Modeling Intrinsic Variability and Connectivity in Shelf and Littoral Circulation

James C. McWilliams
Department of Atmospheric Sciences and
Institute of Geophysics and Planetary Physics, UCLA
Los Angeles, CA 90095-1565
Phone:(310) 206-2829 fax:(310) 206-5219 email: jcm@atmos.ucla.edu

Grant Number: N00014-15-1-2645

ACCOMPLISHMENTS

Major Goals:

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

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 fi experiments in the ONR Departmental Research Initiative (DRI) on the "Inner Shelf" by presenting prototypes of expected phenomena to guide the experimental design and by helping to interpret the measurements.

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 fi tested.

One simulation code is ROMS (Regional Oceanic Modeling System) Shchepetkin & McWilliams (2008), a hydrostatic general circulation model designed for regional and fi e 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 Parameterization (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 gravity 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 horizontal scales (~ 10s - 100s m) with full wave-current interaction in the context of continental-shelf fl ws in relatively shallow water. To obtain realistic fl ws a fi 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 is being coordinated with other elements of the NOPP and DRI projects as they develop. 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 fi evolution in transient disequilibrium conditions and with wave-current coupling, at least on the horizontal scale of kilometers and time scale of hours, if not even fi We also will work closely with Prof. Falk Feddersen (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 alternative source of boundary data for local sub-domains (with Prof. Brain Arbic, U. Michigan). More generally we intend to collaborate with the fi experimentalists in the DRI project.

Accomplished:

1) major activities

During this period the major activities have been: **(1)** investigating surf-zone turbulent processes in idealized computational studies (Akan *et al.*, 2016b,c); **(2)** investigating surf zone turbulence in realistic situations (Marchesiello *et al.*, 2015, 2016); **(3)** analyzing shelf and nearshore submesoscale fronts and material exchange with the shoreline in realistic simulations (Akan, 2016a; Dauhajre and McWilliams, 2016a; Uchiyama *et al.*, 2016); **(4)** investigating submesoscale frontogenesis and interactions with internal waves in idealized computational studies (McWilliams *et al.*, 2015; McWilliams, 2016a,b; Barkan *et al.*, 2016; Sullivan and McWilliams, 2016); Dauhajre and McWilliams, 2016b); **(5)** testing the validity of realistic ROMS simulations in Huntington Beach, CA (Kumar *et al.*, 2015, 2016); **(6)** implementing a new set of multiply nested, realistic simulations for Middle California (MidCal) for investigating wave-current interaction (in collaboration with Dr. Leonel Romero, UCSB) and regional effects of remotely generated internal tides (downscaling from HYCOM, in collaboration with Prof. Brian Arbic, U. Michigan), and for supporting the ONR fi experiments in the Langmuir Turbulence and Inner Shelf DRI programs; **(7)** continuing ROMS model developments for more efficient calculation of vertical advection (Shchepetkin, 2015) and for a fully realistic non-hydrostatic circulation model (led by Jeroen Molemaker in collaboration with the French CROCO (AGRIF) team).

2) specific objectives

To achieve better theoretical understanding of shelf and surf zone dynamical processes and their interaction, and to bring along a new generation of realistic, multiply-nested simulations of the Middle California region as a simulation framework for wave-current interaction, shelf currents, and surf-zone currents.

3) significant results

We focus here on some particular results, augmented with the publication list and supporting fi in accompanying fi

Tidal Fronts at the Columbia River Mouth: In the tidal ebb-cycle at the Mouth of the Columbia River, strong density and velocity fronts form at both sides of the nearshore freshwater plume perpendicular to the coast (Fig. 1; Akan *et al.*, 2016a). We specifically focused on the northern edge of the plume where the front is very strong in spite of satisfying the conditions for centrifugal instability (Akan *et al.*, 2016a). The model results indicate that vertical vorticity develops at every ebb as the fl w passes jetties and steep topographic banks inside and near the mouth, and vorticity is generated by diff tial boundary stress. Geostrophic balance is disrupted for the along-front fl w, and an ageostrophic secondary circulation is generated that induces frontogenesis tendency and sharpens the plume edge density gradient. Frontogenesis keeps the front sharp well past the jetties and delays the development of its lateral shear and centrifugal instabilities until the turn of the tide. Besides the main advective front, smaller gravity bores are emitted by the main front.

Material Dispersal in the Inner Shelf and Surf Zone: We performed offline, 3D Lagrangian particle tracking using the results from our high resolution (dx = 20 m) Santa Monica Bay simulations where passive particles were released from diff t nearshore sites as shown in Fig. 2 (Uchiyama *et al.*, 2016) with the white boxes, under both relatively calm and rough wave conditions. Under rough wave conditions, particles show random widespread distribution patterns traveling over 2 km away from the release site, and they tend to recirculate in the surf-zone reaching to the shoreline because of the intensified littoral currents. The particles are also transported a moderate distance offshore under the calm wave conditions, but their distribution stays more organized, especially in the release box offshore of the surf zone (top right panel) where no particle could be found moving into the surf zone. Similar distribution patterns are observed in the vertical: particles seem to be clustered at certain depths under calm wave conditions, whereas, in the cases under rough wave conditions, they are scattered throughout all depths. Hence, our results suggest that wave-driven currents not only intensify cross-shore mixing and lateral dispersion, but also enhance the vertical mixing.

ROMS simulations of Middle California: We are constructing 5-level nested-grid realistic configurations that downscale the California Current System with a grid resolution of dx = 4 km to various nearshore regions in Middle California with dx = 20 m or so. These solutions will be the basis for wave-current and and shelf-surf interaction studies. They will be used to support and help interpret the measurements in the ONR Langmuir Turbulence and Inner Shelf DRI fi experiments, which will occur within the higher resolution among the nested subdomains. Besides these sites we will make other nested subdomains in diff nt wave and current environments, *viz.,* Point Conception, the Northern Channel Islands, and North Malibu. Illustrations from preliminary results are in Figs. 3-5.

Idealized Surf Turbulence: Shear instabilities are known to generate energetic, very low frequency (VLF) surf zone eddies, and thus play an important role in cross-shore material transport and mixing. We set up several idealized ROMS simulations with tri-dimensional wave-current interactions where we included topographic irregularities in the alongshore direction. For this purpose, perturbations in the form of Gaussian shaped bumps are added to a variety of commonly used idealized topographies to generate a rough bathymetry. Model results show that these topographic features serve as an essential mechanism in the generation of surf zone eddies when compared to their alongshore uniform counterparts (Fig. 6), especially when the incident surface wave direction is near-normal. We also examined diff t coastline shapes with headland and bay cases (Fig. 7); these have the effect of making the surf turbulence inhomogeneous in the alongshore direction, with headlands suppressing surf turbulence and bays extending it further into the interior. Thus, both small-scale roughness and shoreline variations have important infl on the intrinsic variability in littoral currents (Akan *et al.*, 2016b).

Traditionally, surf and rip currents are modeled as depth-independent, and thus most investigations concerning rip currents have been primarily 2D. However, some of the recent studies (including our idealized studies) have shown significant diff and strong depth dependence between 2D and 3D surf-zone simulations. Hence, to help explain these diff and quantify the importance of three-dimensionality, we designed an idealized vortex dipole problem (Akan *et al.*, 2016c). Our initial results show that 2D surf vortices remain stronger than their 3D counterparts and, furthermore, density stratification elongates and further weakens the vortices (Fig. 8); *i.e.,* a 2D vortex decays slower compared to a 3D vortex.

4) key outcomes

There is significant intrinsic variability on continental shelves beyond the wind-, tide-, and river-forced currents and their material transports. This project is developing a framework for understanding what are the important types of variability and how they behave, both in idealized and realistic situations: submesoscale fronts, fi aments and vortices; surf eddies; surface gravity wave interactions; and internal tidal currents made incoherent (non-periodic in time) through interaction with shelf currents.

Training:

Nothing to Report

Dissemination:

Nothing to Report

Plans:

Nothing to Report

Honors:

Nothing to Report

Publications

A list of papers published during the performance period, in press, submitted, or in a late stage of preparation.

Akan, C., J.C. McWilliams, H. T. Ozkan-Haller, S. Moghimi, 2016a: Frontal dynamics at the mouth of the Columbia River. Geophys. Res. Lett., submitted.

Akan, C., J. C. McWilliams, Y. Uchiyama, 2016b: Surf turbulence over rough bathymetry and with coastline variations. In Preparation

Akan, C., J. C. McWilliams, Y. Uchiyama, 2016c: Influence of three-dimensionality and stratification on nearshore vortices. In Preparation

Barkan, R., K.B. Winters, J.C. McWilliams, 2016: Enhancement of eddy kinetic energy dissipation by internal waves. J. Phys. Ocean., submitted.

Dauhajre, D., J.C. McWilliams, 2016a: Submesoscale fronts in the inner contintenal shelf, in preparation

Dauhajre, D., J.C. McWilliams, 2016b: Diurnal evolution of submesoscale front and fi ment circulation, in preparation

Gula, J., M.J. Molemaker, J.C. McWilliams, 2015a: Topographic vorticity generation, submesoscale instability and vortex street formation in the Gulf Stream. Geophys. Res. Lett. 42, 4054-4062.

Gula, J., M.J. Molemaker, and J.C. McWilliams, 2015b: Gulf Stream dynamics along the southeastern U.S. Seaboard. J. Phys. Ocean. 45, 690-715.

Gula, J., M.J. Molemaker, J.C. McWilliams, 2016a: Submesoscale dynamics of a Gulf Stream frontal eddy in the South Atlantic Bight. J. Phys. Ocean. 46, 305-325.

Gula, J., M.J. Molemaker, J.C. McWilliams, 2016b: Topographic generation of submesoscale centrifugal instability and energy dissipation. Nature Comm., in press.

Kumar, N., F. Feddersen, Y. Uchiyama, J. McWilliams, W. O' Reilly, 2015: 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.

Kumar, N., F. Feddersen, S. Sutara, Y, Uchiyama, J.C. McWilliams, 2016: Mid- to inner-shelf coupled ROMS-SWAN model-data comparison of currents and temperature: Diurnal and semi-diurnal variability. J. Phys. Ocean. 45, 1464-1490.

Luo, H., A. Bracco, Y. Cardona, J.C. McWilliams, 2016: Submesoscale circulation in the Northern Gulf of Mexico. Surface processes and the impact of the freshwater river input. Ocean Modelling 101, 68-82.

Marchesiello, P., R. Benshilat, R. Almar, Y. Uchiyama, J.C. McWilliams, A.F. Shchepetkin, 2015: On tridimensional rip current modeling. Ocean Modelling 96, 36-48.

Marchesiello, P., R. Almar, R. Benshila, S. Larnier, B. Castelle, J.C. McWilliams, 2015b: Eddy mixing of longshore currents: Video observation and 3D modeling off Grand Popo Beach, Benin. J. Coastal Res. 75, 408-412.

McWilliams, J.C., J. Gula, M.J. Molemaker, L. Renault, A.F. Shchepetkin, 2015: Filament frontogenesis by boundary layer turbulence. J. Phys. Ocean. 45, 1988-2005.

McWilliams, J.C., 2016a: Submesoscale Currents in the Ocean. Proc. Roy. Soc. A 472, 20160117, 1-32.

McWilliams, J.C., 2016b: Submesoscale surface fronts and fi ments: Secondary circulation, buoyancy fl and frontogenesis. J. Fluid Mech., in preparation.

Romero, L., D.A. Siegel, J.C. McWilliams, Y. Uchiyama, C. Jones, 2016: Characterizing stormwater dispersion and dilution from small coastal streams. J. Geophys. Res., in press.

Shchepetkin, A.F., 2015: An adaptive, Courant-number-dependent implicit scheme for vertical advection in oceanic models. Ocean Modelling 91, 38-69.

Sullivan, P. P. and J. C. McWilliams, 2016: Frontogenesis and frontal arrest of a dense fi t in the ocean surface boundary layer. Journal of Fluid Mechanics, in preparation.

Uchiyama, Y., J.C. McWilliams, C. Akan, H. Kaida, 2016: Shelf-surf interactions in Santa Monica Bay, CA, in preparation.

Figures

Below are illustrative fi referred to in the text of the progress report.

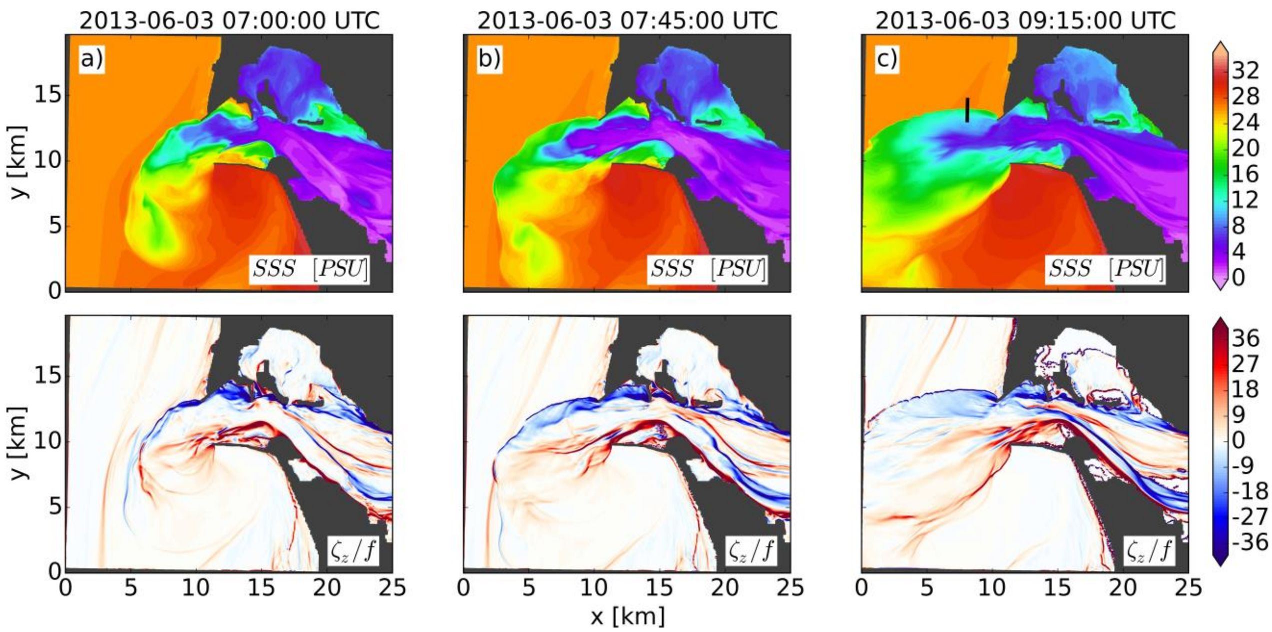

Figure 1: Sea surface salinity (top panels) and normalized surface vertical vorticity (bottom panels) for (a) early, (b) peak, and (c) late ebb conditions at the Mouth of the Columbia River. Notice the very sharp and strong submesoscale fronts as ebb wakes from the mouth edges. (Akan *et al.*, 2016a)

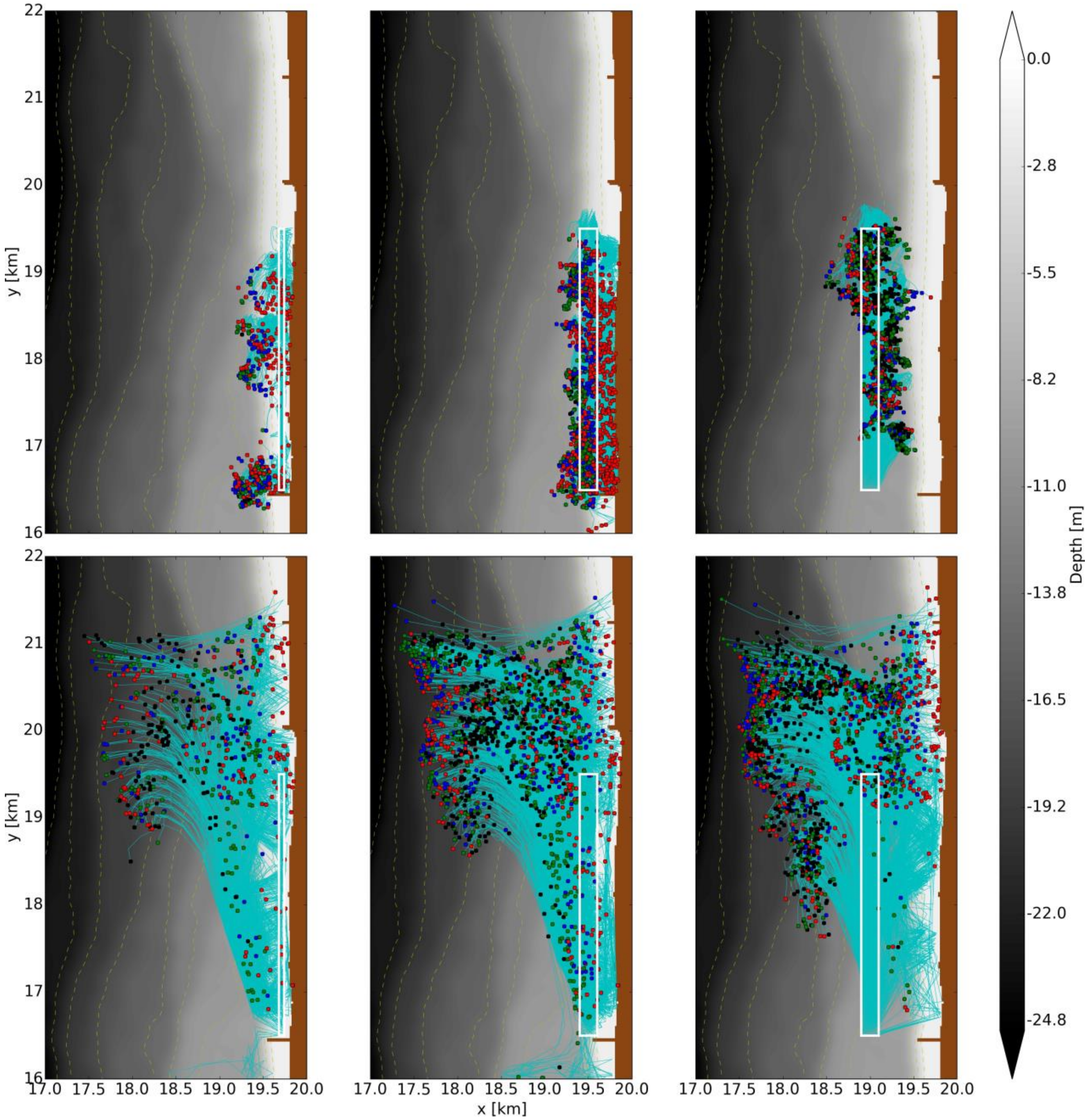

Figure 2: 3-D Lagrangian passive particle trajectories on a day with calm (top panels) and rough (bottom panels) surface wave conditions in Santa Monica Bay, CA, from a 5-level nested grid configuration with $dx = 20$ m at the fi level shown here. White rectangles indicate the area of the release site. Cyan curves and colored circle marks are particle trajectories and their fi destinations for 10 hours after the release. Colors of the circles indicate diff t release depths. Specifically, red circles indicate depths 0-2 m; blue circles indicate 2-4 m; green circles indicate 4-8 m and black circles indicate depths over 8 m. This indicates that, with an active surf zone, there is efficient ejection of materials from the surf zone, with an implied return fl w by particles originally outside it. (Uchiyama *et al.*, 2016)

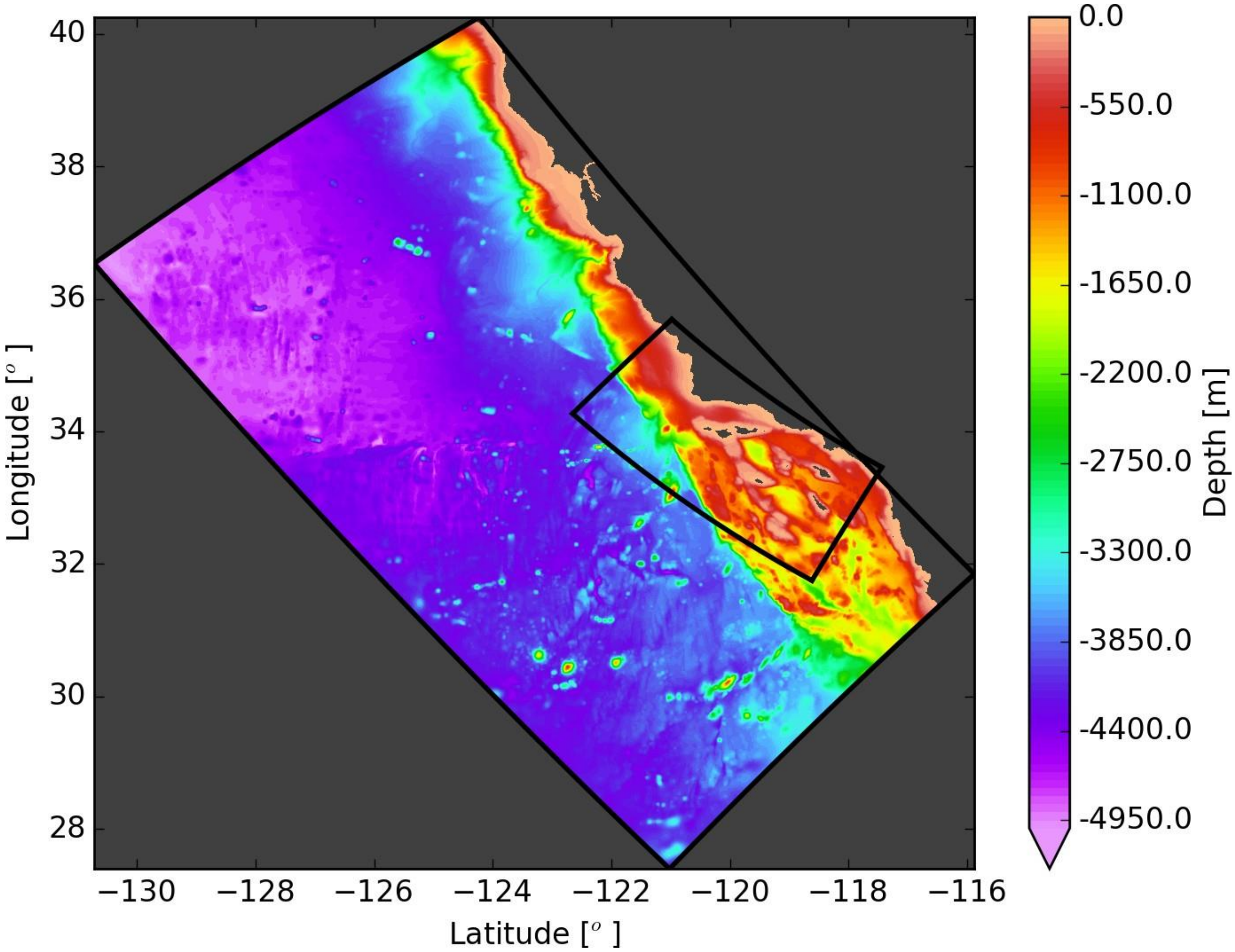

Figure 3: Intermediate level nests with dx = 1000 and 300 m, respectively, for Middle California (MidCal). The bathymetry is colored. These grids will be used for wave-current interaction studies with further nearshore nests at various sites, including the Inner Shelf DRI experiment near Pt. Sal. at latitude 34.9^{o}N.

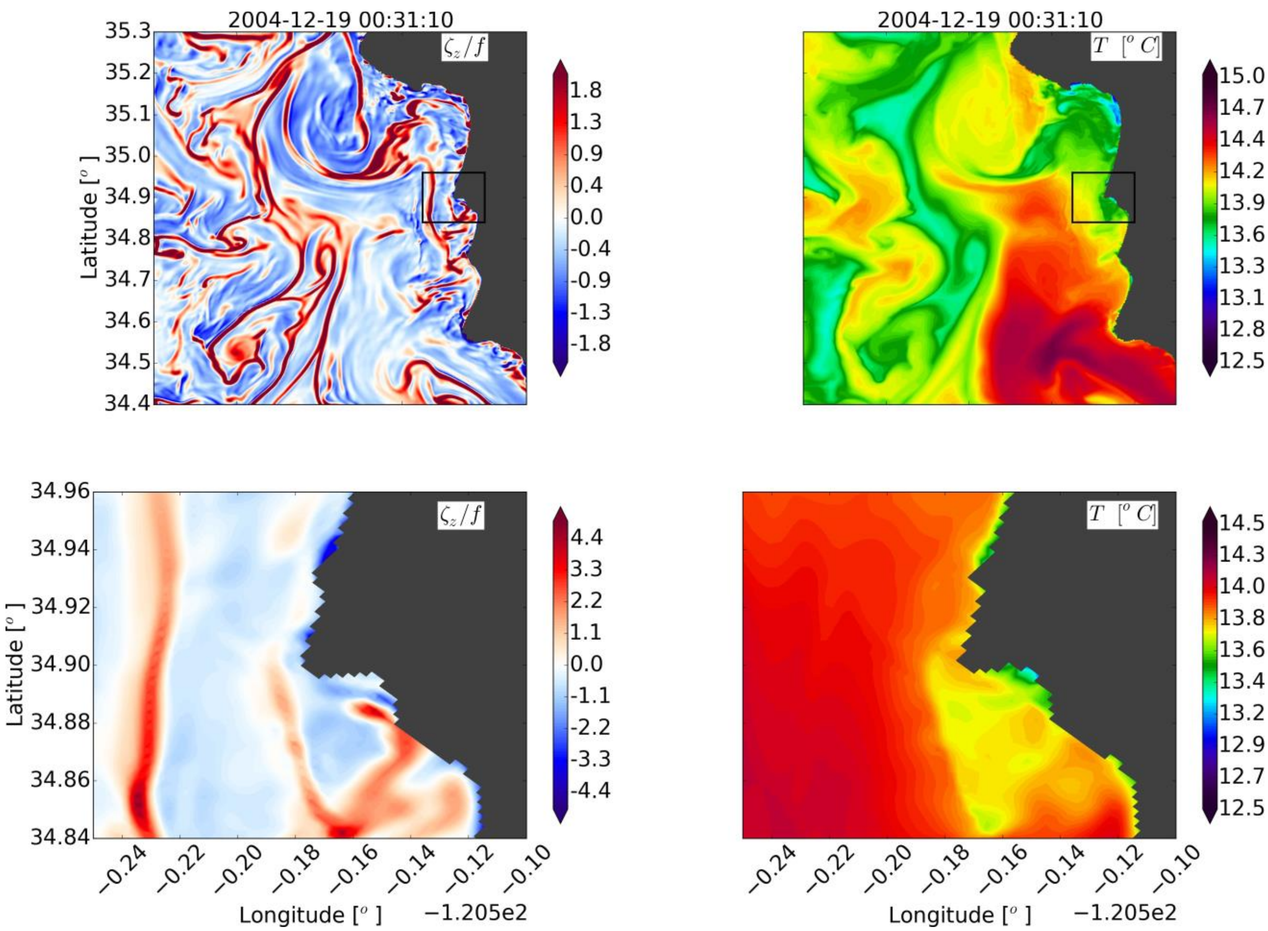

Figure 4: Snapshots of surface vertical voriticity normalized by f and temperature on two scales within the MidCal dx = 300 m nest in Fig. 3, with the bottom row a zoom into the black box that contains the experimental site around Pt. Sal. Around the headlands and bays there is active topographically-induced upwelling and vorticity generation in unstable submesoscale topgraphic wakes, which will become even more active with further nests and with the coupling to surface gravity waves (Fig. 5).

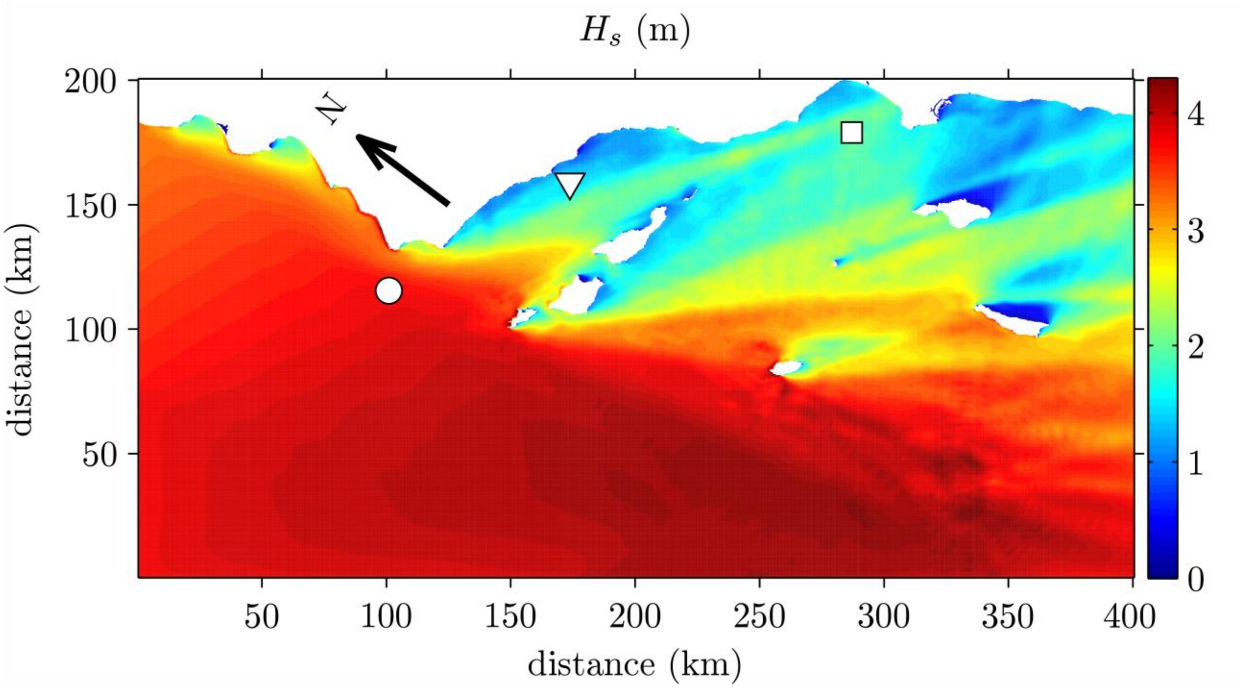

Figure 5: Simulated significant wave height H_s on Dec 6, 2015 at 12:00 pm (UTC) in the MidCal region around the Inner Shelf DRI site. The white circle, triangle and square indicate the location of the Harvest, Goleta, and Santa Monica Bay buoys that can be used for validation. Notice the strong heterogeneity induced by coastline, island, and topographic variations. The wave model is WW3 (Tolman 2009), which will be coupled with ROMS for wave-current interaction studies in the MidCal nested domains. Courtesy of Dr. Leonel Romero, UCSB.

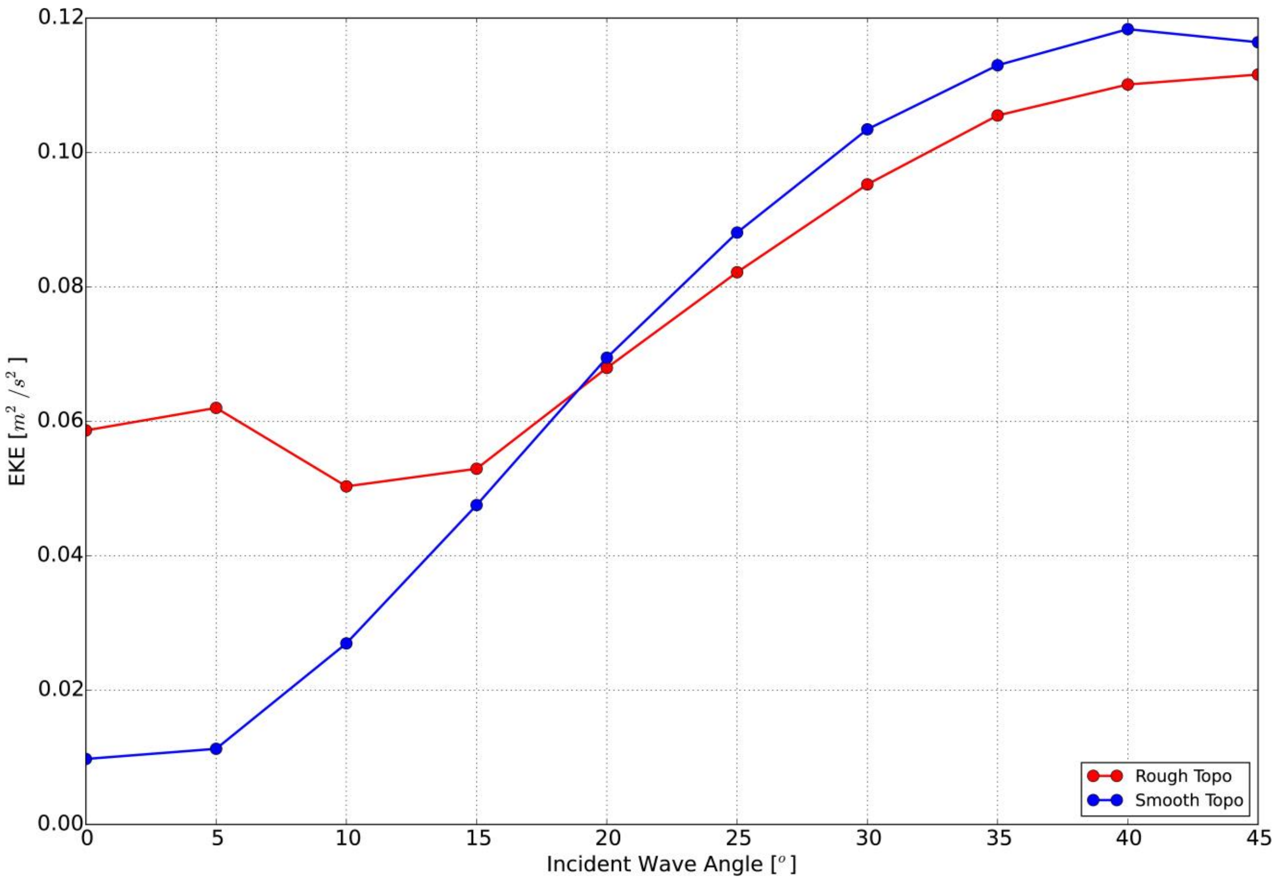

Figure 6: A comparison of curves of eddy kinetic energy vs. incident wave angle for surf-zone currents in an idealized configuration. The blue curve is for smooth shoaling topography, and the red curve is with additional small-scale (rough) topographic variations. For near-normal incident angle (0^o), the roughness adds greatly to the surf eddy turbulent activity. (Akan *et al.*, 2016b)

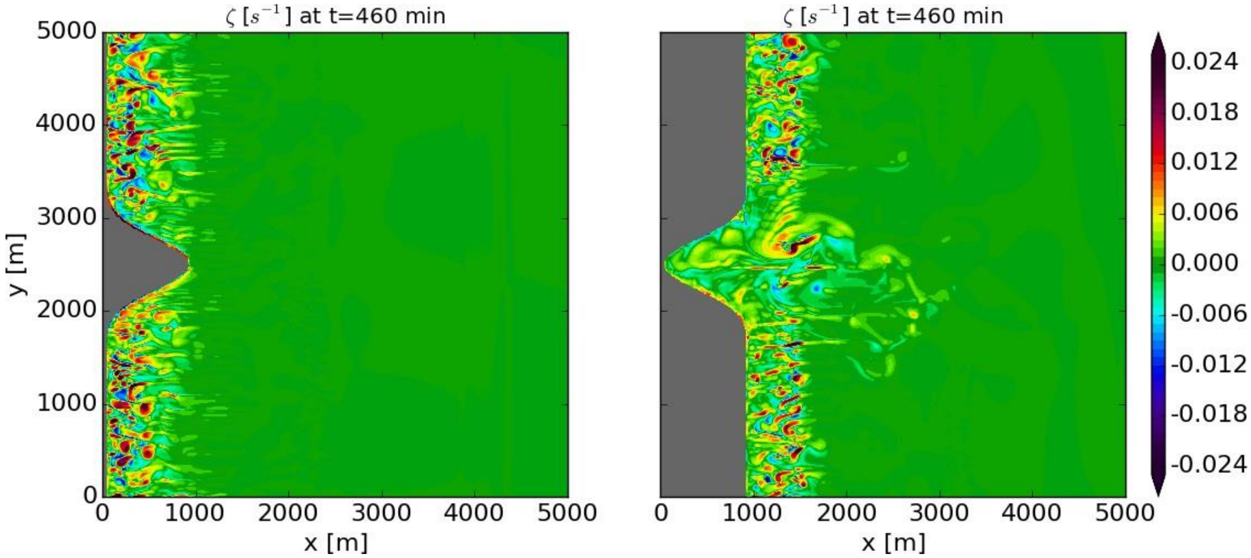

Figure 7: Snapshots of vertical vorticity in the surf zone for surface waves coming from the west and rough shoaling topography. The presence of a headland (left) suppresses the surf eddy turbulence on its fl nks, while a bay generates surf turbulence that extends very far offshore into deep water. (Akan *et al.*, 2016b)

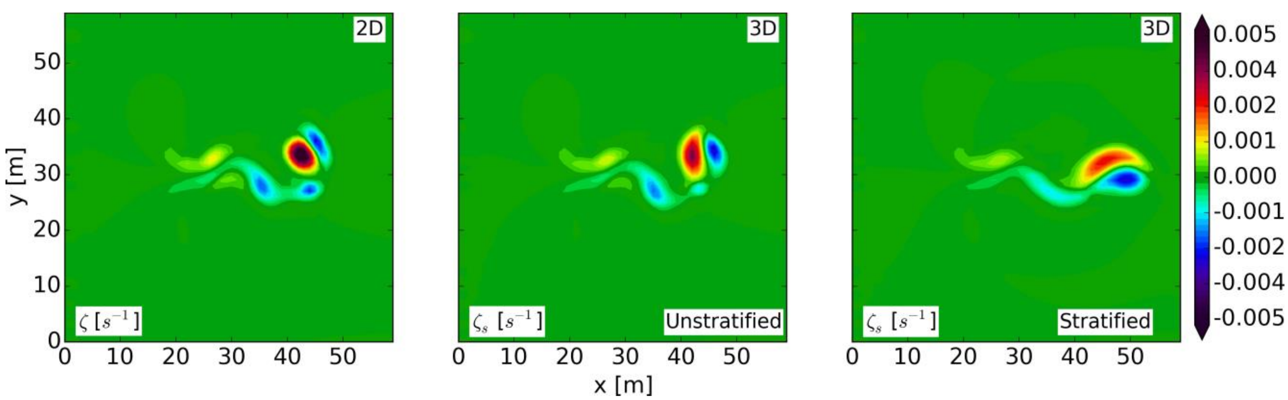

Figure 8: Snapshots of vertical vorticity 2 hours after identical velocity initializations for a vortex dipole in shallower water in an idealized study with a simple sloping topography. The purposes are to demonstrate how depth-averaged (2D) models overestimate the strength and lifetimes of surf eddies, compared to 3D ones, and how vertical density strati-fi provides a further weakening as the surf vortices move into deeper water. (Akan *et al.*, 2016c)