Assimilation of Coastal Radar Surface Current Measurements in Shelf Circulation Models

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LONG-TERM GOALS

To understand the fundamental issues involved with data assimilation in the coastal ocean and to use this knowledge to develop optimal, nowcast and forecast systems.

OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal, methods for the assimilation of data (surface current measurements from land-based radar systems; current and temperature measurements from moored arrays) into coastal circulation models, and to apply these methods to measurements from the Oregon shelf.

APPROACH

An array of SeaSonde HF radars has been deployed along the Oregon coast by P. M. Kosro of the College of Oceanic and Atmospheric Sciences, OSU. Data from a two-site HF array, which provides measurements of surface currents over a region about 50×50 km, have been collected since November 1997. This project is aimed initially at developing and applying, in cooperation with Kosro, methods for the assimilation of these measurements in coastal circulation models. Application to other data sets, including moored arrays from the COAST field experiment are also being pursued.

The full primitive equations are sufficiently complicated that developing and testing nearly optimal data assimilation methods for use with them presents considerable difficulties. For this reason the data assimilation problem has been approached simultaneously from two directions: application of optimal variational inverse data assimilation schemes to simplified linear models and application of simplified, sub-optimal data assimilation schemes to a full primitive equation model.

Studies with a linear stratified model have been undertaken to provide improved understanding of mathematical and physical issues associated with assimilation of surface current measurements. In initial efforts (Scott, 2000; Kurapov et al., 2001a) we worked with a simplified model widely used in previous theoretical studies of shelf circulation (e.g., Clarke and Brink, 1985), which allowed us to obtain analytical inverse solutions. We are now focusing on a numerical inverse model for the linear 3D stratified primitive equations, allowing for realistic shelf topography. Initial efforts involve a frequency domain model, which is being applied to studies of internal tides, and to address fundamental questions about treatment of open boundary conditions in coastal data assimilation.

The P.I.'s have also been working with P. M. Kosro on the development and application of a practical, sub-optimal data assimilation system (DAS) for implementation with the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). A DAS based on optimal interpolation has been developed for use in POM. As part of this effort, direct model simulations of flow on the Oregon shelf have been pursued with the objective of establishing dynamical rationalizations for the observed shelf flow.

WORK COMPLETED

Analytical results obtained by Scott et al. (2001) for a simplified linear stratified model have been extended to consider general time-dependent, three-dimensional flows, while still retaining idealized coastal geometry (Kurapov, et al., 2002a). This linear model has been utilized for statistical comparisons of the generalized inverse method (GIM) and two sequential methods, the Kalman filter (KF) and optimal interpolation (OI), and to derive an optimal form for a steady state forecast error covariance $\mathbf{P}^f$ for OI. In further efforts on simplified data assimilation methods we have taken a numerical approach, allowing us to consider realistic bathymetry. A 3D stratified frequency domain inverse model based on the linear primitive equations has been used for studies of internal tides on the central Oregon shelf (Kurapov et al., 2002b). For a limited domain, such as the area covered by the HF radar systems on the central Oregon coast, an efficient solution method has been developed, based on direct factorization of the coefficient matrix for the second order system satisfied by density perturbations. This approach provides solutions for both the forward and adjoint problems, and makes a variational GIM approach based on representer computations straightforward. The inverse model has been applied to HF radar surface currents harmonically analyzed in 2-week time windows, using a strong constraint formulation with open boundary baroclinic tidal currents corrected to better fit the data. The series of inverse solutions for May-August 1998 has been validated against independent ADP data, and temporal and spatial variability of the internal tide on the Oregon shelf has been analyzed. The tidal inverse model has also been used to study sensitivity of the inverse solution to the choice of the open boundary condition error covariance. A nesting technique, based on computation of representers for a coarse resolution model in a larger domain, has been developed and tested for the tidal problem. A data assimilation study of barotropic tides on the central Oregon coast has also been completed (Erofeeva et al., 2002).

For the DA studies utilizing POM, the model has been applied to a limited-area high-resolution coastal domain for the central Oregon coast (Oke et al., 2002a,b,c). Realistic bottom topography for the Oregon shelf and slope is utilized in a large-scale periodic channel. The covariance fields used for our initial implementation of the OI scheme were calculated from an ensemble of runs, in which the model was forced with observed winds from 17 "typical" summers (July and August) between 1969 and 1998. A time-distributed, sequential assimilation procedure that specifically addresses issues concerning primitive equation initialization and assimilation of low-pass filtered data was developed for use with the OI scheme. The effectiveness of this assimilation procedure has been demonstrated by assimilation experiments applied to CODAR data from summer 1998 and verified with subsurface current measurements (Oke et al., 2002a). Results from the theoretical study of Kurapov et al. (2002a) have been applied to refine the OI scheme. In contrast to the scheme of Oke et al (2002a), where the forecast error covariance $\mathbf{P}^f$ was taken to be proportional to an ensemble estimate of the model covariance $\mathbf{P}^m$, our refined approach uses time lagged covariances of the model only solution to account for the effect of recently assimilated data. The two approaches to estimating $\mathbf{P}^f$ have been compared for a series of assimilation runs using HF radar surface currents for summer 1998.

Sixty-day simulations of the sub-inertial continental shelf circulation off Oregon were performed for a hindcast study of summer 1999. In Part 1 (Oke et al., 2002b), model results were compared with in situ currents, HF-radar derived surface currents and hydrographic measurements obtained from an array of moored instruments and field surveys and the model's sensitivity to initial stratification, surface forcing, domain size and river forcing were assessed. In Part II (Oke et al., 2002c), the modeled three-dimensional, time-varying circulation and dynamical balances were analyzed, providing a detailed synoptic description of the continental shelf circulation off Oregon for summer 1999.

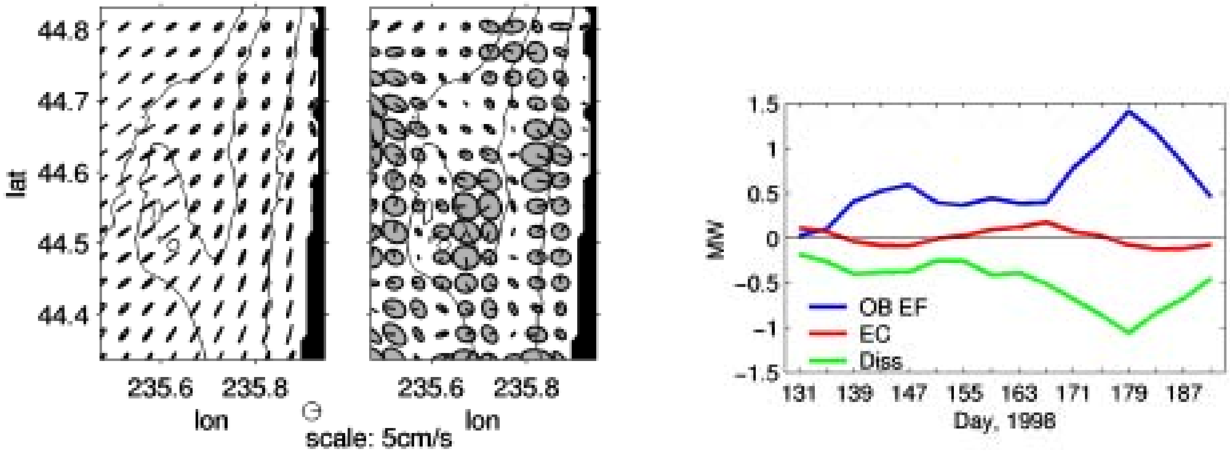
Additional data from the COAST field experiment (spring-summer 2001) have become available, including time series of velocities, temperature and salinity obtained from moorings. HF radar surface currents for the same period are being processed and should be available soon. In preparation for further data assimilation studies, model-data comparisons have been made to assess solution sensitivity to model inputs, for instance heat flux.

RESULTS

In the comparisons of the GIM, KF and OI (Kurapov et al., 2002a), it is shown specifically how GIM can give relatively better results based on the use of future data. This improvement in performance can be explained in terms of wave dynamics. Derivation of the KF and OI schemes in terms of representers suggests approaches for improving the performance of practical OI schemes, based on combining time-lagged prior model covariances with the zero lag model covariances we have used in our implementation of the OI scheme.

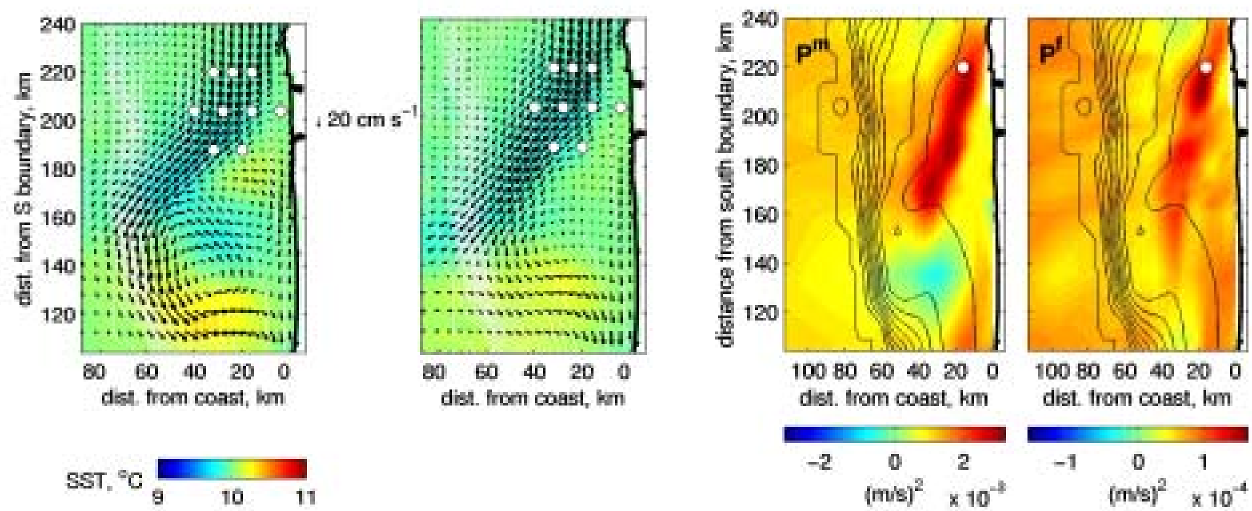
In the stratified tidal model (Kurapov et al. 2002b), for most of the study period (May-Aug., 1998) inverse solutions are in a better agreement with ADP validation data compared to the prior solution, which is forced at the open boundary only with depth-averaged currents. By correcting the open boundary fluxes, data assimilation improves the amplitude and phase of the tidal solution at the ADP location throughout the water column. Later in the summer inversion results are improved if HF radar data closest to the coast are not assimilated. This suggests that the dynamical model should be improved near the coast (e.g., to allow for the upwelling front and coastal jet). The series of tidal solutions provides a uniquely detailed picture of spatial and temporal variability of the internal tide on the central Oregon shelf. Despite high intermittence of the internal tide, some persistent features are found for the study period, for instance the dominant phase and energy propagation was always from the north-west (Figure 1b). At the surface, deviations from the depth-average may reach 10 cm/s, twice typical barotropic currents (Figure 1a-b). Persistent zones of higher and lower internal tide energy extend parallel to the coast. The pattern can be explained in terms of the superposition of incident and reflected low-mode internal waves. Analysis of the energy budget shows that most baroclinic energy is generated outside the area covered by the HF radar (Figure 1c). The study with the linear inverse model also shows how the choice of open boundary error covariance can affect model perfomance. Covariances obtained by nesting are more consistent with the dynamics assumed within the domain, making the inversion more stable with respect to the choice of cost function weights.

In the data assimilation studies utilizing POM, the effectiveness of a practical assimilation scheme based on OI has been demonstrated through assimilation experiments applied to HF radar data from



a) *b)* *c)*

Figure 1, Tidal study. (a-b) Baroclinic M2 tidal currents at the surface (deviations from the depth-average, panel b) may be twice as large as barotropic currents (depth-average, panel a). Shown are tidal ellipses, for time window centered at day 139, 1998; shading denotes clockwise horizontal velocity vector rotation; Contours are bathymetry (50, 75, and 100 m). c) Baroclinic energy flux via open boundaryof the study area (OB EF) dominantes barotropic to baroclinic energy conversion rate (EC) over the topography. Shown are terms in the baroclinic energy equation integrated over the study area and averaged over a tidal period. The OB EF is the result of fitting the HF radar surface currents.



a) *b)* *c)* *d)*

Figure 2, POM study. (a-b) The assimilation solution using an optimized $\mathbf{P^f}$ (panel b) yields a weaker circulation south of HF radar site than the original implementation (panel a). Shown are averaged over 50 days surface current and temperature over an area of Heceta Bank, white circles are HF radar assimilated data locations; (c-d) Structural difference between the model only error covariance (panel c) and forecast error covariance (panel d) of alongshore velocity at the observation location (shown as circle) and cross-shore velocity everywhere on the surface.

summer 1998 (Oke et al., 2002a). Correlations between depth-averaged ADP velocities and those obtained from model-only and assimilation experiments are 0.42 and 0.78 respectively. Analysis of term balances in the assimilation output suggests that uncertainties in the wind forcing are a primary source of model error. The refined forecast error covariance suggested by Kurapov et al. (2002a) yields an assimilation solution very close to that obtained with the simpler scheme of Oke et al. (2002a) within the area of HF radar coverage. However, south of this area, circulation patterns differ significantly with the newer solution showing on average weaker recirculation over Heceta Bank (Figure 2a-b). These results are consistent with the differences between the spatial correlation structure of the two covariances (Figure 2c-d). To assess the significance of this difference, more extensive measurements are required, e.g., those from the COAST field program (2001).

In the modeling studies utilizing POM (Oke et al., 2002b), model outputs compared favorably with in situ currents and hydrographic measurements with correlations between observed and modeled alongshore currents and temperatures in water depths of 50 m are exceeding 0.8. The circulation is clearly wind-driven and strongly influenced by the alongshore variations in shelf topography (Oke et al., 2001c). In the region of the coast where the along-shore topographic variability is small, the upwelling circulation is consistent with standard conceptual models for two-dimensional across-shore circulation. In the regions where topographic variations are greater, the circulation is highly three-dimensional. Over Heceta Bank the upwelling circulation is complicated, with weaker direct coupling to the wind forcing over most of the shelf. Upwelled water found over the mid-shelf off Newport is advected from the north, while upwelled water over Heceta Bank is drawn from the south. The dynamical balances over the inner-shelf are divided into two regimes. In the coastal jet, the tendency of the alongshore depth-averaged velocity V_t is large and is driven by the difference between the surface and bottom stresses during upwelling. Inshore of the coastal jet, V_t is small and is driven by the difference between the surface stress and a negative alongshore pressure gradient during upwelling. When the wind stress becomes small after upwelling, V_t is primarily balanced by the negative alongshore pressure gradient and a northward flow is generated. A region to the south of Newport over the inner-shelf is identified as the region where the northward momentum is initially generated.

IMPACT/APPLICATIONS

The studies with variational inverse schemes applied to linear models have begun to answer some of the basic questions associated with the assimilation of surface current measurements in coastal circulation models. In particular, these questions concern the extent of surface data influence on the flow at depth, the capability to retrieve unknown initial and boundary conditions, and the dependence of the inverse solution on assumed model and data error weights. Results obtained with the stratified inverse model prove that surface currents from HF radars contain information about internal super-inertial tidal flows at depth. The data assimilation studies with POM have produced promising results regarding assimilation of coastal radar surface current measurements in a full primitive equation model utilizing a practical data assimilation scheme. The modeling studies with POM provide new information about the three-dimensional, time varying circulation and the dynamical balances on the Oregon shelf, along with quantitative information regarding circulation modeling capabilities for this environment.

TRANSITIONS

RELATED PROJECTS

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