# Assimilation of Coastal Radar Surface Current Measurements in Shelf Circulation Models

John S. Allen, Robert N. Miller and Gary D. Egbert
College of Oceanic and Atmospheric Sciences
Oregon State University
104 Ocean Admin Building
Corvallis, OR 97331-5503
phone: (541) 737-2928 fax: (541) 737-2064 email: jallen@oce.orst.edu

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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 surface current measurements from land-based radar systems in 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 km square, 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.

The full primitive equations are sufficiently complicated that developing and testing nearly optimal data assimilation methods for use with them presents considerable difficulties. Even basic questions about the nature of information contained in surface current data and its implications for the velocity and density distributions at depth are not easily addressed with such a detailed model. 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 by the P.I.'s together with R. K. Scott and A. Kurapov to provide improved understanding of mathematical and physical issues associated with assimilation of surface current measurements. The present linear stratified model includes the effects of surface and bottom Ekman layers, and has been widely used in previous theoretical studies of shelf circulation (e.g., Clarke and Brink, 1985). Although this model clearly has limitations, it includes representations of the essential physical effects of stratification, surface and bottom frictional processes, and shelf topography. The use of linear models also allows a systematic examination of the

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sensitivity of errors in the assimilation output products to errors in surface velocity measurements, wind stress, heat fluxes, initial conditions and boundary conditions.

At the same time, as part of closely related research in the OSU NOPP project ``The Prediction of Wind-Driven Coastal Circulation'', the P.I.'s have been working with P. Oke and P. M. Kosro on the development of a practical, sub-optimal assimilation scheme for implementation with the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), and on the application of this scheme to HF radar measurements off the Oregon coast. A data assimilation system that employs the mathematical framework of the Physical Space Analysis System (PSAS), utilized by the NASA Data Assimilation Office (Cohn et al., 1998), has been developed for use in POM.

Finally, we are pursing methods for assimilation of HF radar data into high-resolution models of coastal tidal currents. Initial efforts have focused on extension of variational methods developed for satellite altimeter data to allow for assimilation of current data in barotropic models. We are now beginning work on assimilation of tidal current data into a 3-d linear stratified model with realistic topography. Our ultimate intent is to combine the tidal band assimilation with our efforts on assimilation of sub-inertial wind-driven flows.

## WORK COMPLETED

A study of application of an optimal variational inverse scheme for assimilation of surface data in an idealized linear stratified coastal model has been completed and is reported in Scott et al. (2000). Simplified flat bottom geometry is used in this model. Effects of vertical diffusion are represented through vanishingly thin surface and bottom Ekman layers (Allen, 1973). Consideration is restricted to flows varying only with cross-shore distance and depth. The model is forced by wind stress at a single frequency. The use of this idealized model allows significant analytical progress. The inverse problem is formulated as that of finding the minimum of a positive definite "cost functional" defined on the space of candidate solutions, including initial and boundary conditions. Analytic solutions to the inverse problem have been constructed as sums of representer functions, which are themselves constructed as analytic solutions to special forward and adjoint problems.

Work with this linear stratified model has been extended to consider general time-dependent, three-dimensional flows, while still retaining idealized coastal geometry (Kurapov, et al., 1999, 2000a,b). Although this model is simplified, it contains a representation of the coastal-trapped wave dynamics that will be an important physical component of full primitive equation models with realistic topography. A generalized inverse has been developed and again progress with finding analytical solutions in terms of a sum of representer functions has been possible. In applications of coastal circulation models, there are typically considerable uncertainties in initial conditions and in open boundary conditions. The generalized inverse formulation here has been used specifically to investigate the effectiveness of surface data in restoring the state of the system at the initial time and at the open boundary. The linear model has also been utilized for statistical comparisons of the generalized inverse method (GIM) and two sequential methods, the Kalman filter (KF) and optimal interpolation (OI). The availability of analytical solutions for the representers allows straightforward calculations of the statistical functions required for the comparisons, and for studies of the consequences of incorrect prior assumptions about error statistics.

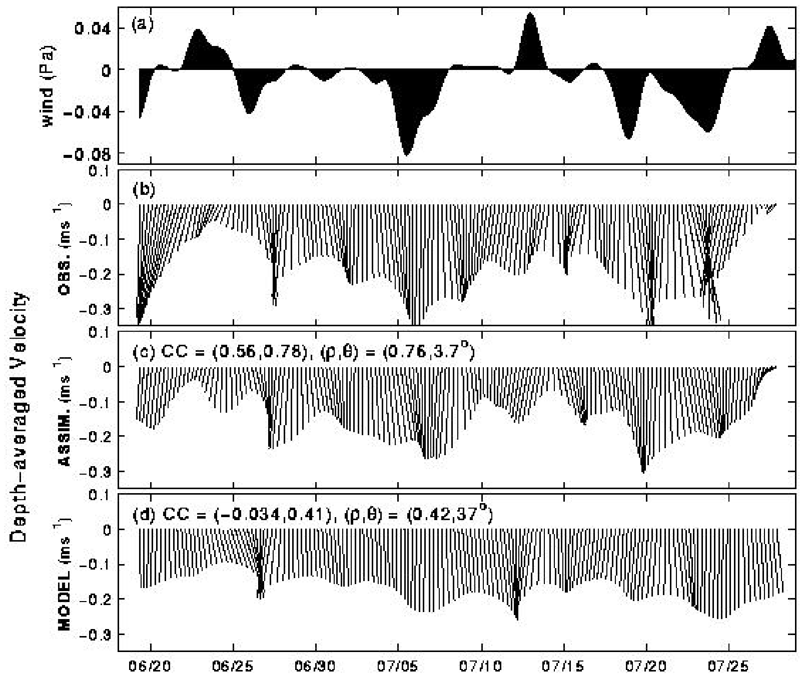
For the studies utilizing POM, the model is applied to a limited-area high-resolution coastal domain for the central Oregon coast (Oke et al., 1999, 2000). Realistic bottom topography for the Oregon shelf and slope is embedded in a large scale periodic channel. This geometry provides a useful domain for well-posed numerical experiments involving wind-driven upwelling circulation on the Oregon shelf. A series of model-data comparisons for summer 1998 indicates that the model is capable of reproducing a substantial fraction of the surface and sub-surface variance in the shelf velocity field. The covariance fields needed for implementation of PSAS were calculated from an ensemble of runs, in which the model was forced with observed winds from 17 different "typical" summers (July and August) between 1969 and 1998. Our sample covariance fields were inhomogeneous and anisotropic. A time-distributed, sequential assimilation procedure, that specifically addresses issues concerning primitive equation initialization and assimilation of low-pass filtered data (that removes tides and inertial period oscillations), was developed for use with the PSAS 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, 2000).

For the tidal studies the OSU tidal inversion software (OTIS; http://www.oce.orst.edu/po/research/tide) has been modified to allow for assimilation of barotropic currents (Egbert and Erofeeva, 2000). HF radar data from 1998 has been analyzed to study tidal band signals, and their temporal variations. Based on this analysis, radar data from the winter months have been used for assimilation into a barotropic model of the central Oregon shelf with a resolution of 1 km. The resulting tidal fields have been compared to harmonic constants estimated from recent and historical current moorings.

## RESULTS

For the two-dimensional linear model study reported in Scott et al. (1999), the assimilation scheme uses an inverse formulation to find the best fit to the model, to the coastal boundary condition, which represents our knowledge of the open ocean, and to the data. Without this inverse formulation, simply replacing the coastal boundary condition with an extra surface boundary condition consisting of the data results in an ill-posed problem. The inverse formulation illustrates explicitly how the ill-posedness is resolved: through the regularization of an ill-conditioned linear operator, whose inverse is a linear transformation from the data to the solution at depth. The inverse solution is constructed as a linear combination of representer functions. The representer functions provide important information about the domain of influence of each data point, about optimal location and resolution of the data points, about the error statistics of the inverse solution itself and about how that depends upon the error statistics of the data and of the model. Twin experiments illustrate how a well known ocean state can be reconstructed from sampled data. Consideration of the statistics of an ensemble of such twin experiments provides insight into the dependence of the inverse solution on the choice of weights, on the data error, and on the sampling resolution.

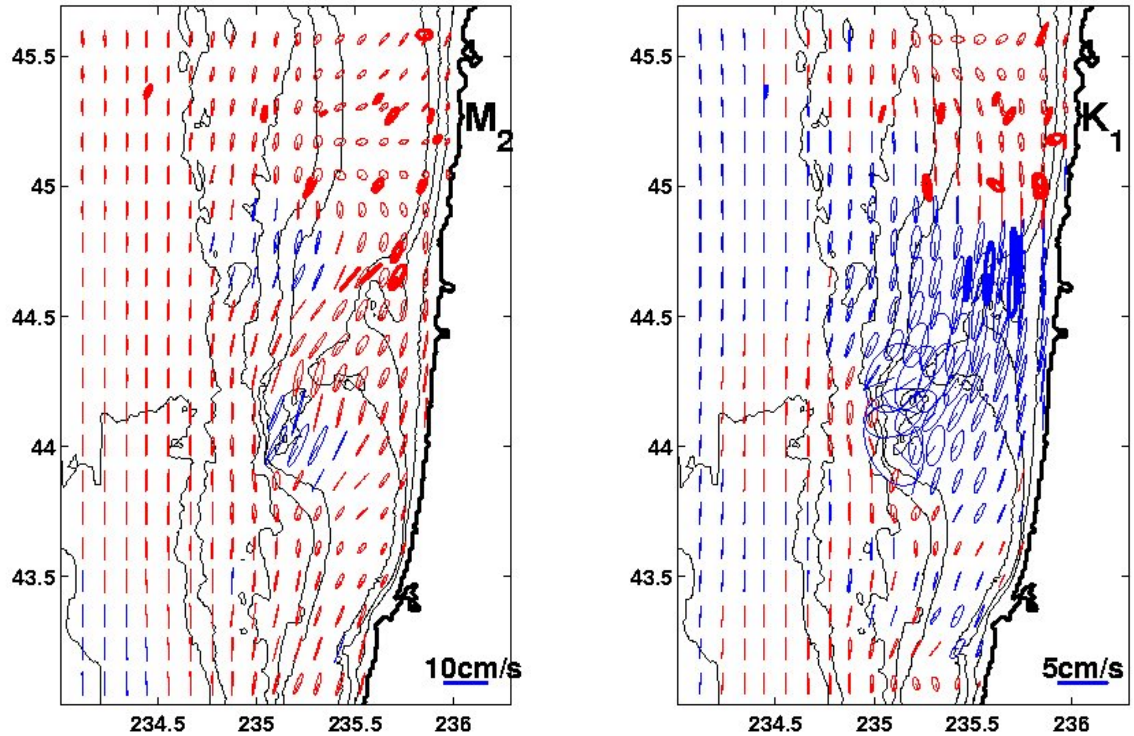
For the three-dimensional, fully time-dependent linear problem (Kurapov et al., 1999,2000), the representer functions show interesting physical features concerning the zone of influence of each surface data point. The representer associated with uncertainty in the governing equation has a significant propagating component associated with the coastal-trapped wave dynamics present in the model. This clearly illustrates the non-local nature, in both time and alongshore coordinate, of surface data influence. Results from twin experiments give an explicit demonstration of the effectiveness of the inverse solution in restoring unknown initial conditions and across-shelf boundary conditions. In the comparisons of the GIM, KF and OI, 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 PSAS scheme.




***1. (a) Alongshore component of the wind stress from winds measured at Newport, OR. Vector time series plot of the depth-averaged velocity from (b) the moored ADP measurements in 80 m water depth, (c) the assimilation experiment 14 and (d) the model-only experiment for summer 1998. CC (.,.) denotes the correlation coefficients with the observed currents for (U,V) where U is across-shore and V is alongshore while (ρ,θ) denotes the amplitude and phase of the complex correlation coefficient (adapted from Oke et al., 2000).***

For the studies utilizing POM (Oke et al., 1999, 2000), the capability of a shelf circulation model to represent important features of the observed shelf surface and subsurface velocity field has been shown. The effectiveness of a practical data assimilation scheme based on PSAS, but structured to address issues of primitive equation initialization and filtered data assimilation, has been demonstrated through assimilation experiments applied to CODAR data from summer 1998. For example, the correlations between depth-averaged velocities calculated from sub-surface current measurements and from sub-surface currents obtained from model-only and from assimilation experiments are 0.42 and 0.78, respectively (Figure 1), showing marked improvement with assimilation of surface currents. Analysis of momentum term balances after assimilation indicate that uncertainties in the wind forcing are probably a primary source of model error.

The tidal assimilation studies reveal complex patterns of currents associated with topographic features, especially in the diurnal band (K1) over Hecate bank (Figure 2). Independent estimates of barotropic current harmonic constants (heavy ellipses in Figure 2) show generally good agreement with the assimilation results. Diurnal currents in the prior hydrodynamic model (with no data) are very sensitive to the assumed bottom drag coefficient. By assimilating the radar data this sensitivity is very significantly reduced, demonstrating that the data can correct for error in the assumed friction. Initial studies of time variations in the tidal band signal in the HF radar data reveal spatially coherent variations that are probably related to intermittent internal tide generation, especially in the semi-diurnal band.




***2: Tidal current ellipses for the principal semi-diurnal (M2) and diurnal (K1) tidal constituents for the central Oregon coast, derived from assimilation of HF radar data into the shallow water equations. All radial current data from winter 1997-98 were assimilated, using the representer approach described in Egbert and Erofeeva (2000). Red ellipses denote clockwise rotation of current vectors, blue counterclockwise. Thick lines are harmonic constants from recent and historical current moorings, and are not assimilated.***

## 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. The 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.

## RELATED PROJECTS

Some aspects of these data assimilation studies are jointly funded by ONR Grant N00014-98-1-0787 (NOPP) "The Prediction of Wind-Driven Coastal Circulation".

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