Modeling of Coastal Ocean Flow Fields

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LONG-TERM GOALS

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

OBJECTIVES

To apply numerical circulation models to process studies and to simulations of continental shelf and slope flow fields, including the inner shelf region and the nearshore surf zone, to help achieve understanding of the flow dynamics.

APPROACH

Numerical finite-difference models based on the primitive equations and the shallow-water equations are applied to two- and three-dimensional flow problems relevant to the dynamics of continental shelf and slope flow fields and to the circulation in partially enclosed seas. At present, the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) is being utilized for studies with the primitive equations. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

In coordination with closely related work in the NOPP project "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean", the Princeton Ocean Model (POM) has been adapted for studies of the three-dimensional, short-wave-averaged circulation in the surf zone. Parameterized forcing from breaking waves, represented by gradients in the radiation stress tensor, and parameterized effects of near-surface wave-induced mass flux are incorporated. Long range objectives include development of a single, unified modeling capability for the low-frequency circulation in the surf zone, forced by breaking surface gravity waves, and for the circulation over the adjacent inner shelf, forced by wind stress.

Research has been initiated on modeling studies for inner shelf flow fields by considering the wind-forced circulation off Duck, NC in August-November 1994 during the time of the Coastal Ocean Processes (CoOP) field experiment. This is part of Ph.D. thesis research by Brandy T. Kuebel. For the initial numerical experiments, the assumption of alongshore uniform two-dimensional flows, with spatial variations in the across-shelf (x) and vertical (z) directions, is utilized. The model is forced by

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14. ABSTRACT

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observed wind stress and heat flux. Model/data comparisons are made for velocity and temperature fields. During the time period of the field experiment and the model calculations, both stratified (August) and unstratified (October-November) conditions exist allowing comparison of the shelf flow response in these two different regimes. Following the initial focus on the characteristics of the Eulerian model fields, attention has been given to a study of fluid particle motion from the Lagrangian perspective. Two different techniques have been employed to track particles. A Lagrangian drifter method uses a fourth-order Runge Kutta scheme to track particles at each model time step and a conservative tracer technique that advects three different tracers (to represent the three initial coordinates of fluid particles) using the model velocities and a higher-order Smolarkiewicz advection scheme.

In a separate effort, numerical model experiments utilizing POM have been conducted to study the mesoscale circulation in the Gulf of California. This is Ph.D. thesis research by Antonio Martinez. The separate effects of forcing by winds and by coastal-trapped waves incident from the south have been examined. A relatively high resolution grid (3 km horizontal grid size, 50 sigma levels in the vertical) has been employed to adequately resolve the mesoscale flow. The wind forcing experiments have been run for 240 days (August 1996 - March 1997). The model results are analyzed for the last 120 day period. The wind stress is obtained from a combined product of scatterometer measurements and NCEP analyses (Milliff et al., 1999). The coastal-trapped wave experiments have been run for an 80 day period 1 July - 19 September 1984 during which time extensive current (Merrifield and Winant, 1989) and hydrographic (Bray, 1988) measurements were made in the gulf. These measurements are utilized for model/data comparisons. It has been concluded from previous observations (Merrifield and Winant, 1989) that storm-generated incident coastal-trapped waves make a major contribution to mesoscale variability in the gulf. The incident coastal-trapped waves are assumed to have the spatial structure of the first baroclinic linear mode with time variability given by coastal sea level measurements at Acapulco. In addition, a series of process-oriented experiments have been pursued to better understand coastal-trapped wave propagation in the gulf. In these experiments, the behavior of idealized incident wave pulses, with varying wavelengths and amplitudes, have been studied.

RESULTS

Initial applications of POM to surf zone circulation studies have focused on alongshore-uniform two-dimensional motion. The model has been applied to studies of the circulation off Duck, NC with model results being compared to velocity measurements from the DUCK94 field experiment (Garcez Faria et al., 1998, 2000). The POM results determine model solutions for the (x,z) structure of the wave-averaged alongshore and across-shore velocity fields. Reasonably good agreement is found between the model and the measured velocities. The effects of tidal elevation change on the circulation are investigated and show, in particular, variations in the strength of the undertow over the bar and in the trough with tidal height that are in general agreement with velocity measurements from the fixed array (Elgar, Guza, personal communication).

Numerical model studies of the two-dimensional circulation off Duck, NC during August-November 1994 provide detailed information about wind-forced inner shelf flow fields. Objectives include determination of the nature of the across-shelf circulation. The model-produced alongshore velocities are well correlated with current measurements from the CoOP field experiment (Lentz et al., 1999) providing confidence in the model results. Comparison between stratified (August) and nonstratified (October) regimes shows marked differences in the across-shelf transport with substantial reduction, relative to predicted Ekman transport calculated from the wind stress, near the coast during nonstratified conditions. Model dynamical balances have been analyzed and utilized to explain these qualitative differences in the circulation.

Particle tracking techniques utilized in the two-dimensional numerical model simulations off Duck, NC provide a quantitative picture of the impact of upwelling and downwelling winds on individual fluid particles. Figure 1 shows the evolution of two conservative tracers during the month of October, in which strong, persistent downwelling winds were observed. The C_1 tracer illustrates across-shelf motion of fluid particles and the C_2 tracer illustrates vertical motion. Following 8 days of forcing by downwelling winds, the distributions show significant movement onshore near the surface and offshore near the bottom, as well as downward vertical movement near the coast. After 24 days of forcing at the end of the simulation, the particles have been advected even farther in these directions. Also shown in Figure 1 are mean across-shelf (U) and vertical (W) velocities for the month of October obtained from net particle displacements using both the Lagrangian drifter technique and the conservative tracers. In addition to providing quantitative values of effective displacement velocities for each particle on the model grid, these plots show that the two techniques give similar results.

Results from the modeling studies of the mesoscale circulation in the Gulf of California, categorized by forcing mechanism, are briefly summarized below.

Wind stress: The dominant winds are aligned along the gulf and are southward. Wind reversals occur, however, so that both sides of the gulf experience some upwelling favorable conditions. The wind-forced surface currents flow out of the gulf during the strong wind season (December-March), while the average currents at depth flow into the gulf. This feature is consistent with observations (Bray, 1988) and helps explain the high productivity in the gulf. The most striking feature of the wind-forced circulation is the formation of eddies in the south and central gulf. These eddies are evident in the mean depth-integrated velocity fields shown in Figure 2. The scale of these eddies is about 90 km and they are generated on both sides of the gulf. Numerical experiments without surface heat flux show that the intensity of the eddies is substantially increased by the presence of the strong surface heat flux in the gulf (annual average 90 W/m^2).

Coastal-Trapped Waves: These waves propagate northward into the gulf along the coast of mainland Mexico. Typical periods of the energetic events are 5 to 7 days. Along the mainland shore of the gulf, the waves lose some energy due to topographic irregularities of the main basins of the gulf. After the waves reach the sill (at $y \approx 900$ km in Figure 2) where the depth decreases abruptly from 1500m to 200m, a small fraction of the energy continues north where it is dissipated in the shallower water. Most of the energy is reflected at the sill as a wave that travels south along the coast of the Baja Peninsula. The wave that leaves the gulf on the Baja side contains only a small fraction of the incident energy. In the process studies with idealized incident wave pulses, it is found that, with amplitudes of realistic magnitude (e.g., sea level disturbances of 20 cm), nonlinear effects result in appreciable wave steepening and in differing behavior of sea level elevation and depression pulses. These effects play an important role in the wave evolution in the gulf.

IMPACT/APPLICATIONS

The numerical modeling studies with the primitive equations applied to both wind-forced inner shelf flows and to wave-averaged currents in the surf zone constitute important initial steps toward development of a single, unified modeling approach to three-dimensional circulation processes in the nearshore inner shelf region. Modeling studies have provided new quantitative information on the nature of the wind- and coastal-trapped wave-driven mesoscale circulation in the Gulf of California.

TRANSITIONS

RELATED PROJECTS

Some aspects of the primitive equation Princeton Ocean Model studies of surf zone flow fields are jointly funded by ONR Grant N00014-99-1-1051, (NOPP) "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean".

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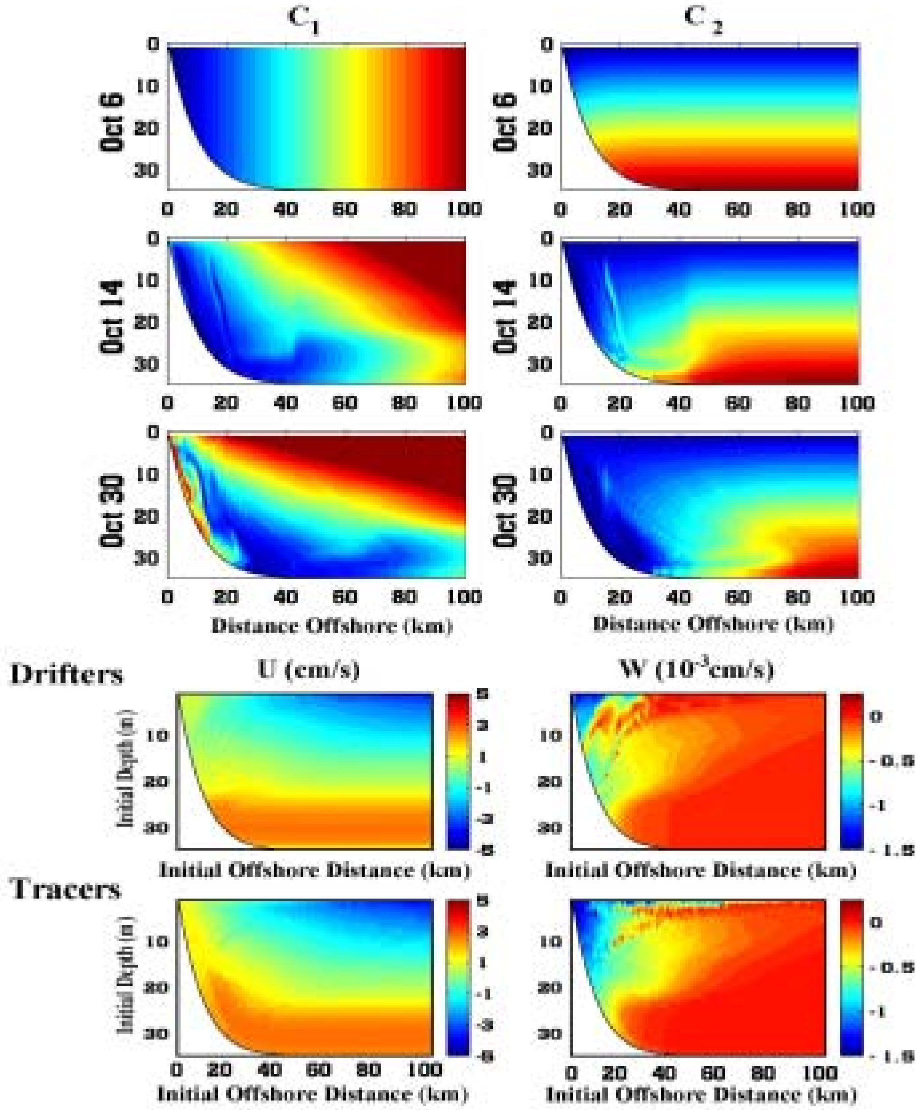

Figure 1. Results from two-dimensional POM simulations of shelf flows off Duck, NC. The six upper panels show two conservative tracer fields, C_1 and C_2, at the start of the simulation (Oct 6), after 8 days of forcing (Oct 14), and at the end of the simulation (Oct 30). The four lower panels show mean across-shelf (U) and vertical (W) Lagrangian velocities for the month of October obtained from net particle displacements using both the Lagrangian drifter technique and the conservative tracers. Comparison of these mean velocity figures shows that the two techniques for tracking fluid particles produce similar results. Both methods illustrate the onshore movement at the surface and offshore movement at depth (at a mean velocity of about 5 cm s^{-1}), as well as significant downward movement near the coast at about 0.15 mm s^{-1}.

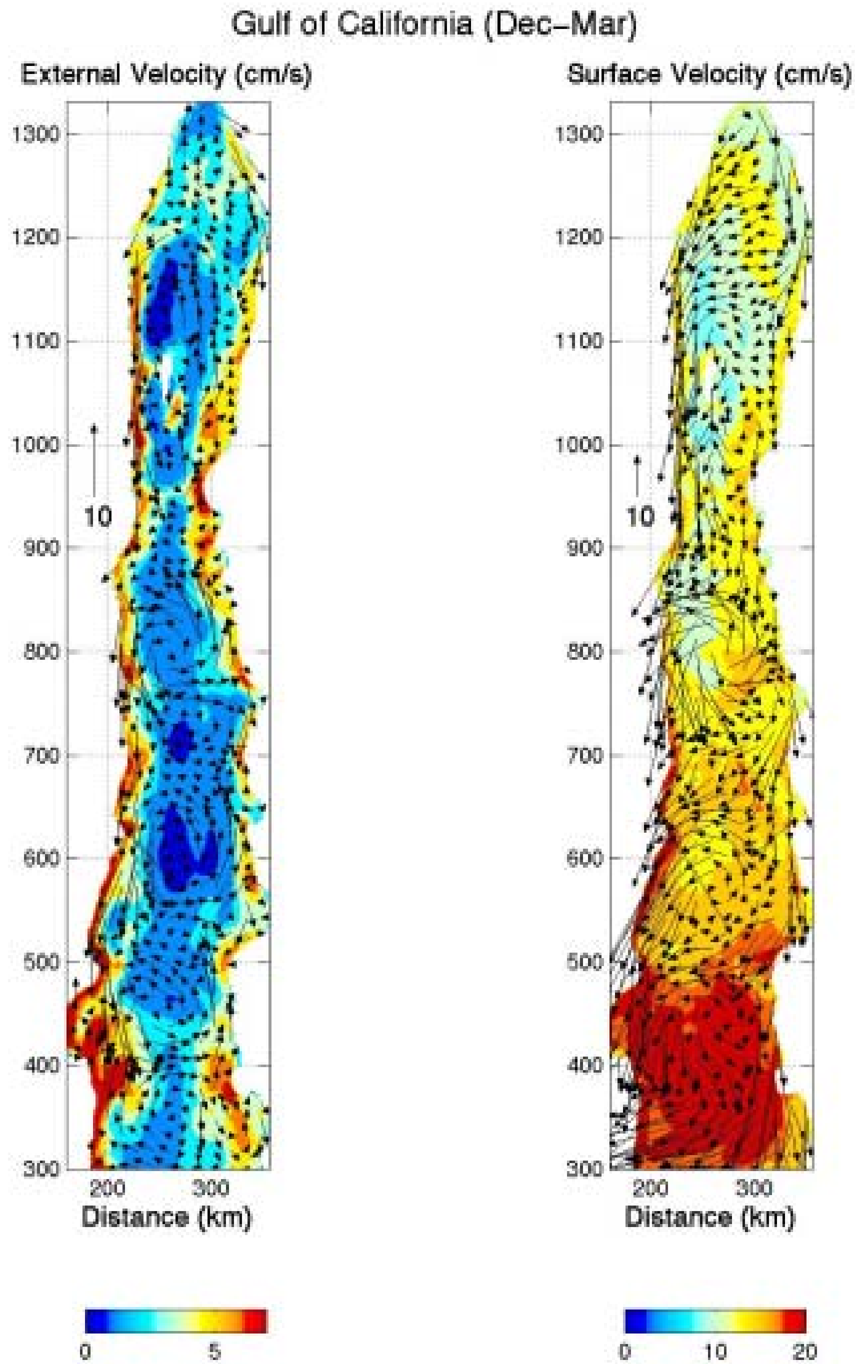

Figure 2. Mean depth averaged (left panel) and surface (right panel) velocity vectors for the wind and surface heat flux driven experiment for the Gulf of California. Color contours show the RMS vector amplitude in cm/s. Note the different scale. The depth-averaged external velocity shows high variability along the coast on both sides, while the surface velocity has high variability in the southern gulf. The magnitude of the surface velocity is about four times larger than the depth-averaged velocity. One of the most robust features is the presence of several gyres in the south gulf which to our knowledge have not been described before. Three strong cyclonic gyres are present at y = 450, 600, and 800 km, as well as weaker anticyclonic gyres at y = 350, 525, and 730 km.