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Variational assimilation of HF radar surface currents in a coastal ocean model off Oregon

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A B S T R A C T

The impact of assimilation of sea surface velocity fields observed by a set of high-frequency (HF) radars is studied using a three-dimensional ocean circulation model configured along the Oregon coast. The study period is June–July 2008 featuring upwelling and separation of the coastal currents into the adjacent interior ocean. The nonlinear model is based on the Regional Ocean Modeling System (ROMS) and the data assimilation (DA) component on the AVRORA system utilizing the representer-based variational algorithm. Assimilation proceeds in a series of 3-day windows, providing an analysis solution in each window and a 3-day forecast into the next window. Experiments with two different initial condition error covariances are compared (one is dynamically balanced, based on the linearized equation of state, temperature-salinity relation, and geostrophic and thermal wind balance relations and the other is multivariate unbalanced). While the assimilation impact is statistically better in the case of the balanced covariance, the case with the unbalanced covariance also provides sensible improvement in terms of surface velocity and sea surface temperature (SST) model-data forecast statistics. The analysis of representer functions shows that even if the initial condition error covariance is unbalanced, the correction fields at the model initial time are partially balanced after each dynamical field is smoothed independently, due to inherent dynamical properties of the adjoint model. Assimilation of the HF radar surface currents improves not only surface velocity forecasts, but also geometry of the upwelling SST front and the sea surface height (SSH) slope near the coast, as verified against unassimilated satellite SSH and SST data. The assimilation also alters the latitudinal distribution of the time-averaged offshore transport. Combined HF radar velocity and other observations, *e.g.*, altimetry, is needed to better constrain surface geostrophic currents in the entire model domain, including the area not covered by the HF radar data.

1. Introduction

Along the Oregon shelf, a strongly wind-driven upwelling system is present in summer (Huyer and Smith, 1978; Springer et al., 2009; Koch et al., 2010). A real-time data assimilation (DA) and forecast system has been implemented in that area as a part of a regional ocean observing system (http://www-hce.coas.oregonstate.edu/~orcoss/ACTZ/SSCforecast.html; http://www.nanoos.org). It has assimilated along-track sea surface height (SSH) from satellite altimetry, sea surface temperature (SST), and high-frequency (HF) radar surface current observations. In a series of hindcast studies we have assessed the impact of some of the assimilated data types, in particular by comparison with unassimilated data and by analyzing dynamical features revealed by the model-data synthesis. Kurapov et al. (2011) provides a comprehensive description of the assimilation system and demonstrates the effect of assimilation of along-track altimetry and SST data. In this study, we use the same DA system to investigate the impact of assimilation of HF radar surface currents.

Coastally-based HF radars (Kosro et al., 1997) measure ocean surface currents at a spatial resolution of several kilometers, capturing essential processes in the coastal ocean, including wind-driven (Oke et al., 2002a; Kosro, 2005) and tidal currents (Erofeeva et al., 2003; Kurapov et al., 2003; O'Keefe, 2005). Data from a combination of six long-range and five standard-range HF radars along the Oregon coast have been available in near-real time (http://bragg.coas.oregonstate.edu/ORCoast/) extending over a distance of 650 km in the alongshore direction and as far as 200 km offshore (Fig. 1). The HF radar data cover both the shelf, where the dynamics are predominantly wind-driven, and the adjacent coastal transition zone (CTZ), where the dynamics are more dominated by nonlinear interactions of jets and eddies, fed by the coastal current instabilities and separation (Strub et al., 1991; Brink and Cowles, 1991; Koch et al., 2010). Similar systems have been in operation elsewhere, including California and the US East Coast (Harlan et al., 2010). An

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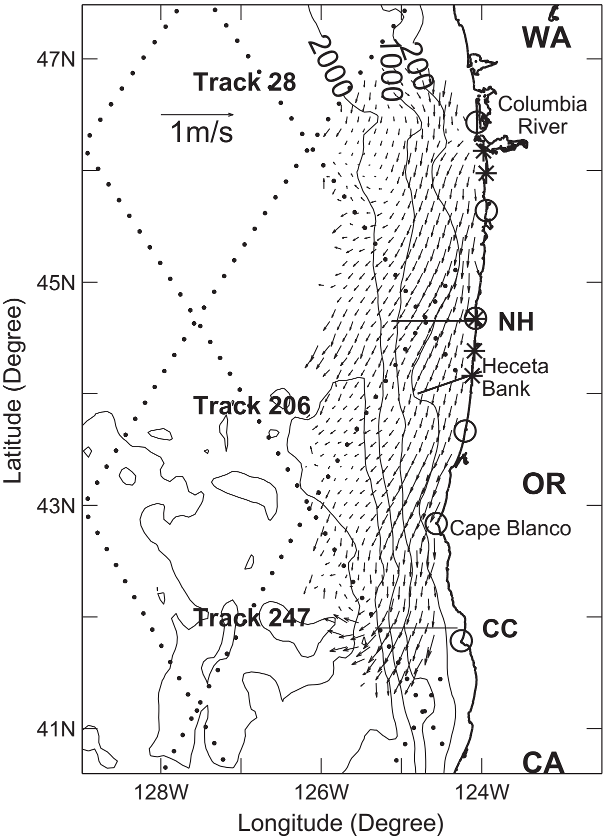

Fig. 1. Model bathymetry and observation locations (arrows: mapped surface currents from HF radars averaged over June and July 2008, dots: Jason-1 altimeter tracks; also shown are NH and CC hydrographic survey sections). Locations of radars are shown as circles (long-range) and asterisks (standard-range). Bathymetric contours are 200, 1000, and 2000 m.

extensive surface current observation network such as the one off Oregon provides a unique opportunity to constrain model estimates of processes that determine shelf-interior ocean exchange.

Earlier studies have shown advantages of assimilating HF radar data (Lewis et al., 1998; Breivik and Saetra, 2001; Oke et al., 2002a; Shulman and Paduan, 2009; Barth et al., 2008; Wilkin et al., 2005; Zhang et al., 2010). To the best of our knowledge, there has not been a study showing a positive impact of surface velocity assimilation on the geometry of the SST front, which will be one of the points of this presentation. One of the features of our assimilation approach is the use of the four-dimensional variational (4DVAR) representer-based DA method (Bennett, 2002; Kurapov et al., 2007, 2009, 2011). It is implemented in a series of time intervals, providing both time and space interpolation of the assimilated data sets in each window, using interpolation (covariance) structures that depend on the time-varying background solution.

2. The model

The nonlinear forecast model component of the DA system is based on the Regional Ocean Modeling System (ROMS, version 3.2, www.myroms.org), a hydrostatic, Boussinesq, primitive equation ocean model with a free surface and a terrain-following vertical *s*-coordinate, featuring advanced numerics (Shchepetkin and McWilliams, 2005). The Mellor–Yamada Level-2.5 subgrid turbulence scheme is utilized in the vertical (Mellor and Yamada, 1982). Harmonic horizontal tracer diffusion and momentum dissipation are implemented along *s*-surfaces with the diffusion and dissipation coefficients equal to 10 m^2/s.

The model domain extends from 40.5°N to 47.5°N, covering the entire Oregon coast and parts of the Washington and California coasts, and from 123.7°W to 129°W, extending more than 300 km offshore (see Fig. 1). The regular horizontal grid is defined in spherical polar coordinates. The resolution is approximately 6-km in each horizontal direction with 15 levels in the vertical. The minimum water depth along the coast is set at 40 m. The resolution of this model is modest compared to those used in our recent process-oriented studies of circulation off Oregon [3-km (Springer et al., 2009; Koch et al., 2010) and 1-km (Osborne et al., 2011)] to facilitate faster turnout of variational DA runs (which can be on the order of 10–100 times as expensive in terms of computational time as a single nonlinear model run).

No-normal-flow and free-slip boundary conditions apply to velocities along the coast. The other three boundaries (north, south, and west) are open with conditions provided by the daily-averaged outputs of the regional Navy Coastal Ocean Model of the California Current System (NCOM CCS; Shulman et al., 2004). NCOM had a 9–10 km resolution in the horizontal and utilized hybrid coordinates in the vertical (with 19 terrain-following layers in the upper 138 m and *z*-coordinates below). Atmospheric forcing for NCOM was obtained from the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS, Doyle et al., 2008). Differences in our free-run ROMS solutions and NCOM can in part be explained by the different atmospheric forcing and vertical discretization. Note that NCOM-CCS did assimilate data through a multi-stage process involving empirical three-dimensional (3D) projection of satellite SSH and SST maps using archives of temperature and salinity (Fox et al., 2002) and model nudging.

The bulk flux formulation (Fairall et al., 1996) is used to calculate the surface momentum and heat fluxes in ROMS. Atmospheric fields, including wind speed, air temperature, relative humidity, and atmospheric pressure, are obtained from the 12-km resolution North America Mesoscale Model (NAM) forecast archives (http://nomads.ncdc.noaa.gov/data.php). A 40-h low-pass filter was applied to the atmospheric parameters used for surface forcing computation, in part for consistency with the available boundary data time series. Filtering the wind speed can reduce the peak stress values. While this is admittedly a shortcoming in our formulation, no model bias was found compared to the surface velocity data (Fig. 2).

Although the tangent linear (TL) and adjoint (ADJ) components are now included in the standard ROMS distribution (Moore et al., 2011), in this application we have used our own, stand-alone TL and ADJ codes AVRORA [Advanced Variational Regional Ocean Representer Analyzer, see (Kurapov et al., 2009, 2011)], which are dynamically and algorithmically consistent with ROMS. Using AVRORA, instead of the DA component integrated in ROMS, has allowed us additional flexibility implementing and studying effects of different initial condition error covariances, data functionals (see Kurapov et al., 2011), and other aspects of the DA system. ROMS, AVRORA, routines facilitating model error covariance implementation, and other elements of the variational method implementation are utilized as stand-alone executables coupled via C shell scripts. TL&ADJ AVRORA allows finding corrections to the initial conditions (including SSH ζ, two components of horizontal velocity u and v, temperature T, and salinity S) and wind stress (not corrected in this study). Similar to ROMS, the output state of AVRORA is defined as fields of SSH, u, v, T, and S provided at all the grid points at equal time intervals (every 4 h in our case). Using AVRORA, any observation, defined as a linear combination of the elements of the multivariate time-and-space-discrete model state, can be assimilated without making any changes to the TL model and its ADJ counterpart. For instance, daily-averaged surface velocity data can be easily matched to the daily-averaged model output. Also, the SSH slope from altimetry can be assimilated to correct