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Modeling Intrinsic Variability and Connectivity in Shelf and Littoral Circulation: Progress and Accomplishments

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Grant Number: N00014-15-1-2645

1 Approach

The 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, including their interactions with internal and surface gravity waves. The technical approach is to make idealized and realistic simulations for different physical and geographical regimes using the Regional Oceanic Modeling System (ROMS) to discover prototypes for the relevant phenomena and to guide the experimental designs and help interpret the measurements.

2 Principal Accomplishments

The scope of the work nearly or fully completed is indicated in the publication list, with the papers most directly relevant to this grant labeled by (*). Below are the primary accomplishments during the past year along with some illustrative figures and citations.

Wave-Driven Littoral Currents: 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 that include topographic irregularities in the alongshore direction. For this purpose, random depth perturbations 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, especially when the incident surface wave direction is near-normal (Fig. 1). We also examine different coastline shapes with headland and bay cases (Fig. 2); 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 influences on the intrinsic variability in littoral currents (Marchesiello *et al.*, 2016; Akan *et al.*, 2017b,c; Uchiyama *et al.*, 2017a).

Spontaneous Submesoscale Shelf Currents: Submesoscale frontal and vortical currents in the surface layer are widespread in the open ocean (McWilliams, 2016). A high-resolution simulation of the shallow shelf region in the Southern California Bight shows that they are also common on the shelf, both by the now-familiar process of frontogenesis and by the phenomenon of vorticity generation by bottom drag stress in a current along a slope, which after separation becomes unstable and generates additional submesoscale currents (Fig.3; Dauhajre and McWilliams, 2017a). Another feature of such currents is a conspicuous diurnal cycle in their strength due to the modulation of the boundary-layer turbulent mixing strength induced by diurnal heating and reversing sea breezes (Dauhajre and McWilliams, 2017b).

Wave Effects on Shelf Currents: The theoretical basis for including the effects of surface gravity waves on oceanic currents is an asymptotic wave-averaged theory based on the separation of evolutionary time scales between surface waves (10 s) and currents (10^3 s). This theory has by now been developed by many authors using alternative approaches, but one prominent, persistent skeptic has been George Mellor, who favors an alternative theory. This year several collaborators and I became sufficiently frustrated with his repeated criticisms and wrote a rebuttal (Ardhuin *et al.*, 2017). A different theoretical study analyzes the secondary circulations and frontogenetic tendencies that waves and boundary-layer turbulence induce near submesoscale fronts and dense filaments (McWilliams, 2017b). Finally, an idealized problem of an oscillating wind-driven unstable coastal upwelling front with incident surface waves provides a strong indication of how significant the Wave Effects on Currents (WEC) can be (Fig. 4-5; Uchiyama *et al.*, 2017b)

River Buoyancy Forcing of Shelf Currents: Three separate studies have been completed this year about how nearshore currents are affected by river runoff and the associated horizontal buoyancy gradient: (**1**) In the tidal ebb cycle of the Columbia River during the peak runoff season strong advective fronts form at the northern edge of the river plume (Akan *et al.*, 2017a). (**2**) Near the mouth of the Mississippi River a broad zone of surface freshwater forms and serves as a potential energy reservoir for submesoscale frontogenesis and even mesoscale jets reaching into the interior of the Gulf of Mexico (Barkan *et al.*, 2017a,b,c; Choi *et al.*, 2017). (**3**) Even small seasonal streams like those near Santa Barbara, CA, can create a shore-trapped freshwater layer after storms, which then is eroded by shore-aligned frontal flows and eddies (Romero *et al.*, 2016).

Topographic Vortical Wakes: It is increasingly clear that oceanic bottom boundaries are an important source for generating submesoscale currents that migrate into the interior. This is especially important in shallow water on continental shelves. The essential mechanism is that alongshore currents over slopes generate vertical vorticity through the bottom drag stress; these narrow vortical currents separate into the interior, and their current profiles are conducive to submesoscale instabilities. One example is the nearshore headland wake in a realistic simulation of the CA shelf (Fig. 3). Other examples have been adduced by a statistical analysis of near-boundary currents in a realistic simulation of the Southwest Pacific (Solomon Sea; Srinivasan *et al.*, 2017a). A fundamental process study is being carried out for a uniform current impinging upon an isolated seamount that can generate either vortical wakes or internal gravity lee waves (Fig. 6; Srinivasan *et al.*, 2017b).

ROMS simulations of Middle California: We have constructed 4-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 simulations are made both with and without surface gravity wave dynamical effects, and they are the basis for wave-current and shelf-surf interaction studies in combination with surface wave solutions from Wave Watch 3, including with full wave-current coupling (Sec. 3). They are being used to support and help interpret the measurements in the ONR Langmuir Turbulence and Inner Shelf DRI field experiments, which will occur within the higher resolution nested subdomains. Besides these sites we will make other nested subdomains in different nearshore wave and current environments, *viz.,* Point Conception, the Northern Channel Islands, and North Malibu. Illustrations from preliminary results are in Figs. 7-8. In addition, we continue the analysis of a previous generation of nested solutions with the finest-scale subdomain in Santa Monica Bay for shelf-surf material exchange and wave effects on shelf submesoscale fronts (Uchiyama *et al.*, 2017c).

3 Plans

The projects underway in Sec. 2 will be carried forward to completion. In addition, we have made recent starts in the following areas:

Eddy-Tide Interaction: A NOPP goal is to exploit and evaluate HYCOM as a source of boundary data for nested regional models like ROMS. A good scientific motivation for this is to evaluate HYCOM's remotely generated internal tide as an augmentation of the locally generated tide and additional internal waves to investigate the hypothesis that energetic inertia-gravity waves stimulate the forward cascade of energy in submesoscale currents, hence increase dissipation and diapycnal mixing (supported by the idealized simulations in Barkan *et al.*, 2016). We will use the U.S. West Coast as the test bed because of its relation to ONR experiments and to the coming NASA SWOT Calibration-Validation experiment. This is a collaboration with Brian Arbic (U. Michigan) and his NRL colleagues.

2-Way WW3-ROMS Coupling: In a collaboration with Leonel Romero (U.C. Santa Barbara) we are developing an on-line, 2-way coupling procedure between Wave Watch 3 and ROMS to be able to investigate the combined Wave Effects on Currents (WEC) and Current Effects on Waves (CEW). This will be used in a sequence of Middle California (*n.b.,* Figs. 7-8) simulations focusing on interactions of submesoscale currents with surface boundary layer turbulence with both modulated by the surface gravity wave field.

New Computational Cluster: Judging the technology releases and prices as at last timely, we have procured the parts for and are constructing the budgeted new computing cluster for mid-sized ROMS calculations within our group. The selection of hardware for the new cluster is optimized to achieve the maximum aggregate computing power for a given total cost. Thus we choose 12 twin nodes based on Supermicro 6018TR-TF 1U servers, Intel Xeon E5-2630v4 10-core 2.20GHz/25MB cache CPUs, resulting in 24 dual-CPU nodes (this $12 \times 2 \times 2 \times 10 = 480$ cores overall) and populating them with 4GB memory DIMMs resulting in 32GB per node (hence 768GB aggregate for all nodes) which is actually the minimum amount of memory needed to populate

all the memory channels (8 per dual-CPU node) as needed for optimal memory performance. The interconnect is via 36-port Mellanox MSX6025F-1SFS SwitchX-2 FDR Infiniband switch.

Non-hydrostatic ROMS: The new non-hydrostatic ROMS code is in a late stage of testing and revision, with the present difficulty being an intermittent computational instability related to the split-explicit time stepping scheme that separates the barotropic and baroclinic vertical modes; its remedy may require changing the time-stepping method. We have already succeeded in implementing an efficient multi-grid Poisson solver for pressure that is much faster than in any other realistic circulation model, incorporating the full physical-process functionality of hydrostatic ROMS, and implementing open boundary conditions successfully. We are optimistic that it will become available in the coming year to apply to problems of inner shelf flows that are potentially significantly non-hydrostatic in their dynamics, *e.g.,* short internal gravity waves.

ONR-Related Publications

UCLA publications relevant to ONR-supported coastal circulation, submesoscale eddies, and air-sea coupling research during the period 10/1/15-6/15/17. The (*) symbol indicates ones of most direct relevance to this grant.

(*) Akan, C., J.C. McWilliams, H. T. Ozkan-Haller, S. Moghimi, 2017a: Frontal dynamics at the edge of the Columbia River plume. Ocean Modelling, submitted.

(*) Akan, C., J. C. McWilliams, Y. Uchiyama, 2017b: Topographic and coastline influences on surf eddies. Ocean Modelling, submitted.

(*) Akan, C., J. C. McWilliams, Y. Uchiyama, 2017c: Influence of three-dimensionality and stratification on nearshore vortices. In Preparation

(*) Ardhuin, F., N. Suzuki, J.C. McWilliams, H. Aiki, 2017: Comments on A Combined Derivation of the Integrated and Vertically Resolved, Coupled Wave-Current Equations. J. Phys. Ocean., submitted.

Barkan, R., K.B. Winters, J.C. McWilliams, 2016: Enhancement of eddy kinetic energy dissipation by internal waves. J. Phys. Ocean., 47, 181-198.

Barkan, R., J.C. McWilliams, A.F. Shchepetkin, M.J. Molemaker, L. Renault, A. Bracco, J. Choi, 2017a: Submesoscale dynamics in the northern Gulf of Mexico. Part I: Regional and seasonal characterization and the role of rivers. J. Phys. Ocean., submitted.

(*) Barkan, R., J.C. McWilliams, M.J. Molemaker, A.F. Shechepetkin, K. Srinivasan, J. Choi, A. Bracco, 2017b: Submesoscale dynamics in the northern Gulf of Mexico. Part II: Temperature-Salinity relations and cross-shelf transport processes. J. Phys. Ocean., submitted.

(*) Barkan, R., J.C. McWilliams, K. Shrinivasan, M.J. Molemaker, 2017c: The dynamical role of horizontal divergence in submesoscale frontogenesis. *Geophys. Res. Lett.*, submitted.

(*) Choi, J., A. Bracco, R. Barkan, A.F. Shchepetkin, .C. McWilliams, 2017: Submesoscale dynamics in the northern Gulf of Mexico. Part III: Lagrangian implications. J. Phys. Ocean., submitted.

(*) Dauhajre, D., J.C. McWilliams, 2017a: Submesoscale fronts in the inner continental shelf. J. Phys. Ocean., submitted.

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Dewar, W.K., J.C. McWilliams, & M.J. Molemaker, 2015: Centrifugal instability and mixing in the California Undercurrent. J. Phys. Ocean., 45, 1224-1241.

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.

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Klymak, J.M., R.K. Shearman, J. Gula, C.M. Lee, E.A. DAsaro, L.N. Thomas, R. Harcourt, A. Shcherbina, M.A. Sundermeyer, M.J. Molemaker, J.C. McWilliams, 2016: Submesoscale streamers exchange water on the North Wall of the Gulf Stream. Geophys. Res. Lett., 43, 1226-1233.

(*) 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.

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(*) 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, R.A. A. Laibi, 2016: Eddy mixing of longshore currents: Video observation and 3D modeling off Grand Popo Beach, Benin. J. Coastal Res. 75, 408-412.

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McWilliams, J.C., 2017a: Submesoscale surface fronts and filaments: Secondary circulation, buoyancy flux, and frontogenesis. J. Fluid Mech., in press.

(*) McWilliams, J.C., 2017b: Surface wave effects on submesoscale fronts and filaments. J. Fluid Mech., in preparation.

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

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(*) Uchiyama, Y., C. Akan, J.C. McWilliams, 2017b: Surface wave influences on transient coastal upwelling fronts, in preparation.

(*) Uchiyama, Y., J.C. McWilliams, C. Akan, H. Kaida, 2017c: Shelf-surf interactions in Santa Monica Bay, CA, in preparation.

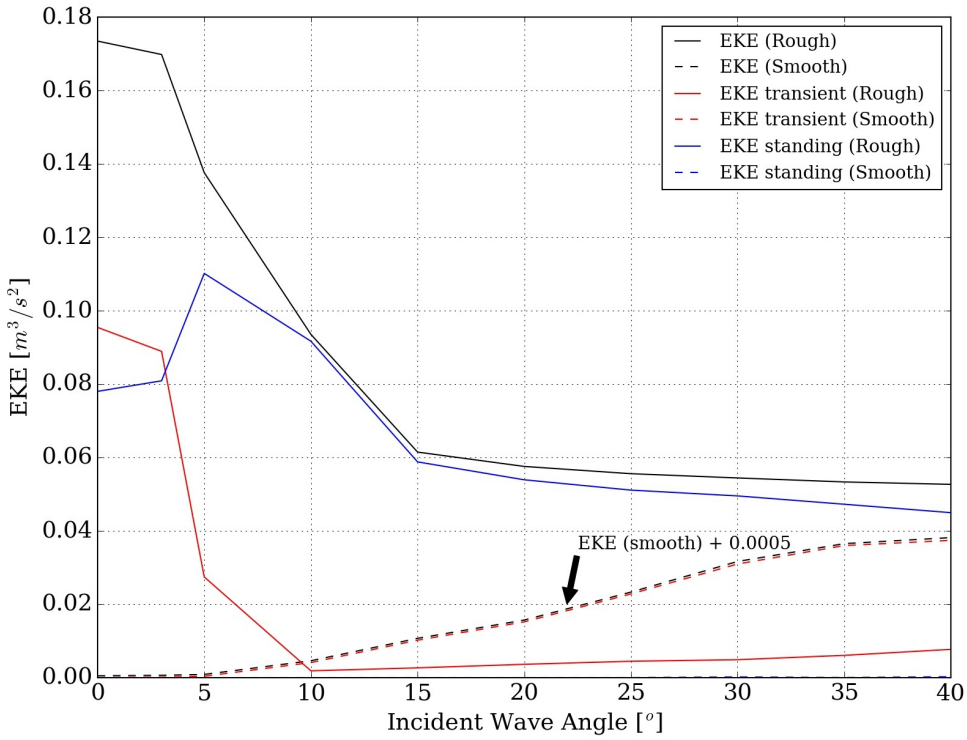

Figure 1: Wave-driven surf currents: total (black), standing (blue), and transient (red) depth-integrated eddy kinetic energy components [$\mathrm{m}^3\ \mathrm{s}^{-1}$] for smooth (dashed lines) and rough (solid lines) barred nearshore topographies as a function of offshore wave incident angles. Because the dashed black and the dashed red lines are indistinguishably close to each other, a small displacement is added to make both lines noticeable. The presence of rough bathymetry enhances the intensity of surf turbulence, especially for normal-incident waves. (Akan *et al.*, 2017b)

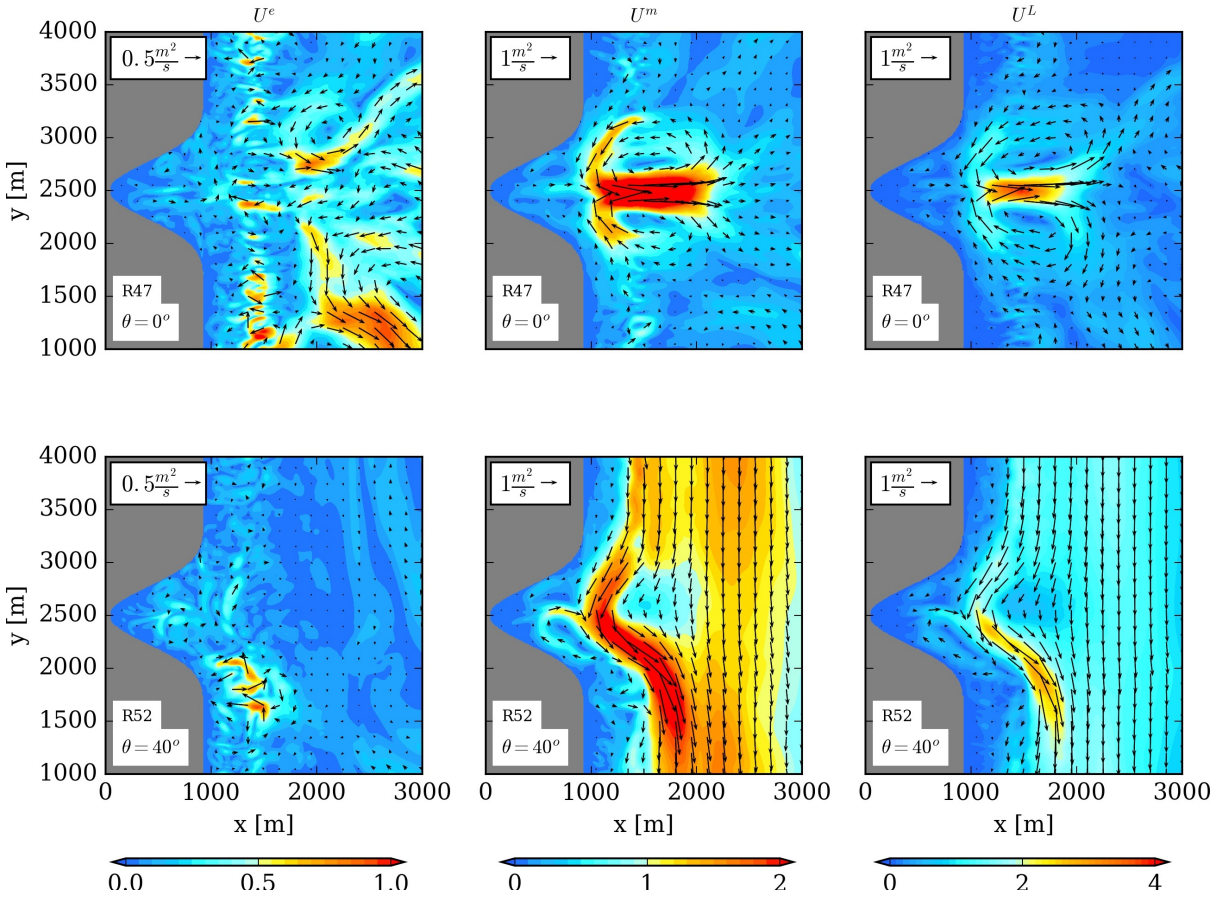

Figure 2: Wave-driven surf currents: depth-integrated and time-averaged horizontal transports for a coastline with a bay and rough topography. The columns are (left) eddy-induced transport, (center) mean-current transport, and (right) total Lagrangian transport that includes Stokes drift. The rows are for (top) normal- and (bottom) oblique-incident waves. The bay creates a larger-scale circulation that extends several km offshore, and the rough topography causes a rectification of eddy currents into an additional mean transport contribution. (Akan *et al.*, 2017b)

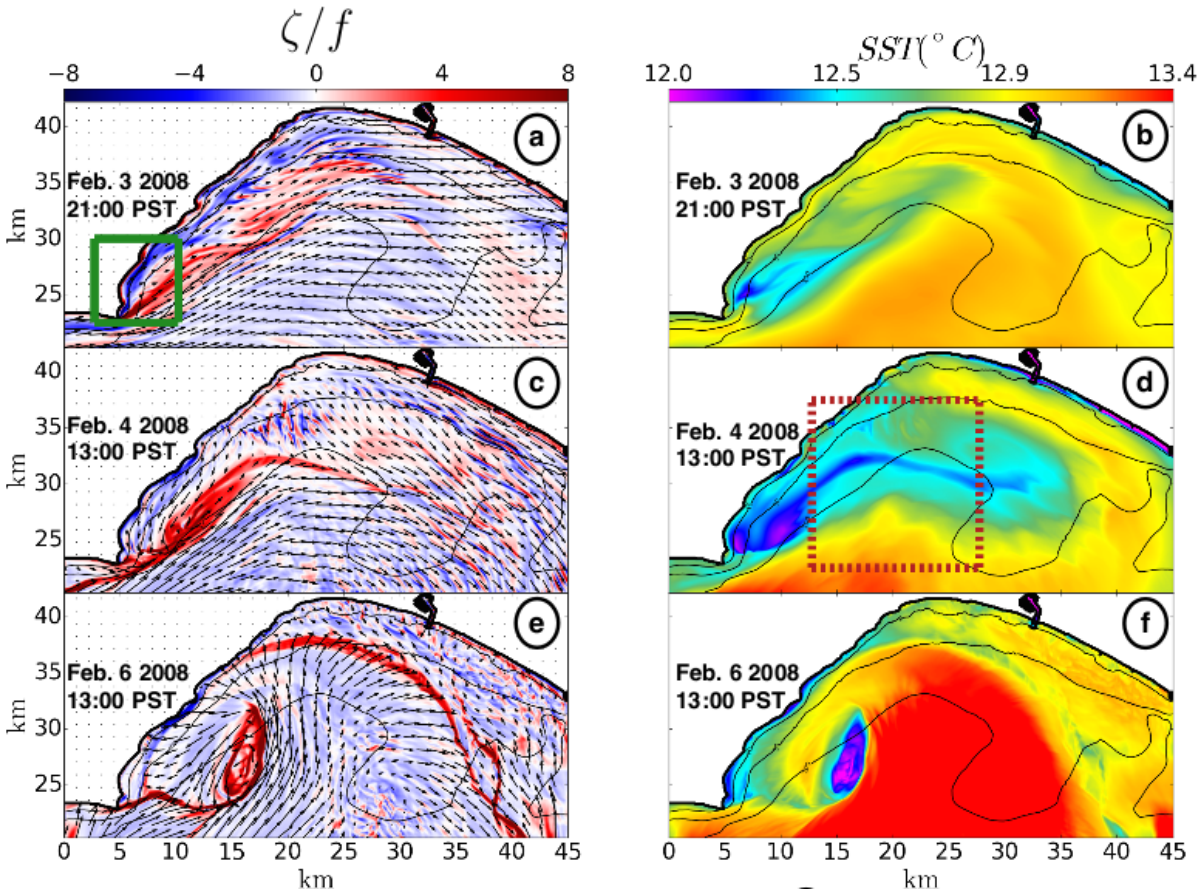

Figure 3: A sequence of snapshots of a simulated submesoscale headland wake due to an eastward current past Pt. Dume in Santa Monica Bay, CA, as seen both in normalized surface vorticity and in SST. Over several days a wake develops behind the headland, undergoes horizontal shear instability, and rolls up into a cold-core submesoscale coherent vortex as well as a bathymetry-aligned vorticity and T front that occupies the inner shelf zone for a sizeable fraction of the Bay. Light black lines are bathymetric contours. Here the grid resolution is dx = 75 m. (Dauhajre and McWilliams, 2017a)

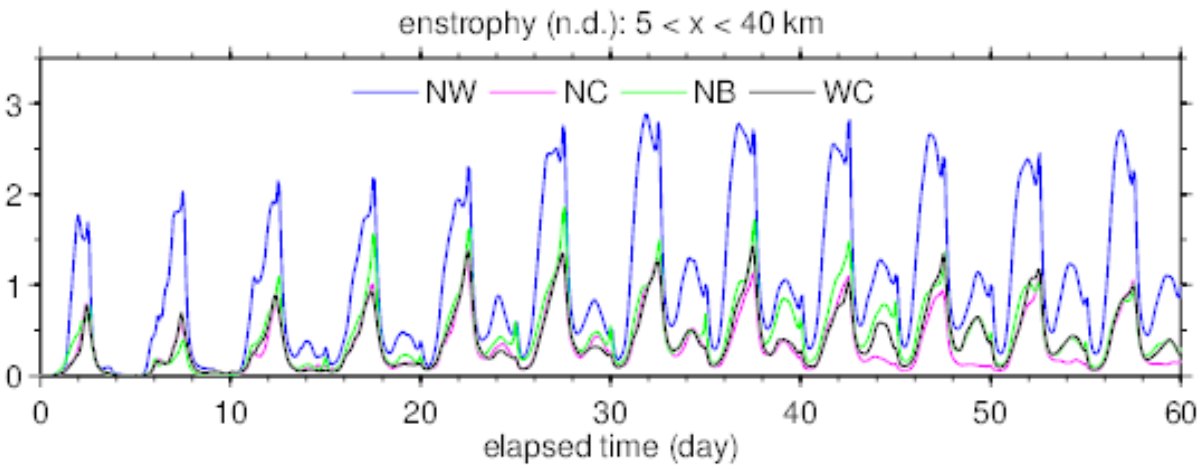

Figure 4: Time series of the variance of the surface vertical vorticity (*i.e.,* the enstrophy) normalized by f for a solution with a time-oscillatory alongshore wind stress and unstable coastal upwelling front in the presence of incident surface gravity waves. The variance is spatially averaged for $5 < x < 40$ km, where x is the cross-shelf distance from the shore. The bathymetry is an idealized Santa Monica Bay with alongshelf variability overlaid, mostly near the shore where $x < 2$ km. While NW indicates a solution without surface waves, all the other three cases are with Wave Effects on Currents (WEC): NC = no current feedback on the waves; NB = no surfzone (breaker acceleration vanishes); and WC = full wave-current coupling. The wave-current interaction acts strongly to weaken and reshape instability-generated shelf eddies. (Uchiyama *et al.*, 2017b)

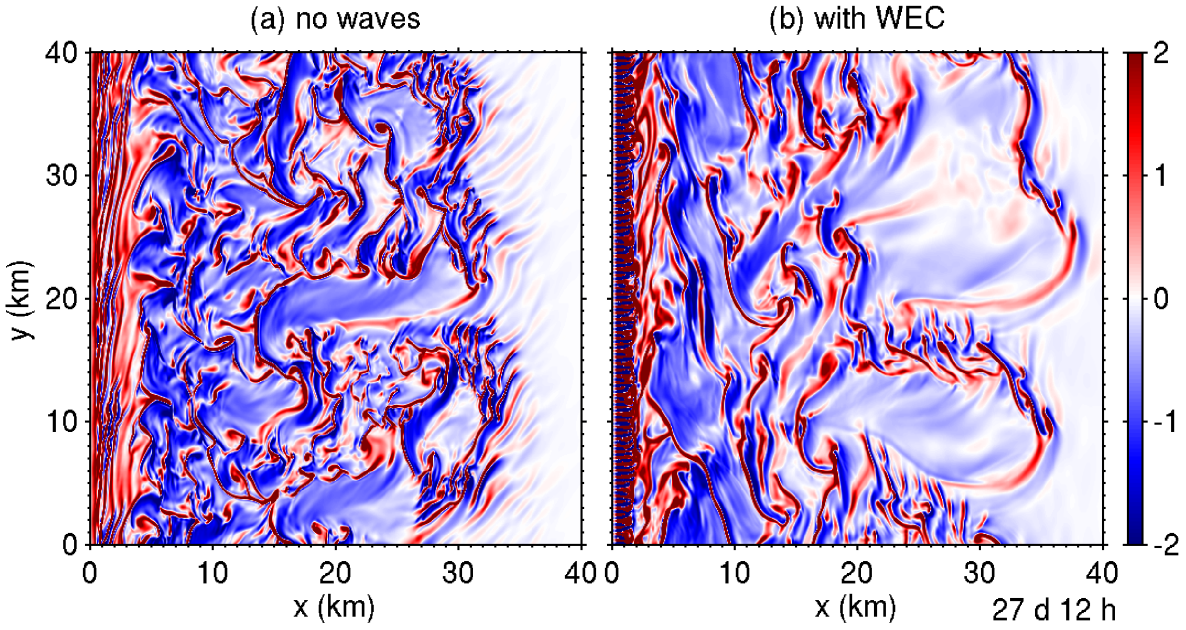

Figure 5: Instantaneous vertical relative vorticity at the surface normalized by a mid-latitude Coriolis frequency for the cases (a) without waves and (b) with Wave Effects on Currents (WEC) and full dynamical coupling with the wave evolution. Eddies and filaments develop with the oscillatory upwelling front induced by a time-dependent oscillating along-shelf wind (as in Fig. 4). Compared to the solution without waves, the waves weaken the eddies and filaments substantially in the offshore region for x $>$ 5 km. Notice that rip currents are generated in (b) near the shore for x $<$ 2 km. The shoreline is at x = 0 with a broad inner-shelf bathymetry extending seaward to the maximum depth of 80 m at x = 40 km. In (b), steady, uniform, narrow-banded spectrum-peak wind waves are incident at the offshore boundary with an amplitude of 1 m, a period of 7 s, and an incident angle of 0° relative to the shore-normal direction. A periodicity is assumed in y, while no-flux and Neumann conditions are applied in x at the shoreline and open boundaries, respectively. (Uchiyama *et al.*, 2017b)

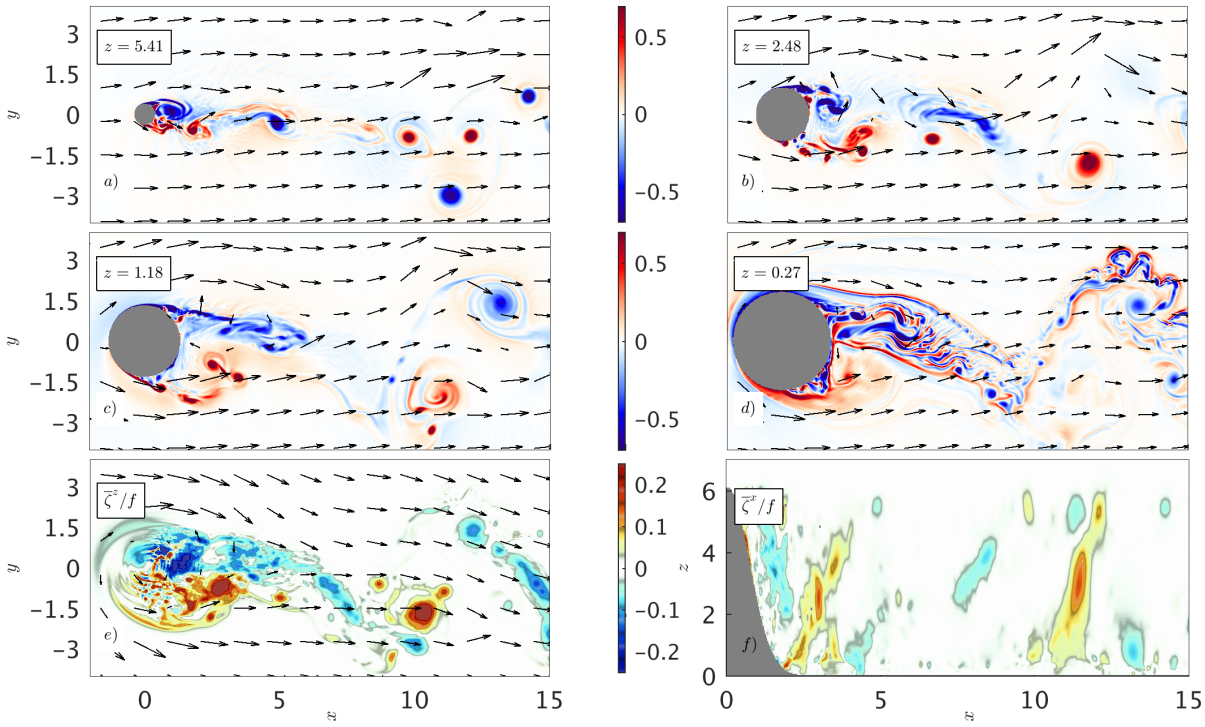

Figure 6: Instantaneous (x, y) maps of normalized vertical vorticity ζ/f in an idealized ocean consisting of barotropic flow past a seamount in a constant background stratification. (a)-(c) Horizontal cross-sections at various depths illustrating the complexity of the vertical structure even though the upstream flow is homogeneous. z is the height above the flat bottom in units of the "Taylor height", $fL/N = 130$ m, where $L = 15$ km is the seamount halfwidth. The total seamount height is 800 m. (d) Same as above but now for vorticity within the bottom boundary layer showing horizontal fronts and frontal instabilities created by the boundary-layer mixing. (e) Barotropic vorticity and (f) cross-stream averaged vorticity. The horizontal resolution is $\Delta x = 350$ m while the vertical resolution varies between $\Delta z = 2$ m and $\Delta z = 20$ m. (Sriniasan *et al.*, 2017b)

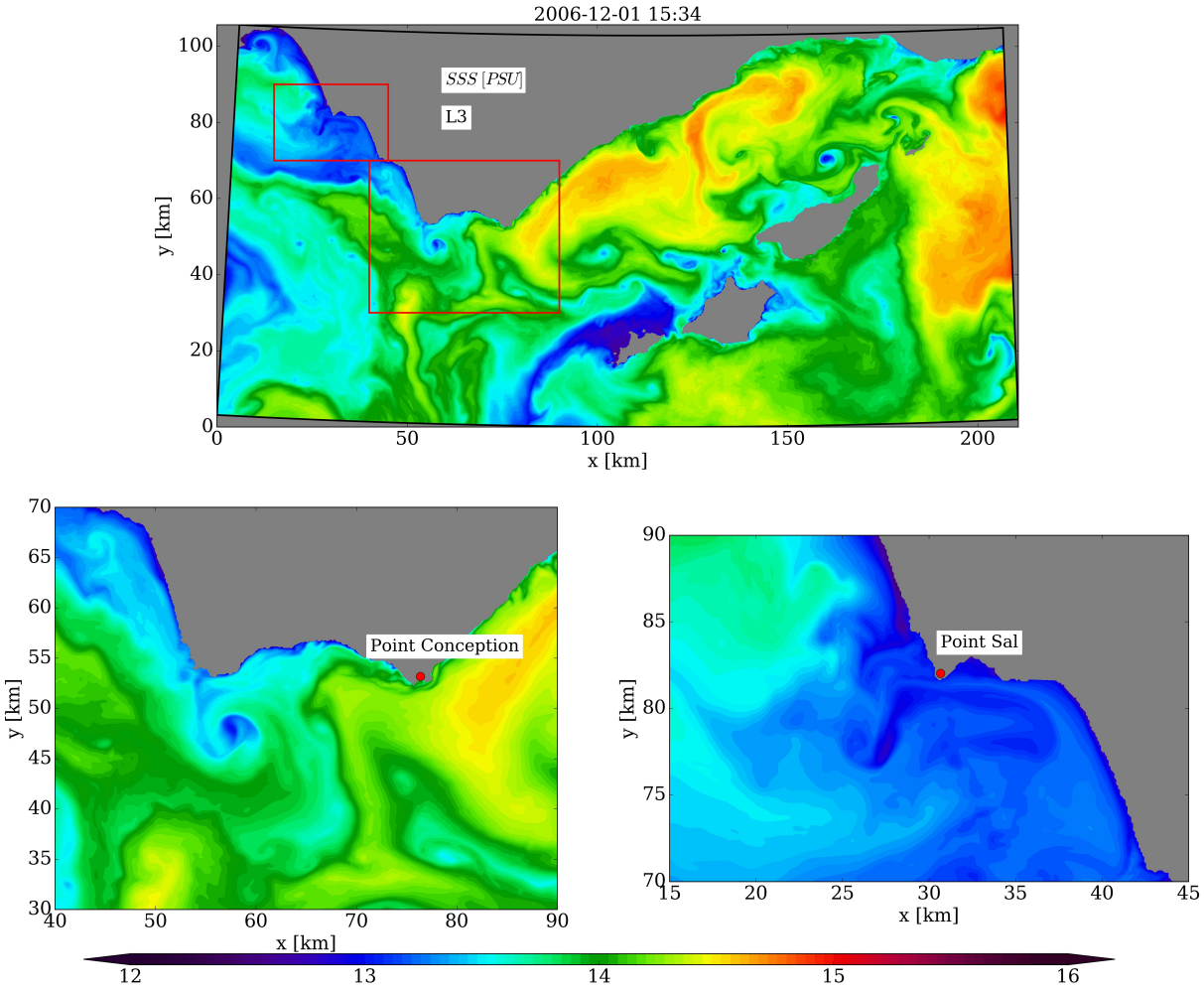

Figure 7: Sea Surface Salinity (SSS [PSU]) maps on December 1, 2006 in a realistic nested-grid simulation of the Middle California coastal zone with a grid-resolution scale of dx = 100 m. The upper panel is the full sub-domain, and the lower panels are zooms into the nearshore regions around Pt. Conception (left) and Pt. Sal (right; the site of the ONR Inner Shelf field experiment). Both sites have nearshore-trapped fresh water and submesoscale shelf-eddy activity associated with the coastline variations.

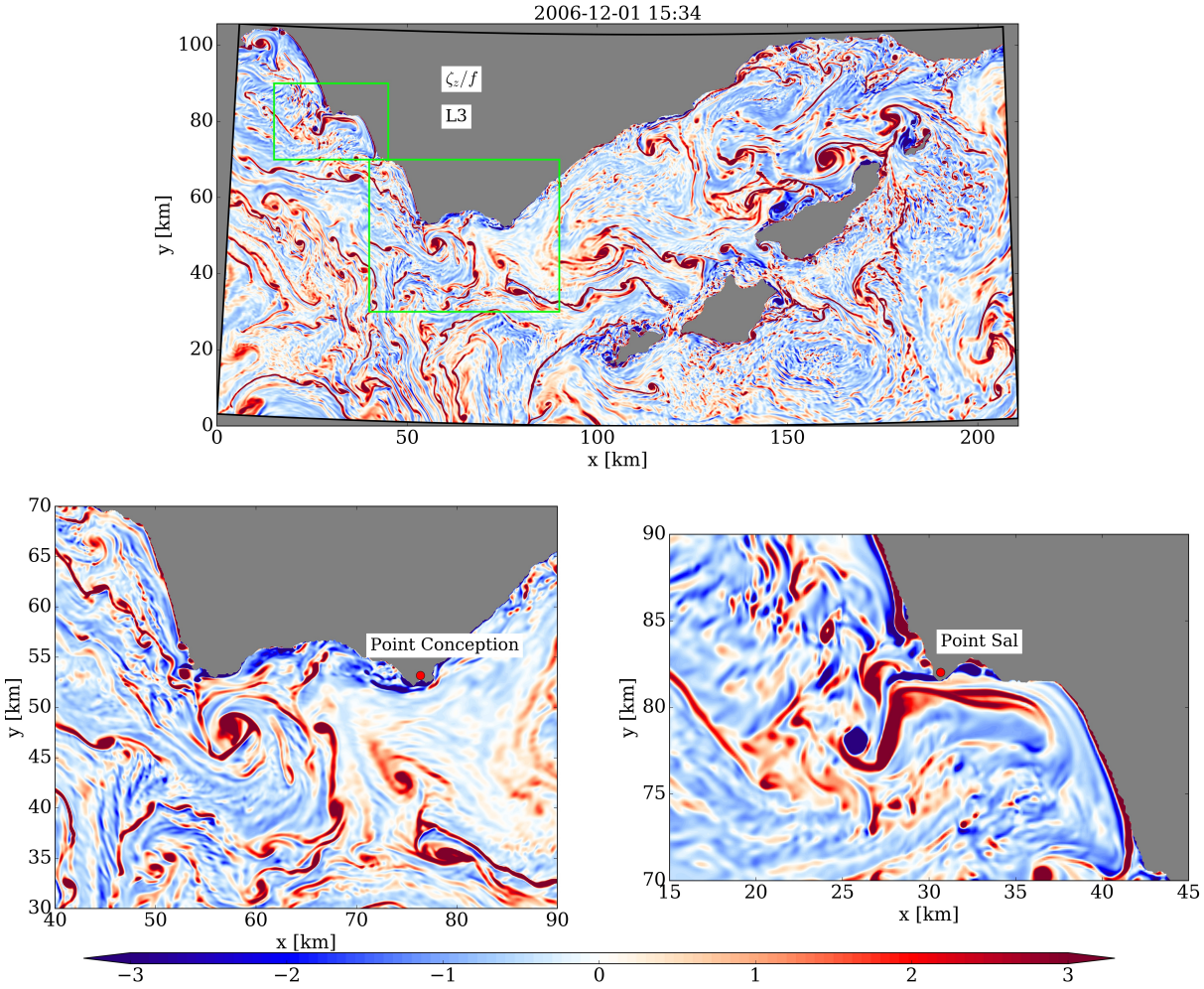

Figure 8: The same as Fig. 7 except for the normalized vertical vorticity, ζ^z/f. This variable emphasizes the submesoscale fronts, wakes, and vortices that arise spontaneously on the shelf.