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A high-resolution ocean circulation model of the Gulf of Naples and adjacent areas(*)

P. de Ruggiero(**)

Dipartimento di Scienze per l'Ambiente, Università di Napoli "Parthenope"
Centro Direzionale Isola C4 - 80128 Napoli, Italy

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Summary. — The implementation of a high-resolution circulation model of a southern Tyrrhenian coastal area is discussed. The sigma-coordinate Princeton Ocean Model (POM) is implemented with a 1/144° resolution in a domain that includes highly urbanized coastal areas, such as the Gulf of Naples and the nearby gulfs of Gaeta and Salerno, that are particularly relevant from oceanographic, ecological and social viewpoints. The model takes initial and boundary conditions from a 1/48° resolution POM model of the whole Tyrrhenian Sea. The main forcing is provided by ECMWF wind data, but an alternative wind field obtained from the Italian Space Agency COSMO-SkyMed X-band Synthetic Aperture Radar data is also tested. Fundamental aspects of coastal modeling, such as the relative importance of local and remote forcing in semi-enclosed seas, and the sensitivity to different wind products are discussed.

PACS 92.10.-c – Physical oceanography.
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1. – Introduction

Understanding the dynamics of coastal waters is a very relevant issue not only from the physical oceanographic viewpoint, but also in a more general environmental perspective, as coherent and turbulent motions near the coasts affect the dispersion of pollutants, the water quality, the local ecology and, indirectly, social and economic aspects, especially in highly populated coastal zones. The application of state-of-the-art ocean circulation models to coastal environments are fundamental to this respect. If properly implemented, these theoretical tools can provide a synoptic picture of the local ocean climate, and can

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(**) E-mail: paola.deruggiero@uniparthenope.it

describe typical dynamic scenarios; moreover, models can even allow to forecast the sea state, especially if data assimilation is included in the treatment.

In this context, the implementation of a high-resolution circulation model of a Mediterranean coastal site is presented in this paper. In general, the main aim is to describe and analyze in detail a series of dynamical scenarios, to identify typical circulation patterns and variability for the different seasons, and to investigate the sensitivity of the model response to changes in several parameters, setups and forcing. Here we will focus on two specific aspects: the role played by the large-scale circulation in the coastal area, and the model sensitivity to the use of different wind products. For a more general treatment (that include a variety of simulations for different seasons of the identification of upwelling events, their relaxation and subsequent formation of Kelvin waves, and a significant experimental validation through current-meter measurements) see [1, 2].

The test site chosen for this study is a coastal area located in the Tyrrhenian Sea, a western Mediterranean sub-basin where very relevant oceanographic processes take place. The basin scale circulation yields an important interannual variability shaped by a strong seasonal cycle and energetic mesoscale features (*e.g.*, [3-6]). Local driving mechanisms are the heat, evaporative and momentum fluxes at the airsea interface, while an important remote forcing is provided by the fluxes of modified Atlantic and Levantine intermediate water masses through the Sardinia and Sicily straits (*e.g.*, [7-12]). In the south-eastern Tyrrhenian Sea a small semi-enclosed basin, the Gulf of Naples, is present: this is a very interesting zone, not only because it is ideal in terms of physical processes occurring in such a regular geometry, but also from environmental, social and economic viewpoints. The local circulation was analyzed both through experimental [13] and modeling studies (*e.g.*, [14, 15]). The modeling study presented in this paper refers to this same coastal area, but, as we will see, it also includes a wide buffer zone.

In sect. **2** the implementation of the sigma-coordinate Princeton Ocean Model (POM, [16]) to a southern Tyrrhenian coastal site, and its nesting with a Tyrrhenian Sea model are discussed. In sect. **3** the importance of the nesting and the relevance of SAR-derived winds in improving coastal circulation modeling are discussed. Finally, in sect. **4** conclusions are drawn.

2. – The model

The coastal area chosen as a test site within the Tyrrhenian Sea is defined by $\lambda = 13/15.36°$ and $\phi = 40/41.3°$: it includes the gulfs of Naples, Gaeta and Salerno and a wide outer buffer zone (fig. 1) necessary to couple this model with a larger-scale model of the Tyrrhenian Sea. The adopted circulation model is one of the most widely used community models in coastal applications. The sigma-coordinate vertical discretization of the governing equations allows one to have a sufficiently high number of vertical levels both in shallow and deep water, a particularly advantageous feature in coastal area such as the one under investigation. Our coastal model has been one-way nested with a POM Tyrrhenian Sea model (TSM, [17]), which is, in turn, nested with the NEMO-OPA (Nucleus for European Modelling of the Ocean-Ocean PArallelise) implemented in the Mediterranean at $1/16° \times 1/16°$ horizontal resolution and 72 unevenly spaced vertical levels [18]. The nesting (that follows the approach of [19]) has required the initialization of the hydrological and dynamical structure of the coastal model with data obtained from the TSM, and the prescription, along the open lateral boundaries, of dynamical boundary conditions derived, again, from the TSM. The adopted horizontal resolution, $1/144°$ (with $\Delta y \cong 772\,\text{m}$ and $\Delta x \cong 579$–$591\,\text{m}$), is 1/3 the resolution of the TSM (for

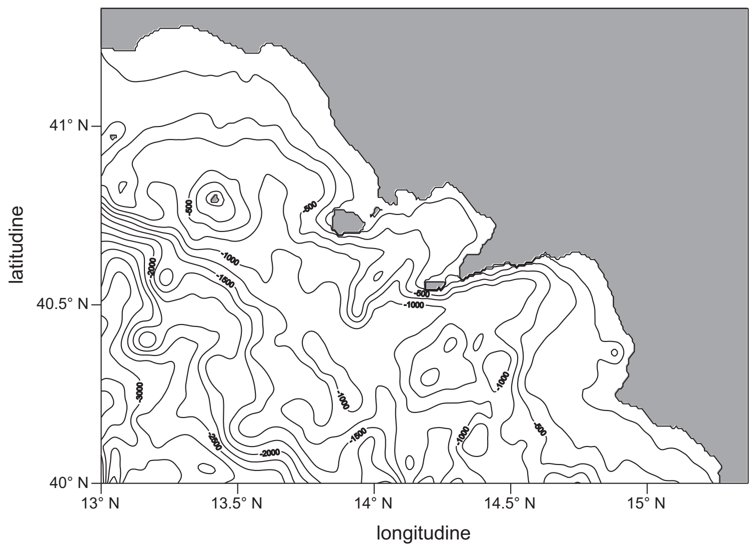

Fig. 1. – Domain of integration of the coastal circulation model, with water depth.

details of the nesting procedure see [2]). The vertical discretization makes use of 40 sigma-levels in both models, so as to allow for a smooth nesting. As for the bottom topography, the 30″ GEBCO (General Bathymetric Chart of the Oceans) data are used.

3. – Sensitivity experiments

Figure 2 shows an example of instantaneous current velocity maps at 1 m and 300 m depth obtained for Autumn 2010 under ECMWF ERA Interim Reanalysis forcing (with a horizontal resolution of 1/4°, which corresponds to ~ 27 km along a meridian and, in

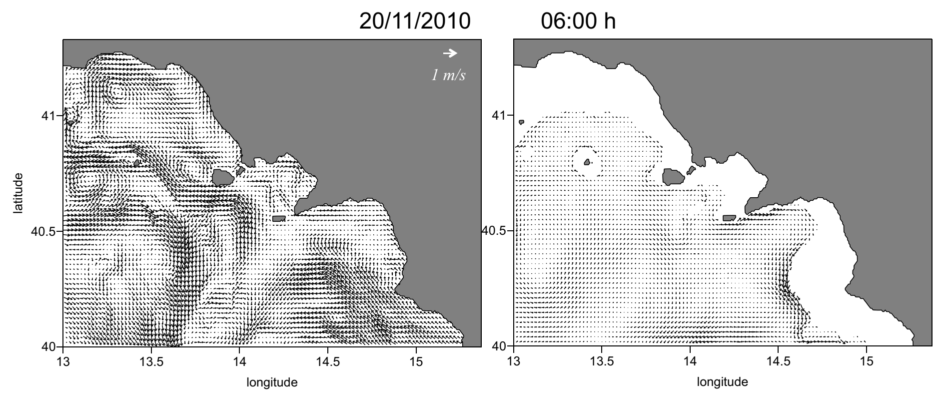

Fig. 2. – Surface current velocity map (left panel) of 20 November 2010 at 06:00 UTC obtained in a simulation with ECMWF forcing and with nesting with the TSM. Current velocity map at $z = 300$ m (right panel) for the same simulation at the same instant.

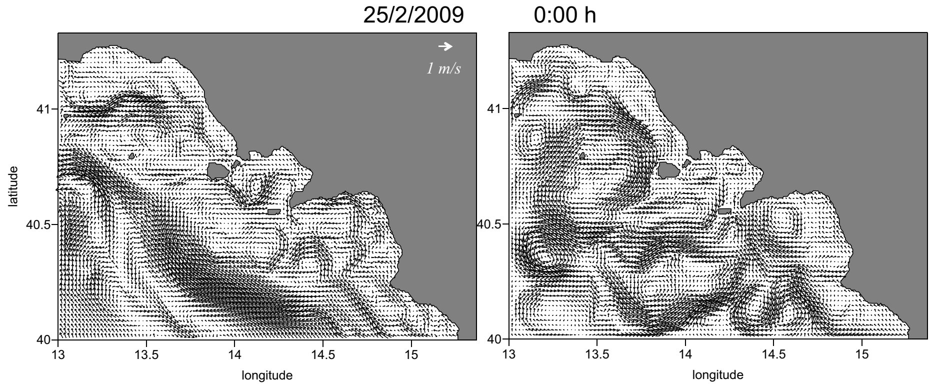

Fig. 3. – Surface current velocity map of 25 February 2009 at 00:00 UTC obtained in a simulation with ECMWF forcing, with (left panel) and without nesting (right panel).

the area under consideration, to $\sim 20\,\text{km}$ along a parallel). Figure 3 shows an example of the relevant role played by the large-scale Tyrrhenian circulation. The strong cyclonic circulation typical of the Tyrrhenian Sea in winter (*e.g.*, [4]) is clearly visible in the left panel, while it is absent without nesting (right panel). The difference in the circulation pattern, however, is not limited to the outer region, but affects considerably also the dynamics within the gulfs, as it is evident by comparing the two images near the coasts.

De Ruggiero *et al.* [2] present a variety of scenarios simulated for different seasons, and show that the ECMWF forcing is successful in simulating dynamical processes over a scale comparable to that of the full basin, but may fail to provide appropriate forcing on the scale of the gulf, especially in locations where strong orographic effects are present (such as those associated with mount Vesuvius and the mountains of the Sorrento peninsula in the Gulf of Naples). In this context, to assess the capability of synthetic aperture radar (SAR) data to improve coastal circulation modeling, a SAR data set of 60 X-band Level 1B DGM ScanSAR Huge Region mode VV-polarized COSMO-SkyMed SAR data, gathered in a Southern Tyrrhenian coastal area on 2010, was properly processed for wind vector field estimation purposes [1]. The SAR wind speed estimation was accomplished by means of a SAR wind speed retrieval algorithm based on the Azimuth cut-off procedure, and the SAR wind direction estimation was accomplished by means of a SAR wind direction retrieval algorithm based on the DWT-MRA method. The surface wind fields thus obtained have then been used to construct a blended wind product which, in turn, was used to force our coastal circulation model.

The results of a simulation lasting 15 days, from 10 November 2010, 0:00 h to 25 November 2010, 0:00 h, are now presented. The SAR-wind data of 20 November 2010 at 5:00 UTC and 21 November 2010 at 5:00 UTC with 12.5 km resolution have been used to construct, together with ECMWF data, the blended wind forcing. The SAR-wind field of day 20 November 2010 at 5:00 UTC, has been spatially interpolated with three ECMWF fields of day 20, at 0:00, 6:00, and 12:00 (see fig. 3 of [1] for maps of the two original wind products; see also the first set of three dots in the upper panel of fig. 4). The same has been done for the second SAR-wind field (see the second set of three dots). This choice is justified by the paucity of available SAR data: in doing so we have increased the weight of each available SAR-wind field without introducing an excessive spurious reduction of the temporal variability (the SAR-wind information has only been extended 6 h before and after the measured data).

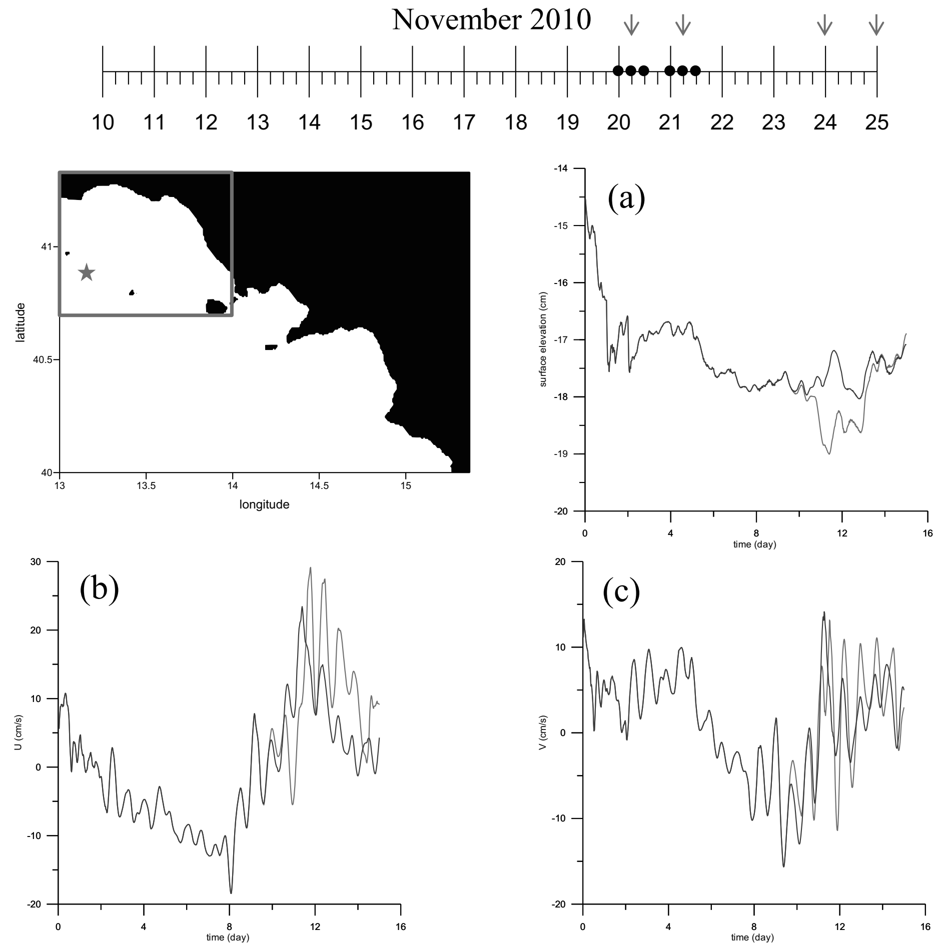

Fig. 4. – Upper panel: representation of the 15-day November 2010 blended wind product (the ticks represent ECMWF winds, the dots show the instants at which COSMO-SkyMed wind data have been blended with ECMWF data, the arrows show the time instants corresponding to the maps shown in the subsequent figures). The gray rectangle inside the map represents the window in which the comparisons shown in the subsequent figures are performed. The graphs of panels (a), (b), and (c) show the time series of the sea surface elevation, of the zonal and meridional surface velocity components, respectively, sampled in the point identified by a star in the map; the black lines refer to the simulation with the purely ECMWF forcing, the gray lines to the simulation with the blended wind forcing ($t = 0$ corresponds to 10 November 2010, 0:00) (adapted from Montuori *et al.* [1]).

Since the SAR data are limited to a north-western part of the integration domain, the results of the simulations are analyzed in the rectangle and in the point identified in the map of fig. 4, where the improvement of the model results is expected to be more substantial. The three graphs of fig. 4 show the time series of the sea surface elevation and of the two components of the surface current velocity: the signal affected by the SAR-wind forcing starts separating from that obtained with the ECMWF wind immediately after the first SAR-wind data insertion, and the difference remains remarkable ever since,

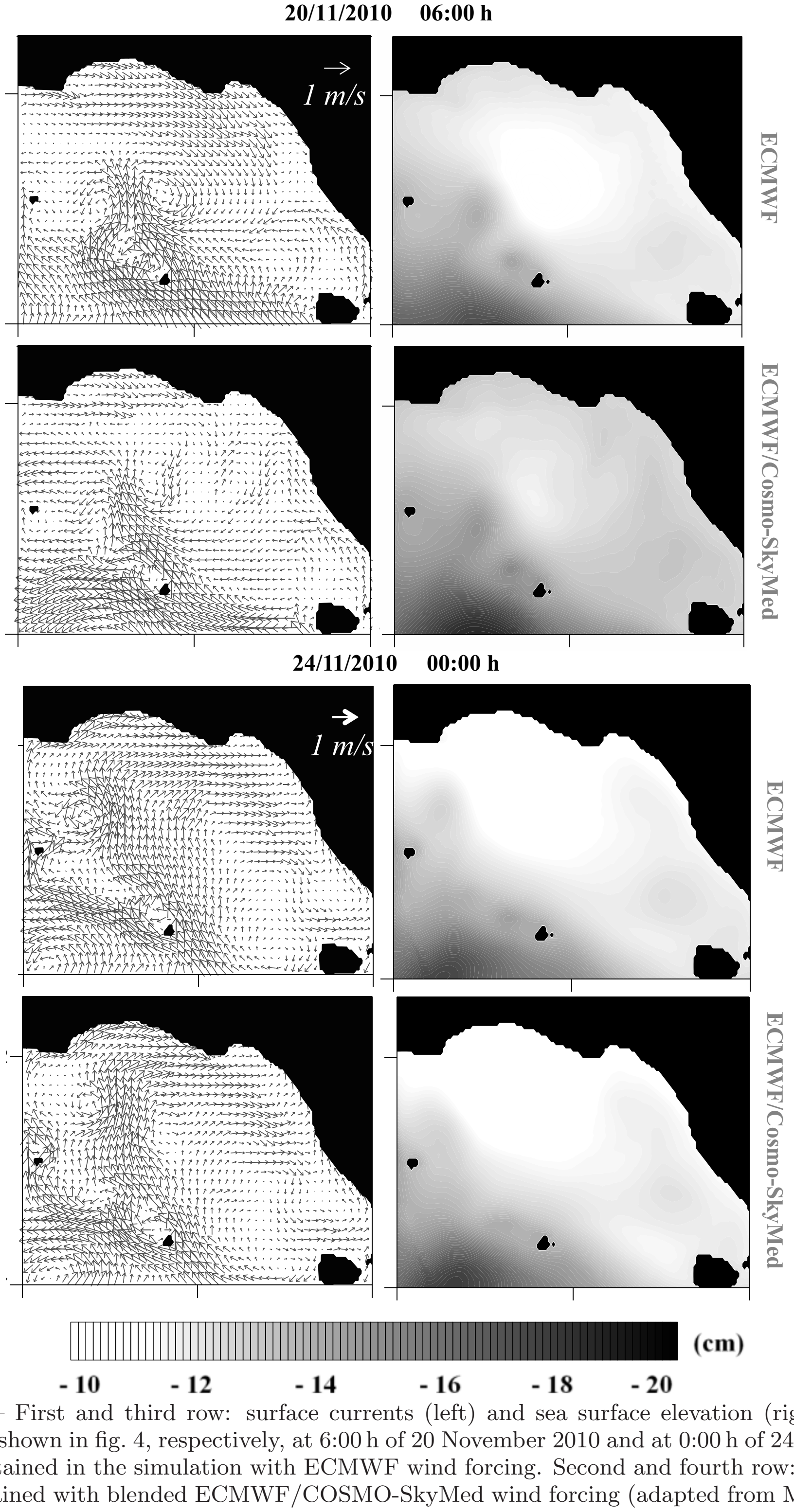

Fig. 5. – First and third row: surface currents (left) and sea surface elevation (right) in the window shown in fig. 4, respectively, at 6:00 h of 20 November 2010 and at 0:00 h of 24 November 2010 obtained in the simulation with ECMWF wind forcing. Second and fourth row: the same, but obtained with blended ECMWF/COSMO-SkyMed wind forcing (adapted from Montuori *et al.* [1]).

even well after the time of the last SAR-wind data insertion. This is clearly due to the different time-dependent adjustments produced by the two forcings that have a typical time scale of few days.

In fig. 5 the surface currents and sea surface elevation obtained with the purely ECMWF forcing (first and third lines) are compared with those obtained with the blended forcing (second and fourth lines) on 20 November 2010, 6:00 UTC and 24 November 2010, 0:00 UTC, respectively. The differences are sometimes quite substantial and are not limited to the region of SAR-wind data coverage. For instance, on day 20 the strong southward current along the coasts of Latium produced by the ECMWF forcing is drastically reduced with SAR-wind data. On day 24 the strong cyclonic gyre east of the northward jet almost disappears with SAR-wind data. In conclusion, our results suggest that the surface wind fields obtained from COSMO-SkyMed SAR data could be used, together with model data (such as ECMWF), to construct a blended wind product that can serve as an alternative wind forcing for improved coastal marine circulation modeling. In fact, the SAR-based wind product is measured instead of modeled, so it bypasses all the model limitations associated with coastal environments with strong orographic features; moreover, those winds have a spatial resolution that can be considerably higher than that of modeled winds, so that more reliable simulations of mesoscale and smaller scale oceanic features can be achieved.

4. – Conclusions

In this paper some relevant results obtained with the POM implemented in a southern Tyrrhenian coastal area are presented. The fundamental role played by the large-scale circulation of the Tyrrhenian Sea in the coastal circulation was emphasized: this implies the necessity of nesting the high-resolution coastal model with a coarser resolution model of a wider area. A feasibility study aimed at evaluating the capability of COSMO-SkyMed SAR data to provide surface wind fields that can improve coastal circulation modeling was also presented. The oceanographic model was forced with a blended wind product that includes ECMWF and SAR-derived winds. Despite both the limitations of available consecutive COSMO-SkyMed SAR acquisitions (and therefore SAR-derived wind field data) and the relatively poor spatial coverage of the adopted coastal test site, our results show that COSMO-SkyMed SAR data do represent a potentially valuable tool for improving coastal circulation modeling, which is very important for oceanographic, ecological, social and economic applications.

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