Coastal HF radars in the Mediterranean: Applications in support of science priorities and societal needs

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Abstract. The Mediterranean Sea is a prominent climate change hot spot, with many socio-economically vital coastal areas being the most vulnerable targets for maritime safety, diverse met-ocean hazards and marine pollution. Providing an unprecedented spatial and temporal resolution at wide coastal areas, High-frequency radars (HFRs) have been steadily gaining recognition as an effective land-based remote sensing technology for a continuous monitoring of the surface circulation, increasingly waves and occasionally winds. HFR measurements have boosted the thorough scientific knowledge of coastal processes, also fostering a broad range of applications, which has promoted their integration in Coastal Ocean Observing Systems worldwide, with more than half of the European sites located in the Mediterranean coastal areas. In this work, we present a review of existing HFR data multidisciplinary science-based applications in the Mediterranean Sea, primarily focused on meeting end-users and science-driven requirements, addressing regional challenges in three main topics: (i) maritime safety; (ii) extreme hazards; (iii) environmental transport process. Additionally, the HFR observing and monitoring regional capabilities in the Mediterranean region required to underpin the underlying science and the further development of applications are also analyzed. The outcome of this assessment has allowed us to provide a set of recommendations for the future improvement prospects to maximize the contribution in extending the science-based HFR products into societally relevant downstream services to support the blue growth in the Mediterranean coastal areas, helping to meet the UN's Decade of Ocean Science for Sustainable Development and the EU's Green Deal goals.

1 Coastal monitoring to support Blue Growth in the Mediterranean Sea

The coastal and ocean economy has been since ancient times and is nowadays, more than ever, the backbone of the Mediterranean countries' blue economy. In 2017, the Mediterranean was the third largest sea basin in terms of Gross Value Added (GVA) and the first in terms of employment (European Commission, 2020). The key sector is clearly coastal tourism, from which the Mediterranean is the world's leading destination, followed by maritime transport, living resources and port activities. Furthermore, coastal tourism and fisheries benefit from the location of the Marine Protected Areas (MPAs) which are currently covering 7% of the northern Mediterranean Sea surface (Meola et al., 2019), and are expected to increase as one of the goals of the United Nations (UN) Decade of Ocean Science for Sustainable Development.

Mediterranean coastal areas and communities are, however, negatively impacted by all human activities related to these traditional sectors. Regarding the sector of maritime transport, it is worth highlighting that the Mediterranean Sea is one of the world's busiest shipping lanes of oil and gas tankers, container vessels and ships, involving a higher risk of marine oil and marine litter (ML) pollution. Although the extent of the latter is not fully understood yet, first estimations provided from Cózar et al., (2015) identify the Mediterranean Sea as a great accumulation zone of plastic debris, being comparable to the accumulation zones described for the five subtropical ocean gyres. Additionally, Soto-Navarro et al., (2021) have recently found that the hot-spots for the ML risk concentrate in the coastal regions, highly impacting on the Mediterranean biodiversity, specially, in the MPAs and, particularly, in those near ML sources.

Given the strategic role of ports in the globalized trading system, it is important to underline that four ports from the Mediterranean (i.e. Algeciras, Valencia, Piraeus and Marseille) are included in the top-five European ports when looking at different categories according to the Eurostat statistics from 2020. Moreover, the Mediterranean Sea hosts the three main migratory routes to Europe, representing a huge humanitarian, political and security challenge for the bordering countries. In this context, we cannot ignore the more than 99400 migrants who arrived in Europe in 2020, mainly by sea and, particularly, to Spain, Greece and Italy by crossing the Mediterranean Sea, according to the data from the International Organization for

Migration (IOM). This complex migratory hub contributes to the increased risk to life and maritime safety in the Mediterranean.

Last but not least, as recently reviewed by Tintoré et al., (2019), the Mediterranean is one of the most vulnerable regions in the world due to the impact of climate change. As a result of large-scale warming, among many other impacts reported by the authors, an increase in frequency and/or intensity of extreme events is expected (Mitchell et al., 2006). In this context, De Alfonso et al., (2021) points out an average of eight storms per year registered in the Spanish Mediterranean coast with particular severe events registered in November 2001 (Gómez et al., 2002), October 2007 (Cohuet et al., 2011), December 2008 (Sánchez-Arcilla et al., 2014), January 2017 and January 2020 (Amores et al., 2020; de Alfonso et al., 2021, Lorente et al., 2021a, Sotillo et al., 2021). Aiming to monitor and understand this regional and sub-regional ocean state and variability, from daily to interannual scales, a set of indicators for the Mediterranean Sea and the Balearic Islands (Juza and Tintoré, 2021) are made available through a user-friendly visualization tool by SOCIB (Tintoré et al., 2013, 2019).

The increased capability to address the above-mentioned regional challenges at the required spatio-temporal scales has directly benefited, *inter alia*, from the key features of the High Frequency Radar (HFR hereinafter) technology, i.e. unprecedented high spatio-temporal resolution (i.e. 0.2-6 km and 15-60 min) over wide coastal areas (up to 200 km offshore, depending on the operational frequency). HFRs provide continuous monitoring of the surface circulation (Lipa, Barrick and Maresca, 1981; Paduan and Graber, 1997; Headrick and Thomason, 1998; Molcard et al., 2009; Paduan and Washburn, 2013; Wyatt, 2014; Roarty et al., 2019; Dumas and Guérin, 2020), increasingly, wave parameters (Lipa et al., 1990, 2005, 2006; Gurgel et al., 2006; Wyatt et al., 2006; Orasi et al., 2018; Wyatt and Green, 2009; Long et al., 2011; Wyatt, 2011; Falco et al., 2016; Saviano et al., 2019; 2020; Basáñez et al., 2020; Bué et al., 2020) and, occasionally, wind field (Long and Trizna, 1972; Heron, 2002; Huang et al., 2004; Shen et al., 2012; Kirincich et al., 2016a; Zeng et al., 2016, 2018; Shen and Gurgel, 2018; Saviano et al., 2021). This land-based remote sensing technology gives us a unique insight to coastal ocean state and variability with relative ease in terms of technical effort, manpower and costs (i.e. for the same amount of information and compared to other conventional observing platforms), allowing us to improve our understanding of sub-mesoscale and mesoscale coastal processes.

Moreover, coastal ocean surface current and wave real-time information, which are the primary and the secondary basic products of HFRs, respectively, are being used extensively by: search and rescue (Ullman et al., 2006; Ličer et al., 2020; Révelard et al., 2021), environmental agencies for pollutant monitoring of oil spill (Abascal et al., 2009), marine litter tracking (Declerck et al., 2019), recreational activities, navigational safety, ports & shipping, ship detection and tracking (Ponsford et al., 2001; Dzvonkovskaya et al., 2007; Maresca et al., 2013; Laws et al., 2016), coastal and offshore engineering applications, aquaculture, marine renewables (Wyatt, 2012; Basáñez and Pérez-Muñunzuri, 2021; Mundaca-Moraga et al., 2021) and early warning detection systems for natural hazards (Lipa et al., 2006; Gurgel et al., 2011; Grilli et al., 2015; Guérin et al., 2018), among others. Furthermore, the mapping of surface currents at high spatio-temporal resolution provided by the HFRs in the coastal strip allow us to use them as a ground truth for coastal model real-time assessment (Wilkin and Hunter, 2013; Lorente et al., 2016, 2019b; Mourre et al., 2018; Aguiar et al., 2020) and improvement, through HFR data assimilation (Breivik and

Saetra, 2001; Paduan and Shulman, 2004; Barth et al., 2008; Iermano et al., 2016; Hernández-Lasheras et al., 2021), as well as for the evaluation of coastal remote sensing products (Manso-Narvarte et al., 2018; Caballero et al., 2020; Gommenginger et al., 2021). The development of advanced HFR data products as the gap-filled nowcasts and Lagrangian trajectories, allow us to satisfactory estimate the transport making the HFR data a key asset in the assessment and protection of the coastal marine environment including: dispersal/retention of particles (Cianelli et al., 2017; Hernández-Carrasco et al., 2018a; Davila et al., 2021), cross-shelf exchanges and transport (Sciascia et al., 2018), eddy tracking (Nencioli et al., 2010; Bagaglini et al., 2020) and 3D eddy characterization (Manso-Narvarte et al., 2021).

In addition to this, many strong coordinated efforts to significantly increase the prompt distribution, availability, easy access and accuracy of HFR data have been made in recent years at the global (Roarty et al., 2019), European (Rubio et al., 2017) and regional levels (Lorente et al., 2021b), also leveraged by national initiatives and specific projects. These joint efforts have enhanced the creation of a community at the HFR operator level, accelerating therefore the speed of the take up of the data, also underpinning the growth of HFR multidisciplinary applications worldwide (Fujii et al., 2013; Paduan and Washburn, 2013; Wyatt, 2014; Rubio et al. 2017 and Roarty et al., 2019).

These wide range of applications have also boosted the positive trend on the HFR installation all around the world. Consistently, HFRs are also nowadays playing a crucial role as one of the backbones of the Coastal Ocean Observing Systems -COOSs- of the Mediterranean Sea, which are currently encompassing more than the half of the existing HFR systems installed in Europe (Lorente et al., 2021b), constituting therefore an important focus of HFR activity.

Demonstrating the potential of the HFR observing and monitoring regional capabilities, this work reviews the existing mature and emerging scientific and societal applications using HFR data, developed to address the major challenges identified in the Mediterranean coastal waters, organized around three main topics: (i) maritime safety; (ii) extreme hazards and (iii) environmental transport processes. Recognizing also the added value of networking, it is worth highlighting that this review encompasses the main outcomes of multidisciplinary, international and intersectoral regional coordinated efforts in the frame of the Mediterranean Operational Network for the Global Ocean Observing System (MONGOOS) HFR Task Team. These endeavors are primarily focused on meeting end-users and science-driven requirements, aiming to unlock HFR data potential, delivering greater uptake, use and value from the data, for the benefit of the ecosystems, services and human activities of the coastal areas of the Mediterranean Sea.

This manuscript constitutes the second part of two complementary contributions, the first one providing a detailed overview of the main achievements, ongoing activities, future challenges and the roadmap towards an integrated, mature HFR network in the Mediterranean Sea (Lorente et al., 2021b). The sections of this paper are as follows: Sect. 2 presents several HFR applications addressing science priorities and societal needs, classified in the above-mentioned three topics. Sect. 3 includes the discussion and a preliminary assessment of the capabilities of the existing HFR applications. Based on this assessment, Sect. 4 outlines the future prospects for HFR applications along with a set of key recommendations aiming to leverage the HFR data to its fullest extent, thus helping to harness the HFRs potential in the further development of operational monitoring systems at the regional level.

This contribution will help to achieve the challenges of the United Nations (UN’s) Decade of Ocean Science for Sustainable Development (Ryabinin et al., 2019) and to address the transitional changes required towards the European Green Deal (Sikora, 2021). Finally, a summary and the main conclusions are provided in Sect. 5.

2 High-Frequency radar applications in the Mediterranean

This section presents the existing advanced and emerging scientific and societal applications using HFR data, aiming to address science priorities and societal needs identified in the Mediterranean coastal waters (Lorente et al., 2021b), organized around three main topics: (i) maritime safety; (ii) extreme hazards and (iii) environmental transport processes.

2.1 Maritime Safety

Around 200.000 large vessels operate annually in the Mediterranean Sea, including ferries, cargo and commercial vessels, of which around 300 tankers transport oil-based products every day accounting for more than 350 million tons per year (more than 25% of the world's oil tonnage) as highlighted by Di Muccio et al., (2020). This intense maritime traffic makes the basin a susceptible area in terms of oil spills, search and rescue (SAR) operations and other maritime emergencies. Over the past half century spills over the sea from tankers have shown a downward trend, reaching its lowest in early 2020 due to the global health and economic crisis triggered by the COVID-19 pandemic (March et al., 2021). However, oil spills as well as chemical spills and other hazardous substance releases are still present, putting marine health at risk. For instance, in the second half of February 2021, around 170 km of coastline from Israel to southern Lebanon suffered from a large oil spill (García-Sánchez et al., 2022), one of the worst ecological disasters in decades. In this context, accurate forecasting of oil spill modeling (for this particular event, the model MEDSLIK-II was used, as described in De Dominicis et al., 2013a, 2013b) and Lagrangian trajectory analysis of floating objects (Sayol et al., 2014; Ličer et al., 2020) have demonstrated to successfully help marine SAR operations and oil spill containment. These forecasts depend strongly on the accuracy of the forcing data (i.e. wind, waves and currents, as stated in Sect. 2.1.2) ingested in atmospheric and oceanographic models, where in particular ocean surface currents maps from HFRs can greatly improve short-term model outputs due their high resolution and their near-real time nature (Abascal et. al., 2009; Abascal et. al., 2012; Breivik et al. 2013), as described in Sect. 2.1.3. In this context real-time HFR data was accepted as a reliable operational tool for SAR, oil spill and other operational protocols in coastal waters (Roarty et al., 2019). Concerning the last two sections, it is important to mention the wider implementation of the ocean models and the short-term predictions in other cross-cutting areas from the three addressed main topics. Nevertheless, we have included them in this section to highlight the HFR strengths for SAR applications through model assessment and improvement, backtracking and short term forecasting.

2.1.1 Search and Rescue

Agencies in charge of SAR operations, marine pollution response and maritime traffic control are among the most significantly targeted users of reliable met-ocean information. Access to multi-platform quality controlled near real-time met-ocean observations and high-resolution forecasts available for their specific areas of responsibility for marine SAR, assigned by the IMO (International Maritime Organisation), is essential for them to support emergency response missions. Winds, waves and surface currents observations and forecasts are needed to be seamlessly integrated into their SAR emergency tools in order to predict the trajectory of a drifting target for determining the optimal search region. In the sphere of maritime safety, HFRs have the great advantage of providing high spatio-temporal resolution surface currents in wide coastal areas, very close to the coastline when HFR gap-filling methods are applied (listed in Sect. 2.1.3) and where most of the SAR incidents occur (as shown by the Fig. 1), as the review of the location of the SAR incidents from 5 countries (i.e. Croatia, France, Italy, Slovenia and Spain) along 2019 and from Malta along 2020, clearly shows:

(i) Croatia: 612 SAR interventions were registered in 2019, of which 389 are SAR interventions and 223 are MEDEVAC ones (i.e. actions related to transportation of injured or sick persons). Most of these incidents occur during summer, from June to September and over 98% in inner and territorial waters. Coastal waters from Croatia are operationally monitored by the HFR-SPLIT Wera Radar System, consisting of 2 WERA HFR sites (Ražanj and Stončica) in the eastern part of the eastern mid-Adriatic basin. The HFR-NASCUM system is a historical network located in the eastern part of the Gulf of Venice. All 4 sites were used to build NEURAL project short term predictions (described in Sect. 2.1.3).

(ii) France: has 5 SAR responsibility areas in the continental littoral coordinated by 340 SAR operators from the 5 Maritime Rescue Coordination Centre, including 1 for the French Mediterranean responsibility area. In 2019, a total of 13507 SAR incidents occurred (with 22313 people assisted), of which 51% were from June to September, as indicated in the website of the French Ministry of the Sea. In particular, the number of SAR incidents in the French Mediterranean responsibility area accounts for 23% (3110) of the total number of cases and 32% (7293) of the people assisted, as included in the 2019 activity report of the French Mediterranean Coordination Center. 94% of the SAR incidents occur in coastal areas in the first 12 nm (22.2 km) and mostly during summer season (from June to September), with more of the 89% related to recreational boating and sailing. Currently, two HFR networks are operating in the French Mediterranean coastal waters of Nice and Toulon, named HFR-MedTln and HFR-MedNce.

(iii) Italy: SAR operations are under the responsibility of the Italian Coast Guard covering 500000 km^2 of sea and 8000 km of coast. In 2019 the Italian coast guard responded to 1875 SAR missions, 226 of them related to human migration. SkyTruth, a non-governmental agency reported one spill 60 km south of Genoa in the Ligurian sea. Six HFR networks are currently monitoring the coastal areas of the Tyrrhenian and Ligurian Sea (HFR-TirLig) and the Tuscan Archipelago (HFR-LaMMA), Gulf of Naples (HFR-GoN), the Malta-Sicily Channel (HFR-CALYPSO), the Northern Adriatic Sea and the Gulf of Trieste (HFR-NAdr) and the recently deployed in the southwest of Sicily island (HFR-SIC). Two additional HFR networks in the Gulf of Manfredonia (HFR-GoM) and the Gulf of Venice (HFR-NASCUM) are historical deployments.

(iv) Malta: there is one Maritime Rescue Coordination Centre with around 50 SAR operators, covering one Search and Rescue Region (SRR) of 267874 km^2 with 196.8 km coastline (including Comino & Gozo). During 2020, 429 missions were coordinated by the MRCC (Maritime Rescue Coordination Centre) in Malta, 26% of which were reported as SAR cases occurring within Maltese Territorial Seas. The HFR-CALYPSO monitors the Malta-Sicily channel, accounting for 7 HFR sites and the HFR-CALYPSO-SOUTH, is composed by two HFR sites located in the South of Malta. HFR data are combined with forecast model outputs to get the best representation of the sea state during SAR operations.

(v) Slovenia: has 42 km of coastline and a semi-enclosed coastal area. During 2019, the SAR agency has responded to 9 SAR missions (7 times the rescue boat went out to sea while 2 rescues were of injured people on a moored boat in port). All cases occurred within the 3 nm from the coast (i.e. 3 within 200 meters, 3 around 1 nm and 1 at 3 nm from the coast). The HFR-NAdr, in the Northern Adriatic Sea and the Gulf of Trieste, is jointly operated through trans-national collaboration with Italy.

(vi) Spain: the 4 SAR responsibility areas cover 1 500 000 km2 of marine surface (3 times the size of the Spanish national territory) and 8 000 km of coastline. The Spanish Maritime Safety and Rescue Agency (SASEMAR hereinafter) is divided in 19 MRCCs plus 1 National Centre, with more than 370 SAR operators. SASEMAR responded to 5 891 missions in 2019, of which almost 88% were SAR operations. Fifty percent of the total SAR incidents occurred within 3 km off the Spanish coastlines. Of the 7 HFR networks operating inside their 4 responsibility areas, 3 of them are located in the Western Mediterranean, monitoring the Strait of Gibraltar (HFR-Gibraltar), the Ebro Delta (HFR-Ebro) and the Ibiza Channel (HFR-Ibiza) and all of them are integrated in the SASEMAR Environmental Data Server.

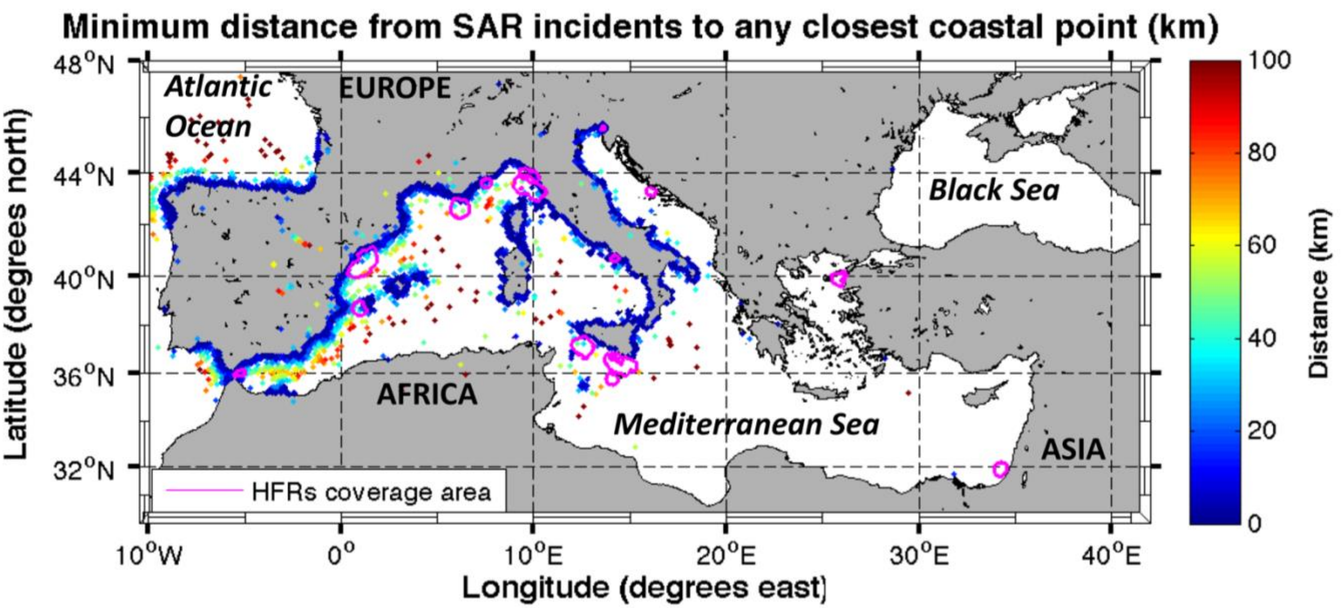

Figure 1. Map of the Mediterranean showing the HFR mean spatial coverage (pink contours) and the location of SAR incidents of France, Italy, Slovenia and Spain from 2019 colored based on their distance to the closest coastal point. For further details about the operational status and the names of the HFR systems the reader is referred to Lorente et al, (2021b).

As aforementioned, maritime SAR operations most often depend on leveraging Lagrangian tracking tools using timely and reliable knowledge of surface circulation, near surface winds and, if applicable, surface gravity waves. Surface circulation is generally provided by numerical circulation models but HFR observations can offer valuable insight into marine conditions over the region of the accident and can - especially when coupled to short term prediction models (see Sect. 2.1.3) - act as a complementary input for Lagrangian predictions, hindcasts or back-tracking simulations. Révelard et al. (2021) evaluated the use of HFR-derived trajectories to complement drifter observations for assessing the performance of different models (i.e. GLO-, IBI- and MED-MFC, provided by the Copernicus Marine Service and WMOP) in predicting Lagrangian trajectories. They used the Skill Score (SS) metric, based on the Normalized Cumulative Lagrangian Separation distance (Liu and Weisberg, 2011), which is a commonly used metric for assessing Lagrangian performance. They have concluded that whereas drifters only provide assessment along their drifting paths, HFR allows for a large number of trajectories, improving not only the robustness of the Skill Score statistics but also the spatial and temporal assessment of the model performance (Fig. 2). Since HFR data are quasi-continuous in time, this method can be applied in near-real-time, which is a strong advantage for evaluating extremely scenario-dependent models. Indeed, the quality of any numerical model performance varies with time and can have substantial fluctuations on short temporal and spatial scales even if the model otherwise exhibits good overall forecasting skills. In cases like these, quality controlled HFR observations represent particularly valuable short-term inputs for Lagrangian products assisting SAR efforts.

Aiming to improve the applicability of this model assessment methodology for SAR operations in coastal areas, Révelard et al. (2021) also analyzed the SS sensitivity to different forecast horizons and showed that, in coastal regions: (i) the SS is sensitive to the forecast time, i.e. the longer the forecast (i.e. 72 hours), the higher the SS value, due to the high variability of the surface currents; (ii) a shorter forecast time (e.g. 6 hours), consistent with the duration of the search that maximizes survivors in SAR missions, is therefore more appropriate. In addition, they have shown that whereas the original definition of the Skill Score from Liu and Weisberg (2011) is correct for analyzing its spatiotemporal distribution, the use of a novel Skill Score (SS*) is recommended to assess the average model performance over an area of interest and along a specified period to avoid biased conclusions. The advantage of the SS* is that, despite its similar formulation to the SS defined by Liu and Weisberg (2011), SS* does not impose the negative values to zero, allowing to obtain a correct average, as in Fig. 2. However, they clarified that only SS* values > 0.5 should be interpreted as a good agreement between HFR surface current observations and model outputs.

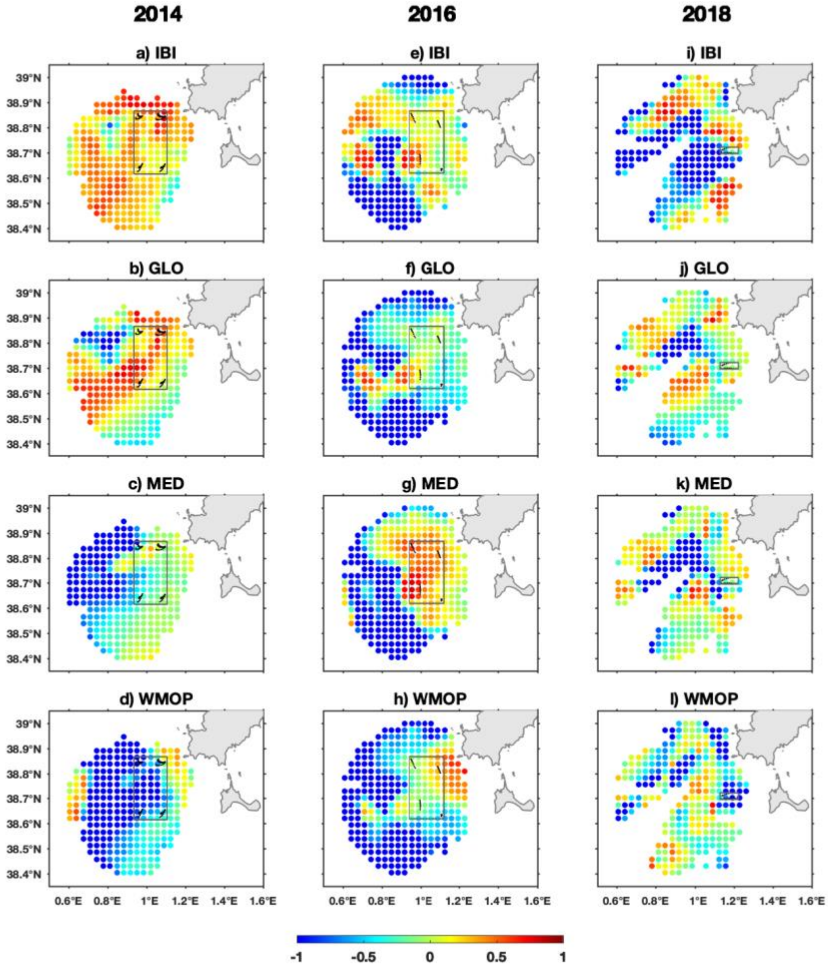

Figure 2.: Temporally averaged Skill Score SS* obtained for four models as indicated in the title of each panel by comparing against the HFR-derived trajectories of the Ibiza Channel during a forecast time of 6 hours. Simulated trajectories are initialized hourly at each grid points on 30-sept-2014 from 13:00 to 16:00 (left panels), on 28-July-2016 from 16:00 to 22:00 (middle panels) and on 15-Nov-2018 from 13:00 to 16:00 (right panels). SS* values, with red colors representing the higher average model performance, are only obtained in those grid points with data temporal availability equal or higher than 80%. Black lines show the drifter paths available during the same periods, and the boxes indicate the regions where the averages are applied for comparison with the results obtained with drifter observations. Original source: From Révelard et al. (2021).

A further academic study of the value of quality controlled HFR observations in SAR operations was the recent case of a person lost at sea in the Northern Adriatic during a Sirocco storm on 29 Oct 2018. In this case, HFR-NAdr observations were employed for hindcasting and survivor's drift trajectory verification (Ličer et al., 2020). Fig. 3 depicts Lagrangian drifter dispersal computed from modeled surface winds (the dominant contribution to the drift in this case) and HFR surface currents from the HFR-NAdr network in the Gulf of Trieste after this accident.

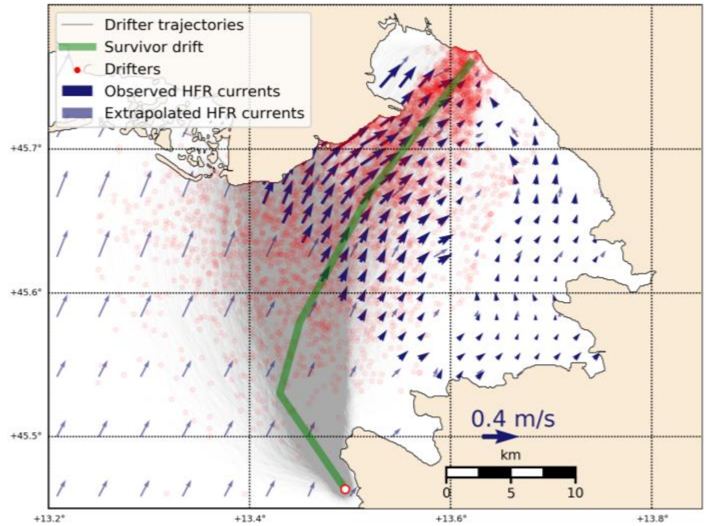

Figure 3. Using HFR currents for Lagrangian hindcasting of an accident on 29 Oct 2018 in the Gulf of Trieste, details in (Ličer et al., 2020). Blue arrows denote the HFR surface current field on 29 Oct 2018 22UTC. Thinner (but scaled to length) light-blue arrows depict nearest-neighbor extrapolated currents outside the HFR domain (every third point is plotted for clarity). Red dots denote modeled virtual drifter locations after 24 hours of the drift, starting from the accident location (white circle at 13.495 E, 45.4635 N). Green line indicates the survivor's estimate of his drift trajectory. Adapted from Ličer et al., 2020.

Even though in this case part of the survivor's trajectory outside of the HFR-NAdr domain had to be inferred from extrapolated currents, such HFR-based nowcasting products would have been valuable during this and similar rescue attempts. However, since HFR data arrive in near real time, some sort of model-based extension of their prediction horizon is necessary before they can be used for operational nowcasting. One possible solution is data assimilation of HFR data into a numerical model (see Sect. 2.1.2.), followed by a forecasting time window. An alternative and numerically less demanding option, gaining ground in recent years, is the machine learning approach where a neural network model is trained on past data and then used to create short term predictions of surface currents, addressed in Sect. 2.1.3.

2.1.2 Model assessment and improvement

This section addresses one of the main interests and needs of end-users of operational oceanography information: users want to be able to have confidence in modelled data and they need to know how good they are. Addressing end-user overarching concerns, model assessment, essentially built upon comparison to observations, is crucial to evaluate the quality of the diversity of modelling products available in a systematic and long-term routine manner, and to inform users about their usefulness for a given application.

For this reason, seeking also to strengthen end-user loyalty, the validation of Operational Ocean Forecasting Systems against independent measurements constitutes a core activity in operational oceanography (Hernández et al., 2015) since it aids: (i) to infer the relative strengths and weaknesses in the modelling of several key physical processes; (ii) to compare different versions of the same operational ocean forecasting system and evaluate potential improvements and degradations before a new version is transitioned into operational status; (iii) to compare coarse-resolution “parent” and nested high-resolution “child” systems to quantify the added value of downscaling; (iv) to inform end-users about the consistency and skill of the modeling products disseminated.

Developments in ocean modelling have clearly advanced to address the challenges associated with the increased resolution and its application to coastal areas, also responding to the high demand of providing 4D estimates of multiple oceanic variables at fine-scales (Mourre et al., 2018; Fox-Kemper et al., 2019). Coastal modeling faces numerous challenges and issues such as downscaling and representation of open boundary conditions or land-sea/air-sea interactions (Kourafalou et al.et al. 2015a). Synergies between models and ocean observations are needed to face these challenges and improve ocean processes representation (Kourafalou et al.2015b; De Mey-Frémaux et al., 2019; Davidson et al., 2019). Additionally, it is worth mentioning the current lack of real-time and historical availability of observations on the coastal areas, which limits the operational capability and reduces the potential of skill assessment operational services aiming to provide synthetic metrics addressing specific user’s needs (Révelard et al., 2021).

Within this context, HFR systems play a first-order role thanks to their unique ability to provide fine-resolution maps of the surface currents over broad coastal areas. This ability of the HFR system makes them particularly appropriate for the validation of numerical models in coastal areas, where other observations are scarce and/or their resolutions (i.e. in space or in time) are not high enough to capture the fine scale. Many HFR systems have therefore been used with this purpose in several regions of the Mediterranean Sea including the Northern Current area off Toulon (Berta et al., 2014a), the Ebro Delta area (Lorente et al., 2016; Ruiz et al., 2020; Aguiar et al., 2020; Lorente et al., 2021a; Sotillo et al., 2021), the Northern Adriatic (Vilibić et al., 2016), the Gulf of Naples (Uttieri et al., 2011), the Ibiza Channel (Mourre et al., 2018; Aguiar et al. 2020; Révelard et al., 2021; Sotillo et al., 2021) and the Strait of Gibraltar (Lorente et al., 2019a; Aguiar et al., 2020).

An example of this added-value of the HFR data was recently shown in the multi-model comparison exercise performed in the Strait of Gibraltar in 2017 (Lorente et al., 2019a). In that case, the IBI-MFC model (Sotillo et al., 2015) was compared against their partially nested SAMPA (Sánchez-Garrido et al., 2013) high-resolution coastal forecast system to elucidate the accuracy of each system characterizing the Atlantic Jet (AJ) inflow dynamics. To this aim, HFR-derived hourly currents at the midpoint of the selected transect (square in Fig. 4,a) were used as a benchmark. The scatter plot of HFR-derived hourly current speed versus direction (taking as reference the north and positive angles clockwise) revealed interesting details (Fig. 4, b): (i) the AJ flowed predominantly eastwards, forming an angle of 78º with respect to the north; (ii) the current velocity, on average, was 1 ms^{-1} and reached peaks of 2.5 ms^{-1}. Speeds below 0.5 ms^{-1} were registered along the entire range of directions; (iii) westwards currents, albeit in the minority, were also observed and tended to predominantly form an angle of 270º (i.e. towards the Atlantic), mostly related to intense easterly winds episodes (Garret, 1983; García-Lafuente et al., 2002; Menemenlis et al., 2007; Péliz et al., 2009; Reyes et al., 2015; Lorente et al., 2019b and 2019b; Bolado-Penagos et al., 2021), as further detailed in Sect. 2.2.1. The scatter plot of SAMPA estimations presented a significant resemblance in terms of prevailing current velocity and direction (Fig. 4,c). Although the time-averaged speed and angle were slightly smaller (0.9 ms^{-1}) and greater (88º), respectively, the main features of the AJ were qualitatively reproduced: maximum velocities (up to 2.5 ms^{-1}) were associated with an eastward flow and an AJ orientation in the range of 50º–80º. Besides, surface flow reversals to the west were properly captured. By contrast, noticeable differences emerged in the scatter plot of regional IBI-MFC estimations (Fig. 4, d): surface current velocities below 0.3 ms^{-1} were barely replicated and the AJ inversion was only observed very occasionally. Despite the fact that IBI-MFC appeared to properly portray the mean characteristics of the eastwards flow, the model tended to favor flow directions between 60º and 180º and to overestimate the current velocity, with averaged and maximum speeds around 1.17 and 2.80 ms^{-1}, respectively.

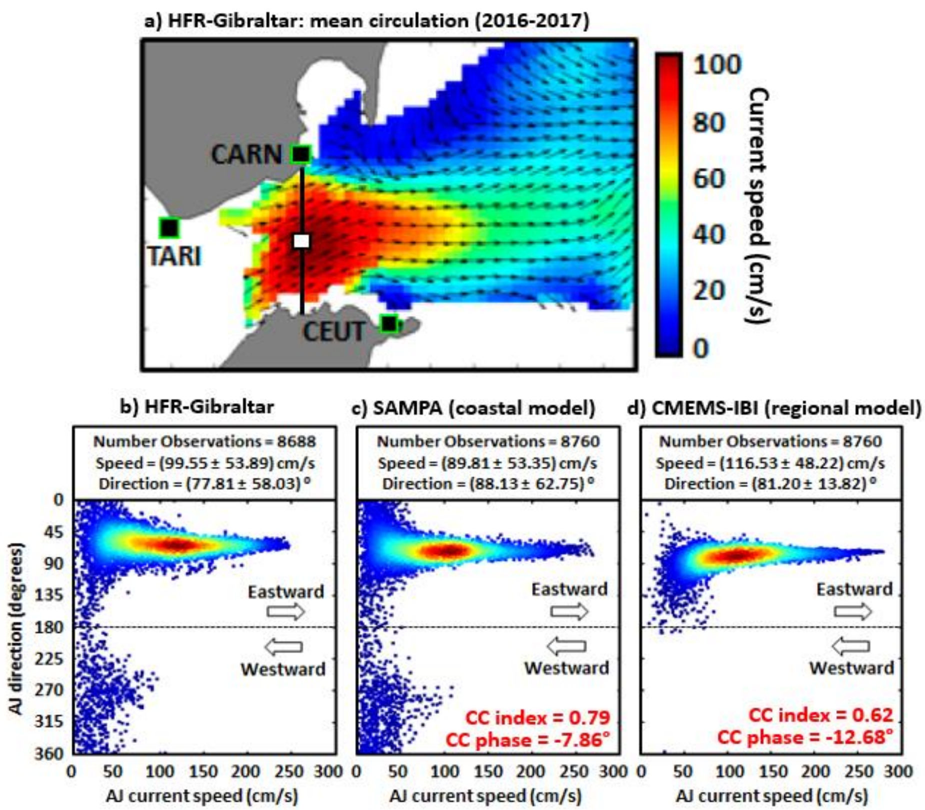

Figure 4. (a) HFR-derived mean surface circulation pattern in the Strait of Gibraltar for 2016–2017: classical Atlantic Jet inflow into the Mediterranean, with strong surface currents flowing to the NE. Solid black squares represent radar sites. Black line and the related white square indicate the selected transect and its midpoint, respectively. (b-d) Quantitative validation at the selected grid point (5.43ºW, 35.99ºN) within the Strait of Gibraltar: annual (2017) scatter plot of hourly current speed versus direction (angle measured clockwise from the north); estimations provided by HFR-Gibraltar (b), SAMPA high-resolution coastal model (c) and IBI-MFC (d), a regional model in which SAMPA is nested into. Mean and standard deviation values of both AJ speed and direction are gathered in black boxes. Magnitudes of the complex correlation (i.e. CC index) and phase between HFR and model-predicted currents are provided in red font color. Adapted from: Lorente et al., 2019a.

In summary, HFR measurements are able to precisely assess the added value of the downscaling performed through the SAMPA coastal system with respect to the IBI-MFC regional solution, in which SAMPA is nested. Overall, a steady improvement in the Atlantic Jet characterization is evidenced in model performance when zooming from regional to coastal configurations, highlighting the benefits of the downscaling approach adopted and also the potential relevance of a variety of factors at local scale, among others: a more refined horizontal resolution, a tailored bathymetry or the higher spatio-temporal resolution of the atmospheric forcing. Furthermore, SAMPA appeared to better reproduce the reversal events detected with HFR estimations, demonstrating the added value of imposing accurate meteorologically driven barotropic velocities in the open boundaries, imported from the NIVMAR storm surge model (Álvarez-Fanjul et al., 2001), in order to consider the remote effect of the atmospheric forcing over the entire Mediterranean basin, which was only partially included in IBI-MFC.

During the next phase of the Copernicus Marine Service, the higher focus will be on coastal downstream applications (e.g., very high-resolution ocean models integrated with coastal observatories) for a wide range of coastal stakeholders including ports and environmental agencies. Despite the significant progress in the field of coastal modelling, some storm-induced hazards are still not properly resolved (or even misrepresented) by ocean models due to a variety of factors (e.g. too coarse horizontal resolution, inadequate meteorological forcing, poor representation of land-sea interactions and the related river freshwater outflows, among others) as described by Sotillo et al. (2021). Within this framework, HFR might act as a monitoring cornerstone to calibrate and validate successive, upgraded versions of operational ocean forecasting models with the aim of better capturing extreme events in terms of strength, extension and timing (Lorente et al., 2021a).

Aguiar et al. (2020) used the three HFR systems available in the Western Mediterranean Sea (Gibraltar Strait, Ibiza Channel - described in Lana et al., 2016 - and Ebro Delta) to evaluate the impact of downscaling on the surface coastal circulation in the case of the Western Mediterranean OPerational forecasting system (WMOP) (Juza et al., 2016; Mourre et al., 2018). The authors showed that the time-average circulation in the coastal areas of the Ebro delta and Ibiza Channel were improved through downscaling. In particular, the nested model showed a better representation of the small-scale coastal flow intensification at the mouth of the Ebro River and a refinement in the characterization of the circulation in the Ibiza Channel. Notice that HFR-Gibraltar, HFR-Ebro and HFR-Ibiza *versus* model comparisons are updated daily on SOCIB WMOP webpage -https://socib.es/?seccion=modelling&facility=wmedvalidation-. Those HFR systems, among others, are also integrated in the IBISAR science-based data downstream service (Reyes et al., 2020) –freely available under registration in wws.ibisar.es- for visualizing, comparing and evaluating the performance of ocean current predictions in the Iberian-Biscay-Irish regional seas.

IBISAR allows the identification of the most accurate ocean current dataset in a specific area and period of interest, thus facilitating decision-making to SAR operators and emergency responders. Lorente et al., (2021b) consider the IBISAR service as a successful example of the long-lasting engagement built in collaboration between HFR operators with end users (i.e. the Spanish Maritime Safety and Rescue Agency). Additionally, those HFR systems are also being used for the IBI-MFC model assessment purposes by means of the NARVAL multi-parameter and multi-platform validation tool (Lorente et al., 2019c) for the IBI-MFC model validation.

Another added-value of HFR systems is their use to improve model forecast through data assimilation (DA). DA aims at optimally combining observations and models to provide a better representation of the ocean dynamics. In this sense, HFR provides very valuable high-resolution observations in areas where satellite observations tend to suffer limitations due to the vicinity of the coast (Vignudelli et al., 2019). While the assimilation of HFR measurements has been applied in many regions of the world since the first studies from Breivik (2001) and Oke et al. (2002), only a limited number of studies have been performed in the Mediterranean Sea. Marmain et al. (2014) assimilated radial velocity observations from Toulon HFR system in a regional model in the Gulf of Lion. They showed how HFR observations can be successfully used to correct the wind forcing used to constrain the model coastal surface circulation. In the Ligurian Sea, Vandenbulcke et al. (2017) were able to correct surface currents and improve the representation of inertial oscillations after the assimilation of all the available hourly radial observations in a regional model of the area. Variational methods were also applied to improve model dynamics through multi-platform data assimilation including HFR in the southern Tyrrhenian Sea (Iermano et al., 2016) and in the Adriatic Sea (Janeković et al., 2020).

More recently, Hernández-Lasheras et al. (2021) specifically assessed the impact of assimilating HFR observations on the surface currents in the Ibiza Channel using the WMOP operational system. They compared the performance of both radial and total daily mean HFR-Ibiza surface currents (Tintoré et al., 2020) for correcting meso and submesoscale circulation using different initialization methods in an operational-like context. An independent Lagrangian validation performed by comparing non-assimilated, assimilated without and with HFR measurements with a set of 14 surface drifters (Tintoré et al., 2014) showed that the best results were obtained when using HFR total observations along with the traditional observation sources (i.e. satellite altimetry, sea surface temperature (SST) and Argo temperature and salinity profiles). After 48 hours, the mean separation distance between virtual buoys and real drifters was reduced by 53% compared to the simulation without any data assimilation, and by 29% compared with the simulation assimilating traditional observations only (as shown in the Fig. 5).

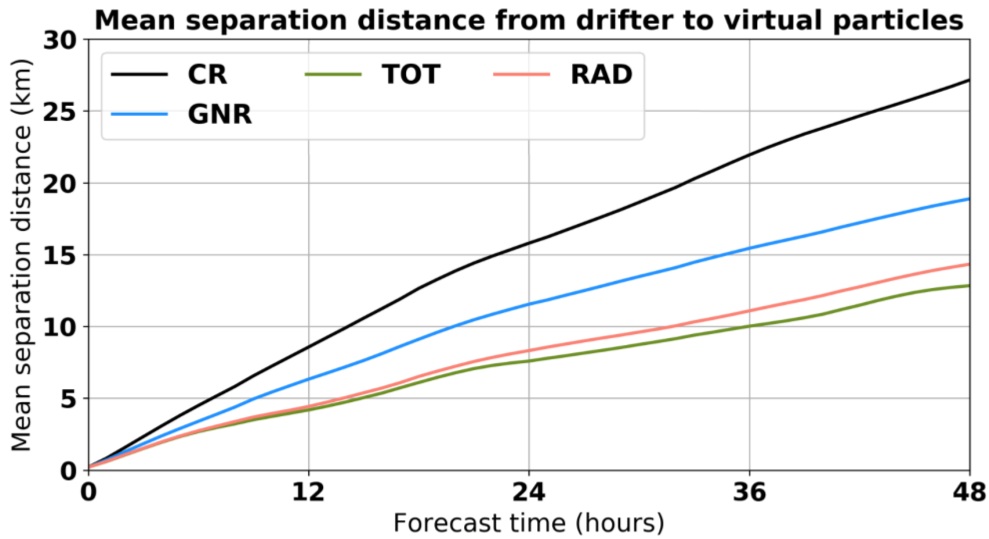

Figure 5. Mean separation distance between virtual particles and drifters as a function of the forecast horizon. Black color represents the simulation without DA (i.e. control run, CR). Blue stands for generic (GNR), which assimilates data from satellite altimetry, SST and Argo profiles. Green and red lines represent the simulation which assimilates HFR daily mean total (TOT) and radial (RAD) observations, respectively, together with generic observation sources. Original source: Hernández-Lasheras et al. (2021)

To the best of authors´ knowledge, SOCIB WMOP (https://socib.es/?seccion=modelling&facility=forecast) is presently the only system in the Mediterranean Sea including an assimilation scheme of HFR data in its operational chain.

2.1.3 Short Term Predictions

Assimilation of HFR data into models is still computationally expensive and a complex issue, not to mention operational capabilities of such a procedure. Because of these constraints, the availability of real-time high-resolution HFR current fields has led to alternative solutions in order to obtain short term prediction (STP) of surface coastal currents, through the direct use of HFR historical and nowcast observations using different approaches (e.g. Zelenke 2005; Frolov et al. 2012; Barrick et al., 2012; Orfila et al. 2015; Vilibić et al, 2016).

The above-mentioned studies develop and implement different STP approaches (harmonic analysis of the last hours, genetic algorithms, numerical models, etc.) which often require additional data, or long training periods of data without gaps. Hardware failures due to power issues, communications or environmental conditions often result in spatio-temporal gaps within HFR datasets. Spatial gaps can be filled on a real-time basis but the filling of long temporal gaps is not straightforward. Several gap-filling methodologies have been developed for HFR data sets: Open Modal Analysis – OMA - (implemented by Lekien et al., 2004 and further optimized by Kaplan and Lekien, 2007), Data Interpolating EOFs -DINEOF- (Beckers and Rixen, 2003; Alvera-Azcárate et al., 2005; Hernández-Carrasco et al., 2018b, Bourg and Molcard, 2021), Self-Organizing Maps -SOM- (Kohonen, 1982, 2000, 2001; Hernández-Carrasco et al., 2018b), Reduced Order Optimal Interpolation -ROII- (Kaplan et al., 1997), Optimal Interpolation -OI- (Kim et al., 2008), Artificial Neural Network -ANN- (Ren et al., 2018), Variational Analysis (Yaremchuk and Sentchev, 2011) and Data-Interpolating Variational Analysis in n-dimensions -DIVAnd- (Barth et al., 2021). HFR derived short term predictions were developed by Zelenke (2005), Frolov et al. (2012), Barrick et al., (2012), Orfila et al. (2015), Solabarrieta et al., (2016), Vilibić et al, (2016), Abascal et al., (2017). More recently, Solabarrieta et al. (2021), developed a Lagrangian-based empirical real-time, Short-Term Prediction (L-STP) system in order to provide short term forecasts of up to 48 hours of ocean currents from HFR data.

Through the NEURAL project (http://www.izor.hr/neural), an innovative neural network-based ocean forecasting system has been developed, providing gridded hourly surface current forecasts in the northernmost part of the Adriatic for the next 72 hours. The forecasting system is using an unsupervised neural network algorithm, Self-Organizing Maps (SOM, Kohonen, 1982; Liu et al., 2006), to train joint solutions coming from the HFR measurements and numerical weather prediction model as hourly surface currents and surface winds, respectively. Once the joint SOM solution has been trained, the surface current forecast follows the predicted surface winds being the closest to the specific SOM solution (Fig. 6). Such a system requires a strong relationship between the predictor (i.e. surface winds) and the predictand (i.e. surface currents), which is largely found in coastal regions of the Mediterranean, yet it can be applied for any other combination of predictors and predictands. Also to add, high-frequency processes such as tides are removed from the system as being minor to the wind-driven dynamics, yet the tides can be added to the forecast.

The quoted northern Adriatic forecast system has been trained using 20 SOM solutions (so-called Best Matching Units, Liu et al., 2006) on HFR data measured between February and November 2008 conjoined with 3-hourly surface winds interpolated to 1-hour resolution coming from Aladin/HR operational model run once a day by the Croatian Meteorological and Hydrological Service (Tudor et al., 2013). The forecasting system performance has been tested in the forecast (hindcast) mode during 2009 and 2010. Unfortunately, the HFR system has had substantial problems since 2010 and the antennas were eventually removed in the following years, resulting in a relatively short dataset possibly not sufficient to put a strong reliability to the forecasting system solutions. However, Vilibić et al. (2016) compared this SOM-based surface current forecast system (available online in http://jadran.izor.hr/neural/about.htm) with the operational ROMS -Regional Ocean Modelling System- (Shchepetkin and McWilliams 2003, 2005) ocean model for the Adriatic, showing the former lower biases and root-mean-square errors.

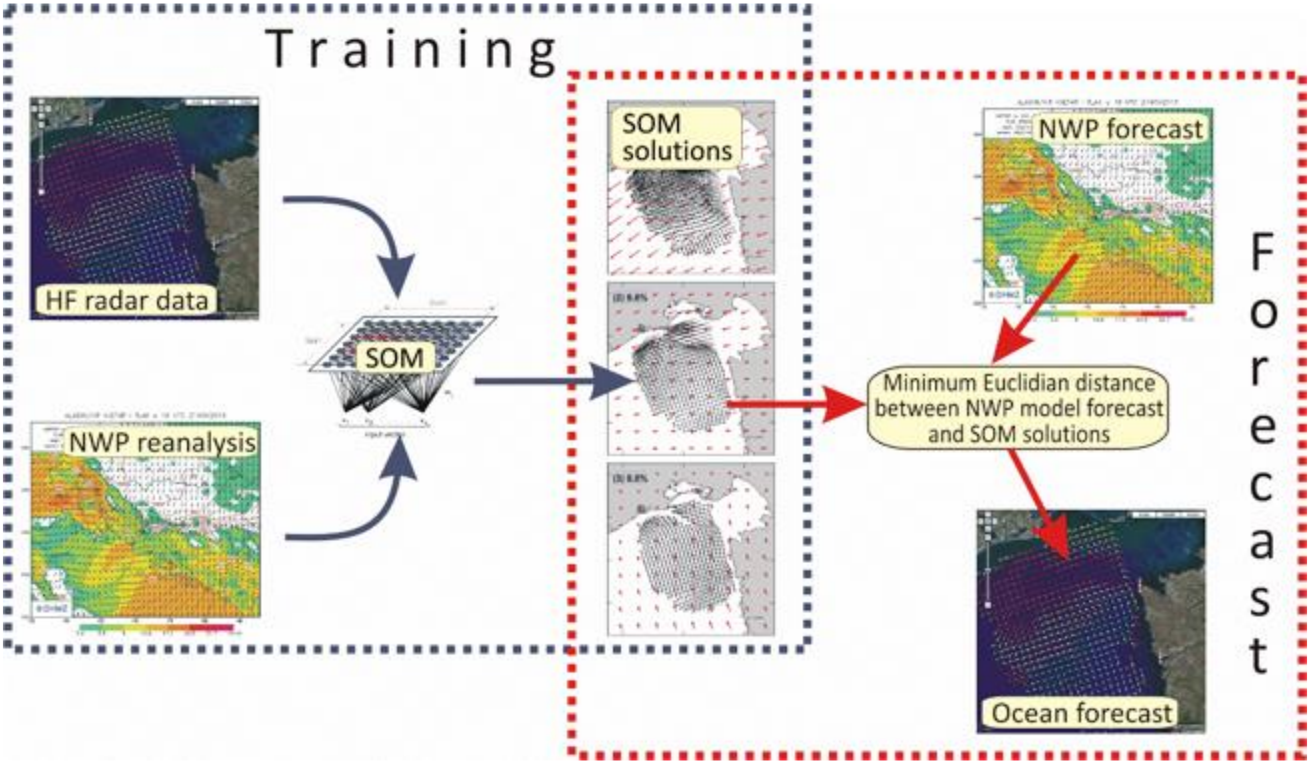

Figure 6. The architecture of the SOM-based surface currents forecasting system in the northern Adriatic. Original source: from Vilibić et al., 2016.

2.2 Extreme hazard coastal monitoring

Under the current climate-change scenario, no portion of the coastline is safe from the threat of metocean hazards, which are expected to increase in frequency, duration and virulence during this 21st century (Mitchell et al., 2006; Stott, 2016). HFR constitute a profitable asset for wise decision-making since it presents a wide range of practical applications, including the effective monitoring in near real time of extreme coastal hazards, such as: (i) extreme wind events; (ii) severe river discharges; (iii) record-breaking storms and (iv) strong flow reversals (all above-mentioned events are addressed in Sect. 2.2.1.); (v) storm surges; (vi) tsunamis (in Sect. 2.2.2); (vii) typhoons and hurricanes (Barrick and Lipa, 1986; Miles et al., 2017; Lipa et al., 2019).

In response to the increasingly frequent extreme events associated with climate change, their detailed characterization by means of surface current, waves and wind maps derived from HFRs may aid the Blue Economy development in coastal vulnerable areas of the Mediterranean region. Regardless of this, the increasing retrieval of waves and winds maps derived from HFRs (Lorente et al., 2021b), is very relevant for the development of renewable ocean energy, an emerging and innovative Blue Economy sector.

2.2.1 Extreme events monitoring

HFRs have been used to investigate the upper ocean response to an extreme wind event in the Ligurian Sea (NW Mediterranean) during October-November 2018, as described in Berta et al. (2020). This work focused on the analysis of coastal submesoscale structures, shaping surface currents and passive transport. Authors estimate the pattern and magnitude of kinematic properties (e.g. divergence/convergence and vorticity patterns), derived from surface currents measured by the HFR-TirLig network (Fig. 1) to characterize the evolution (before and after the event) of ocean scales at a few kilometers. During the storm, sea surface vorticity (Fig. 7, top panels) and divergence (not shown but available in Berta et al., 2020) reach order of the Coriolis parameter f, indicating ageostrophic activity typical of submesoscale structures. The evolution of the sea surface structures suggested nonlinear interactions with the wind forcing. Considering the time series of wind speed and sea currents properties (Fig. 7, lower panels), during and right after the storm (around October 29), currents magnitude increased approximately four times while vorticity and divergence associated with the small features almost doubled. Such abrupt changes in horizontal currents and transport might impact also the vertical properties and in turn the ecosystem.

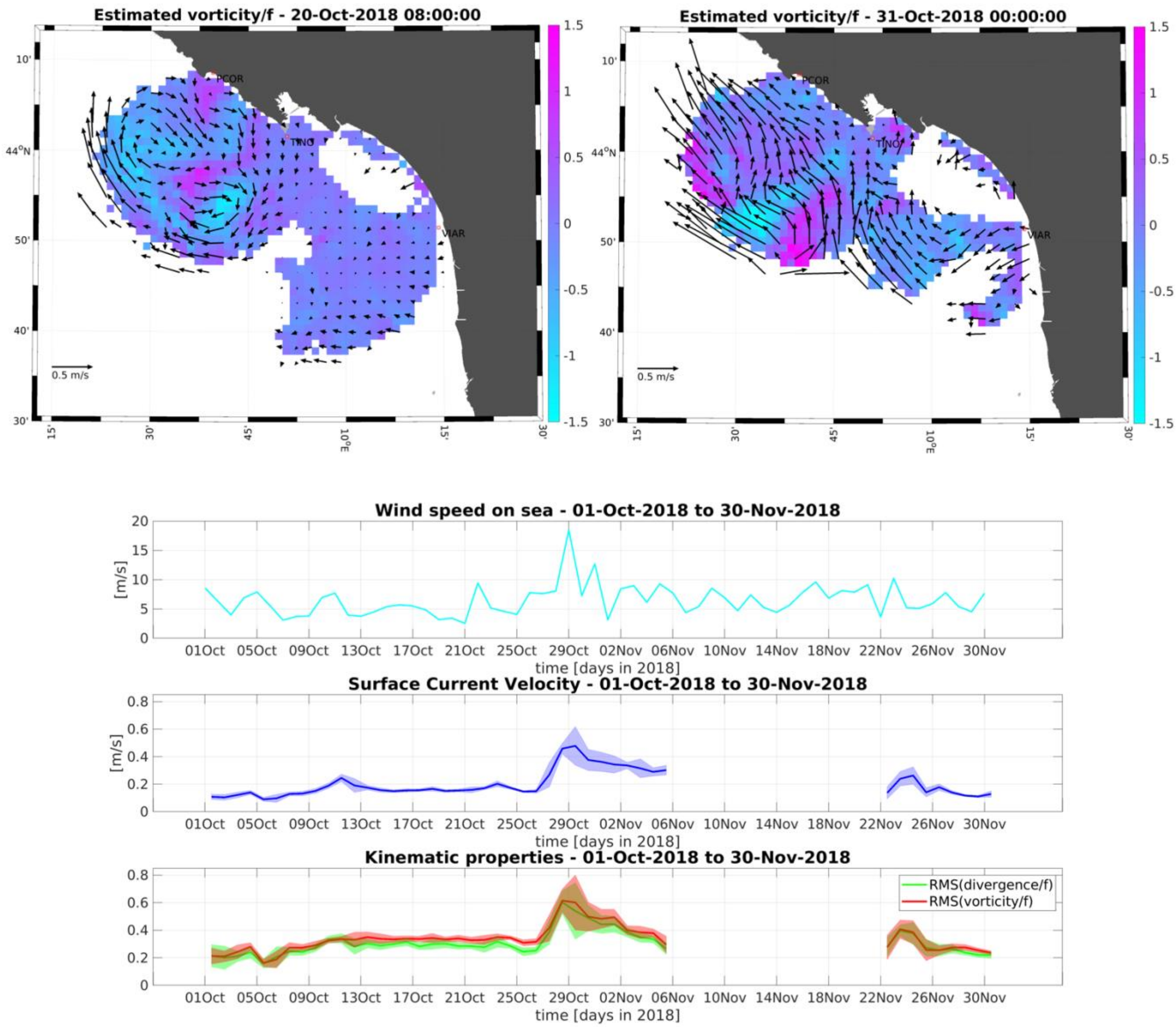

Figure 7. From top to bottom: example map of normalized vorticity before/during the extreme event. Time series of wind speed, surface currents magnitude, and RMS of normalized vorticity and divergence. Original source: from Berta et al., 2020.

In the Delta of the Ebro river (NW Mediterranean), the HFR-Ebro system observations have been crucial to capture the evolution of the most extreme Ebro river freshwater discharge event registered over the last 15 years in April 2018 (Ruiz et al., 2020). Results show the high impact of the freshwater-pulse discharged on the surface circulation pattern, exhibiting a clear correspondence with high concentrations of satellite-derived Chlorophyll-a (Chl-a hereinafter) concentration. Hovmöller diagrams of HFR derived meridional and zonal currents indicate an increase of the south-eastward velocity during the period of the extreme river discharge. The proper representation of the basic oceanographic features of the HFR-Ebro, as the Ebro river impulsive-type freshwater discharged, was previously reported by Lorente et al. (2015).

This same region (i.e. Delta Ebro) has been severely impacted by an exceptional storm in January 2020 (19-24), which surpassed the 99th percentile for several parameters (i.e. wind speed, significant wave height, wave period and surface current velocity), compared with the climatology and with a previous storm in January 2017. Particularly for this event, Lorente et al. (2021a) have assessed the ability of the HFR-Ebro to characterize waves and currents under the record-breaking storm Gloria. By analyzing the data from the HFR-Ibiza and HFR-Gibraltar, authors have also evidenced Gloria's remote-effect in the Ibiza Channel and the Strait of Gibraltar, altering the usual water exchanges between adjacent sub-basins. Furthermore, the effect of Gloria was also manifested on the highest rates of particle dispersion at the Ebro river mouth on the 21st of January.

As in the previous case, the HFR system strategically installed in the Strait of Gibraltar (SoG) is considered an appropriate asset to effectively monitor the Atlantic Jet (AJ) inflow (Lorente et al., 2019b) and the water exchanges between the Atlantic Ocean and the Mediterranean Sea. The classical picture of the surface circulation is characterized by current pulses often exceeding 2 ms^{-1} and time-averaged north-eastward speeds around 1 ms^{-1} in the narrowest section of the SoG (Fig. 4, a). Complete collapse of the AJ and quasi-permanent inversion of the surface inflow during prevalent intense easterlies is a singular phenomenon that deserved detailed exploration (as previously mentioned in Sect. 2.1.2). Under this temporal premise, a monthly Hovmöller diagram was computed for HFR-derived zonal currents at the selected transect to easily detect a 2-day full reversal episode during March 2017, represented by black boxes in Fig. 8, a. The event detected consisted of an abrupt interruption of the eastward inflow and complete reversal of the surface stream through the narrowest section of the SoG (Fig. 8, b). The circulation in the easternmost region of the study domain was accelerated up to 0.8 ms^{-1}, following clockwise rotation that likely fed the Western Alboran Gyre (WAG), which was out of the picture.

The prevailing atmospheric synoptic conditions were inferred from ECMWF predictions of sea level pressure and zonal wind at 10 m height (U-10), as shown in Fig. 8, c-d. A significant latitudinal gradient of sea level pressure was observed, with high pressures over the Gulf of Biscay and isobars closely spaced in the SoG, leading to extremely intense easterlies (above 10 ms-1), channeled through the Strait due to its specific geometric configuration. Therefore, high pressures and intense, permanent, and spatially-uniform easterlies prevailed over the entire study domain, inducing a westward outflow through the SoG as revealed by the 2-day averaged HFR circulation maps. Local wind forcing at this scale seemed to play a primary role in explaining such AJ collapse and the related inflow reversals in agreement with previous studies (Garret, 1983; García-Lafuente et al., 2002; Menemenlis et al., 2007; Péliz et al., 2009; Reyes et al., 2015; Lorente et al., 2019b, 2019b; Bolado-Penagos et al., 2021).

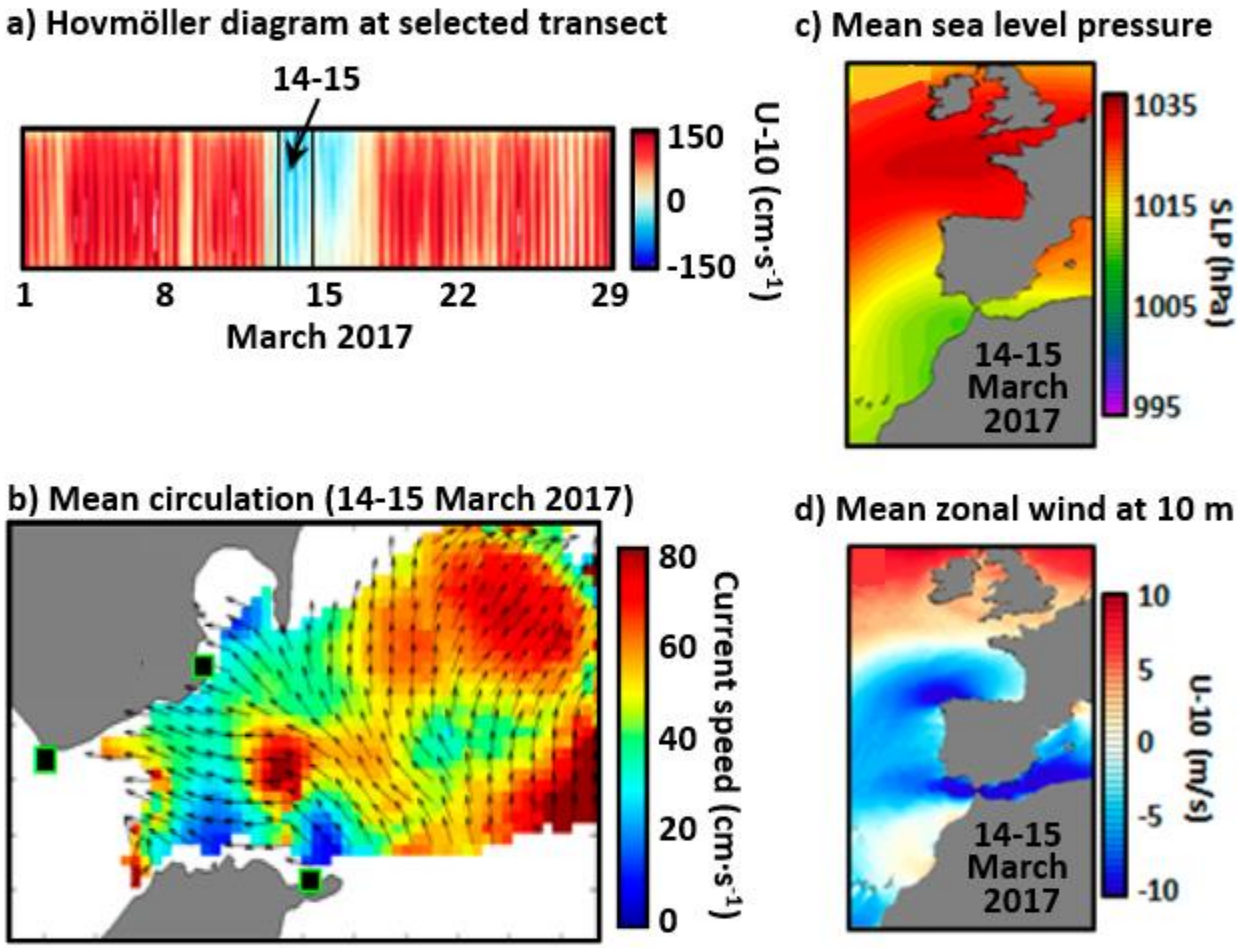

Figure 8. (a) Monthly Hovmöller diagram of HFR-derived zonal current speed at the selected transect (shown in Figure 4, a). Red (blue) colors represent eastward (westward) surface flow. A 2-day episode of permanent flow reversal is marked (14-15 March). (b) HFR-derived mean surface circulation for 14-15 March 2017: permanent flow reversal. (c-d) 2-day mean sea level pressure and zonal wind at 10 m height (U-10), respectively, as provided by the ECMWF: intense and persistent easterlies were the driver of the flow reversal. Original source: from Lorente et al., 2019b.

2.2.2 Tsunami detection

Tsunami early warning and alert is an emerging and promising application of HFR. The main principle underlying the detection is that the abnormal surface current pattern induced by the orbital velocity of the tsunami wave train can be measured and interpreted in real-time by an appropriate detection algorithm. The idea was first proposed by Barrick (1979), but it was only after the 2004 Indian Ocean disaster that the proof of concept was made on the basis of actual HFR data. It was shown numerically with simulated (e.g. Lipa et al., 2006; Gurgel et al., 2011) and real (e.g. Lipa et al., 2011 & 2012; Dzvonkovskaya et al., 2012) events that the tsunami signature could be clearly seen in the HFR radial currents and some appropriate detection algorithms were proposed. One strong point of HFR tsunami detection is that it is not bound to the nature of the source (i.e.

seismic or atmospheric) and can be used as a useful complement to other warning systems in places where those are either not available or non-effective. Today, more than 20 real tsunamis have been detected ‘offline’ with the reanalysis of HFR data. In view of the growing interest for these new capabilities of HFR, some radar manufacturers now provide commercial toolboxes along with their hardware system for the early detection of tsunamis; such systems have been installed in some places at risk (e.g. Vancouver Island Canada, Oman, New Jersey USA, Sagres in the SW Portugal). To date, the only real-time detection was issued following a meteotsunami that occurred on the 1st of October 2016 in Tofino, BC, Canada (Dzvonkovskaya et al., 2017; Guérin et al., 2018).

However, no such HFR tsunami alert system has been yet installed in the Mediterranean Sea, even though there is a non-negligible tsunami hazard in this region, as witnessed by very destructive co-seismic events in recent history (e.g. Messina, Sicily, 1908). Some worst-case scenarios with a strong (M7.8) earthquake in the North Algerian margin predict important tsunami waves with 3-4 meter amplitude on the French-Italian Riviera (BRGM, 2007). Moderate earthquakes such as the M6.9 21 May 2003 Boumerdes-Zemmouri are sufficient to cause 1-3 meter amplitude harbor oscillations within 40-60 minutes in the Balearic Islands, which would be the most impacted spot by seismic sources in North Algeria (Wang et al., 2005; Sahal et al., 2009). The impact in the French Mediterranean coast impacted by a seismic source in the North Algerian margin is shown in Fig. 9.

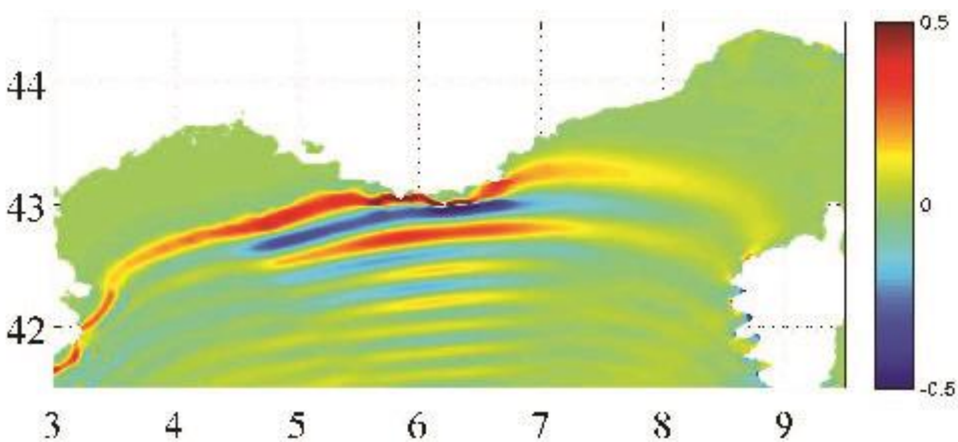

Figure 9.: Map of the French Mediterranean coast (close to the HFR-Tln system) within the simulated surface elevation (in meter) after 1h10 propagation for a tsunami generated by a M7.8 seismic source in the North Algerian margin. The numerical simulation uses FUNWAVE-TVD software with 3 nested grids in the West Mediterranean basin (courtesy of Stephan Grilli, University of Rhode Island, USA).

In addition to co-seismic tsunamis, frequent meteotsunamis (i.e. tsunamis of meteorological origin) have been reported in the Balearic Islands, named –“rissaga”- (Jansa, 2007), Adriatic Sea – “šćiga"- (Vilibić and Šepić 2009; Orlić, 2015), Sicily Channel –“marrobbio"- (Candela et al., 1999; Zemunik et al., 2021), Malta – milgħuba"- (Drago, 2008), northern Persian Gulf (Kazeminezhad et al., 2021), Black Sea (Vilibić et al., 2021) and Aegean Sea (Papadopoulos, 1993). Even though these events have limited regional impact, they can cause severe local damage in harbors and bays due particularly to the micro-tidal regime, resulting in rapid sea level changes (Vilibić et al., 2021). Indeed, the strongest known meteotsunami in the Mediterranean Sea (and likely in the world) was in the Adriatic, the so-called Great Vela Luka Flood (June 1978), with an amplitude of 6 m and periods of about 20 min, as detailed by Vučetić et al. (2009) closely followed by the event from Ciutadella Harbor (Menorca island, Spain) in June 2006 (Jansa et al., 2007) with 4-5 m of amplitude. Meteotsunamis are caused by atmospheric disturbances combined with several further possible amplification mechanisms of the induced sea surface wave; these are mostly the so-called Proudman-, Greenspan-, shelf- resonances in coastal areas which can lead to strong harbor resonances in semi-closed basins (Orfila et al., 2011). Today, the generation of these meteotsunamis is better understood (Monserrat et al., 2006; Šepić et al., 2009, 2015; Vilibić and Šepić 2009; Ličer et al., 2017) but their prediction is still a very challenging task (Denamiel et al., 2019, Romero et al., 2019, Mourre et al., 2020).

When located in the areas affected by the meteotsunamis, HFR-based tsunami early warning systems could be a useful complement to these forecasting systems, helping issuing specific alerts on the basis of the actual observed surface currents 20-40 km offshore a few minutes before the generation of the extreme sea level oscillations. Note that tsunami early warning systems only require software update of existing HFR and could be installed at reduced cost in some places. However, some strategic spots are not covered yet and would deserve a novel installation to monitor the travel directions of incoming waves from the most probable sources (North Algerian earthquake, West Corsica submarine mass failure, North Ligurian earthquake, etc.). Another related issue is extending the range of these HFR, which would imply operating at lower frequency bands (4-5 MHz or 9 MHz) than those usually employed in the Mediterranean region (13, 16 or 25 MHz). A HFR prototype (i.e. Stradivarius radar) operating at 4.5 MHz with 200-300 km range was developed by the Diginext Ltd. a few years ago for the Gulf of Lion as a proof of concept (Grilli et al., 2015). Such HFR systems can serve the double purpose of warning and characterizing abnormal surface current patterns arising from tsunami-like waves of seismic or atmospheric origin. As recently suggested by Domps et al. (2020), they can also be used as proxies for the observation of low-pressure fronts of atmospheric gravity waves that could lead to storm surge, if not meteotsunamis.

2.3 Environmental Transport Processes

In the Mediterranean, as elsewhere in the world, the coastal zones serve as the main entry point of nutrients, pollutants and sediments into the ocean, being the multi-scale coastal ocean dynamics the key drivers for their transport, also impacting their dispersal and retention and the cross-shelf exchanges. HFRs have demonstrated a capacity to provide very valuable measurements to continuously monitor the mesoscale structures and frontal dynamics that organize the coastal surface flow and associated transport, by the developments in the understanding of Lagrangian dynamics from HFR data (Rubio et al., 2020). The comprehension of the coastal ocean conditions and variability underlying ocean productivity that correlate with fish stock abundance, fish recruitment in coastal areas, dispersion and retention of larvae, etc., is critical for a sustainable management of fisheries resources (Sciascia et al., 2018). Coastal and littoral areas are also very vulnerable target regions for pollution, in terms of environmental and ecosystem impact as well as economic and societal consequences, being also essential to assist water quality management by tracking source and drift of contaminants (e.g. chemical, sewage, oil spills or harmful algal blooms). In the Mediterranean Sea, the applicability of HFRs in the study of environmental transport processes are particularly relevant due to its limited exchange with the oceanic basins, its microtidal character and its intense internal meso and submesoscale circulation. These specific characteristics of this semi-enclosed sea reduce the potential of dilution and dispersion of dissolved and particulate wastes, maximizing the impact of one of the most commonly identified threats (i.e.. marine litter and contaminants). In addition, despite being considered one of the most oligotrophic areas in the world ocean, it is also one of the world's hot spots for biodiversity (Coll et al. 2010, Gabrié C., et al. 2012), providing vital areas for the reproduction of pelagic species (e.g. Atlantic bluefin tuna, white shark and sea turtles) and hosting sensitive ecosystems in the shallow coastal waters (e.g. seagrass meadows of the endemic *Posidonia oceanica*, the key intertidal habitat of vermetid reefs built by endemic gastropod *Dendropoma petraeum*, the coralligenous assemblages, etc., as detailed by Coll et al., 2010).

2.3.1 Pollution and floatables tracking

Coastal regions in the Mediterranean Sea are heavily inhabited with strong tourism pressure and maritime activity resulting in human and industrial waste intentionally or accidentally dumped into coastal waters. These pollutants evolve according to their chemical transformation over time and are caught in the 3D general circulation and carried offshore and to other distant coastal areas by currents. For example, heavy metals or other chemical contaminants that may be present in semi-enclosed harbors (Tessier et al., 2011) could have important consequences on the ecosystem, and plastic litter is today a massive and particularly harmful component (e.g. Ryan et al. 2009; Declerck et al., 2019) of the marine pollution in the Mediterranean Sea. Furthermore, detecting, monitoring and cleaning up oil slicks following an offshore spill before they reach the coast is a major challenge. Consequently, monitoring, understanding and forecasting coastal dynamics is a critical step to develop adequate strategies to mitigate the effects of pollution in marine environments, from or towards coastal areas. However, forecasting coastal dynamics is one of the most challenging issues in geosciences due to their strong space-time variability as well as the complexity of the processes controlling the dynamics that interact simultaneously over a broad range of time–space scales, as previously highlighted in Sect. 2.1.2. Thanks to the growing importance of HFR as a key element of coastal observing systems, coastal currents can nowadays be continuously measured in relatively large coastal areas, thus enabling the analysis of transport properties of the surface flow by means of different diagnostics based on the Lagrangian approach (i.e. addressing the effects of the spatio-temporal variability of the velocity field on drifted particles or tracers). Recent studies have demonstrated the potential of this land-based remote sensing technology for different applications in the field of tracking oil spills (Abascal et al., 2009), marine litter (Declerck et al., 2019) or phytoplankton (Hernández-Carrasco et al., 2018a).

In this regard, the trajectories of passive tracers are determined by the velocities measured by HFR (e.g. Ullman et al., 2006), often including the effect of subgrid scale diffusion. When chemical pollutants are considered, additional processes should be included. For instance, when simulating oil spill trajectories, the advection term is a linear combination of the surface current velocity, the wind velocity and the stokes drift, and spreading, evaporation and emulsification should be included in the transport model.

Here we provide evidence to support the reliability of the HFR currents for tracking substances at coastal areas. The Lagrangian validation has been performed using data from 8 drifters' trajectories available in the domain of the HFR area of coverage in the Ibiza channel (HFR operated by SOCIB, Tintoré et al., 2020) during October 2012. We use the HFR velocity fields to compute the Lagrangian Coherent Structures (LCS) which are very suitable to provide a template of the fluid flow transport (see Haller, 2015, and references therein), allowing the detection of transport barriers, which are of great relevance for marine dynamics. For example, LCS obtained from ridges of the Finite Size Lyapunov Exponents have been correlated with filaments of remote-sensed Chl-a (Lehahn et al., 2007; Hernández-Carrasco et al., 2014, 2018a, 2020), sea bird foraging behavior (Tew Kai et al., 2009), with the modelled extension of oxygen minimum zones (Bettencourt et al., 2015) and with wind forcings (Berta et al. 2014b). At coastal scales, the dynamical picture in the Lagrangian frame has been analyzed using data from HFR currents to identify relevant small-scale transport barriers (Lekien et al., 2005; Gildor et al., 2009; Rubio et al., 2018), some of them focusing on coastal areas of the Mediterranean Sea (Haza et al., 2010; Berta et al., 2014b; Hernández-Carrasco et al., 2018a). Fig. 10 shows the evolution of a set of virtual neutrally buoyant particles initially deployed on the northern (blue dots) and southern (black dots) flank of a given LCS measured from the HFR-Ibiza in January 25^{th}, 17:00 UTC in 2013 (Fig. 10a). Although the location and magnitude of this LCS evolve in time, the LCS persists for several hours manifesting the presence of a coherent transport barrier preventing both sets of particles to be mixed up. A meridional LCS is formed and maintained during the simulated period, limiting water exchanges between the coast and the open ocean (Fig. 10a–c).

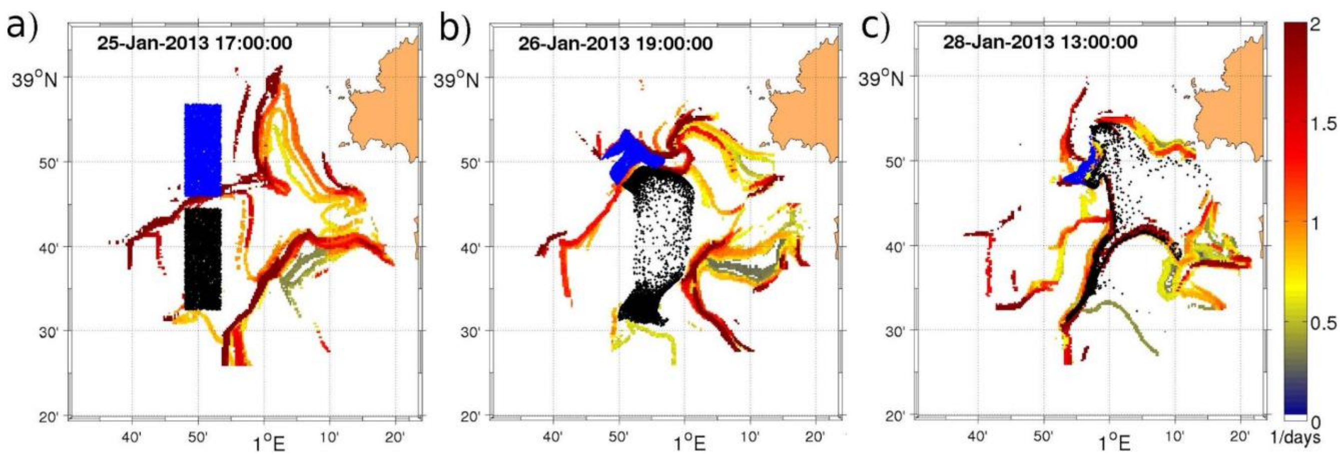

Figure 10. Evolution of two sets of particles (black and blue) in the area covered by the HFR-Ibiza in January 2013 superimposed on the backward FSLE (colorbar). The virtual particles are initially deployed at both sides of a barrier revealed by a zonal LCS on Jan 25th, 2013 at 17:00 evolving for 68 hours.

Another example of application of the Lagrangian properties derived from the HFR focuses on the monitoring of the physical mechanisms that can influence the escape times of mesotrophic and/or polluted coastal waters to the oligotrophic offshore areas, as described in Rubio et al., (2020). Using as input gap-filled HFR velocity fields a Lagrangian Particle-Tracking Model provides the particle trajectories. From the Lagrangian model outputs, it is possible to infer the characteristic time-scales for transport processes in the HFR footprint area by means of the escape rate of active particles (Fig. 11). Thus, HFR shows to be an excellent tool to monitor conditions and identify the different scenarios that favor the local retention and dispersal of shelf waters in two study areas under the influence of ocean boundary currents.

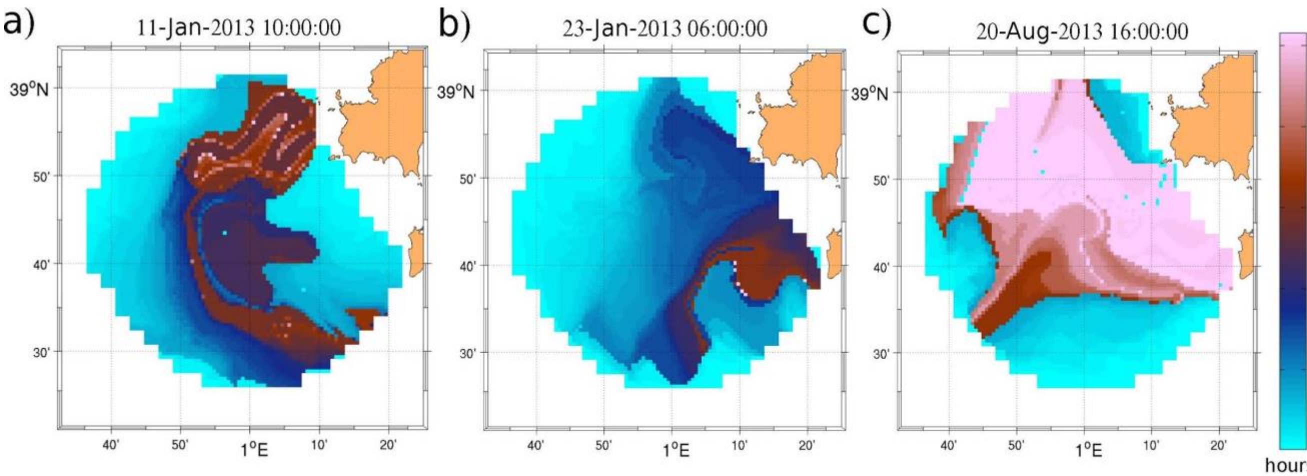

Figure 11. Maps of particle residence times (hours) computed for different dates and seasons, from HFR observations in the Ibiza Channel SOCIB (a,b for winter and c for summer conditions). Original source: from Rubio et al., 2020.

2.3.2 Eddy tracking

Ocean eddies are ubiquitous, pervasive flow structures which dominate the ocean velocity field at several scales, from the meso- to the local scale (Chelton et al., 2011). They play a fundamental role in sea dynamics, being responsible for the energy transfer among different scales (down to the dissipative range) as well as for their ability to transport nutrients, biomass, sediments and pollutants. Mesoscale eddies, produced by geostrophic instabilities, are not able to advance the energy transfer, being constrained by geostrophic and hydrostatic balance (Charney, 1971). When the balance is broken, the downscale may continue through inertia-gravity waves emitted from currents, ageostrophic instabilities, and bottom boundary layer turbulence, which are responsible for the formation of submesoscale eddies. At a lower scale, three-dimensional turbulence proceeds toward the dissipative range (McWilliams, 2019).

The presence of ocean eddies has become more evident in recent years, thanks to the introduction of new oceanographic measurement techniques, while their exhaustive characterization would require synoptic time series of the velocity field in the ocean (Robinson, 1983). Such synoptic observations are made available only through satellite data, however, besides being limited to relatively large scales, and preferably to the open ocean, they do not provide direct measurements of the total velocity field. Indeed, altimetry data can be used to retrieve the surface geostrophic field, which lacks a possibly important portion of the dynamics (Rinaldi et al., 2010; Conti et al., 2016). Other ways to observe eddies from satellites consist in the observation of their presence in the sea surface temperature or in the tracer field patterns, as displayed by ocean color (Robinson, 2010).

Coastal HFRs overcome all the above limitations, enabling the detection and the tracking of the time history of surface eddies down to submesoscale, at the cost of a reduced spatial extent.

Mandal et al. (2019) provide quite an extensive list of recent literature reporting submesoscale features observed by HFRs, with examples of observations in various coastal areas, from the Atlantic to the Pacific and Indian oceans (Shay et al., 1995, 2000; Kirincich, 2016b; Archer et al., 2017; Lai et al., 2017; Arunraj et al. 2018). It is worth noticing that such features may have a strong vertical signature that HFR data fail to account for, and therefore need to be complemented with further information, spanning from direct measurements of the horizontal and vertical velocity profile to indications indirectly derived from, e.g., satellite turbidity measurements (see discussion in Uttieri et al., 2011).

A vast HFR network now covers the North-Western Mediterranean coastal areas (see Lorente et al., 2021b), which is characterized by significant mesoscale variability and eddy generation that, in some cases, shows recursive and seasonal patterns. Allou et al. (2010) used HFR to observe and characterize vortex structures, mostly anticyclonic, in the Gulf of Lion. They also argued they were correlated with specific wind patterns. Schaeffer et al. (2011) improved the analysis and employed both HFR measurements and numerical modeling to analyze the eddy generating mechanism. They found it is primarily influenced by wind forcing and its interaction with topographic constraint (northerly offshore wind), and freshwater input from Rhone river (southerly onshore wind). The combination of HFR and *in-situ* observations, and modelling tools, allowed Guihou et al. (2013) to identify an anticyclonic coastal eddy which was generated in front of Nice by a meander of the Northern Current, and advected downstream toward the Toulon area, interacting with the mean circulation. More recently, the analysis of the long 2012-2019 HFR time-series in Toulon allowed to identify cyclonic and anticyclonic recurrent eddies mainly generated by wind and boundary current undulations (Bourg and Molcard, 2021).

The development of monitoring networks providing long time series of data, is making automatic eddy detection methods more and more topical and important. Generally speaking, existing eddy detection algorithms can be divided into three families: (i) those that are based on the geometrical features of the velocity field, typically in terms of streamline closeness, winding angle or vector geometry (Sadarjoen et al. 1998; Heiberg et al. 2003; Ebling and Scheuermann 2003; Nencioli et al. 2010); (ii) those based on dynamical characteristics, such as parameters quantifying the eddy intensity, its vorticity, etc. (Jeong and Hussain 1995; Fang and Morrow 2003; Isern-Fontanet et al. 2003; Morrow et al. 2004); (iii) and hybrid methods, based on the combination of geometric and dynamical criteria (Mkhinini et al. 2014; Conti et al., 2016, see also the extensive review in the paper by Le Vu et al., 2018).

Algorithms specifically devised for HFR data are very few. The methods tested in the Mediterranean Sea (Caldeira et al., 2012) are limited to those by Nencioli et al. (2010), and by Bagaglini et al. (2020). The former, even though developed for HFR data (and for high resolution numerical model outputs), has found a widespread range of applications to observations collected by different platforms, as witnessed by current oceanographic literature (Liu et al., 2012; Dong et al., 2014). It is a method based on the geometry of the velocity vectors. It was conceived for geostrophic or quasi-geostrophic recirculating features, showing very little divergence. For this reason, it is very suitable to describe mesoscale eddies, but may fail in detecting submesoscale ones, which often are characterized by divergence or convergence and by a high degree of deformation of the velocity field geometry. The YADA (Yet Another eddy Detection Algorithm) algorithm developed by Bagaglini et al. (2020) was conceived specifically to overcome this limitation and be utilized to automatically detect submesoscale eddies, which may exhibit highly non-geostrophic characteristics. It is a hybrid method, which focuses on both the dynamical and geometric features of the velocity field, first identifying the local extrema of a dynamical field characterizing recirculation (e.g., the local normalized angular momentum, see Mkhinini et al., 2014; or the Okubo-Weiss parameter, Okubo, 1970; Weiss, 1991), similarly to the first step from AMEDA (Angular Momentum Eddy Detection and tracking Algorithm) defined by Le Vu et al. (2017), and thereafter analyzing the streamline geometry in a neighborhood of the extremum. The YADA (Bagaglini et al., 2020) has been successfully applied to 1 km-resolution HFR data from the Gulf of Naples, showing its ability to identify strongly asymmetric, convergent or divergent submesoscale eddies. Its application to coastal HFR data from other areas of the Western Mediterranean is presently under way.

The HFR system from LaMMA Consortium (described in Lorente et al., 2021b) covers part of the Ligurian Sea and the Tuscany Archipelago, which is a shallow area separating the Ligurian and Tyrrhenian basins, bordering eastward the Corsica Channel, with complex topography and coastal morphology, also due to the presence of several islands (Elba, Capraia, Montecristo, Gorgona). Sea dynamics are strongly influenced by seasonality and characterized by the presence of the Tyrrhenian boundary current and its bifurcation, the Eastern Corsica Current (Astraldi and Gasparini, 1992; Millot, 1999; Vignudelli et al., 2000). Through drifters, *in-situ* data, and a numerical model, Poulain et al. (2020) studied the area in the summer season. They found prevailing southward current flowing next to the Italian coast, then turning westward and northward encountering Elba island. A further eastward motion led to the formation of anticyclone centered on Capraia island, which exhibited variations correlated to wind forcing. The presence of an anticyclone north of Corsica Channel, in summer and autumn seasons was previously documented by Ciuffardi et al. (2016) by means of *in-situ* profiles and altimetric data. Furthermore, they argued that the characteristics of the anticyclone (position and size) may affect the general circulation, by isolating the Tyrrhenian and Ligurian basin, mostly in summer. These hydrodynamics features can influence the concentration of floating marine litter, which was shown to be particularly high in certain periods of the year (Fossi et al 2017).

Here, we show the application of both the YADA and Nencioli et al. (2010) algorithms to the surface currents derived from the HFR- LaMMA system, during the year 2019.

Figure 12 reports four eddies detected by the YADA algorithm, and the corresponding surface currents in August 2019.

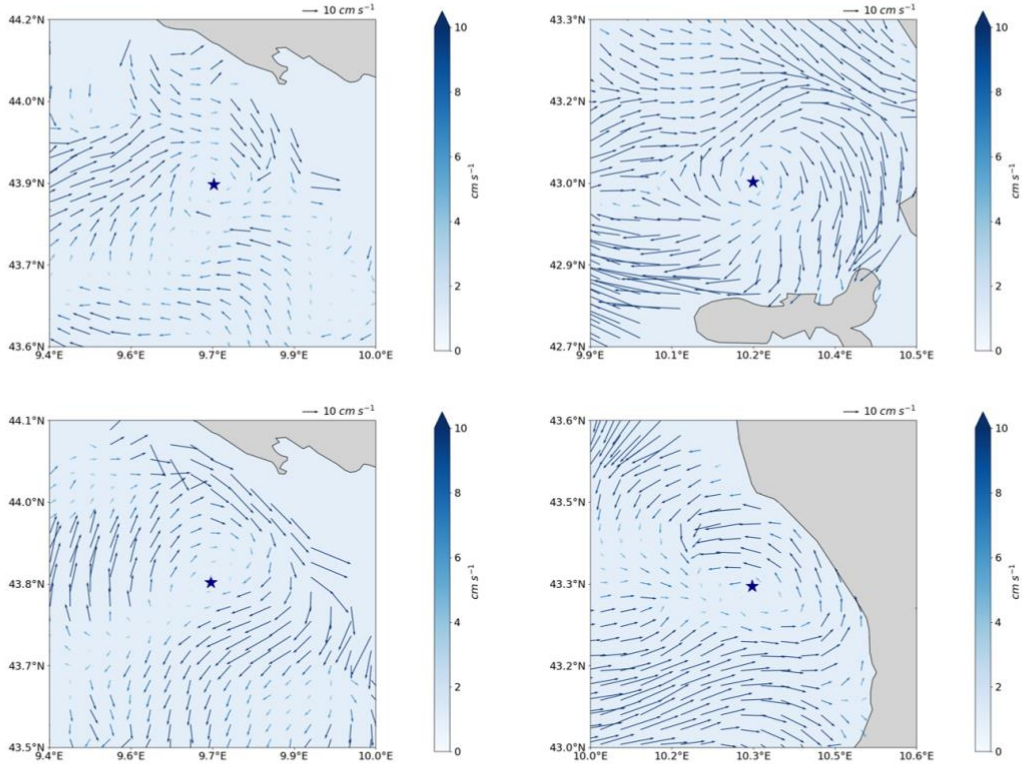

Figure 12. Maps of the area of eastern Ligurian Sea and Tuscany Archipelago showing the HFR derived surface currents (colored arrows indicating the current speed) and the detection of four eddies in early August 2019 by the YADA algorithm. The blue star marks the eddy center.

Fig. 13 shows the results of the application of the algorithm by Nencioli et al. (2010) to the whole year 2019, which provided a seasonal census of anticyclonic and cyclonic eddies in the area sampled by the HFR- LaMMA system. The HFR coverage was not uniform during the year with generally lower percentages for the warmer seasons (i.e. spring, summer). The area north of Elba island was characterized by the highest eddy activity throughout the year, with a predominance of anticyclonic eddies in colder seasons, and a clustered pattern in summer, showing anticyclonic eddies east of Capraia island and cyclonic ones toward the coast.

The number of detected eddies depended also on the availability of HFR data; indeed, a smaller number of eddies was found in spring (28) with respect to the other months (62 winter, 68 summer, 62 autumn). Median eddy life-span was around 1.125 days for all seasons except in spring, although some were able to survive up to 6 days.

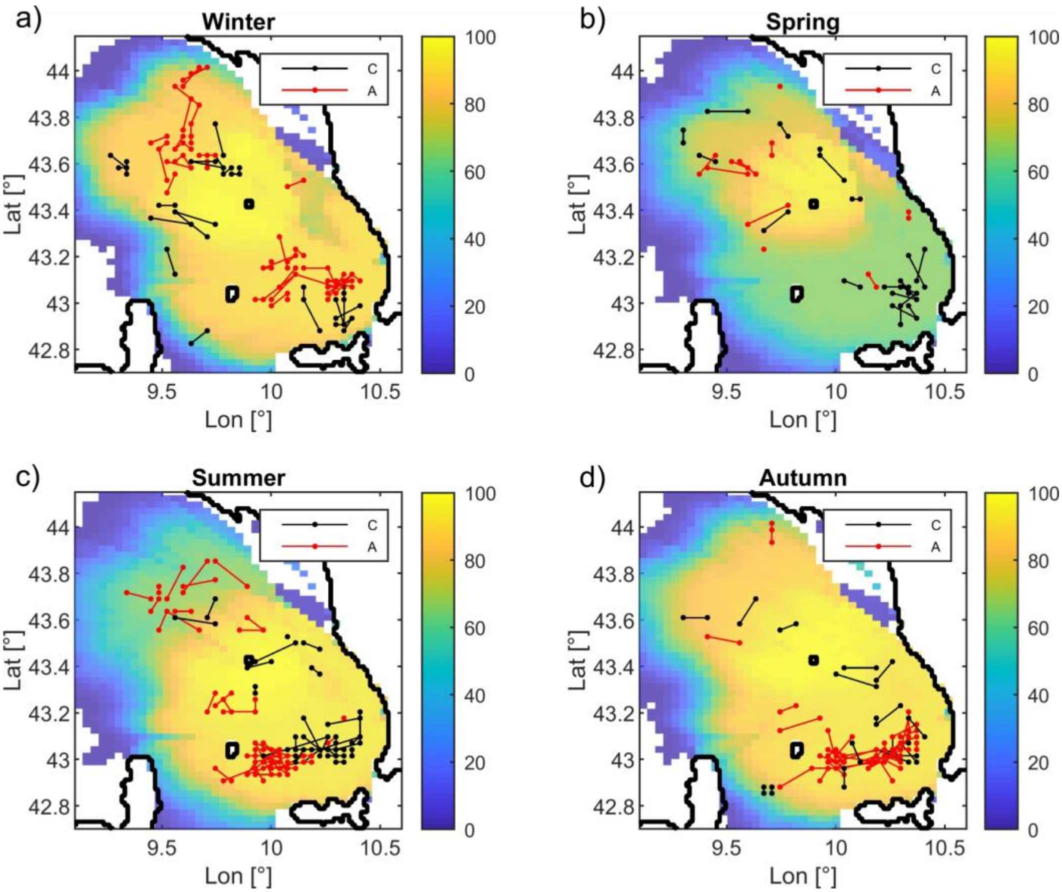

Figure 13. Maps of the area covered by the LaMMA HFR network showing the percentage of HFR data availability along 2019 for a) winter; b) spring; c) summer and d) autumn. The Tuscany Archipelago (i.e. Elba island) is at the lower-right corner of the figures. Tracked cyclonic (black) and anticyclonic (red) eddies detected in each season are overlaid.

Although the present work is preliminary, it may lay the basis for a detailed analysis concerning the seasonal features of eddy activity within the Tuscany Archipelago, and its effect on the general circulation. Surface currents from HFR can be combined with the numerical model outputs both to bridge the gap relative to the spatial and temporal coverage of data, and to improve the representation and forecast of the real sea state: HFR observations enhance numerical simulations by resolving fine-scale processes in intricate regions with complex-geometry configurations. In turn, hydrodynamic models can reciprocally serve as integrative connectors of sparse *in-situ* observations and gappy HFR surface current maps by offering a seamless predictive picture of the three-dimensional ocean state.

2.3.3 Transport of biological quantities and connectivity

The necessity to preserve the marine ecosystem equilibrium and the water quality, has fostered the use of HFR data in supporting the coastal zone management and assessing the variability in the dynamics of marine ecosystems. In particular, HFR data have been used worldwide to address ecological and water quality issues such as: (i) to understand the transport and retention processes of plankton or wastewater discharge in some regions of NW Spain (Ria de Vigo) (Piedracoba et al., 2016) and Western Mediterranean (Hernández-Carrasco et al, 2018a), at coastal upwelling fronts off central California (Bjorksted and Roughgarden, 1997) and in Monterey Bay (Coulliette et al., 2007); (ii) to investigate the enhancement of productivity due to the retain of phytoplankton within the flow in the Santa Barbara Channel (Brzezinski and Washburn, 2011) and (iii) to analyze the relationship between populations of larval and juvenile fishes and the mesoscale flow field in the California Current System (Nishimoto and Washburn, 2002).

Here we present examples of application of HFR data to investigate ecological questions in three Mediterranean coastal areas: the Gulf of Naples (GoN, Tyrrhenian Sea), the Gulf of Manfredonia (GoM, western Adriatic Sea) and the Malta-Sicily Channel (mid Mediterranean Sea).

In the GoN, the continuous observations of the HFR current fields highlighted several characteristics of the surface circulation and water exchange between the interior of the gulf and the neighboring open Tyrrhenian Sea (Cianelli et al., 2013). An oscillating plankton population dynamic has been also frequently observed in the GoN, at Long-Term Ecological Research station MareChiara (LTER-MC), where plankton abundance is monitored weekly since 1984. A proof of concept study (Cianelli et al., 2017), was thus conducted in order to characterize the spatial scales and the provenance of phytoplankton assemblages detected at LTER-MC and to dissect processes regulating plankton dynamics.

The study focused on a year-long analysis carried out for 2009, which was characterized by a very accurate estimate of the surface dynamics, with a reduced number of gaps among ecological measurements and HFR data. The approach followed these conceptual steps: (i) Reconstruction of the annual and seasonal regimes of HFR currents detected at the LTER-MC site; (ii) Computation of Lagrangian backtracking simulations advecting virtual phytoplankton patches (VPPs) in the HFR field (Fig. 14, a). VPPs were released at LTER-MC site on the dates of the weekly oceanographic campaigns and tracked backward, allowing thus the estimation of the positions of the VPPs up to 4 days (i.e. 96 h) prior to its arrival at LTER-MC; (iii) Identification of the prevailing directions from which the VPPs arrive at LTER-MC site, as resulting from backtracking simulations (Fig.14, b), also allowing the definition of the spatial distribution of the VPPs origin zones (not shown) in the GoN; (iv) Comparison among backtrack Lagrangian reconstruction and ecological analysis based on salinity and Chl-a data obtained through weekly sampling at LTER-MC (Fig. 14, c); (v) Identification of different modes of coupled physical and ecological functioning in the GoN as resulting from physical transport and biological processes ('allogenic' and 'autogenic' factors, respectively).

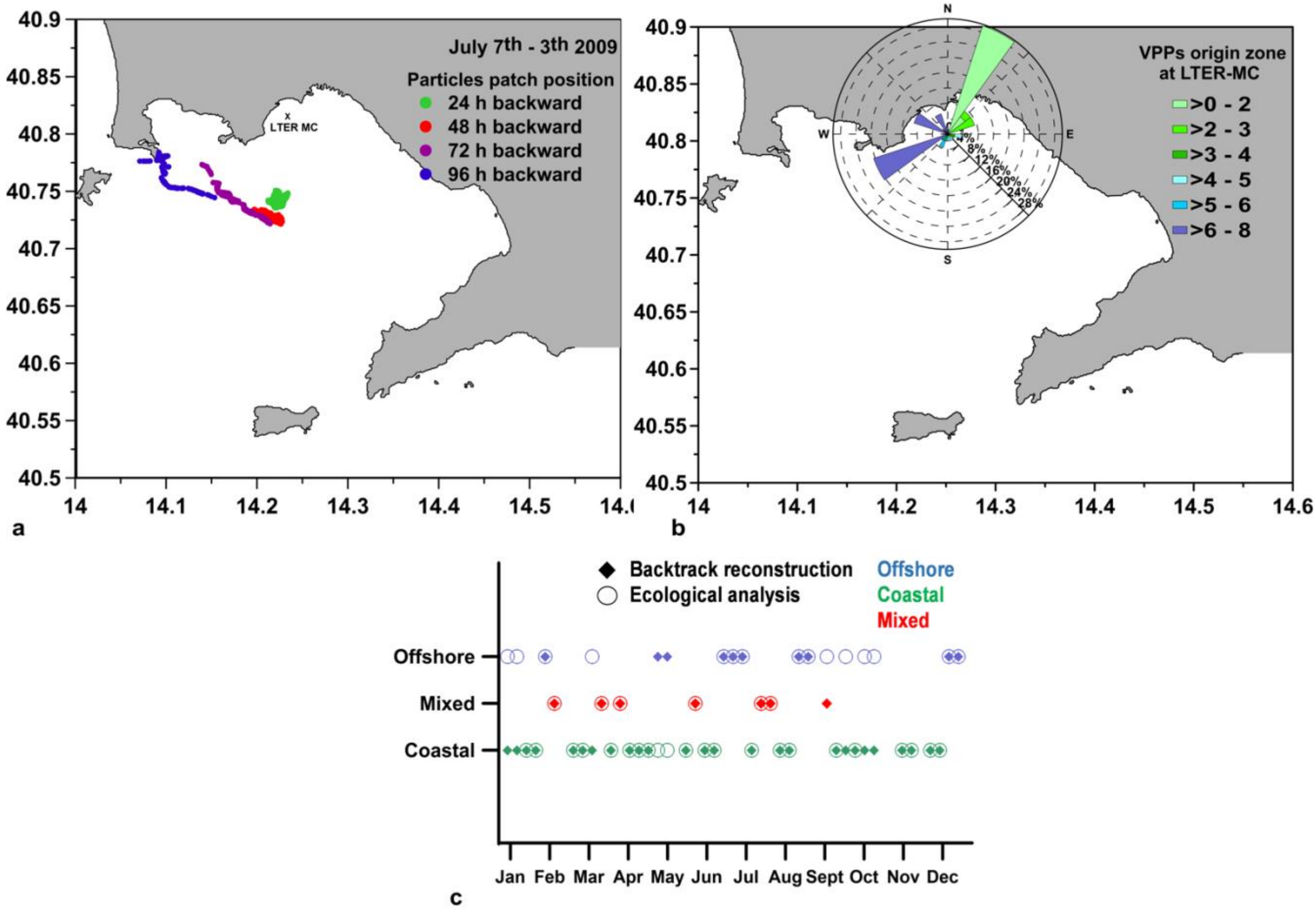

Figure 14. a) Map of the Gulf of Naples (southern Tyrrhenian Sea) showing the: a) Lagrangian backtracking trajectories of Virtual Phytoplankton Patches (VPPs) in the period 7th- 3th June 2009 and b) main origin sectors of the VPPs at LTER-MC site resulting from backward simulations, index sectors of VPPs are 1-2-3-4-5 for coastal areas and 6-7-8 for offshore areas; c) comparison among backtrack Lagrangian origin and ecological analysis based on salinity and Chl-a data weekly measured at LTER-MC. Green = VPPs originating from coastal areas; blue= VPPs originating from offshore areas; red = VPPs originating partly from coastal and partly from offshore areas. Adapted from: Cianelli et al., 2017.

The results showed an alternation in plankton dynamics between phases reflecting the influence of coastal (green) and offshore (blue) circulation patterns on the biological community. The phytoplankton community detected at LTER-MC generally originated from the coast, whereas the offshore inflow marginally changed the main traits of phytoplankton assemblages. Backtracking simulations and biological data strictly agree, highlighting that the plankton community at LTER-MC during 2009 is affected by the alternation of coastal and offshore influence.

Biological autogenic factors drive the modifications of coastal phytoplankton communities during the coastal 'green' phases, thus suggesting that the GoN tends to retain the same communities via coast-ward circulation, especially during summer. Physical allogenic factors are important in driving dilution and species advection of coastal phytoplankton, during the offshore 'blue' phase. This marked alternation between coastal and offshore water masses acts to promote phytoplankton diversity, because the dilution in the phytoplankton density may decrease the impact of the dominating species over the available resources.

The integration of long-term biological data and high-resolution current fields represents an optimal tool to investigate the role of surface circulation in structuring the marine plankton community, thus confirming the value of HFR systems to analyze the seasonal fluctuations in marine ecosystems dynamics and to unveil the mechanisms of coastal connectivity.

The GoM is a well-known recruitment area in the Adriatic Sea (Sciascia et al., 2018; Corgnati et al., 2019a). In this region, HFRs have been used to understand the role of ocean currents in the recruitment of small pelagic fishes (i.e. European sardines, *Sardina pilchardus*). Fig. 15 shows residence times within the GoM, estimated using trajectories of virtual drifters computed from the surface currents measured by HFRs. Months with high (October)/low (February) residence times are associated with weaker/stronger surface currents in the central area of the Gulf. The relatively short (<12-day) average residence times have shown that local spawning is less likely to take place than the transport to the Gulf from remote spawning areas through advection pathways. Results agree with otolith measures, suggesting that the arrival of larvae within the Gulf is characterized by repeated pulses from remote spawning areas that are likely to play a fundamental role in maintaining the nursery.

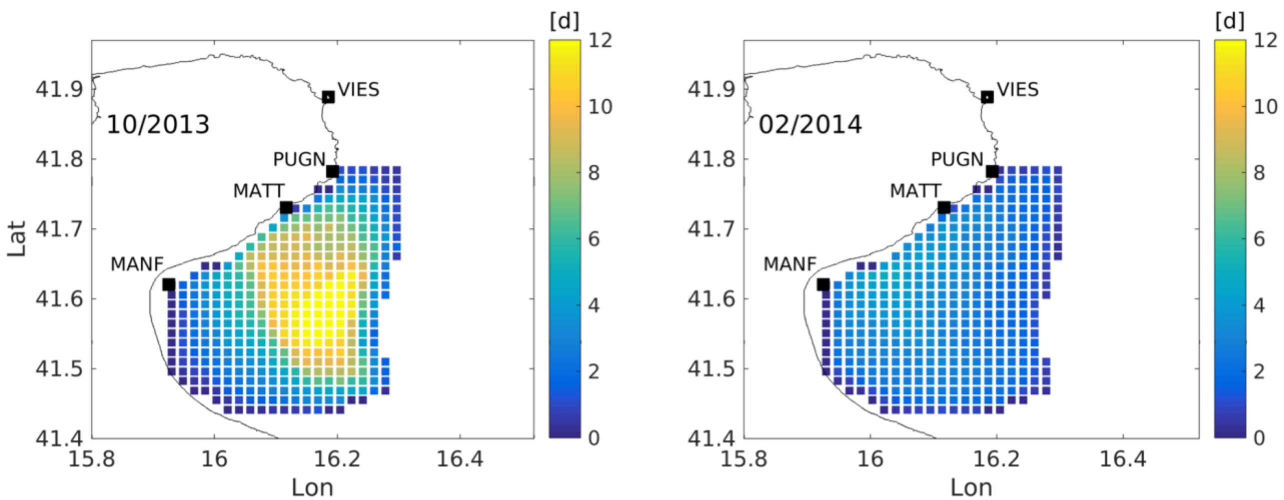

Figure 15. Maps of the Gulf of Manfredonia showing monthly bootstrap estimates of average residence times (in days) of virtual particles advected in the HFR velocity field and released within the Gulf of Manfredonia for the months of October 2013 (left panel) and February 2014 (right panel). Black squares represent the locations of the four HFR antennas along the Manfredonia gulf. Adapted from: Sciascia et al., 2018.

The Malta-Sicily Channel is both the most fished area in western Mediterranean Sea and a very important hotspot of biodiversity (Médail & Quézel, 1999). In this region, Capodici et al., (2018) combined the HFR-CALYPSO surface currents together with satellite images of Chl-a and SST, to explain physical driving mechanisms that can help interpret ocean productivity and plan maritime activities in a more adaptive and proactive way. On the one hand, as mentioned by the authors, monitoring water quality data provides valuable insight into the understanding of processes driving spatial and temporal changes in productivity at sea (Behrenfeld et al., 2006). Chl-a and SST are generally accepted as proxies for water quality and are very helpful to detect upwelling events, which are frequently occurring along the Sicilian coast. In particular, sea currents are responsible for dispersion, transport or retention of nutrients of which Chl-a is widely used as a proxy variable; moreover, current jets or eddies are often observable as cold or warm areas in the SST maps, respectively. Even if both Chl-a and SST maps are usually retrieved by means of satellite data maps, cloudiness often reduces the satellite data availability; thus, temporal aggregated products (e.g. at 8 or 16 days) are the only data available. In this framework, the integration of sea surface current data provided by HFRs can fill the gap of knowledge due to the inadequate temporal (and sometimes spatial) resolution of these water quality maps. Capodici et al., (2018) used the Principal Component Analysis -PCA- (Preisendorfer, 1988) to firstly extract the dominant spatial patterns of these variables in 2013 (Fig. 16, left panels) and to secondly quantify the degree of correlation between SST (or Chl-a) and HFR derived surface current spatio-temporal patterns (see Fig. 16, bottom-right panel). The spatial correlation analysis suggests the importance of current advection in the phytoplankton transport, being characterized by fringes where very high positive correlation areas are surrounded by very high negative ones and viceversa. Moreover, the spatial distributions of time-averaged radar currents and corresponding TKE (Total Kinetic Energy), EKE (Eddy Kinetic Energy) and the absolute value of the products between temporal fluctuations of the deviations from the time-averaged zonal and meridional velocity components (ReS), shown swirling areas for the first time at high spatio-temporal resolution. The trapping zones, characterized by low values of TKE (see Fig. 16, top-right panel), EKE and ReS at their cores, may help explain why this channel is particularly rich in pelagic species, highlighting how the continuous high resolution HFR derived surface currents can improve the decision-making in fisheries resource management.

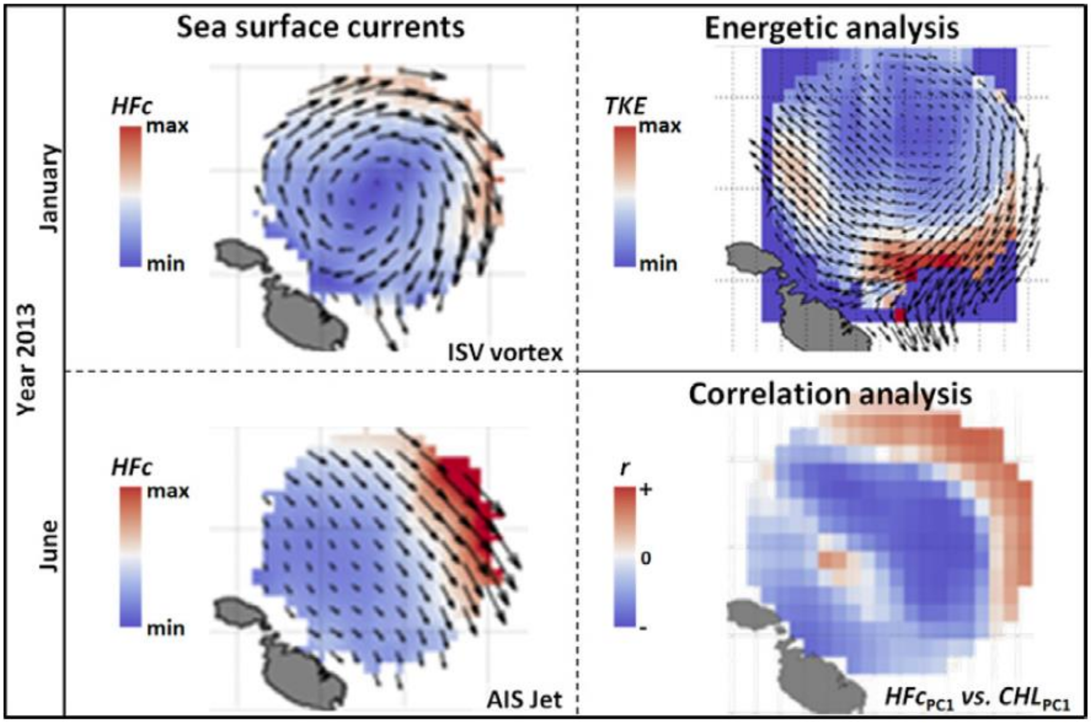

Figure 16. Map of the Malta-Sicily Channel showing the monthly averaged HFR sea surface currents for January and June 2013 (top left and bottom left panels, respectively), spatial distribution of the Total Kinetic Energy (top right panel) and of the correlation coefficient between the first PC of both HFR and Chl-a (bottom right panel). Original from: Capodici et al., (2018), graphical abstract.

3 Discussion and preliminary assessment of the HFR regional capabilities

This initial review of scientific and societal applications using HFR data, implemented in the Mediterranean coastal areas, have allowed us to know their potential and limitations to continue contributing to the regional observing system in addressing the regional existing environmental threats, the scientific key priorities and the societal needs. Considering also the current threats and the opportunities ahead along the UN Ocean Decade (2021-2030), we have conducted a SWOT (i.e. strengths, weaknesses, opportunities, and threats) analysis, as schematized in Fig. 17.

One of the main weaknesses found is the limited adoption of common data and metadata models for HFR surface currents. As a result of international and European efforts made in recent years towards the HFR data harmonization and distribution, detailed in Lorente et al., (2021b), it has already been defined: (i) the common data and metadata model for HFR surface currents (Corgnati et al., 2018, 2019b; Mantovani et al., 2020); (ii) the tools for near real-time (Corgnati et al., 2020) and for historical data processing (Corgnati et al., 2019c); (iii) the guidelines (Reyes et al., 2019) and (iv) the training activities. Despite of that, only 23% of the near real-time and 15% of the historical data from the Mediterranean HFR sites are integrated to the

European HFR node (Lorente et al., 2021b), established in November 2018 as a focal point for data management and distribution.

In the sphere of maritime safety, the main strength of HFRs is the provision of high spatio-temporal resolution surface currents over wide coastal areas, where most of the SAR incidents occur (see Sect. 2.1.1). HFRs are used as alternatives of the models for backtracking drifting objects in near-coastal risk-prone environments and for complementing other scarce *in-situ* observations, also helping to assess and to improve the ocean models, through data assimilation (see Sect. 2.1.2). In this regard, the provision of HFR data uncertainties (Moore et al., 2019) might boost the use of HFR data for data assimilation and model assessment. In addition to that, the machine learning approach where a neural network model is trained on past data and then used to create short term predictions (see Sect. 2.1.3) is gaining ground in recent years. The steadily growing of the European HFR network (Rubio et al., 2017; Roarty et al., 2019), increasing both the coastal coverage in many countries and the length of the time series, will allow us to implement these self-learning algorithms in other Mediterranean areas. Nevertheless, there is a strong need for consensus on the methodology to generate these scientific added-value products, and on the definition and further adoption of a common data and metadata model as well as the quality control tests. This lack of consensus hinders the operational distribution of standardized HFR gap-filled data and derived STPs, which may lock the HFR data potential for their use in several Lagrangian applications.

Additional efforts for unlocking interoperable HFR (basic or added-value) data access will greatly contribute to deliver greater uptake, use and value from the HFR data. Once we are able to turn HFR data into customized information, the further challenge is to extend the science-based added-value products and applications into societal relevant downstream services (Tintoré et al., 2019). To face this challenge, a clear stakeholder engagement strategy is needed to identify, categorize and analyze the user needs and requirements. By strengthened links with the identified stakeholders, the HFR community will reinforce the user's loyalty, whereas by involving them along the life cycle of the application development, it will ensure the achievement of their needs, raising their interest and usage. Furthermore, emerging HFR applications will enable new communities and sectors to discover and use the HFR data.

As a land-based remote sensing technology, HFRs are able to continuously monitor the coastal ocean response to extreme events without the need to be deployed at sea under severe metocean conditions, thus avoiding the risk to be faced by other observing platforms (i.e. research vessels, ferry boxes or even autonomous instruments). Moreover, HFRs are also unaffected by cloud coverage, which is usually associated with extreme storms and that prevent the ocean color satellites and infrared radiometers to infer and further observe the Chl-a concentration and the SST, which are generally being used as proxies of surface circulation. In addition, it is worth highlighting that under severe weather phenomena, near-real time met-ocean information gains value since it is essential to avoid risky situations and to support the emergency response at sea. The resilience of HFRs under unfavorable weather conditions, has allowed us to monitor and deeply investigate the impacts of intense wind episodes, severe river freshwater discharges and record-breaking storms as well as to observe the weakening or even the reversal of main surface currents and jet streams (Sect. 2.2.1). Furthermore, being demonstrated that tsunami signature, irrespective of its origin (i.e. seismic or atmospheric), could be clearly seen in the HFR radial currents, it opens up the possibility of using them as a useful complement to other warning systems in places where those are either not available or non-effective (Sect. 2.2.2). Nevertheless, despite the existing risk from tsunamis and the frequent occurrence of meteotsunamis in particular coastal areas of the Mediterranean Sea, there has not been installed any HFR tsunami alert system in this region. Facing a growing interest in these HFR new capabilities, several threats must be previously addressed: (i) the installation of new systems to monitor the most probable source areas and (ii) the extension of the range by using lower operational frequencies in the Mediterranean Sea to be able to detect the tsunami-induced currents far offshore, to offer early warning.

The recognized capabilities of the continuous HFR observations to analyze the transport properties of the surface flow and to detect and track surface eddies down to submesoscale (Sect. 2.3.2), have allowed us: (i) to understand the phytoplankton distribution and to identify different local retention scenarios (Sect. 2.3.1) as well as (ii) to investigate the role played by the characteristic mesoscale variability and eddy generation in the transport of biomass, pollutants and in the recruitment and abundance of small pelagic species in the Mediterranean coastal waters (Sect. 2.3.3). These practical applications have fostered the use of HFR data in supporting the coastal zone management (CZM) and assessing the variability in the dynamics of marine ecosystems, becoming a valuable asset for contributing in the achievement of the Good Environmental Status (GES) of the Mediterranean waters. However, it has been found that the number of detected eddies depend on the HFR data availability, highlighting the need to combine the HFR data with numerical model outputs aiming to bridge the spatio-temporal gap of the observed data and to improve the reliability of the simulations. It should also be noted that the HFR limited coverage reduces the potential of the larger scale applications and connectivity studies, thus requiring their integration with other *in-situ* and satellite observations as well as models, which in turn will benefit from the future expansion of the HFR network.

Considering the key features (see Sect. 1) of HFRs as their main competitive strengths when compared versus other observing platforms, it must be recognized that the provision of information at the very near surface layer constitutes its most serious limitation, as highlighted in the SWOT analysis from Lorente et al., (2021b). In order to fully understand ocean dynamics, the knowledge of the 3D processes in the entire water column is essential as well. A significant number of coastal ocean observatories in the Mediterranean Sea (as described by Tintoré et al., 2019) encompass a complex multi-platform network including HFRs, aiming to meet the primary but challenging need to monitor both the surface and the water column. This has motivated the development of techniques able to combine the information of the processes in the entire water column, in order to provide a three-dimensional picture of the overall dynamics. The combination of such observations is challenging mainly for two reasons: surface and ocean interior are prone to different processes and forcings with different spatio-temporal scales and at, the same time, the capabilities to resolve and characterize the diverse processes may be different for observing platforms at the sea surface and in the water column. Despite the promising results obtained by Berta et al. (2018) and Guihou et al. (2013) in the Mediterranean Sea, necessary efforts must continue towards the further development of methodologies to combine HFR data with water column measurements and models.

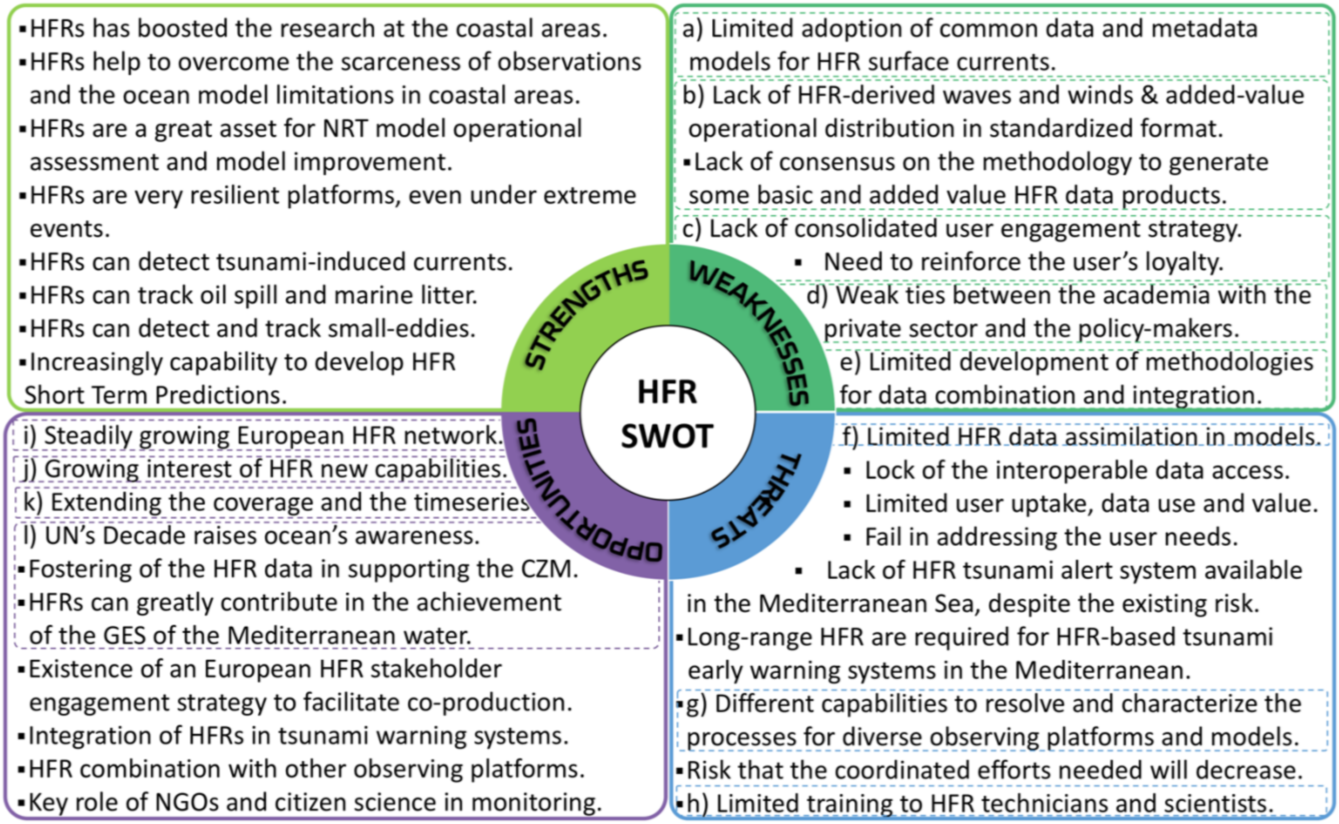

Figure 17. SWOT analysis of the HFR capabilities and applications. Dashed-line boxes around the text highlight those weaknesses, threats and opportunities that have been addressed in the recommendations.

4. Future prospects for HFR applications and recommendations

After the description of the current implementation status of the HFR applications in the Mediterranean coastal areas, and based on the results obtained from the previous SWOT analysis, we present here the prospects for the future and a set of key recommendations. Future prospects for HFR applications will benefit from the progressive implementation of the defined recommendations: (i) to ensure that the potential of the HFR data is fully exploited in the development of operational monitoring systems at the regional level; (ii) to help to derive the added-value achieved by the European HFR network (Rubio et al., 2017; Rubio et al., 2021; Corgnati et al. 2021; Lorente et al, 2021b), such as the data management centralization and the standard data distribution, the development of new products and cross-disciplinary emerging applications, the provision of training workshops, etc.; (iii) to include the recommendations in the long-term monitoring strategy. This last point is crucial for: (i) the development and the integration of the different COOSs into a robust regional ocean observatory; (ii) ensuring that such integration is fully aligned with the European and the global roadmap; and (iii) addressing key science priorities and societal challenges of the Mediterranean coastal regions.

Although the future prospects at the regional level are shared far beyond the geographical borders of the Mediterranean Sea, recommendations have a stronger regional focus: (i) to coordinate cross-national efforts (i.e. implementation of technical, financial and management approaches at national and regional level, establishment of cross-border agreements for obtaining dedicated frequency allocation for HFR technology); (ii) to account for regional specificities (e.g. north-south unbalance in the monitoring capabilities, prominent use of medium and short range HFR frequencies, existence of ship noise and radio frequency interferences due to high marine traffic density, high restrictions for obtaining the required HFR installation licenses in coastal tourism areas, etc.) and to respond to regional needs (in terms of scientific key priorities, societal needs and existing environmental threats) and (iii) to map the existing and potential HFR data regional end-users, also facilitating the interaction with them. On the basis of the future prospects, 12 recommendations can be highlighted in the same alphabetical order as the weaknesses (items a-e) and threats (items f-h) which are intended to be covered, as well as the opportunities (items i-l) to be seized by each one of them (as in the schema of the Fig. 17).

a) **Keep promoting the HFR data interoperability and distribution at the regional level:** In order to reduce the bottlenecks that hinder the HFR data harmonization and their provision as open data, a data policy or data sharing agreement between the parties providing and receiving data should be defined and put in place. It might also partly resolve the difficulties for sharing the HFR data held by companies or controlled by arrangements with the private sector, who partially or fully funded the installations. The collaboration with international initiatives will ensure convergence and interoperability. The HFR data harmonization and sharing will ultimately contribute to provide the research community with continuous and more valuable coastal data and to underpin the development of the HFR applications.

b) **Reinforcing the Mediterranean's leadership for defining the standard models of HFR basic and added-value products.** The Mediterranean institutions are key players in the European and international HFR research effort in multidisciplinary fields and in the development of applications, as mostly covered in the Sect. 2 of this work. In addition to that, HFR experts from the Mediterranean institutions are actively contributing to the definition of the European HFR network roadmap detailed in Rubio et al., (2021), leading crucial tasks. One of these tasks aims to define the standard model and to increase the availability and accuracy of the HFR wave parameters, which are weaknesses included in Lorente et al., (2021b). Another important task focuses on seeking consensus on the methodology for the provision of the HFR added-value data products (i.e. gap-filling data). The creation of partnerships between different research groups and institutions in the context of European, regional and national projects (Lorente et al., 2021b) is contributing to move forward both the expansion of the HFR network and the main research areas, also fostering the HFR data interoperability and distribution, helping to unlock the HFR data potential, discovery and usage.

c) **Enhancing data discoverability, access and usability:** The EuroGOOS HFR Task Team has already taken the first steps towards the definition of the user engagement strategy (Rubio et al., 2021), building a database of current and potential stakeholders, with the input of some Mediterranean institutions. However, a stronger involvement is needed to avoid imbalances between countries and greater efforts are required to move it forward by means of programs that promote networking and coordination. Tight interactions with stakeholders on a fit-for-purpose basis and the enhancement of the societal impact of the HFR data are major elements of the strategy, especially, towards ensuring long-term sustainability. Boosting the regional involvement in this strategy will result in the spreading of end-user applications at the regional/local level, stimulating also the development of new ones in response to the users' feedback.

d) Strengthening public-private-partnerships: (i) at the regional level, by enhancing inter-institutional collaboration, to exchange expertise, to build consortia and for sharing job opportunities in this field. In this sense, the Mediterranean HFR network is being benefited from both, the activities carried out in the context of EuroGOOS HFR Task Team, summarized in Rubio et al., (2021), and from the ongoing regional joint projects and the existing national HFR coordination structures, as listed in Lorente et al. (2021b). It is also highly recommended the participation in annual fora led by stakeholders, like the 1st MED-FORUM that brought together the Heads of maritime services or Coast Guards of almost all Mediterranean States, aiming to develop a regional policy in the field of maritime safety and to improve the efficiency of SAR services in the Mediterranean area (Trevisanut et al., 2010); (ii) at the European level, by being aligned with ongoing initiatives and projects, contributing to the EuroGOOS HFR Task Team and the main marine data portals (e.g. Copernicus Marine Service, EMODnet, SeaDataNet), that will avoid duplication of efforts; (iii) at the Global level, by collaborating with the international institutions that are world leaders in HFR and ocean observation as well as with the Global HFR network, to ensure the consistency in the data standards and best practices; (iv) with the private sector, by transferring the knowledge and the applications from the academia to the operational oceanography industry to turn them into commercial services, improving the links between research and new technologies. The development of the existing and potential applications will also assist the HFR manufacturers in marketing their technologies.

e) Fostering the HFR data integration with other *in-situ* and satellite data: Exploiting the nature of their measurements, HFRs are currently being used for filling the gaps of other sparse or lower spatio-temporal resolution observations in coastal areas, as well as for improving and assessing satellite observations. In this context, it should be considered the opportunity that the launch of the wide-swath Surface Water & Ocean Topography (SWOT) altimeter expected for November of 2022 will offer. SWOT altimeter should be complemented with other remote and *in-situ* sensors to fully resolve the typical Mediterranean mesoscale structures of 10-100 km (Gómez-Navarro et al., 2018). Additional complementarities might be fostered with the monitoring of surface current worldwide using the information from the Automatic Identification System -AIS- data streams (Benaïchoucheet al., 2021), where HFR measurements can be used as a consistent ground-truth dataset for validation purposes and for increasing the spatial resolution of the AIS-reconstructed fields at coastal areas. The integration of HFR measurements with other multi-platform observations from gliders or ADCPs (Manso-Narvarte et al., 2020) have already been implemented and tested, particularly under the umbrella of the JERICO-NEXT project (Griffa et al., 2019). This multi-platform combination underpins sound understanding of the three-dimensional coastal circulation, allowing the broadening of the HFR applications (i.e. below the surface). Data fusion and integration will contribute to increasing the societal and scientific value of all observations, not only the HFR ones.

f) Boosting the HFR data assimilation for model improvement**:** As shown in the Sect. 2.1.2 of the present work, HFR surface current data assimilation have demonstrated to improve the model performance in many studies (Paduan and Shulman, 2004; Barth et al., 2008; Hernández-Lasheras et al., 2021). Furthermore, the HFR standard data distribution in near real-time throughout the main European marine data portals, facilitating the data access and ensuring the timeliness, make them an ideal dataset for efficient data assimilation in operational modelling (Capet et al., 2020). However, WMOP is the only regional model from the Mediterranean, which is systematically assimilating HFR data in its operational chain (Hernández-Lasheras et al., 2021). As highlighted by Capet et al., (2020), the lack of expertise, training and capacity building is limiting the uptake of assimilation practices.

g) Expansion of the pool of expertise by including not only HFR technology, but data management and applications, satellite remote sensing, ocean modelling, data assimilation, training aspects, and exchanging and sharing knowledge, tools, data, know-how between diverse research groups at the European, regional and global levels.

h) Training of the new generations of HFR technicians and scientists are needed to ensure the knowledge exchange, the sufficient expertise to allow for a significant expansion of the coverage and the sustainability of the operations and the HFR applications. This is currently being done in the context of periodic workshops and summer schools (such as the recent ISSOR and SICOMAR plus summer schools, etc.) within the academia context. Moreover, the development of best practices for demonstrations are not only key to reach satisfactory quality standards but also for fostering the learning process. However, additional technical training courses provided by the manufacturers at the HFR operator level are recommended. Furthermore, the participation of Mediterranean institutions and companies in the creation of an international, intersectoral and interdisciplinary qualified supporting training network will contribute to boost knowledge and know-how exchanges, involving all actors (e.g. academia, operators, manufacturers, private sector, etc.).

In addition to all above-mentioned recommendations, the seeking for funding is a compulsory task aiming to support, together with the stakeholder's engagement and the training of the new generations, the long-term sustainability of the HFR network, their data and applications at national, regional and European levels. To this end, EuroGOOS HFR Task Team has taken early steps to prepare a competence matrix that will facilitate the building of effective, interdisciplinary, intersectoral and well-balanced consortia, grounded in shared research interests and goals, aiming to prepare competitive bids and applications for funding, taking advantage of the expertise of the team in diverse grant calls (Rubio et al., 2021). In addition to the research/grant funding, long-term infrastructure funding at national, regional and European government level with financial input from other operational users through regional consortia will be needed towards a truly sustainable infrastructure. For further details about the diverse socioeconomic and technical challenges to be tackled during the implementation of a sustained and integrated HFR regional network, the reader is referred to the Sect. 5.1 of the companion publication from Lorente et al., (2021b).

The Mediterranean HFR network must also take advantage of the opportunities the arise in the framework of the UN Decade of Ocean Science for Sustainable Development and the European Green Deal to lead the way towards the future prospects. Four recommendations are given to benefit from the opportunities, as included in the SWOT analysis (Fig. 17, bottom-left panel) are as follows:

i) Expansion of the Mediterranean HFR network: although this network is already representing the 55% of the HFR sites existing in the European inventory (Lorente et al., 2021b), and despite the very recent installations (i.e. in Port of Licata, Portofino and Celle Ligure -Italy-, in Port of Menton and Mimizan -France- and in Ta' Cenc in Gozo -Malta), and several new deployments in an initial planning stage (i.e. in Haifa Bay -Israel-, Sardinia and Sicily islands, Gulf of Genoa and Gulf of Naples, Tuscany Archipelago -Italy-, Gulf of Trieste -Slovenia- and in the Aegean -Greece-), the Mediterranean coastal areas are still under-sampled. In this regard, it should be noted that the spatio-temporal scales currently provided by the HFRs in the Mediterranean allow us to monitor the current environmental threats adequately, but always in limited coastal areas, thus reducing the potential of the larger scale applications (e.g. transport of organic matter and pollutants, connectivity studies, data assimilation into models, etc.). Therefore, aiming to improve the strategy of the ocean observatories to respond to regional needs for a better understanding of region-specific processes towards a fit-for-purpose design, an increased monitoring effort by expanding and improving the HFR network is required, allowing for a covering of a large geographical area on a routine basis. Accordingly, a review of major scientific and social questions is needed including the environmental stressors and their impacts in the Mediterranean waters and blue economy sectors, identifying the benefit of the new deployments, in coordination with the current monitoring actions (e.g. to identify gaps for monitoring these risks, ensuring cost-effectiveness of observations, etc.). To this end, the cross-border coordination activities are key for the involvement of other countries bordering the Mediterranean Sea in the eastern and southern coastlines and to address issues related to frequency sharing for avoiding interferences, as highlighted in Lorente et al., (2021b).

j) Further development of emerging HFR applications in the Mediterranean. The extension of the HFR surface current to fit for multiple purposes, aiming to address from single to multiple environmental threats, scientific questions and societal needs, requires a multidisciplinary integrative approach and coordinated monitoring of different essential ocean variables. In this context, it is worth mentioning that the HFRs multi-parameter monitoring of the sea state allows the development of diverse applications to tackle a wide range of coastal threats: (i) to monitor eutrophication in high-productive coastal waters, combining HFR surface currents with thermistor chains, oxygen and turbidity sensors at various depth increments, and to address physical-biological interactions in coastal basins (Cianelli et al., 2017; Hernández-Carrasco et al., 2018a); (ii) to monitor the transport of floating marine litter and other contaminants using surface current fields from HFRs and models (Declerck et al., 2019); (iii) for ship-tracking (Dzvonkovskaya et al., 2007; Laws et al., 2016); (iv) for early tsunami/meteotsunami detection (Lipa et al. 2006; Monserrat et al., 2006; Guèrin et al., 2008 ; Lipa et al. 2011 & 2012; Gurgel et al. 2011, Dzvonkovskaya et al. 2012); (v) for freshwater monitoring (Meadows et al., 2013); (vi) for extracting new information from the HFR signals aiming to advance the understanding of key processes at the coastal areas, such as stratification (Shrira and Forget, 2015), air-sea interaction (Berta et al., 2018) and mixing in the upper ocean, near-surface current shear, etc.; (vii) for promoting the HFR use for supporting marine renewable energy resource assessment (i.e. winds, currents, waves) in the coastal zone (Wyatt, 2012, 2021; Basáñez and Pérez-Nuñunzuri, 2021; Mundaca-Moraga et al., 2021), etc. Additionally, since the intensity of the multiple stressors (e.g. climate change effects, habitat loss and degradation, eutrophication, introduction of alien species, fishing practices) is increasing throughout most of the Mediterranean basin, trend analysis is an essential process in assessing the state of the ocean of a region. This will contribute to effectively informing current and future marine policies and management actions as well as to underpin longer-term scientific objectives.

k) Extension of the Mediterranean HFR time series that would enable the widespread implementation of novel data science methodologies. It is expected that the HFR measurements will be expanded in the next decade, both in space (i.e. new HFR systems) and time (i.e. longer time series). This will increase the availability of multi-year surface current datasets, thus contributing to boost the application of the HFR derived STPs that uses self-learning algorithms to other Mediterranean locations. For such sites, the stability of SOM-solutions in time may be tested as well, or the self-learning and training of SOM solutions might change in time to properly reflect long-term changes in oceanographic conditions in a coastal area. The further development of short-term predictive systems based upon HFR surface current fields and their adaptation to the Mediterranean HFR network by incorporating non-tidal component of current will enhance the STPs' integration into operational maritime safety applications, where it has been demonstrated their capacity to reduce the searching area (Roarty et al., 2010).

l) Regional contribution to long-term major effort towards building a sustained and fit-for-purpose European Ocean Observing System capable to support the UN Decade of Ocean Science for Sustainable Development and the European Green Deal should be two-fold: (i) On the one hand, the Mediterranean HFR network outcomes should be scientifically grounded to further ensure the extension of the science-based added-value products into societal relevant downstream services (Tintoré et al., 2019) and, (ii) on the other hand, the Mediterranean HFR community's long-standing cooperation must be further strengthened towards a co-designed and sustained regional network, contributing to and, simultaneously, benefited by the European HFR Task Team (Corgnati et al., 2021, Rubio et al., 2021) endorsement, roadmap and main achievements (as recommended by Lorente et al., 2021b).

5 Summary and conclusions

The socio-economically vital and environmentally stressed coastal areas of the Mediterranean Sea are some of the most exposed regions in the world due to the impact of climate change, being also highly vulnerable target regions for maritime safety, oil and marine litter pollution, fish stocks overexploitation and met-ocean hazards. The high spatio-temporal variability of the coastal dynamics requires the monitoring of these (sub)mesoscale processes at the right scale. HFRs are nowadays the only technology for continuously monitoring surface currents (increasingly waves and winds) at unprecedented high spatio-temporal resolution over coastal areas and with relatively low cost-effort, when compared with other traditional ocean observing platforms. Their integration in ocean observing has boosted the progress in the research of small-scale features and their interaction with larger scales, also underpinning the further development of applications. In this work, we present a review of the existing mature and emerging scientific and societal applications using HFR data, developed to address the major challenges identified in the Mediterranean coastal waters, organized around three main topics: (i) maritime safety; (ii) extreme hazards and (iii) environmental transport processes. In addition to previous studies carried out at global and at the European scale on this topic, this work also provides a list of strengths, weaknesses, opportunities and threats of the existing HFR applications in the Mediterranean Sea. Finally, we discuss the prospects for the future of the HFR applications and we provide a set of recommendations aiming to maximize the contribution in extending the science-based HFR products into societal relevant downstream services (Tintoré et al., 2019) to support the blue growth in the Mediterranean coastal areas, helping to meet the UN's Decade of Ocean Science for Sustainable Development and EU's Green Deal goals.

Considering the steadily growing integration of HFRs in the COOSs of the Mediterranean Sea and once their capabilities as an active and expanding field of investigation has been demonstrated by a wide range of practical applications, we can conclude that this consolidated land-based remote sensing technology plays a key role in the development of fit-for-purpose services for marine and maritime end-users. However, still major efforts should be done for unlocking the HFR interoperable data access and potential as well as for the further development of HFR scientific and societal applications at the regional level, thus, delivering greater uptake, use and value. Fortunately, the opportunities provided in the framework of the UN Decade of Ocean Science for Sustainable Development and the European Green Deal can help to ensure the full exploitation of this HFR potential that will contribute to further deepen our understanding of coastal ocean dynamics and support the sustainable blue growth in the Mediterranean Sea. In this sense, the collaboration at regional level is crucial to address region-specific processes towards a fit-for-purpose and coordinated design of the monitoring actions, to identify the environmental threats and their impacts in the environment and in the blue sectors, to easily identify the existing stakeholders, also fostering the interaction with them and to engage the potential users. This will help improve the long-term sustainability together with the training activities to the next generations and the seeking for funding. Certainly, this regional approach to strengthen collaborations should always be aligned with the global and European strategies to ensure the integration, benefiting from the European HFR roadmap and the availability of near real-time and long-term HFR interoperable data that will boost the research and to underpin the further development of the HFR scientific and societal applications in the Mediterranean coastal areas.

This manuscript constitutes the second part of a double contribution. Both parts support each other in an integrative way and should be interpreted as a single entity. The first part from Lorente et al., (2021b) provides a comprehensive overview on the current status, achievements, challenges, coordinated efforts and the roadmap to transform individual HFR systems into a fully integrated HFR network in the Mediterranean. Additionally, this work shows how these joint efforts have benefited and boosted the HFR data integration into services and the development of a broad range of multidisciplinary science-based and fit-for-purpose applications, contributing to leverage the HFR data to its fullest potential.

Author Contributions

ER and PL conceived the idea of this manuscript and fostered the collaboration as MONGOOS HFR Task Team co-chairs, being in charge of overall direction and planning. All authors contributed to the writing of the different sections of the manuscript, as follows:

ER took the lead in writing the abstract, and Sect. 1, 3, 4 and 5, contributing also to Sect. 2.1. Other authors contributed in the edition of Sect. 1 (CAG, DD, MB, SS) and Sect. 4 (YT, MB, RG). MB also contributed to the summary of HFR capabilities in Sect. 3 and Sect. 5.

CRS, VC, ML, HM, AD, AG, AM, AR and ER (designed the Fig. 1) collected the information from the Maritime Safety and Rescue Agencies for their respective countries.

CRS and ML (designed the Fig. 3) contributed to the introduction of the Sect. 2.1 and, together with VC, AR (designed the Fig. 2), JT and ER they shaped the Sect. 2.1.1.

PL (designed the Fig. 4), BM, JHL (designed the Fig. 5), EA, and ER wrote the Sect. 2.1.2.

IHC, AO, HM (designed Fig. 6), IV, VD took the lead in writing the Sect. 2.1.3.

MB (designed Fig. 7), AG, LC, CM contributed to the data analysis and text drafting in Sect. 2.2.1, in particular for the case study in the Ligurian Sea. In this section, PL (designed Fig. 8) and ER addressed two cases studies in the Delta Ebro and one in the Strait of Gibraltar.

CAG took the lead in writing the Sect. 2.2.2, where BM, ML and MJF also contributed.

AM, ACE, IHC (designed Fig.10 and Fig.11), AO contributed to the writing of the Sect. 2.3.1.

MBen - Consorzio LaMMA - (designed the Fig. 12 and Fig. 13), CB, ST, BD, MU, MF, PF, EZ, HM, IV wrote the Sect. 2.3.2.

MM, DC (designed the Fig. 14), RS (designed the Fig. 15), FC (designed the Fig. 16), CG, MB, AG, IHC, AO contributed to the Sect. 2.3.3. Particularly, RS and MM focused in the Gulf of Manfredonia; DC in the Gulf of Naples and FC in the Malta-Sicily case studies.

AM, IV, CAG, JT and the MONGOOS co-chairs, VC and AO provided critical feedback and helped shape the final version of the manuscript during the internal review process.

All authors have read and agreed to the submission of the manuscript for publication.

Acknowledgements

This work has been possible thanks to MONGOOS (Mediterranean Operational Network for the Global Ocean Observing System) collaborative network, aimed toward long-term synergies between multi-disciplinary working groups in the Mediterranean Sea in order to launch strategic initiatives and pursue funding for innovative research projects.

This work was supported by the EuroSea (EU Horizon 2020 research and innovation programme, grant agreement ID 862626). We also thank the partial support of the project CMEMS-INSTAC phase II, which provides the context of the activities for HFR data harmonization, standardization and distribution, and to the IBISAR CMEMS User-Uptake project (67-UU-DO-CMEMS-DEM4_LOT7). Eva Aguiar and Baptiste Mourre are also very grateful for the MEDCLIC project (LCF/PR/PR14/11090002) supported by La Caixa Foundation, contributing to the development of the WMOP model. The methodology for the extreme events monitoring in the Ligurian Sea (Sect. 2.2.1) has been developed under the framework of the CARTHE III project (Prime Award n. SA 18-14, subcontract agreement SPC-000649) and the CALYPSO Departmental

Research Initiative (Grant number N00014-18-1-2782). The HFR network in the Ligurian Sea has been supported by the IMPACT project (EU funded, PC Interreg VA IFM 2014-2020, Prot. ISMAR n. 0002269). Investigation of Mediterranean Sea dynamics and applications of HFR observations are also supported by the JERICO-S3 project (EU Horizon 2020 research and innovation programme, grant agreement no. 871153). The assimilation of HFR data in WMOP (Sect. 2.1.2) and the biological connectivity application in the Gulf of Manfredonia (Sect. 2.3.3) have been developed under the JERICO-NEXT project (EU Horizon 2020, grant agreement no. 654410). In the latter case, the COCONET project (EU FP7, grant agreement no. 287844) and the Italian national projects SSD-PESCA and RITMARE should also be acknowledged. Recent upgrades in the radar installations of the MIO in Toulon were supported by the SICOMAR-PLUS EU Interreg Marittimo project.

Pier Falco and Enrico Zambianchi acknowledge partial funding from the Italian Ministry for University and Research through the “Exploring the fate of Mediterranean microplastics: from distribution pathways to biological effects” (EMME) PRIN Project.

We are furthermore grateful for the valuable information about the Maritime Rescue activity for 2019 provided by the Spanish Maritime Search and Rescue Agency, the Italian Coast Guard, the French CROSSMED, the Ministry of Maritime Affairs, Transport and Infrastructure from Croatia, and the Search and Rescue Coordination Centers from the SRR (Search and Rescue Regions) of Slovenia and Malta. We also acknowledge the Spanish Meteorological Agency AEMET for providing HARMONIE atmospheric fields. The authors would like to thank Stephan Grilli, from the University of Rhode Island (USA) for the design of Fig. 9 (from Sect. 2.2.2) and to Leonardo Bagaglini for processing the data shown in Fig.12 (from Sect. 2.3.2). Finally, authors would like to express their gratitude to the internal reviewers, Anne Molcard, Ivica Vilibić, Charles-Antoine Guèrin and Joaquín Tintoré and to the MONGOOS co-chairs, Vanessa Cardin and Alejandro Orfila, for their careful and meticulous reading of the manuscript. Their detailed and comprehensive reviews have been very helpful to improve the structure, the reading and to finalize the manuscript.

Code availability

Corgnati, L. (2019, December 10). LorenzoCorgnati/HFR_Node__Historical_Data_Processing: EU_HFR_NODE_Historical_Data_Processing (Version v2.1.1.6). Zenodo. http://doi.org/10.5281/zenodo.3569519

Corgnati, L. (2020, May 26). LorenzoCorgnati/HFR_Node_tools: EU_HFR_NODE_Tools (Version v2.1.2). Zenodo. http://doi.org/10.5281/zenodo.3855461

Data availability

IMO data, mentioned in Sect. 1, is available in the Flow Monitoring Displacement Tracking Matrix website: https://migration.iom.int/europe?type=arrivals

Eurostat statistics for Maritime transport of goods, mentioned in the Introduction, are available in: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Maritime_transport_of_goods_-_quarterly_data&oldid=485429#EU_ports:_activity

The "Sub-regional Mediterranean Sea Indicators" tool, mentioned in the Sect. 1, is available in the website: https://apps.socib.es/subregmed-indicators/

The SAR incidences in France, included in Sect. 2.1.1, were obtained from the website of the French Ministry of the Sea: https://www.mer.gouv.fr/surveillance-et-sauvetage-en-mer

SOCIB HFR-Ibiza data, used in Sect. 2.1.1 (Fig. 2), Sect. 2.1.2 (Fig.5), Sect. 2.3.1. (Fig. 10 and Fig. 11), are available in the https://doi.org/10.25704/17gs-2b59.

SOCIB drifter's data, used in Sect. 2.1.1., are available in https://doi.org/10.25704/mhbg-q265 for 2014 (they have also been used in Sect. 2.1.2, Fig. 5), https://doi.org/10.25704/bb7m-zv61 for 2016 and https://doi.org/10.25704/84ze-sf42 for 2018.

SOCIB's WMOP simulations are available upon request to info@socib.es

Standardized HFR data is available in the Thredds Server from the European HFR Node for some of the HFR systems mentioned in this research (http://150.145.136.27:8080/thredds/HF_RADAR/HFradar_CMEMS_INSTAC_catalog.html)

MIO's HFR-Toulon data is available http://hfradar.univ-tln.fr/HFRADAR/squel.php?content=accueil and real-time total currents (hourly data) in standard format are available for 2020 and 2021 in https://erddap.osupytheas.fr/erddap/files/cmems_nc_cf0e_c84a_8ead/

HFR-LaMMA data, used in Sect. 2.3.2, can be viewed in http://www.lamma.rete.toscana.it/meteo/osservazioni-e-dati/radar-hf.

HFR data for the Northern Adriatic, used in Sect. 2.1.3 (Fig. 6), can be viewed in http://jadran.izor.hr/hazadr/geoserver_en2.html

HFR-NAdr data, used in Sect. 2.1.1. (Fig. 3), can be viewed in http://www.nib.si/mbp/en/oceanographic-data-and-measurements/other-oceanographic-data/hf-radar-2

Competing interests

Authors MF, RG and PL are currently employed at Qualitas Instruments Lda, at HELZEL Messtechnik GmBH and at NOLOGIN Consulting SL, respectively. However, authors have not advertised commercial products and the research has not been sponsored by any one of the companies.

AO and VC are guest members of the editorial board of the Special Issue from the Journal. The peer-review process was guided and overseen by another member of the editorial board.

The remaining authors declare that there are no relevant financial or non-financial competing interests to report.

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