CMEMS Service Evolution 21-SE-CALL1

Guidelines towards increasing HFR data assimilation capacities into CMEMS (D2.1)

July 26th, 2017

PURPOSE

This document is the deliverable D.2.1 from INCREASE WP2. The main goal of this deliverable is to provide the basic aspects on HF radar data characteristics that can help the strategy of future DA experiments and evaluate the potential of future developments of HF radar products tailored for DA purposes. This document has been produced mainly under the perspective of HF radar and coastal ocean specialists following the discussions with several data assimilation experts.

APPLIES TO

HF radar surface current data. CODAR and WERA HF radar systems and data from the EU standard in definition within the framework of JERICO-Next and INCREASE projects.

DEFINITIONS

APM: Antenna Patterns Measurement
CMEMS: Copernicus Marine Environment Monitoring Service
CODAR: Coastal Ocean Dynamics Application Radar
DA: Data Assimilation
GDOP: Geometric Dilution Of Precision
HFR: High Frequency Radar
JERICO-NEXT: Joint European Research Infrastructure network for Coastal Observatory – Novel European eXpertise for coastal observaTories
MFC: Monitoring and Forecasting Centres
NRT: Near Real Time
QA/QC: Quality Assessment/Quality Control [1]
QUID: Quality Information Document (contains detailed validation results for each CMEMS product)
SNR: Signal to Noise Ratios
WERA: WavE Radar

---

[1] As in INCREASE D3.1 we define Quality Assessment as the process to ensure the measurements are taking place in the best available conditions, monitoring the state of the system and all the parameters that can affect the quality of the measurements time by time and trying to optimize them. QA involves processes that are mostly employed with hardware. Quality Control is the process that ensures the automated or not delivery of high quality data in real or delayed time.

Index

1 Contributing Experts

Anna Rubio (AZTI, INCREASE TEAM)
Annalisa Griffa (CNR-ISMAR, EuroGOOS HFR Task Team)
Julien Mader (AZTI, INCREASE TEAM)
Lorenzo Corgnati (CNR-ISMAR, EuroGOOS HFR Task Team)
Antonio Novellino (ETT, INCREASE TEAM)
Carlo Mantovani (CNR-ISMAR, EuroGOOS HFR Task Team)

In addition, the following experts reviewed and contributed to the contents of this deliverable:

Eric Jansen and **Stefania A. Ciliberti** (Fondazione CMCC - Centro Euro-Mediterraneo sui Cambiamenti Climatici, Lecce, Italia)
Baptiste Mourre, Jaime Hernández, Paz Rotllán and **Emma Reyes** (SOCIB, Palma de Mallorca, Spain)
Marina Tonani and **Christine Pequignet** (Met Office, Exeter, United Kingdom)
Vicente Fernández (EuroGOOS, Bruxelles, Belgium)

2 Context

Around 400 High Frequency Radars (HFRs) are installed worldwide and are being used in a diverse range of applications (Paduan and Washburn, 2013; Roarty et al., 2016). In Europe, the number of systems is growing with over 50 HFRs currently deployed and a number in the planning stage (Rubio et al., 2017). HFR have proved potential for monitoring (e.g. Berta et al 2014, Molcard et al, 2009) and for providing short-term prediction of coastal currents (e.g. Orfila et al., 2015; Solabarrieta et al. 2016). Moreover, HFR current data have been used as inputs for data assimilation (DA) and the validation and calibration of numerical ocean forecasting models, especially near the coast (e.g. Marmain et al, 2014; Barth et al. 2008, 2011; Iermano et al., 2016; Stanev et al. 2015, Breivik and Saetra 2001, Sperrevik et al. 2015; to mention only a few examples of recent works in Europe). In parallel, several efforts have also focused on the assimilation of HFR-derived wave data, which have not been as extensively explored since they are much more sensitive to the noise of the Doppler spectrum than current estimations (e.g. Siddons et al., 2009, Waters et al., 2013).

In Europe, 72 % of the data systems have been used in past DA exercises or are planned to be used future experiments. However, only a 26% of the HFR operators state that their data are currently being assimilated in operational models (Mader et al., 2016). This is not surprising since the real-time assimilation of HFR surface current data in operational models is not straightforward.

Despite the methodological and computational difficulties which have still to be solved, HFR data are expected to become a systematic input to oceanographic operational models in the forthcoming years. Indeed, the effort on the integration of European HFR data into operational modelling systems is growing. An example of this is the work being done in the JERICO-NEXT project (WP3 and WP4), where various DA technologies in various coastal regions are used to develop advanced infrastructures by performing observing system experiments (OSEs) and observing system simulation experiments (OSSEs). These exercises include in some of the study areas data form HFRs, both for model assessment and data assimilation.

It is foreseen that, in the upcoming years, the numerical modeling system for European seas implemented as part of CMEMS will, at least in some regions, provide spatial resolutions, which are comparable to HFR observations. HFR data could then provide routine data used for the validation of numerical forecasts of the ocean, and to be assimilated together with other observations in the models. Indeed, the combined assimilation of these data with satellite altimetry and multi-platform observations, could be expected to improve both the representation of small-scale features and the understanding of the impact of coastal processes on larger scales.

In this context, the main objective of these guidelines is to define, from the HFR operators' perspective, and in collaboration with modellers working in data assimilation, the basic requirements on the HFR data characteristics that can help the strategy of future DA experiments. The goal of this effort is also to ease the development of CMEMS capacity to assimilate HFR data and to set the basis to jointly define advanced data products adapted to this task.

Under this perspective, an important step for the HFR data assimilation in models starts by a detailed understanding of HFR measurement errors (amplitude as well as time and space structure). Characterizing observational errors is not a trivial issue, as measurement uncertainties are linked to the ocean and atmospheric conditions (e.g. extreme winds event, highly perturbed sea state). HFR systems also have their own limitations on the observations of ocean processes, as for instance, the limited vertical extent of HFR current patterns, which depends on the transmitted central frequency (Stewart and Joy, 1974).

Then, HFR data can also be used to fulfil an additional prerequisite to data assimilation, which is to test and validate simulations in the study area. The careful validation of the simulations with respect to the different ocean processes is a necessary starting point towards successful numerical data-assimilating model configurations. A complex issue to address is related to the physical content of the simulations and the observations to assimilate. For instance, tides, inertial waves, as well as, processes related to surface waves may not be fully represented in the model, while their signature in currents impacts significantly the HFR data.

The present document deals only with surface current data although, as already mentioned, there is a growing potential on the use of wave HFR data for data assimilation. Concerning currents, several authors recommend the direct assimilation of radial velocities, instead of using totals (e.g. Vandenbulcke et al. 2017). However, since the past EU radar survey showed that no preferences for one level of current data (radials vs. totals) are shown by the operators involved in DA, these guidelines will be focused on both radial and total current HFR data.

3 HFR observation capabilities and limitations

The description of the operation of radars is provided in INCREASE D1.1 (see also review papers from Paduan and Washburn, 2013 or Rubio et al., 2017). Also, INCREASE D3.1 provides a detailed study on current Quality Assessment (QA) and Quality Control (QC) procedures, and provides basic recommendations for the correct application of the QC tests identified by the HFR community to be necessary for ensuring the good quality of real-time data. Since these documents already detail HFR observation capabilities and limitations, only the main concepts of interest for the DA community are reported here.

3.1 Spatial and temporal resolution

The main potential of HFR resides in the fact that these systems can offer continuous and high temporal and spatial resolution synoptic current maps over wide coastal areas, not available from any other observational technology (Paduan and Washburn, 2013).

Coverage area and spatial resolution depend respectively on HFR operating frequency and available bandwidth (which is limited by international and national regulations and most of the time is connected with the HFR operating frequency, see table 1). Coverage and resolution of the total map are also affected by the geometry of the radar network along the coast (Heron and Atwater, 2013).

Common values for a system of two HFRs operating at 13MHz are: coverage of 70 km x 70 km; range resolution of 1-3 km; angle resolution of 5º.

Table 1: Typical values for HFR data spatial and temporal resolution vs. operating frequency. Adapted from Rubio et al. 2017.

	Operating frequency (MHz)	***Integration depth for currents (cm)***	***Minimum acquisition time (minutes)***	***Range resolution (km)***	***Maximum range (km)***
Long Range	4.438-4.488	420	35	12	220
	5.250-5.275	356	30	12	175
	9.305	201	16	12	80
Medium range	9.355	201	16	12	80
	13.450-13.550	139	11	3	60
	16.100-16.200	116	9	3	60
	16.200	116	9	3	60
	24.450	76	6	1	30
High Resolution	24.600	76	6	1	30
	26.200-26.350	71	6	1	30
	39.000-39.500	48	4	300 m	20
	42.000-42.500	44	4	250 m	15

During normal operation, spatial and temporal data gaps may occur at the outer edge, as well as inside the measurement domain. This can be due to several environmental and electromagnetic causes: the lack of Bragg scattering ocean waves or severe ocean wave conditions, low salinity environments, the occurrence of radio interference. The application of advanced interpolation methods to obtain gap-free data is required.

3.2 Vertical extension of the information

HFRs provide current data only relative to the surface within an integration depth ranging from tens of cms to 1-2 m, depending on the operating frequency (see typical values in Table 1)

Several authors have developed methodologies to calculate the depth of the mixed layer depth (e.g. Zervakis et al., 2016) or the stratification strength (e.g. Shrira and Forget, 2015) directly from HFR data (or in combination with observed winds). These approaches can provide valuable information for the validation of model stratification and vertical covariance functions with the consequent potential improvement of the projection of the surface information downward in the models.

3.3 Observability of ocean processes

Ocean dynamics of the coastal and shelf-break zones are characterized by a large variety of processes (current instabilities, wind driven response, coastal jets and eddies) acting simultaneously over a broad spectrum of scales. HFR data series offer the opportunity to isolate and characterize these processes, critical to forecast the physical/biological coupling in the coastal zone.

The typical spatial scales resolved by the HFRs depend mainly on the resolution of the data, and thus mainly on the frequency of operation of the systems (Table 1). In addition to the observation of large and mesoscale processes, HFR can also observe small scale eddies O(10-20 km) (e.g. Sentchev et al. 2013) and, using very high frequency radars, of O(2-3 km) vortices over the shelf in different areas (e.g. Kirincich, 2016) which are difficult to observe in NRT using other monitoring systems. Also, tidal and inertial processes are well resolved by HFR.

At all these scales (and depending on the length of the data series) HFRs can provide maps with spatio-temporal patterns that can be very useful for the model validation. The assimilation of tidally resolving surface currents by means of time-evolving variational approaches has given remarkable results in some study areas (Paduan and Washburn, 2013). Recently, Vandenbulcke et al. (2017) have shown how HFR observations are able to correct the phase of modelled inertial oscillations and lead to a skill score of about 30 % for the forecasts of surface velocity.

3.4 MFCs and EU HFRs overlap

The performed inventory of the operational HFR systems in Europe (Mader et al., 2016; see also INCREASE D1.1 at: http://www.cmems-increase.eu/static/INCREASE_Report_D1.1.pdf) includes 51 HFR stations (distributed in 20 networks) with potential impact in CMEMS. These systems have the potential to benefit different MFCs where data could be used for quality assessment (QUID, real-time indicators) or through data assimilation. The MFC meshes overlap so one HFR station could impact different MFC areas. The potential impact of the currently available data in the INCREASE catalogue is shown in table 2.

Table 2: Number of HFR networks and systems available in three of the CMEMs MFC-meshes (based on the European HFR systems inventory (Mader et al, 2016[2]).

MFC mesh	*Number of ongoing HFR networks (systems)*
MED-MFC	13 (32)
IBI-MFC	9(29)
NWS-MFC	9(20)

These numbers will grow at a mid/long term scale, because countries like Portugal, France or UK are establishing plans for developing their networks. Moreover, the HFR data could allow a fundamental assessment in the buffer zone between CMEMS regional models and downstream coastal modelling tools. The products based on the real-time 2D monitoring of shelf/slope surface circulation will deliver key information for assessing the boundary conditions applied in the coastal models of intermediate users. The most part of MED-MFC HFR systems are typically operating at frequencies between 13 and 27 MHz, while in IBI-MFC and NWS-MFC there are several HFR systems operating at frequencies under 13 MHz.

The number of systems worldwide is much larger and the data are being collected by the Global High Frequency Radar Network (http://global-hfradar.org/). Established at the GEO-VIII Plenary in Istanbul, Turkey, the Global High Frequency Radar Network is a vision for a global operational system measuring ocean surface currents to support monitoring of marine and coastal ecosystems. EMODNET-physics has already started to integrate the HFR systems available in the global network to those available in Europe, with a total of 142 systems connected and accessible in the world (http://www.emodnet-physics.eu/map/).

4 HFR current data uncertainties

As described by Lipa (2013), if we assume that the radar hardware is operating correctly, we can identify different sources of uncertainty in the radial velocities:

RE1- Variations of the radial current component within the radar scattering patch

RE2- Variations of the current velocity field over the duration of the radar measurement

RE3- Errors/simplifications in the analysis (e.g. incorrect antenna patterns or errors in empirical first order line determination)

RE4- Statistical noise in the radar spectral data, which can originate from power-line disturbances, radio frequency interferences, ionosphere clutter, ship echoes, power-line disturbances, or other environmental noise (Kohut and Glenn, 2003).

In addition to the errors in radial data, two main additional sources of inaccuracies are produced in the radial-to-vector mapping:

TE1 - The Geometric Dilution Of Precision – GDOP (Chapman et al., 1997), related to the angle between radial velocities used to compute the total velocities, is at the origin of systematic low reliability of velocity vectors at the edge of the observed domain, as well as along the baseline connecting receiving antennas.

TE2 - The accuracy of the total velocities also depends on the number of radial velocities from each radar site involved in the combination process, known as Geometrical Dilution of Statistical Accuracy (Barrick, 2002).

Because of these errors, and since radial velocities offer a more extended spatial coverage and range, there is a rising tendency to assimilate directly the radial currents, as several authors recommend (Barth et al. 2008; Paduan and Washburn 2013; Marmain et al. 2014; Vandenbulcke et al. 2017).

4.1 Variables that can be used for the assessment of HFR uncertainties

The assessment of HFR uncertainties is a considerable challenge, intrinsically related to the complex nature of the measurements. In a practical way, the most part of the sources of inaccuracy described in the previous section can be inferred from the information provided by native radial or total radar files. This information is contained under supplementary variables whose names and characteristics depend on the different operating systems.

Under the perspective of offering DA experts a useful guide for finding the suited variables in the HFR files, Table 3 provides a quick view of which are the variables that can be used to quantify each of the uncertainties described above (R1-4 for radial data and TE1-2 for total data). The table has been elaborated for the three most extended radar data format files in Europe: WERA native files, CODAR native files and the European common data and metadata model for real-time HFR data (as defined in Corgnati et al., 2017).

For a more detailed description of these variables the reader is referred to the provider's documentation and the INCREASE D3.1 deliverable.

Table 3. Names of variables that can be used to quantify each of the uncertainties described in the previous section (R1-4 for radial files and TE1-2 for total files) for the three most extended radar data format files in Europe. In CODAR systems: STDV and SCDV are a radial or elliptical standard deviation of current velocity over coverage period and the scatter patch, respectively. SSN1, SSN2 and SSN3 are the Cross Spectra Signal to Noise of loop 1, loop 2 and monopole antennas, respectively. CQAL is the current vector covariance. S1CN, S2CN… SnCN are the number of radial/elliptical vectors from site n, which contributed to the total vector. In WERA systems: EVAR is a radial variance of current velocity over coverage period and EACC is a radial accuracy of current velocity over coverage period. In the EU standard (Corgnati et al. 2017) the definition for ESPC and ETMP correspond to that of STDV and SCDV.

	CODAR NATIVE FILES	**WERA NATIVE FILES**	**EU STANDARD**
RE1	SCDV(outdated use ESPC)	NA*	ESPC
RE2	STDV (outdated use ETMP)	EVAR, EACC	ETMP
RE4	SSN1, SSN2, SSN3 in tables in radial files footers	NA*	NA*
TE1	CQAL	File GDOP.dat	GDOP
TE2	S1CN, S2CN,… SnCN, being n the total number of contributing sites	NA*	NA*

*NA = not available or not applicable.

RE3 errors are difficult to detect, one of the methods to test the correctness of the Antenna Patterns Measurements (APM) for CODAR systems is to compare the corresponding velocity component from the two antennas in the baseline (the area where the radial vectors from the two sites make an angle of less than 30°). Low correlation between radial data in this area could be used to evaluate additional uncertainties.

4.2 Real-time quality control of HFR data uncertainties

Most of the variables in Table 3 are used for real-time self-contained QC of radar data, through the definition of the suited thresholds. Previous works have focused on defining optimum threshold levels in the quality control test to identify and eventually replace occasional non-realistic radar current vectors but there is still no worldwide consensus. Current initiatives intend to use also non-velocity-based metrics related to the characteristics of the received signal (radial and total coverage analysis, hardware status, quality of the received signal) to implement advanced quality controls (Kirincich et al., 2012). A thorough discussion on the caveats and recommendations for choosing the correct thresholds was presented in INCREASE D3.1 (http://www.cmems-increase.eu/static/INCREASE_Report_D3.1.pdf) and the reader is referred to this document for more information.

In addition, a number of validation exercises have been performed based on comparisons of HFR currents against independent in situ or remote measurements (Ohlmann et al., 2007; Cosoli et al., 2010; Solabarrieta et al., 2016; Kalampokis et al., 2016, Chavanne and Klein, 2010). These validation exercises are limited by the fact that part of the discrepancies observed through these comparisons are due to the specificities and own inaccuracies of the different measuring systems (Kalampokis et al., 2016). However, these are interesting exercises to evaluate how the different ocean processes are observed by different measuring systems and to evaluate the best strategy in case of multi-platform data assimilation.

Examples of real-time HFR data quality assessment is provided by Puertos del Estado (Lorente et al. 2015a, 2015b) or SOCIB, which in addition to NRT radar data validation (Figure 1) provide reports (including tidal and spectral analysis of the data).

Figure 1. Near real-time validation of HFR surface currents (~0.9 m) against point-wise current meter measurements (at a depth of 1.5 m) of the Ibiza Channel Buoy (located inside the HFR total footprint). Time series of zonal, meridional, sea water velocity and direction of sea water velocity are displayed and available online in NRT.

SOCIB has developed a tool (https://github.com/socib/HFRadarReports) to generate automatic monthly reports, as a new product for HFR data quality assessment, which are available online (e.g. http://www.socib.es/files/reports/HF_Radar/SOCIB_HFRadar_Report201705.pdf).

5 Model assessment using HFR currents.

The characterization of the model errors is probably the trickiest part of data assimilation. In the context of surface currents, a large variety of potential error sources exists, like those associated to open boundary or meteorological forcing, bathymetry errors, bottom roughness errors, or deficiencies in turbulence parametrization. In addition, surface currents are affected by complex coupling processes between the current field, wind driven surface waves and the atmosphere (e.g., Staneva et al. 2016). The optimal treatment of these processes in numerical models is still subject to ongoing research and HFR data can play an important role in this context.

The potential of HFR data for real-time validation of numerical models is showcased by Puertos del Estado NARVAL tool (Figure 2) and the works performed by Lorente et al. (2016a, 2016b).

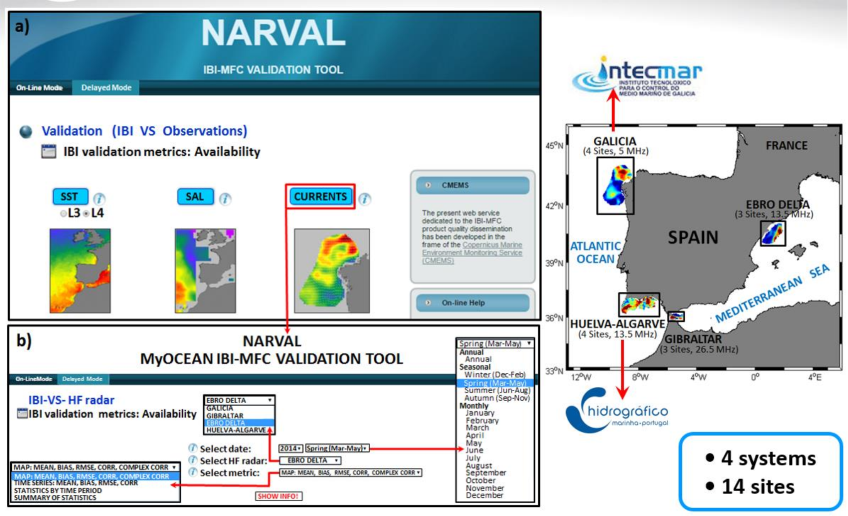

Figure 2. Webtool NARVAL which routinely evaluates IBI-MFC performance in terms of accuracy, consistency and variability by computing and compiling a complete collection of skill metrics and which includes some of the HFR available operational data in the Iberian Peninsula (extracted from Lorente et al. 2016, INCREASE meeting in La Spezia presentation).

Systematic validation of the high-resolution Western Mediterranean Sea Operational Forecasting System (WMOP) developed at SOCIB, includes multi-platform observations, as satellite-derived products and in-situ measurements (Argo floats, fixed mooring and HFR data), as described in Juza et al. (2016). Near real-time (NRT) validation is performed daily and figures illustrating the model performance are published online. Figure 3 shows some examples of the NRT qualitative validation of WMOP against HFR data.

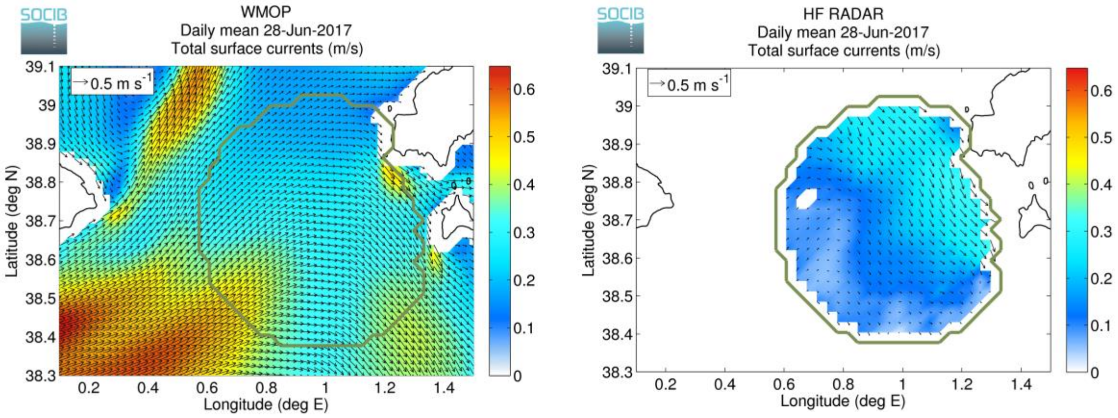

Figure 3. Comparison of the daily average current field of WMOP against the last available total surface currents derived from the SOCIB HFR in the eastern part of the Ibiza Channel. Green contour defines the area with HFR data availability greater than 50%.

Following the recommendations from Puertos del Estado, other sets of statistical metrics (e.g.: complex-correlation, eddy kinetic energy, BIAS, RMSE and correlation of zonal and meridional components) are being considered to be included in the systematic validation of WMOP.

A non-exhaustive list of HFR data derived products that could be used for data validation follows:

- Pointwise series of Eulerian currents

- Sections of zonal or meridional Eulerian low-pass currents

- Maps of EKE for different processes

- Power-spectral density of current velocities

- Detided (band pass filtered) velocities

- Gap filled products

- Lagrangian estimation of transport, residence times, escape rates, Lagrangian Coherent Structures (e.g. using FSLEs).

An example of a validation exercise for the CMEMS IBI (**IBI_REANALYSIS_PHYS_005_002**) simulations using two sections of Eulerian low-pass currents for the HFR system in the SE BoB (Euskalmet, AZTI) is provided in Figure 4.

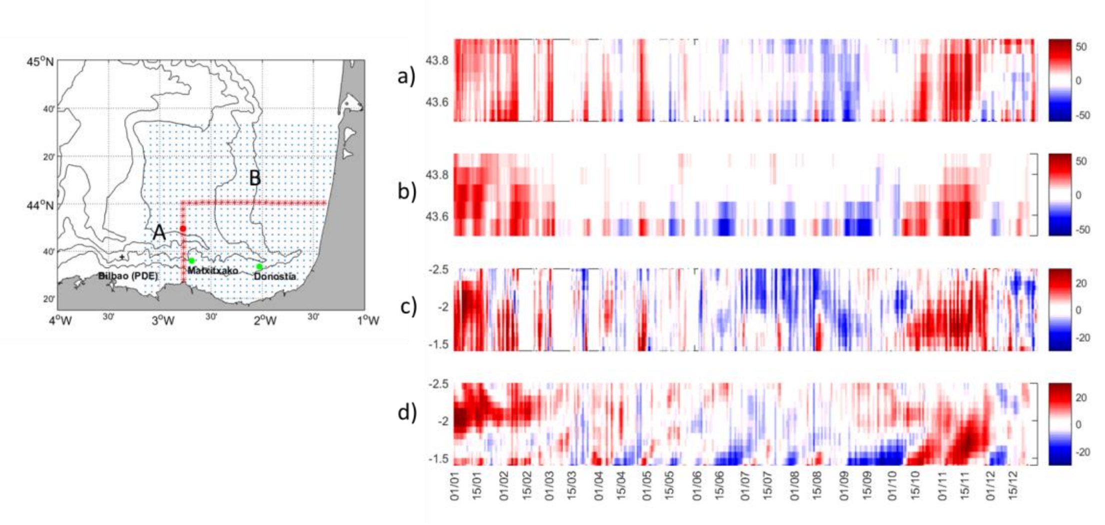

Figure 4. Zonal and meridional currents for sections A (a,b) and B (c,d), respectively, obtained from HFR lowpass filtered daily data (a, c) and daily currents from IBI_REANALYSIS_PHYS_005_002 (b, d) simulations in the SE Bay of Biscay. A and B sections are depicted in the map, where the HFR coverage area is shown by the blue dots. Isobaths: 200, 1000, 2000, 3000, 4000 m.

6 References

Barrick, D. E. (2002). Geometrical dilution of statistical accuracy (GDOSA) in multi-static HF radar networks. Codar ocean sensors, (Available at http://www. codaros. com/Manuals/SeaSonde/Docs/Informative/GDOSA Definition. pdf).

Barth A, Alvera-Azcárate, A., Beckers, J.M., Staneva, J., Stanev, E.V., Schulz-Stellenfleth, J. (2011). Correcting surface winds by assimilating HFR surface currents in the German Bight, *Ocean Dynam.*, 61, 5, 599

Barth, A., Alvera-Azcárate A., Weisberg R. H. (2008). Assimilation of high-frequency radar currents in a nested model of the West Florida Shelf, *J. Geophys. Res.,* 113, C08033, doi:10.1029/2007JC004585.

Berta M., Bellomo, L., Magaldi, M.G., Griffa, A., Molcard, A., Marmain, J., Borghini, M., Taillandier, V. (2014). Estimating Lagrangian transport blending drifters with HF radar data and models: Results from the TOSCA experiment in the Ligurian Current (North Western Mediterranean Sea), *Progr. Oceanogr*., 128, 15-29, doi: 10.1016/j.pocean.2014.08.004.

Breivik, O., Saetra, O. (2001) Real Time Assimilation of HF Radar Currents into a Coastal Ocean Model. *J. Marine Syst*., 28 161–182.

Chapman, R.D., Shay, L., Graber, H., Edson, J., Karachintsev, A., Trump, C., Ross, D. (1997). On the accuracy of HF radar surface current measurements: Intercomparisons with ship-based sensors. *J. Geophys. Res.-Oceans* (1978–2012),102, C8, 18 737–18 748

Chavanne, C. P., and P. Klein (2010), Can oceanic submesoscale processes be observed with satellite altimetry? Geophys. Res. Lett., 37, L22602, doi:10.1029/2010GL045057.

Corgnati L., Mantovani, C., Novellino, A., Rubio, A., Mader, J., Reyes, E., Griffa, A., Asensio, J.L., Gorringe, P., Quentin, C., Breitbach, G. (2017). Recommendation Report 1 for HFR data implementation in European marine data infrastructures. http://www.jerico-ri.eu/download/jerico-next-deliverables/JERICO-NEXT-Deliverable-5.13_V1.pdf

Cosoli, S., Mazzoldi, A., Gacic, M. (2010). Validation of surface current measurements in the Northern Adriatic Sea from High Frequency radars. *J. Atmos. Ocean. Tech*., 27, 908–919

Heron, M.L., Atwater D.P (2013). "Temporal and spatial resolution of HF ocean radars." Ocean Science Journal 48.1: 99-103.

Iermano I., Moore, A.M., Zambianchi, E. (2016). Impacts of a 4-dimensional variational data assimilation in a coastal ocean model of southern Tyrrhenian Sea. *J. Mar. Sys.* 154: 157-171

Juza, M., Mourre, B., Renault, L., Gómara, S., Sebastián, K., Lora, S., Beltran, J.P., Frontera, B., Garau, B., Troupin, C., Torner, M., Heslop, E., Casas, B., Escudier, R., Vizoso, G., Tintoré, J. (2016) SOCIB operational ocean forecasting system and multi-platform validation in the Western Mediterranean Sea. Journal of Operational Oceanography 9, s155-s166.

Kalampokis, A., Uttieri, M., Poulain, P. M., Zambianchi, E. (2016). Validation of HF Radar-Derived Currents in the Gulf of Naples With Lagrangian Data. IEEE *Geosci. Remote Sens. Lett*., doi: 10.1109/LGRS.2016.2591258

Kirincich, A. (2016). The Occurrence, Drivers, and Implications of Submesoscale Eddies on the Martha's Vineyard Inner Shelf. *J. Phys. Oceanogr.*, 46, 2645–2662, doi: 10.1175/JPO-D-15-0191.1.

Kohut, J. T., Glenn, S. M. (2003). Improving HF radar surface current measurements with measured antenna beam patterns. *J. Atmos. Ocean. Tech*., 20, 1303–1316, 2003.

Lipa, B. (2013). Uncertainties in SeaSonde current velocities. Proc. of the IEEE/OES Seventh Working Conference on Current Measurement Technology. DOI: 10.1109/CCM.2003.1194291 Source: IEEE Xplore

Lorente, P., Piedracoba, S., Soto-Navarro, J., and Alvarez-Fanjul, E. (2015a). Evaluating the surface circulation in the Ebro delta (northeastern Spain) with quality-controlled high-frequency radar measurements, Ocean Sci., 11, 921-935, doi:10.5194/os-11-921-2015

Lorente, P., Piedracoba, S., and Alvarez-Fanjul, E. (2015b) Validation of high-frequency radar ocean surface current observations in the NW of the Iberian Peninsula, Cont. Shelf Res. 92, 1–15

Lorente P., Piedracoba S., Sotillo M.G., Aznar R., Amo-Baladrón, A., Pascual, A., Soto-Navarro J., Álvarez-Fanjul, E. (2016a). Ocean model skill assessment in the NW Mediterranean using multi-sensor data. J. Oper. Oceanogr., doi: 10.1080/1755876X.2016.1215224.

Lorente P, Piedracoba S, Sotillo MG, Aznar R, Amo-Baladrón A, Pascual A, Soto-Navarro J, Álvarez-Fanjul E. 2016b. Characterizing the surface circulation in Ebro Delta (NW Mediterranean) with HF radar and modeled current data. J Mar Syst. 163:61–79. doi: 10.1016/j.jmarsys.2016.07.001

Mader J., Rubio A., Asensio J.L, Novellino A., Alba M., Corgnati L., Mantovani C., Griffa, A., Gorringe P., Fernandez V. (2016). The European HF Radar Inventory, EuroGOOS publications. http://eurogoos.eu/download/publications/EU_HFRadar_inventory.pdf

Marmain, J., Molcard, A., Forget, P., Barth, A. (2014). Assimilation of HF radar surface currents to optimize forcing in the North Western Mediterranean sea, *Nonlinear Process. Geophys.*, 21, 659–675, doi:10.5194/npg-21-659-2014.

Molcard, A., Poulain, P. M., Forget, P., Griffa, A., Barbin, Y., Gaggelli, J., De Maistre, J. C., Rixen, M. (2009). Comparison between VHF radar observations and data from drifter clusters in the Gulf of La Spezia (Mediterranean Sea), *J. Mar. Sys.*, 78S, S79-S89.

Ohlmann C., White, P., Washburn, L., Emery, B., Terrill, E., Otero, M. (2007). Interpretation of Coastal HF Radar–Derived Surface Currents with High-Resolution Drifter Data. *J. Atmos. Oceanic Technol*, 24(4), 666-680.

Orfila, A., Molcard, A., Sayol, J.M., Marmain, J., Bellomo, L., Quentin, C., Barbin, Y. (2015). Empirical Forecasting of HF-Radar Velocity Using Genetic Algorithms, *Geoscience and Remote Sensing*, IEEE Transactions on , vol.53, no.5, pp.2875-2886, doi: 10.1109/TGRS.2014.2366294

Paduan J. D., Washburn, L. (2013). High-Frequency Radar Observations of Ocean Surface Currents. Annual Review of Marine Science, 5.

Roarty, H., Hazard, L., Alvarez-Fanjul, E. (2016). Growing network of radar systems monitors ocean surface currents. EOS, 97, doi:10.1029/2016EO049243.

Rubio, A., Mader, J., Corgnati, L., Mantovani, C., Griffa, A., Novellino, A., Quentin, C., Wyatt, L., Schulz-Stellenfleth, J., Horstmann, J., Lorente, P., Zambianchi, E., Hartnett, M., Fernandes, C., Zervakis, V., Gorringe, P., Melet, A., Puillat, I., 2017. HF Radar Activity in European Coastal Seas: Next Steps Towards a Pan-European HF Radar Network. Front. Mar. Sci. 4:8. doi: 10.3389/fmars.2017.00008.

Sentchev, A., Forget, P., Barbin, Y., Yaremchuk, M. (2013). Surface circulation in the Iroise Sea (W. Brittany) from high resolution HF radar mapping. *J. Mar. Syst.,* 109-110, S153–S168, doi: 10.1016/j.jmarsys.2011.11.024

Shrira, V. I., Forget, P., 2015. On the Nature of Near-Inertial Oscillations in the Uppermost Part of the Ocean and a Possible Route toward HF Radar Probing of Stratification. Journal of Physical Oceanography 45 (10), 2660–2678.

Siddons, L.A., Wyatt, L.R., Wolf, J. (2009). Assimilation of HF radar data into the Swan wave model. *J. Mar. Syst.,* 77, 3, 312-324.

Solabarrieta, L., Frolov, S., Cook, M., Paduan,J., Rubio, A., González,M., Mader, J., Charria, G. (2016). Skill assessment of HF radar-derived products for lagrangian simulations in the Bay of Biscay. *J. Atmos. Oceanic Technol.,* in press, doi: 10.1175/JTECH-D-16-0045.1.

Sperrevik, A.K., Christensen, K.H., Röhrs, J. (2015). Constraining Energetic Slope Currents through Assimilation of High-Frequency Radar Observations. *Ocean Sci.*, 11, 2, 237–249.

Stanev, E. V., Ziemer, F., Schulz-Stellenfleth, J., Seemann, J., Staneva, J., Gurgel, K.-W. (2015). Blending Surface Currents from HF Radar Observations and Numerical Modeling: Tidal Hindcasts and Forecasts. *J. Atmos. Oceanic Technol*., 32, 256–281, doi: 10.1175/JTECH-D-13-00164.1.

Staneva, J., Wahle, K., Günther, H., Stanev, E. (2016). Coupling of Wave and Circulation Models in Coastal–ocean Predicting Systems: A Case Study for the German Bight. *Ocean Sci.*, 12, 3, 797–806.

Stewart, R.H., Joy, J.W. (1974) HF radio measurements of surface currents. Deep-Sea Research and Oceanographic Abstracts 21, 1039-1049.

Vandenbulcke, L., Beckers, JM. & Barth, A. Ocean Dynamics (2017) 67: 117. doi:10.1007/s10236-016-1012-5

Waters, J., Wyatt, L.R., Wolf, J., Hines, A. (2013) Data assimilation of partitioned HF radar wave data into Wavewatch III. *Ocean Model*., 72, 17-31

Zervakis, V., Kokkini, Z., Potiris, E. (2016). Estimating Mixed Layer Depth with the use of a coastal High-Frequency radar. *Cont. Shelf Res*. In Press. doi: 10.1016/j.csr.2016.07.008