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Mesoscale vortices in the Ligurian Sea and their effect on coastal upwelling processes

Elisa Casella [a,*], Anne Molcard [b], Antonello Provenzale [c]

[a] CIMA Research Foundation, University Campus, Via Armando Magliotto 2, I-17100 Savona, Italy
[b] Laboratoire de Sondages Electromagnétiques de l'Environnement Terrestre (LSEET), Université du Sud Toulon-Var, Batiment F, BP 20132, 83957 La Garde Cedex, France
[c] Istituto di Scienze dell'Atmosfera e del Clima (ISAC), Consiglio Nazionale delle Ricerche, Corso Fiume 4, I-10133 Torino, Italy

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ABSTRACT

We study numerically the dynamics of intense anticyclonic eddies in the Ligurian Sea (NW Mediterranean Sea). To this end, we use the Regional Ocean Modeling System (ROMS) with a resolution of 3 km for a domain covering the whole Ligurian Sea, with an embedded child grid covering the northwestern part of Ligurian Sea at resolution 1 km. The model is forced with daily boundary conditions obtained from the MFS dataset for the year 2006 at the open lateral boundaries. Surface heat and evapotranspiration fluxes are provided by the monthly climatological dataset COADS at 1/2° spatial resolution. For wind forcing, we consider two configurations. In the first setting, the model is forced by the COADS climatological monthly mean wind stresses; in a second configuration, the model is forced by the daily mean wind stresses provided by a mesoscale meteorological model for the area of interest in the year 2006. The latter setting shows the formation of intense anticyclonic eddy structures in the coastal area, generated by the variable winds and by the interaction of transient currents with bottom and coastal topography (in the NW part of the Ligurian Sea). Comparison of model output with satellite SST data shows definite agreement between numerical results and observations. Analysis of the simulation results over the whole year 2006 and of SST satellite images in 2006 and 2007 indicates that coastal anticyclonic eddies are of common occurrence in the Ligurian Sea, with several events per year, mainly concentrated in autumn and winter. The eddies are characterized by a complex pattern of intense vertical velocities and induce strong, long-lasting coastal upwelling events. For this reason, anticyclonic vortices in the coastal area can generate bursts of nutrient input in the euphotic layer and contribute to the fertilization of the Ligurian Sea, with potentially important effects on the dynamics of phyto- and zooplankton.

1. Introduction

The northwestern Mediterranean Sea displays several characteristics that make this region a good test area for modelling studies (Mounier et al., 2005). The Liguro-Provençal-Catalan current flows cyclonically along the coasts of Italy, France and Spain. Millot (1991) has shown that the major surface currents flowing along the coastal slope are affected by instability processes that generate mesoscale eddies, capable of inducing relatively intense currents and producing significant dynamical heterogeneity of the hydrological characteristics in this area. Molcard et al. (2002) have suggested that the main features of the general circulation are induced by the structure of the wind stress curl, pointing out that the magnitude and spatial variability of the wind is essential in determining characteristics of the local circulations.

The presence of mesoscale eddies is well documented in the western Mediterranean Sea and in the Ligurian Sea. For example, Santoleri et al. (1983) and Marullo et al. (1985) discuss observations of small submesoscale eddies ascribed to the baroclinic instability of the coastal current. The hydrographic measurements discussed by Gasparini et al. (1999) indicate the presence of winter intermediate water lenses, suggested to be the product of the sinking of water in the central region of the basin. A summary of the properties of the circulation in the Mediterranean Sea, including the dynamics of mesoscale eddies in the Ligurian Sea, is given by Robinson et al. (2001). Numerical simulations with regional models confirm the presence of intense mesoscale and submesoscale activity in the Ligurian Sea (Echevin et al., 2003).

In coastal regions and in the open ocean, mesoscale and submesoscale vortices play a crucial role in determining transport processes and the statistical properties of the mesoscale turbulence field (Provenzale, 1999; Bracco et al., 2000; 2003). In addition, eddies can significantly affect the dynamics of the marine ecosystem (Jenkins, 1988; Falkowski et al., 1991; McGillicuddy and Robinson, 1997; Abraham, 1998; Martin et al., 2002; Lévy and Klein, 2004; Pasquero et al., 2005). A particularly important aspect of mesoscale and submesoscaled eddies, rooted in the ageostrophic nature of the intense circulations associated with strong vortices, is the fact that

* Corresponding author. Tel.: +39 019 230271.
E-mail address: elisa.casella@cimafoundation.org (E. Casella).

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they can generate significant upward and downward vertical velocities, up to 50 m/day, that are comparable with the strongest velocities found in proximity of frontal areas, as shown by Koszalka et al. (2009) in a study of coherent vortices in an idealized primitive-equation configuration representing the open ocean. Similarly, shallow-water mesoscale vortices impinging on a coastal slope generate a complex pattern of strong vertical velocities (Zavala Sanson and Provenzale, 2009). Such an intense vertical velocity field provides a link between the nutrient-rich deep waters and the upper layer where phytoplankton thrive. For this reason, mesoscale and submesoscale eddies can play an important role in the fertilization of the euphotic layer of the ocean.

In this work we use the ROMS (Regional Ocean Modelling System) model and study numerically the dynamics of the Liguro-Provençal-Catalan current. We show that the coastal current undergoes meandering associated with the presence of intense anticyclonic mesoscale and submesoscale eddies in the Ligurian Sea. Vortex generation is particularly efficient when high-resolution wind forcing, instead of climatological wind forcing, is adopted, confirming the importance of the interaction between variable winds, surface currents and topographic features. The anticyclonic eddies are associated with strong upwelling and can thus provide an intermittent nutrient input into the Ligurian Sea. In addition, the intensity of the vertical velocity field increases when high-frequency wind forcing is adopted.

The rest of this paper is organized as follows. Section 2 provides a description of the principal characteristics of the ROMS model, with details on the configuration used for the Ligurian Sea and on the atmospheric and marine forcings used in this work. The analysis of the simulations and the results are presented in Section 3. Discussion and conclusions are given in Section 4.

2. Description of the numerical model

The Regional Ocean Modeling System (ROMS) is a new-generation ocean circulation model (Shchepetkin and McWilliams, 2003, 2005) that has been designed for simulation of regional oceanic system. ROMS solves the flow primitive equations in an Earth-centered rotating environment, based on the Boussinesq approximation and hydrostatic vertical momentum balance. The prognostic variables are surface elevation, potential temperature, salinity, barotropic and baroclinic horizontal velocity components. The 2D and 3D equations are time-discretized using a third-order accurate predictor (Leap-Frog) and corrector (Adams-Moulton) time-stepping algorithm. In the vertical, the primitive equations are discretized over variable topography using stretched terrain-following coordinates (Song and Haidvogel, 1994). Stretched coordinates allow for increased resolution in the areas of interest, such as the thermocline and the bottom boundary layer. In this configuration we use centred, second-order finite differences on a staggered vertical grid.

On the horizontal, the primitive equations are evaluated using boundary-fitted, orthogonal coastline curvilinear coordinates on a staggered Arakawa C-grid. As in the vertical, the horizontal stencil utilizes a centred, second-order finite differences. Advection is computed with a third-order, upstream-biased scheme. This scheme has a velocity-dependent, hyper-diffusion dissipation as the dominant truncation error and it allows the generation of steep gradients, enhancing the effective resolution of the solution for a given grid size (Shchepetkin and McWilliams, 1998). The horizontal mixing of momentum is along geopotential surfaces. The vertical mixing parameterisation in this configuration is a non-local, K-profile planetary (KPP) boundary layer scheme which parameterises unresolved physical vertical subgrid-scale processes. Explicit lateral viscosity is set to zero everywhere in the model domain except in sponge layers near the open boundaries, where it increases smoothly close to the open lateral boundaries. At the lateral boundary facing the open ocean, an active, implicit, upstream-biased radiation condition connects the model solution to the surroundings (Marchesiello et al., 2001). The time step is chosen from the CFL criterion.

In the runs discussed in this work, the model domain includes the northwestern part of the Mediterranean Sea, i.e. the Ligurian Sea, from 42.5° N to 44.5° N and from 6.5° E to 11.1° E. The bottom topography, shown in Fig. 1, is based on the global topography dataset at 2′ resolution (Smith and Sandwell, 1997). In this figure one can see the major features characterising the Ligurian Sea domain, including the northern part of Corsica and the Elba island. In the model version adopted here (Ligurian Sea version, LS-ROMS) there are three open lateral boundaries: at 42.5° N, 6.5° E and 11.1° E. In the basic configuration of the LS-ROMS model used here we have chosen a horizontal resolution of 1/32°. At this resolution, the Rossby radius of deformation (of the order of 5–12 Km in the whole Mediterranean and for different seasons, see Grilli and Pinardi, 1998) is resolved and consequently the model configuration is adequate to simulate mesoscale structures. A reduced-domain model (the "child grid" model) with resolution 1 km is embedded in the "parent" model to better resolve the dynamics of intense coastal eddies. The domain of the child grid is located in the northwestern part of the study region and it extends from 6.8° E to 8.3° E and from 43° N to 44.1° N. The child grid is embedded in a one-way nesting within the parent grid: information on the state of the model is passed from the parent to the child grid at each time step, while no back-transfer from the child grid to the parent model occurs. Both grids have 32 vertical levels with vertical refinement near the surface, to obtain a satisfactory representation of the surface layer and the euphotic zone.

At the open lateral boundaries, the LS-ROMS model is forced with temperature, salinity and velocity fields obtained from the MFS dataset of the year 2006. MFS, the Mediterranean Forecasting System, is an operational model of the Mediterranean Sea. In MFS, the horizontal spatial resolution is 1/16° and the temporal resolution is daily. The code used in MFS is OPA (Ocean Parallelise), a primitive equation model which solves the Navier–Stokes equations in the approximation of thin-shell, Boussinesq, hydrostatic and incompressible fluid (Madec et al., 1998). Initial condition for the experiments reported here are provided by the state of the solution on January 1, 2006, obtained from the MFS operational model with data assimilation (Pinardi et al., 2003), and a continuously repeated 2006 run is made to ensure KE equilibrium. Since the LS-ROMS model has not the same horizontal and vertical resolution of the MFS model, horizontal and vertical linear interpolation of the MFS fields was necessary.

At the surface, we force the LS-ROMS model with the monthly-mean climatologies of heat and freshwater fluxes derived from the Comprehensive Ocean-Atmosphere Data Set, COADS (da Silva et al., 1994). COADS contains the global surface flux and wind-stress climatology at 1/2° spatial resolution and monthly temporal resolution. For wind-stress forcing, we adopt two different types of forcing: we use either the COADS monthly wind-stress data or the wind stresses obtained from a limited-area, non-hydrostatic model of the atmosphere at high spatial and temporal resolution. In this second forcing configuration, we use the winds and wind stresses provided by the Limited Area Model Italy (COSMO-I7) in the year 2006. COSMO-I7 (Marsigli et al., 2001; Montani et al., 2003), a non-hydrostatic and fully compressible numerical weather prediction model, is a regional version of the Lokal Model (Doms and Schattler, 1998) used for operational and research forecast in Italy. The runs used here have horizontal resolution 1/16° and temporal resolution 3 h (Steppeler et al., 2003). Validation of the COSMO-I7 wind fields has been widely performed, see also the scientific documentation available from http://www.cosmo-model.org/. From the 10-m COSMO-I7 wind speed, the wind stress has been calculated using bulk formulae (Large and Pond, 1981) which consider wind velocity-dependant drag coefficient. Also in this type of simulation, we use heat and freshwater fluxes provided by COADS at monthly timescale;