Development and Utilization of Regional Oceanic Modeling System (ROMS). Delicacy, Imprecision, and Uncertainty of Oceanic Simulations: An Investigation with the Regional Oceanic Modeling System (ROMS). Mixing in the Ocean Surface Layer Using the Regional Oceanic Modeling System (ROMS).

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LONG-TERM GOALS

Our long-term goal is the continuing evolution of the Regional Oceanic Modeling System (ROMS) as a multi-scale, multi-process model and its utilization for studying a variety of oceanic phenomena. The dynamical processes span a range from turbulence to basin-scale circulation. A complementary goal is to explore, document, and explain the nature of the delicacies of the simulations for highly turbulent oceanic circulation. We expect that our experience will be relevant to analyze and forecast uncertainties for other atmospheric and oceanic simulation models. These activities are of interest to ONR through its core, DRI, and NOPP programs, including submesoscale parameterization (AESOP), strong internal waves (NLIWI), high-resolution air-sea interaction (HIRES), tropical cyclones, sediment transport, and horizontal mixing (LATMIX).

OBJECTIVES

Our core objectives are code improvements and oceanographic simulation studies with the Regional Oceanic Modeling System (ROMS). The targeted problems are submesoscale wakes, fronts, and eddies; nearshore currents; internal tides; regional and Pacific eddy-resolving circulations and their low-frequency variability; mesoscale ocean-atmosphere coupling; and planetary boundary layers with surface gravity waves. To address these problems we are making ROMS more of a multi-process, multi-purpose, multi-scale model by including the coupling of the core circulation dynamics to surface gravity waves; sediment resuspension and transport; biogeochemistry and ecosystems; non-hydrostatic large-eddy simulation; and mesoscale atmospheric circulation, and by providing a framework for data-assimilation analyses (led by others). Our major algorithmic objectives are cross-scale grid-embedding in turbulent flows; improved accuracy in the Boussinesq approximation with a realistic Equation of State (EOS); accurate advection; dynamically adaptive, vertical coordinates; surface-wave-averaged vortex

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force and Lagrangian transport; and parameterization of wave-breaking and other mixing effects. Finally, we continue to further improve the pre- and post-processing tools and on-line documentation for ROMS.

A parallel objective is to establish the characteristics of model uncertainty in ROMS for realistic simulation of complex flows, as an intrinsic model contribution to analysis and to forecast errors. The premise is that defensible alternative model designs — in parameter values, subgrid-scale parameterizations, resolution, algorithms, topography, and forcing data — may often provide a range of answers comparable to the model-measurement discrepancies, although as yet this kind of sensitivity is largely undocumented. A corollary is that alternative models may have a sizable degree of mutually irreproducible answers for complex flows. We hypothesize that at least some part of the model-to-measurement and model-to-model differences may be irreducibly inherent in the mathematical structure of modern simulation models.

APPROACH

Computational simulation of currents and material distributions is an important and evolving tool in the geosciences. ROMS is a loosely coordinated modeling approach with a substantial international community of developers and users (www.myroms.org). It uses a generalized terrain-following coordinate and is implemented as a modern, efficient parallel code, accompanied by an infrastructure of pre- and post-processing and visualization tools. ROMS provides a test-bed for some of the most innovative algorithms and parameterizations in ocean modeling, and it is now the most widely used model among academic researchers for regional, high-resolution simulations of highly turbulent flows. At UCLA we are among the lead architects of ROMS. Our approach is problem-driven: the algorithmic formulation and code implementation are advanced to meet the requirements for simulating particular processes and phenomena.

To test the hypothesis of irreducible uncertainty, we use ROMS to evaluate model sensitivity with respect to plausible variations in several test configurations: flow past idealized sea mounts; realistic Pacific basin circulation comparable to present and near-future operational analysis configurations; and Western- and Eastern-Pacific nested-subdomain currents and eddies with mesoscale and submesoscale flow-topography interaction.

WORK COMPLETED

Our work is comprised of algorithm design, code implementation, forcing and topographic data preparation, performing and analyzing simulations, and theoretical interpretation.

In the past year we have worked on the following circulation regimes and phenomena: decadal Pacific circulation; equilibrium regional circulations along the U.S. West Coast, central Alaska, Central America, South America, the Kuroshio, and the Gulf Stream; mesoscale eddy detection and tracking; submesoscale surface fronts, filaments, and eddies; topographic current separation, form stress, and submesoscale vortex generation; surface waves and nearshore currents in North Carolina and Southern California; internal tides in the South China Sea and Southern California; surface wave influences on the oceanic surface layer; bubbles generated by wave breaking; and mesoscale air-sea coupling. The algorithmic work has been on adapting the oceanic equation of state for split-explicit time stepping of barotropic and baroclinic modes; accurate time-stepping for the bottom boundary layer in shallow water ($\sim$ meters) and wake flows past topography; open boundary conditions for highly turbulent flows; incorporating surface wave effects in ROMS; diagnosing spurious diapycnal mixing due to advection errors and designing remedies; a new model of a size-distributed bubble population; a new multi-scale data assimilation methodology; and the exploration of several test-bed configurations for the simulation delicacy investigation.

RESULTS

We present a few highlights briefly. The publications list (from 2010 up to papers likely to be submitted within the 2011 calendar year) provides a complete view of finalized results.

Bubbles in the Surface Boundary Layer: We continue to study surface wave effects on the turbulence in the surface boundary layer through Large-Eddy Simulations (Sullivan and McWilliams, 2010). New results are obtained for the evolution of gas bubbles generated by air injected in breaking waves (Liang *et al.*, 2011). The bubbles dissolve, change size, rise due to buoyancy, and are subducted by boundary layer turbulence, while they also modify the density of the liquid-bubble mixture. Bubbles are brought down into the boundary layer by episodic bubble plumes and form near-surface streaks in the convergence zone of Langmuir circulations. The equilibrium bubble distribution (Fig. 1) is a manifestation of intermittent bubble plumes whose bubble number density is at least one order of magnitude higher than the mean bubble number density. Bubble distribution in the injection zone is influenced by breaker injection, turbulent transport, and dissolution. Bubble distribution below the injection zone is determined by the strength of turbulence and dissolution. In contrast to previous studies which conclude that wind speed is the governing parameter on bubble penetration depth; we find that both wind and waves that jointly determine turbulent intensity are the governing parameters for bubble penetration. The buoyancy of bubbles weakens both Langmuir circulations and near-surface dissipation. Gas flux through bubble not only depends on whitecap coverage, but also subsurface turbulent strength.

Submesoscale Lateral Mixing in the Surface Layer: Submesoscale currents are abundant in the upper ocean due to frontogenesis and filamentogenesis induced by neighboring mesoscale eddies and "mixed-layer" baroclinic instability. Regional simulations spontaneously develop $\sim$ 0.1-10 km features with strong velocity and even stronger tracer gradients and vorticity. A comparison between California and Peru in different seasons (Fig. 2) shows that the dominant patterns, hence dynamical processes, occur with different regimes. The Gulf Stream and its Rings (Fig. 3) show further morphological differences, with geographically and temporally distinctive submesoscale lateral mixing. Inspired by these discoveries of submesoscale transitions, we have made theoretical studies of frontal instability during frontogenesis, cold-filamentogenesis, and the arrest of continuing frontogenesis by its own cross-frontal eddy flux and secondary circulation.

Interaction of Shelf and Surf Currents: The interaction of mesoscale and submesoscale eddy currents on the continental shelf with nearshore currents driven by breaking waves in the surf-zone is being simulated with ROMS in a realistic configuration for the Southern California Bight, together with process studies in more idealized shoreline configurations. The approach to realistic, multi-scale simulations with ROMS is grid nesting, where outer domains are forced by large-scale winds and empirically estimated oceanic boundary conditions, and successive stages of embedded subdomains with finer grid sizes allow local currents to emerge while retaining important influences of their larger-scale environment (Fig. 4). The combined techniques of grid nesting and surface wave effects incorporated into ROMS enables us to address an important outstanding question: how do the dominant mesoscale and submesoscale currents in the interior approach the shoreline in shallow water where wave-driven currents are strong? A related practical question is: how efficiently are materials (including biota) exchanged across this interaction zone just outside the surf-zone, around the 10 m isobath? We have calculated nested circulations for the Southern California Bight (Fig. 3), including an inner zone near the shoreline within Santa Monica Bay with a horizontal grid resolution of $dx = 20$ m. A snapshot of the vertical vorticity field (Fig. 5) indicates that the interaction zone is typically one of intermittent flow activity: the eddy flows are mostly shore-parallel and rapidly weaken in shallow water through bottom drag, and the wave-driven littoral currents extend only weakly much beyond the surf zone except during particular eruption events. In between there is "sticky water", as has long been intuited by marine biologists though not yet given a firm dynamical demonstration or explanation. We expect that further analysis of our present simulations will provide a quantitative characterization of the sticky water phenomenon.

Algorithms for Large-Scale Circulation Simulation: The use of sigma-coordinate ocean models (as in ROMS) has been historically considered as a disadvantage for large-scale climate studies. The main reason resides in the non-alignment of the vertical coordinate isosurfaces with either geopotential surfaces or isopycnals making it harder to accurately compute the horizontal pressure gradient, advection, and isoneutral tracer diffusion. Moreover, this class of models requires a vertical mixing parameterization robust to large changes in the vertical resolution between shallow and deep areas. In Lemarie *et al.* (2011) we show that, with some adjustments of the tracer advection, the surface boundary layer parameterization and the vertical grid, a sigma-coordinate model can achieve an accurate representation of the oceanic interior and mixed-layer dynamics. To do so, a new way to handle the temporal discretization of the rotated biharmonic operator is used to achieve tracer variance dissipation in an adiabatic and computationally efficient way. Furthermore a redesign of the K-Profile surface layer Parameterization (KPP) in order to improve the regularity of the solution and the overall numerical efficiency of the scheme is introduced. To validate the new algorithmic developments, we perform a set of coarse-resolution realistic basinscale Pacific simulations. Besides improving the conservation of water mass properties, the use of an isoneutral tracer hyperdiffusion is shown to have a negative feedback on the circulation error growth rate, thus significantly reducing the sensitivity of the model solution to the level of topographic smoothing (Fig. 6). The overall validation of our simulations, focusing on the key characteristics of the circulation in the Pacific Ocean, provides some evidence of the efficacy of a terrain-following coordinate for large scale applications.

Circulation Delicacy due to Winds and Currents: Widespread experience in basin-scale oceanic modeling indicates a high degree of sensitivity of strong currents to many aspects of the simulation configuration. We are exploring the influences of the wind forcing and domain configuration. Following the approach described in Lemarie (2011), we have a basin-scale ROMS solution of the Pacific Ocean at a nominal resolution of $12.5\ km$. Figure 7 shows how two well-regarded wind climatologies — the scatterometry product SCOW and the Tropical Atmosphere Ocean (TAO) buoy product — yield dramatically different answers for the strength and structure of the North Equatorial Current. This is probably best interpreted as a dynamically provable response to small wind differences that influence the wind derivative pattern, and thus place a particular realism constraint on wind products used for ocean models. A different sensitivity to the domain shape is manifested in the path of the Kuroshio Current. While this is not entirely surprising, given the highly nonlinear nature of the Kuroshio near its point of separation from the Japanese island of Honshu, the degree of sensitivity to remote changes is extremely large. In Figs. 8-9, the results of two simulations runs, which differ only in the shape of the land mask (*i.e.,* coastline) in the Solomon Sea in the southwest Pacific, are shown. Maps of annual mean sea surface height are shown for a landmask that is derived though automated means (left panel) and another landmask that is edited by hand to more accurately represent the straits and (island) obstacles in the real Solomon Sea area (right panel). From Fig. 8 it can be seen that the local changes in the sea surface height (and associated geostrophic transport) are modest but do show the expected changes where the western boundary current now correctly primarily flows around the furthest extend of the island chain at the southeastern tip of Papua New Guinea. However, in addition to these local, modest changes, Fig. 9 shows a remote effect on the Kuroshio in the northwestern Pacific. This is an example of the extreme sensitivity of the Kuroshio path to small changes in model set-up or forcing at these (decadal) time scales. By our present understanding, there may be no means of reducing this extreme sensitivity.

IMPACT/APPLICATIONS

Geochemistry and Ecosystems: An important community use for ROMS is biogeochemisty: chemical cycles, water quality, blooms, micro-nutrients, larval dispersal, biome transitions, and coupling to higher tropic levels. We collaborate with Profs. Keith Stolzenbach (UCLA), Niki Gruber (ETH), Curtis Deutsch (UCLA), and David Siegel (UCSB) on these topics.

Data Assimilation: We collaborate with Drs. Zhinjin Li and Yi Chao (JPL) and Kayo Ide (U. Maryland) by developing model configurations for targeted regions and by consulting on the data-assimilation system design and performance. Current quasi-operational, 3DVar applications are in Monterey (AOSN, ASAP), CA; more broadly in CA (SCCOOS and CenCOOS); and in Alaska (Prince William Sound).

TRANSITIONS

ROMS is a community code with widespread applications (http://www.myroms.org).

RELATED PROJECTS

Three Integrated Ocean Observing System (IOOS) regional projects for California and Alaska (SCCOOS, CenCOOS, and AOOS) are utilizing ROMS for data assimilation analyses and forecasts.
We are participating in VOCALS, which is a CLIVAR and NSF project to investigate coupled regional climate processes of the west coast of South America.

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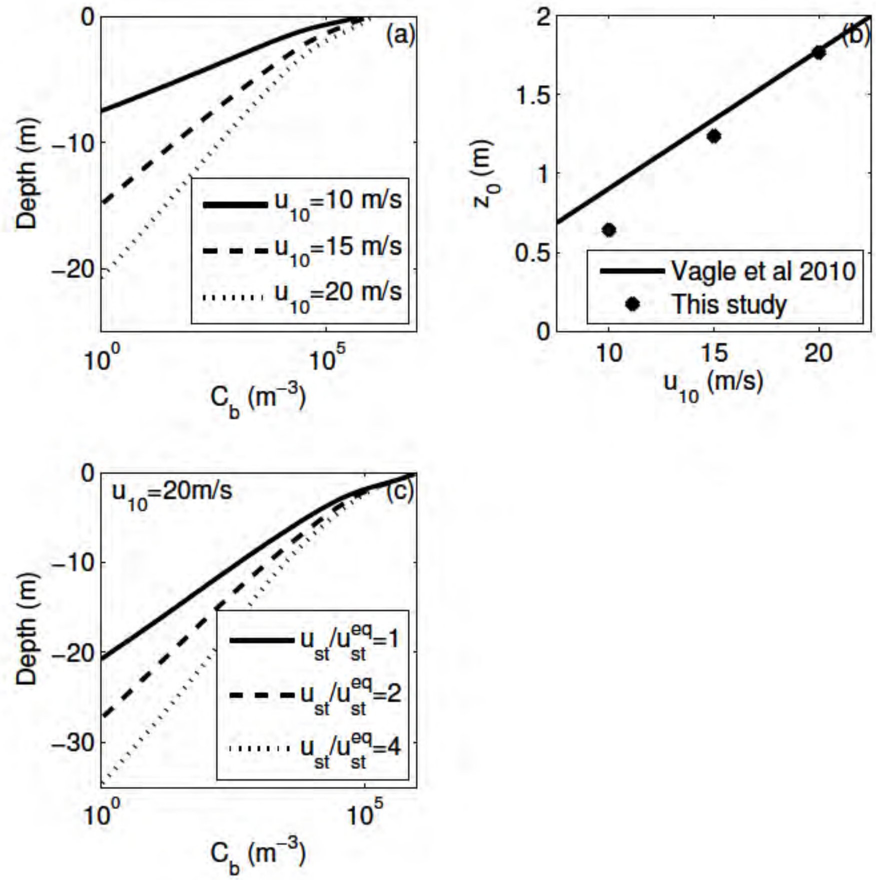

Figure 1: ***Simulation of the breaker-generated bubble population in the turbulent surface boundary layer (Liang** et al.**, 2011). (a) Mean bubble number concentration C_b at different wind speed u_{10}; (b) Bubble e-folding depth z_0 (the rate of exponential decay) vs. wind speed; (c) Mean bubble number concentration for different magnitudes of surface-wave Stokes drift u_{st} at u_{10}=20 m/s. The bubble penetration is different even under the same u_{10} but at different u_{st}, mainly due to Langmuir circulations. This demonstrates the importance of including wave information in the parameterization of bubble penetration and air-sea gas transfer in regional and global climate models. The comparison date are from Vagle** et al.** (J. Geophys. Res., 2010).***

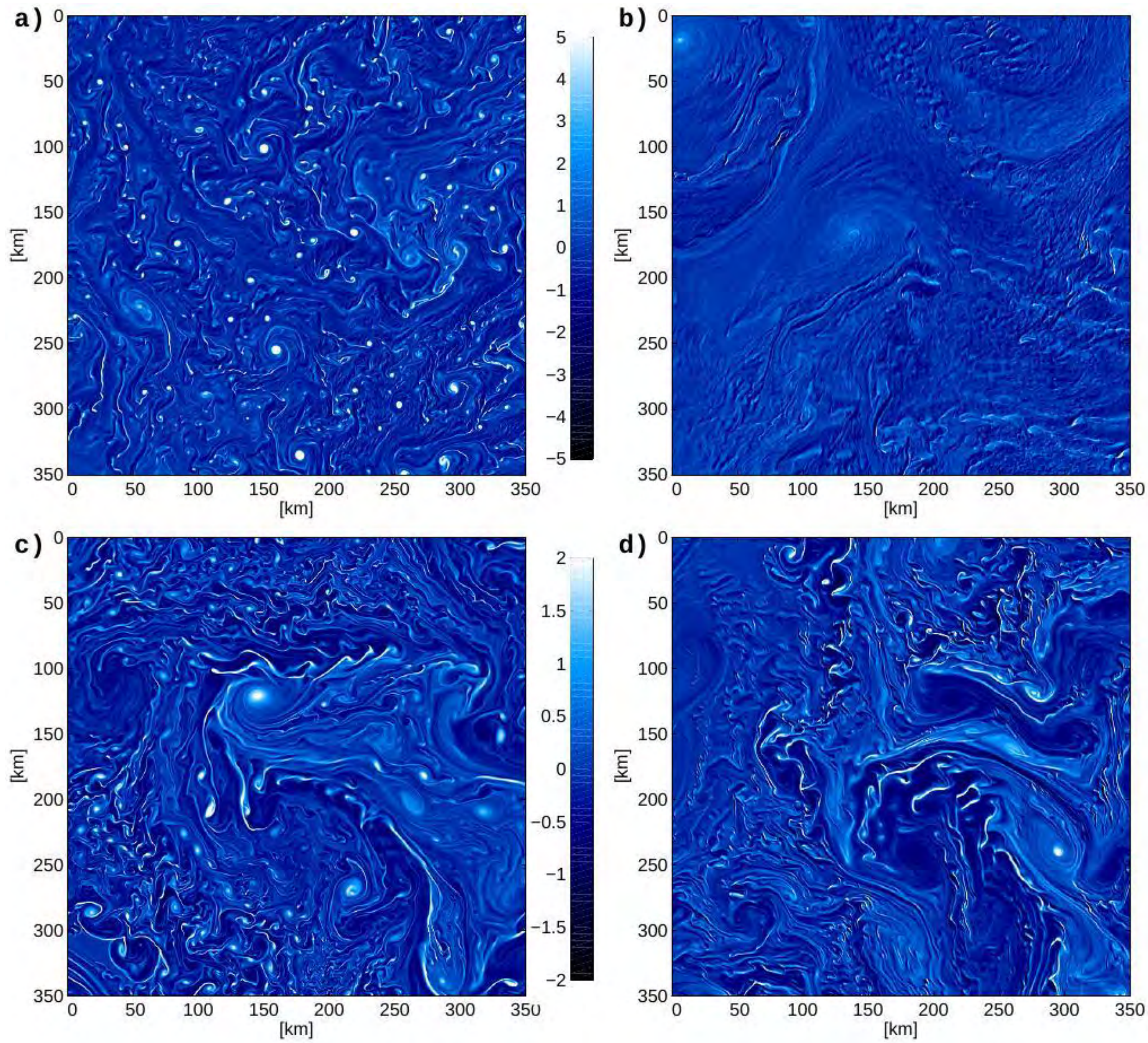

Figure 2: ***Snapshot of normalized vertical vorticity (ζ^z/f) at the surface off Peru (top row) and off California (bottom) in winter (left column) and summer (right). The visible features are primarily submesoscale, although the organizing mesoscale eddies can be perceived in the background. There is strong regional and seasonal variability in the intensity and morphology of the submesoscale flows. In California the flows are primarily frontal, especially in summer when they are especially unstable, whereas in Peru the cold filaments are very strong (note the different scale) and produce many coherent vortices.***

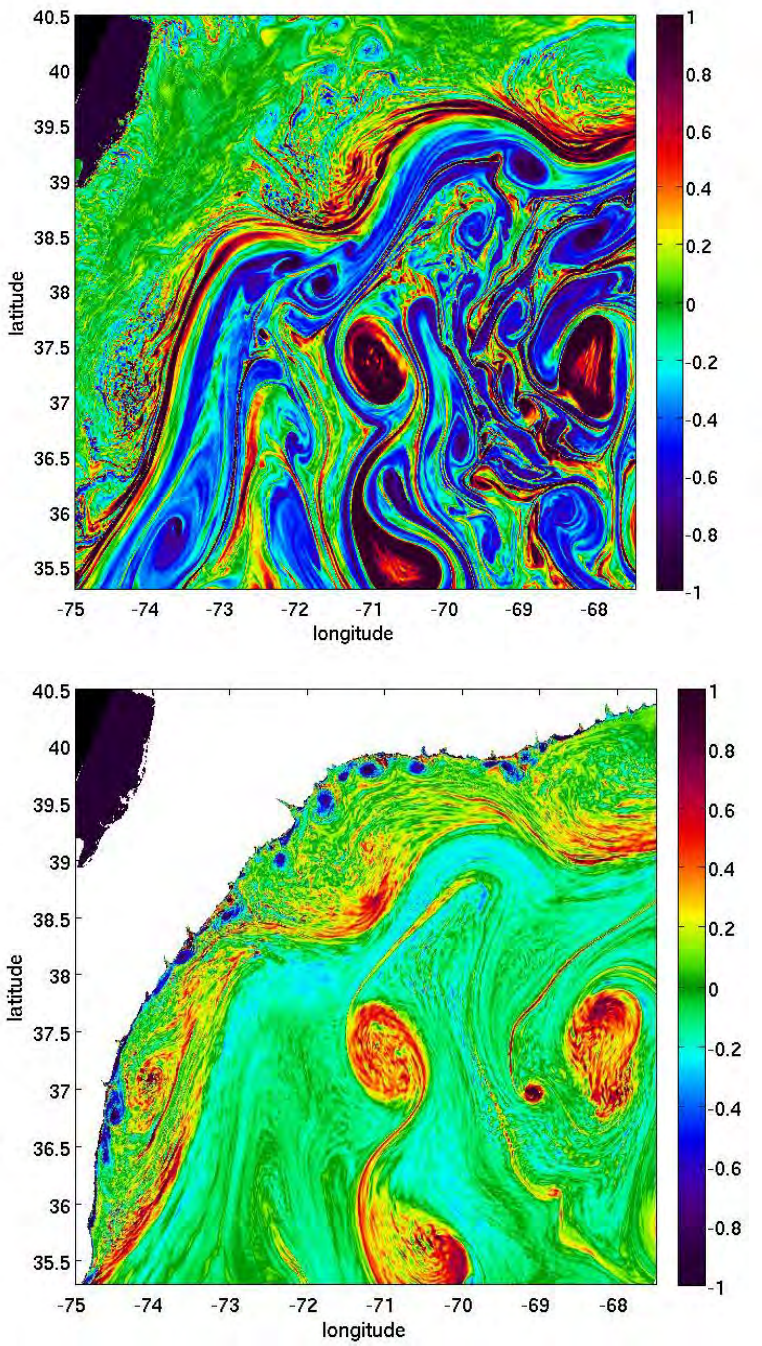

Figure 3: ***Snapshot of normalized vertical vorticity (ζ^z/f) at $z = 0$ (top) and -500 m (bottom) in a regional simulation of the separating Gulf Stream near Cape Hatteras, embedded in an eddy-resolving North Atlantic domain. Notice the submesoscale instabilities,*** *e.g.,* ***on the north wall of the Stream and within cyclonic Rings. Also, notice the topographic generation of submesoscale anticyclones against the continental slope. The surface-layer submesoscale currents are the dominant influence on lateral tracer mixing over horizontal scales of 0.1-10 km.***

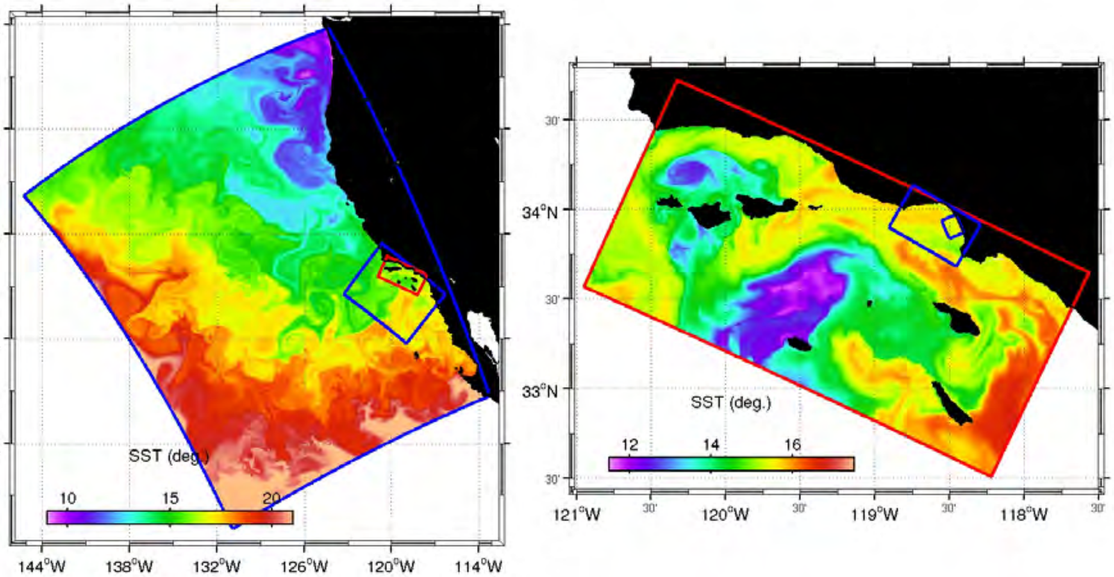

Figure 4: ***Snapshot of SST in successive grid nests starting at the scale of the Eastern Subtropical Pacific (*** $dx = 4$ ***km) descending down, in this application, to the Santa Monica Bay (*** $\Delta x = 20$ ***m). It is used to simulate local phenomena of mesoscale and submesoscale eddies, internal tides, and nearshore surface wave breaking and rip currents (Uchiyama*** et al.***, 2010). The methodology is most recently explained in Mason*** et al. ***(2010).***

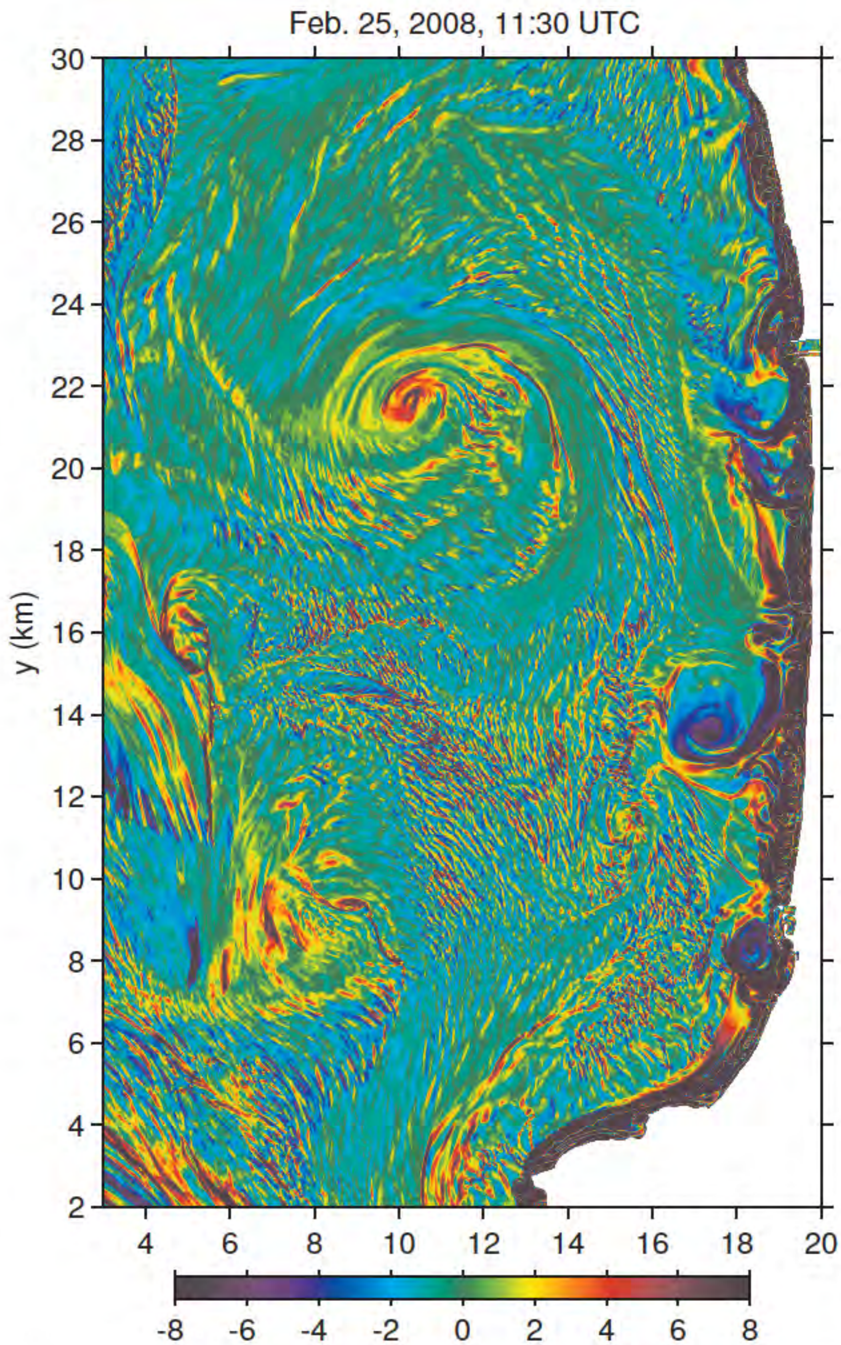

Figure 5: ***An instantaneous plot of normalized vertical vorticity, ζ^z/f, in the inner-most nested domain within Santa Monica Bay with a grid spacing of $\Delta x = 20$ m. Wave-driven littoral currents show intense vorticity within the surf-zone in the inner 0.5 km, and eddy and frontal flows populate the continental shelf in the Bay (e.g., the cyclonic submesoscale eddy around (10, 22) km). Intermittent, offshore-headed rip currents lead to eruptions of highly vortical flows at several near-shore locations, reaching up to about 3 km from the shore and penetrating the "sticky water" zone.***

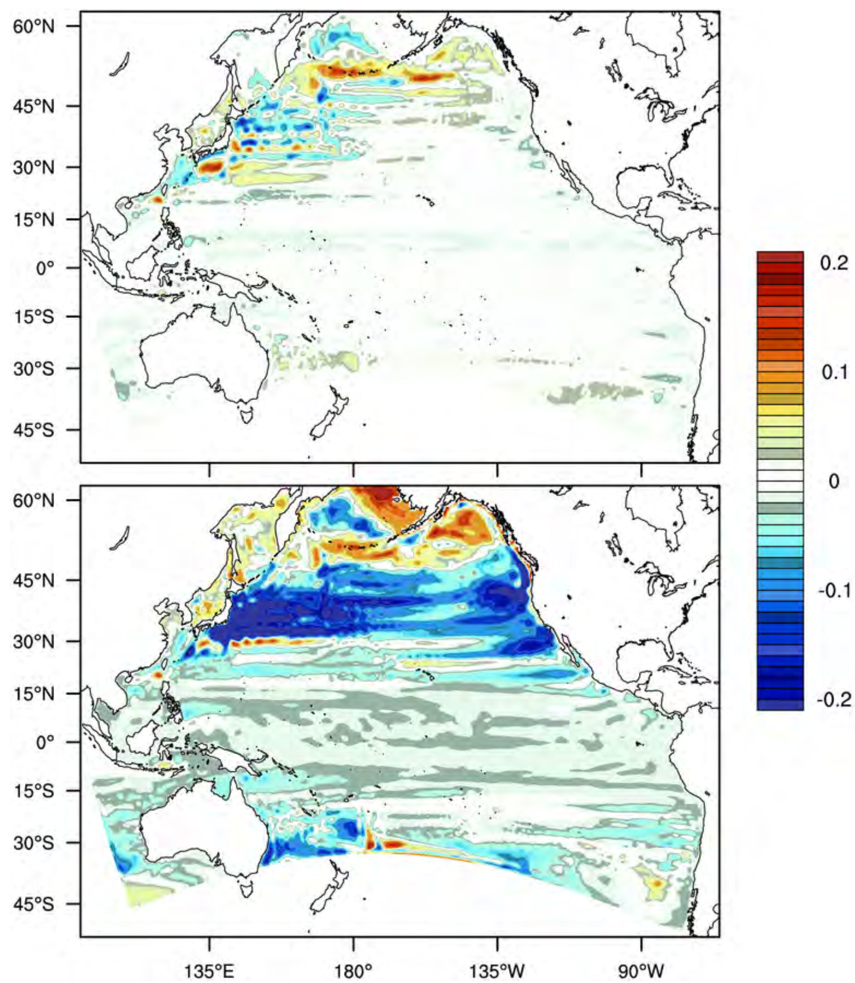

Figure 6: ***Difference in the annual mean of sea surface height [m] between two coarse-grid scale ($\Delta x = 50$ km) Pacific solutions due to two different levels of bathymetry smoothing, with an isopycnal hyperdiffusion (top), and with an isosigma hyperdiffusion (bottom). This demonstrates an important algorithmic sensitivity to how advection discretization errors are handled in a simulation model, and demonstrate the new isopyncal hyperdiffusion approach that usefully diminishes this sensitivity, in addition to otherwise reducing spurious diapycnal mixing errors (Lemarie et al., 2011).***

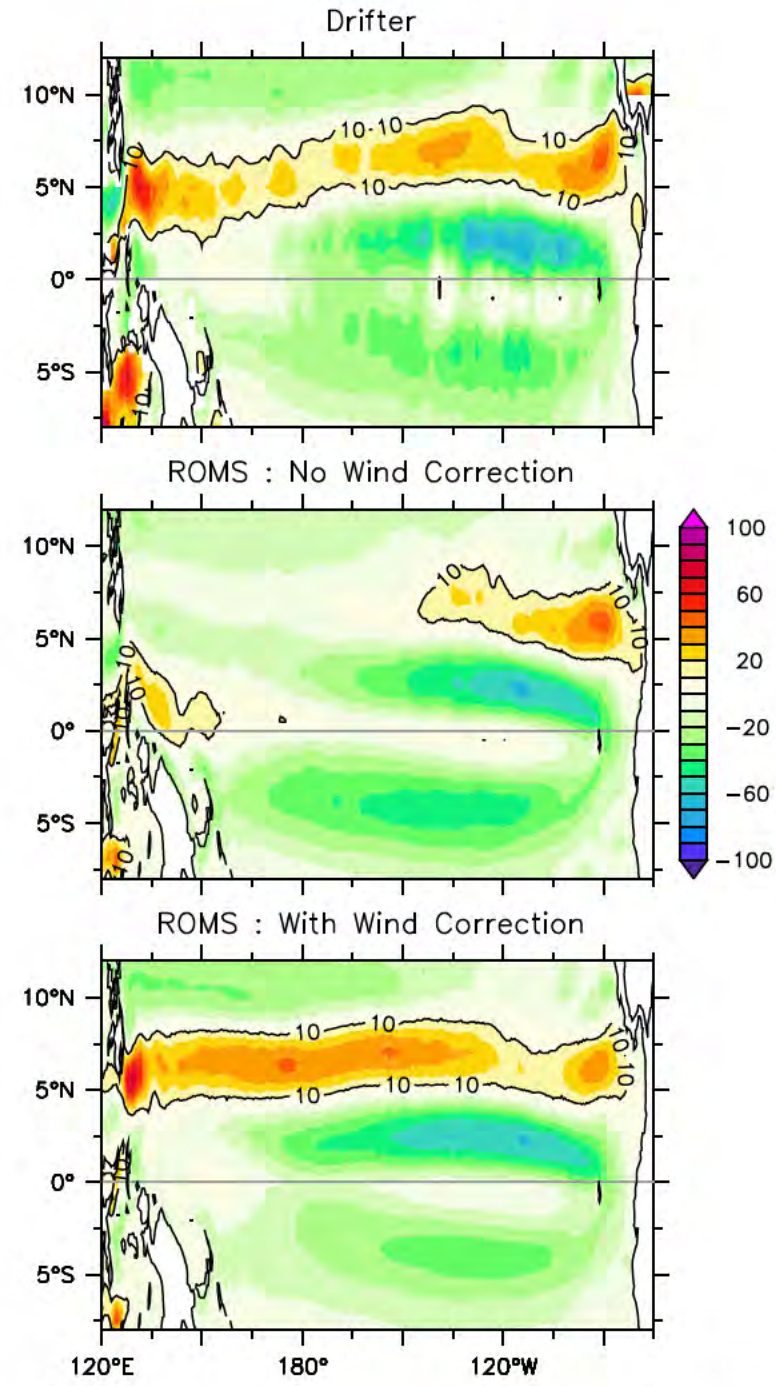

Figure 7: ***Annual mean surface zonal currents (cm/s) from drifter climatology (Lumpkin and Garzoli,** Deep-Sea Res.**, 2005) (left) and from Pacific basin simulations (averaged over 7-22 m depth) forced with uncorrected QuikSCAT winds (middle) and with QuikSCAT zonal winds corrected to match the Tropical Atmosphere Ocean (TAO) climatology (Lemarie** et al.**, 2011). Even this rather subtle difference in the wind forcing between two well-regarded data sets makes a big difference in the realism of the North Equatorial Countercurrent.***

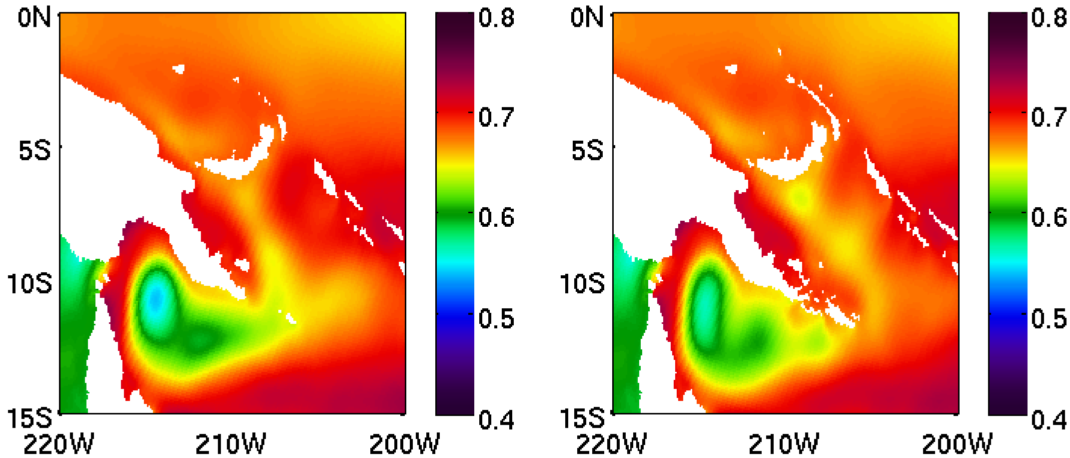

Figure 8: Maps of annual mean Sea Surface Height in the South West Pacific. The landmask that is used by the model is shown in white. The left panel shows an land mask that is obtained automatically by interpolating the etopo2 topography data on the model grid. The right panel shows an improved land mask that is closer to the actual configuration of obstacles and straits in the Solomon Sea. All other components of the 12 year model run are identical. The changes in the land mask lead to modest local changes in sea surface height and associated geostrophic currents that correspond to an improved mean flow in the area, respecting the absence of actual transport *through* the archipelago at the South Eastern tip of Papua New Guinea but instead leading to a path of the Western boundary Current around the Easternmost extension of the island chain.

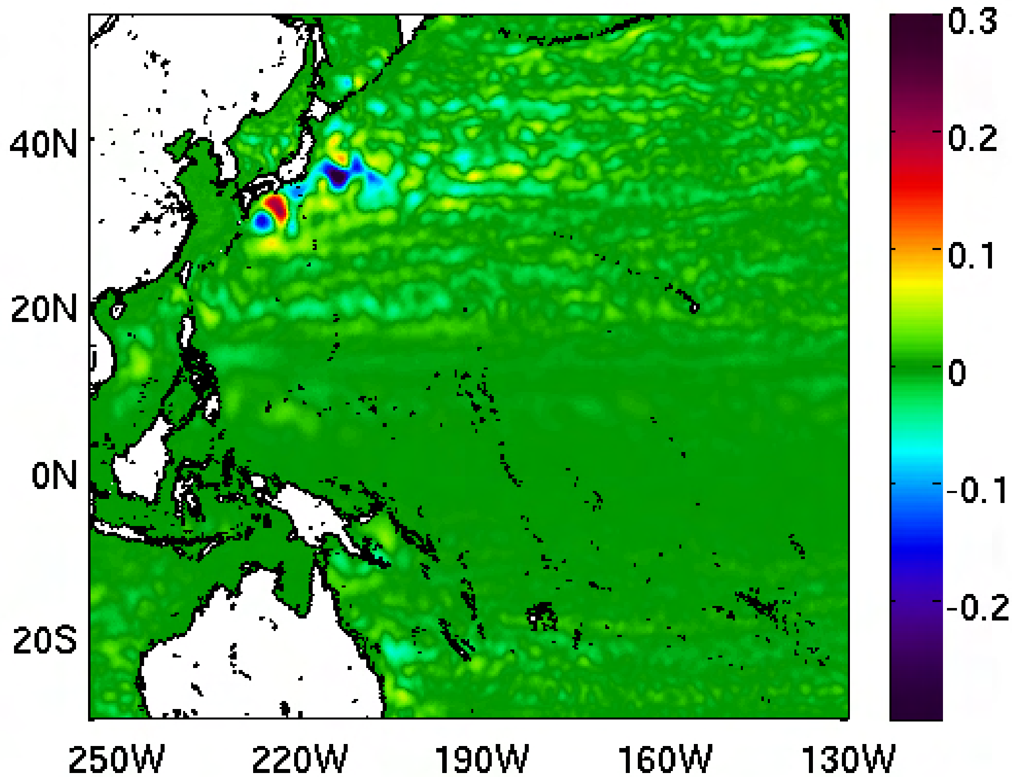

Figure 9: The annual mean Sea Surface Height difference between two simulations with small difference in the land mask in the South West Pacific. Local changes in the solution are small where the changes in the mask occur, but large in the area of the Kuroshio. There are no obvious differences in the solution between the Kuroshio region and the region of perturbation. The large changes in Kuroshio path may be related to an extreme sensitivity that may not be possible to reduce.