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. A shallow-water equation model has been developed and applied to studies involving vorticity dynamics of wave-averaged currents in the nearshore surf zone. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

Numerical experiments addressing the nature of nonlinear, finite amplitude shear instabilities of alongshore currents in the surf zone through the solution to idealized, forced, dissipative, initial-value problems have been performed. Bottom topographies with constant slope, with an alongshore-uniform sand bar, and with an alongshore variable sand bar, have been used with periodic boundary conditions in the alongshore direction. Forcing effects from breaking surface waves are calculated from gradients in the radiation stress tensor. These are determined using the formulation of Thornton and Guza (1986) generalized, for the alongshore variable topography, to two-dimensional situations. Dissipative effects are modeled by linear bottom friction.

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

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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 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.

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, by coastal-trapped waves incident from the south, and by the tides 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 365 days (August 1996 - July 1997) after a 60 day spin-up 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. The emphasis in the experiments involving tidal forcing has been on a study of the characteristics of the internal tides and of the associated tidal mixing in the gulf.

RESULTS

Results from the study of nonlinear shear instabilities of alongshore currents in the surf zone over beach topography with alongshore-variable sand bars (Slinn, Allen, and Holman, 2000) show significant influence of alongshore topographic variability on the nearshore circulation. In particular, one notable feature is the tendency for contours of both the time mean and the root mean square vorticity fields to align along contours of constant depth. This tendency is attributed to both the direct effect of the variable topography on the wave forcing and also to the dynamical response of the currents to variable topography. The contributions from each of these two mechanisms are of comparable magnitudes.

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. Reasonable 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.

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. A comparison between measured and modeled alongshore currents at two across-shelf positions shows a good correlation (see Figure 1). Also plotted in Figure 1 are monthly means and standard deviations of the model potential density, streamfunction and alongshore velocity fields, which are significantly different during stratified and unstratified conditions. In August (stratified), both upwelling- and downwelling-favorable winds force the stratified flow on the shelf, with an apparent mean upwelling circulation. A well-formed northward coastal jet develops, with opposing southward velocities both below and offshore of the jet. In October (unstratified), strong downwelling-favorable winds prevail and the shelf becomes almost completely mixed in the vertical. Alongshelf velocities are southward everywhere and decrease in magnitude with depth.

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

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. This process is illustrated in Figure 2. The wave that leaves the gulf on the Baja side contains only a small fraction of the incident energy.

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 yearly-averaged wind-forced surface currents flow out of the gulf, while the average flow at depth is 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. 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).

Tides: The external M_2 tide is sufficiently energetic (2m and 1.5 m s^{-1}) to generate a strong residual circulation (max velocities 0.18 m s^{-1}) in the vicinity of the sill and in the region farther north. There is substantial generation of internal tides (20-30 m amplitude) in the neighborhood of the sill. Mixing produced by tidal forcing is important in the sill region. The total energy conversion as a result of tidal mixing is comparable to the total energy dissipated by bottom friction.

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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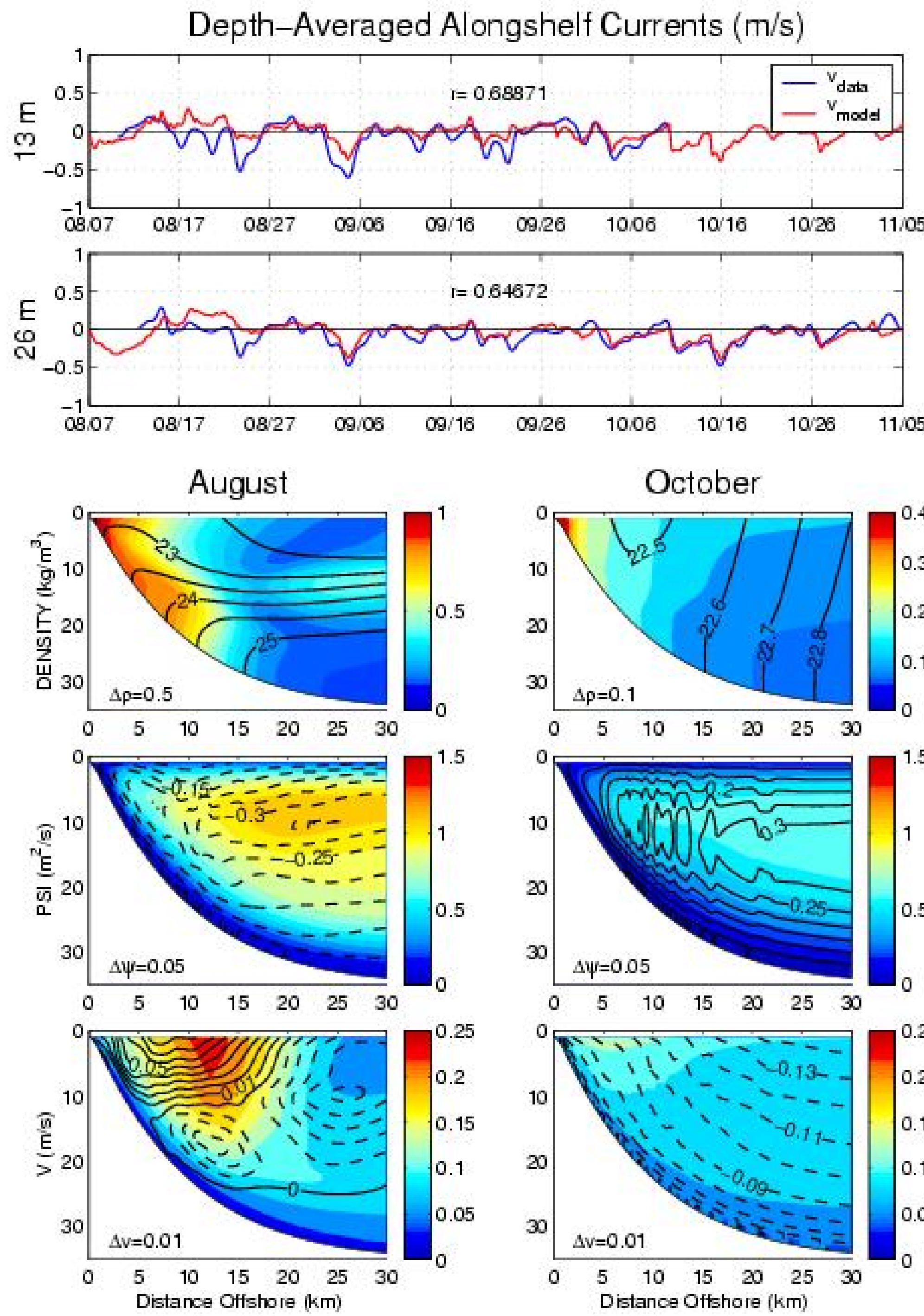

Figure 1. Results from two-dimensional POM simulations of shelf flows at Duck, NC. The two upper panels show depth-averaged alongshore currents at 13 m and 26 m from both the data (blue) and the model (red) for the period August 7, 1994 to November 11, 1994. The corresponding correlation coefficients are also included. The six lower panels give monthly mean fields of the potential density (σ_θ), streamfunction, and alongshore velocity and their standard deviations for August (stratified shelf) and October (unstratified shelf). Standard deviations are in color, while the monthly means are overlaid as black lines.

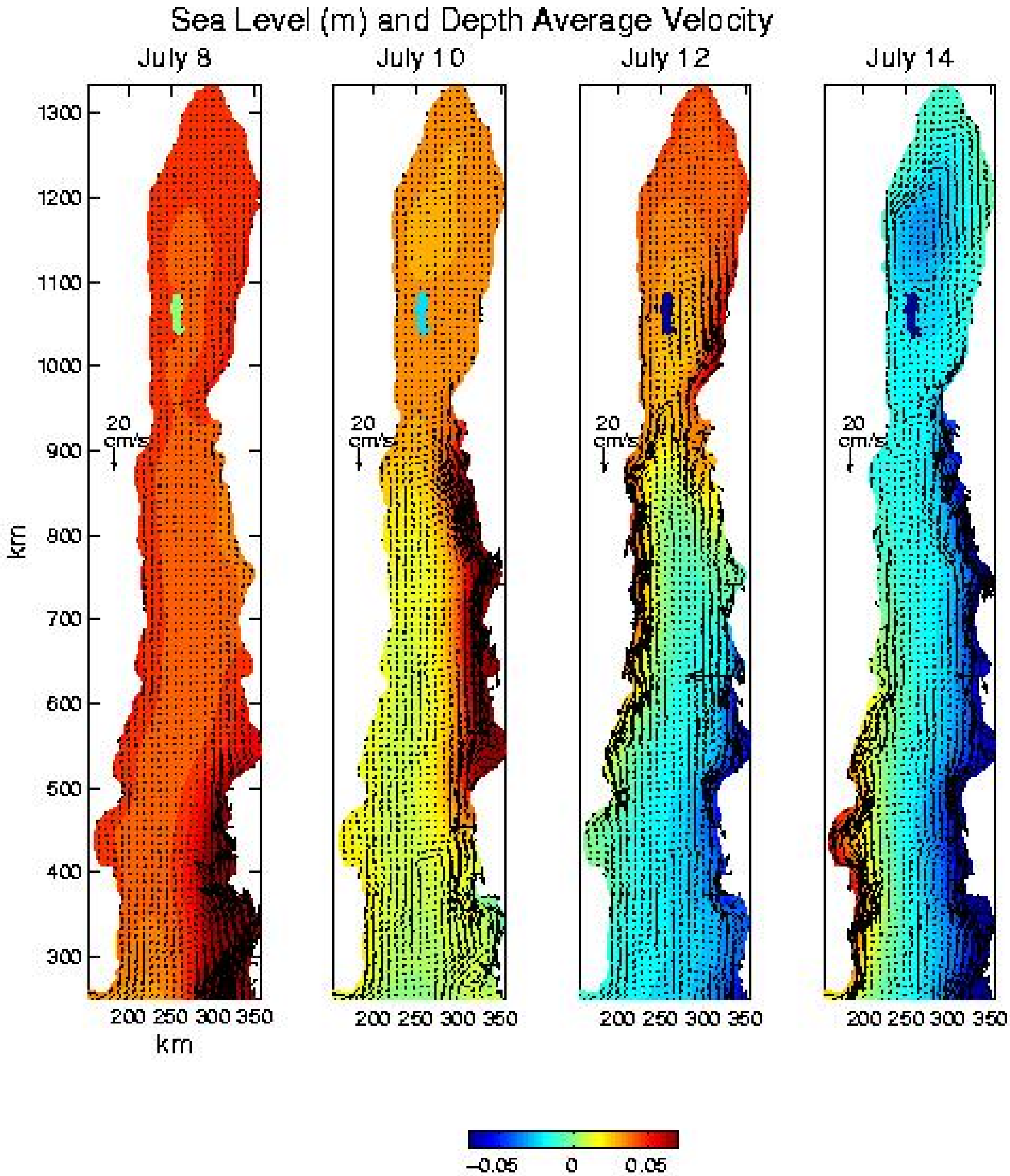

Figure 2. Results from numerical model studies of the mesoscale circulation in the Gulf of California. This experiment involves forcing by coastal-trapped waves that propagate northward into the gulf along the coast of mainland Mexico. The propagation and decay in the gulf of a coastal-trapped wave disturbance are evident in the sea level elevation (color contours) and depth-averaged velocity vector fields from 8-14 July 1984.