Ocean Dynamics (2011) 61:779–796
DOI 10.1007/s10236-011-0401-z

Multiplatform observation of the surface circulation in the Gulf of Naples (Southern Tyrrhenian Sea)

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Received: 30 September 2010 / Accepted: 1 March 2011 / Published online: 5 April 2011

Abstract The Gulf of Naples (Southern Tyrrhenian Sea) is a highly urbanised area, where human activities and natural factors (e.g. river runoff, exchanges with adjacent basins) can strongly affect the water quality. In this work we show how surface transport can influence the distribution of passively drifting surface matter, and more in general if and how the circulation in the basin can promote the renovation of the surface layer. To this aim, we carried out a multiplatform analysis by putting together HF radar current fields, satellite images and modelling tools. Surface current fields and satellite images of turbidity patterns were used to initialise and run model simulations of particle transport and diffusion. Model results were then examined in relation to the corresponding satellite distributions. This integrated approach permits to investigate the concurrent effects of surface dynamics and wind forcing in determining the distribution of passive tracers over the basin of interest, identifying key mechanisms supporting or preventing the renewal of surface waters as well as possible areas of aggregation and retention.

Keywords Gulf of Naples · HF radar · Satellite · Transport model

Responsible Editor: Pierre-Marie Poulain

This article is part of the Topical Collection on *Multiparametric Observation and Analysis of the Sea*

Electronic supplementary material The online version of this article (doi:10.1007/s10236-011-0401-z) contains supplementary material, which is available to authorized users.

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1 Introduction

The dynamics of marine ecosystems and the proper management of environmental resources often face critical conditions in coastal areas. These are very valuable assets from the socio-economic as well as environmental standpoint: they are used for recreational and transportation purposes, as well as for fishery and resource exploitation (Oppenheimer et al. 1981). The situation is even more crucial in those regions where tourist activities require an optimal water quality, and where urban settlements and industrial activities undermine ecosystem equilibrium.

The Gulf of Naples (GoN heretofore), in southern Italy, is a natural semi-enclosed embayment of the southeastern Tyrrhenian Sea (western Mediterranean Sea). Tourist attractions such as Sorrento, Capri and Ischia are appreciated worldwide, and this makes the GoN an area of intense leisure activities, particularly in the summer. On the other hand, however, the GoN is subject to a severe anthropic pressure which makes it a critically sensitive region from an environmental perspective (Oppenheimer et al. 1981). The GoN receives the urban and industrial sewage from the city of Naples and its neighbourhood, and the maritime traffic due to commercial and pleasure boating represents another source of intense stress. In addition, the heavily polluted Sarno river pours its waters into the southeastern sector of the GoN (Gulf of Castellammare). Not only may all these sources of potential environmental impact affect the very critical ecological dynamics of the area, but they can also have important consequences on tourism and consequently on the economy of the region (e.g. Ribera d'Alcalà et al. 2004; Zingone et al. 2006, 2010).

The necessity of preserving and sustainably exploiting the environmental resources requires an accurate understanding and monitoring of the circulation and of the transport processes acting in the basin, by which forestalling or mitigating potentially hazardous events. In recent years, the increasing awareness of the importance of operational oceanographic systems (e.g. Flemming et al. 2002; Dahlin et al. 2003) has promoted the development of new techniques and instruments to investigate the real-time, multi-scale circulation patterns in a target area and their effects on transport and diffusion of pollutants, with a special emphasis on coastal zone management.

In this framework, in the present study we have followed a multiplatform approach, integrating synoptic surface currents, ocean colour satellite imagery and a Lagrangian tool to investigate how surface dynamics in the GoN affect the patterns of distribution of passively drifting surface particles. Satellite data and surface current fields were used to initialize and run model simulations of particle transport and diffusion. Final modelled distributions were then compared to satellite images to validate the obtained results.

The period chosen for our study was summer 2009. As discussed above, the summer season is critical for the socio-economic assets of the GoN region, and the water quality issues related to recreational activities (e.g. swimming, boating, diving) are of extreme importance. In particular, the summer of 2009 was characterised by episodes of drastic reduction of the coastal water quality in some areas of the GoN; this was probably due to the concomitance of strong river runoff, of interruptions of the normal functioning of sewage treatment plants, and of local mechanisms of hampered water renewal induced by the circulation pattern. In summer, the circulation of the GoN is mostly driven by the breeze regime, determining very long surface water flushing times (Buonocore et al. 2010; Cianelli et al. 2011). The integrated multiplatform approach used in this work permits to investigate the concurrent effects of surface dynamics and wind forcing in determining the distribution of passive tracers over the basin of interest, identifying key mechanisms supporting or preventing the renewal of surface waters as well as possible areas of aggregation and retention.

2 Study area

The GoN is an approximately rectangular marginal basin of the southeastern Tyrrhenian Sea (Mediterranean Sea; Fig. 1). It has an average depth of 170 m and an area of approximately 900 km^2 (Carrada et al. 1980), a complex bottom topography featuring two submarine canyons (Magnaghi and Dohrn) with depths up to 800 m, and a continental shelf with widths ranging from 2.5 to 20 Km in the centre of the basin. The islands of Ischia, Procida and Capri bond the external part of the GoN; the northern limit is represented by the Campi Flegrei area, whereas the Sorrento peninsula is the southern one. The exchanges between the GoN and the southern Tyrrhenian Sea occur along the Bocca Grande, the main aperture of the gulf between Ischia and Capri. The communications with the neighbouring basins of the Gulf of Gaeta (in the north) and the Gulf of Salerno (in the south) are respectively guaranteed by the Ischia and Procida channels and by the Bocca Piccola (the passage between Capri and the Sorrento peninsula). The morphology of the coasts varies from N to S: the sandy coasts present in the northern and eastern part of the basin are replaced by rapidly declining calcareous cliffs in the south.

The study area is also characterised by peculiar orographic aspects influencing wind and sea dynamics. The Vesuvius volcano (elevation: 1,281 m) and the hills surrounding the city of Naples (with altitudes up to 450 m) can shelter northeasterly winds blowing over the basin mostly in winter, creating jet currents responsible for rapid coast–offshore water exchanges (Moretti et al. 1976–1977; De Maio et al. 1983, 1985; Gravili et al. 2001; Grieco et al. 2005; Menna et al. 2007; Buonocore et al. 2010; Cianelli et al. 2011). Mountains are also present in the southern edge of the GoN (Lattari Mountains; Mount Faito, 1,131 m).

Three marginal sub-basins of the GoN can be identified: the Bay of Pozzuoli in the northern part, the Bay of Naples in the northeastern sector of the region, the Gulf of Castellammare in the southeastern part of the basin. The environmental quality of the marine ecosystem in these areas is directly influenced by human activities, and their waters present hydrographic and biological properties reflecting anthropic stress (Ribera d'Alcalà et al. 1989, 2004; Zingone et al. 1990, 1995, 2006, 2010). With specific reference to the present work, our interest will be mostly focused on the dynamics evolving in the latter two sub-regions. The Bay of Naples constantly receives urban sewage and other eutrophising inputs from the city of

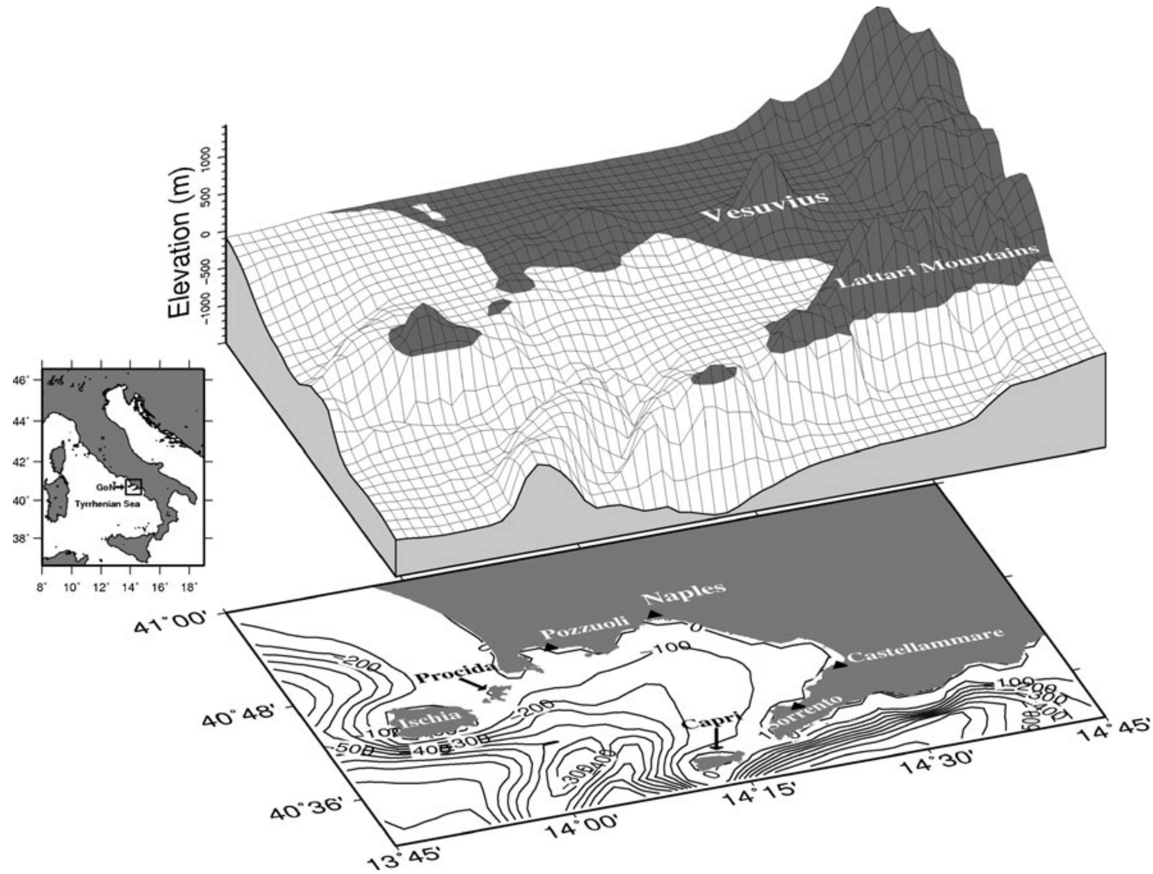


Fig. 1 Bathymetry and orography of the GoN area

Naples and adjacent areas (Ribera d'Alcalà et al. 1989), while the riverine input is limited and generally associated with highly intermittent events that are able to advect freshwater also from quite remote sources (Zingone et al. 2010). On the other hand, the Gulf of Castellammare is affected by the pulsing runoff of the Sarno river (Zingone et al. 1995) and owing to its vicinity to the Sorrento peninsula the dynamics of transport and diffusion in this area deserves peculiar attention.

3 Multiplatform analysis

The approach used in our investigation is based on the combination of the surface current measurements obtained by an HF radar network with available ocean colour satellite images. The two datasets are exploited to configure and run a mixed Eulerian/Lagrangian transport and diffusion model. In practice, radar data is used as the background surface circulation input for the advection model, while the distribution of the diffuse attenuation coefficient, as measured by satellite visible sensors at the wavelength 490 nm (considered here as a proxy of the water turbidity), serves to define the initial position of the drifting particles used to track the turbid waters. The simulation is run over a selected time period, using hourly radar data as input for model. At the end of the simulation, the modelled final distribution of tracer particles is compared to the corresponding satellite-derived one. The aim of this approach is to verify the reliability of the integration of measured data and modelling tools in monitoring and tracking the evolution of the transport and diffusion of surface floating matter, while identifying, at the same time, the key processes affecting the distribution of particles.

3.1 HF radar network

Nowcasts of the surface circulation of the GoN are provided by a network of HF radars (a SeaSonde system manufactured by CODAR Ocean Systems of Mountain View, USA), operating in the basin since 2004. By transmitting an electromagnetic wave and using surface gravity waves as target, an HF radar measures the direction and intensity of surface currents: when a Bragg scattering coherent resonance occurs (Crombie 1955), the echo recorded by the receiving antenna displays a peak in the signal spectrum (Barrick et al. 1977), with a Doppler effect shift revealing the presence of a current beneath the gravity waves. The system installed in the GoN is composed of monostatic, direction-finding systems with a three-element crossed loop/monopole antennas used to transmit and receive the signals. To determine the bearing of the incoming signal, it exploits then the directional properties of the antennas and applies a variant of the multiple signal classification algorithm (Schmidt 1986). Each antenna can measure only the radial component of surface velocity; consequently, at least two antennas are necessary for the measurement of current fields (Barrick and Lipa 1986). Exhaustive reviews on HF radar principles and functioning can be found in Paduan and Graber (1997) and Teague et al. (1997).

During the period October 2004–May 2008, the HF radar system installed in the GoN was composed of two antennas only, located respectively in Portici and Massa Lubrense; in May 2008, a third antenna was installed in Castellammare di Stabia, with an improvement in the resulting surface current fields in terms of both spatial coverage and resolution (1.0×1.0 Km, see Fig. 2); further details are summarised in Table 1. The three remote sites collect hourly radial fields of surface currents and deliver them to a central site where they are processed to create a total vector map of the direction and intensity of the surface currents at basin scale.

To account for possible distortions due to the electromagnetic environment surrounding the antennas (causes may range from the presence of nearby metal structures to radiowave interferences, see e.g. Kaplan et al. 2005), a local measured antenna pattern must be determined and then used to correct radials prior to the determination of the current field in the study area.

As current fields derived by HF radar may present gaps due to intrinsic variations in the spatial and temporal

Table 1 Technical specifications of the HF radar system installed in the Gulf of Naples

Radial maps acquisition	
Frequency	25 MHz
Sweep rate	2.01 Hz
Samples per sweep	2,048
Band width	150.147 KHz
Range step	0.999 Km
Range	~40.0 Km
Wavelength	12.50 m
Radial maps combine options	
Grid spacing	1.0 Km
Averaging radius	1.8 Km
Distance angular limit	25° GDOP limit
Current velocity limit	80 cm s^{-1}

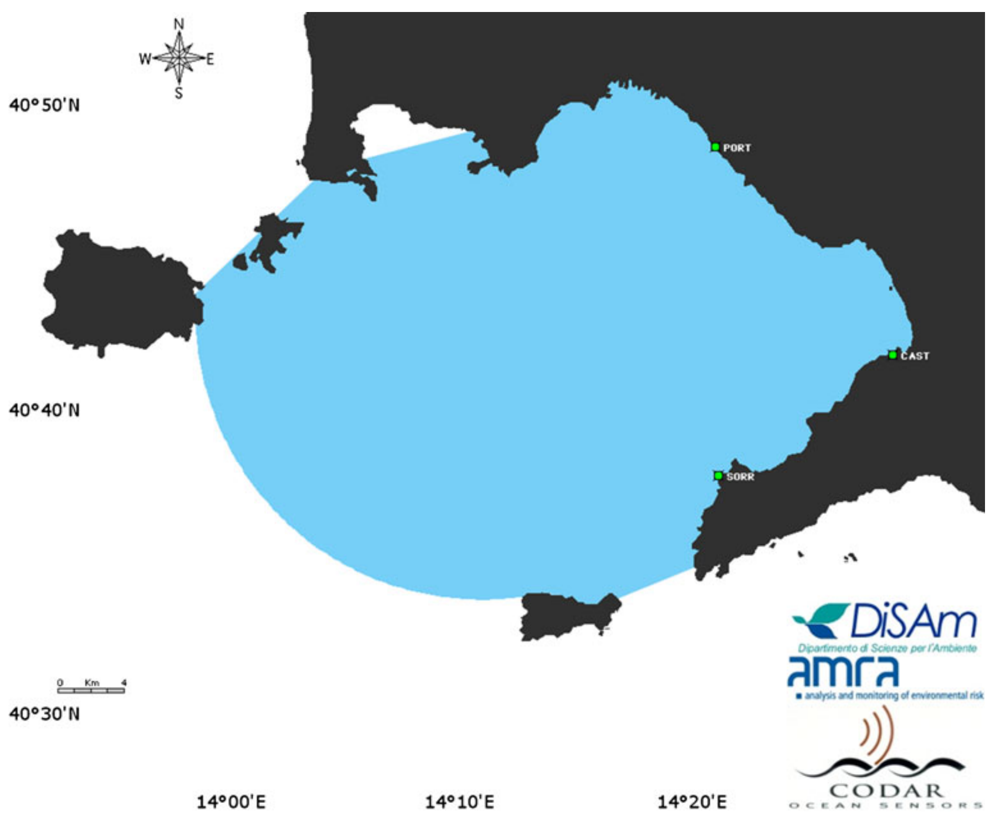


Fig. 2 Maximum HF radar coverage in the GoN

coverage, a normal mode analysis (Lipphardt et al. 2000) or an open modal analysis (Lekien et al. 2004; Kaplan and Lekien 2007) can be used to fill in empty regions. In our simulations this intermediate step was not necessary, since for the entire investigated period radar fields always presented a high spatial and temporal quality.

3.2 Satellite imagery

Even though the remote sensing of the sea surface in the visible range of the spectrum provides a synoptic, relatively high resolution view of the ocean colour, the quantitative characterization of specific indicators of the water quality from satellite data is not straightforward. In particular, while standard algorithms for the retrieval of specific parameters (e.g. chlorophyll-a) can be applied for the open ocean yielding relatively accurate estimates, specific regional algorithms should be applied for coastal areas. This is due, on one hand, to the relatively stable ratio among the substances contributing to open ocean water colour (classified, from the optical point of view, as case 1 waters, e.g. Morel and Prieur 1977; Gordon and Morel 1983; Morel 1988) and, on the other hand, to the presence of rivers, of sewage from large cities and human settlings, to sediment re-suspension processes, as well as to a high variability in the biological communities in the coastal areas: all elements that may significantly modify the near-shore water colour and transparency. Coastal waters are thus generally classified as case 2 waters, and applying the case 1 algorithms to coastal areas may lead to inaccurate estimates of several parameters (e.g. Mobley et al. 2004, and references therein). However, building specific algorithms for the GoN case 2 waters is far beyond the scope of the present work, as the satellite data will be basically used here to track the presence/absence of turbid waters and their dispersal/retention in the GoN. To this aim, we decided to look at the estimates of the diffuse attenuation coefficient at the wavelength 490 nm (K490), as commonly derived from ocean colour satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Esaias et al. 1998). The K490 is directly related to the turbidity of the water column (e.g. to the presence of scattering particles) and has been used several times to track cross-shelf exchange and dispersion of coastal turbid waters towards the open sea, as well as to monitor sediment re-suspension, intense mixing and increased delivery of terrestrial materials during extreme atmospheric events in the coastal zones (e.g. Arnone and Parsons 2005; Gibbs et al. 2006; Bignami et al. 2007; Lohrenz et al. 2008 and references therein). The operational algorithm for deriving the diffuse attenuation coefficients that was used here is a polynomial function (estimated through a regression with in situ measurements) that relates the log-transformed K490 to a log-transformed ratio of the remotely sensed blue (488 nm) and green (547 nm) reflectances (J. Werdell, http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/kdv4/).

3.3 Transport modelling

General NOAA Operational Modeling Environment (GNOME) is a freely available trajectory model developed by the Hazardous Materials Response Division, Office of Response and Restoration of the National Oceanic and Atmospheric Administration (Beegle-Krause 1999). It has been conceived as a multi-purpose trajectory model designed both to simulate potential oil spills and to estimate passive particle trajectories by processing oceanographic as well as atmospheric data for a fixed geographic region (Beegle-Krause 2001; Engie and Klinger 2007). Applying a mixed Eulerian/Lagrangian approach, GNOME simulates the trajectories of Lagrangian Elements (LEs or splots) moving in an Eulerian current and wind field. The model computes a “best guess” particle position based on the underlying assumption that all model inputs are correct (Beegle-Krause 1999). Output trajectories may also include a “minimum regret” solution which accounts for uncertainties in the current and wind data used in the simulations (Beegle-Krause 1999).

GNOME offers three user modes differing in the degree of control on input parameters (for further details on technical features of GNOME, see Beegle-Krause 2001). In our study, we used GNOME as a classic transport model in the diagnostic mode which allows the user to set all model data fields and scaling options for any study area (Beegle-Krause 2001). Currents, wind and horizontal mixing are considered by GNOME as typical movers of the Lagrangian particles.

For this work, we developed a numerical procedure to use the surface velocities detected by the HF radar system operating in the GoN as time-dependent current fields to be supplied to the model. The current data are defined on a regular grid and provide the advection component of simulated particle trajectories: the subgridscale processes are parameterised by a random walk process (Csanady 1973). It is worth noticing that in this work we focused exclusively on the two-dimensional, surface current fields as provided by our HF radar system, without including the vertical component of the motion or the velocity shear along the water column. Vertical motion is of paramount importance in the context of particle dynamics, since dispersion occurs in three dimensions (see also below, Section 5). Future implementations of the proposed multi-platform approach will address this issue, likely by using as inputs to the transport model results from numerical circulation models which are currently being specifically implemented for the GoN. When simulating the particle trajectories, GNOME also takes into account the refloat half-life of the particles (default value, 30 min), i.e. the time after which stranded particles detach from the coast and are again passively transported.

In this work, we simulated the motion of "generic" tracer particles, advected by the surface currents measured by the radar and diffused by subgridscale processes parameterized by a diffusion coefficient. Differently from what would happen in the case of oil spill simulations, in which leeway (or windage) effects, i.e. the effects of direct wind drag on oil particles floating on top of the very surface upper layer would be very important, in our study the effect of wind stress on the surface water motion, and consequently on the transport of tracer particles floating at the surface, is incorporated in the current field measured by the HF radar, partly induced by the local meteorological forcing. For this reason, wind data collected by the Italian Institute for the Environmental Research and Protection (Istituto Superiore per la Protezione e la Ricerca Ambientale, ISPRA) in the Port of Naples will be presented and discussed in the next section just for diagnostic purposes to gain insight on the wind-induced portion of the coastal dynamics of the GoN.

4 Surface dynamics in the GoN

The surface circulation in the GoN is the result of the superimposition of driving factors acting over different spatio-temporal scales and of their interaction with the complex bottom topography and orography of the basin. Such forcings can be differentiated as local and remote (Gravili et al. 2001); for the former category wind is the

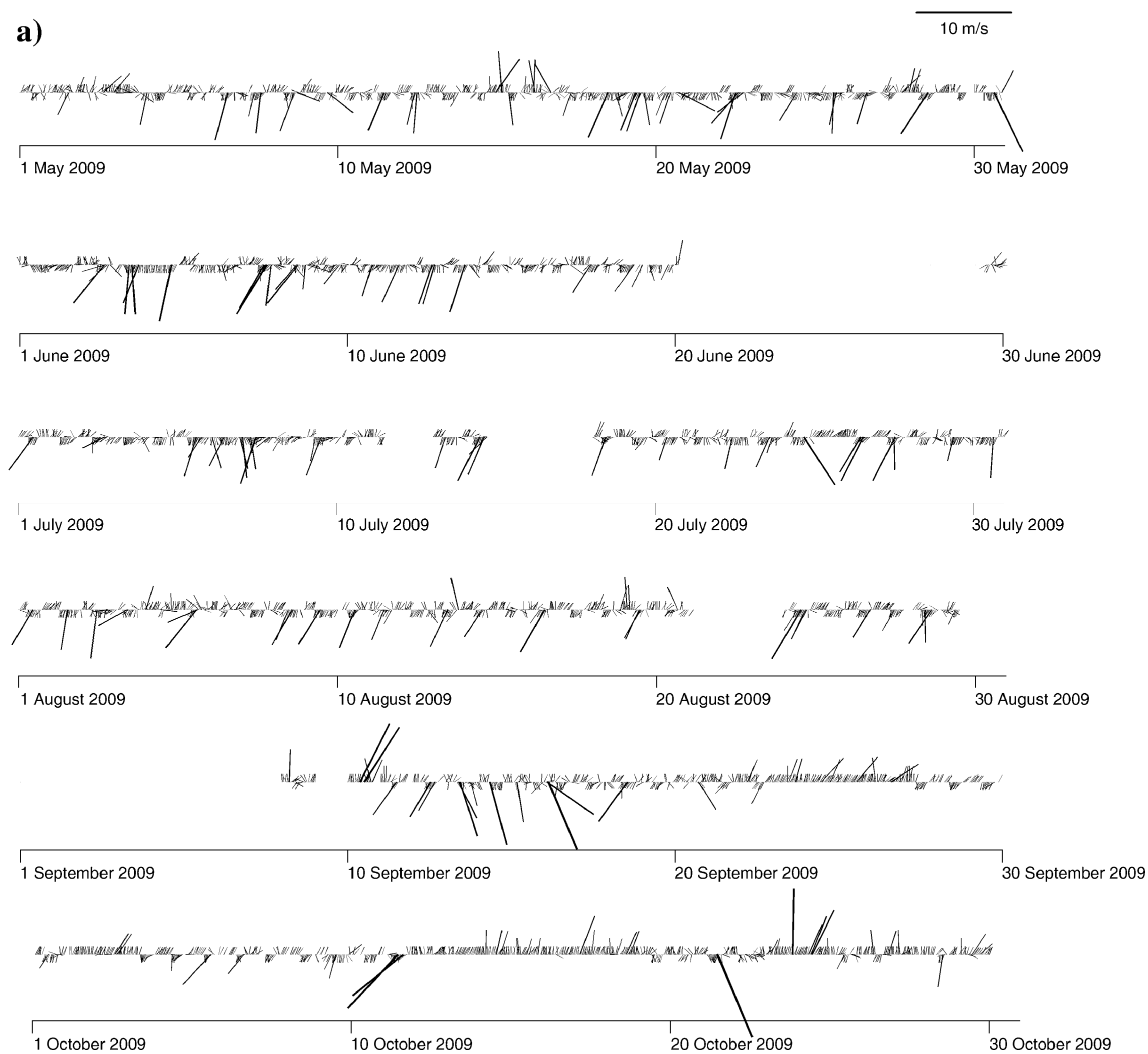


Fig. 3 Stick diagrams (**a**) of the hourly winds measured at the Port of Naples station in the period May-October 2009 (data provided by ISPRA); frequency spectrum (**b**) of wind data for the trimester July–September 2009, with a peak frequency corresponding to 24 h in both the zonal and meridional components

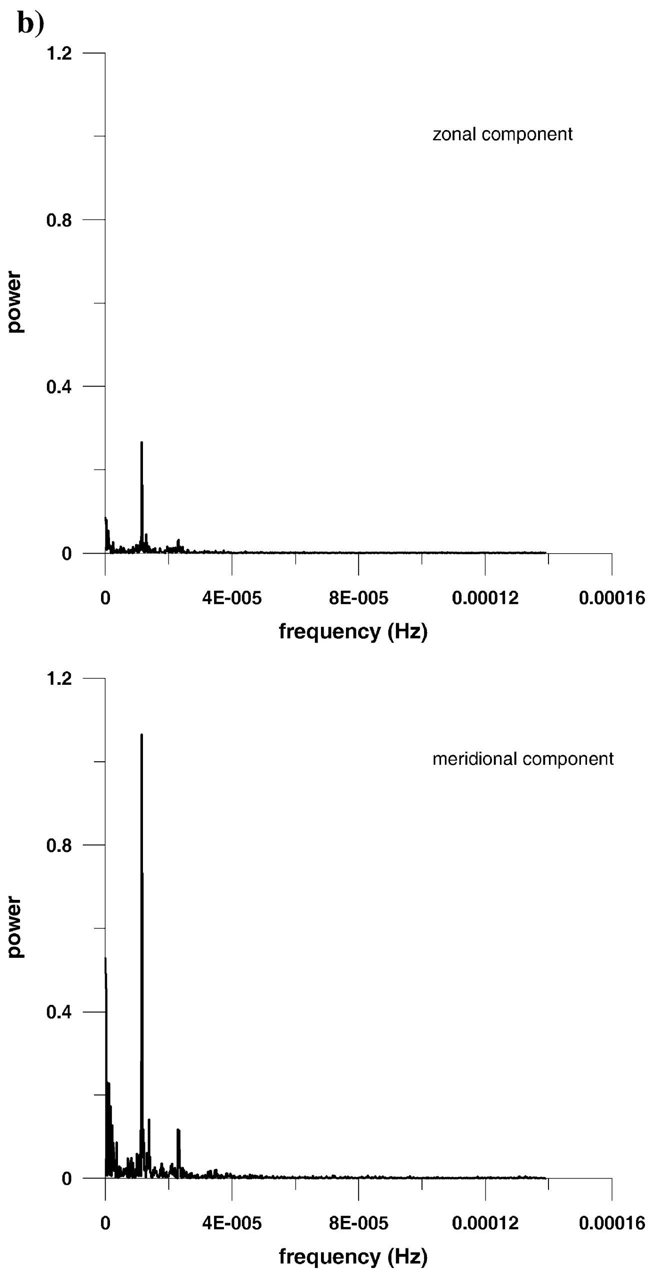


Fig. 3 (continued)

most important contributor (Moretti et al. 1976–1977; De Maio et al. 1985; Menna et al. 2007), whereas for the latter the main role is played by the circulation of the southern Tyrrhenian Sea (Pierini and Simioli 1998; Gravili et al. 2001). By virtue of this differentiation, it is possible to identify five main circulation schemes developing in the GoN, each representative of the combination of specific seasonal and dynamic conditions (Cianelli et al. 2011). Two of them are driven by the offshore Tyrrhenian currents: when they are oriented towards the north-west, an intense flux enters the GoN from the Bocca Piccola and creates a broad basin-scale meander with a counterclockwise tendency in the interior of the gulf, with the freshwaters from the Sarno river and the urban sewage of the city of Naples being advected offshore (De Maio et al. 1983). When the Tyrrhenian current reverses its direction, a cyclonic gyre in the central part of the GoN isolates the offshore from the coastal area, where anticyclonic structures sustaining the stagnation of surface waters are instead formed (De Maio et al. 1983).

The three remaining scenarios can be assumed as being wind-driven. When winds from the north-east blow (as typical in winter), the Vesuvius funnels the wind stress over the surface of the GoN creating an offshore directed jet (Moretti et al. 1976–1977; De Maio et al. 1983, 1985; Gravili et al. 2001; Grieco et al. 2005; Menna et al. 2007), a condition sustaining the rapid renewal of surface waters (Grieco et al. 2005; Menna et al. 2007). In presence of depressionary systems, intense southwesterly winds arise and the GoN responds with the contemporary formation of cyclonic and anticyclonic structures evolving over different spatial and temporal scales (Gravili et al. 2001; Grieco et al. 2005; Menna et al. 2007). In this case, currents are mostly coastward and surface waters are retained in the littoral area.

Finally, the typical summer condition, in which stable high pressure fields act upon the Tyrrhenian Sea and the Italian coasts; in such a condition, despite their low energy, breeze winds become the dominant local forcing, with a diurnal alternation of sea and land breezes affecting the coastal area (Perusini et al. 1992; Menna et al. 2007; Cianelli et al. 2011). The highest intensities are recorded with sea breezes blowing around hours 12:00–13:00, while the weakest winds are tallied during night hours. As a response, the surface current field makes a complete clockwise rotation over 24 h, with relatively strong coastward-oriented currents under the action of sea breeze in contrast to relatively weaker offshore moving waters in presence of land breeze. Under these dynamical conditions, the renewal times are very long and the exchanges between coastal areas and open waters are hampered (Buonocore et al. 2010).

Summer 2009 respected this somehow standard dynamics. From May until the beginning of September the breeze regime was dominant over the area, driving the surface circulation for the entire study period. Only from September onwards more intense, larger-scale wind forcings began to act over the GoN, determining changes in the dynamics of the upper layer of the basin. In Fig. 3a we show the stick diagram of the hourly wind data measured by ISPRA in the Port of Naples May through September 2009; Fig. 3b shows the power spectra of the wind zonal and meridional components for the period July–August–September 2009. Spectra highlight the predominance of the 24 h breeze regime; the noticeable difference between the two components may be due to the location of the ISPRA weather station, which results to some extent sheltered from zonal winds, as discussed in Menna et al. (2007).

To get a quantitative indication of the responses of the GoN, we present the time evolution of the average surface current as measured by HF radar over the period May–October 2009 for the innermost area of the basin (the area of the Gulf of Castellammare, see inset Fig. 4a); in addition, with the aim of determining the inshore–offshore exchanges the average zonal component along a strip 2 Km wide and 20 Km long at the external boundary of this sector has been analysed as well. This area has been selected as representative of the coastal dynamics of the GoN, also because it is one of the most critical sub-basin as directly influenced by the Sarno river freshwater input. Over an entire day, surface currents typically rotated clockwise under the effect of land and sea breeze (Fig. 4a); the associated zonal components at the edge of

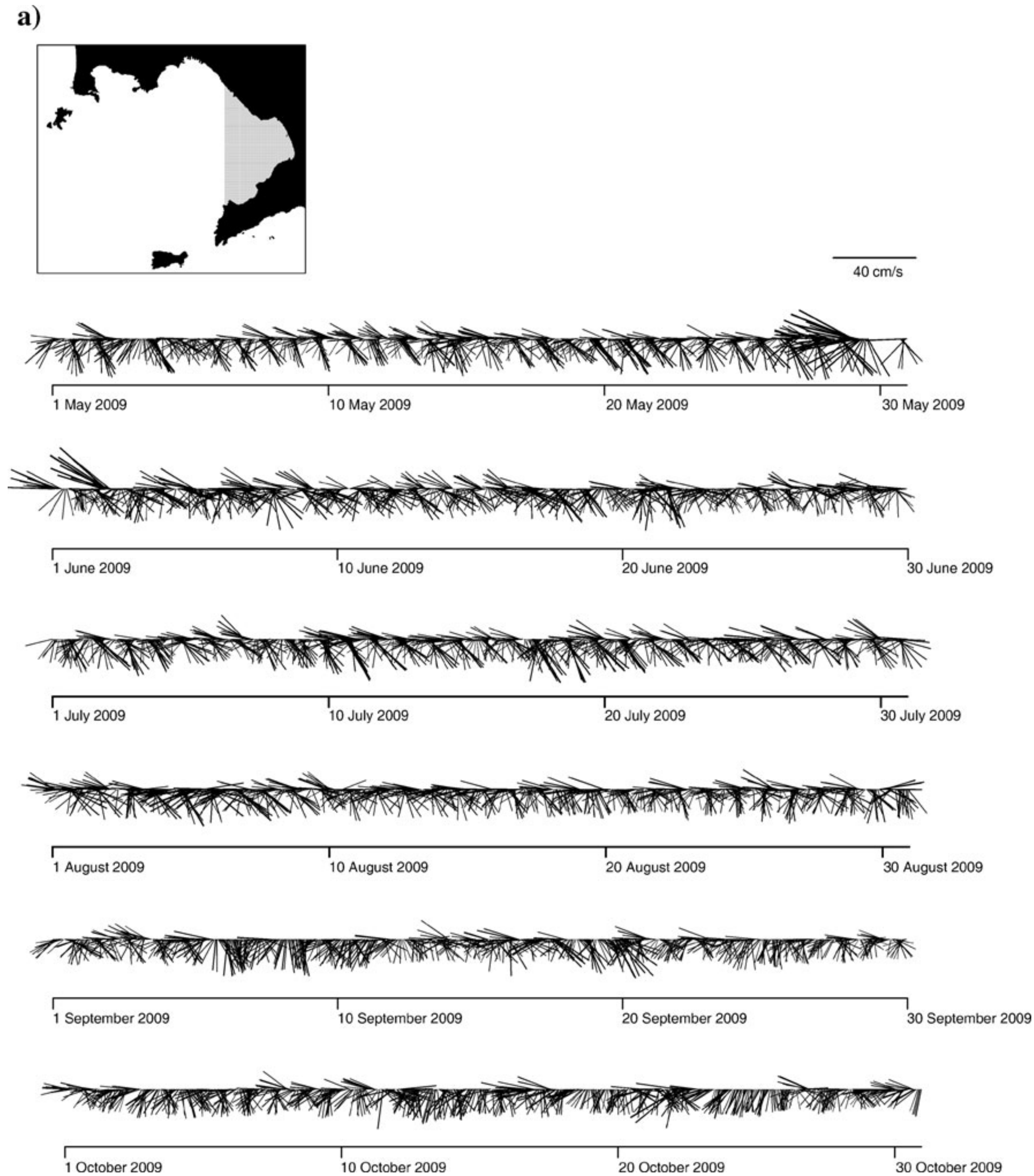


Fig. 4 Stick diagrams (**a**) of the average surface current in the area of the Gulf of Castellammare (see *inset*) and the associated zonal component (**b**) indicating the coast–offshore exchange at the edge (see *inset*); frequency spectrum (**c**) for a radar grid point in the Gulf of Castellammare, showing the peak frequencies at 24 and 12h, with a more intense contribution for the meridional component

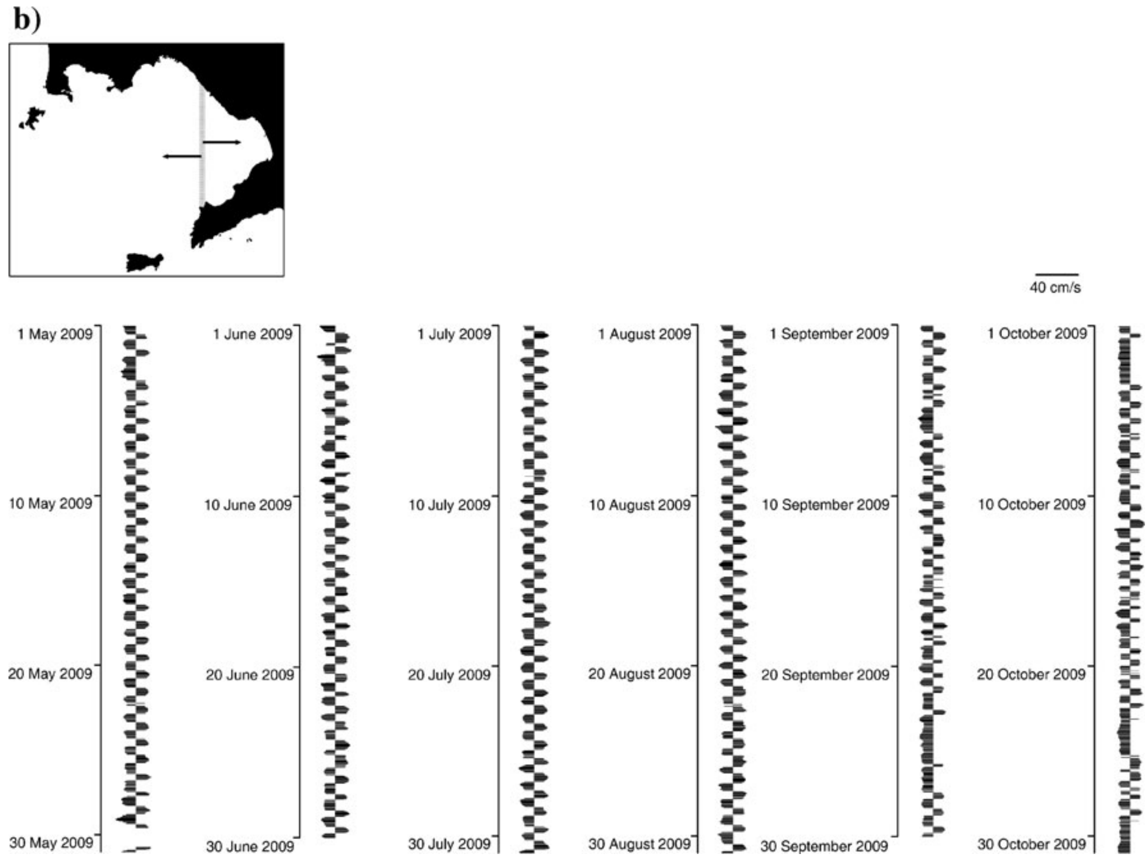


Fig. 4 (continued)

the sector (Fig. 4b) showed an alternation of coastward- and offshore-directed flows, the former accumulating waters in the littoral area and determining their stagnation, the latter favouring the renewal of coastal water. This condition was maintained all over the summer period. The setup of more intense winds blowing at regional scales in the first days of September determined a change in the current fields in the GoN and the break of the breeze induced periodicity in the surface dynamics. As for wind data, also for the surface currents we analysed the frequency composition using spectral analysis. The strong influence of the breeze regime on the circulation is shown by the presence of a dominant 24 h peak in the power spectra (Fig. 4c), that also displays a tide-associated 12 h peak and a less marked difference between zonal and meridional component with respect to the wind.

5 Multiplatform simulations

Following the multiplatform approach discussed in Section 3, over the time window August 7–September 3, 2009, we extracted four periods each lasting 48 h during which peculiar turbidity patterns could be distinguished in satellite imagery. Our aim was to understand if, using the integrated procedure proposed, it was possible to reconstruct the evolution of the high turbidity patches over time lags short enough to ensure the tracking of the initial splot but long enough to affect the water quality of the region.

These "short-term" analyses have then been corroborated by "long-term" simulations, each lasting 1 month, accounting for the renewal of surface waters during the summer and the (subsequent) fall circulation regimes. In this case, in order to highlight potential retentive features of the GoN we evaluated the first exit and the residence times of particles released in the inner part of the basin. To stress the importance of the driving factors in the dynamics determining the transport and diffusion of tracers, the long-term simulations have been run for the period August 7–September 3, 2009, during which the breeze regime was dominant, and for comparative purposes during the period October 1–31 2009, when larger scale winds began to blow (Fig. 3a).

Hourly HF radar data provided the current patterns for the GNOME simulations, while the horizontal diffusion was set equal to 10^4 cm^2 s^{-1}, as a typical value of coastal areas (Okubo 1980). The selection of an appropriate coefficient of diffusion is critical, as varying values can yield different final patterns of distribution (Buonocore et al. 2010).

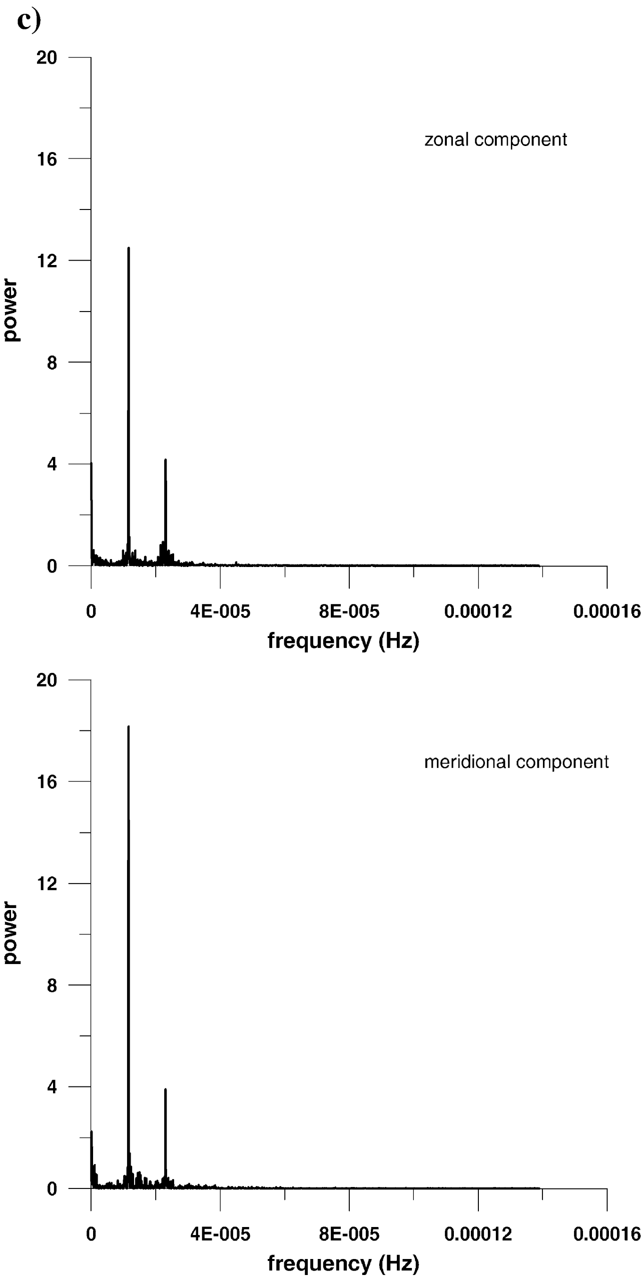


Fig. 4 (continued)

HF radar current estimates present intrinsic uncertainties when compared to in situ measurements (e.g. Chapman et al. 1997; Emery et al. 2004; Ullman and Codiga 2004; Paduan et al. 2006). Even though the accuracy of our system has been recently validated by comparison with surface drifter data (unpublished data), to account for this effect we set in GNOME a±15% error estimate in both along- and cross-current directions. For each selected period, we choose to instantaneously release a cloud of 10,000 passive and conservative particles in selected areas of the GoN. Particle trajectories for all the considered cases were simulated setting an integration time step of 10 min as suggested by stability considerations linked with the cell Peclet number (Bellucci et al. 2001). For the sake of clarity, videos showing the modelled surface particle motions are made available in the supplementary material for each investigated period. In short-term simulations, the advance frame rate is 1 h, while for month-long ones the frame rate has been set to 3 h.

For the short-term simulations, particles were released according to satellite-observed distributions of K490, whereas for long-term runs the tracers were uniformly distributed in the interior of the GoN.

When looking at the comparison between transport simulations and turbidity distribution, it is worth keeping in mind that the simulations are purely two-dimensional, whereas the satellite-derived turbidity distributions are the horizontal signature of a three-dimensional transport process in which dispersion occurs also in the vertical direction. This is shown by the fact that jets in satellite images have occasionally lower turbidity in their offshore portion with respect to particle concentration (see below, August 16th and 23rd), an effect most likely associated to vertical exchange not resolved in the simulations.

5.1 Short-term simulations

5.1.1 August 7–9, 2009

On August 7, 2009 (12:00 GMT), a patch of turbid water was detected in the inner part of the Gulf of Castellammare (Fig. 5a), likely associated with the riverine input from the Sarno river and used in GNOME as initial condition (Fig. 5b). Over the following 48 h (see Video 1 in electronic supplementary material, ESM) particles were moved back and forth owing to the breeze-induced surface currents recorded by the HF radar, while the diffusion spread the initial splot over the release domain. By the end of the simulation, all particles were still inside the launch area. The final modelled distribution matched well with the satellite-derived one (Fig. 5c, d), indicating a scarce renewal of littoral waters.

5.1.2 August 14–16, 2009

The K490 pattern detected by the satellite on August 14, 2009, displayed three main areas of interest (Fig. 6a and b). As in the previous case, an intense patch of suspended matter could be observed in the inner part of the Gulf of Castellammare. In addition to this, a nearly 25 Km long slick marked almost uninterruptedly the littoral between the city of Naples and the area at the base of the Vesuvius. A third spot was detected a few miles offshore the southern edge of the Vesuvian area. Model simulations revealed two distinct dynamics (see Video 2 in ESM). The patch in the

Gulf of Castellammare tended to remain inside the release basin, being diffused over larger scales but without moving offshore, as evident by satellite-model comparison (Fig. 6c and d). By contrast, the coastal slick and the single spot merged together: both of them were alternatively transported towards the coast or towards the open waters depending on the breeze winds blowing over the GoN. A portion of the particles launched in the Bay of Naples remained along the coasts after 2 days, while a greater amount moved offshore and, together with the single spot, created a complex structure compatible with the plume and the eddy detected by the satellite (Fig. 6c, d).

5.1.3 August 21–23, 2009

Satellite imagery showed a very large patch (~150 Km^2) of high turbidity in the Bay of Naples and in the area at the base of the Vesuvius, together with a filament protruding from the Gulf of Castellammare and a smaller splot in the area of Sarno river mouth (Fig. 7a, b). Surface currents (see Video 3 in ESM) moved most of the particles of the patch towards the southern edge of the GoN, directly influencing the waters off the Sorrento peninsula, merging with the previously observed filament and creating a front long a few kilometres (Fig. 7c, d). On the other hand, a smaller fraction was transported towards the coasts of the Bay of Naples. Tracer particles launched in the inner part of the Gulf of Castellammare did not exit the release area, but accumulated all along its coasts (Fig. 7c, d).

5.1.4 September 1–3, 2009

At the beginning of September, a wide area of turbid waters (~180 Km^2) covered the Gulf of Castellammare and the Sorrento peninsula (Fig. 8a, b). The current regime acting during the following 48 h (see Video 4 in ESM; wind data

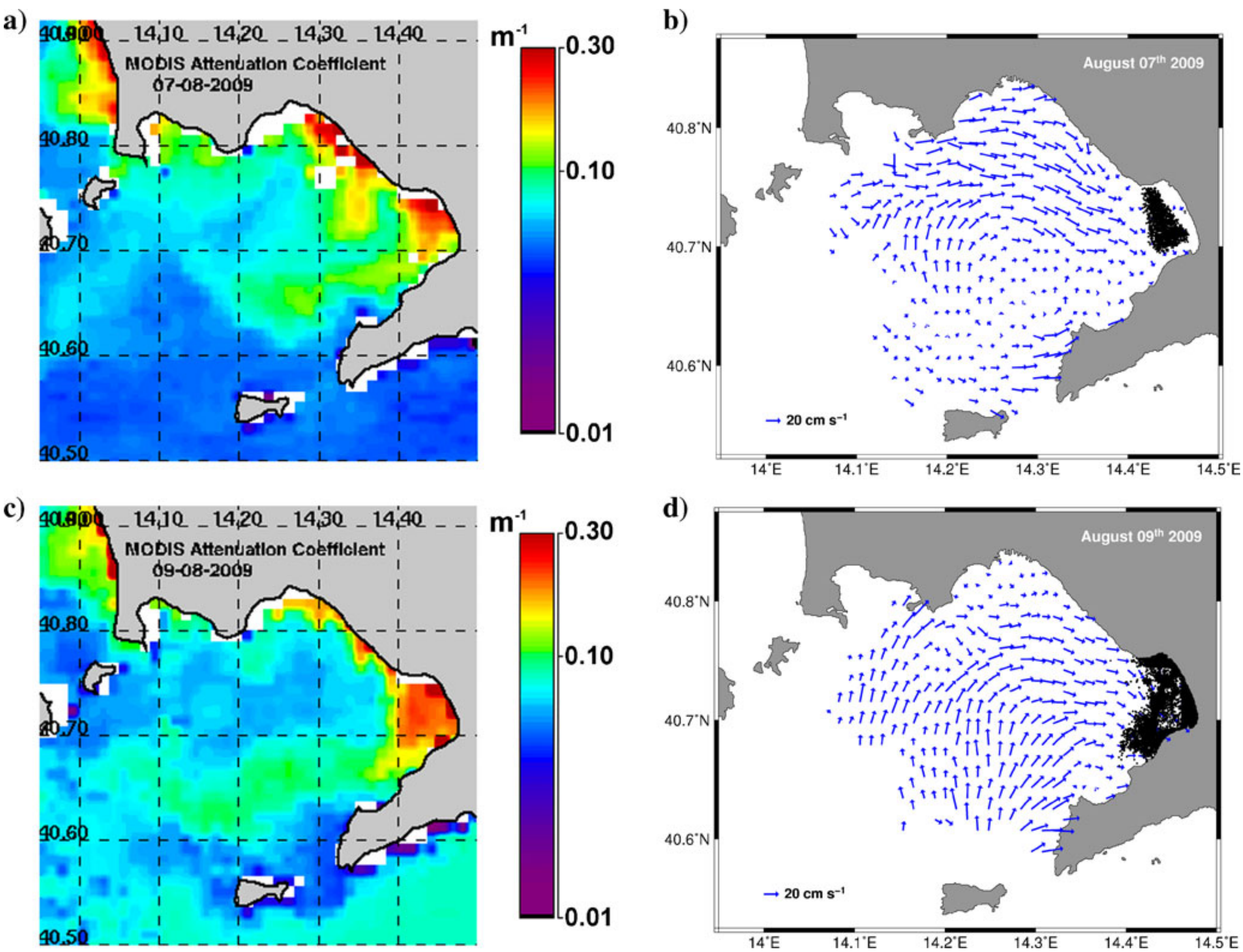


Fig. 5 (**a**) Satellite-derived turbidity distribution (K490) of August 7, 2009, and (**b**) corresponding initial condition in the first short-term simulation; (**c**) satellite-derived K490 pattern of August 9, 2009, and (**d**) corresponding final state of the simulation

not available, see Fig. 3) determined the strong retention of particles in the release area, as supported by satellite images and model simulations (Fig. 8c, d). In addition, a fraction of particles was exported to the north, affecting the southern sector of the Vesuvian area, while an offshore moving filament could be detected on the external part of the launch sector (Fig. 8c, d).

5.2 Long-term simulations

For the long-term simulations, particles were uniformly distributed in the interior of the GoN (Fig. 9), whose threshold was set to correspond to the fluid boundary between Nisida (in the north, between Pozzuoli and Naples; see Fig. 1) and Punta Campanella (in the south, tip of the Sorrento peninsula; see Fig. 1); those particles crossing this line were considered as completely abandoning the coastal area. With the aim of investigating the inshore–offshore exchanges over month-long periods, in these simulations we calculated the normalised number of particles that, in time, remained in the release sector as (Buffoni et al. 1997):

$$\mathrm{Q}(t) = \frac{N(t)}{N(0)}$$

where $N(t)$ is the number of particles that, at a given time t, were inside the launch area and $N(0)$ is the total number of initially released tracers. When applicable, the residence time—i.e., an estimator of the time spent by a tracer particle in the release sector before abandoning it—was computed as (Buffoni et al. 1997):

$$T = \lim_{t \to \infty} T^*(t)$$

with:

$$T^*(t) = t\,Q(t) + \sum_{i=1}^{N_e(t)} \frac{t_{ei}}{N(0)}$$

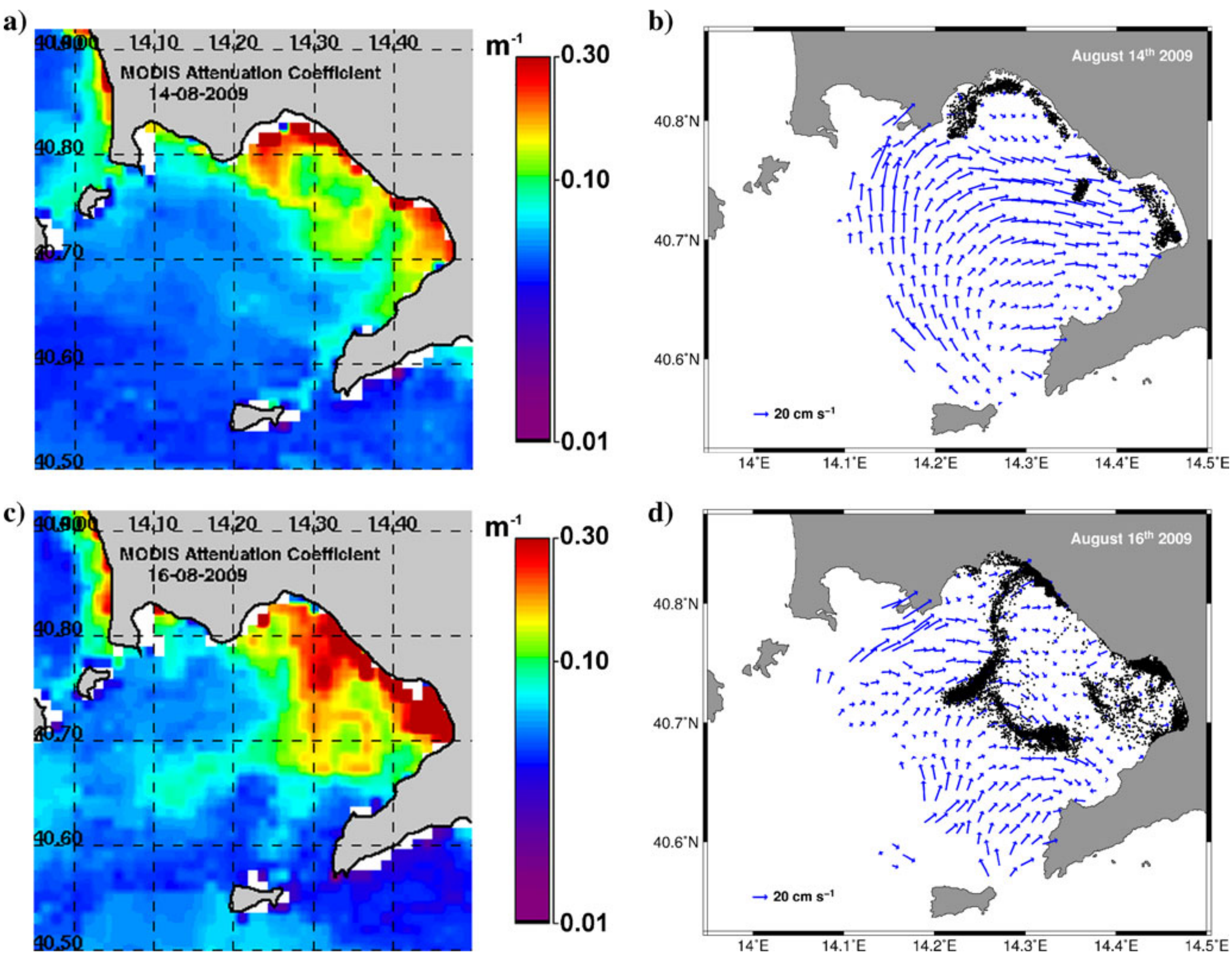


Fig. 6 (**a**) Satellite-derived turbidity distribution (K490) of August 14, 2009, and (**b**) corresponding initial condition in the second short-term simulation; (**c**) satellite-derived K490 pattern of August 16, 2009, and (**d**) corresponding final state of the simulation

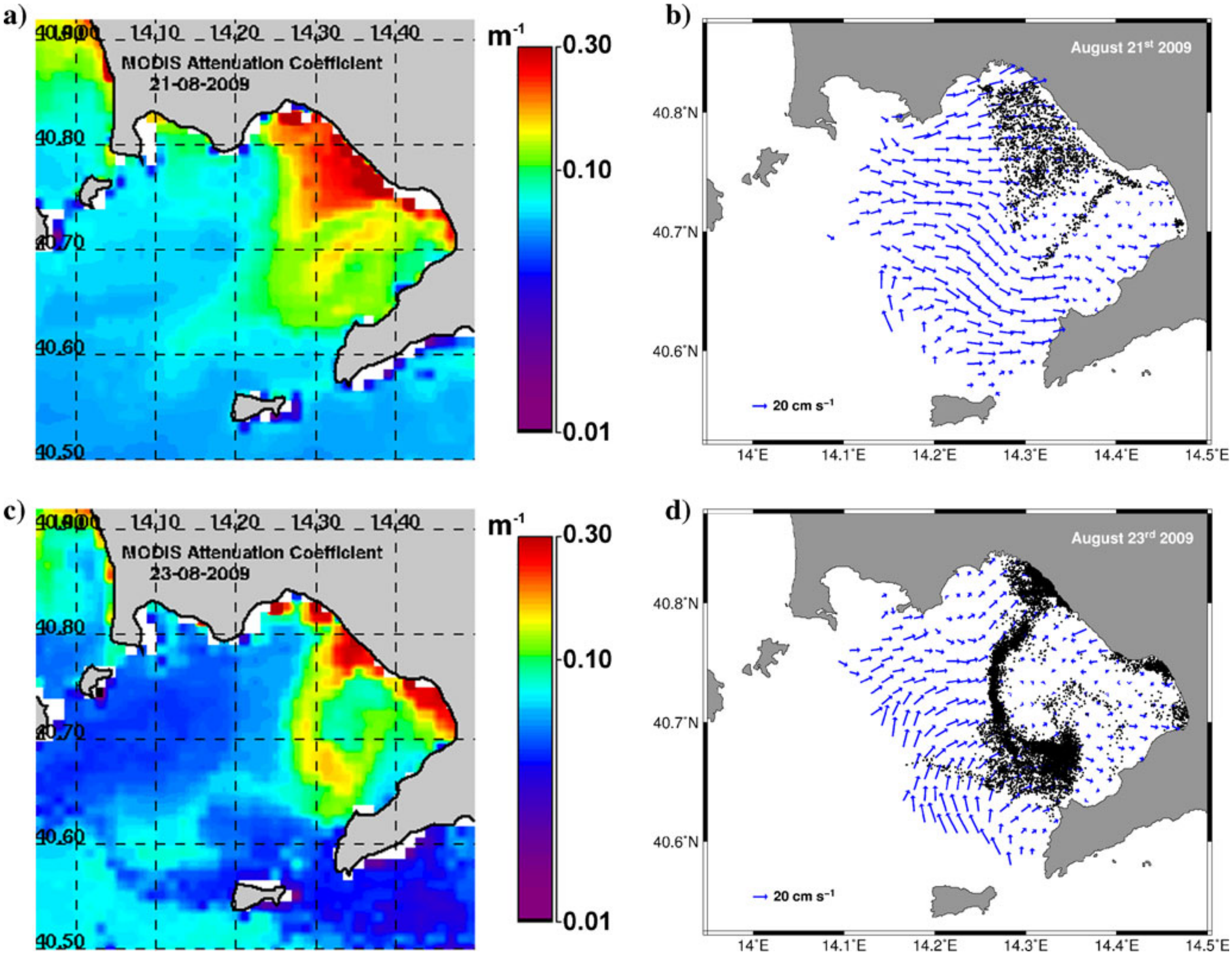


Fig. 7 (**a**) Satellite-derived turbidity distribution (K490) of August 21, 2009, and (**b**) corresponding initial condition in the third short-term simulation; (**c**) satellite-derived K490 pattern of August 23, 2009, and (**d**) corresponding final state of the simulation

where $N_e(T) = N(0) - N(t)$ is the number of particles which have already abandoned the release area at t, and t_{ei} is the time taken by the ith particle to exit from it.

5.2.1 August 7–September 3, 2009

Since the beginning, the alternating coastward–offshore currents moved the particles back and forth in the launch sector (see Video 5 in ESM). Many of them got to the coast in a few days and remained trapped in the littoral areas. A minor part was moved offshore, mostly those tracers launched close to the boundary, but only few of them abandoned the GoN for good. After 1 week, approximately 60% of particles were still inside the release area (Figs. 10a and 11). In the following 3 weeks, only an additional 10% was exported offshore (Figs. 10b,c and 11). On the last day of simulation, about 50% of tracers were still present in the original launch area (Figs. 10d and 11). As a result of the limited exchanges between coast and offshore, the residence times T* were very high, with particles remaining in the deployment area on average for more than 15 days before reaching offshore.

5.2.2 October 1–31, 2009

A couple of days after the beginning of the simulation, the original patch was divided in three main parts (see Video 6 in ESM). A first group of tracer particles was rapidly exported towards the Bocca Grande; a second one remained in the release sector but in open waters; the remaining particles moved towards the coasts. After 1 week, almost 50% of particles abandoned the release sector, while aggregations of them in several coastal areas were reported (Figs. 11 and 12a). In the following weeks (Figs. 11 and 12b and c), another 40% of tracers moved offshore and on October 31 (Figs. 11 and 12d) only approximately 14% of drifters were still inside the release sector. Estimated residence times T* were much shorter than in the

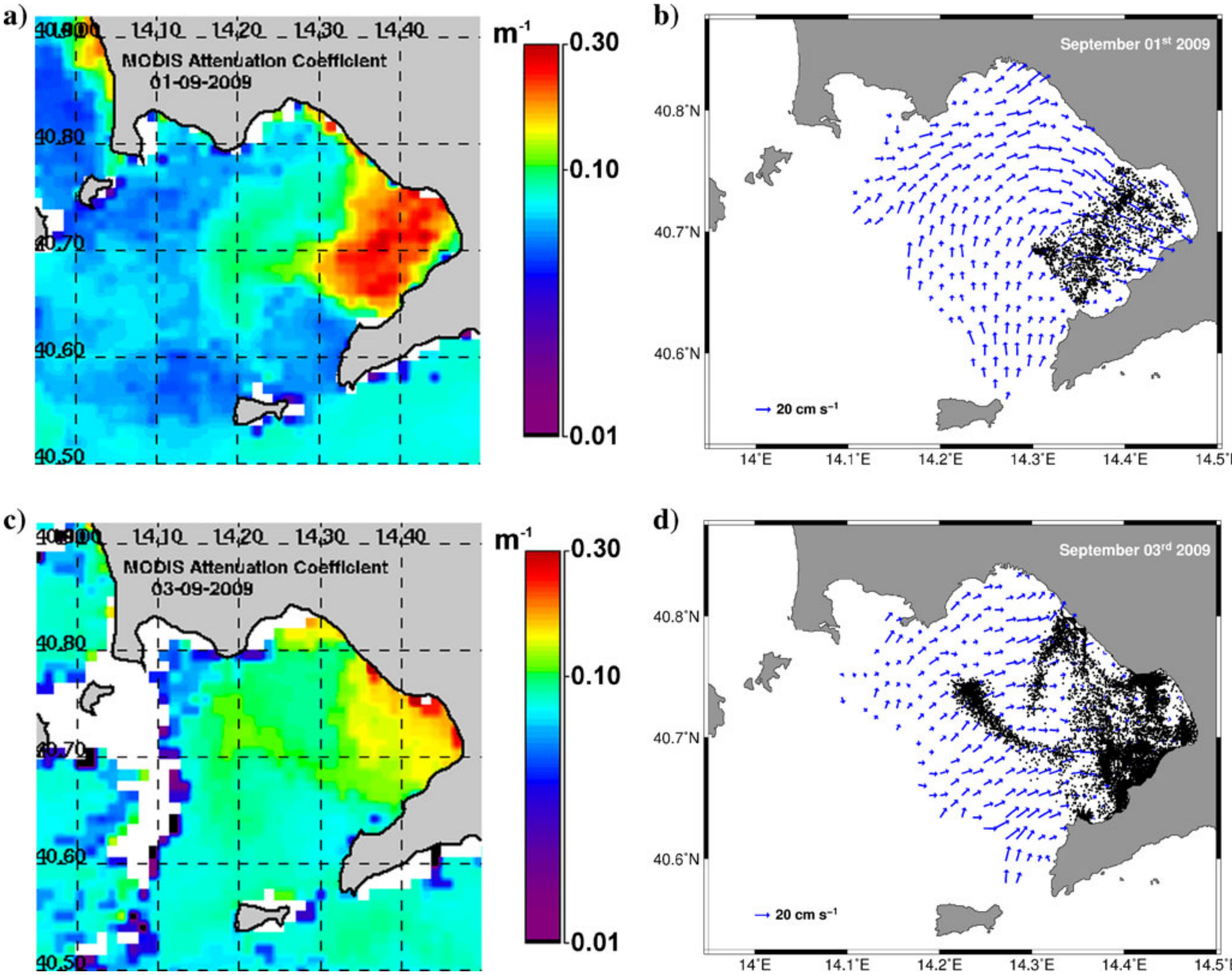
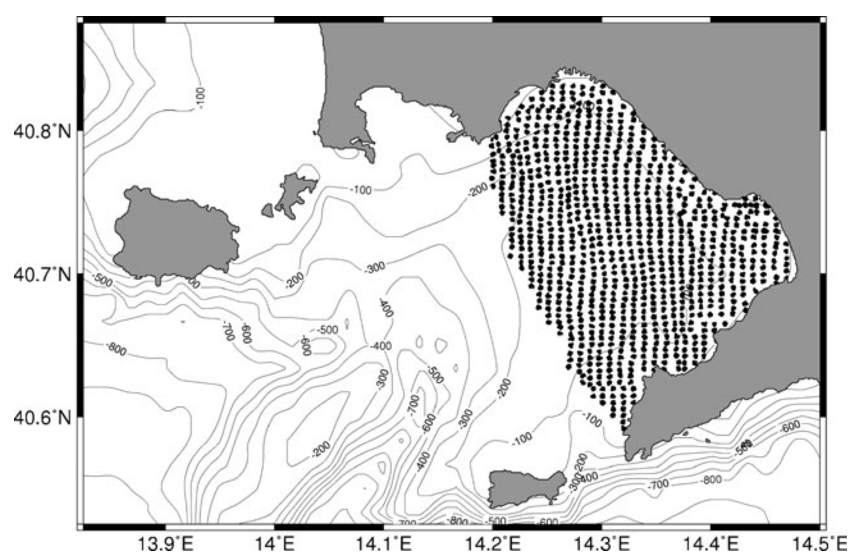


Fig. 8 (**a**) Satellite-derived turbidity distribution (K490) of September 1, 2009, and (**b**) corresponding initial condition in the fourth short-term simulation; (**c**) satellite-derived K490 pattern of September 3, 2009, and (**d**) corresponding final state of the simulation

Fig. 9 Initial distribution of passive particles and location of the boundary separating the inner and the outer sectors of the GoN in long-term simulations



August–September period, with values in the order of 10 days.

6 Discussion and conclusions

In the last decade, both scientists and policy makers have achieved a clear awareness of the importance of identifying the main natural and anthropogenic pressures acting on the marine ecosystem and of the necessity of defining efficient policies to reach and maintain a ‘good environmental status’ in coastal areas. In particular, the need to accurately assess the status of the marine ecosystem and to protect the marine environment from excessive human pressure has been clearly recognised by the European Commission (e.g. within its Marine Strategy Framework Directive, 2008/56/EC).

In this perspective, coastal areas must be considered of primary importance, as they represent critically sensitive ecosystems deserving focused investigations; this will allow to devise an efficient management of resources and to pursue the preservation of the environment. Coastal areas have been exploited for transportation and fishery purposes since the first urban settlements, and in the course of the centuries the human impact on these zones has increased enormously. The Gulf of Naples is a good example of a potentially critical area, subject to extremely strong impacts: it is located in a densely populated region, with a relevant stress on the marine environment, and on the other hand its ecological value is such that it requires a constant monitoring. Particularly in the summer, the necessity of preserving the water quality of the littoral zones of the GoN is fundamental for ensuring the course of recreational and tourist activities. Understanding the mechanisms that drive the renewal of surface waters in the different littoral sub-areas of the GoN thus becomes of crucial importance. This problem has been tackled in the present work by combining Lagrangian/Eulerian modelling, HF radar and satellite observations.

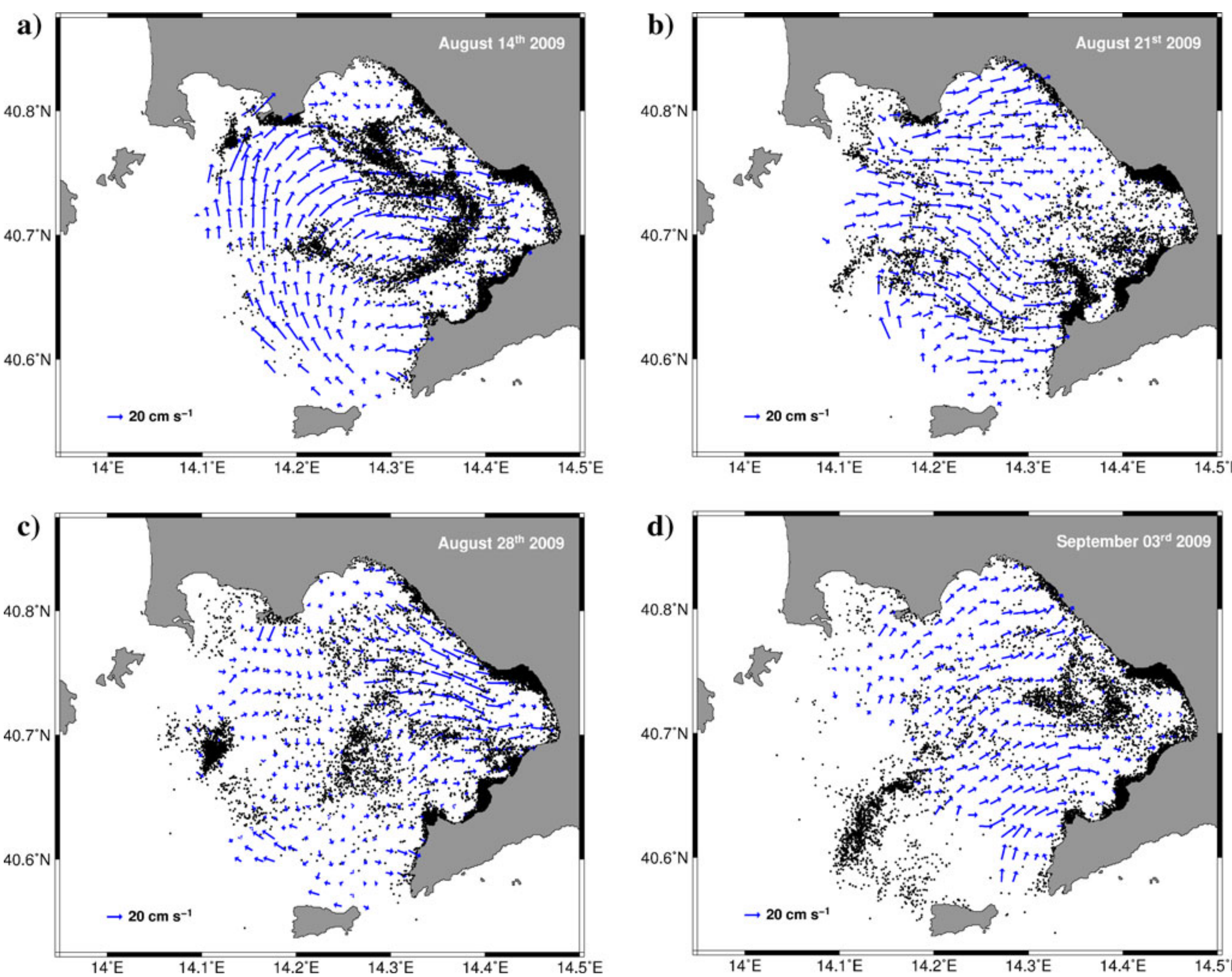


Fig. 10 Time evolution of the position of particles in the long-term simulation for the period August 7–September 3, 2009

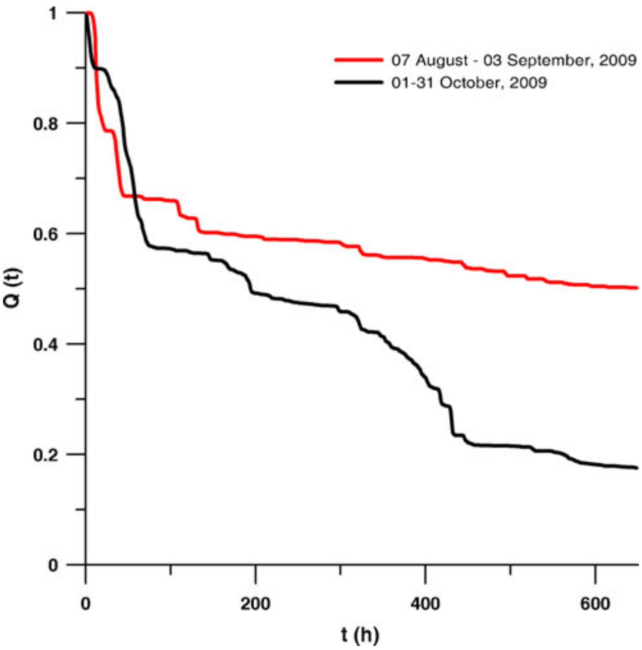


Fig. 11 Temporal evolution of the normalised quantity Q(t) of particles released in the inner part of the GoN for the long-term simulations (August 7–September 3, 2009; October 1–31, 2009)

The particular setting of the basin, its bottom topography, the orographic reliefs and the seasonally changing forcings act together to create a very complex surface dynamics, resulting in different flushing mechanisms and exchange patterns between the interior of the gulf and the Tyrrhenian waters (Buonocore et al. 2010; Cianelli et al. 2011). During the summer, surface circulation is mostly subordinate to the local breeze winds, with a diurnal alternation of coastward and offshore directed currents. The simulations performed in this study for the summer of 2009 demonstrate that such pattern determined a scarce renewal of coastal waters, both over short (i.e., 48 h) and long (i.e., 1 month) periods. The good agreement between model results and satellite observed turbidity patterns also pinpointed the presence of retention areas along the coasts of the GoN. With specific reference to the two investigated sub-basins, the Gulf of Castellammare showed a strongly retentive component, with intense aggregations of particles that recirculated in the area and were unable to rapidly abandon it. The Bay of Naples displayed a less marked retention, its local surface circulation promoting exchanges—though moderate—with neighbouring coastal areas and with the open waters.

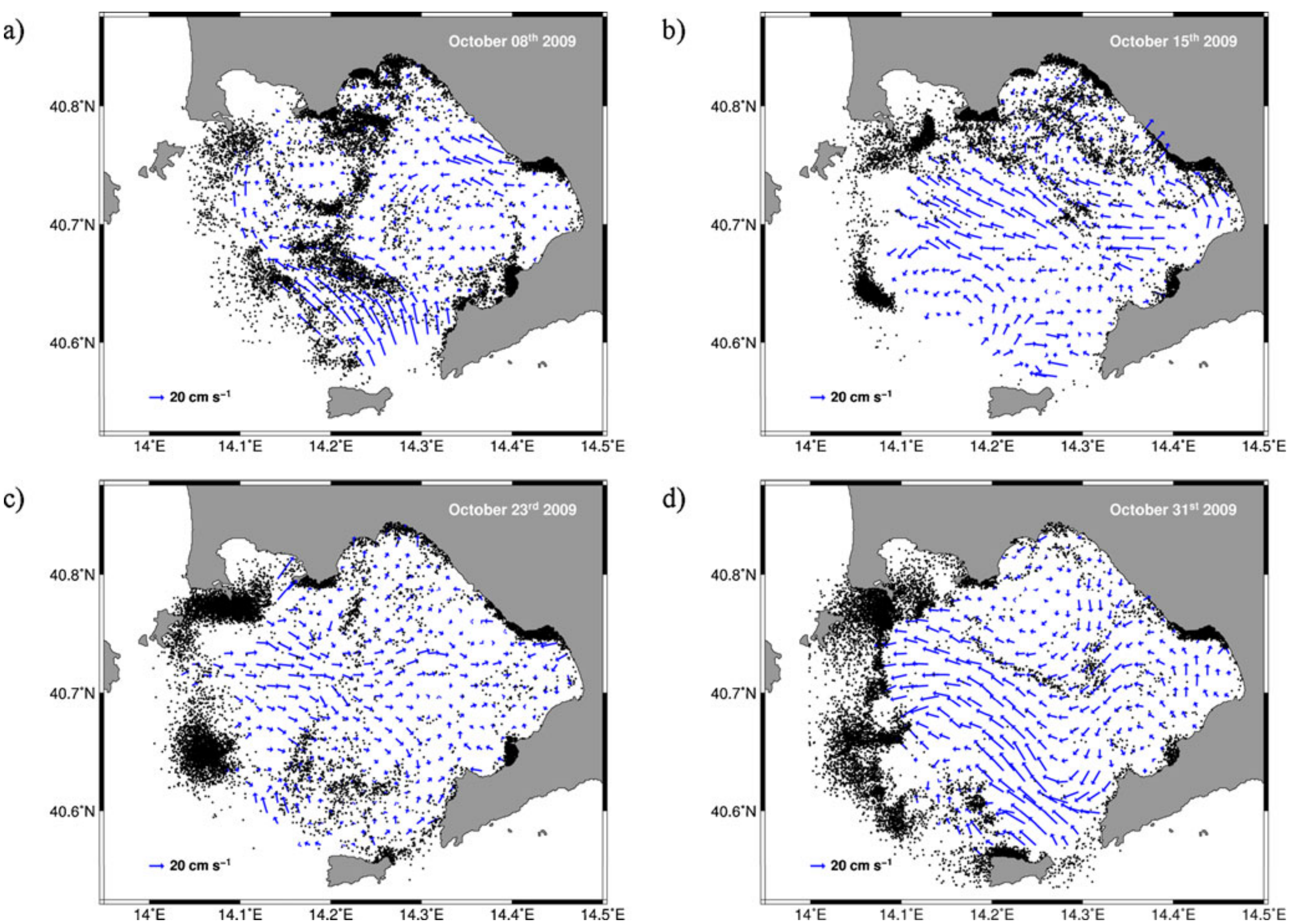


Fig. 12 Time evolution of the position of particles in the long-term simulation for the period October 1–31, 2009

Finally, the comparison between the long-term simulations presented in this work shows that in the fall 2009 the surface water renewal mechanisms were much more efficient than in the previous summer, thus explaining why the episodes of drastic decrease of the water quality which took place in the area in August 2009 ceased after the end of the summer.

The importance of building up observation networks to perform multi-parametric, real-time monitoring of the coastal ocean has been repeatedly stressed by scientists, and is now being recognised also at a political and general public level (e.g. following the recent disaster of the Deepwater Horizon oil spill in the Gulf of Mexico). The multiplatform approach proposed in this work has demonstrated its usefulness and reliability in highlighting key processes affecting the transport and diffusion of surface floating matter. While the combination of HF radar and satellite imagery has already been proved successful (e.g. Paduan and Cook 1997; Largier et al. 2006), our proposed methodology represents an innovative implementation due to the integration of modelling procedures to track the evolution of surface patches. This method has proved successful in the GoN using the signature of turbidity, but it might be equally helpful to track the progress of harmful algal blooms, oil spills and other natural or human induced phenomena.

Acknowledgments The authors wish to thank the organisers and participants of 42nd International Liege Colloquium on Ocean Dynamic for the constructive discussions on multiparametric observation of the sea. Insightful comments from two anonymous reviewers greatly improved this manuscript. The authors wish to thank Jeffrey Paduan for advice on coastal radar setup and data processing. Credits are also due to Giovanni Zambardino, Gennaro Bianco and Pasquale Mozzillo for supportive collaboration. The Dipartimento di Scienze per l'Ambiente of the "Parthenope" University operates the HF radar system on behalf of AMRA scarl (formerly CRdC AMRA), a Regional Competence Center for the Analysis and Monitoring of Environmental Risks. Our radar remote sites are hosted by the ENEA centre of Portici, the Fincantieri shipyard in Castellammare, the "Villa Angelina Village of High Education and Professional Training" and "La Villanella" resort in Massa Lubrense, whose hospitality is gratefully acknowledged. This work was partly funded by the MED TOSCA project, cofinanced by the European Regional Development Fund; by the PROMETEO project, funded by the Campania Region; by the PRIMI project, financed by the Italian Space Agency; by the FISR–VECTOR project (subtasks 4.1.5 and 4.1.6). Partial support from the Procura della Repubblica (Public Prosecutor's office) of Torre Annunziata is also acknowledged. M. U. was financially supported by a PROMETEO grant (WP03).

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