Development and Testing of Embedded Gridding within the Regional Ocean Modeling System: Interactions Between Near-Shore and Off-Shore Currents and Materials

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LONG-TERM GOALS

The goals of this project are (1) to improve the algorithms for computational modeling of local oceanic regions that have significant interactions with their surrounding regions and (2) to simulate and understand the controlling processes for dynamical coupling and material exchanges between near-shore regions over continental shelves and adjacent off-shore regions over continental slopes and in deep water.

OBJECTIVES

The objectives of this project are (1) to continue the development of the Regional Oceanic Modeling System (ROMS) with respect to its hydrodynamic algorithms, physical transport parameterizations, and range of represented biogeochemical processes; (2) to further refine and apply its nesting capabilities using adaptive open-boundary conditions (OBCs) for imposing large-scale boundary data; (3) to develop a Multi-Grid embedding capability in ROMS for simultaneously calculating solutions on coarse-resolution (outer) and fine-resolution (inner) grids; (4) to use ROMS to investigate dynamical coupling and material transport between near-shore and off-shore regions along the North American West Coast (NAWC), with special attention to Monterey Bay, the Southern California Bight, and the GLOBEC NE Pacific region off Oregon and Northern California; and (5) to use ROMS to investigate the response of the NAWC region to remote forcing in the Pacific basin and the influence of NAWC coastal phenomena (e.g., upwelling) on Pacific basin-scale phenomena.

APPROACH

The technical approach is computational simulation of oceanic fields for velocity, temperature, and salinity; chemical concentrations of nutrients, O_2, CO_2, etc.; and planktonic populations. The computational model is ROMS, which is based on the hydrostatic Primitive Equations in terrain-following curvilinear coordinates with a free upper surface. The boundary-value problems are posed for various regional domains along the NAWC with specified surface forcing fields and boundary data. The latter are imposed by adaptive OBC (Marchesiello et al., 2000). We are developing an embedding capability for the local, fine-resolution grid in a sub-domain within the coarse-resolution grid spanning the entire domain. Key researchers at UCLA on this project are Patrick Marchesiello,

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James McWilliams, Pierrick Penven (newly hired), and Alexander Shchepetkin, as well as Keith Stolzenbach and Nicholas Gruber for biogeochemical issues. Aspects of the grid embedding are being done collaboratively with Yi Chao and Tony Song of JPL/NASA, and there are several other related projects (Related Projects).

WORK COMPLETED

This project has been underway for less than a year, although it does grow out of related model developments and scientific studies that are just beginning to be written up for publication. The basic algorithmic structure of ROMS involves a quasi-monotonic advection scheme (Shchepetkin & McWilliams, 1998), adaptive open boundary conditions (Marchesiello et al., 2000; Results), and an conservative external/baroclinic mode-coupling and time-stepping scheme with exact material conservation and substantially extended temporal stability and efficiency (mss. in prep.). We added a message-passing capability into ROMS for distributed-memory multiprocessors, as an extension of its previous shared-memory parallelization, and we are in the process of carrying this to a fully two-level hybrid parallelization, appropriate to distributed clusters of shared-memory multiprocessors (e.g., IBM Blue Horizon at SDSC). We have devised and implemented a new discretization by local vertical polynomials, and are now testing its efficacy for reducing the chronic pressure-gradient error in terrain-following coordinates (Results). We have extensively analyzed physical and ecosystem simulations of the mean-monthly U.S. West Coast (USWC) equilibrium state (Results). We are beginning the analysis of oceanic response to high winds across the mountains of Central America (a Ph.D. thesis project for June Chang). We have begun calculations of Pacific basin simulations with multi-decadal NCEP forcing, to be used in a 3-tier, 1-way nesting procedure (basin → USWC → Monterey Bay) in our first study of near-shore dynamics with high resolution. Finally, we are making design studies of Multi-Grid embedding procedures (e.g., Sullivan et al., 1996), with the intention of implementing a variant of the adaptive mesh refinement procedure of Blayo & Debreu (1999) this fall during an extended visit by Debreu to UCLA.

RESULTS

Out of the work completed (Work Completed), we emphasize three results. **First**, in Marchesiello et al. (2000) we show that OBCs—with novel procedures for radiation and adaptive (i.e., treating inward and outward information fluxes differently) nudging to specified external data—perform well by the criteria of long-term stability and avoidance of boundary-trapped artifacts. This has been demonstrated in three different applications: the mean-monthly USWC equilibrium circulation with boundary data from Levitus et al. (1994), the transient-wind response in the Central American West Coast region, and eddy-shedding from the Agulhas Current off South Africa (Penven et al., 2000). **Second**, when steep topography and sharp stratification occur together (as is often the case in realistic coastal modeling), existing second-order discretization schemes for pressure-gradient force do not guarantee sufficient accuracy, which results in unphysical currents. The problem is further aggravated by the use of nonuniform vertical grid spacing and the step-like profiles generated by boundary-layer vertical mixing. It turns out that the intuitively attractive path of using higher-order discretization schemes has only limited success because the model fields are never smooth enough for these schemes to avoid unphysical oscillations. To address the issue we have developed adaptive techniques which use local limiting of polynomial interpolants in such a way that the oscillations are prevented but in smooth regions yield full high-order accuracy. The limiting is performed using the methodology of shock-capturing techniques (specifically the Piecewise Parabolic Method, Colella & Woodward, 1984, and Weighted Essentially Non-Oscillatory schemes, Liu et al., 1994), which were further generalized to constrain the coefficients of quartic polynomial interpolants. This is done a using multi-stage method where the order of the polynomial interpolant (hence the order of accuracy) is increased gradually in such a way that the lower-order method provides both an initial estimate of interfacial values and the criterion for smoothness, which locally restricts the higher-order method to avoid undesirable oscillations. Currently these adaptive techniques are employed for computation of pressure gradient and advection of tracers, and tests are underway with realistic coastal simulations (mss. in prep.). **Third**, we have demonstrated that the simulations of the equilibrium USWC circulation (i.e., the California Current System; Miller et al., 1999) with mean-monthly forcing are fairly skillful in reproducing observational climatologies of surface currents, sea level, and ocean color—time-mean, seasonal cycle, and non-seasonal variance (see Fig. 1)—as well as the synoptic patterns of upwelling filaments and mesoscale eddies (mss. in prep.). This implies that most of the variability is due to intrinsic instabilities of the prevailing currents rather than transient wind forcing (which often dominates on the continental shelf near shore). The primary mechanism is baroclinic instability, and, besides shaping the mean currents through eddy fluxes of heat and momentum, this leads to a westward and downward propagation of eddy energy off-shore. Finally, in a process study of the role of along-shore ridges and capes, we have shown that upwelling intensity is concentrated on the poleward edge of such features, and that the amount of cross-shore material exchange between shelf and deep-water regions is greatly enhanced over what occurs without along-shore topography, as predicted by an analytical model of Tony Song (mss. in prep.).

IMPACT/APPLICATIONS

The validated technical innovations in our evolving model are prototypes for future improvements in operational observing-system, data-assimilation, and prediction capabilities. The scientific issues of near-shore/off-shore coupling and material exchange are central ones in coastal oceanography.

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 our code. Current users of our version of ROMS include Chao and Song (NASA/JPL), Miller and Cornuelle (SIO), Moisan (NASA/Wallops), and Powell (Berkeley); also, Arango and Haidvogel (Rutgers) have adapted many features for their version of ROMS. In the near future we anticipate additional users, principally through the NAWC and Monterey NOPP projects (Related Projects). We expect to contribute useful knowledge about coastal phenomena through papers yet to be written.

RELATED PROJECTS

Our recent venture into coastal oceanography now extends into several related projects. We began with a focus on the Southern California Bight, especially with regard to its water quality [an EPA/NSF project on the L.A. Urban Watershed, now ending, and a California Sea Grant project, whose renewal grant is pending]. We have a joint project with Chao [NASA/JPL] on using embedded gridding in ROMS for studying Eastern and Western Boundary Current interactions with the North Pacific gyres [NASA]. We have a project to model the NAWC carbon cycle [NASA]. Finally, we are partners in two NOPP projects, one on the NAWC (led by Allen [OSU], McWilliams, and Powell [UCB]) and one on the Monterey National Marine Sanctuary (led by Chavez [MBARI]).

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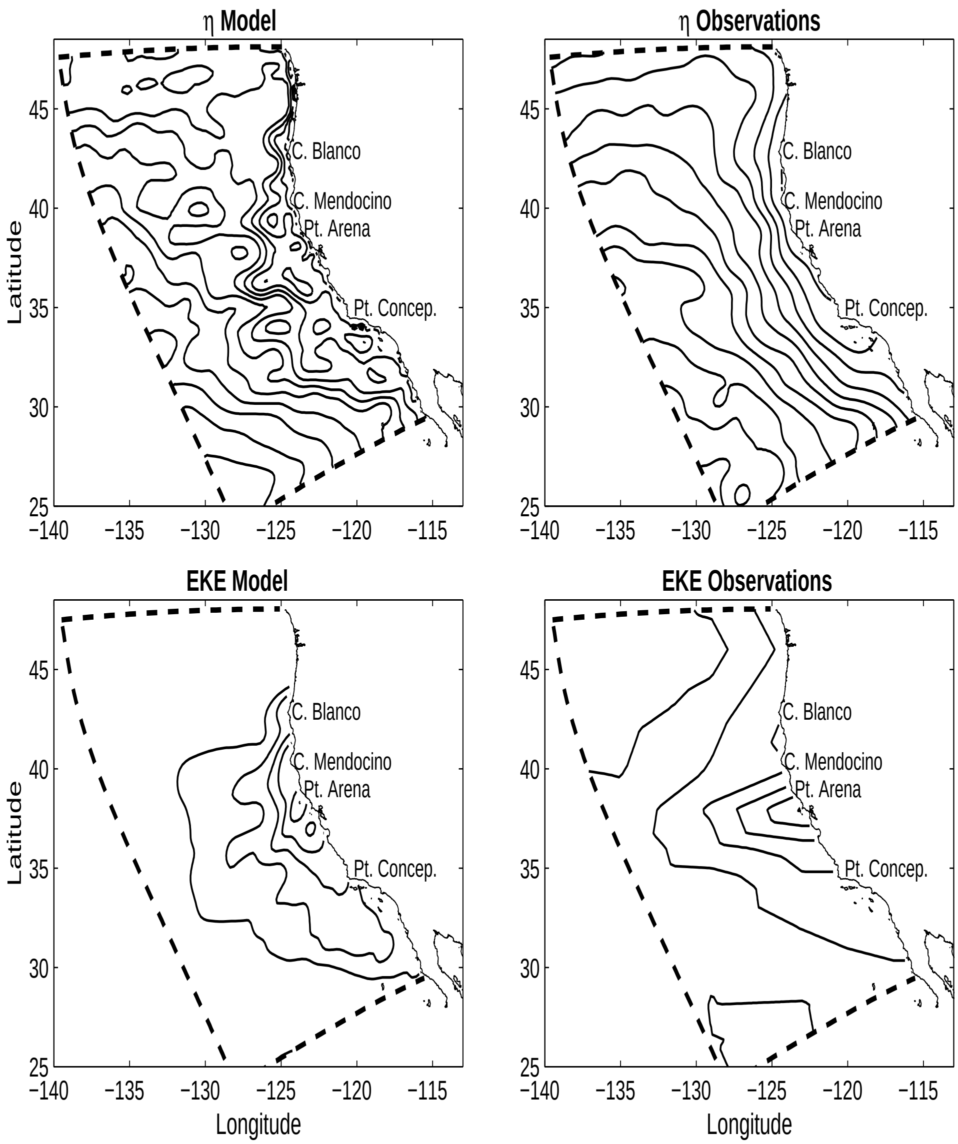

Figure 1: Comparisons of USWC summer-mean surface elevation (top; CI = 2 cm) and eddy kinetic energy (bottom; CI = 50 cm^{2}s^{-2}) between ROMS (left) and observations (right) with hydrography and drifters. There are different degrees of smoothing in the different panels.