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Impacts of a 4-dimensional variational data assimilation in a coastal ocean model of southern Tyrrhenian Sea

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ABSTRACT

The impact of the assimilation of satellite sea surface height, sea surface temperature and surface velocity fields observed by a set of high-frequency (HF) radars is studied using a three-dimensional ocean circulation model configured for the southern Tyrrhenian Sea. The study period is October–December 2010 covered by a large number of data. The nonlinear model is based on the Regional Ocean Modeling System (ROMS) and the data assimilation component on the four-dimensional variational (4D-Var) algorithm.

Assimilation proceeds in a series of 7-day windows, providing an analysis solution in each window.

The assimilation of surface velocity combined with other observations has more utility in recovering the density fields based on the theory of geostrophic adjustment and a strong impact both on near-surface horizontal volume fluxes and subsurface flows, constraining surface geostrophic currents in the area not covered by the HF radar data.

The adjoint of the 4D-Var gain matrix was used to quantify the impact of individual observations and observation platforms on different aspects of the 4D-Var circulation estimates during both the analysis and subsequent forecast cycles. In this study, we focus on the alongshore transport of the surface and intermediate waters in the eastern zone of southern Tyrrhenian Sea. The majority of the observations available during any given analysis cycle are from HF radar, and on average these data, together with SSH data, exert the largest controlling influence on the analysis increments of coastal transport. Also, observations from satellite platforms in the form of SST have a considerable impact on analyses and forecasts of coastal transport, even though these observations represent a relatively small fraction of the available data at any particular time.

During 4D-Var, the observations are used to correct for uncertainties in the model control variables, namely, the initial conditions, surface forcing, and open boundary conditions. It is found that correcting for uncertainties in the initial conditions and only secondarily in the boundary conditions has the largest impact on the analysis increments in alongshore transport.

Finally, we note that both the control vector and the observation impact calculations are a useful way for monitoring the performance of the data assimilation system, as well as quantifying the impact of the observations on the circulation estimates.

1. Introduction

State-of-the-art numerical ocean models are widely used in coastal oceanography to simulate the three-dimensional circulation of limited area domains for studies of regional ocean dynamics, biogeochemistry, geomorphology, and ecosystem processes.

When operated as real-time now-cast or forecast systems, these models offer predictions that assist decision makers on issues related to water quality and public health, coastal flooding, shipping, maritime safety, and other applications. The dynamic ocean state estimate provided by ocean circulation models critically depends on the model boundary conditions, as well as on its capability to resolve the water parameters, both spatially and temporally.

However, research and development in technology over the last three decades have substantially improved coastal ocean observing systems, e.g. by buoys, satellites, moorings, coastal radars, etc. These advanced ocean observing systems now provide a large volume of ocean measurements in real-time, addressing the traditional "scarcity" of observational data in oceanography.

The increasingly available ocean observations are appropriate for establishing "data assimilation" (hereafter DA) approaches, a series of mathematical techniques of growing complexity in which observational

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data are dynamically combined with numerical models in order to obtain the best representation of the ocean state. The use of complex DA approaches provide better results with respect to those obtained by using only the numerical model or by analyzing the observational data alone (Anderson et al., 1996). The key point about DA techniques is that oceanic observations are sparse and numerical models are limited in accuracy; but if taken together, they may yield a quantitative description of the state of the ocean that is superior to either models or data alone.

DA can be used at different scales and in various applications to integrate diverse available data sets with dynamical models in order to perform more accurate process studies; to provide a foundation for hypothesis testing and model improvement, including estimating model and data errors (uncertainty modeling); to initialize ocean models, or the ocean component of coupled models, and assimilate subsequent observations for optimal forecasting; to estimate model parameters and parameterizations, including forcing and lateral boundary conditions, and provide the means to assess observing systems, measure the usefulness of new data, and collect the most useful observations through adaptive sampling; eventually, to obtain a better understanding of the ocean.

The assimilation of satellite-derived data can be considered nowadays as an advanced and widespread activity (e.g. Dombrowsky et al., 2009; Lellouche et al., 2013; Pinardi and Coppini, 2010), even in coastal regions of the Mediterranean Sea, as demonstrated by the works of Vandenbulcke et al. (2006) in the Gulf of Lions, Korres et al. (2009) in the Aegean Sea, and Olita et al. (2012, 2013), respectively, in the Sicily Channel and in the western Sardinian Sea.

In particular, there is a large body of literature dealing with assimilation of satellite data using variational techniques. The time-dependent variational method is one DA approach largely applied to studies of ocean variability on regional and coastal scales, as demonstrated by various works in literature. Hoteit and Köhl (2006) applied an adjoint data assimilation in the eastern subtropical North Atlantic using in situ and satellite data as constraint. Powell et al. (2008) presented the theory and application results of the incremental 4DVAR assimilation method in ROMS in the Intra-Americas Sea using remotely sensed surface observations including sea surface temperature (SST) and sea surface height (SSH).

Other regional applications of variational technique are those of Broquet et al. (2009a) to the California Current System as well as the work of Chao et al. (2009); Kuparov et al. (2009, 2011) to a coastal ocean model off the western coast of the U.S; Zhang et al. (2010) to a coast domain in the center of the Mid-Atlantic Bight; Janekovic et al. (2013) to a coastal domain of Hawaiian islands.

The assimilation of velocity data is a recent phenomenon and is still evolving, although radar observational systems are potentially one of the most important data sets for coastal ocean state estimation (Paduan and Washburn, 2013).

One of the earliest DA studies using high-frequency (hereafter HF) radar data was reported by Lewis et al. (1998) for the Monterey Bay, CA, in which a pseudo-shearing stress, defined as the difference between the model surface current and HF radar data, was used to correct the model wind forcing. Breivik and Sætra (2001) reported HF radar surface current assimilation into a realistic coastal model for the Norwegian coast using an optimal interpolation (OI) method. An HF radar DA study for the Oregon coast was reported by Oke et al. (2002b), which used a sequential OI scheme based on the physical-space statistical analysis system (PSAS), and a time-distributed averaging procedure (TDAP). A representer-based 4-dimensional variational method (4D-Var) (Bennett, 2002) was used by Kurapov et al. (2003) to assimilate HF radar data into a simplified ocean model. Paduan and Shulman (2004) assimilated HF radar data using a PSAS scheme based on data-dependent velocity covariance functions in the Monterey Bay, CA.

Assimilation of HF radar data using a melding/nudging approach was reported by Wilkin et al. (2005) for the New Jersey inner-shelf. Barth et al. (2008) assimilated HF radar surface currents in the West Florida shelf using an ensemble-based error covariance method. Li et al. (2008) have used a three-dimensional variational assimilation (3D-Var) of HF radar data in the Southern California on an operational basis. A 4D-Var method was used by Hoteit et al. (2009) to assimilate HF radar data in the San Diego coastal region. More recently, Shulman and Paduan (2009) reported assimilation of HF radar-derived radial/total surface currents using PSAS scheme for the Monterey Bay, CA. In Gopalakrishnan and Blumberg (2012), a surface current observation system based on HF radar has been developed for the Raritan Bay, NJ, and the coastal waters of New York and New Jersey. The impact of the HF radar DA is analyzed by computing the DA skill by comparing (non-assimilated/assimilated) model solutions with *in situ* observations of three-dimensional currents, temperature, and salinity which have not been included in the assimilation.

In Yu et al. (2012), the impact of assimilation of sea surface velocity fields observed by a set of HF radars was studied using a three-dimensional ocean circulation model configured along the Oregon coast. The nonlinear model was based on the ROMS and the DA component on a system utilizing the representer-based variational algorithm.

Among the Italian coastal zones, the Gulf of Naples (hereafter GoN), and the surrounding area of the southern Tyrrhenian Sea, represent a particularly interesting area that is influenced by numerous environmental, socio-economic, and interacting cultural factors (strong anthropogenic impact, intense maritime traffic, the presence of the polluted Sarno River, tourist and economic activity, and four protected areas). Thus, pollutant release in this basin may have serious consequences in terms of the environmental sustainability and management of the coastal area.

For these reasons, a comprehensive understanding of the coastal circulation in this basin is of fundamental importance for proper planning and management of the coastal area and for the maintenance and improvement of environmental quality in the GoN.

The peculiar dynamics of the GoN qualify the region as a natural challenging laboratory for testing the skill of coastal ocean models and data assimilation methodologies.

Here we proceeded to implement a limited area ROMS (Shchepetkin and McWilliams, 2005) model in the southern Tyrrhenian Sea and a 4-dimensional variational data assimilation system was applied in the model domain using HF radar data, satellite sea surface height (SSH), and surface temperatures (SST).

The expected goal of this study was to assess the effects of the HF radar data, together with surface data coming from satellite in the form of SST and SSH on a coastal modeling system of the GoN area and surroundings.

In particular, we focus here on the impact of the observations on the 4D-Var circulation which is one of the many capabilities of the ROMS 4D-Var system (Moore et al., 2011c).

As described in Moore et al. (2011c), the observation impact calculations can be used to quantify the contribution of each individual datum to the difference between the background (or prior) and the analysis (or posterior) of some aspect of the ocean circulation and can also demonstrate the influence of initialization shocks on the circulation that are associated with each individual observations.

The observation impact calculations presented here are based on an adjoint approach and utilize the property of adjoint operators for identifying the subspace of the model state vector that is activated by the observations. While adjoint-based methods have been used previously in oceanography in attempts to identify optimal observing locations and observation types (e.g. Köhl and Stammer, 2004; Zhang et al., 2010), our focus here is on the impact of existing observations on estimates of the ocean circulation, following the approach originally developed in meteorology by Langland and Baker (2004), Daescu (2008), Zhu and Gelaro (2008), and Gelaro and Zhu (2009) and in oceanography by Moore et al. (2011c).

Our primary focus is the winter circulation in the vicinity of a coastal area of the southern Tyrrhenian Sea (namely, the Campania region