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 are applied to 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 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, wave-averaged circulation in the surf zone. Parameterized forcing from breaking waves, represented by gradients in the radiation stress tensor, and effects of wave-induced mass flux are incorporated. Effects of wave-current interactions on the bottom boundary layer are also represented through a boundary layer submodel. 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.

In support of the effort to develop a three-dimensional model for wave-averaged circulation in the surf zone, additional research on the dynamics of wave-current bottom boundary layers has been initiated. This research is being pursued by post-doctoral research associate Stephen Henderson. Time-dependent wave-current boundary layer processes are modeled using a one-dimensional modified version of POM. Wave momentum fluxes are included by assuming that waves propagate without

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14. ABSTRACT

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

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rapidly changing form. The boundary layer model is forced using observed velocities from the DUCK94 and SandyDuck field experiments. Sediment transport is predicted using stress-based bedload models and an advection-diffusion equation for suspended sediment transport.

A modeling study for inner shelf flow fields that examines the wind-forced circulation off Duck, NC in August-November 1994 during the time of the Coastal Ocean Processes (CoOP) field experiment has been completed (Kuebel et al., 2002). This is part of Ph.D. thesis research by Brandy T. Kuebel. For these 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 observed wind stress and heat flux. Model/data comparisons are made for velocity and temperature fields. During the time period of the field experiment, both stratified (August) and unstratified (October-November) conditions exist allowing comparison of the shelf flow response in these two different regimes. Objectives include determination of the nature of the across-shelf circulation. Following the initial focus on the characteristics of the Eulerian model fields, attention has been given to a study of Lagrangian fluid parcel motion. Two different techniques have been employed to track fluid parcels. A Lagrangian drifter method that uses a fourth-order Runge-Kutta scheme to calculate parcel trajectories from the model velocities and a Lagrangian label technique that advects three different tracer label fields that represent the three initial coordinates of fluid particles.

The sensitivity of model produced, time-dependent wind-driven shelf circulation to the turbulent closure scheme employed is studied using POM with a two-dimensional approximation and realistic topography from the Oregon shelf (Wijesekera et al., 2002). The level 2.5 Mellor-Yamada closure, k-ε closure, and K-Profile Parameterization (KPP) schemes are used to evaluate the mesoscale fields and the spatial and temporal variability of turbulent mixing.

In another effort, numerical model experiments utilizing POM have been conducted to study the mesoscale circulation in the Gulf of California (Martinez and Allen, 2002a,b,c). This is the result of 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 (Martinez and Allen, 2002a) 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). 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. Coastal-trapped wave experiments (Martinez and Allen, 2002b) 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. 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 (Martinez and Allen, 2002c). In these experiments, the behavior of idealized incident wave pulses, with varying wavelengths and amplitudes, has been studied.

RESULTS

In the wave-current boundary layer studies, previously known results concerning boundary layer streaming and the phase differences between bed stress and free stream velocity are recovered. The predictions for sediment transport, however, differ from those of the widely used energetics-based BBB (Bagnold, 1966; Bowen, 1981; Bailard, 1981) models. The mean transport predicted under regular asymmetric waves is greater than two-thirds of the transport predicted under skewed waves, whereas BBB models predict zero transport under asymmetric waves.

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. 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. The Lagrangian analysis provides quantitative information concerning the impact of upwelling and downwelling winds on the three-dimensional trajectories and the net displacements of fluid parcels.

Model studies of turbulent mixing over the continental shelf (Wijesekera et al., 2002) show that during upwelling favorable winds, the majority of turbulent mixing occurs in the top and the bottom boundary layers and in the vicinity of the vertically and horizontally sheared coastal jet. Turbulent mixing in the coastal jet is primarily driven by shear-production. The near-surface flow on the inner-shelf becomes convectively unstable as wind stress forces the upwelled-water to flow offshore in a turbulent surface layer. During downwelling favorable winds, the strongest mixing occurs in the vicinity of the downwelling front. The largest turbulent kinetic energy TKE and dissipation ε are found near the bottom of the front. Turbulence in the bottom boundary layer offshore of the front is concentrated between recirculation cells that are generated as a result of symmetric instabilities in the boundary layer flow. Here TKE is generated by shear-production.

Model results (Martinez and Allen, 2002a) for the atmospherically-forced mesoscale circulation in the Gulf of California show a complex pattern dominated by the presence of multiple eddies, both cyclonic and anticyclonic, in the southern gulf. The eddies have horizontal scales the order of the gulf width (•100 km) and vertical scales of 1000 m. Near the coast along both sides and in most of the north gulf, the circulation is wind-driven and has high variability. Away from the coast in the interior, the velocity fluctuations are characterized by lower variability and are poorly correlated with the wind. The temporal-mean surface circulation consists of southward down-gulf currents along the coast on both sides, with larger magnitude currents on the west side. In the temporal-mean circulation, the cyclonic eddies generally include a northward up-gulf current that is 800 m deep along the east side and a southward down-gulf current with similar depth along the west side. In the vicinity of anticyclonic eddies, the circulation is more complex with southward down-gulf currents on both sides and a northward -gulf current near the center of the gulf that is accompanied by southward flow at depth. Positive relative vorticity at the surface seems to be produced along the west side and to extend into the interior in the vicinity of cyclonic eddies. Negative vorticity values are significant near anticyclonic eddies and seem to be connected to the east coast. Regions of relatively high values of turbulent kinetic energy $1/2\ q^2$ are found in the interior, away from surface and bottom boundary layers and away from the coast, near the center of the gulf at depths 350-500 m and are associated with low values of the Richardson number Ri. High values of q^2 typically occur where the vorticity is negative, and appear to be related to the concentration of near-inertial wave energy.

The evolution of remotely forced coastal-trapped waves in the Gulf of California is studied using numerical experiments with POM (Martinez and Allen, 2002b). Forcing is provided by observed sea level time variability at a remote station south of the gulf that is assumed to propagate northward into the gulf as a mode 1 coastal-trapped wave (CTW). In general, sea level fluctuations are reasonably well represented by the model, with model/data correlations decreasing from 0.76 at Topolobampo, close to the entrance to the gulf, to 0.52 at Santa Rosalia in the central gulf. Model-data correlations of velocity are lower (<0.6). In the gulf, coastal-trapped wave (CTWs) propagate northward along the east side with no significant changes south of the sill, which is 600 km north of the entrance. When incident waves propagating northward in the gulf along the east side arrive at the sill, a small fraction of the wave energy enters the northern gulf and is dissipated. Most of the wave energy is steered at the sill to the west side of the gulf where it propagates southward with decreased sea level amplitude. The weakened waves leave the gulf at the southwest boundary approximately 6-7 days after entering. Some of the incident wave energy is lost into down-slope propagating disturbances generated as the CTWs pass, resulting in relatively intense bottom currents. The contribution of remotely-forced CTWs in the Gulf of California to the total kinetic energy is comparable to that produced by the wind.

The behavior of idealized incident CTW disturbances with different amplitudes and time scales is also examined (Martinez and Allen, 2002c). Incident waves with large, but realistic sea level displacement magnitudes exhibit nonlinear properties. Phase speeds increase as the sea level displacements of the incident waves increase from -30 m to +30 m. Waves of sea level elevation steepen. On the east side, large amplitude elevation waves produce a down-gulf current adjacent to the coast such that the up-gulf currents associated with the waves separate from the coast. The separation process seems to be connected with subsequent down-slope propagation of energy. Energetic anticyclonic eddies with spatial scales of 50-80 km can be generated by long time scale or large amplitude elevation waves (see Figure 1).

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.

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".

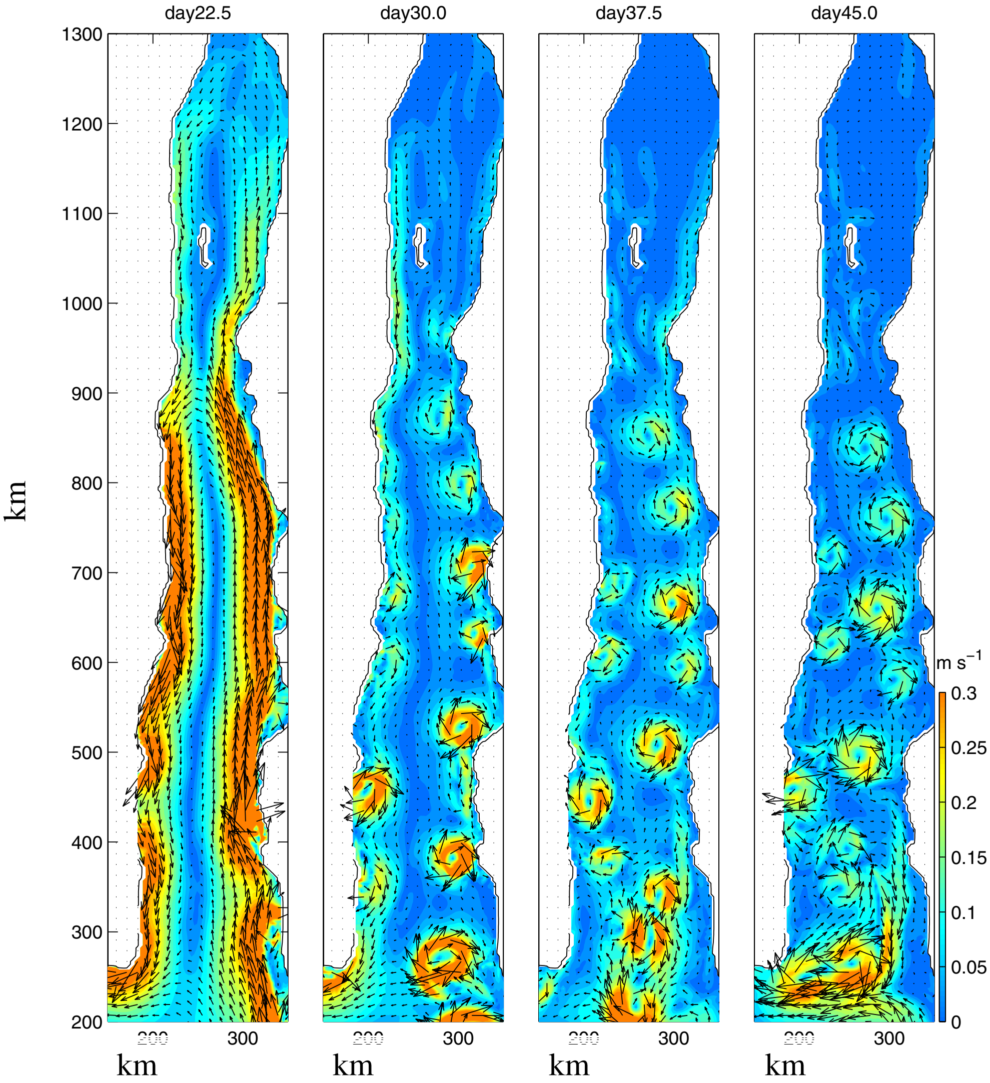

Figure 1. Results from the Martinez and Allen (2002c) study involving the propagation of idealized incident coastal-trapped waves in the Gulf of California. Surface velocity vectors are plotted every 7.5 days from day 22.5 to day 45. The color contours represent the magnitude of the velocity vectors (m s^{-1}). The incident wave has a sea level amplitude of 16 cm and a time scale of 16 days. Energetic anti-cyclonic eddies are generated following the passage of the incident wave.

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Martinez, J. A., and J. S. Allen, 2002a: A modeling study of the atmospherically-forced mesoscale circulation in the Gulf of California, submitted to *J. Phys. Oceanogr.*

Martinez, J. A., and J. S. Allen, 2002b: A modeling study of coastal-trapped wave propagation in the Gulf of California. Part 1, response to remote forcing, submitted to *J. Phys. Oceanogr.*

Martinez, J. A., and J. S. Allen, 2002c: A modeling study of coastal-trapped wave propagation in the Gulf of California. Part 2, response to idealized forcing, submitted to *J. Phys. Oceanogr.*

Wijesekera, H. W., J. S. Allen, and P. A. Newberger, 2002: Modeling study of turbulent mixing over the continental shelf: Comparison of turbulent closure schemes, submitted to *J. Geophys. Res.*