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Dynamics of Upper-Ocean Submesoscale and Langmuir Turbulence

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LONG-TERM GOALS

The long term objective of our research for the Office of Naval Research Departmental Research Initiative (DRI) on "Waves, Langmuir Cells, and the Upper Ocean Boundary Layer" is to uncover the fundamental dynamics that connect motions on scales ranging from 1 m to 10 km in the upper ocean.

OBJECTIVES

Our primary objective is to understand how surface boundary layer turbulence, submesoscale currents and density gradients, and surface gravity waves interact with each other and evolve together under transient larger-scale forcing conditions (*e.g.,* changing wind or remote swell). A related objective is to help design and interpret the field measurements that will be made in this DRI.

APPROACH

Our approach to understanding the dynamics of the upper-ocean boundary layer (OBL) relies on two modeling methodologies. Both modeling approaches are based on mature computational codes that are evolving in the context of extending their applications to new phenomena, and in some cases have been the means of phenomenological discoveries subsequently borne out by measurements.

One 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 boundary layer turbulence as represented in the K-Profile Parameterization (KPP). It incorporates surface gravity wave interactions based on the theory of wave-averaged currents, including subgrid-scale mixing induced by surface gravity waves McWilliams *et al.* (2004). The general thrusts of the new research are to investigate submesoscale currents on small horizontal scales ($\sim$ 10s-100s m) with full wave-current interaction, partly in the context of continental-shelf flows in relatively shallow water. A particular focus is on how the boundary layer turbulence interacts with the submesoscale, first using ROMS with KPP, then doing analogous problems using Large Eddy Simulation (LES) with resolved Langmuir turbulence. Some of the problems will be chosen with shallow water near the shoreline.

The other code is the incompressible, non-hydrostatic LES model Sullivan & McWilliams (2010) used for simulations of boundary layer turbulence with subgrid-scale parameterization only for the smaller turbulence scales of $\sim$ 1 m. It includes the same wave-averaged dynamics as above, presently with the simplification of a horizontally uniform wave field, consistent with previous applications in small horizontal domains McWilliams *et al.* (1997). An important, and challenging, development is to accommodate horizontally non-uniform waves (*e.g.,* wave refraction across a submesoscale density front). The general thrusts of the new research are on transient boundary-layer evolution for disequilibrium wind and wave conditions, and on the interaction of boundary layer turbulence with local submesoscale current features in idealized domains. Furthermore, Langmuir turbulence simulations with a specified moving wavy surface, rather than assuming wave-averaged dynamics, will be investigated to test the completeness of the wave-averaged theory.

The research will be coordinated with other elements of the DRI project as it develops. In particular, we will work closely with Dr. Leonel Romero 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 kilometers and time scale of hours, if not even finer. More generally we intend to collaborate with the other field experimentalists in this DRI project.

WORK COMPLETED

This research project is a new start with funding only available in late FY14. The listed publications are restricted to recent related papers by the PIs.

To date our work has focused on: 1) acquiring a sizable computer allocation of 6.5 million hours on the NCAR petascale machine *Yellowstone* to carry forward the LES computations. The allocation has a duration of one calendar year; 2) acquiring a sizable computer allocation on NSF XSEDE computers to carry forward the ROMS computations; 3) drafting a theoretical plan for posing LES problems with initial submesoscale temperature filaments similar to those captured in ROMS solutions. The objective is to create a database of LES solutions that overlap in scale with ROMS; 4) analyzing idealized ROMS solutions driven by submesoscale temperature filaments that utilize KPP as its boundary layer scheme. These solutions will provide a comparison with (2); and 5) generating preliminary WW3 solutions for idealized transient wind and wave scenarios. This body of work will be further developed and coordinated with the measurement and modeling plans for the DRI in FY15.

RESULTS

A primary goal of our project is to determine how Langmuir turbulence evolves under forcing by transient winds and waves and at a larger-scale by submesoscale buoyancy fronts and filaments. The computational solutions covering the range of scales [1 m to 10 km] will provide a clearer picture of the important dynamics in the upper-ocean boundary layer. Our research program is motivated by past efforts where we found Langmuir turbulence responds quite differently to transient disequilibrium winds and waves than to equilibrium steady winds and waves, and also by the growing appreciation of the importance of submesoscale dynamics (McWilliams, 2010).

Transient winds and waves: One example comes from a simulation of Hurricane Frances, contrasting locations on the right and left sides as it passes by (Fig. 1). To gain fundamental insight into the OBL dynamics we are posing idealized transient wind scenarios and computing the evolution of the wave field with WW3 – the wave spectrum from WW3 is integrated and used to compute a time varying Stokes drift profile, a key input to LES models with phase-averaged wave-current interactions. Figure 2 illustrates a typical transient wind regime with the response of the fully developed wave field to a wind decay from 20 to 4 $\mathrm{m\,s^{-1}}$ over a period of 12 hours. The Large & Pond (1981) prescription is used here to compute the surface drag. Notice the dominant period of the wave field grows to more than 15 s with significant wave heights greater than 3 m, and the resulting surface based turbulent Langmuir number, $La = \sqrt{u_*/U_{Stokes}}$, is ~ 0.3 over multiple days. We expect the resulting long wavelength swell that persists after day seven to drive significant Langmuir turbulence despite the low surface layer winds.

Langmuir turbulence in swell: Our coming LES solutions will be further compared to the recent results obtained by McWilliams *et al.* (2014a) for idealized swell. There the Langmuir turbulence problem was posed and solved for the oceanic surface boundary layer in the presence of wind stress, stable density stratification, equilibrium wind-waves, and remotely generated swell-waves. The addition of swell causes an amplification of the Lagrangian mean current and rotation toward the swell-wave direction, a fattening of the Ekman spiral and associated vertical Reynolds stress profile, an amplification of the inertial current response, an enhancement of turbulent variance and buoyancy entrainment from the pycnocline, and for very large swell an upscaling of the coherent Langmuir circulation patterns (Fig. 3). A new proposal is made for parameterization of Langmuir turbulence influences on the mean current profile and the material entrainment rate in oceanic circulation models based on the orderly scaling behavior of the entrainment rate as a function of the turbulent Langmuir numberLa_t as a criterion for determining the surface boundary layer depth in the KPP scheme.

Filament frontogenesis by boundary layer turbulence: A submesoscale filament of dense water in the oceanic surface layer can undergo frontogenesis with a secondary circulation that has a surface horizontal convergence and downwelling in its center (Fig. 4). This secondary circulation occurs either due to mesoscale straining deformation or due to the surface boundary layer turbulence that causes vertical momentum mixing. In the latter case the circulation approximately has a linear horizontal momentum balance among the baroclinic pressure gradient, Coriolis force, and vertical momentum mixing, *i.e.,* a turbulent thermal wind. The frontogenetic evolution induced by the turbulent mixing sharpens the transverse gradient of the longitudinal velocity (*i.e.,* it increases the vertical vorticity) through convergent advection by the secondary circulation. In an approximate model based on the turbulent thermal wind, the central vorticity

approaches a finite-time singularity, and in a more general hydrostatic model (ROMS), the central vorticity and horizontal convergence amplify by shrinking the transverse scale to near the models grid resolution limit within a short advectve period on the order of a day (McWilliams *et al.*, 2014b). This process commonly helps maintain the sharp submesoscale filaments seen in realistic computational simulations and in nature.

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.

TRANSITIONS & RELATED PROJECTS

The current work is a collaborative effort between UCLA and NCAR, with related modeling projects at both places. The ROMS and LES codes are widely used by other oceanic scientists.

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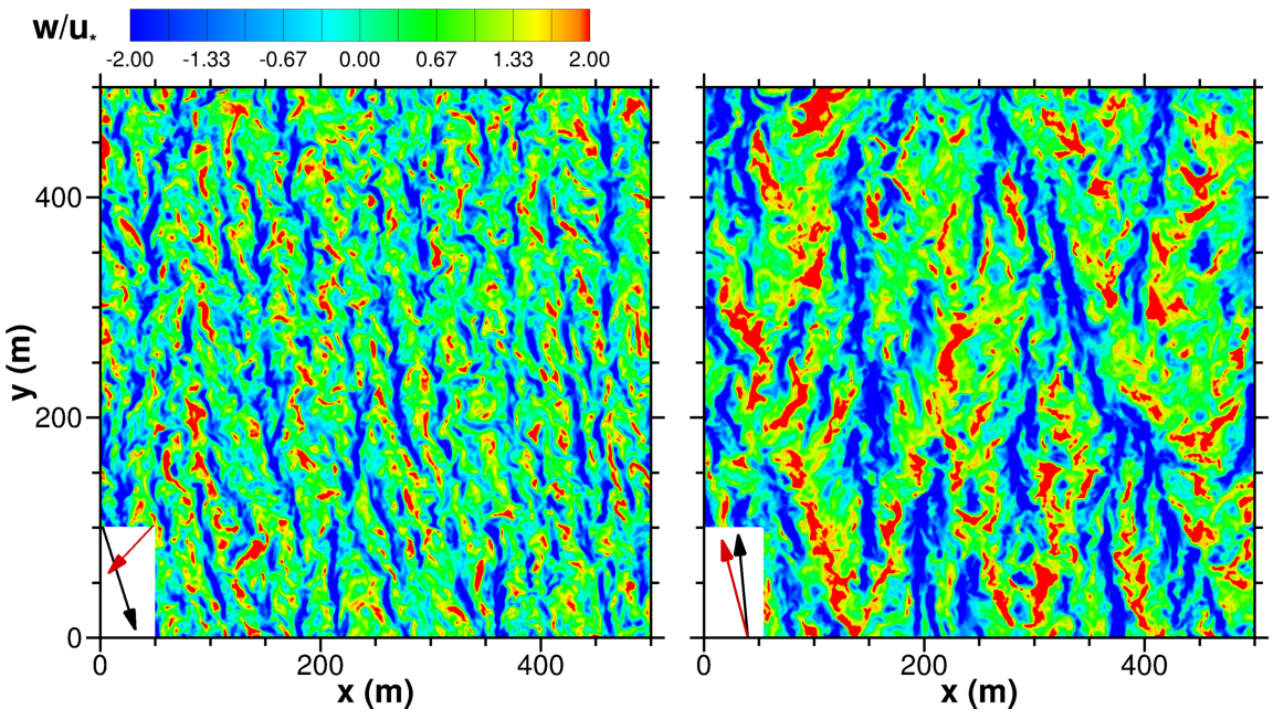

Figure 1: ***Contours of vertical velocity normalized by friction velocity*** u_* ***at the time of maximum winds at*** $z = -7.2$ ***m along the track left of the hurricane storm eye (left panel) and at*** $z = -12.6$ ***m along the track right of the storm eye (right panel). The sub-area depicted in the (left, right) panels is (44, 11)% of the total*** $x - y$ ***area in their respective computational domains. The (black, red) vectors are the directions of the surface (wind, Stokes drift), respectively. Results are from Sullivan*** *et al.* ***(2012).***

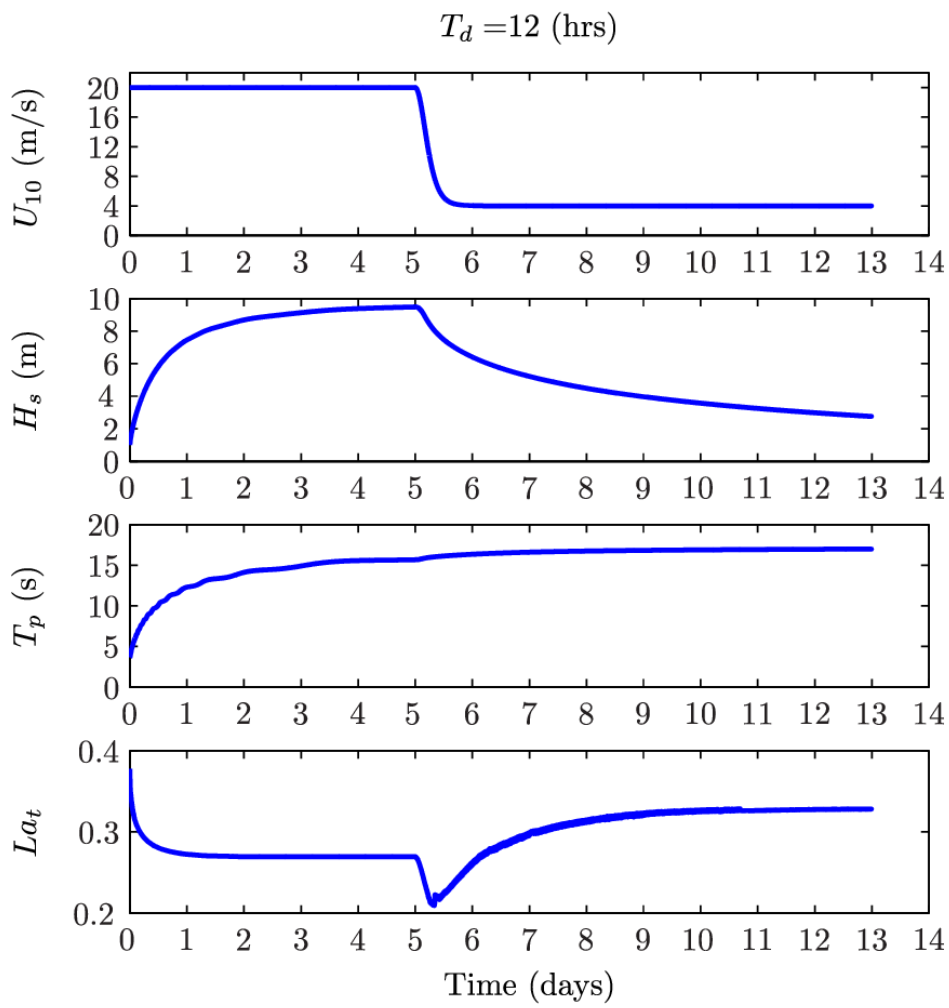

Figure 2: ***Time series of key wave parameters from WaveWatch III driven by a decaying transient wind event. Upper panel: wind variation; upper-middle panel: significant wave height; lower-middle panel: wave period, and lower panel turbulent Langmuir number*** La_t ***computed from water friction velocity and Stokes drift, courtesy L. Romero.***

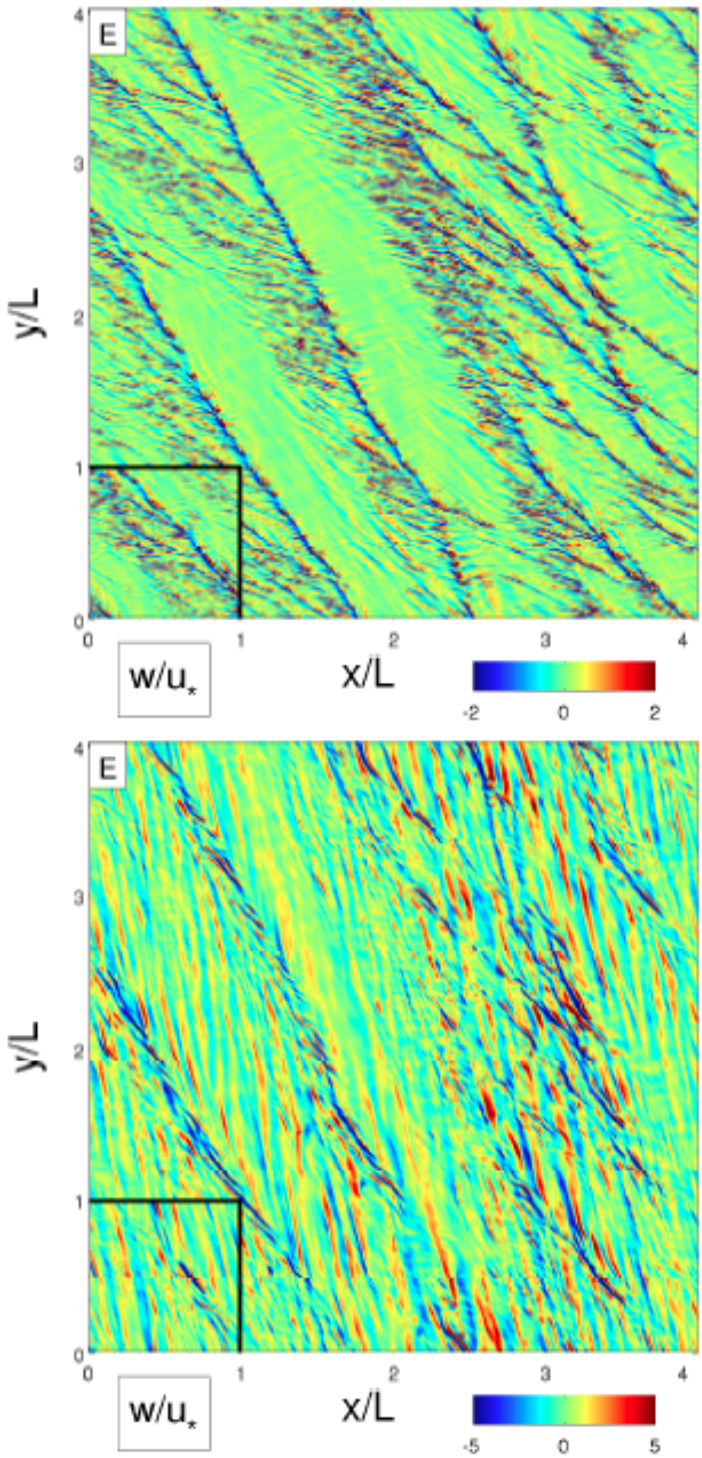

Figure 3: ***A snapshot of vertical velocity*** $w(x, y)$ ***snapshots at depths of 1 (top) and 10 m for a wind-driven surface boundary layer with both local equilibrium wind waves and remotely generated swell waves of large amplitude and wavelength. The domain size is 1200 m in width. Notice the multi-scale character of the Langmuir circulations, including patterns with longitudinal correlations of a kilometer or more, in contrast to the much shorter lengths in equilibrium wind and waves. Results are from McWilliams*** *et al.* ***(2014a).***

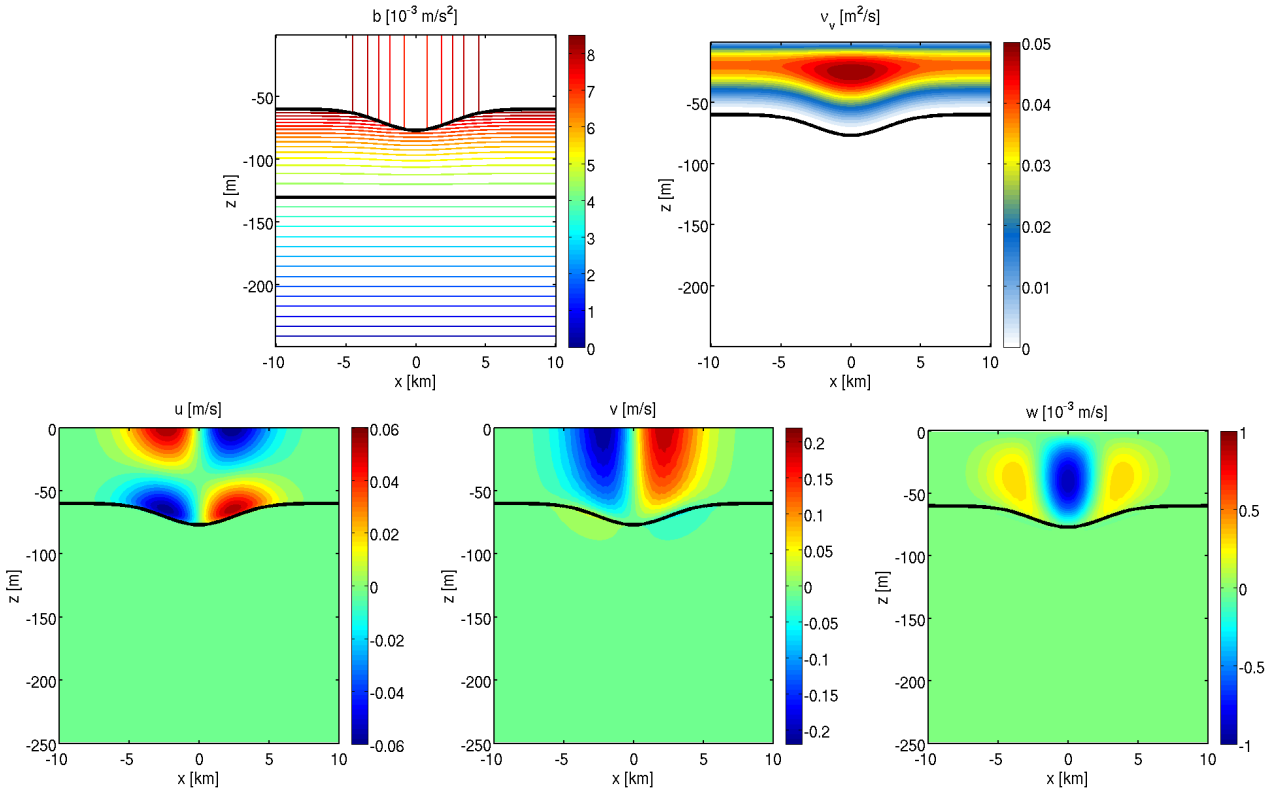

Figure 4: ***Buoyancy, vertical eddy viscosity (from the K-Profile Parameterization scheme), and (across, along, vertical) velocity fields for an idealized submesoscale filament that satisfies a turbulent thermal wind balance. The black line denotes the boundary layer depth at $z = h(x)$. Due to the horizontal convergence at the surface in the center, when these fields are used as an initial condition in ROMS with the K-Profile Parameterization for ν_v(x, the velocity gradient, $\partial v/\partial x$, fronto-genetically increases very rapidly. Results are from McWilliams $et\ al.$(2014b).***