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Modeling Intrinsic Variability and Connectivity in Shelf and Littoral Circulation

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LONG-TERM GOAL

The long term goal of our research for the Office of Naval Research (ONR) National Oceano- graphic Partnership Program (NOPP) on "Shelf Physics" is to elucidate the fundamental dynam- ics for currents and their material transport on continental shelves reaching from beyond the shelf break through the inner shelf and into the surf zone.

OBJECTIVES

The primary objectives are (1) to accurately simulate the intrinsic submesoscale variability that develops on the shelf in response to the large-scale wind, tide, freshwater run-off, and surface wave forcings of the shelf circulation; (2) to analyze idealized approximations to these simulated phenomena; and (3) to support field experiments in the ONR Departmental Research Initiative (DRI) on the "Inner Shelf" by presenting prototypes of expected phenomena to guide the experi- mental design and by helping to interpret the measurements.

APPROACH

Our general approach is to computationally simulate geographically realistic situations with high spatial resolution with the expectation, borne out by previous experience, that this will yield new phenomenological discoveries that can then be analyzed, interpreted, and field tested.

One simulation code is ROMS (Regional Oceanic Modeling System) Shchepetkin & McWilliams (2008), a hydrostatic general circulation model designed for regional and fine-scale multi-level grid nesting. It requires subgrid-scale mixing parameterizations for all non-hydrostatic motions, including the surface and bottom boundary layer turbulence as represented in the K-Profile Pa- rameterization (KPP; Large *et al.*, 1994). It incorporates surface gravity wave interactions based on the theory of wave-averaged currents, including subgrid-scale mixing induced by surface grav- ity waves and their breaking (McWilliams *et al.*, 2004; Uchiyama *et al.*, 2010). It is coupled to surface wave models of varying degrees of complexity, ranging from a spectrum peak ray-theory model, to the full-spectrum models such as WaveWatch III (Tolman, 2009) and the reduced- complexity model by Donelan *et al.* (2012).

The general thrusts of the new research are to investigate submesoscale currents on small hori- zontal scales (∼ 10s - 100s m) with full wave-current interaction in the context of continental shelf flows in relatively shallow water. To obtain realistic flows a fine-grid shelf subdomain must be nested within a sequence of coarser-grid domains that transition circulation from regional to mesoscale to submesoscale (Mason *et al.*, 2010).

The research will be coordinated with other elements of the NOPP and DRI projects as they de- velop. In particular, we will work closely with Dr. Leonel Romero (UCSB), who will use the WaveWatch III (WW3) code for determining the surface gravity wave field evolution in transient disequilibrium conditions and with wave-current coupling, at least on the horizontal scale of kilo- meters and time scale of hours, if not even finer. We also will work closely with Prof. Falk Fed- dersen (UCSD) on the design of a parameterization of stochastic wave breaking to use in forcing ROMS. We also plan to test the new 4-km, tide-resolving HYCOM analysis product as an alter- native source of boundary data for local sub-domains. More generally we intend to collaborate with the field experimentalists in the DRI project.

WORK COMPLETED

Because the grant is only a few months old, our recent work is a continuation of projects begun previously; these are described in the next section. We are presently contemplating one or more new sites for realistic, nested-grid configurations that extend to the shoreline with very high res- olution. One of these is likely to be in the vicinity of Point Conception, California. Further site consideration will occur after the fall DRI meeting in Seattle.

This grant provides funding for a new computing cluster, to replace an elderly one we have been using for our ROMS simulations. We are presently engaged in its design and expect to construct it this fall, led by Dr. Alexander Shchepetkin.

RESULTS

Shelf Fronts: In realistic, multi-month simulations of shelf regions in the Southern Califor- nia Bight, we have discovered the spontaneous emergence of depth-filling, submesoscale den- sity fronts and filaments throughout the shelf (Figs. 1-3). These flow structures are recognizable by along- and cross-shore oriented lines of cyclonic vorticity that are coincident with regions of strong horizontal temperature and salinity gradients. Other important dynamical signatures of these features include strong downward vertical velocity (induced by surface convergence via continuity) and overlapping surface and bottom boundary layers indicative of strong vertical mix- ing throughout the water column. The universally strong surface convergence leads to trapping of surface material (proven by Lagrangian particle releases in offline ROMS simulations) and in- dicates the potential importance of these features in transport along and across the shelf. Close to the shoreline the flow structures have a preferential alignment parallel to the shore, but this anisotropy diminishes in the offshore direction to an eventual deep water isotropic regime off the shelf. Life-cycles of these shallow water surface convergence lines typically last 3-5 days with formation dominated by the advective tendency of frontogenesis. Coastline geography can also play an important role in generating submesoscale features on the shelf via filaments forming from the remnants of headland wake vortices. The dynamical ingredients necessary to

produce the observed strong vertical velocities and relative vorticity are rotation f, a strong buoyancy gra- dient $\nabla\rho$, and substantial vertical mixing of momentum K_v. A quasi-steady balance of these horizontal forces, known as Turbulent Thermal Wind (TTW) [Gula *et al.*, 2014; McWilliams *et al.*, 2015], allows for a diagnostic prediction of 3D velocity given only density and vertical mixing fields; this is well confirmed for the example shown in Fig. 3. These features also undergo a hefty diurnal cycle in conjunction with solar heating and its influence on ρ and K_v.

Dispersal in the Inner Shelf and Surf Zone: An important dynamical and practical question is how material is moved around on the inner shelf by the currents. In multi-level, nested-grid realistic simulations of several sites in Southern California, we have analyzed particle disper- sion from nearshore releases (Romero *et al.*, 2013), urban pollution effluent dispersal and dilution (Uchiyama *et al.*, 2014), and the inflow and spreading of small river plumes along the Santa Bar- bara coast during storms (Romero *et al.*, 2015). In a solution with even finer grid resolution (dx = 20 m) and which includes surface wave dynamical effects, we performed offline, 3D Lagrangian particle tracking in Santa Monica Bay (Fig. 4). For releases both within the wave-breaking region and just outside the surf under rather high wave conditions, there is an efficient particle exchange between the inner shelf and surf zone.

ROMS Validation in the Inner Shelf: In collaboration with colleagues at UCSD, we took advantage of an inner-shelf mooring array deployed off Huntington Beach, CA, in fall 2006 to evaluate the validity of ROMS simulations made for the same period. Although there was little correlation between the observed and modeled currents and temperature fluctuations at sub-tidal frequencies, their statistical characteristics in shape and amplitude were in good agreement (Ku- mar *et al.*, 2015a,b). (Note that no data assimilation was used for the model.) In the diurunal and semi-diurnal frequency bands, with more predictable tidal and sea-breeze forcing, the correla- tions were rather good between the observed and modeled currents and temperature.

Idealized Surf Turbulence: We are engaged in several studies of the surf zone with only inci- dent surface wave forcing. Two studies, led by French colleagues who are using a wave-current interaction formulation in their ROMS AGRIF code that is adapted from our code (Uchiyama *et al.*, 2010), were made for beaches in the Bay of Biscay and along the west coast of Africa using the measured bathymetry and beach cameras to detect the surf (Marchesiello *et al.*, 2015a,b). The primary analysis focus is on very low frequency (VLF) currents, which in these solutions arise from shear instability of the alongshore currents forced by obliquely incident waves.

A similar idealized study we are leading is on the role of complex, small-scale bathymetry in in- stigating VLF currents that are highly turbulent and eddy-like (Fig. 5), in contrast to another case with a much smoother bathymetry. As part of these studies, we are comparing 2D and 3D solu- tions to see how much is inaccurate about the much-practiced depth-averaged modeling for the surf zone. One such distinction in this regime of surf turbulence is the different characteristics of the coherent eddies that arise (Fig. 6).

Tidal Fronts at the Columbia River Mouth: A recent ONR Multidisciplinary University Research Initiative project, called DARLA: Data Assimilation and Remote Sensing for Littoral Applications, made extensive measurements within and just outside the mouth of the Columbia River, OR. Cigdem

Akan worked on that project and made some high-resolution ROMS-COAWST simulations, before she came to UCLA to work on this grant. The solutions demonstrate a strik- ing phenomenon of very sharp freshwater fronts on either edge of the river plume as it exits the mouth during the ebb tide (Fig. 7). We are presently engaged in an interpretive analysis of the associated frontogenetic and frontal instability processes captured in these simulations and will attempt to validate them with measurements.

Non-Hydrostatic Pressure Solver: As we approach finer and finer scales, the hydrostatic approximation that is used in ROMS becomes increasingly tenuous. Successful implementation of a non-hydrostatic correction for pressure would allow further nesting of the ROMS computational grid that is currently used with great success. In that case, we would not be limited by a reso- lution of $(100\ m)$, for which non-hydrostatic effects are expected to be small, but we could use ROMS at arbitrarily small scales. The facility of the latter can not be overstated as the problems that we want to study often depend on larger scale gradients and straining fields and as a result are very difficult to formulate in an idealized set-up. The ability of ROMS to successfully account for larger scale information through its open boundaries in combination with the ability to prop- erly simulate small scale non-hydrostatic phenomena would be a very powerful tool with a wide range of applications. A prototype non-hydrostatic ROMS was developed by us in Kanarska *et al.* (2007), and we have been slowly working toward a better code for realistic applications.

Due to the terrain following formulation of ROMS, the implementation of physically and numer- ically sound operators for the non-hydrostatic pressure is non-trivial. Current versions of models with terrain following coordinates that compute non-hydrostatic pressure make use of Poisson stencils that are large and lead to relatively non-sparse, non-symmetric matrices that are relatively expensive to solve. Additionally, the iterative solvers that are used in this class of non-hydrostatic models all scale poorly with increasing resolution. This makes these models increasingly slow to run for larger grid sizes.

Led by Jeroen Molemaker, we recently successfully formulated a version of the Poisson opera- tor for non-hydrostatic pressure that is compact and leads to a sparse, symmetric, positive defi- nite matrix. We have obtained this new operator by using concepts from geometric differentiation based on a dual representation of vectors on the computational grid. The momentum equa- tions are represented by contra-variant vectors, while the momentum fluxes are represented by co-variant vectors. The dual representation make it possible to arrive at a much more compact symmetric operator. The optimal numerical properties of our new Poisson operator make it viable to solve the system using a multi-grid approach. Multi-grid is the only existing form of itera- tive solver for elliptic systems that, when properly implemented, promises linear scaling with the number of degrees of freedom of the system (*i.e.,* model variables X grid points). This property guarantees that the relative cost of the computation of non-hydrostatic pressure will not increase with the problem size.

We have implemented our new approach in a set of Matlab scripts that serve as a proof of con- cept. They show our method to be discretely energy conservative and that the resulting operators have the desired properties. We are now in the process of constructing a stand alone multi-grid solver for the resulting system using High Performance Computing techniques in a Fortran code. The next phase will consist of merging the multi-grid solver with the existing ROMS code base. Papers are in preparation (Molemaker *et al.*, 2015a,b).

IMPACT/APPLICATIONS

The computational tools developed and the database of numerical solutions from this work will be utilized to guide the deployment of measurements during the field campaign and also aid the interpretation of the observations. The ROMS code is widely used by other oceanic scientists.

TRANSITIONS & RELATED PROJECTS

The UCLA modeling group works on several projects for ONR, *inter alia*, and there is a high degree of interaction among the participants. Two current ONR projects are "Eddy Effects in the General Circulation, Spanning Mean Currents, Mesoscale Eddies, and Topographic Generation, Including Submesoscale Nests" and "Dynamics of Upper-Ocean Submesoscale and Langmuir Turbulence".

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RELATED RECENT AND PROSPECTIVE PUBLICATIONS

Akan, C., J. C. McWilliams, & Y. Uchiyama, 2015a: Surf eddies over rough bathymetry. [in preparation]

Akan, C., J.C. McWilliams, H. T. Ozkan-Haller, S. Moghimi (and R. Geyer?), 2015b: Frontal dynamics at the mouth of the Columbia River. [in preparation]

Dauhajre, D., & J.C. McWilliams, 2015: Submesoscale fronts in the inner contintenal shelf. [in preparation]

Kumar, N., F. Feddersen, Y. Uchiyama, J. McWilliams, & W. O'Reilly, 2015a: Mid-shelf to surf zone coupled ROMS-SWAN model-data comparison of waves, currents, and temperature: Diagnosis of subtidal forcings and response. *J. Phys. Ocean.* **45**, 1464-1490. [published, refereed]

Kumar, N., F. Feddersen, S. Sutara, Y, Uchiyama, & J.C. McWilliams, 2015b: Mid- to inner-shelf coupled ROMS-SWAN model-data comparison of currents and temperature: Diurnal and semi-diurnal variability. *J. Phys. Ocean.* [submitted]

Marchesiello, P., R. Benshilat, R. Almar, Y. Uchiyama, J.C. McWilliams, & A.F. Shchepetkin, 2015a: On tridimensional rip current modeling. *Ocean Modelling*. [in press]

Marchesiello, P., R. Almar, R. Benshila, S. Larnier, B. Castelle, J.C. McWilliams, & R.A. A. Laibi, 2015b: Eddy mixing of longshore currents: Video observation and 3D modeling off Grand Popo Beach, Benin. [in preparation]

Molemaker, M.J., G. Roullet, & T. Dubos, 2015a: A compact symmetric stencil for the Poisson operator in models with terrain-following coordinates. [in preparation]

Molemaker, M.J., A. Shchepetkin, & J.C. McWilliams, 2015b: On the pressure-gradient error and available potential energy in models with terrain-following coordinates. [in preparation]

Romero, L.E., Y. Uchiyama, D. Siegel, J. McWilliams, & C. Ohlmann, 2013: Simulations of particle-pair dispersion in Southern California. *J. Phys. Ocean.* **43**, 1862-1879. [published, refereed]

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Uchiyama, Y., E. Idica, J.C. McWilliams, & K. Stolzenbach, 2014: Wastewater effluent dispersal in two Southern California Bays. *Cont. Shelf Res.* **76**, 36-52. [published, refereed]

Uchiyama, Y., J.C. McWilliams, & C. Akan, 2015: Shelf-surf interactions in Santa Monica Bay, CA. [in preparation]

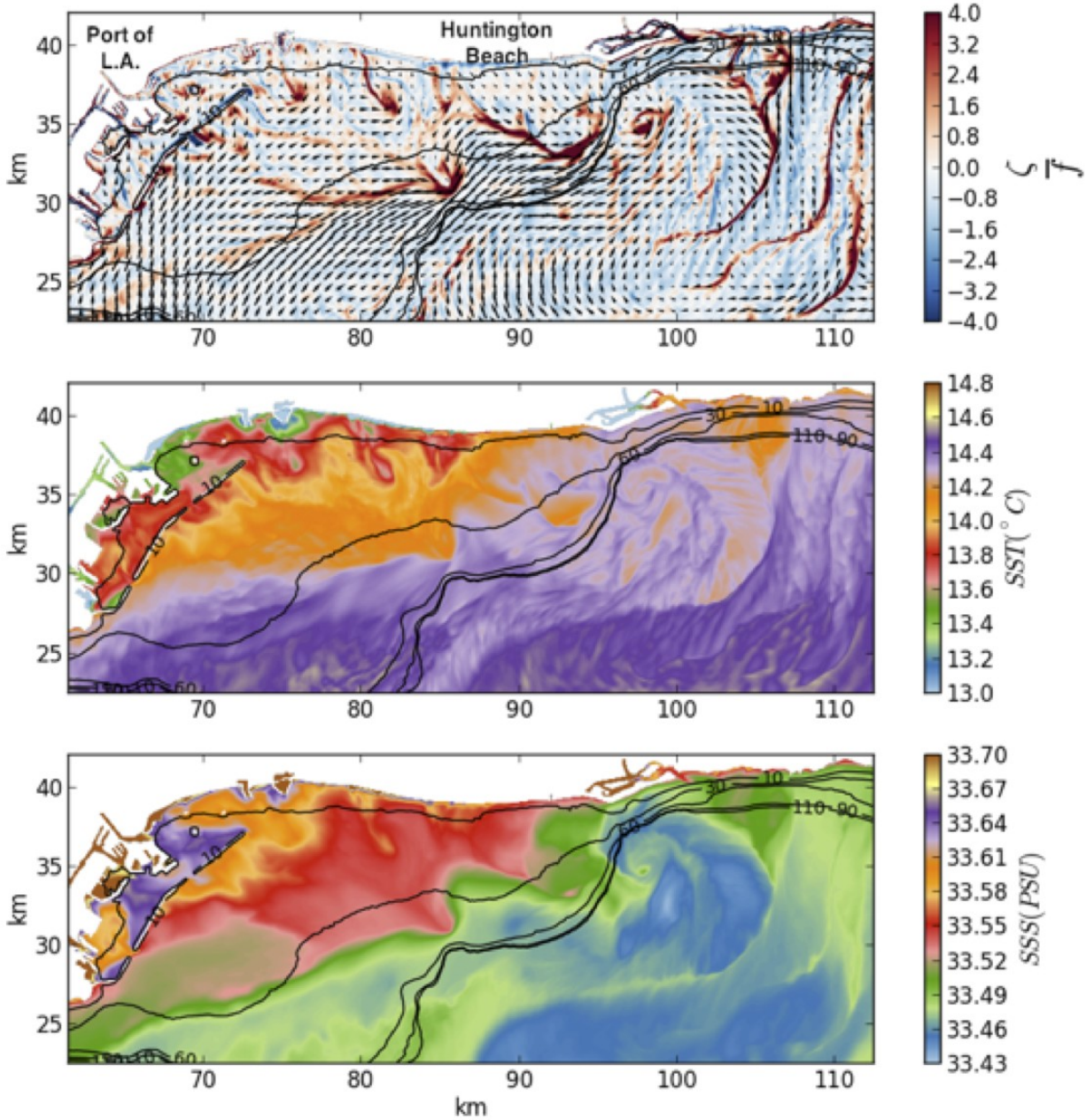

Figure 1: Snapshots of (top) relative vorticity (colors) with velocity (arrows), (middle) temperature, and (bottom) salinity at the surface in San Pedro Bay, CA. The horizontal grid resolution is 75 m. The black lines are the isobaths of 10, 30, 60, and 110 m. This is from a realistic multi-level, nested-grid simulation of the central Southern California Bight. (Dauhajre and McWilliams, 2015)

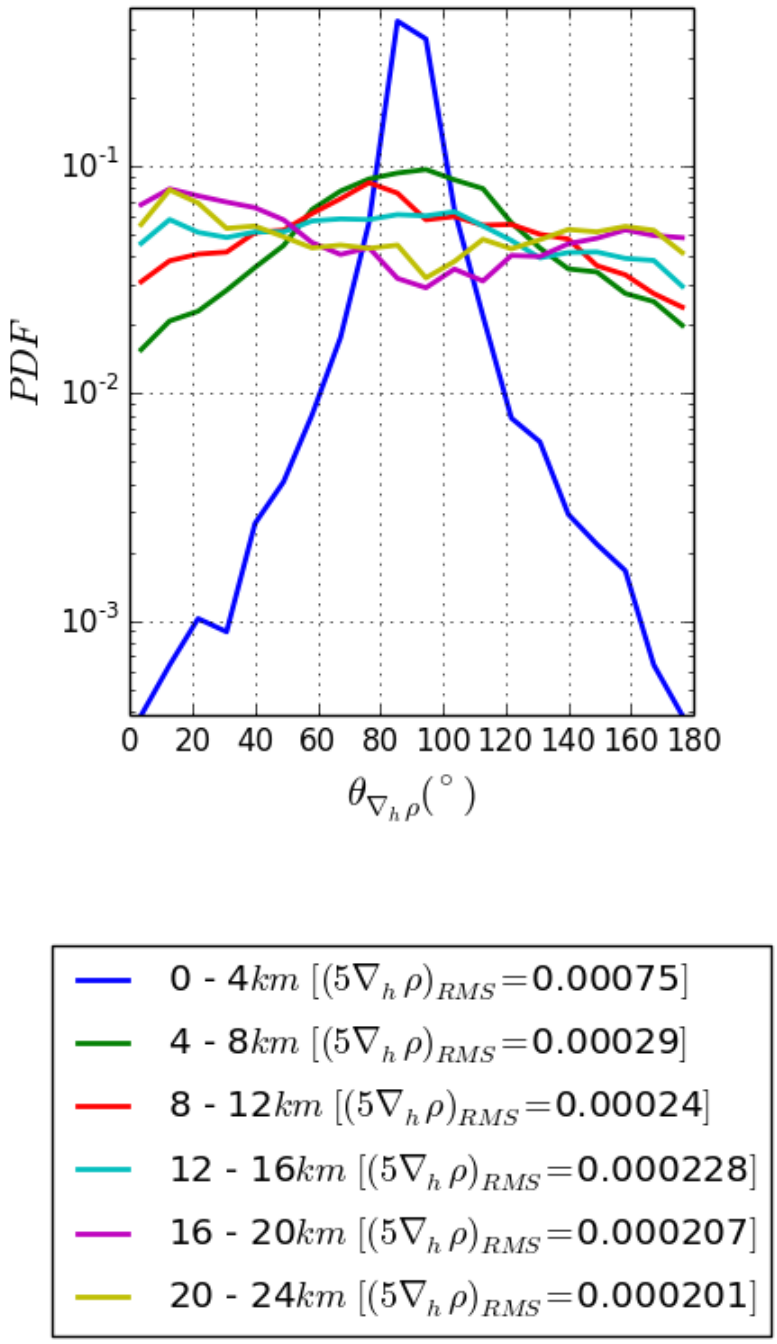

Figure 2: Probability density functions (PDFs) of the horizontal density gradient angle relative to isobaths. PDFs were calculated for six 750 m x 750 m boxes in Santa Monica Bay for different offshore distances. To isolate submesoscale fronts and filaments, horizontal density gradients in each region were only retained for the PDF calculation if they exceeded five times the root-mean-square (RMS) value of density gradient in that region. These thresholds are indicated in the legend in kg/m^4. This is from the same simulation as in Fig. 1. (Dauhajre and McWilliams, 2015)

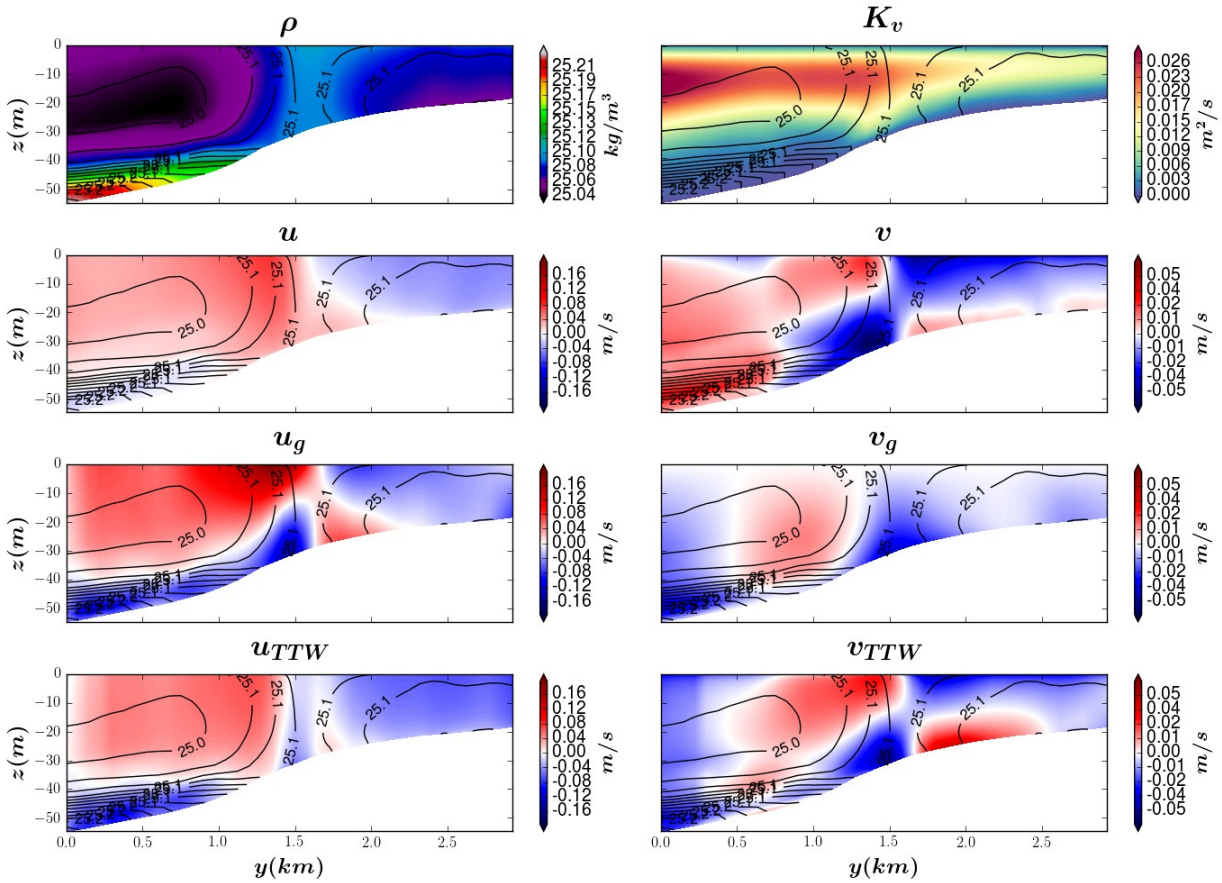

Figure 3: Along-front averaged fields for a shelf filament in Santa Monica Bay. Top: Density ρ (left) and vertical mixing coefficient K_v (right) calculated from the KPP scheme used in ROMS. Second row: total horizontal u with along-front in the left column (positive out of the page) and across-front in the right column (positive to the right). Third row: geostrophic velocities. Fourth row: Turbulent Thermal Wind (TTW) velocities calculated from ρ and K_v. Density contours are repeated in all panels. This is from the same simulation as in Fig. 1. (Dauhajre and McWilliams, 2015)

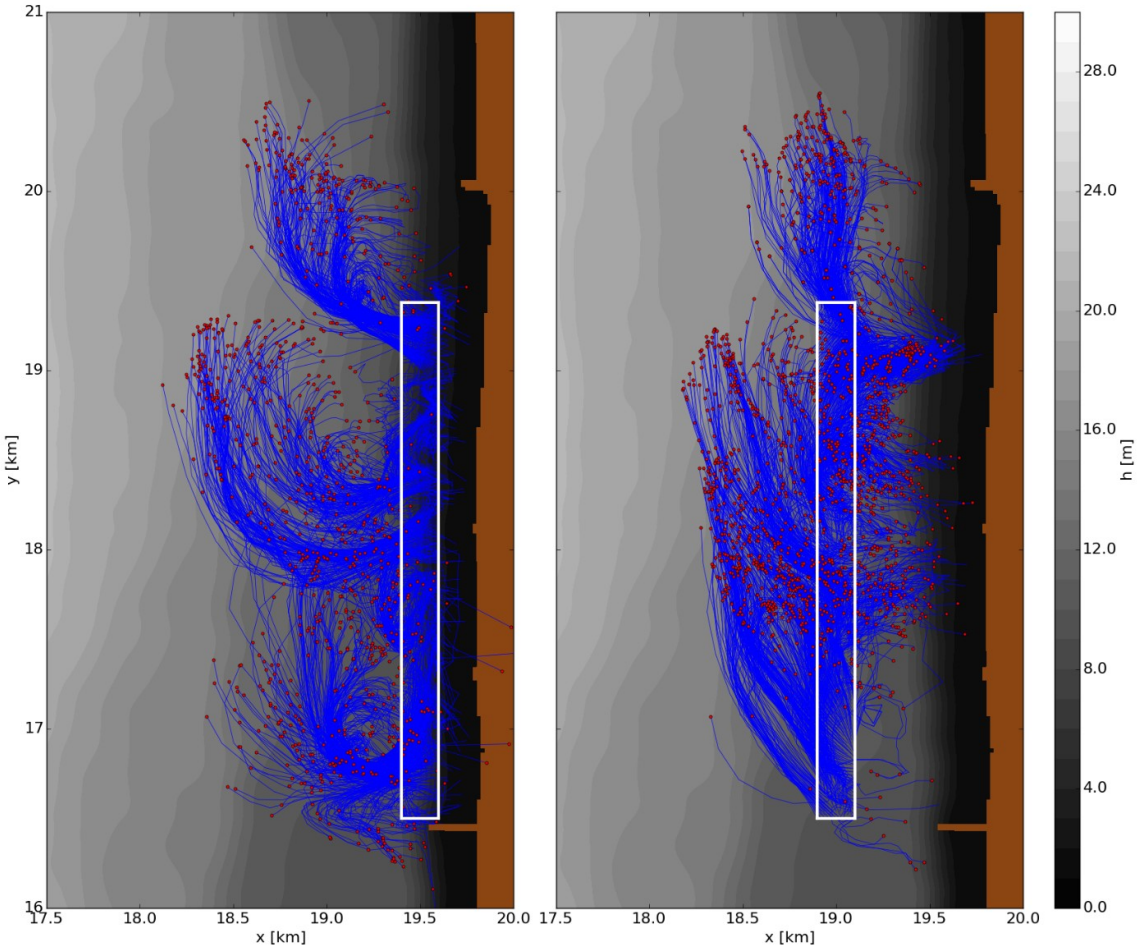

Figure 4: 3-D Lagrangian trajectories of passive particles released under rough wave conditions after 10 hours from the initial release. White boxes denote the area of release locations: the box in the left panel is within the breaker zone, while the box in the right panel is just outside it. This is from a nearshore portion of a multi-level nested-grid realistic simulation of Santa Monica Bay during fall, 2004. This shows that there is an efficient exchange of material between the inner shelf and surf regions. (Uchiyma** *et al.*, **2015)

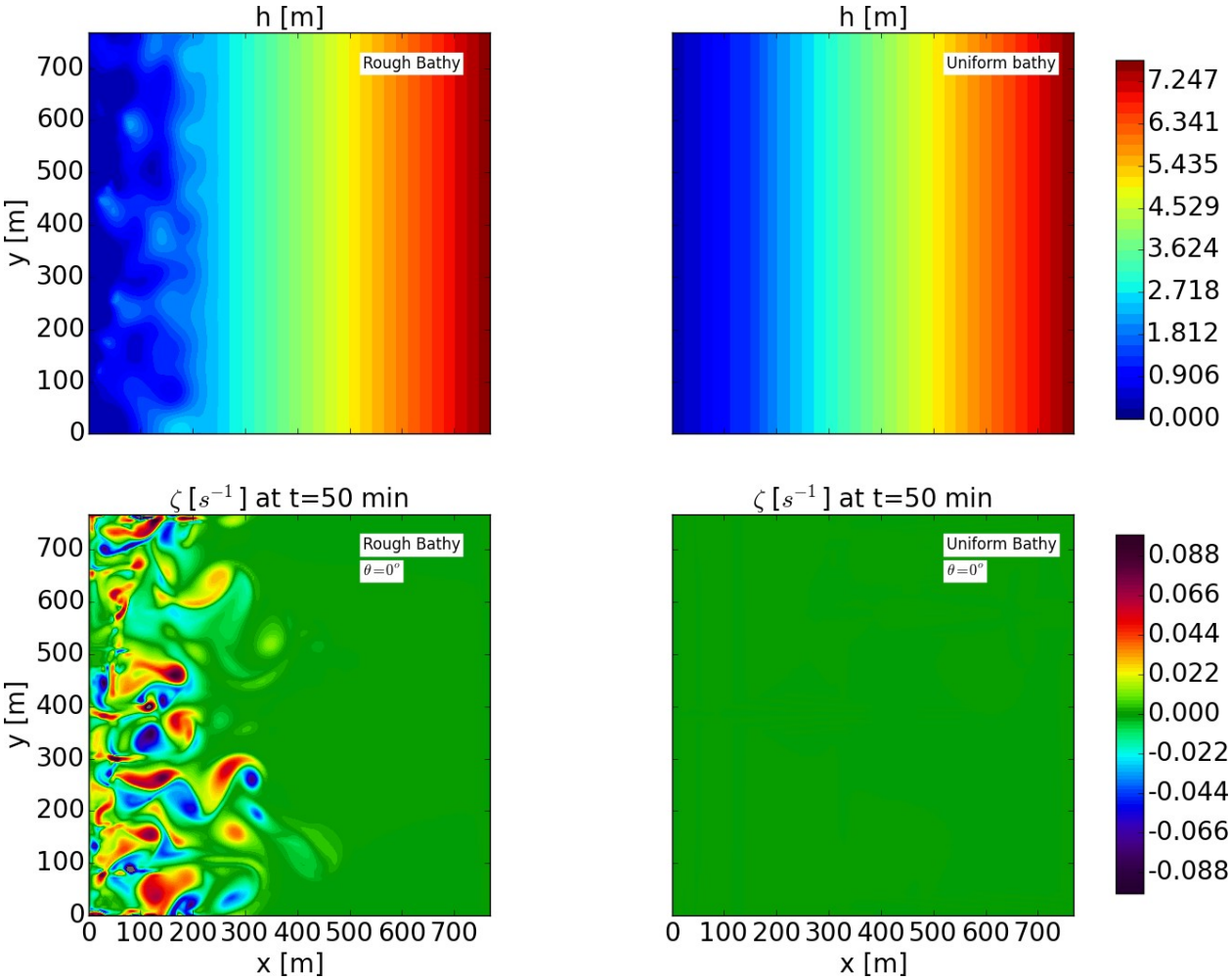

Figure 5: A comparison of two idealized 3D simulations with normally incident waves. Both have an overall bottom slope in $h(x, y)$, but the one in the right column also has smaller scale variations. For the rough topography, there is strong surf eddy turbulence evident in the surface vorticity field (lower left) while for the smooth topography there is essentially no evident surf eddy variability (*i.e.,* it is very weak; lower right). (Akan* et al.*, 2015a)

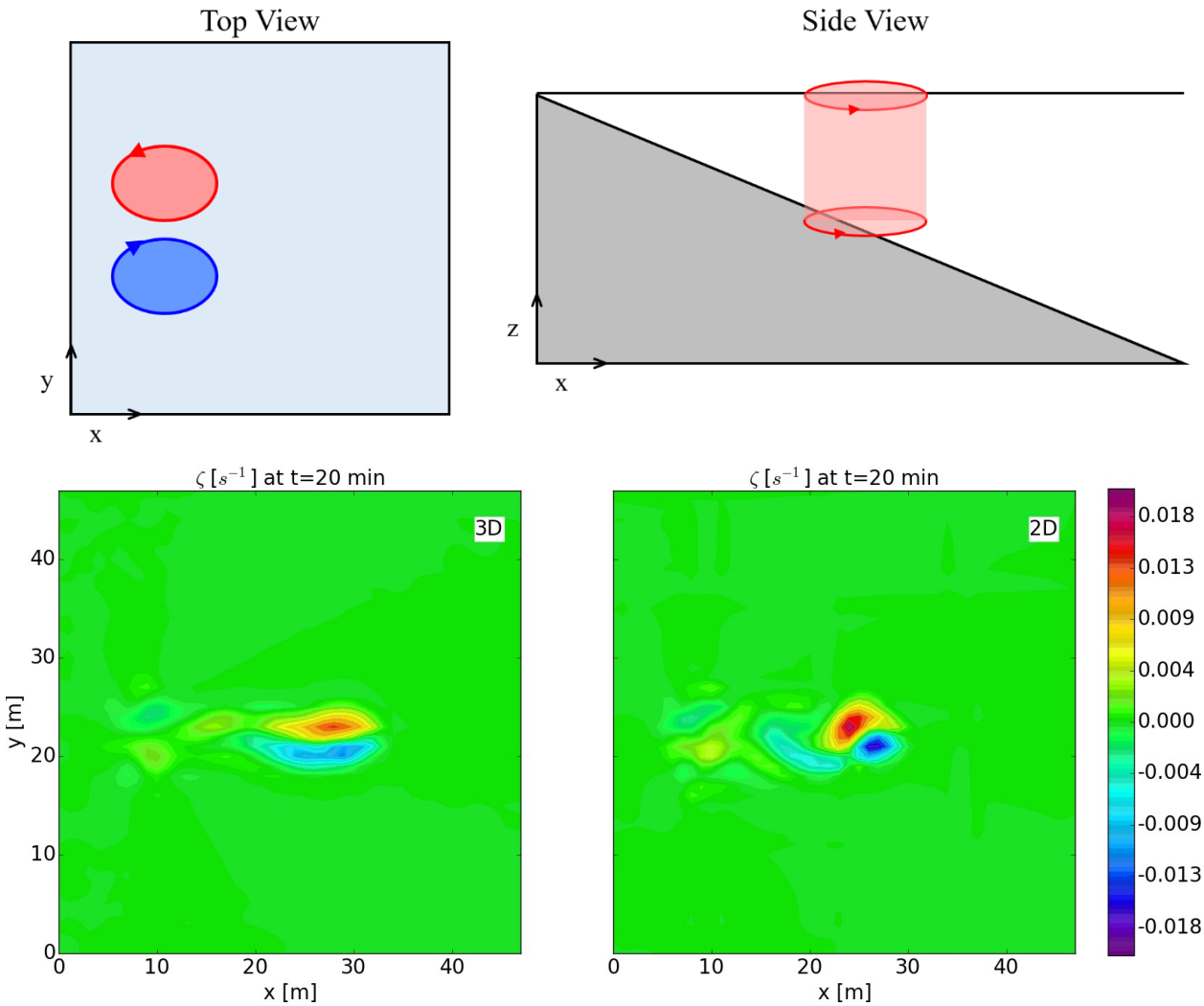

Figure 6: Idealixed process study of the evolution of an offshore-propagating dipole vortex, from an initially barotropic vertical structure in unstratified water over a simple nearshore sloping bottom (top). After a time of 20 minutes, the surface relative vorticity is compared between a fully 3D model (bottom left) and a depth-averaged 2D model (bottom right). The vortex pair has weakened more in 3D than in 2D because of the different action of vortex stretching as the water depth changes.

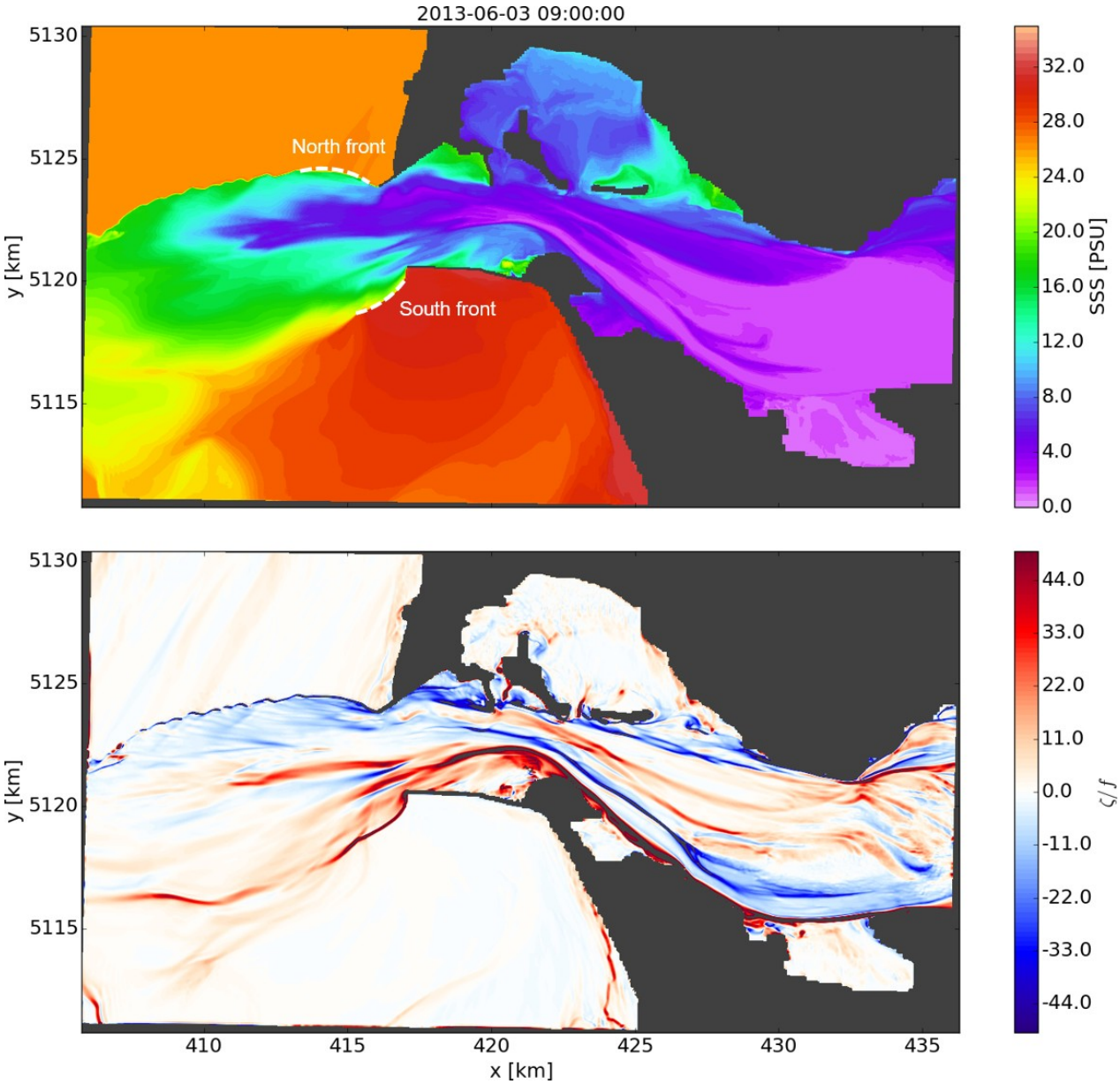

Figure 7: ***Surface salinity (top panel) and normalized relative vorticity at the Mouth of the Columbia River where white dashed lines denote strong fronts that form during the peak of the ebb tide outflow. (Akan*** *et al.****, 2015b). Our focus is on analzying frontogenesis process and the flow structure near the fronts.***