Journal of Marine Systems xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Assimilating Ferry Box data into the Aegean Sea model

G. Korres *, M. Ntoumas, M. Potiris, G. Petihakis

Institute of Oceanography, Hellenic Centre for Marine Research, 46,7 km Athens Sounio ave. P.O. Box 712, P.C. 19013, Anavyssos, Attiki, Greece

ARTICLE INFO

Article history:
Received 31 August 2013
Received in revised form 28 February 2014
Accepted 28 March 2014
Available online xxxx

Keywords:
Aegean Sea
Data assimilation
SEEK filter
FerryBox
POSEIDON system

ABSTRACT

Operational monitoring and forecasting of marine environmental conditions is a necessary tool for the effective management and protection of the marine ecosystem. It requires the use of multi-variable real-time measurements combined with advanced physical and ecological numerical models. Towards this, a FerryBox system was originally installed and operated in the route Piraeus–Heraklion in 2003 for one year. Early 2012 the system was upgraded and moved to a new high-speed ferry traveling daily in the same route as before. This route is by large traversing the Cretan Sea being the largest and deepest basin (2500 m) in the south Aegean Sea. The HCMR Ferry Box is today the only one in the Mediterranean and thus it can be considered as a pilot case. The analysis of FerryBox SST and SSS in situ data revealed the presence of important regional and sub-basin scale physical phenomena, such as wind-driven coastal upwelling and the presence of a mesoscale cyclone to the north of Crete. In order to assess the impact of the FerryBox SST data in constraining the Aegean Sea hydrodynamic model which is part of the POSEIDON forecasting system, the in situ data were assimilated using an advanced multivariate assimilation scheme based on the Singular Evolutive Extended Kalman (SEEK) filter, a simplified square-root extended Kalman filter that operates with low-rank error covariance matrices as a way to reduce the computational burden. Thus during the period mid-August 2012–mid January 2013 in addition to the standard assimilating parameters, daily SST data along the ferryboat route from Piraeus to Heraklion were assimilated into the model. Inter-comparisons between the control run of the system (model run that uses only the standard data set of observations) and the experiment where the observational data set is augmented with the FerryBox SST data produce interesting results. Apart from the improvement of the SST error, the additional assimilation of daily of FerryBox SST observations is found to have a significant impact on the correct representation of the dynamical dipole in the central Cretan Sea and other dynamic features of the South Aegean Sea, which is then depicted in the decrease of the basin wide SSH RMS error.

1. Introduction

The South Aegean Sea is situated in the central part of Eastern Mediterranean, a marginal Sea with densely populated coastal areas. The advanced technological societies surrounding the Mediterranean exert considerable pressure on its marine ecosystem; agriculture, fishery, tourism, commerce, industrial and urban waste to mention a few. To add to these questions, global issues such as climatic change (Giorgi and Lionello, 2007) and the consequent ocean acidification (Arnold et al., 2012) combined with regional ones, e.g. Lessepsian migration (Azzurro et al., 2012); rapidly alter the area's “living map” with unpredictable consequences (Galil, 2012). The Aegean and Ionian Seas surrounding Greece constitute one of the main links of Europe to the Eastern Mediterranean and Russia. Therefore, these waters serve as the main routes of oil transportation to Europe, which results in a continuous pressure to the marine environment. Recent developments in naval architecture lead to a growth of the amount of oil transport throughout the Aegean Sea. The continuously increasing oil traffic in the area coupled with the increased size of tankers and the large number of scattered islands and ports situated at short distances from international shipping routes result in a high risk of a serious accidental pollution. Accurate predictions of the hydrodynamic component of integrated ocean forecasting systems, such as POSEIDON, are crucial for the realistic reproduction of in situ observations as other components of the system such as the POSEIDON Oil Spill Model (Perivoliotis et al., 2006) and the Ecosystem Model (Petihakis et al., 2002) are significantly affected from the outputs of the hydrodynamic model (HD). Oil spill chemical transformation in time depends on the hydrographic characteristics of the water column and their drift is dictated by currents, which are produced as prognostic variables by the HD model. Recent work in the Eastern Mediterranean showed that the accurate circulation obtained from an operational system can achieve more realistic predictions of oil spill drift and reduce deviations between forecasts and observations, compared to non-operational hindcast model runs. From the perspective of ecosystem forecasts, the HD model outputs force coupled ecological

* Corresponding author at: Hellenic Centre for Marine Research, P.O. Box 712, 19013, Anavyssos, Greece. Tel.: +30 22910 76400.
E-mail address: gkorres@hcmr.gr (G. Korres).

http://dx.doi.org/10.1016/j.jmarsys.2014.03.013
0924-7963/

models whose output validity, at least in the case of complex 3D setups, heavily depends on the physical characteristics of circulation patterns, such as advection or vertical diffusivity (Petihakis et al., 2012; Skliris and Djenidi, 2006; Triantafyllou et al., 2003). Moreover, the oligotrophic nature of the Aegean and the restricted spatial extension of relative high primary productivity areas such as the continental shelf of Thrace Sea, are to be accounted for, as the fisheries stocks are reported to be under severe pressure due to overwhelming exploitation (Politikos et al., 2012; Stergiou and Pollard, 1994); ecological modeling can provide a valuable assistive tool for the effective management of coastal systems (Petihakis et al., 2012). Thus, realistic modeling of circulation patterns and hydrographic characteristics is the corner stone for successful ecosystem (Campbell et al., 2013) and pollution assessment (Coppini et al., 2011), improving at the same time management of biological resources.

Acknowledging the significance of the accelerating transitions, as well as the necessity for sustainable utilization of biological resources, EU maritime policy makers created, funded and implemented the frameworks required to describe the state of the ecosystem over the last decades, identify the most important marine processes across many disciplines (physical, biological, chemical, geological), evaluate the results and propose viable solutions. The comparatively smaller dimensions of the Mediterranean make this semi-enclosed sea suitable for research studies whose advances will directly satisfy societal needs. Towards the prospect of not only keeping functional the present installations but invigorating them too to extend Aegean's monitoring capacity, HCMR installed on the High-speed Ferry Olympic Champion a FerryBox (FB) monitoring system, the only one in the Mediterranean hitherto. The FerryBox (Petersen et al., 2007) is an automated system, usually installed on ferries or cargo ships, used for measuring physical and biogeochemical parameters of surface waters along the ship's route.

Both the FB and the Aegean Sea hydrodynamic model are parts of the Poseidon monitoring, forecasting and information system (http://www.poseidon.hcmr.gr/). The POSEIDON was developed in 1997–2000 and has been operational since then with various upgrades through national and EU funded projects (Nittis et al., 2010; Soukissian et al., 2002). It includes multiple observing components (Buoys, FerryBox, HF Radar) and a complete set of atmosphere and ocean forecasting models (meteorological, hydrodynamics, waves, ecosystem). It has undergone several additions and upgrades and today offers a wide variety of services (Oil Spill Drifts, FerryBox, HF remote sensing) and products (Sea State, Ocean and Ecosystem forecasts) for the Greek Seas.

The main objective of Phase II of the POSEIDON system development was to upgrade and extend the operational monitoring and forecasting capacity of the system in the Eastern Mediterranean Sea in order to support the requests of environmental information for integrated marine ecosystem management and maritime safety on a national and regional scale. Specific objectives of the project were to upgrade the existing forecasting capability by improving the model's resolution, introducing non-hydrostatic models and appropriate assimilation schemes and to move towards a pre-operational capacity for ecosystem forecasting.

Any ocean monitoring and prediction system must rely on the integrated use of available remotely sensed and in situ measured ocean observations coupled with models in order to achieve the best possible estimation of the true state of the ocean. Data assimilation is the method used to blend ocean observations of various types and model dynamics minimizing errors in ocean simulations due to missing dynamics and inaccurate ocean forcing, and to extrapolate observations of surface properties into the ocean interior. Assimilation techniques can be classified into two classes: sequential approach and variational approach (Ghil and Malanotte-Rizzoli, 1991). Sequential methods proceed by incrementally correcting the discrepancy between observations and a model prediction based on prior information about uncertainties in the model and data. Variational methods seek to minimize the misfit between data and model trajectory over a given period of time through the adjustments of a set of control parameters. For linear dynamics the sequential Kalman filter produces the same state at the end of the assimilation period as the variational methods provided that the error statistics are known. In spite that, sequential methods are more suitable for data assimilation in high resolution models as the behavior of the cost function of variational methods can be problematic in highly nonlinear models (Hoteit et al., 2005).

Sequential methods are generally based on the Kalman filter which is only optimal for linear models (Ghil and Malanotte-Rizzoli, 1991). The Kalman filter recursively generates an optimal analysis, in the least-square sense, of the state of a linear system given a set of measurements. It operates in two steps starting from an initial estimate of the state and the corresponding error covariance matrix: (i) forecast step using the dynamical model, and (ii) analysis step to correct the forecast each time new observations are available. In the work we use the Singular Evolutive Extended Kalman (SEEK) filter an alternative to the Kalman filter, designed for data assimilation with realistic ocean models (Pham et al., 1997). SEEK filter uses the tangent linear model to evolve the error covariance matrix being at the heart of the filter functioning.

The hydrodynamic modeling and data assimilation component of the POSEIDON system is composed of a Mediterranean ~10 km resolution model along with nested models that downscale the basin scale solution up to the resolution of approximately 3 km on the Aegean and Ionian Seas. A data assimilation scheme based on the Singular Evolutive Extended Kalman (SEEK) filter and a multivariate set of observations including upon their availability satellite SSH and SST data, ARGO floats T/S profiles and XBT in order to periodically correct the ocean states forecasted by the Mediterranean model. SEEK is a simplified EK filter in which computational cost reduction is achieved through the approximation of the EK filter error covariance matrices by singular low-rank matrices (Pham et al., 1998). The SEEK filter has been successfully implemented in different ocean models (e.g. Ballabrera et al., 2001; Hoteit et al., 2002, 2003; Korres et al., 2007). Covariance localization first proposed by Houtekamer and Mitchell (2001) was then applied by Nerger et al. (2006) to the SEIK filter and by Korres et al. (2009, 2010, 2012) to the SEEK filter using high resolution hydrodynamic models. In the version of the filter used in the POSEIDON forecasting system, a finite number of directions are selected in the state-space and the model forecast state is then corrected with the new observations along these directions only in order to intermittently bring back the system to its most probable trajectory. These “directions of correction” further evolve in time with the tangent linear model to follow changes in the system dynamics.

The assimilation system for the Aegean Sea hydrodynamic model has been presented in the works of Korres et al. (2009, 2010). It is based on the SEEK filter with covariance localization and partial evolution of the correction directions. In the framework of FerryBox EU research project (http://www.ferrybox.org/eu_project_ferrybox/i), daily Ferrybox SSS data along ferry tracks from Piraeus to Heraklion were successfully assimilated for the first time into a pre-operational version of the Aegean Sea model for a test 6-month period (Jan–Jun 2004) using a localized version of the SEEK filter (Korres et al., 2009). In this work assimilation experiments (retaining and not retaining the SSS observations) had been performed in order to validate the system and to demonstrate its effectiveness in assimilating a multivariate set of satellite SSH, SST and FB SSS measurements. It must be noted that the additional assimilation of the FB SSS data carried out in another 6-month experiment demonstrated their important but geographically localized impact on the hydrology of the southern Aegean Sea where the FB tracks were referring to.

The main purpose of this paper is to present some salient oceanic features of the South Aegean that were successfully modeled by the HCMR version of POM model using FB assimilated data and evaluate the advantage of this paired observing-modeling effort. For completeness we also synoptically refer to the model assimilation techniques, the area's phenomenology, the technical–functional characteristics of FB and the results from in situ data analysis. The rest of the paper is organized as follows. In the section that follows we present the