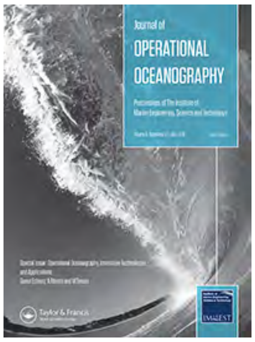

Journal of Operational Oceanography

ISSN: 1755-876X (Print) 1755-8778 (Online) Journal homepage: http://www.tandfonline.com/loi/tjoo20

Dynamics and sea state in the Gulf of Naples: potential use of high-frequency radar data in an operational oceanographic context

P. Falco, B. Buonocore, D. Cianelli, L. De Luca, A. Giordano, I. Iermano, A. Kalampokis, S. Saviano, M. Uttieri, G. Zambardino & E. Zambianchi

JOURNAL OF OPERATIONAL OCEANOGRAPHY, 2016
VOL. 9, NO. S1, s33–s45
http://dx.doi.org/10.1080/1755876X.2015.1115633

Dynamics and sea state in the Gulf of Naples: potential use of high-frequency radar data in an operational oceanographic context

P. Falco[a], B. Buonocore[a], D. Cianelli[a,b], L. De Luca[a], A. Giordano[a], I. Iermano[a], A. Kalampokis[a], S. Saviano[a], M. Uttieri[a], G. Zambardino[a] and E. Zambianchi[a]

[a]Department of Sciences and Technologies, Università 'Parthenope' and CoNISMa, Naples, Italy; [b]Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Rome, Italy

ABSTRACT
High-frequency coastal radars (HFRs) have proved to be excellent tools for monitoring coastal circulation, providing synoptic, high spatial and temporal resolution surface current data in real time. They may also give detailed information on the surface wave field of coastal areas. An HFR has been operating in the Gulf of Naples (south-eastern Tyrrhenian Sea) since 2004. In this paper we show the results of their utilisation in the study of the Gulf dynamics and sea state, with a focus on potential applications in the context of operational oceanography.

Introduction

The use of high-frequency radars (HFRs) in operational coastal monitoring is becoming increasingly important. The very first studies (Crombie 1955; Barrick 1971; Stewart and Joy 1974) were aimed at clarifying and testing the relationships between the echoes originated by radio-wave reflection due to sea gravity waves and the sea surface currents. The continuous development of hardware, echo-detection algorithms and real-time data dissemination systems has made it possible to manufacture very compact and effective systems that have been and continue to be used for various objectives (Barrick 2010). HFRs have proved to be extremely useful for understanding coastal dynamics that are characterised by processes concurrently acting on different time and spatial scales and often determining a complex current field structure. Such a structure can be efficiently identified through synoptic HFR measurements, while it would likely be unmeasurable using traditional current measurement instruments. HFR near real-time data are also becoming very important tools in the operational oceanography field in general, and for applications such as coastal management, pollution mitigation, maritime security and safety at sea in particular.

Moreover, coastal models are now being increasingly integrated with the growing network of regional coastal ocean observing systems through data assimilation. In particular, HFR data assimilation into coastal circulation models can greatly improve the model performance in an operational context (Wilkin et al. 2011; Iermano et al. 2016).

While they are mainly utilised for looking at surface currents, information on wave fields can be also extracted from HFR data (Wyatt et al. 2006). HFR current and wave data represent a unique opportunity to support coastal erosion studies, as these factors are the main erosion sources; a continuing availability of both fields is of great help to decision-makers.

For the above reasons, the number of HFRs installed worldwide has grown considerably over the last two decades. The most impressive HFR network has been set up along United States (US) coastlines where, by means of overlapping systems (over 130 radar units), the coverage of surface current monitoring both on the eastern and western coasts (Harlam et al. 2010) is nearly complete. In other countries such as Australia, an HFR network aimed at mapping the surface current over as extensive a range of coastal areas as possible is becoming an environmental priority (Atwater et al. 2013). In the Mediterranean Sea, HFR systems have been deployed in relatively few coastal areas, even though the number is quickly increasing. One of these areas is the Gulf of Naples (Figure 1).

A coastal ocean dynamics applications radar (CODAR; Barrick et al. 1977) has been working in the Gulf of Naples since 2004. The system is a SeaSonde manufactured by CODAR Ocean Sensors Ltd. (Mountain View, CA, USA). Three mono-static radar units (see Figure 1 for the locations) working at about 25

CONTACT P. Falco pierpaolo.falco@uniparthenope.it

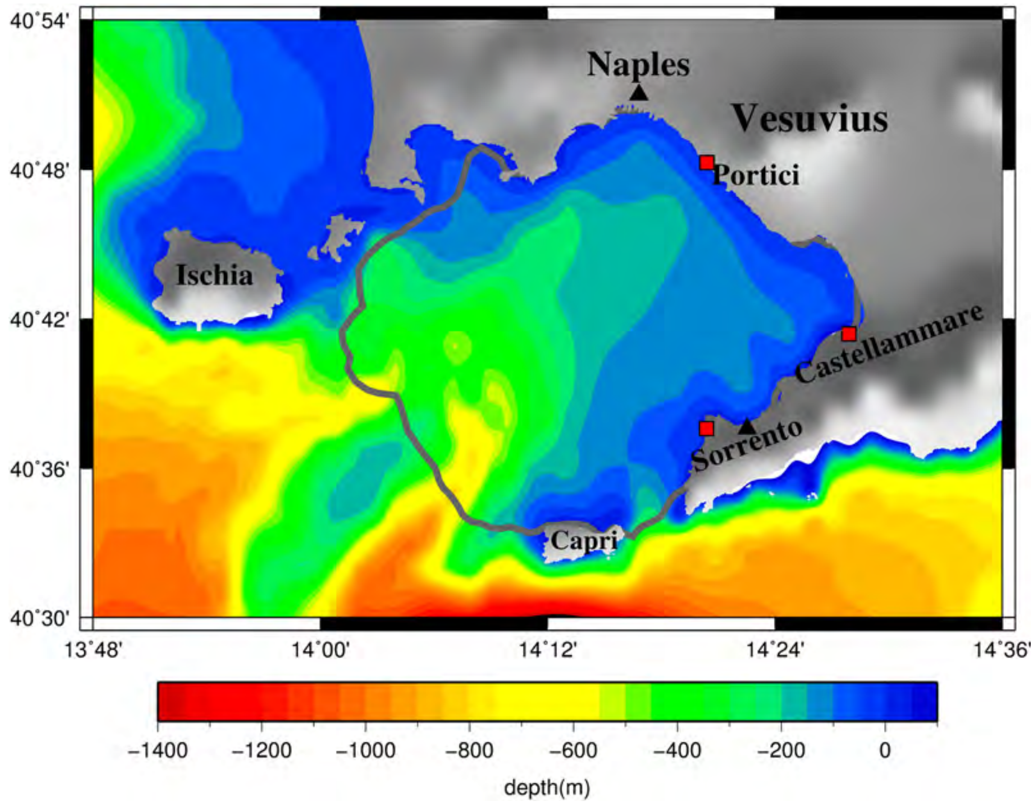

Figure 1. Map of the Gulf of Naples with the locations of the three HFR sites.
Note: The grey line represents the CODAR offshore coverage limit.

Mhz ensure the surface current mapping over nearly the entire Gulf area (Figure 1). The grid resolution is 1 km with a range of approximately 40 km. Data are available every hour with an accuracy ranging between 2 and 5 cm s^{-1} (Bellomo et al. 2015). Data collected at each radar unit are sent in real time to a central computer where they are combined so as to obtain a continuously updated surface current vector field.

In this paper, the general functioning principles of HFRs are outlined, followed by a brief review of HFR applications in different areas of the world's oceans. After this, an overview of applications and results obtained in the Gulf of Naples is presented, focusing mainly on studies with a prevalent operational character.

General principles of HFR functioning

HFRs measure three basic parameters that are utilised to determine the surface current field in a coastal area: the target distance from the antenna (where the target is a sector of the sea surface, or cell), the angle between the target and the antenna, and the surface current radial component in the cell. The cell dimensions depend on the radar frequency.

The radar antenna emits a signal and then receives the echo from the wavy sea surface. According to the resonant Bragg scattering theory, if the transmitted radar signal wavelength is twice the wavelength of the reflecting sea surface then the backscattered signal spectrum will show two well-defined energy peaks at frequencies that can be determined resolving the deepwater phase speed relation for the Bragg resonant surface waves (Hammond et al. 1987). These peaks are due to the coherent reflections which occur as each echo, coming from a wave crest, lines up to the previous one, resulting in a much more energetic signal being returned to the receiver. One of the two spectral peaks has more energy than the other because both advancing and receding (with respect to the radar antenna) waves reflect the radar signal; the faster a wave front moves towards the antenna, the more energetic a peak will be found at a higher frequency compared to the transmitted one, and conversely for a wave front moving away from the antenna, resulting in a lower frequency. The backscattered signal energy distribution is expressed in terms of the Doppler shift spectrum (Figure 2), on whose basis the radial current velocity is computed.

Radars calculate the target distance from the antenna by measuring the time the signal takes to hit the target and be backscattered. Given the typical HFR cell dimensions (of the order of one or very few km), time differences are very small, thus possibly affecting the

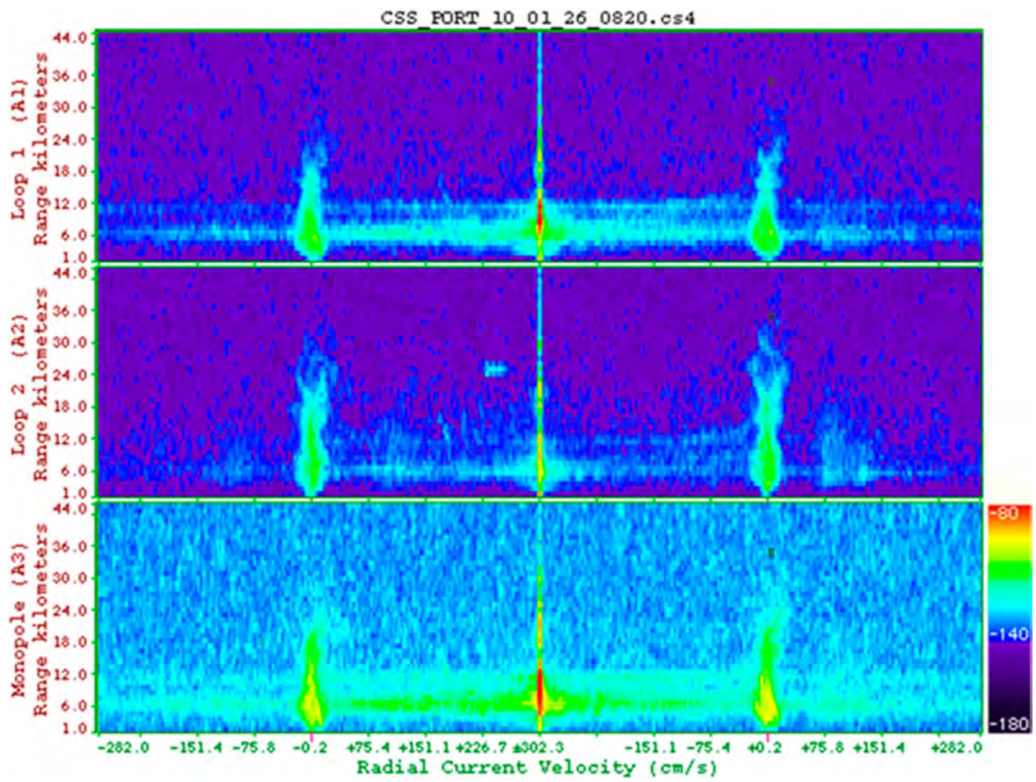

Figure 2. Example of a Doppler shift spectrum obtained from a HR radar measurement.
Note: From the top, the first two spectra refer to the two loop antennas while the third refers to the monopole (omni-directional) antenna.

accuracy of the velocity retrieval. In order to overcome this problem, an HFR sends a signal with a frequency increasing linearly in time. The backscattered signal will then be of the same shape but delayed in time. The difference between the two signals is constant when the signals are both present (because they both increase at the same rate) but will increase as long as the backscattered signal comes back to the antenna (Teague et al. 1997). The time lag during which the signal difference is not constant provides the time that must be multiplied by the electromagnetic wave velocity to obtain the range to the target.

HFRs are divided into two categories based on the kind of algorithm they use to determine the target angular direction. HFRs for sea current measurement electronically scan the direction from which the backscattered signal is coming. There are two methods of performing this: beam forming (BF) and direction finding (DF). BF HFRs have transmitting and receiving antennas which are physically separated. Ocean surface current radars (Shay et al. 1995) and, in a specific configuration, Wellen radars (WERA; Gurgel et al. 1999a) use BF to detect the backscattered signal arrival direction (WERA instruments can also work in a DF mode). Details about how BF works can be found in Gurgel et al. (1999b). Based on a more compact configuration, CODAR uses a DF method to determine the backscattered signal arrival angle. CODAR radars are monostatic, with two crossed-loop antennas and one monopole loop one, oriented at 90 deg with respect to each other so that they can be used in combination to determine the incoming direction of the signal, whereas the monopole is omnidirectional and used to normalise the information collected by the two loop antennas. DF radars compare the signals received by the two loop co-located antennas in phase or in amplitude using specific algorithms to obtain the incoming signal angular direction. In particular, CODAR systems mainly apply a multiple signal classification (MUSIC; Schmidt 1986) algorithm. MUSIC was conceived just to determine the parameters of multiple wave fronts arriving at a receiving array or co-located antennas. The algorithm provides unbiased estimates of different elements characterising the wave front, including the direction of arrival. The antenna location is a crucial element for the radar-receiving performance. In general, the antenna receiving-pattern is quite different with respect to the ideal one because of all kinds of obstacles (both physical and electromagnetic) that can prevent the incoming signal from reaching the antennas and affect the signal-to-noise ratio. Each loop antenna ideal pattern is a cosine function of the angle when normalised by the monopole signal. Distortions and deviations from this ideal condition may be caused by a noisy environment. To limit this problem, the real antenna receiving-pattern must be assessed. For SeaSonde HFRs (Paduan et al. 2006) such as the one working in the Gulf of Naples, this operation is carried out using a transponder that echoes the radar-transmitted signal, moving it following an arc-shaped path centred on the antenna location. This operation provides a measure of the phase and amplitude response for all three antennas (the two loops and the monopole), typically at a 1 deg angular resolution.

Examples of HFR applications

HFRs have been demonstrated over the years as being unique in terms of their capability to describe the surface current patterns in coastal areas. A recent, extensive review regarding HFR applications can be found in Paduan and Washburn (2013).

Together with currents, HFRs have proved to be very efficient in determining the wave field of the covered area (Weber & Barrick 1977) and also the wind field, which can be obtained particularly in areas where the wave field is wind induced (Wyatt et al. 2006).

Wind is a primary surface current force so its role and contribution in driving the upper layer circulation has been one of the most studied aspects of coastal dynamics using HFRs. Wind-forced dynamics spread over a wide range of temporal scales and HFRs have proven to be very effective in resolving nearly all of them. The high-frequency component primarily includes the sea breeze (Uttieri et al. 2011; Cianelli et al. 2013) and the inertial response (Kaplan et al. 2005), whereas the low-frequency component ranges from scales of a few days associated with changes in the wind field (related to local variation and atmospheric mesoscale variability; see Gough et al. 2010) up to the residual and seasonal circulation of the investigated area (Prandle & Player 1993; Sentchev et al. 2009; Muller et al. 2010; Kim et al. 2011).

To determine the residual circulation it is necessary to filter out the tidal contribution to the total current field. HFR data were successfully used in the evaluation of tide constituents (Prandle 1991; Solabarrieta et al. 2014). Each measurement grid point can be considered as a Eulerian current observation site; the time series measured at each grid point can then be used to reconstruct the tidal signal and the tidal current pattern.

Based on HFR data, a number of studies have focused on small-scale eddies forming in coastal regions (Shay et al. 1995; Bassin et al. 2005; Brown & Marques 2013). The observable smallest eddy spatial scale is a function of radar spatial resolution, and consequently of the working frequency. Thus, HFRs may allow the detection of eddies at the limit of the sub-mesoscale (even rapidly evolving ones, thanks to the high temporal resolution; see Parks et al. 2009). This has a number of interesting aspects, with implications on substance retention and more generally on local ecosystem dynamics.

The coastal dynamics in terms of dispersion processes has been mainly studied through Lagrangian trajectories. HFR synoptic and repeated surface current fields are well suited to the reconstruction of particle paths that can be statistically analysed to characterise several processes, such as pollutant-retention area formation (Kaplan & Largier 2006), oil spill evolution (Klemas 2010), discharged ballast ship water fate (Larson et al. 2005), larval transport from spawning areas to other regions (Bjorkstedt and Roughgarden, 1997) and residence time calculation at basin and sub-basin scales (Uttieri et al. 2011). HFRs have been also used in marine ecology; eddies, convergence and divergence zones, sub-mesoscale dynamics and tidal flows (Roughan et al. 2005; Kim 2010; Brown & Marques 2013) can be of great importance for understanding processes that govern fish assemblages and fish egg dispersion, the delivering of nutrients in coastal areas and the bacteria dispersion pattern from a near coast source (Kim et al. 2009). Backward trajectories reconstructed using HFR current fields have helped to reconstruct larval paths from source to settlement regions in a number of studies (Helbig & Pepin 2002; Nishimoto & Washburn 2002; Mantovanelli & Heron 2012). These kinds of applications can be included in the wider context of coastal ocean connectivity studies (Gawarkiewicz et al. 2007), which can be greatly improved by the availability of high-resolution (in time and space) surface current fields.

The Gulf of Naples HFR system: earlier studies and current developments

HFR observations of the Gulf of Naples surface circulation patterns

The Gulf of Naples circulation has been the subject of experimental studies since the mid-1970s (Moretti et al. 1977). More recently, modelling studies made important contributions to the overall description and comprehension of the Gulf circulation (Gravili et al. 2001; Grieco et al. 2005).

Since the first two antenna installations of the HFR system in the Gulf (October 2004), continuous observations of the surface current fields have been made available and several characteristics of the surface circulation have been assessed. One of the most prominent findings is the effect of the wind field in forcing the surface current.

The Gulf wind field is essentially bipolar, with two preferential origin directions, namely from the north-east and south-west quadrants, with an exception during the summer when a breeze regime characterises the daily pattern (Menna et al. 2007; Uttieri et al. 2011).

The Gulf of Naples wind-driven surface circulation is described by means of HFR data in a number of studies (Menna et al. 2007; Uttieri et al. 2011; Cianelli et al. 2012, 2013, 2015). In these works, particle transport was also studied by means of two integral quantities: the residence time and the normalised tracer particle quantity (Buffoni et al. 1997). Particle transport is driven by the wind-forced circulation pattern; wind forcing thus indirectly determines conditions favourable to water renewal (typically when the wind comes from the easterly sector) or to retention. The latter condition occurs in correspondence to winds blowing from the western quadrants; in this situation a gyre can generally be observed in the centre of the Gulf, with a lifetime of the order of a few (two to three) days. A number of other structures have been observed in the Gulf under different conditions, the most important being the formation of an anticyclonic circulation in its interior induced by a north-westward coastal current developing in the Tyrrhenian Sea and entering the Gulf through the Bocca Piccola, the channel through the mainland and Capri island (see below).

Typical wind-driven surface current patterns are showed in Figure 3. Applying a linear regression model to HFR measured currents and wind data, the wind-induced current showed an intensity ranging from 1.3 to 2.0% with respect to that of the wind (Poulain et al. 2012), whereas the angle ranged between 21 deg and 26 deg to the right of the wind (Cianelli et al. 2013). Moreover, it was found that the variance explained by the Ekman current is highest in summer under the sea breeze regime (21%) and lowest (<1%) when the Tyrrhenian coastal current is the main forcing of the Gulf circulation (21).

In Figure 3(d), a snapshot of the Gulf surface circulation when it is mainly forced by the interaction with the outer coastal current is shown, a pattern already observed in De Maio et al. (1985). Gyres can also form along the Gulf coast as a consequence of the outer coastal current reversal (De Maio et al. 1985; Cianelli et al. 2012). In particular, when the outer current flows towards the south-east, two gyres occur: one approximately in on front of the city of Naples and the second in the Gulf of Castellammare (see Figure 1).

Reconstruction of Lagrangian trajectories

The surface dynamics of the Gulf of Naples play a crucial role in devising response strategies and procedures in emergency cases, such as pollutant dispersion (e.g. oil spills, waste water and ballast water discharge) or search and rescue situations. HFR hourly updated surface current maps can provide an important contribution in such fast-moving situations. Also, in order to achieve a higher time and spatial resolution, HFR data can be used to drive Lagrangian models simulating surface transport and diffusion processes (Cianelli et al. 2013; Uttieri et al. 2011). To build an operational tool to be used in emergency situations, two Lagrangian transport models were tested using CODAR data as the advection component, namely MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting (De Dominicis et al. 2013a; De Dominicis et al. 2013b) and the General National Oceanic and Atmospheric Administration (NOAA) Operational Modelling Environment (GNOME), a mixed Lagrangian–Eulerian transport model developed by the NOAA (Uttieri et al. 2011; Cianelli et al. 2013).

HFR measured current data were used to build Lagrangian trajectories to simulate dispersion of passive tracers inside the Gulf of Naples. To validate such simulations, a comparison with real trajectories was also carried out. An example is reported in Figure 4 in which a 30-hour-long drifter track (deployed in the Gulf on 25 November 2009) and the trajectory simulated by means of the two particle-following transport models (MEDSLIK-II and GNOME) are shown.

Both models simulate the real drifter path assuming that the Lagrangian particle is a non-weathering tracer moved by the Eulerian current fields supplied by the HFR. The drifter trajectory simulations also take into account the stochastic component of particle motion parameterised as a random walk tuned by the horizontal turbulent diffusion coefficient.

The results show that both simulated tracks are in good agreement with the real data. The modelled trajectories move in the same direction as the real drifter, even though the MEDSLIK-II path develops more slowly than the drifter trajectory (almost half of the real drifter speed), as previously pointed out in (De Dominicis et al. 2013a, 2013b).

HFR wave measurements in the Gulf of Naples

Waves are one of the most important elements in a coastal-management framework. HFRs may provide an estimate of the main parameters characterising the wave field: wave direction, significant height and period. A preliminary confirmation of our radar system validity in measuring the wave field was recently given by Serafino et al. (2012).

Some results regarding the monitoring of surface waves using data acquired during 2009 from one of the

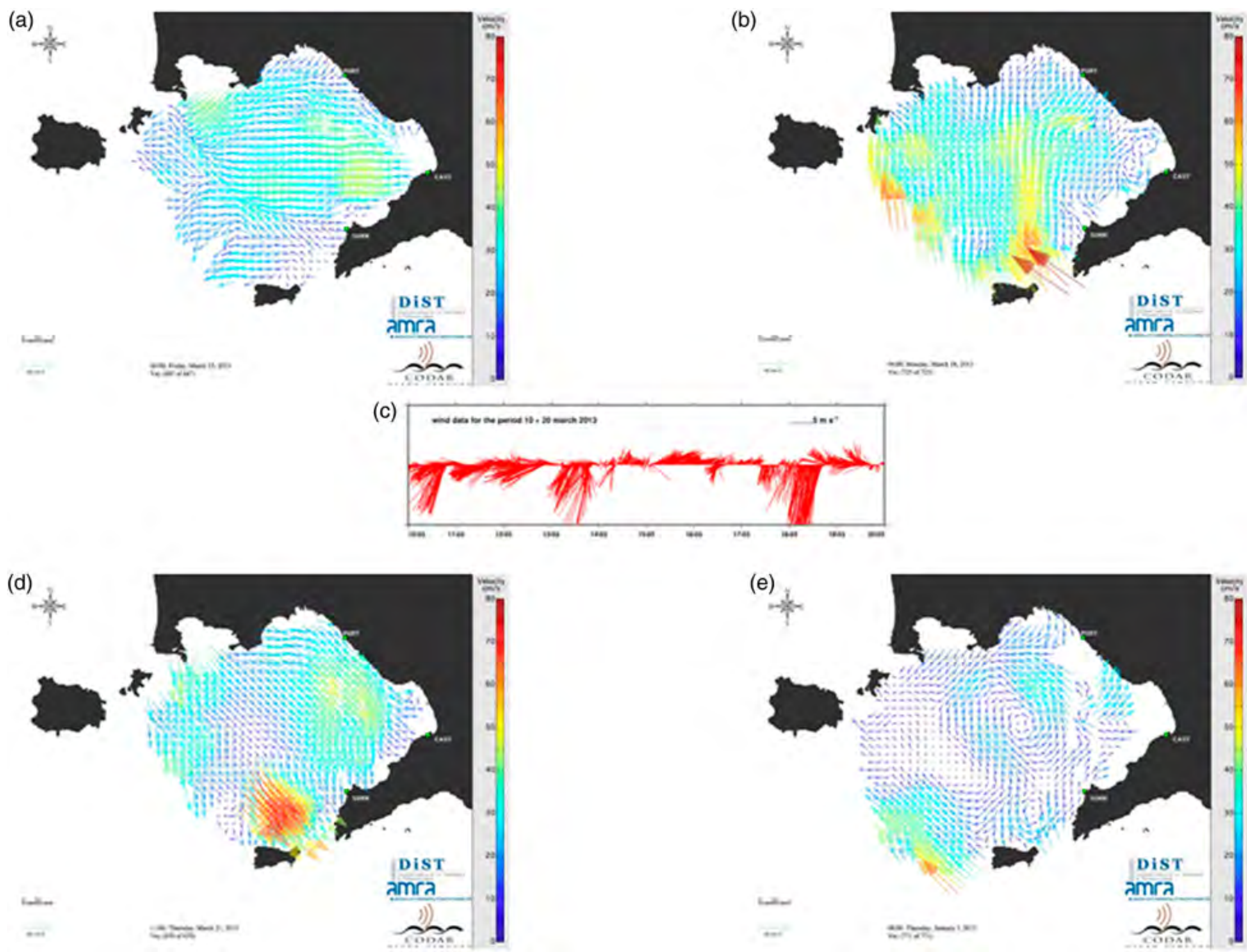

Figure 3. Surface current field response to (a, b, c and d) different wind patterns and (e) the Tyrrhenian coastal current. Note: (c) is shown in the form of stick diagrams.

three stations installed in the Gulf, namely the Portici site (see Figure 1), are shown in Figures 5 and 6. The system provided wave parameters averaged every 10 minutes. The data were grouped into trimesters to observe seasonal variations.

Waves were studied over a range cell located between 5 and 6 km from the coast. This choice, based upon preliminary sensitivity studies (not reported here), allowed us to analyse the surface gravity wave field in a region sufficiently far from the coast (thus avoiding strictly shallow water conditions) but not too much offshore (where the echo might reduce drastically, rendering data retrieval infeasible).

HFRs use first-order echoes to determine surface currents, while second-order ones can be exploited to determine surface wave parameters, namely the significant height H_s, the period T and wave direction (Barrick 1986). The maximum recordable wave height is equal to $h_{sat} = 2/k_0$ m, with $k_0 = 2\pi/\lambda$ m^{-1}, thus depending on the operating wavelength of the antenna λ. Since λ=12 m for a 25 MHz system, we have $h_{sat} \cong 4\,m$, which will be the maximum value of significant height the HFR can measure.

The effectiveness of HFR wave measurements has been demonstrated in different sea states and coastal environments (Graber & Heron 1997; Wyatt et al. 2006; Wyatt 2010; Atwater et al. 2013), in very specific conditions such as during sea storms (Lipa et al. 1990) and also in the framework of using HFRs as tsunami-detection systems (Lipa et al. 2006, 2012).

Wave height data are shown in Figure 5; the highest average values were reported in winter (1.51 m) and autumn (1.13 m), whereas slightly lower values were recorded in spring (1.06 m) and summer (1.08 m). Wave height showed some peak events during sea storms, particularly in winter. This is strongly linked to the typical Gulf of Naples atmospheric seasonality, where the transition from the stable high-pressure systems and weak breeze regime in spring and summer to the low atmospheric pressure systems and strong wind events in autumn and winter result in the creation of severe sea storms. Wave period over the investigated

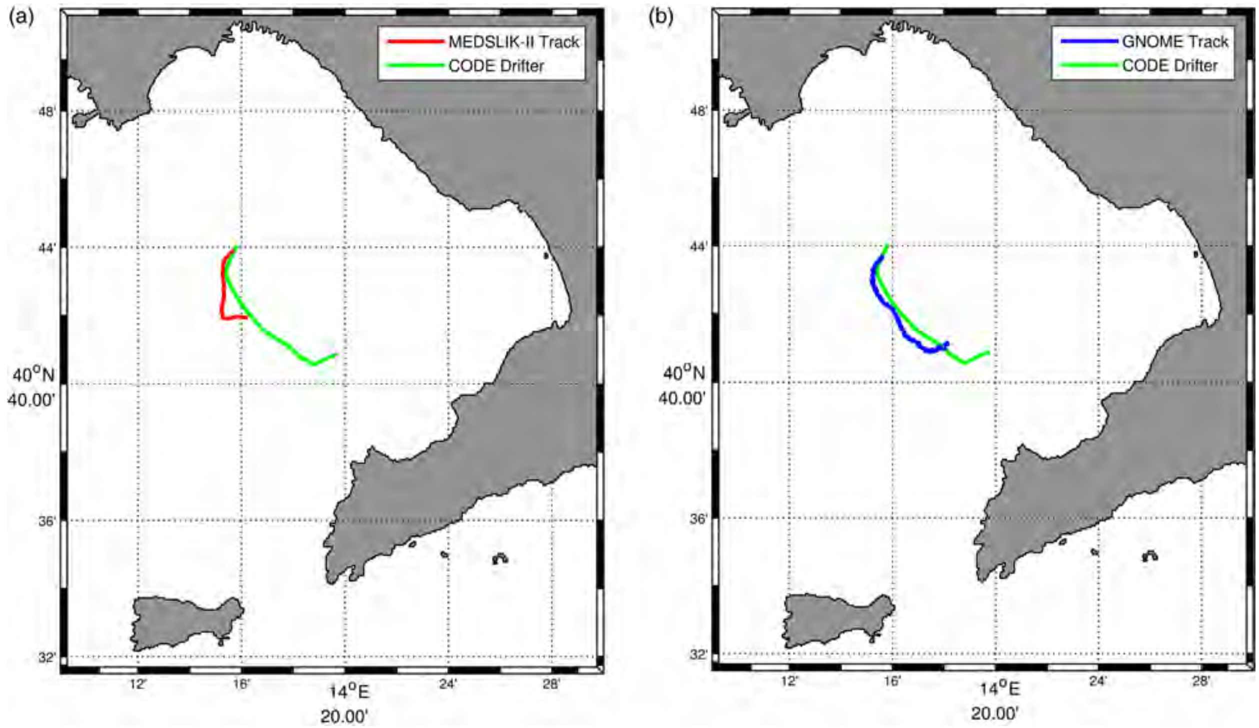

Figure 4. Comparison of real code drifter trajectories (green lines) with model reconstructions trajectories for (a) MEDSLIK-II simulation (red line) and (b) GNOME simulation (blue line).

time span did not reveal any significant seasonal variations. HFR significant wave height and period estimates are comparable with those reported in the literature, obtained from data acquired with a wave rider buoy (Buonocore & Zambardino 2003). The analysis of wave direction (Figure 6) shows a prevalent direction of waves from the third sector in all seasons due to the geomorphological configuration of the site. It is worth stressing that in the summer the functioning of the wave-detection system was less reliable as, owing to the breeze

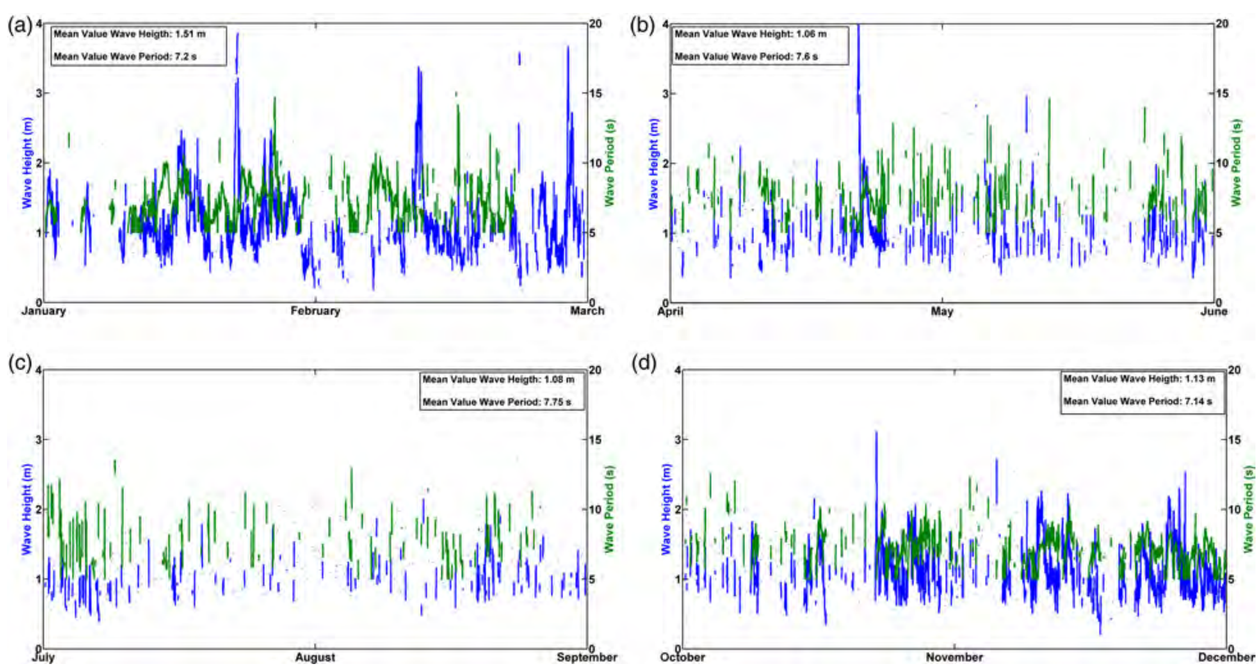

Figure 5. HFR wave height and period data from the Portici site for 2009.
Note: Data are clustered in trimesters. In each plot, the straight line represent the mean value over the trimester.

regime, waves were often below the detectability threshold (approx. 40 cm).

Assimilation of HFR data

The assimilation of velocity data into three-dimensional circulation models can be considered as a very recent field of study that is still evolving. A number of modelling studies using a variety of methods and error models have been carried out in order to assess the impact of surface current assimilation (Breivik & Saetra 2001; Paduan & Shulman 2004; Wilkin et al. 2005; Li et al. 2008; Hoteit et al. 2009; Shulman & Paduan 2009; Xu 2010; Zhang et al. 2010; Wilkin et al. 2011; Gopalakrishnan & Blumberg 2012; Yu et al. 2012). As part of the continuously evolving activities related to the Gulf of Naples HFR observation system, a four-dimensional approach of variational data assimilation (4D-Var) using a long-term HFR current time series within a high-resolution numerical model – namely, the Regional Ocean Modeling System (ROMS) – has been implemented.

ROMS is an open-source, ocean community-modelling framework (Haidvogel et al. 2000; Shchepetkin & McWilliams 2005) supporting three different 4D-Var data assimilation methodologies (Moore et al. 2011a, 2011b).

The model domain covers the Gulf of Naples and the adjacent deep-sea region extending between 39 deg N to 42 deg N and 12 deg E to 16 deg E with a 3 km horizontal resolution and 30 terrain-following vertical levels. The model forcing was derived from the global reanalysis output of the Era Interim dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF). The ocean surface fluxes were derived using the bulk formulations of (Fairall et al. 1996) and represent the background (or prior) surface forcing $fb(t)$ in the incremental formulation of 4D-Var.

The model domain has open boundaries at the northern, southern, and western edges where the tracer and velocity fields are also prescribed, while the free surface and vertically integrated flow are subject to Chapman (1985) and Flather (1976) boundary conditions, respectively. The prescribed open-boundary solution was taken

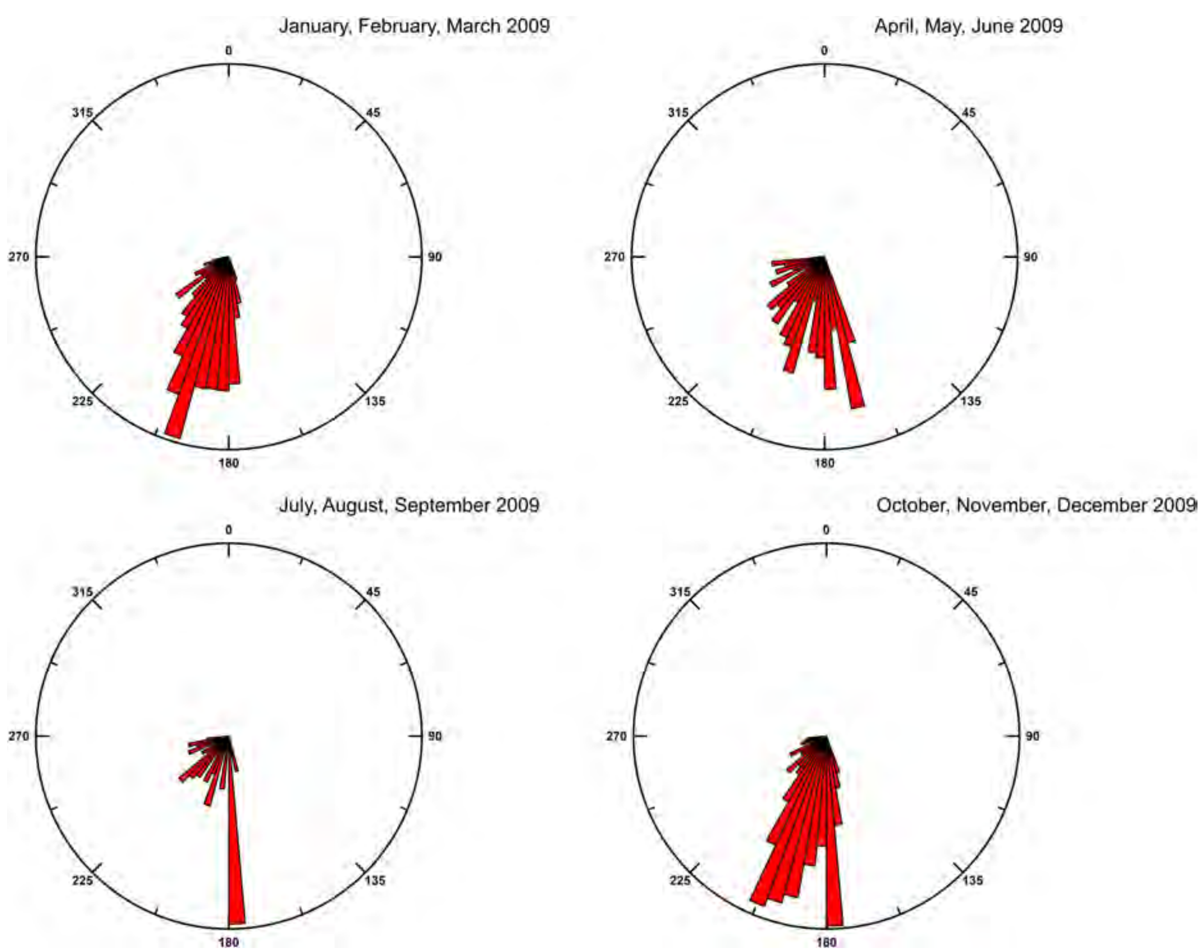

Figure 6. Rose diagrams of the HFR wave direction data for the Portici site for 2009.

from the High Resolution Atlantic and Mediterranean Mercator Ocean dataset (Madec et al. 1998).

The starting point for the ROMS/4D-Var experiment presented here, including the estimation of background error standard deviations for the control vector initial condition components, was taken from an inter-annual run performed without any data assimilation for the period 2007–2010. Strong constraint 4D-Var was performed starting on 1 December 2009 (the beginning of an HFR good coverage period; see Figure 7) using a 7-day assimilation window and adjusting the initial and boundary conditions and the atmospheric forcing fields.

One of the interesting questions raised by the assimilation of surface velocities in a coastal region is how sensitivity spreads from the surface to the rest of the domain. The sensitivity propagates as free waves (internal waves, Rossby waves, and topographically trapped waves, such as coastally trapped waves) in addition to advection by existing flows (Hoteit et al. 2009). Figure 8 shows the increments due to the data assimilation correction with respect to the temperature and salinity fields along a cross-section starting from the Gulf of Naples where the HFR observations are available.

As the integration of the adjoint model proceeds backward in time, the sensitivity spreads out horizontally away from the observed region and shows obvious interactions with the depth.

The vertical sections show how information is being transferred from the surface via the vertical correlations and the dynamics and confirm that, over a 7-day assimilation window, the tangent linear and adjoint models can effectively dynamically interpolate the HFR observations far away from the region under observation due to horizontal advection and wave dynamics (Figure 8).

Summary and conclusions

HFRs are unrivalled tools for the monitoring of coastal areas; besides applications to coastal management, they may prove to be of fundamental importance for operational oceanography as well. The possibility of retrieving a synoptic, high-resolution real-time view of the surface current field allows the study of local dynamics and transport processes. These features make HFRs invaluable to decision-makers and stakeholders in devising ecosystem-sustainable policies.

In various countries HFR systems are already operational. For instance, HFR surface currents are used by the US Navy Coast Guard in search and rescue operations, and it is demonstrated that the search area is reduced by about 66% using HFR data (Harlam et al. 2010). Oil spill models and HFR data can be combined to describe and forecast tracer dispersion (Emery et al. 2004; Klemas 2010). Furthermore, HFR data are used in other fields of application, such as maritime security, coastal engineering and fisheries (Emery et al. 2004; Roarty et al. 2008; Abascal et al. 2009; Dzvonkovskaya et al. 2009).

At the same time, new application areas are coming up, ranging from ship detection (Dzvonkovskaya et al. 2009) to wave measurement in the framework of marine renewable energy (Wyatt 2011). Recently it has been shown that HFRs can play a role as tsunami early-warning detection systems (Lipa et al. 2006). HFR data are also proving useful in marine biology studies, such as in connectivity

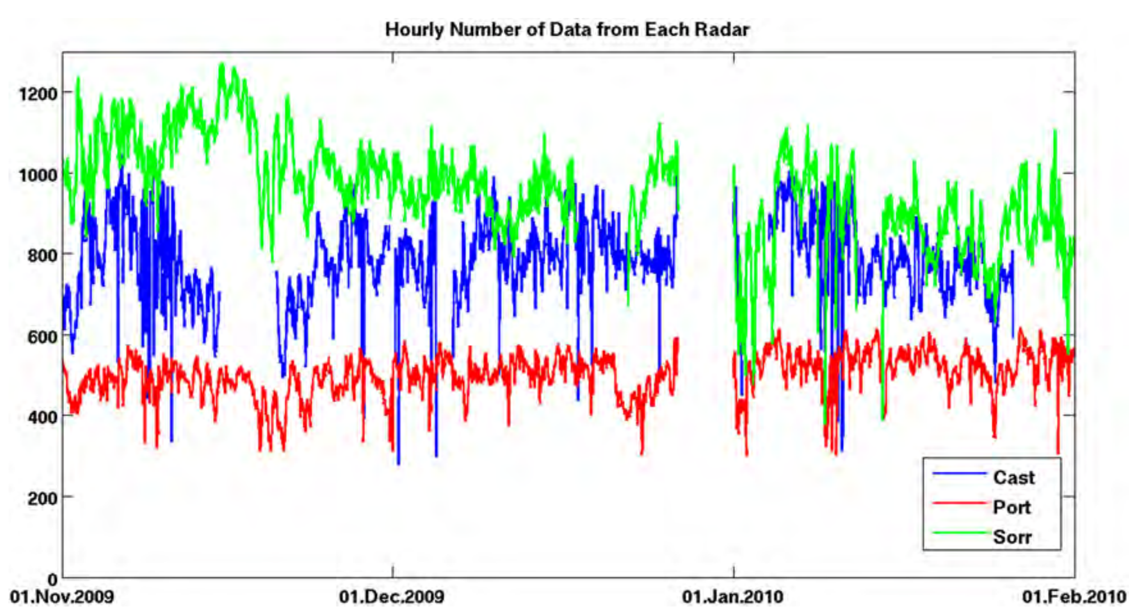

Figure 7. Hourly count of data from the three radars deployed at the Portici, Castellammare and Sorrento sites for assimilation experiments performed over a 7-day assimilation window in December 2009.

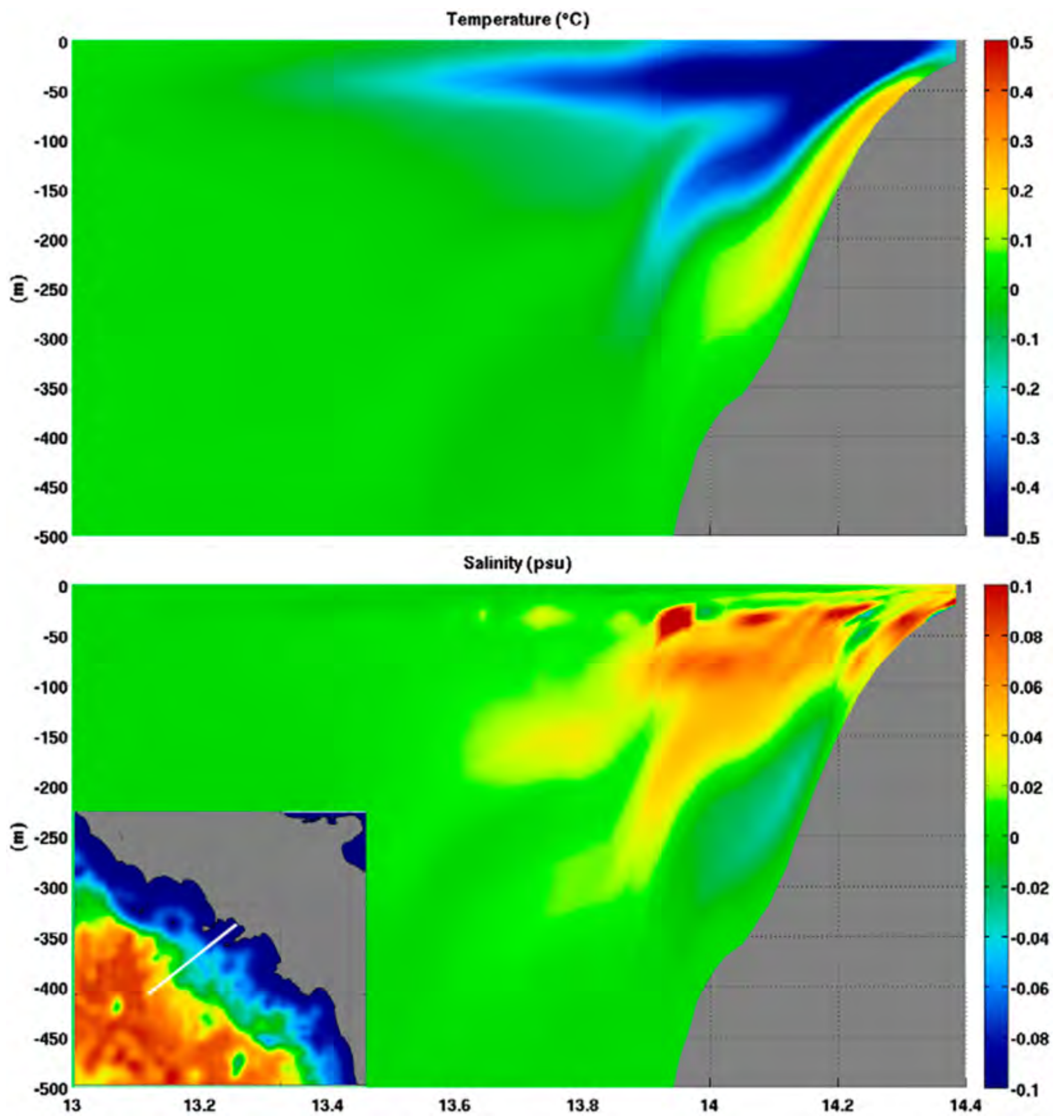

Figure 8. Increments in the temperature and salinity fields due to the data assimilation correction along the transect showed in the inbox.

studies, where HFR data can be successfully used to reconstruct Lagrangian trajectories and assess the transition probability between coastal subareas for larvae and planktonic organisms (Gawarkiewicz et al. 2007).

In this paper we presented a small subsample of the results obtained using the Gulf of Naples CODAR SeaSonde system, which has been active since 2004. The surface dynamics and in particular its variability is now well established; important information has been gathered on transport processes and exchange mechanisms between the coast and the open sea (Menna et al. 2007; Cianelli et al. 2012, 2013, 2015). Particle dispersion (Uttieri et al. 2011) assessed on the basis of HFR data has been used in the framework of oil spill simulations.

Waves are also being measured by the system installed in the Gulf. Data collected within the period January to July 2009 are consistent with earlier measurements obtained with a wave rider buoy (Buonocore & Zambardino 2003) and are also coherent with the expected seasonal variability.

Data assimilation in high-resolution coastal ocean models represents one of the most innovative use of the HFR current field in the framework of operational oceanography. The experiments presented here emphasise the effectiveness of HFR data assimilation in high-resolution numerical ocean models and suggest that the ROMS/4D-Var system is feasible for coastal area applications; it has to be underlined, however, that our results are still preliminary and that the full operational utilisation of the Gulf HFR data in the framework of a numerical circulation modelling effort will require substantial further work.

Acknowledgments

The Department of Sciences and Technologies (formerly the Department of Environmental Sciences) of the University of Naples 'Parthenope' operates the HFR system on behalf of the AMRA consortium (formerly CRdC AMRA), a regional competence centre for the analysis and monitoring of environmental risks. Our radar remote sites are hosted by the ENEA Centre of Portici, the 'Villa Angelina Village of High Education and Professional Training', 'La Villanella' resort in Massa Lubrense and the Fincantieri shipyard in Castellammare di Stabia, whose hospitality is gratefully acknowledged.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Italian National Research Council and the Italian Ministry of Education, University, and Research, within the National Research Programme 2011–2013 through the MED TOSCA project and the Flagship Project RITMARE (The Italian Research for the Sea).

References

Abascal AJ, Castanedo S, Medina R, Losada IJ, Alvarez-Fanjul E. 2009. Application of HF radar currents to oil spill modelling. Mar Pollut Bull. 58:238–48.

Atwater D, Mantovanelli A, Prytz A, Rehder S, Wyatt L. 2013. Operational requirements for oceanographic ground-wave HF radars: experiences from the Australian Coastal Ocean Radar Network. Radar (Radar), 2013 International Conference, 118–121.

Barrick DE. 1971. Theory of HF and VHF propagation across the rough sea, 2: application to HF and VHF propagation above the sea. Radio Sci. 6:527–533.

Barrick DE. 1986. The role of the gravity-wave dispersion relation in HF radar measurements of the sea surface. IEEE J Oceanic Eng. OE-11:286–292.

Barrick DE. 2010. 30 years of CMTC and CODAR, Current Measurement Technology, 2008. CMTC 2008. IEEE/OES 9th Working Conference.

Barrick DE, Evans MW, Weber BC. 1977. Ocean surface currents mapped by radar. Science. 198:138–144.

Bassin CJ, Washbirn L, Brezinski M, McPhee-Shaw E. 2005. Sub-mesoscale coastal eddies observed by high frequency radar: a new mechanism for delivering nutrients to kelp forest in the Southern California Bight. Geophys Res Lett. 32:1–4.

Bellomo L, Griffa A, Cosoli S, Falco P, Gerin R, Iermano I, Kalampokis A, Kokkini Z, Lana A, Magaldi MG, […], Mazzoldi A, Molcard A, Orfila A, Poulain P.-M, Quentin C, Tintoré J, Uttieri M, Vetrano A, Zambianchi E, Zervakis V. 2015. Toward an integrated HF radar network in the Mediterranean Sea to improve search and rescue and oil spill response: the TOSCA project experience. J Oper Oceaongr 8:1–13.

Bjorkstedt E, Roughgarden J. 1997. Larval transport and coastal upwelling: an application of HF radar in ecological research. Oceanography. 10:64–67.

Breivik Ø, Saetra Ø. 2001. Real time assimilation of HF radar currents into a coastal ocean model. J Mar Sci. 28:161–82.

Brown WS, Marques GM. 2013. Transient tidal eddy motion in the western Gulf of Maine, part1: primary strcture. Cont Shelf Res. 63:S90–S113.

Buffoni G, Falco P, Griffa A, Zambianchi E. 1997. Dispersion processes and residence times in a semi-enclosed basin with recirculating gyres: an application to the Tyrrhenian Sea. J Geophys Res. 102:699–713.

Buonocore B, Zambardino G. 2003. Rilievi ondametrici nel Golfo di Napoli. Annali IUN. LXVII:203–211.

Chapman DC. 1985. Numerical treatment of cross-shelf open boundaries in a barotropic coastal ocean model. J of Phys Oceanogr. 15:1060–1075.

Cianelli D, Falco P, Iermano I, Mozzillo P, Uttieri M, Buonocore B, Zambardino G, Zambianchi E. 2015. Inshore/offshore water exchange in the Gulf of Naples. J. Mar. Syst. 145:37–52

Cianelli D, Uttieri M, Buonocore B, Falco P, Zambardino G, Zambianchi E. 2012. Dynamics of a very special Mediterranean coastal area: the Gulf of Naples. Mediterranean Ecosystem: Dynamics, Management & Conservation, p. 170.

Cianelli D, Uttieri M, Guida R, Menna M, Buonocore B, Falco P, Zambardino G, Zambianchi E. 2013. Land-based remote sensing of coastal basins: use of an HF radar to investigate surface dynamics and transport processes in the Gulf of Naples. Remote Sensing: Techniques, Applications and Technologies, p. 198.

Crombie DD. 1955. Doppler spectrum of sea echo at 13.56 Mc/s. Nature. 175:681–682.

De Dominicis M, Pinardi N, Zodiatis G, Lardner R. 2013a. MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting – part 1: theory. Geosci Model Dev. 6:1851–1869.

De Dominicis M, Pinardi N, Zodiatis G, Archetti R. 2013b. MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting – part 2: numerical simulations and validations. Geosci Model Dev. 6:1871–1888.

De Maio A, Moretti M, Sansone E, Spezie G, Vultaggio M. 1985. Outline of marine currents in the Bay of Naples and some considerations on pollutant transport. Nuovo Cim. 8:955–969.

Dzvonkovskaya A, Gurgel KW, Rohling H, Schlick T. 2009. HF Radar WERA application for ship detection and tracking. European Journal of Navigation. 7:18–25.

Emery BM, Washburn L, Love MS, Nishimoto MM, Ohlmann JC. 2004. Do oil and gas paltforms off California reduce recruitment of boccaccio (Sebastes Paucispinis) to natural habitat? an analysis based on trajectories derived from high-frequency radar. Fishery Bullettin. 104:391–400.

Fairall CW, Bradley EF, Rogers DP, Edson JB, Young GS. 1996. Bulk parameterization of air-sea fluxes for tropical ocean-global atmosphere coupled-ocean atmosphere response experiment. J Geophys Res. 101:3747–3764.

Flather RA. 1976. A tidal model of the northwest European continental shelf. Memoires de la Societe Royale de Sciences de Liege. 6:141–164.

Gawarkiewicz G, Monismith S, Largier J. 2007. Observing larval transport processes affecting population connectivity. Oceanography. 20:40–53.

Gopalakrishnan G, Blumberg AF. 2012. Assimilation of HF radar-derived surface currents ontidal-timescales. J Oper Oceanogr. 5:75–87.

Gough MK, Garfield N, McPhee-Shaw E. 2010. An analysis of HF radar measured surface currents to determine tidal, wind-forced, and seasonal circulation in the Gulf of the Farallones, California, United States. J Geophys Res. 115: C04019:1–19.

Graber HC, Heron ML. 1997. Wave height measurement from HF radar. Oceanography. 10:90–92.

Gravili D, Napolitano E, Pierini S. 2001. Barotropic aspects of the dynamics of the Gulf of Naples (Tyrrhenian Sea). Cont Shelf Res. 21:455–471.

Grieco L, Tremblay LB, Zambianchi E. 2005. A hybrid approach to transport processes in the Gulf of Naples: an application to phytoplankton and zooplankton population dynamics. Cont Shelf Res. 25:711–728.

Gurgel KW, Antonischki G, Essen HH, Schlick T. 1999a. Wellen Radar (WERA): a new ground-wave HfR for ocean remote sensing. Coast Eng. 37:219–234.

Gurgel KW, Essen, Kingsley HH, Kingsley SP. 1999b. High-frequency radars: physical limitations and recent developments. Coast Eng. 37:201–218.

Haidvogel DB, Arango HG, Hedstrom K, Beckmann A, Malanotte-Rizzoli P, Shchepetkin AF. 2000. Model evaluation experiments in the North Atlantic Basin: simulations in nonlinear terrain-following coordinates. Dynamics of Atmosphere and Oceans. 32:239–281.

Hammond TM, Pattiaratchi CB, Eccles D, Osborne MJ, Nash LA, Collins MB. 1987. Ocean surface current radar (OSCR) vector measurements on the inner continental shelf. Cont Shelf Res. 7:411–431.

Harlam J, Terril E, Hazard L, Keen C, Barrich D, Whelan C, Howden S, Kohut R. 2010. The intergrated ocean observing system high-frequency radar network: status and local, regional and national applications. Marine Tecnology Society Journal. 44:122–132.

Helbig JA, Pepin P. 2002. The effects of short space and time scale current variability on the predictability of passive ichthyoplankton distributions: and analysis based on HF radar observations. Fish Oceanogr. 11:175–188.

Hoteit I, Cornuelle B, Kim SY, Forget G, Kohl A, Terrill E. 2009. Assessing 4D-VAR for dynamical mapping of coastal high-frequency radar in San Diego. Dynamics of Atmosphere and Oceans. 48:175–197.

Iermano I, Moore AM, Zambianchi E. 2016. Impacts of a 4-dimensional variational data assimilation in a coastal ocean model of southern Tyrrhenian Sea. J Mar. Syst. 154:157–171.

Kaplan DM, Largier J, Botsford LW. 2005. HF radar observations of surface circulation off Bodega Bay (northern California, USA). J Geophys Res. 110:C10020:1–25.

Kim SY. 2010. Observation of submesocale eddies using high-frequency radar-derived kinematic and dynamic quantities. Cont Shelf Res. 30:1639–1655.

Kim SY, Terrill EJ, Cornuelle BD. 2009. Assessing coastal plumes in a region of multiple discharges: the U.S.–Mexico border. Environmental Science Technology. 43:7450–7457.

Kim SY, Terrill EJ, Cornuelle BD, Jones B, Washburn L, Moline MA, Paduan JD, Garfield N, Largier JL, Crawford G, Klemas V. 2010. Tracking oil slicks and predicting their trajectories using remote sensors and models: case studies of the Sea Princess and Deepwater Horizon oil spills. J Coastal Res. 265:789–797.

Kosro PM. 2011. Mapping the U.S. West Coast surface circulation: a multiyear analysis of high-frequency radar observations. J Geophys Res. 116:C03011.

Larson MR, Foreman MGG, Levings GC, Tarbotton MR. 2005. Dispersion of discharged ship ballast water in Vancouver Harbour, Juan De Fuca Strait, and offshore of the Washington Coast. J Environ Eng and Sci. 2:163–176.

Lipa B, Barrick D, Bourg J, Nyden B. 2006. HF radar detection of tsunamis. J Oceanogr. 62:705–716.

Lipa B, Barrick D, Isaacson J, Lilleboe PM. 1990. CODAR wave measurements from a North Sea semisubmersible. IEEE Oceanic Engineering. 15:119–125.

Lipa B, Isaacson J, Nyden B, Barrick D. 2012. Tsunami arrival detection with high frequency radar. Remote Sens. 4:1448–1461.

Li Z, Chao Y, McWilliams JC, Ide K. 2008. A three-dimensional variational data assimilation scheme for the Regional Ocean Modeling System: implementation and basic experiments. J Geophys. Res. 11:C05002:1–19.

Madec G, Delecluse P, Imbard M, Levy C. 1998. OPA8.1, ocean general circulation model reference manual. Notes du pole de modelisation IPSL, 11.

Mantovanelli A, Heron M. 2012. Radar-based tracking of pollutants in the Coral Sea. Proceedings of the 12th International Coral Reef Symposium.

Menna M, Mercatini A, Uttieri M, Buonocore B, Zambianchi E. 2007. Wintertime transport processes in the Gulf of Naples investigated by HF radar measurements of surface currents. Nuovo Cim. 30:605–622.

Moore AM, Arango HG, Broquet G, Edwards C, Veneziani M, Powell B, Foley D, Doyle JD, Costa D, Robinson P. 2011a. The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems: part II – performance and application to the California current system. Prog in Oceanogr. 91:50–73.

Moore AM, Arango HG, Broquet G, Powell BS, Weaver AT, Zavala-Garay J. 2011b. The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems: part I – system overview and formulation. Prog in Oceanogr. 91:34–49.

Moretti M, Sansone E, Spezie G, Vultaggio M, De Maio A. 1977. Alcuni aspetti del movimento delle acque del Golfo di Napoli. Annali Ist Univ Nav. 3:207–217.

Muller H, Blanke B, Dumas F, Mariette V. 2010. Identification of typical scenarios for the surface Lagrangian residual circulation in the Iroise Sea. J Geophys Res. 115:C07008:1–14.

Nishimoto MM, Washburn L. 2002. Pattern of coastal eddy circulation and abundance of pelagic juvenile fish in the Santa Barbara Channel, California USA. Mar Ecol Prog Ser. 241:183–199.

Paduan JD, Kim KC, Cook MS, Chavez FP. 2006. Calibration and validation of direction-finding high frequency radar ocean surface current observations. IEEE Journal of Oceanic Engeneering. 31:862–875.

Paduan JD, Shulman I. 2004. HF radar data assimilation in the Monterey Bay area. J Geophys Res. 109:C07S09:1–17.

Paduan JD, Washburn L. 2013. Observation of ocean surface currents. Annu Rev of Mar Sci. 5:115–136.

Parks AB, Shay LK, Johns WE, Martinez-Pedraja J, Gurgel KW. 2009. HF radar observations of small-scale surface current variability in the Straits of Florida. J Geophys Res. 114: C08002:1–17.

Poulain PM, Menna M, Mauri E. 2012. Surface circulation of the Mediterranean Sea derived from dirfter and satellite altimeter data. Journal of Physical Oceangraphy. 42:973–990.
Prandle D. 1991. A new view of near-shore dynamics based on observations from HF radar. Progress in Oceanography. 27:403–438.
Prandle D, Player R. 1993. Residual currents through the Dover Strait measured by H. F. Radar. Estuarine, Coastal and Shelf Science. 37:635–653.
Roarty H, Kohut J, Glenn S. 2008. The Mid-Atlantic Regional Coastal Ocean Observing System: Serving Coast Guard and Fisheries Needs in the Mid-Atlantic Bight. Proceedings ofthe IEE/EOES/C¶ktTC Ninth Working Conference on Current Measurement Technology p. 151–155.
Roughan M, Terril EJ, Largier JL, Otero MP. 2005. Observation of divergence and upwelling around Point Loma, California. J Geophys Res. 110:C04011:1–11.
Schmidt RO. 1986. Multiple emitter location and signal parameter estimation. IEEE Transaction on Antennas Propagation. 34:276–280.
Sentchev A, Forget P, Barbin Y. 2009. Residual and tidal circulation revealed by VHF radar surface current measurements in the southern Channel Isles region (English Channel). Estuarine Coastal Shelf Science. 82:180–192.
Serafino F, Lugni C, Ludeno G, Arturi D, Uttieri M, Buonocore B, Zambianchi E, Budillon G, Soldovieri F. 2012. REMOCEAN: a flexible X-band radar system for sea-state monitoring and surface current estimation. IEEE Geosci and Remote S. 9:822–826.
Shay LK, Graber HC, Ross DB, Chapman D. 1995. Mesoscale ocean surface current structure detected by HfR. J of Atmos and Oceanic Tech. 12:881–900.
Shchepetkin AF, McWilliams JC. 2005. The regional ocean modeling system: a split–explicit, free-surface, topography following coordinates ocean model. Ocean Model. 9:347–404.
Shulman I, Paduan JD. 2009. Assimilation of HF radar-derived radials and total currents in the Monterey Bay area. Deep-Sea Res II. 56:149–160.
Solabarrieta L, Rubio A, Castanedo S, Medina R, Charria G, Hernández C. 2014. Surface water circulation patterns in the southeastern Bay of Biscay: new evidences from HF radar data. Cont Shelf Res. 74:60–76.
Stewart RH, Joy JW. 1974. HF radar measurement of surface current. Deep-Sea Res. 21:1039–49.
Teague CC, Vesecky JF, Fernandez DM. 1997. HF radar instruments, past to present. Oceanography. 10:40–44.
Uttieri M, Cianelli D, Buongiorno Nardelli B, Buonocore B, Falco P, Colella S, Zambianchi E. 2011. Multiplatform observation of the surface circulation in the Gulf of Naples (Southern Tyrrhenian Sea). Ocean Dynam. 61:779–796.
Weber BL, Barrick DE. 1977. On the nonlinear theory forgravity waves on the ocean's surface. Part I: derivations. J Phys Oceanogr. 7:3–10.
Wilkin JL, Arango HG, Haidvogel DB, Lichtenwalner CS, Glenn SM, Hedstrom KS. 2005. A regional ocean modeling system for the long-term ecosystem observatory. J Geophys Res. 110:C06S91:1–13.
Wilkin JL, Zhang WG, Cahill B, Chant RC. 2011. Integrating coastal models and observations for studies of ocean dynamics, observing systems and forecasting. Operational Oceanography in the 21st Century. Springer; p. 729: 487–512.
Wyatt L. 2010. Wave mapping with HF radar. Proceedings of the IEEE/OES/CWTM Tenth Working Conference on Current Measurement Technology, p. 25–30.
Wyatt L. 2011. Use of HF radar for marine renewable applications. IEEE Digital Library, 10.1109/OCEANS-Yeosu.2012.626343.
Wyatt LR, Green JJ, Middleditch A, Moorhead MD, Howarth J, Holt M, Keog S. 2006. Operational wave, current, and wind measurements with the pisces HfR. IEEE J Oceanic Eng. 31:819–834.
Xu J. 2010. Assimilation of high frequency radar data into a shelf sea circulation model. PhD thesis. Univ. Hamburg; p. 113.
Yu P, Kurapov AL, Egbert GD, Allen JS, Kosro PM. 2012. Variational assimilation of HF radar surface currents in a coastal ocean model off Oregon. Ocean Model. 49–50:86–104.
Zhang WG, Wilkin JL, Arango HG. 2010. Towards an integrated observation and modeling system in the New York Bight using variational methods. Part I: 4DVAR data assimilation. Ocean Model. 35:119–133.