdomains in each direction, which, in its turn, also requires redesign of parallel I/O. The infrastructure of UCLA ROMS is adapted so the model can become a component of a coupled system. This implies a separation of the MPI communicator used for array halo exchange within the same physical grid from the other communicators (exchanges between different models) and a corresponding modification of the initialization routines. This step is necessary for ROMS-SUNTANS coupling via MPI. ROMS now allows a perfect restart from a netCDF file with subsequent output that is binary-identical to the output of a continuous run.

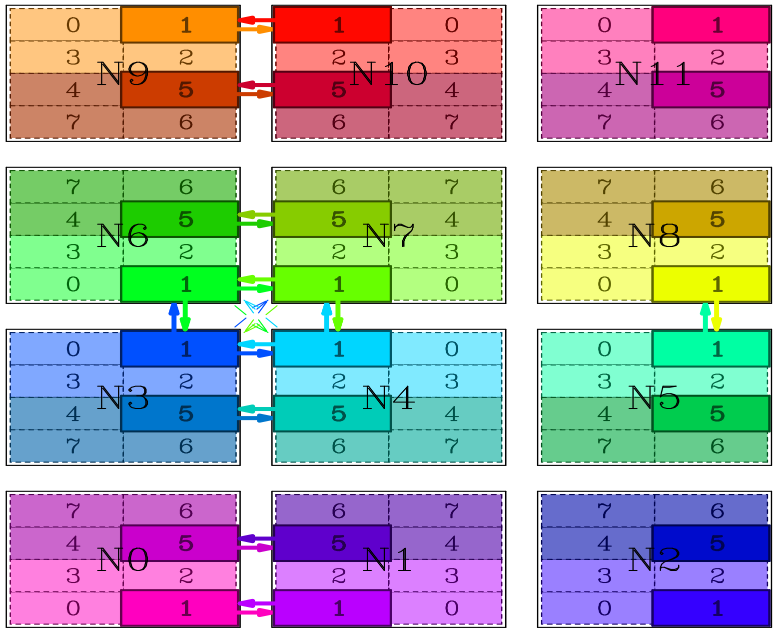

Figure 3: ***A snapshot on the time sequence of tile processing in sparse hybrid (MPI + Open MP) computing in the case of 12 MPI nodes (large rectangles, labelled*** `N0,N1,...,N11`***), 2 threads within each node, and*** 2×4 ***tiling within each nodes. Different colors indicate collections of tiles processed by different CPUs, and highlighted colors indicate tiles currently being processed. Arrows show MPI messages being sent at this moment. Digits*** `1,2,...,8` ***indicate tile number within each subdomain, which also corresponds to the order of processing:*** `thread #0` ***in each node processes tiles*** `0,1,2,3` ***in this sequence, while*** `thread #1` ***is responsible for*** `4,5,6,7`***. Note that tile numbering of adjacent MPI subdomains are mirror images of each other (this applies to both east-west and north-south directions). This ensures that threads working within adjacent subdomains are properly timed to receive messages sent by each other. This also eliminates the situation when the two threads in each node are simultaneously trying to send messages all directions, which results in competition for access to shared network interface. In fact, this algorithm allows partial overlap of communication and computation in time, because when*** `thread #0` ***is sending north-south messages at the beginning of the sequence,*** `thread #1` ***is not attempting to send and north-south messages, and simply proceeds with computing. This is reversed at the end of the sequence.***

RESULTS

North-Equatorial Pacific simulation: the primary goal is to achieve correct 3D structure of T,S fields for multiannual simulations, which requires correct interaction of all components of the model: hydrodynamic kernel, tracer advection schemes with low spurious mixing, physically accurate parameterization of Planetary Boundary Layer (PBL), and surface wind stress and thermodunamic fluxes. We are now computing a solution on a $22km$ (at Equator) to $12\ km$ (at Northern extent of the domain) grid.

Nonlinear Internal Waves Initiative (NLIWI): Large-amplitude nonlinear internal waves are observed in the South China Sea (SCS) region. The generation mechanism and properties of these waves are still debated. A likely source for the waves is the interaction of the barotropic tide with topography in the Luzon Strait. This might include several mechanisms: (a) lee-wave generation where a depression forms on the lee-side of topography, travels back over the top as the tide relaxes and subsequently breaks up into solitary waves; (b) interaction of an internal wave beam with the thermohaline; (c) nonlinear steepening of the internal wave beams in the far-field. We performed several studies for the generation of internal waves in the SCS that included simulation of lab experiments and idealized and regional simulations to understand the observed behaviors of nonlinear waves in the SCS region. Our initial plan for the process studies was mostly concerned with the NLIWI generation area where our collaborators, O. Fringer and R. Street (Stanford), were working on conversion and dissipation in the shelf area.

Laboratory Modeling: We simulated the lab experiments of Thomas Peacock and Paula Echevierri (MIT) for a Gaussian ridge configuration. Overall, the results agree well in the amplitude and form of the radiated wave field, although the amplitude in the simulation is slightly stronger (Fig. 4).

Coastal Tidal Modeling: In parallel with the NLIWI research, we more generally moved to include tidal boundary forcing and response in coastal simulations of both the Monterey region and the Southern California Bight. Wang et al., (2006) shows that the simulation skill is rather good for barotropic tide in the Monterey region in the standard model configurations with a grid scale of several km. But, the internal tide generated around the edge of the shelf is underestimated in its amplitude using this grid resolution; it does improve with finer resolution, and its pattern has only an intermediate skill in comparison to moored and CODAR currents. This framework will be applied to help interpret the AESOP internal tidal measurements and will be used in coupling to SUNTANS for this region.

Submesoscale Parameterization (AESOP): The analysis of high-resolutions solutions for the U.S. West Coast has led to considerable insight into ocean submesoscale processes and their interplay with the mesoscale (Capet *et al.*,, 2007a Capet *et al.*,, 2007b Capet *et al.*,, 2007c). In particular, both frontogenesis induced by the mesoscale strain field and some type of frontal instability are the key ingredients for the energization of the submesoscale, and submesoscale currents have several significant effects that must be parameterized: conversion of potential to kinetic energy, restratification of the surface boundary layer, and energy dissipation by a forward cascade process. Having contributed to the design of part of the AESOP measurement effort [1], we expect the data is

[1] For example, our solutions have been used by E. D'Asaro and colleagues to test their float deployment strategies

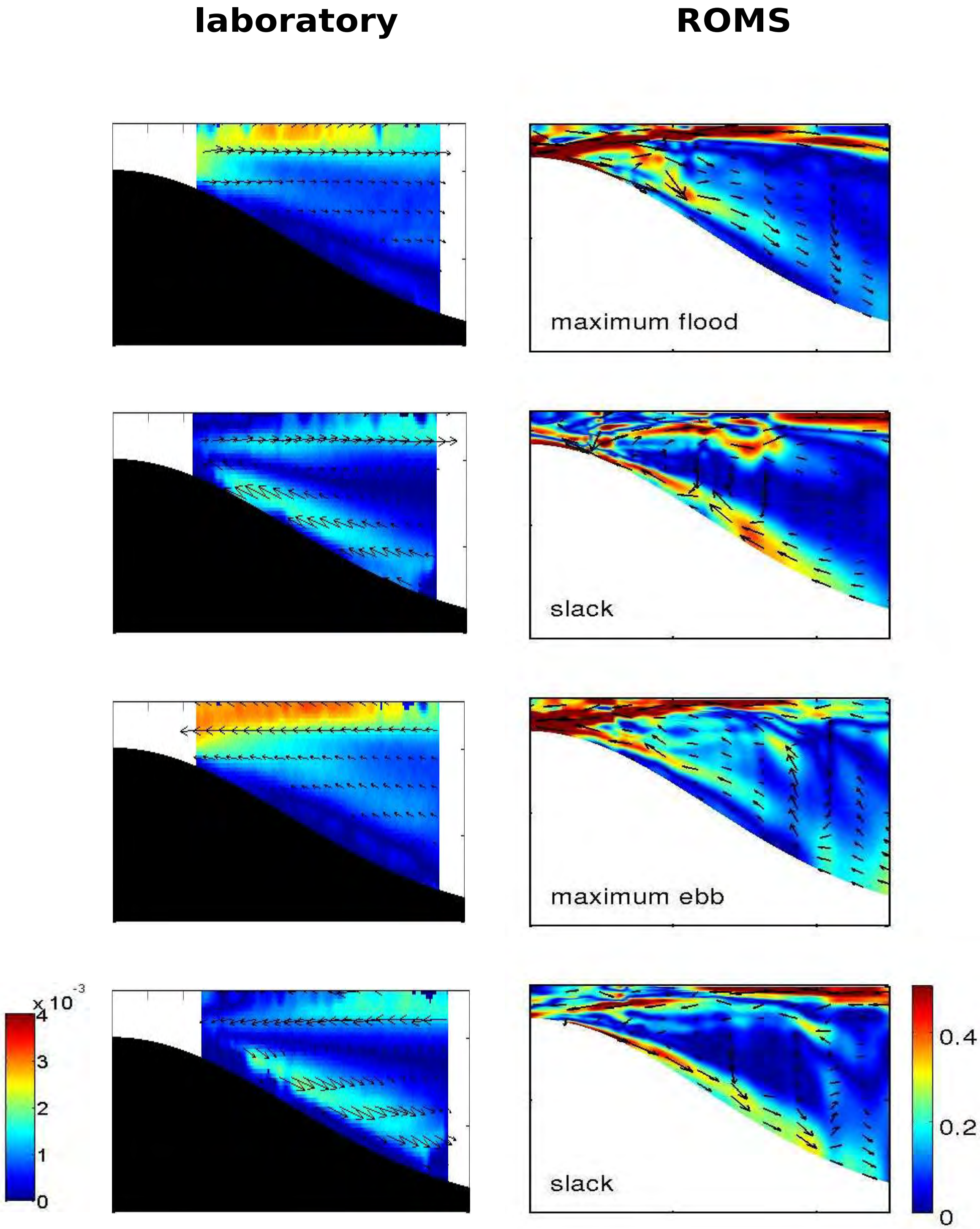

Figure 4: ***Comparison between laboratory (left) and ROMS (right) experiments in which a harmonic barotropic current in a stratified water column moves over a Gaussian topographic ridge. Subplots show half the ridge. Colors indicate magnitude of the flow and arrows indicate directions. In the laboratory experiments the height of the sea mount is 0.12 m and in the ROMS experiment 3500 m. Non-dimensional parameters were equalized to ensure similar response to the topography.***

well-suited for model/real ocean submesoscale comparisons. Although we anticipate that our conclusions regarding the submesoscale are quite generic, we plan to obtain new submesoscale-resolving solutions with increased realism (so far we have focused on an idealized eastern boundary under constant summer-time climatological atmospheric forcing) to make the model/data comparison as meaningful as possible.

IMPACT/APPLICATIONS

The validated technical innovations in our evolving model are prototypes for future improvements in operational observing-system, data-assimilation, and prediction capabilities. These are being implemented in the data assimilation system at JPL (Li et al., 2006, Li et al.,2007a,b; Chao et al., 2007).

TRANSITIONS

One tangible measure of the utility of our results is that other researchers are either using our evolving ROMS code or adapting its algorithms for their own code. Current users of our version of ROMS include Chao and Li (NASA/JPL), Miller and Cornuelle (SIO), Di Lorenzo (Georgia Tech.), Moisan (NASA/Wallops), and the Monterey Bay NOPP SCOPE and AOSN teams —Chavez (MBARI), Chai (Maine). Arango and Haidvogel (Rutgers) have adapted many features for their version of ROMS. In the near future we anticipate additional users, partly through the ONR-sponsored, terrain-coordinate model development project (TOMS). We are contributing useful knowledge about coastal modeling methodology and phenomena through published papers.

RELATED PROJECTS

A significant portion of our work on this project is in collaboration with Robert Street, Oliver Fringer, and Margot Gerritsen at Stanford University and is centered around coupling of ROMS with the high- resolution, unstructured grid model SUNTANS to study generation and propagation of internal waves. We started a collaboration with Thomas Peacock at MIT, who specializes in laboratory scale investigations of the generation and evolution of non-linear internal waves within the NLIWI framework and is interested in the accompanying numerical modeling.

In addition, we continue our traditional partnerships established during the previous years on the Southern California Bight, especially with regard to its water quality and sediment transport [a California Sea Grant and USGS project], and it has extended to supporting the data assimilation for the prototype Coastal Oceanic Observing Systems in Southern and Central California, and Alaska (Prince William Sound). We have a joint project with Chao (NASA/JPL) on using embedded grids in ROMS for the ONR AOSN data assimilation and forecast project. We are partners in the NOPP SCOPE project for developing models and analyses for the Monterey National Marine Sanctuary. We are partners with Doney (WHOI), Gruber (ETH and UCLA), Chao (JPL), Chavez (MBARI), and Berelson (USC) on expanding the biogeochemical component of the model [NSF ITR and NASA IDS]. Current ONR projects using ROMS at UCLA are on cross-scale, dynamical coupling along the North American West Coast and the effects of surface gravity waves on coastal currents and large-scale infragravity waves.

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prior to the AESOP experiment.

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