

The Effects of Surface Gravity Waves on Coastal Currents: Implementation, Phenomenological Exploration, and Realistic Simulation with ROMS

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LONG-TERM GOALS

The long-term goal of this line of research is the creation of a realistic oceanic circulation code that the oceanographic community can use to study and simulate a variety of geophysical problems typical of the coastal, shelf, and littoral environments: wave and current forecasts and simulation; evolution and transport of erodible sea floor beds; transport of pollutants; dispersal or retention of plankton populations; cycles of heat, freshwater, and other biogeochemical constituents; intrusions of fresh water river plumes into the ocean; and the dynamics of man-made structures. Specific to this project are the goals of implementing a recent theoretical formulation of the effects of wind-driven surface gravity waves on coastal currents and infragravity waves (McWilliams, *et al.*, 2004) within the Regional Oceanic Modeling System (ROMS) code and then investigating the consequences of these effects in several different coastal circulation regimes.

OBJECTIVES

Our recent research objectives have focused on further developing the asymptotic theory of wave-averaged effects on currents, designing their computational implementation within ROMS, and configuring ROMS for the principal situations where the wave effects will be investigated. All of these steps are necessary preparation for simulating wave-current interaction phenomena with ROMS.

APPROACH

We are investigating how wind-generated surface gravity waves propagate and break, and also act to influence the more slowly evolving oceanic currents and the larger-scale infragravity waves. The basis for specifying these effects in an oceanic circulation model has two parts:

1. A new multi-scale, fluctuation-averaged, asymptotic theory has been derived for the conservative (*i.e.*, non-breaking) evolution and interaction of currents and surface gravity waves typical of stratified coastal shelf waters (McWilliams *et al.*, 2004). In this theory the essential character of the dynamical interaction is that the currents modulate the slowly evolving amplitude of the wave field, and the waves provide wave-averaged forcing of long surface (*i.e.*, infra-gravity) waves and currents through the action of a three-dimensional vortex force and a Bernoulli head in the momentum equations. The waves

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also contribute additional wave-averaged Lagrangian advection for all material concentrations; this includes oceanic mass with consequent effects on the wave-averaged sea level. This theory is both more general and more explicitly prescriptive than the extant theories for vortex force (Craik & Leibovich, 1976; McWilliams & Restrepo, 1999) and radiation stress (Longuet-Higgins & Stewart, 1964; Longuet-Higgins, 1970; Hasselmann, 1971).

2. For the non-conservative wave-breaking effects, a population of stochastic impulses is added to the current and infragravity momentum equations with distribution functions taken from measurements. In offshore wind-wave equilibria, these impulses replace the conventional surface wind stress, and they cause significant differences in the surface boundary layer currents and entrainment rate, particularly when acting in combination with the conservative vortex forces (Sullivan *et al.*, 2004). In the surf zone, where breaking associated with shoaling removes nearly all of the primary wave momentum and energy, the stochastic forcing plays an analogous role as the widely used nearshore radiation stress parameterizations.

The equations in this theory will be implemented in ROMS to calculate numerical solutions under both instructively idealized and typically realistic conditions. This will provide a practical three-dimensional model with which shelf dynamics may be explored and computationally simulated without the necessity of resolving features of the flow on the short space and time scales typical of the primary gravity-wave oscillations. ROMS is an innovative oceanic simulation model whose capabilities are evolving with contributions from many different scientists. Its present functions encompass circulation, planktonic ecosystem population dynamics, biogeochemical cycling, Lagrangian diagnostic trajectories, sediment transport, tides, embedded gridding, data assimilation, and subgrid-scale turbulent mixing parameterizations. To include the wave-averaged effects in ROMS requires empirical wave statistics, such as two-dimensional wavenumber spectra and associated phase-average amplitude, frequency, and prevailing direction as a model-input field; an implementation of the new terms in the governing equations listed above; and a parameterization of surface wave dissipation through breaking near the shoreline.

Once ROMS is capable of representing these wave-averaged effects, a sequence of test problems will be designed, solved, and analyzed to expose the wave influences in competition with other, more familiar coastal dynamics. The methodology is to compare solutions in a given situation with and without the extra wave-averaged terms included. The test problems will be selected for their relevance to wind-driven currents, mesoscale eddies, and fronts along the U.S. West Coast, using our existing high-resolution configurations for the Oregon Coast, Monterey Bay, Santa Monica Bay, San Pedro Bay, Channel Islands, and San Diego coast. Test problems with much finer resolution configurations will also be selected for their relevance to conventional barotropic nearshore currents (longshore currents and rip currents) driven by surface gravity waves on barred beaches in a coastal regime. We will attempt to identify appropriate measurement strategies for field testing the predictions of the theory. On a longer time scale we hope to design an improved regional surface wave simulation model that more fully incorporates the two-way interactions between the waves and currents.

WORK COMPLETED

The principal activities during the past year are the following:

1. A paper on development of a forced-dissipative infragravity long-wave model based on the depth-averaged ROMS and its application to generation and propagation of deep-ocean infragravity

waves in the idealized U.S. West Coast and the north Pacific Ocean, in conjunction with the generation mechanism of Earth's seismic free oscillation on the ocean floor, referred to as "hum" (Rhie & Romanovicz, 2004; Tanimoto, 2005; Webb, 2007), has been submitted for publication (Uchiyama and McWilliams, 2007).

2. The multi-scale asymptotic theory by McWilliams *et al.*, (2004) is extended appropriate for strong current regimes (*i.e.*, Stokes drift is smaller than depth-averaged current) applicable to wave-driven nearshore currents around surf zones. A set of WKB wave ray equations, and current and tracer equations has been derived for the barotropic ROMS with appending non-conservative parameterization to account for wave energy loss due to depth-induced wave breaking. The resultant barotropic current equation is consistent with that derived by Smith (2006). The wave-averaged effects on currents and the WKB equations are implemented into the barotropic ROMS.

3. An investigation of littoral currents driven by incident gravity waves in depth-averaged configurations on an instructive idealized and a more realistic barred beach topographies relevant to a natural sandy beach in Duck, NC, using the extended asymptotic theory in **2**, is being carried out with Dr. Juan Restrepo. A parameterization for depth-induced wave breaking in a surfzone is also implemented based on the empirical model proposed by Thornton and Guza (1983). A non-conservative source term in the asymptotic equations is determined by either the WKB equation or an external wave driver (*i.e.*, SWAN; Booij *et al.*, 1999).

4. Extending the barotropic model to a full three-dimensional, wave-current interaction model is underway for a high-resolution study for the inner-shelf field experiment in Huntington Beach, CA. A three-dimensional ROMS configuration is being updated for the Southern California Bight with 1 km horizontal resolution (parent grid) and with embedded 200 m resolution encompassing Santa Monica and San Pedro Bays around Palos Verdes (child grid). So far the wave-averaged effects are implemented merely in the bed boundary-layer and sediment dynamics (Blaas *et al.*, , 2006). A compatible implementation of the third-generation spectral wave model, SWAN (Booij *et al.*, 1999) on the same nested grids has also been done to evaluate the wind-sea/swell applicable to the ROMS configuration.

5. A theoretical paper that explains the relationship between different wave-averaged current theories, in particular between a widely-used radiation stress formalism and the preceding asymptotic derivation by McWilliams *et al.*, (2004) on the basis of a vortex force formalism, has been published (Lane *et al.*, 2007).

6. The representation of surface gravity wave effects on the oceanic surface boundary layer in Large Eddy Simulations — done jointly with Peter Sullivan, who is funded on another ONR grant through NCAR — has proceeded to the stage where the combined influences of a stochastic model of wave breaking and of the conservative, wave-averaged vortex force due to Stokes drift has been completed with fits to empirical statistical relationships between wind and wave amplitude and breaker spectra. There is a significant interplay between these two wave effects in selecting a larger scale for the Langmuir circulations and enhancing the vertical velocity and pycnocline entrainment rate through downwelling jets in the branches of the Langmuir circulations (Sullivan *et al.*, , 2004, 2007).

RESULTS

A wave-current interaction theory for barotropic strong current regimes. Surf-zone-resolving, fine-scale nearshore simulations on barred beaches with the depth-averaged barotropic ROMS have

been carried out for examining effects of surface primary waves on slowly-evolving barotropic currents based on the wave-current interaction theory extended from the fluctuation-averaged asymptotic theory by McWilliams *et al.*, (2004). The wave-averaged forcing terms are evaluated through the WKB wave driver directly implemented into the ROMS code; this enables us to conduct fully-coupled wave-current interaction experiments. The barotropic model is derived as a vertical integral of the continuity and momentum equations and a vertical average of the tracer-conservation equation:

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot \mathbf{U} = -\frac{\partial \hat{\zeta}}{\partial t} - \nabla \cdot \mathbf{T}^{St}, \quad (1)$$

$$\frac{\partial \mathbf{U}}{\partial t} + \tilde{\nabla} \cdot (\tilde{\mathbf{U}}\bar{\mathbf{u}}) + f\tilde{\mathbf{z}} \times \mathbf{U} + gD\nabla\zeta - \frac{\tau_s}{\rho} + \frac{\tau_b}{\rho} = -\bar{\mathbf{u}}(\nabla \cdot \mathbf{T}^{St})$$

$$- (\tilde{\mathbf{z}} \times \mathbf{T}^{St}) (\tilde{\mathbf{z}} \cdot \nabla \times \bar{\mathbf{u}} + f) + \frac{S\mathbf{k}}{\rho\sigma}, \quad (2)$$

$$\frac{\partial c}{\partial t} + \bar{\mathbf{u}} \cdot \nabla c - \mathcal{C} = -\frac{1}{D} \mathbf{T}^{St} \cdot \nabla c \quad (3)$$

where \mathbf{k} and σ are wavenumber vector and angular frequency of primary waves; \mathbf{T}^{St} and $\hat{\zeta}$ are Stokes transport and quasi-static sea-level referred to as set-up; S is a non-conservative dissipation rate during wave breaking; τ_b and τ_s are the non-conservative bottom and surface stress terms; and \mathcal{C} is the tracer non-conservative term, and

$$\bar{\mathbf{u}} = \frac{\mathbf{U}}{D} = \frac{1}{D} \int_{-h}^{\zeta} \mathbf{u} dz'; \quad D = h + \zeta + \hat{\zeta}. \quad (4)$$

The primary-wave-averaged effects, which we call WEC (wave effects on currents), are on the right-hand-side of these equations. The dot product in the second left-side term in (2) connects the vectors with tilde symbols above them. The non-conservative term due to wave breaking, S , in (2) is given by an external wave model (*e.g.*, SWAN) or by the WKB wave model which is based on conservation equations of wave action, $\mathcal{A} = E/\sigma$, and wavenumber, \mathbf{k} :

$$\frac{\partial \mathcal{A}}{\partial t} + \nabla \cdot \mathcal{A} \mathbf{c}_g = -\frac{S}{\sigma}, \quad (5)$$

$$\frac{\partial \mathbf{k}}{\partial t} + \mathbf{c}_g \cdot \nabla \mathbf{k} = -\tilde{\mathbf{k}} \cdot \frac{\partial \tilde{\mathbf{u}}}{\partial \mathbf{x}} - \frac{k\sigma}{\sinh 2kD} \nabla h, \quad (6)$$

along with the linear dispersion relation, $\sigma^2 = gk \tanh kD$. Current effects on wave (CEW) appear in the group velocity of the primary carrier waves modulated by the Doppler shift due to currents on waves as:

$$\mathbf{c}_g = \bar{\mathbf{u}} + \frac{\sigma}{2k^2} \left(1 + \frac{2kD}{\sinh 2kD} \right) \mathbf{k}, \quad (7)$$

A parameterization proposed by Thornton and Guza (1983) represented below is introduced for the S term:

$$S = \frac{3}{16} \sqrt{\pi} \rho g \frac{B^3}{\gamma^4 D^5} \frac{\sigma}{2\pi} H_{rms}^7 \quad (8)$$

where B and γ are empirical parameters related to wave breaking, and H_{rms} is R.M.S. wave height.

A comparative simulation with DUCK 94. The barotropic ROMS with WEC and the WKB wave model with CEW are developed and tested by comparing with the field experiment at the Field

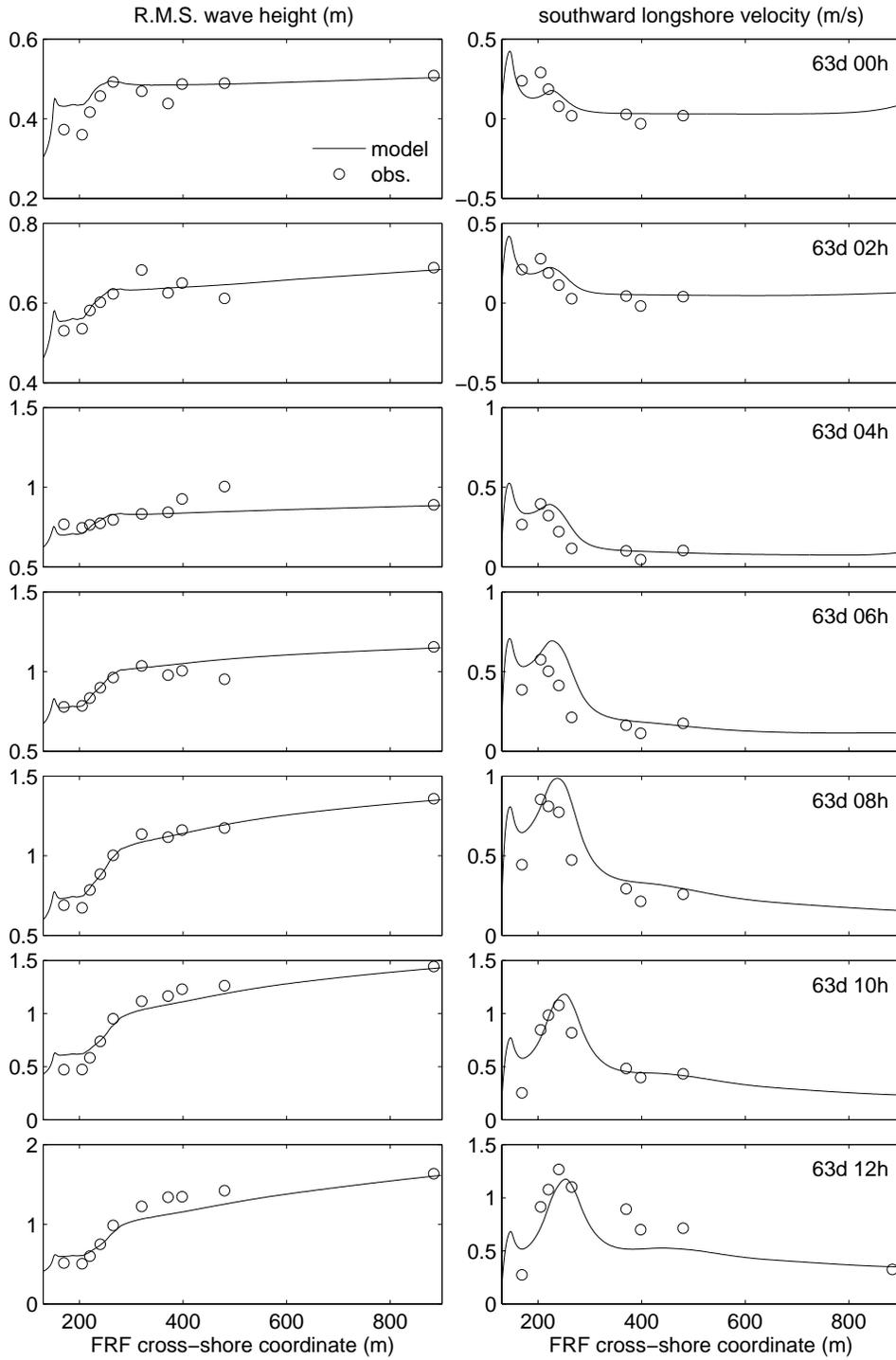
Research Facility (FRF) of U.S. Army Corps of Engineers at Duck, NC, during August to November, 1994 (DUCK 94 experiment: <http://www.frf.usace.army.mil>). The observed forcing field, involving offshore incident waves, low-frequency surface elevation such as tides and surface wind stresses, and the surveyed nearshore topography are adapted into the model. With an appropriate choice of breaking parameters $\gamma = 0.42$ and $B = 0.762$ and a bottom friction formulation (*i.e.*, linear drag with a drag coefficient of $c_D = 2.0$ m/s), simulated cross-shore distribution of longshore current velocity and wave height show a good agreement with the observation (*e.g.*, Elgar *et al.*, 1997; Gallagher *et al.*, 1998; Feddersen *et al.*, 1998) as shown in Fig. 1.

Nearshore instability problem. Nearshore longshore currents are known to be substantially unstable as first reported by Oltman-Shay *et al* (1989) because of shear instability in horizontal nearshore current driven by obliquely incident waves to beaches. The barotropic WEC-ROMS is used to carried out an experiment for reproducing shear waves on an idealized single-barred beach topography, to examine WEC and CEW within the present framework based on vortex force rather than radiation stress in a nearshore current field dominated by meandering longshore currents and by the generation of rip cells. The imposed forcing is only of obliquely incoming monochromatic waves at 20 degrees to the straight coastline. The idealized topography is introduced from that proposed by Yu and Slinn (2003). A small background kinematic viscosity is $0.1 \text{ m}^2/\text{s}$, and a linear bottom drag with the coefficient of $c_D = 1 \times 10^{-3} \text{ m/s}$ is imposed. A total of three cases are considered: case 1 (with WEC and without CEW), case 2 (with WEC and CEW), and case 3 (without WEC and CEW). For case 3, cross-shore one-dimensional distribution of the mean longshore velocity, V , is implemented in the barotropic ROMS as a part of bottom stress term, $c_D/h(\bar{v} - V)$, where \bar{v} is depth-averaged alongshore velocity. So for case 3 wave forcing terms are all eliminated from the model. Figure 2 shows temporal evolution of vorticity for the three cases. Horizontal scale of eddies associated with shear instability and resultant cross-shore momentum exchange is strongest in case 3 (without both of WEC/CEW), then case 1 (with only WEC) followed by case 2 (with both of WEC/CEW). Inclusion of CEW significantly alters wavenumber as shown in Fig. 3.

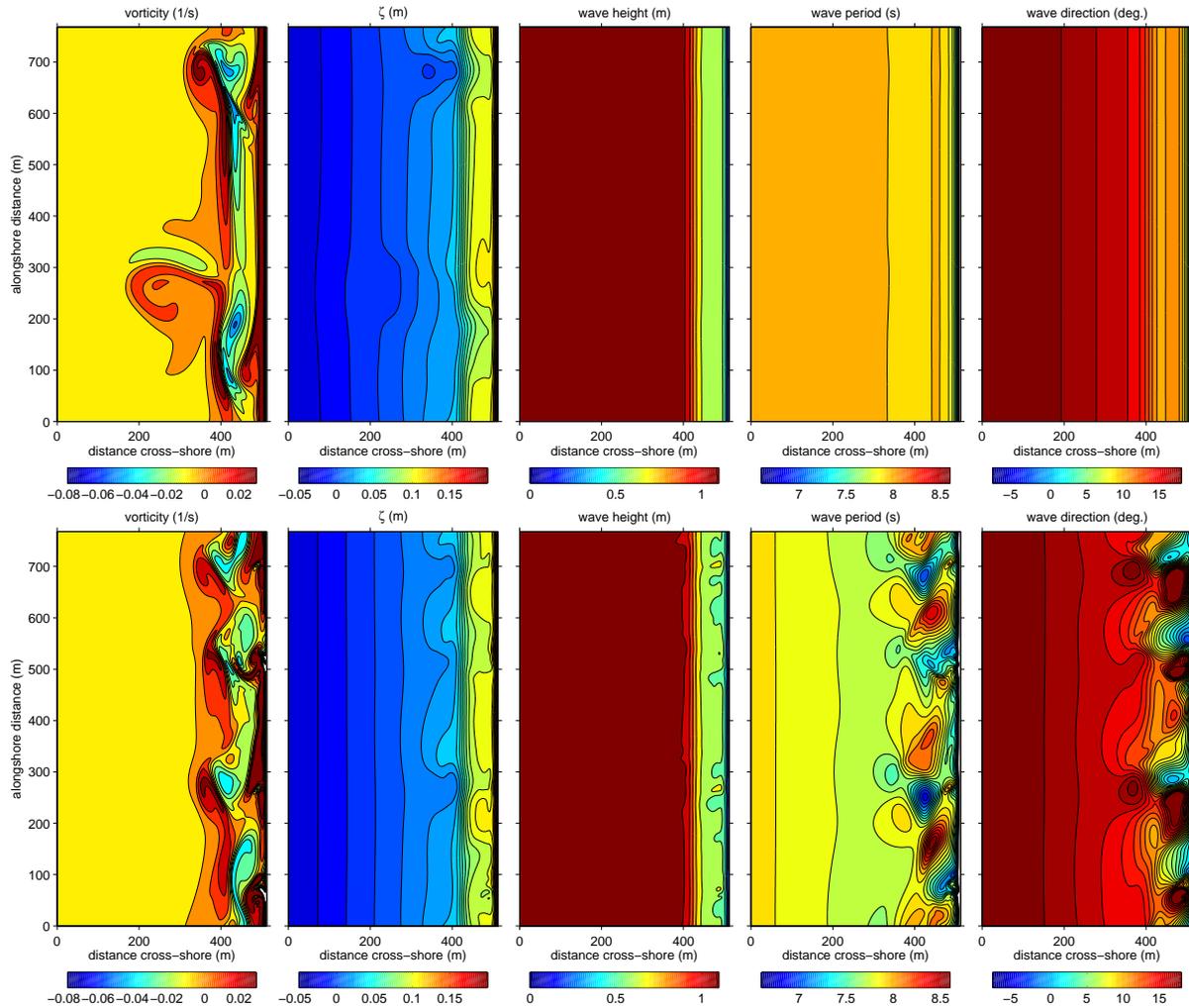
High-resolution coastal experiment in Palos Verdes, CA. A three-dimensional ROMS simulation with wave-averaged effects has also been performed on the parent SCB 1-km and child PV 200-m grids. A new configuration is being tested particularly for realistically continuous solutions with much less boundary noises and rim currents in the nesting configuration by modifying radiation open boundary schemes (Figure 4) through collaboration with Dr. Alexander Shchepetkin. The model is forced by wind sea and swells reproduced by a compatible simulation with SWAN (Booij *et al.*, 1999) on the same nested grids as well as the analytical tide, MM5-produced high-resolution wind and COADS monthly-mean surface fluxes. The wave-current interaction has been considered only in the bed boundary layer (BBL) thus far (Blaas *et al.*, 2006), and the fully three-dimensional WEC implementation will be made as the next step. Increasing the resolution appears to enhance sub-mesoscale activities and intensity of the upwelling event observed off Santa Monica in March 2002 (Fig. 4 and the two right panels in Fig. 5). Surface waves effectively induce skin friction near the coastline, and thus sediment resuspension is most significant in shallow water, as illustrated in Figure 5.

IMPACT/APPLICATIONS

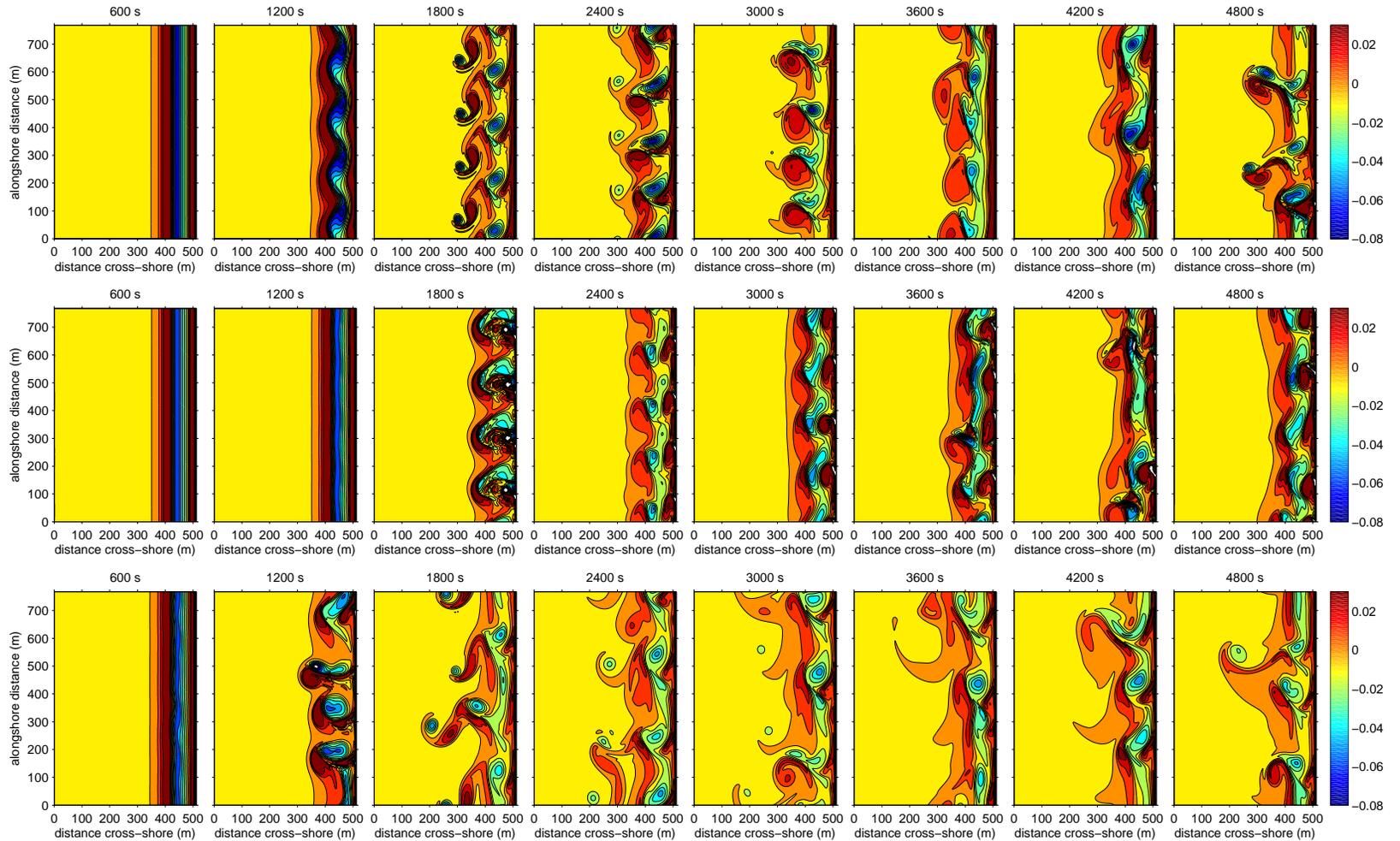
This research will significantly change how coastal circulation modeling is done by the more complete inclusion of the effects of surface gravity waves. To the extent that these effects will be shown to be significant, a more accurate and useful coastal simulation capability will then become widely available.



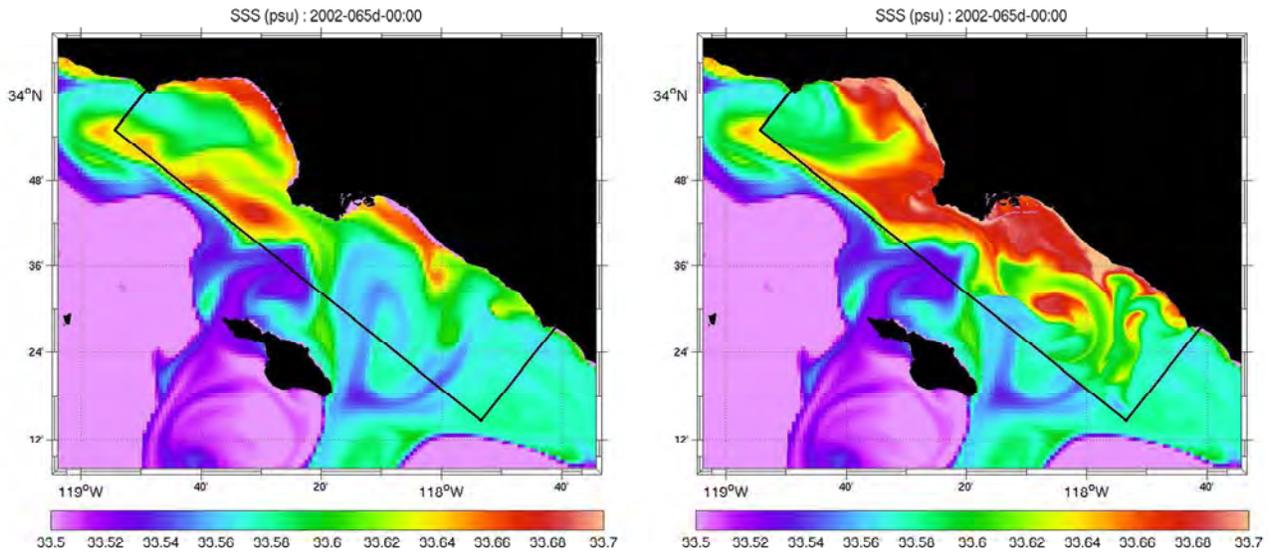
[Figure 1. Cross-shore comparison of wave height, H_{rms} , (left) and southward longshore velocity (right) by the observation (circle marks) and the model (solid curves) along the cross-shore transect $y = 930$ m in the FRF coordinate.]



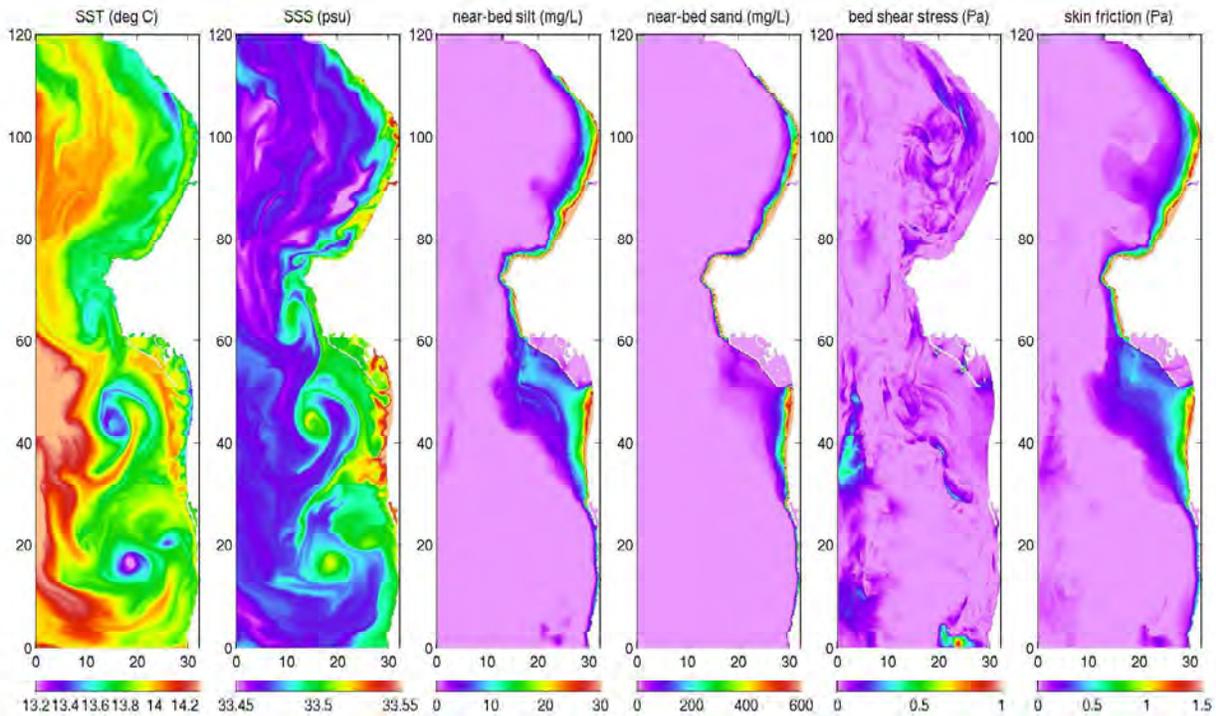
[Figure 2. Cross-shore comparison of wave height, H_{rms} , (left) and southward longshore velocity (right) by the observation (circle marks) and the model (solid curves) along the cross-shore transect $y = 930$ m in the FRF coordinate.]



[Figure 3. Temporal evolution of relative vorticity on an idealized single-barred beach for three cases. Right: case 1 (with WEC and without CEW), middle: case 2 (with WEC and CEW) and left: case 3 (without WEC and CEW).]



[Figure 4. Comparison of instantaneous surface salinity distribution on the 65th Julian day in 2002, when an extensive upwelling event was observed in Southern California Bight. (Right) the parent SCB grid solution with 1-km spacing and (left) with embedded PV 200-m grid solution superposed. Note that the color map is scaled suitable to the inner domain solution. The high-resolution nested simulation is capable of reproducing more intense upwelling.]



[Figure 5. Snapshots of surface temperature, surface salinity, near-bed silt fraction concentration, sand-fraction concentration, combined wave-current induced bottom shear stress, and corresponding skin friction for sediment resuspension on the 8th Julian day, 2002, on the inner child grid. Skin friction is largely affected not by ambient currents, but by surface waves.]

TRANSITIONS & RELATED PROJECTS

This project is being done within a broader context both of coastal circulation modeling and forecasting using ROMS (*e.g.*, ONR's AOSN project in Monterey Bay and the Southern and Central California Coastal Oceanic Observing Systems that includes surface current and wave measurements with data assimilation in ROMS) and the broader context of modeling surface wave effects on currents (ONR's Surface Gravity Waves and Coupled Marine Boundary Layers project centered at NCAR).

Improvements to ROMS involving surface wave effects will make a direct contribution to these related projects.

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