CMEMS User Uptake 67-UU-DO-CMEMS-DEM4_LOT7

Validation of the Skill Assessment methodology

December 13th, 2019

PURPOSE

This document addresses the **validation of the skill assessment methodology** used in the IBISAR service.

The quantitative method used for assessing the skill of each data source is detailed in section 1. Furthermore, in this section, the pilot areas and the Lagrangian model used are also presented. Additionally, the complementary databases of drifters are listed and the methodology used to obtain maps of High-Frequency radar currents without spatio-temporal gaps is described.

The validation consists of two phases:

1. First, we **evaluate the skill assessment methodology** by applying the methodology to four different IBI sub-regions from Spain that have been selected as pilot areas (section 2).

2. Second, we **evaluate the service outcomes** for the same experiments performed in the pilot areas (section 3), to assess the usefulness of the service for these cases from the point of view of the final user.

Finally, the **general conclusions** from all experiments are drawn (section 4), as well as the **limitations of the methodology** (section 5).

DISCLAIMER

The content of this document is part of the work carried out during the IBISAR (67-UU-DO-CMEMS-DEM4_Lot7) project. Findings are being the subject of further investigation in the context of the Ocean State Report (version 4) and a specific peer-reviewed journal article, where methodological limitations are being addressed. Therefore, these results must be interpreted with caution, particularly the spatial averages of the skill score.

LIST OF ACRONYMS AND ABBREVIATIONS

AC	Algerian Current
BC	Balearic Current
BoB	Bay of Biscay
CADIZ	Cadiz IBI sub-region
CALYPSO	Coherent Lagrangian Pathways from the Surface Ocean to Interior
CMEMS	Copernicus Marine Environment Monitoring Service
COSMO	Ocean Currents and Maritime Safety (from the Spanish, "Corrientes Oceánicas y Seguridad en el Medio marinO")
CSIC-ICM	Spanish National Research Council - Institute of Marine Science (from the Spanish, "Consejo Superior de Investigaciones Científicas-Instituto de Ciencias Marinas")
EAG	Eastern Alboran Gyre
GIBST	Strait of Gibraltar
GLO	Global
HFR	High-Frequency Radar
HYCOM	HYbrid Coordinate Ocean Model
IBI	Iberia-Biscay-Ireland
IBISAR	Skill assessment service for real-time met-ocean data product ranking in the IBI area for emergency and SAR operators.
IC	Ibiza Channel
IPC	Iberian Poleward Current
KAUST	King Abdullah University of Science and Technology
LPTM	Lagrangian Particle-Tracking Model
MFC	Monitoring and Forecasting Centre
MRCC	Maritime Rescue Coordination Centre
NC	Northern Current
NCLS	Normalized Cumulate Lagrangian Separation distance
NetCDF	Network Common Data Form
NIBSH	North Iberian Shelf
NPS	Naval Postgraduate School
NRT	Near Real Time
OMA	Open-boundary Modal Analysis
PUERTOS	Spanish Port System (from the Spanish, Puertos del Estado)
RK	Runge-Kutta
SA	Skill Assessment
SAMOA	Met-Ocean information Services for Port Authorities (Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria)
SAR	Search And Rescue
SASEMAR	Spanish Maritime Safety and Rescue Agency (Sociedad de Salvamento y Seguridad Marítima)
SOCIB	Balearic Islands Coastal Observing and Forecasting System (Sistema de Observación y predicción Costera de las Islas Baleares)
STP	Short Term Prediction
SS	Skill Score
SVP	Surface Velocity Program
SWODDIES	Slope Water Oceanic eDDIES

TAC	Thematic Assembly Centre
USCG	United States Coast Guard
WAG	Western Alboran Gyre
WIBSH	Western Iberian Shelf
WMOP	Western Mediterranean OPerational forecasting system
WSMED	Western Mediterranean

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1. Description of the work.

1.1. Pilot areas.

Pilot areas were used for the validation of the skill assessment methodology of the service. These sub-regions were selected for several reasons:

- They **cover three** of four **areas of responsibility** of the **Spanish SAR Agency**;
- There are **HFR data available** in each of them;
- **Several** CMEMS-MFCs, regional and coastal **models overlap** (see Fig. 1);
- They show **diverse average circulation patterns**, allowing the evaluation of the methodology in regions with different dynamics;
- **IBISAR** team members and external contributing experts have a **broad research experience** in those areas.

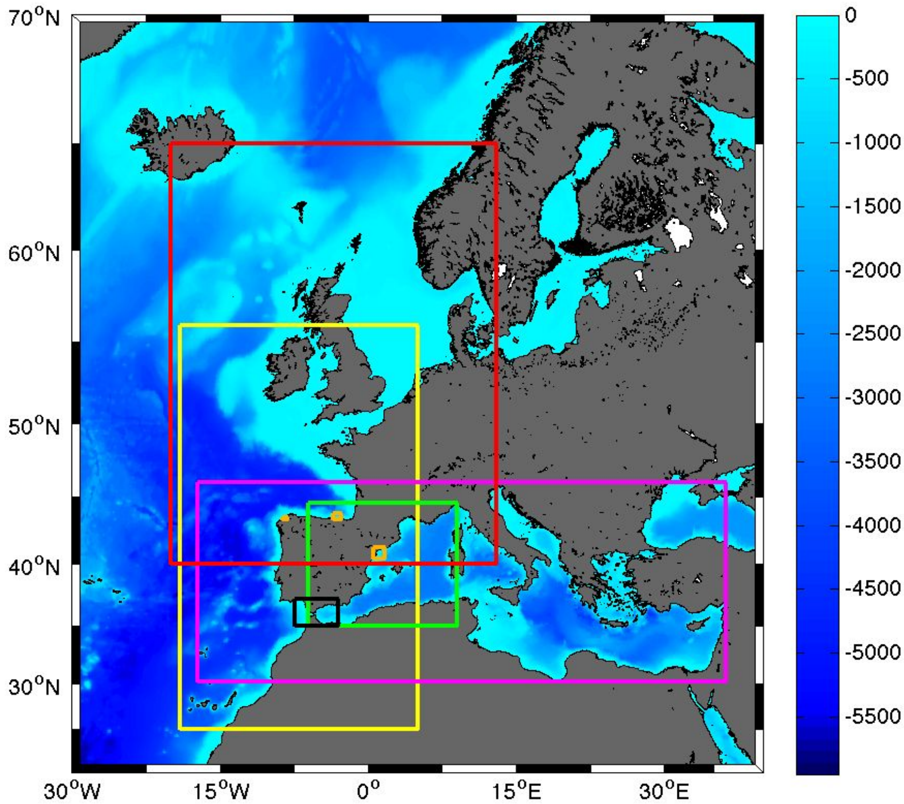

Figure 1: Map showing different regional models overlapping in the IBI area from CMEMS-MFCs and complementary databases (e.g. SOCIB and PUERTOS). Red box=CMEMS-NWS-MFC; Yellow box = CMEMS-IBI-MFC; Magenta box=CMEMS-MED-MFC; Green box=SOCIB-WMOP; Black box=PUERTOS-SAMPA; Orange boxes= PUERTOS-SAMOAs.

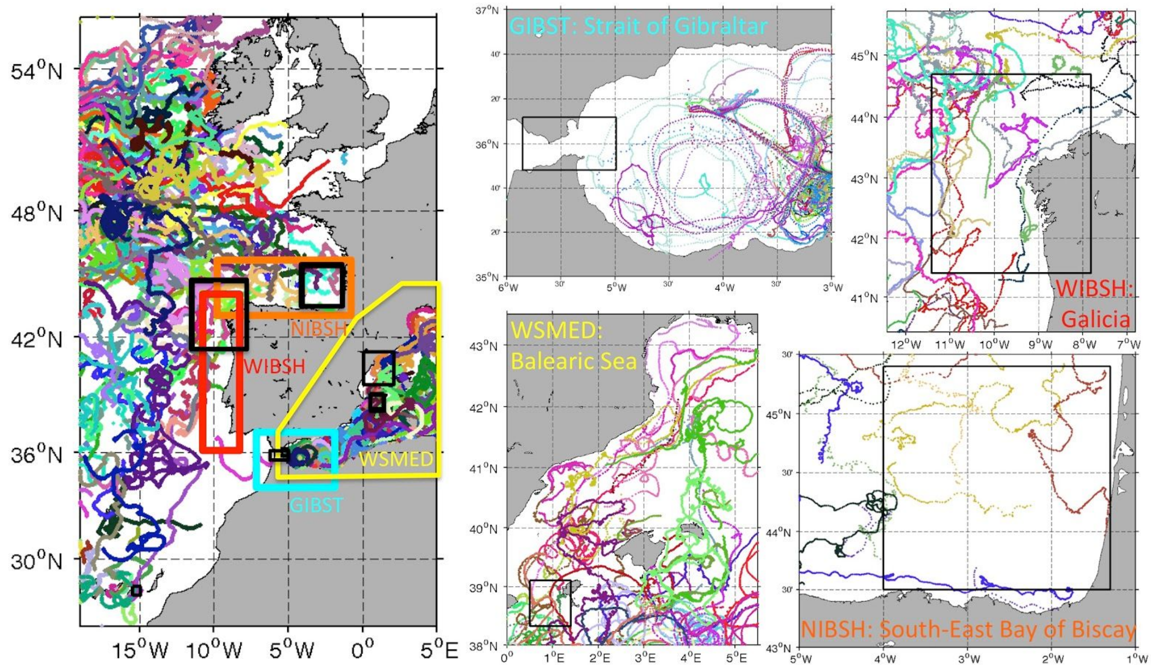

Figure 2: Drifter trajectories available at CMEMS since February 2014 in (left panel) the IBI region, showing the different IBI sub-regions (Red box=WIBSH; Orange box=NIBSH; Cian box= GIBST; Yellow box=WSMED), taken from Sotillo et al. (2015), and in (right panels) the four pilot areas considered for the service validation experiments. Black boxes show the HFR domains used.

Due to the lack of drifters in some regions (for example the Gulf of Cádiz, see left panel of Fig. 2), the **4 regions** considered were:

- The Balearic Sea in the Western Mediterranean (**WSMED**)
- The South-eastern Bay of Biscay in the Northern Shelf of Spain (**NIBSH**)
- The Strait of Gibraltar and the Alboran Sea (**GIBST**)
- The Galicia Coast in the North Western Shelf of Spain (**WIBSH**).

1.2. Skill Assessment methodology.

The **IBISAR Skill Assessment (SA) service** consists of an automated process that first simulates the trajectory of a particle using ocean models and HFR datasets and then evaluates the performance using the normalized cumulative Lagrangian separation -NCLS- distances (Liu and Weisberg, 2011), which computes an easily interpretable metric named Skill Score (SS).

The **SS is defined as** following:

$$SS=\begin{cases} 1-\dfrac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} l_{oi}} & \text{if} \quad \sum_{i=1}^{N} d_i \le \sum_{i=1}^{N} l_{oi} \\ 0 & \text{if} \quad \sum_{i=1}^{N} d_i > \sum_{i=1}^{N} l_{oi} \end{cases} \qquad \text{with} \quad l_{oi}=\sum_{k=1}^{i} l_k$$

(Eq. 1)

where d_i is the separation distance between the modeled and observed trajectories at time step i (as shown in Fig. 3), l_{oi} is the cumulative sum of the observed trajectory at time step i and N is the total number of time steps. N=6 in our case because we evaluate the simulated trajectories every hour over a 6-hour simulation. The SS is a dimensionless index ranging from 0 to 1; the higher the SS value, the better the model performance, with a value=1 implying a perfect match between drift observation and prediction.

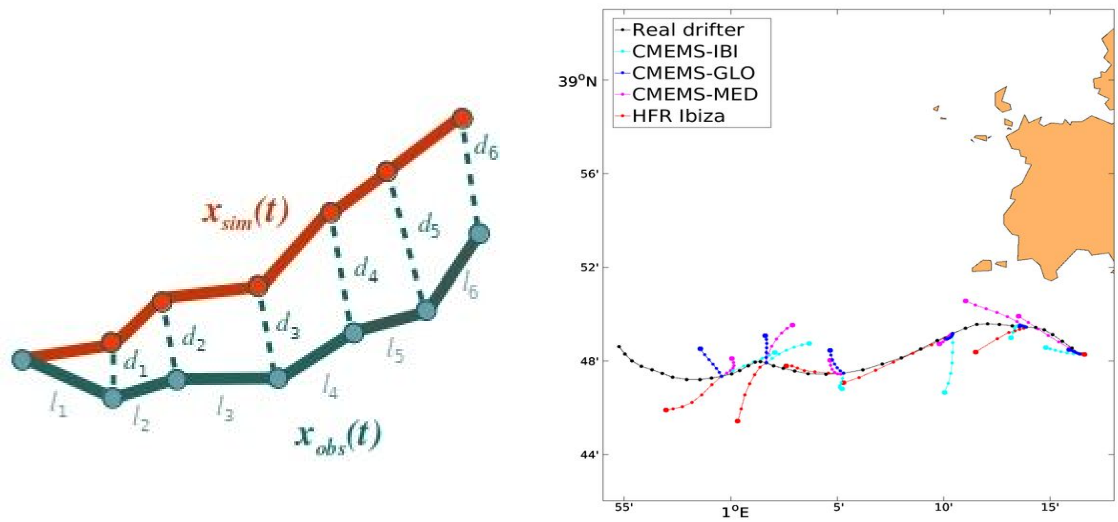

Figure 3.- Left panel: illustration of the separation distances d_i between observed drifter data (green line) and modeled (red line) trajectories, adapted from Liu and Weisberg (2011). Right panel: simulated trajectories from different datasets (CMEMS-IBI-MFC in cyan, CMEMS-GLO-MFC in blue, CMEMS-MED-MFC in magenta and HFR in red dotted lines) over the observed one (black dotted line) in the Ibiza Channel.

This SS was used in several studies **to assess numerical ocean circulation models.** It was applied in particular to evaluate the performance of the Global HYCOM hindcast surface currents in the eastern Gulf of Mexico during the 2010 Deepwater Horizon oil spill (Liu and Weisberg, 2011; Mooers et al., 2012; G. R. Halliwell et al., 2014). It also gained popularity in evaluating performance of trajectory models for oil spill and drifts for SAR operations (Ivichev et al., 2012; Mooers et al., 2012; Röhrs et al., 2012; Liu et al., 2014b).

1.3. COSMO: the trajectory model.

For the validation experiment, the **virtual trajectories were computed using the COSMO Lagrangian model** (Jiménez Madrid et al., 2016), which is a free software available in GitHub repository (https://github.com/quimbp/cosmo, version from 5 June 2019, DOI: 10.5281/zenodo.3522268) with the following characteristics:

- Language: Fortran 2003, following the standard ISO/IEC 1539-1:2004
- Advection method: RK5 (fifth-order Runge-Kutta method).
- Spatial interpolation: bicubic spatial interpolation in space.
- Temporal interpolation: third order Lagrange polynomials in time.
- Beaching: not included
- Diffusion method: none
- Particle advected by wind action: not included
- Stokes-drift: not included
- Grids supported: Arakawa-A grid
- Primary use: offline surface particle tracer dispersion (particle advection only 2D)

This model has been **developed at the Institute of Marine Sciences of Barcelona (ICM-CSIC)** in the context of the **COSMO project** -http://www.icm.csic.es/en/projects- (CTM2016-79474-R, MINECO/FEDER, UE. IP: Joaquim Ballabrera from CSIC-ICM, Barcelona, Spain). This project aims to improve the knowledge about the variability of the surface ocean currents near the Iberian Coast in order to improve the systems used by the Spanish SAR Agency and the National Police.

Among all other Lagrangian models considered (e.g. TRACMASS-A initially developed by Döös, 1995; LPTM-Lagrangian particle Tracking Model developed by AZTI from Ferrer et al., 2009), **COSMO model was selected** because of four main **reasons:**

- The model characteristics were compliant with the needs of IBISAR project, and the use of a single model in all areas allowed a more accurate cross-area comparison of the results with different datasets and models, as explained hereafter.

- To boost synergies between IBISAR and COSMO projects with same end-users (i.e. Spanish SAR Agency)

- To homogenize tools developed for the same end-users (i.e. SASEMAR).

- To promote the use of free software, available on GitHub with a viewer in python.

All experiments have been performed with the same lagrangian model in order to avoid the introduction of any other source of error. In general, the accuracy of trajectories computed in model fields depend on the accuracy of the time stepping scheme, as well as accuracy of the interpolation scheme used to estimate velocity at the time and position of the particle (van Sebille et al., 2018). However, the trajectories differ in numerical implementations due to algorithmic differences and truncation errors. Fig. 4 shows the uncertainty of the simulated trajectories using three different lagrangian models: COSMO (Jiménez Madrid et al., 2016), TracPy-TRACMASS (Thyng and Hetlands, 2014) and CDrift (Sayol et al. 2014), with diverse advection schemes and different spatio-temporal interpolation (Table 1), using the SOCIB-WMOP dataset (Juza et al., 2016). . Results show very similar trajectories between COSMO and CDrift, while differences are found with TracPy-TRACMASS.

COSMO (blue) vs TracPy (red) vs CDrift (black) simulated trajectories

With WMOP from 30-Oct-2014 00:00 to 30-Oct-2014 21:00

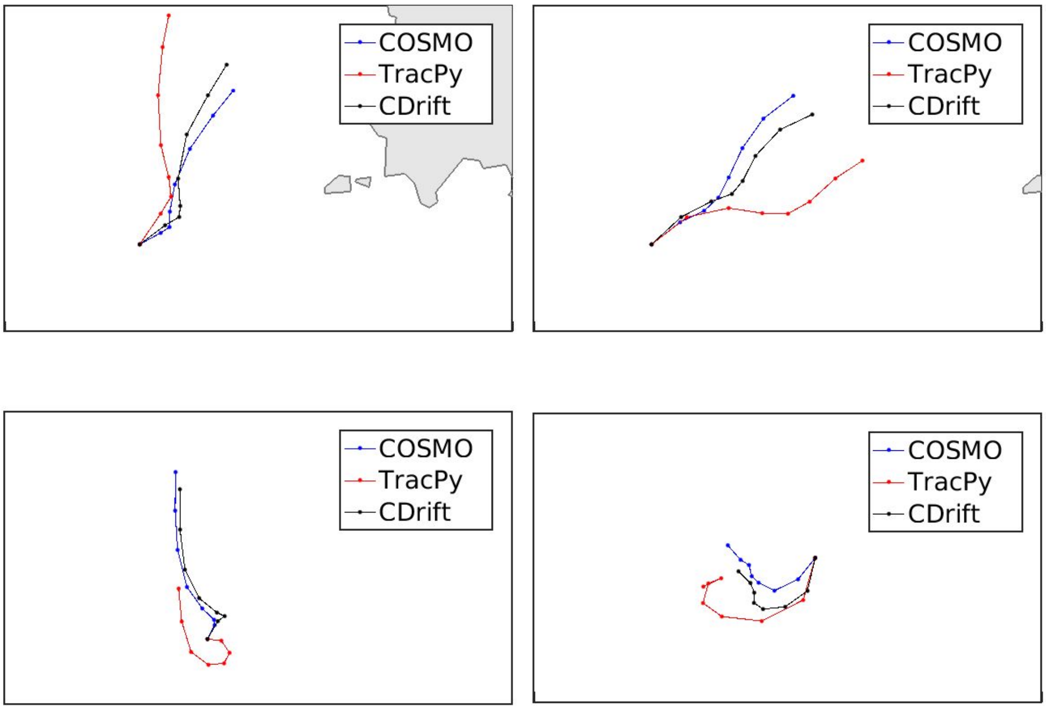

Figure 4. Virtual particle trajectories simulated by different trajectory models: COSMO (blue line); TracPy-TRACMASS (red line) and CDrift (black line).

Table 1.- Summary of characteristics of the different trajectory models used for comparison

Model	COSMO	CDrift	TracPy
Advection method	RK5	RK4[1]	Analytic

[1] The 4th order Runge-Kutta scheme (e.g., Butcher, 2016) is one of the most popular. Better accuracy of the trajectories can be obtained by using higher-order methods for the temporal integration of the virtual particle trajectory equations.

Temporal interpolation	cubic	linear	linear
Spatial interpolation	cubic	linear	linear

1.4. Drifter observations from complementary databases.

The **lack of drifter observations** in some coastal areas in the CMEMS INSITU_GLO_UV_NRT_OBSERVATIONS_013_048 product forced us to **use drifter observations from complementary databases.** We used drifters from:

- **The COSMO experiment**. This experiment has been done in the context of the COSMO project. 18 drifters were deployed in the Alboran Sea in February 2018 and were tracked until June 2018.
- **SOCIB:** several drifter deployments have been done in the Ibiza Channel by SOCIB for HF radar calibration: in 2014, 2016 and 2018.
- **SASEMAR:** the Spanish SAR Agency also deploys drifters for routine exercises or in case of emergencies.

Those complementary databases should be accessible for the whole european community and therefore we highly recommend its integration into CMEMS In Situ TAC.

1.5. Gap-filled HF Radar data.

HFR is a remote sensing technique that **provides 2D maps of the surface currents**, resulting from the combination of the measurements obtained from two or more radial stations. The radio signal emitted by the antennas in each of the stations travels along and back through the ocean surface, being the current velocity measured thanks to the Bragg scattering phenomena (Barrick et al., 1977) of the received signal. **Any affection to this process can result in gaps** in the final data (i.e. individual antenna failures, range and/or bearing reduction due to adverse environmental conditions and/or electromagnetic problems and the occurrence of radio interference, external noise, topographical shadowing, etc). In addition, no total currents can be computed in an accurate way in the base-line region between the antennas. The baseline is defined as the area where the radial components from the two stations make an angle of less than 30°, so the total velocity vectors created from radial data within this data contain greater uncertainties.

Thus, when using HFR-derived surface current maps, **gap-filling must be previously applied** to the data in order to obtain maps of currents that have not spatial neither temporal gaps to be able **to compute accurate trajectories** (Solabarrieta et al., 2016, Hernandez-Carrasco et al., 2018a, 2018b).

The **Open-boundary Modal Analysis -OMA-** (Kaplan and Lekien, 2007) has been **applied** using the modules in the HFR Progs Matlab package (https://cencalarchive.org/~cocmpmb/COCMP-wiki/index.php/HFR_Progs_Installation_Instructions). The **OMA** is based on a set of linearly **independent velocity modes** that are calculated before they are fit to the data.

- These modes describe all possible current patterns inside a two-dimensional domain (taking into account the open boundaries and the coastline).
- The amplitude of those modes is then fitted to current measurements inside the domain.

OMA considers the kinematic constraints imposed on the velocity field by the coast since OMA modes are calculated taking into account the coastline by setting a zero normal flow. Depending on the constraints of the methodology, it can be limited in representing localized small-scale features as well as flow structures near open boundaries. Also, difficulties may arise when dealing with gappy data, especially when the horizontal gap size is larger than the minimal resolved length scale (Kaplan and Lekien, 2007) or when only data from one antenna are available. In the case of large gaps, unphysically fitted currents can be obtained if the size of the gap is larger than the smallest spatial scale of the modes, since the mode amplitudes are not sufficiently constrained by the data (Kaplan and Lekien, 2007). This is why when using OMA it is recommended to reach a compromise between the number of modes used for spatial scales larger than the largest gap and a sufficient number of modes correctly representing the spatial variance of the original fields (knowing that the spatial smoothing increases as the number of modes decreases). Despite the described limitations, a recent work by Hernández-Carrasco et al. (2018b), shows that the use of OMA for small gaps provides similar results in terms of Lagrangian diagnostics than other gap-filling techniques. In our case, in order to avoid the reconstruction of large spatial gaps no reconstruction is performed when only data from one antenna is available, and the trajectories are computed only for those periods where HFR data series without temporal gaps are available.

With the purpose of obtaining radar-derived Lagrangian trajectories in each one of the pilot areas, the OMA analysis has been applied for generating the HFR gap-filled data as seen in Fig. 5:

- **NIBSH:** 85 OMA modes, built setting a minimum spatial scale of 20 km
- **WSMED:** 189 OMA modes, built setting a minimum spatial scale of 6 km
- **GIBST:** 313 modes, built setting a minimum spatial scale of 5 km
- **WIBSH:** 198 OMA modes, built setting a minimum spatial scale of 20 km

, were used to generate hourly total fields without gaps.

OMA nowcasts are an added-value data product that should be provided on an operational basis.

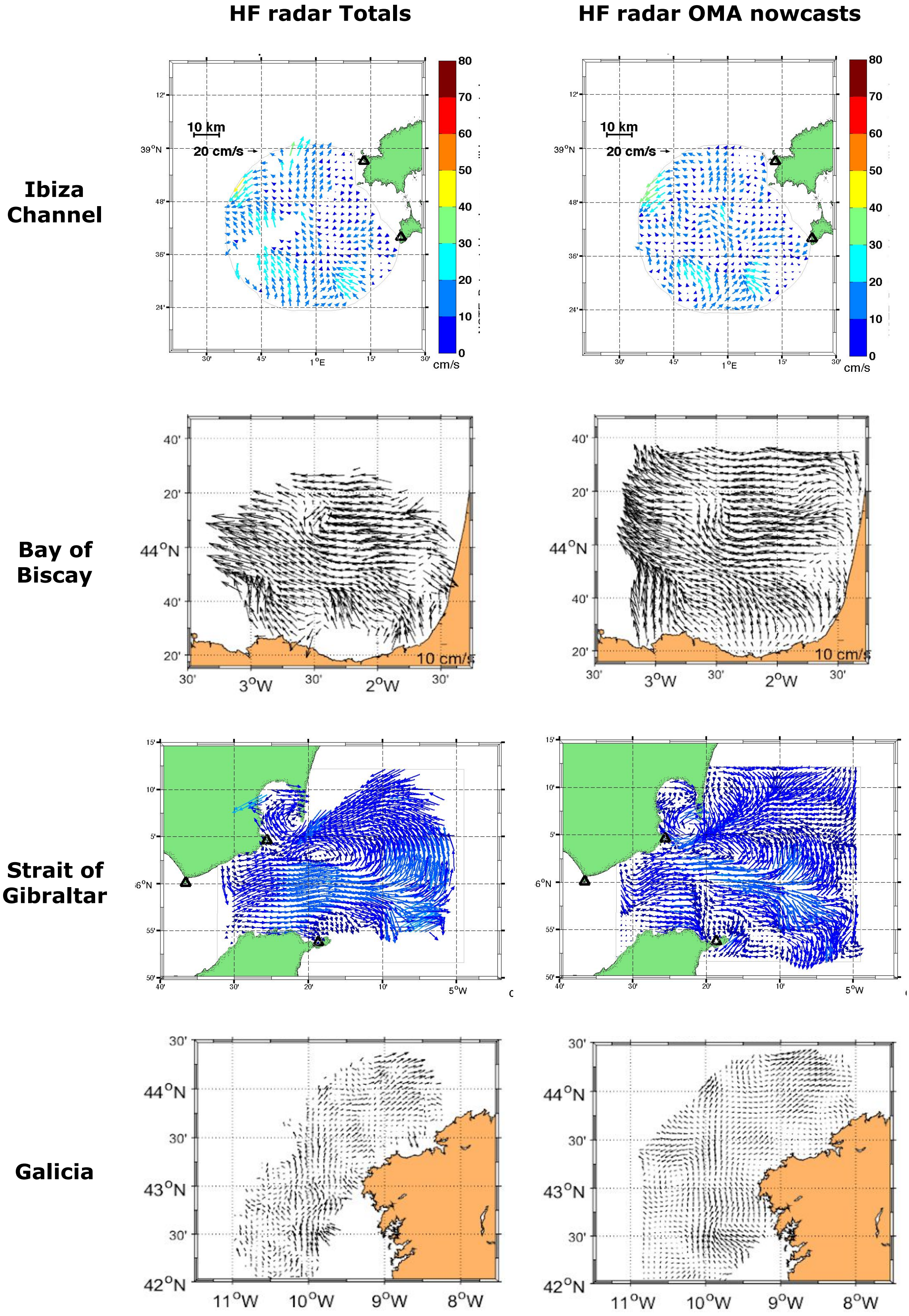

Figure 5. HF radar surface currents maps using the Least Mean Squares solution -left panels- and gap-free total currents using the OMA solution -right panels- from the HF radar system in Ibiza Channel, Bay of Biscay, Strait of Gibraltar, and Galicia (from top to bottom).

Furthermore, we have taken this opportunity to develop a **guideline on the use of the OMA technique** for HFR surface currents gap-filling in order to help other HFR operators to obtain HFR gap-filled data, needed for Lagrangian applications. **The guidelines have been edited** by several IBISAR team members and collaborators (P. Lorente from NOLOGIN-Puertos del Estado) and have been reviewed by Loihtzune Solabarrieta (KAUST, Saudia Arabia), as one of the experts in HFR gap-filling and by Michael Cook (from the NPS, US), as one of the primary authors of the HFR_Progs used. Once published, with previous announcements in the NEWS sections of SOCIB, IBISAR and CMEMS-INSITU websites, the document will be available on the IBISAR webpage. This will be an added-value generated in the context of IBISAR project that directly impacts the HFR operator community.

1.6. Validation experiment procedure.

In order to **evaluate the skill assessment methodology,** the experiments are performed in **four steps:**

1) The real drifter trajectories files are read, processed when necessary to ensure the positions are all realistics and inside the corresponding HFR footprint areas, and hourly positions selected.

2) The hourly positions are written in a file named release.ini (longitude, latitude, depth and time) to give initial conditions to the COSMO Lagrangian model.

3) The COSMO model is executed following the indications of the developers and as specified in the GitHub repository.

4) The NetCDF files generated by COSMO are read by Matlab® and the SS calculated following the above-described methodology.

In order to interpret the SS results, the mean surface currents during the analyzed periods from each model/HF radar data were plotted (not shown). This allowed us to see the differences in the model features during the analyzed periods and therefore understand the skill assessment results.

2. Skill Assessment results.

2.1. Results in the Balearic Sea.

Intense mesoscale and submesoscale variability occurs at sub-basin and basin scales in the WSMED, resulting in an amalgam of intricate processes that require high-resolution and comprehensive observations to be fully understood (Pinot et al., 2002; Pascual et al., 2002; Ruiz et al., 2009; Barceló-Llull et al., 2019). The surface circulation of the Balearic Sea is characterized by **two permanent density-driven currents** (La Violette et al., 1990). One is located on the continental shelf slope (the **Northern Current**, NC) and flows south-eastward along the Eastern coast of the Iberian Peninsula, and the other is located on the Balearic Islands shelf slope (the

Balearic Current, BC) and flows north-westward along the Northern coasts of the Balearic Islands (Fig. 6). At the south-westernmost part, **the Ibiza Channel is a circulation choke point**, governing the meridional water mass exchanges between the adjacent sub-basins, under strong topographic constraints. The **surface current** variability is mainly **driven by local winds**, showing a **strong seasonal pattern** (Lana et al., 2016).

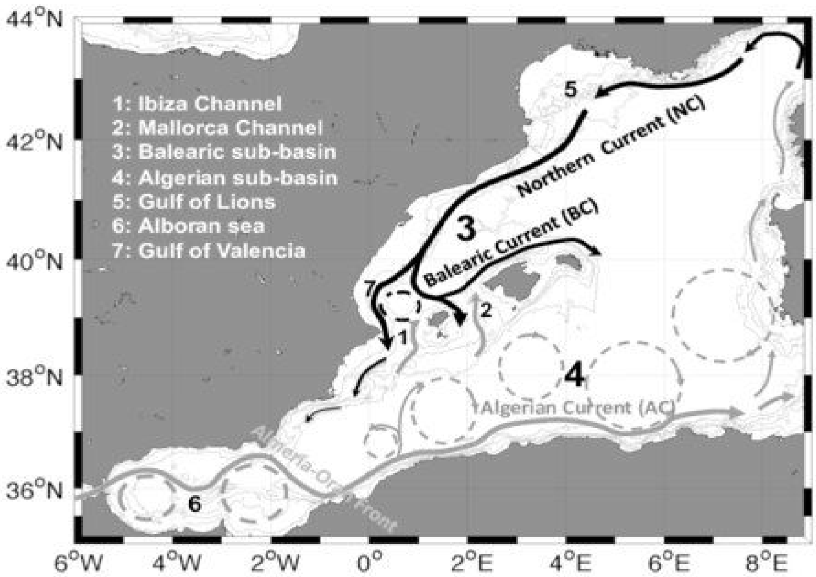

Figure 6: Map of the WSMED region, showing the main currents characterizing the regional circulation. The Northern (NC) and Balearic (BC) Currents are shown as thick black arrows. *From López-Jurado et al. 2015*.

In total **22 drifters** from SOCIB database were found in this region, as detailed in table 2:

Table 2.- Drifters used for experiments in the Balearic Sea.

Year	Drifters in Balearic Sea	Analyzed period
2014	13 (4 CODE; 5 MDO3i, 4 ODI) drifters from SOCIB	30/09/2014-02/12/2014
2016	4 ODI drifters from SOCIB	28/07/2016-17/09/2016
2018	5 CARTHE eco-friendly drifters from SOCIB	15/11/2018-25/12/2018

Drifters considered were of several types:

- **CODE**: is a robust solution to acquire coastal and estuarine water currents within a meter of the water surface, minimizing wind drag effects (Davis, 1985).
- **MDO3i**: is a cylinder shaped drifter, which has a diameter of 0.1 m and a length of 0.32 m, where only approx. 0.08 m are above the water surface when deployed. To enhance the drag, a drogue was attached 0.5 m below the sea surface with a 0.5m length and diameter. Due to the very small sail area above

the water surface the drifter's path represents the current in the upper meter of the water column.

- **ODI**: from Albatros Marine Technologies has a spherical shape with small diameter (⌀=0.2 m) and low weight (3 kg) possessing less than 50% of its body emerged. A drogue of 2 kg was attached at 0.5 below the sea surface, minimizing their area exposed to winds above the water surface, and thus the wind drag, ensuring the current measurement within the first meter of the water column.

- **CARTHE**: they are biodegradable and eco-friendly surface drifter for ocean sampling, similar to the traditional CODE (Novelli et al., 2017; D'Asaro et al., 2018) with wind speed at 10 m of 5-7 m/s. CARTHE seems to be representative of the upper 0.60 m (including Stokes drift), with minimal wave-rectification issues, with wind-induced slip velocity < 0.5% of the neutral wind speed at 10 m (U10).

Four different models were assessed, plus **HFR** data of the Ibiza Channel (Table 3). Before 2016, the reanalysis of the CMEMS models are used instead of forecast since forecast are only available starting from 2016.

Table 3.- Models and HF radar datasets used for experiments in the Balearic Sea.

Models/HF radar	Temporal resolution	Spatial resolution
CMEMS-IBI-MFC	Before 2016: daily After 2016: hourly	Before 2016: ~8km After 2016: ~2km
CMEMS-GLO-MFC	Before 2016: daily After 2016: hourly	~8km
CMEMS-MED-MFC	Before 2016: daily After 2016: hourly	Before 2016: ~6km After 2016: ~4km
SOCIB-WMOP	3-hourly	~2km
HF radar - Ibiza (OMA nowcasts)	Hourly	~3km

While CMEMS-GLO-MFC and CMEMS-MED-MFC include assimilation of data from satellite altimetry and Argo floats over the whole period of study, CMEMS-IBI-MFC and SOCIB-WMOP prediction systems have only implemented data assimilation in March 2018 and November 2018, respectively.

Summary of the results:

On average over the whole region, SS values range from 0.124 to 0.261, being the **CMEMS-GLO-MFC** the model showing the **best performance** for **2016 and 2018**, whereas the SOCIB-WMOP presentes a higher score in 2014. It must be highlighted that the **higher resolution models do not always show a better performance** than the lower-resolution ones. However, the SS in all experiments appear to be **very region-dependent and scenario-specific**, so the averaged SS depends on the region of interest and the period selected. For example, whereas CMEMS-GLO-MFC shows the best SS on average over the whole domain in the 2018 experiment, SOCIB-WMOP shows the best SS values in the northern part of the Ibiza Channel.

On average over the HFR coverage area (Ibiza Channel; IC), SS values range from 0.101 to 0.619, and **HFR shows the best SS**, with a value much higher than the models in 2014 and 2018, which is not surprising since HFR-derived surface current fields are based on observations. However in 2016, CMEMS-MED-MFC unexpectedly shows a better performance than HFR and its child model forecast, the regional model SOCIB-WMOP, with SS=0.619. This is because the CMEMS-MED regional model was capable of predicting the observations of inertial oscillations depicted by drifters, while the HFR derived surface currents were not able to properly reproduce some of these circularly polarized currents.

Results for the 2014 experiment:

In this experiment, 13 drifters of different types were released by SOCIB in the area of the Ibiza Channel as described in Lana et al., 2016. Some of them stayed in the Ibiza Channel until they reached the western coast of Ibiza, while the rest drifted north and got trapped in the Balearic Current flowing northeastward along the Balearic Islands shelf slope. North of Mallorca, part of the drifters entered the Menorca channel and ended in the northern coast of Mallorca. Fig. 7 shows the skill assessment performed over these 13 buoys and the Table 4 gives the average Skill Scores.

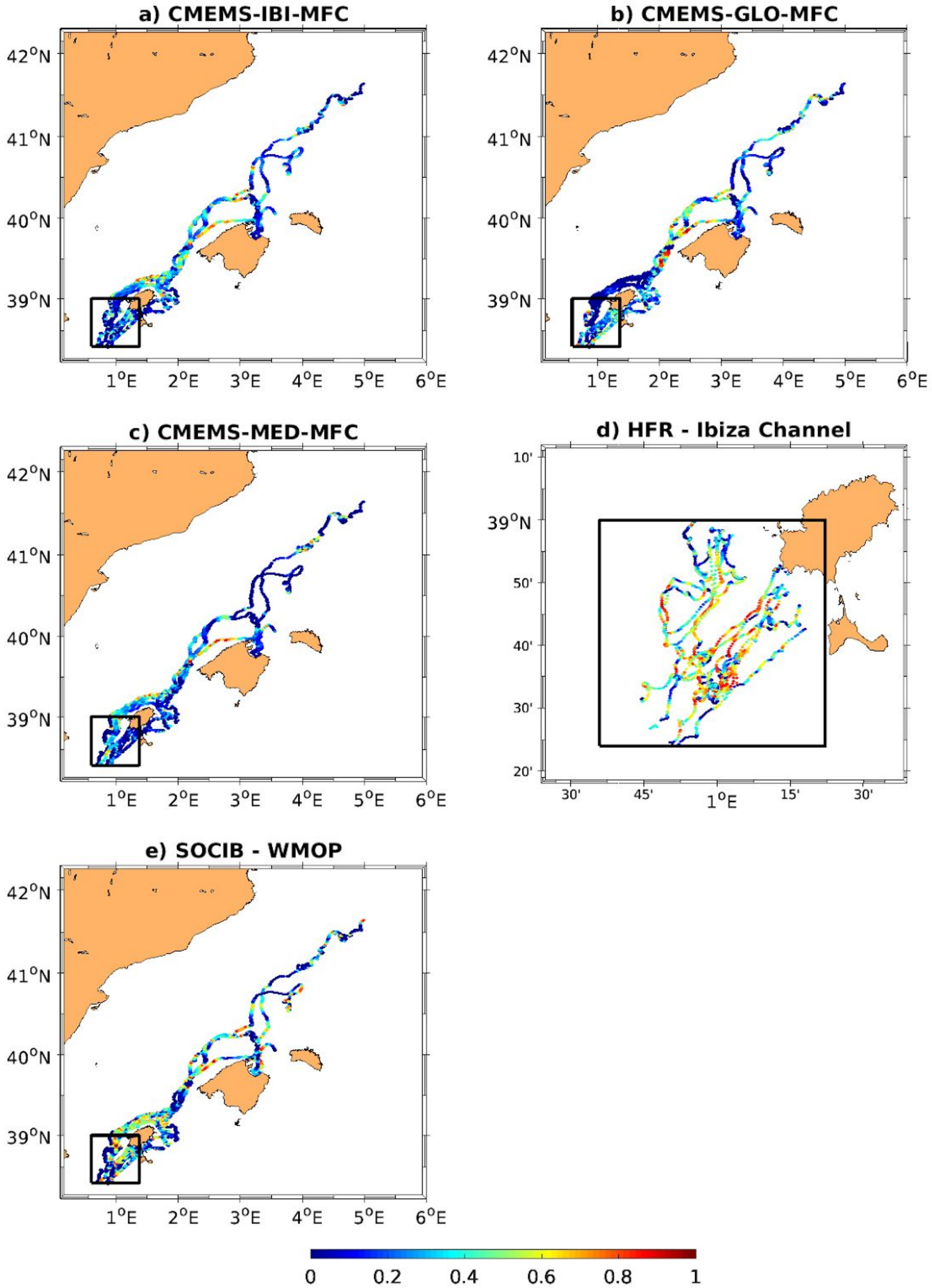

Figure 7: Map of the Balearic Sea showing the spatial distribution of Skill Scores for 2014 experiment and the models indicated in each figure title. Black line boxes show the bounding box around the region of the Ibiza Chanel, covering the HFR footprint area.

Table 4.- Results of 2014 experiment in Balearic Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the HFR domain (IC) for all drifters
CMEMS-GLO-MFC	0.195	0.197
CMEMS-MED-MFC	0.182	0.162
CMEMS-IBI-MFC	0.214	0.168
SOCIB - WMOP	**0.231**	0.168
HF radar - Ibiza	-	**0.406**

SOCIB-WMOP shows the best SS on average over the entire region. A common feature is the better performance of all velocity fields in the region northwest of Mallorca. In the northern coast of Ibiza, SOCIB-WMOP shows the best performance, being able to improve its parent model CMEMS-MED-MFC. On the contrary, CMEMS-GLO-MFC shows very low performance in this region. The same occurs on the northern coast of Mallorca, where SOCIB-WMOP shows the best SS, while the other models show much lower performance.

In the Ibiza Channel, HFR exhibits the best SS, as HFR-derived surface current fields are based on observations. SOCIB-WMOP does not show a good performance in the Ibiza Channel because it overestimates the intensity of the northern current (not shown), whereas CMEMS-GLO-MFC shows the highest SS among all other models.

Results for the 2016 experiment:

In this experiment, 4 ODI drifter buoys were deployed in the Ibiza Channel in the context of a SOCIB's HFR calibration experiment and tracked from July to September 2016. During this experiment, all drifters went straight northward and got outside the Ibiza Channel in less than 3 days. Once in the Balearic basin, they all got trapped by the Balearic Current and drifted northeastward, until reaching the northwest coast of Mallorca. There, one drifter rapidly reached the Mallorca coast, another continued northeastward, while the two other drifters went northwestward until reaching the catalan coast. Fig. 8 shows the skill assessment performed over these 4 buoys, and Table 5 shows the average Skill Scores.

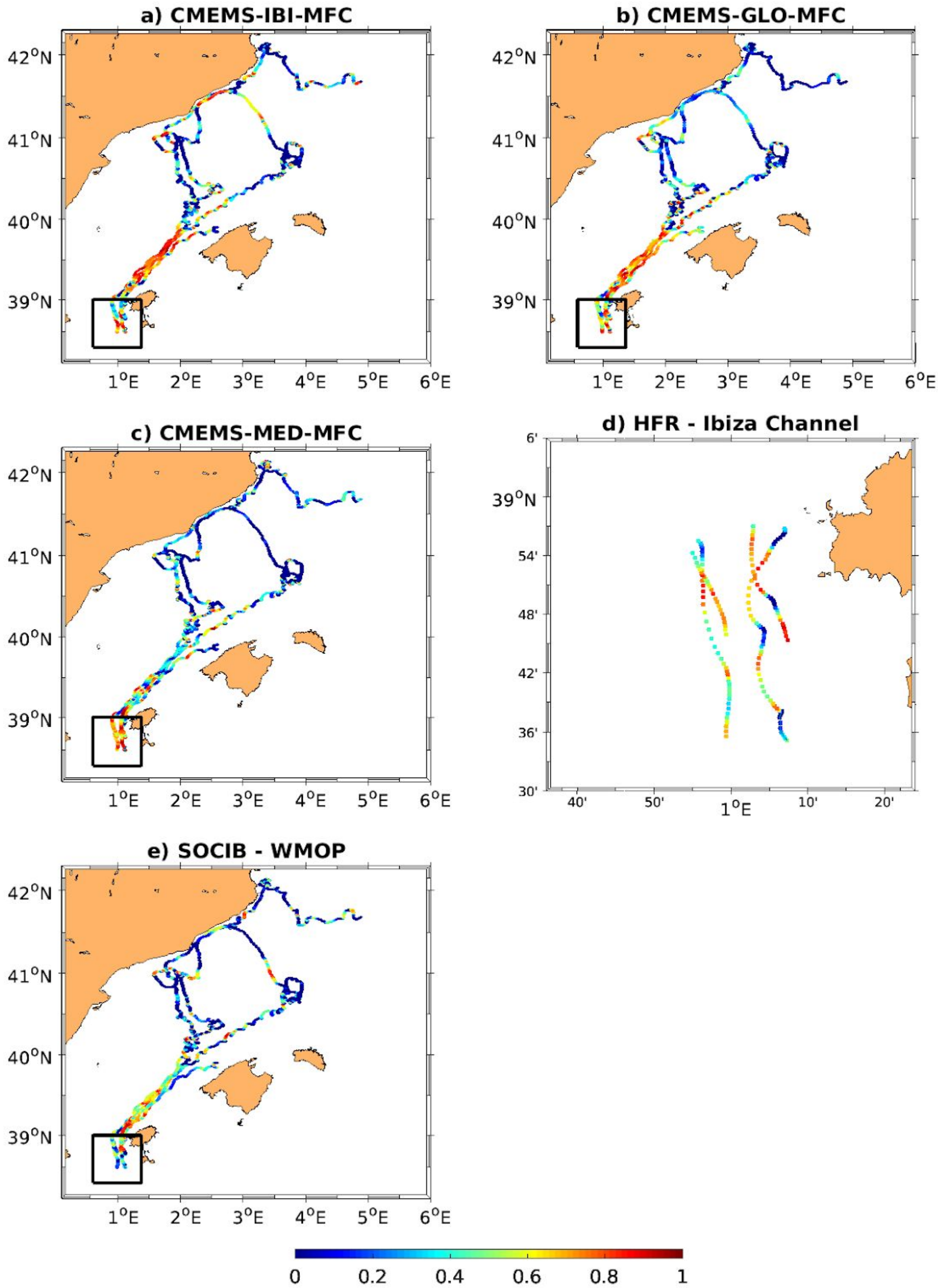

Figure 8: Map of Balearic Sea showing the spatial distribution of Skill Scores for 2016 experiment and the datasets indicated in each figure title. Black line boxes show the bounding box around the region of the Ibiza Chanel, covering the HF radar footprint area.

Table 5.- Result of 2016 experiment in Balearic Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the HFR domain for all drifters
CMEMS-GLO-MFC	**0.261**	0.487
CMEMS-MED-MFC	0.241	**0.619**
CMEMS-IBI-MFC	0.260	0.493
SOCIB - WMOP	0.213	0.362
HF radar - Ibiza	-	0.482

In this experiment, all models perform better than in the previous experiment due to the northeastward straight trajectory of the drifters during this period, following the mean circulation of this area.

On average over the entire domain, CMEMS-GLO-MFC shows the best SS, closely followed by the CMEMS-IBI-MFC model. They both show good performance (SS > 0.7) in the northern part of Ibiza and Mallorca channel, where the drifters had the straight northeastward trajectory. On the contrary, CMEMS-MED-MFC does not show a good performance, probably because it is not able to properly reproduce the Balearic Current during this specific period. Its child-model SOCIB-WMOP shows better performance than its parent models in this region. On the contrary, in the northern part of the Balearic Sea, none of the models show a good performance, and SOCIB-WMOP is not able to improve the performance of its parent model. This is probably due to the bad representation of the Northern Current in all models.

On the other hand, **in the Ibiza Channel**, all models except SOCIB-WMOP show good performance (SS > 0.45 in most cases), and **CMEMS-MED-MFC appears to be the most robust model** solution for this specific period, followed by the CMEMS-IBI-MFC and the CMEMS-GLO-MFC. It shows even better performance than the HFR, because it is able to reproduce the inertial oscillations, while the HFR derived surface currents were not able to properly reproduce some of these circularly polarized currents in this specific event (not shown). In this case, the SOCIB-WMOP could not improve its parent model, the CMEMS-MED-MFC, because of its well-known overestimation of the zonal intensity in the southern part of the HFR domain and due to the confinement of the northward flow to the eastern part of the channel (Aguiar et al., 2019).

Results for the 2018 experiment:

In this experiment, 5 eco-friendly CARTHE drifters were deployed in the Ibiza Channel in the context of a SOCIB's HFR calibration experiment on November 15th and tracked until mid-December. During this experiment, the drifters became temporarily entrapped in small-scale circulation patterns and stayed in the region of the Ibiza Channel until they were caught up in the Balearic Current flowing towards the Mallorca Channel. Fig. 9 shows the skill assessment performed over these 5 buoys, and Table 6 shows the averaged Skill Scores.

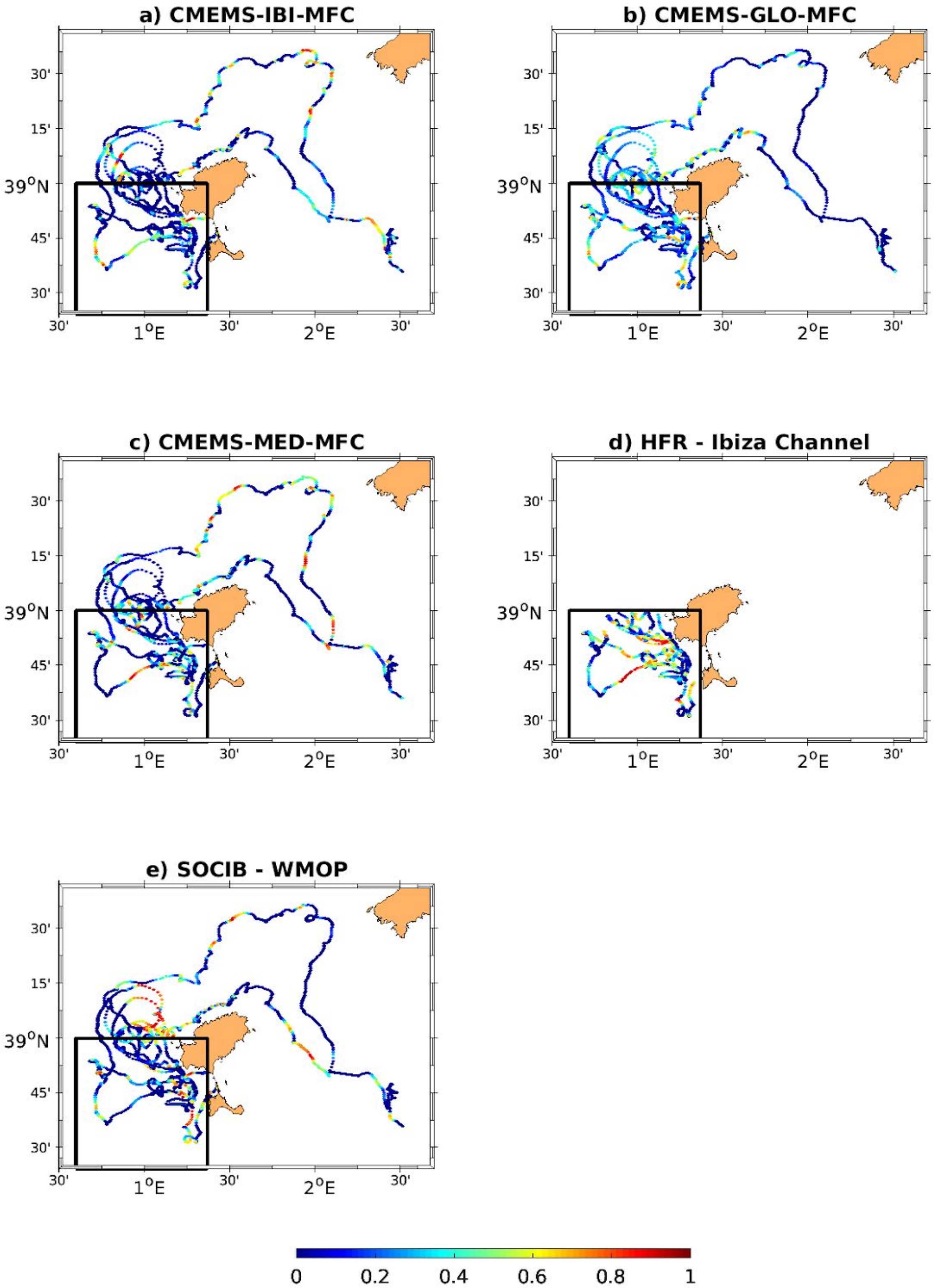

Figure 9: Map of the Balearic Sea showing the spatial distribution of Skill Scores for 2018 experiment and the datasets indicated in each figure title. Black line boxes show the bounding box around the region of the Ibiza Chanel, covering the HF radar footprint area.

Table 6.- Result of 2018 experiment in Balearic Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the HFR domain for all drifters
CMEMS-GLO-MFC	**0.179**	0.204
CMEMS-MED-MFC	0.160	0.168
CMEMS-IBI-MFC	0.124	0.101
SOCIB - WMOP	0.151	0.148
HF radar - Ibiza	-	**0.265**

On average over the entire domain, **CMEMS-GLO-MFC shows the best performance**. However, in the region northwest of Ibiza, SOCIB-WMOP shows better performance (SS value > 0.6), and in the Mallorca channel, CMEMS-IBI-MFC and CMEMS-MED-MFC shows better performance. Nevertheless, none of the evaluated models shows good performance (SS < 0.18 on average), because of the turbulent character of the trajectories.

In the Ibiza Channel, HFR shows the best performance (0.265), with better values inside the coverage area but not at the edges of the domain. Among the models, **CMEMS-GLO-MFC shows the best performance.** However, none of the models show high SS values because each model reproduces a different dynamic in the area, in particular in the northern part of the Ibiza Channel where most of the trajectories are (not shown).

2.2. Results in the Southeastern Bay of Biscay.

The ocean circulation in the Southeastern Bay of Biscay shows relatively **complex pattern**s. The **wind is the main forcing** of the circulation **over the shelf**, driving highly variable currents in this area, in terms of strength and direction (Rubio et al. 2013a). Winds have a marked seasonality, being more intense and more persistent in winter. This leads to **strong seasonality** in the intensity and direction of the boundary current: **the Iberian Poleward Current (IPC)**, with stronger currents in winter (Fig. 10). **Significant mesoscale variability** has been observed **along the slope**, where the interaction of the current and the bathymetry gives rise to coherent mesoscale structures, identified like long-lived anticyclonic eddies, commonly known as **SWODDIES** – Slope Water Oceanic eDDIES (Pingree and Le Cann, 1990; Caballero et al. 2014).

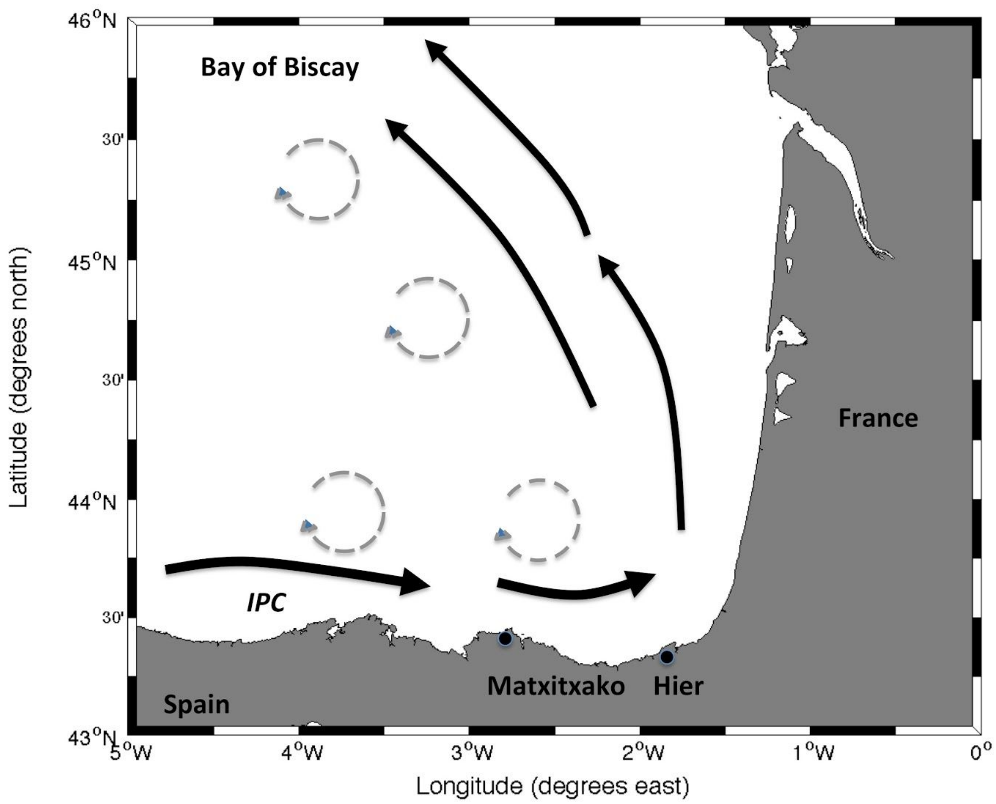

Figure 10: Map of the Biscay Bay showing the main characteristics of the oceanic circulation. The winter Iberian Poleward Current (IPC) is represented by the blacksolid arrows, whereas the light grey dashed lines show the mesoscale eddy regime (although only anticyclonic arrows are represented, eddies of anticyclonic and cyclonic polarity are observed in different locations along the slope). The black dots represent the HFR stations: Matxitxako (left) and Higer (right). Adapted from Rubio et al., 2018.

In this region, **5 drifters** have been used (Table 7). **Two of them** were released during two **SASEMAR exercises**. These drifters, with cylindrical shape, were designed to be at the sea surface and are highly influenced by the wind. Each drifter consisted of a wide mouth and high-density polyethylene container (height: 19.4 cm; external and opening diameters: 19 and 22 cm, respectively; usable volume: 4 L; and empty weight: 2,600 g) containing a SPOT Trace device and an additional weight. The volume of the drifter is 20-30% emerged so they respond to the surface currents and partially to the direct wind drag effect. Drifter 1 was released at the end of the summer (17-19 September 2018), while drifter 2 was launched during winter (12-14 February 2019). Then **three drifters from CMEMS** (with platform codes: 4401627; 6203505, 4101616) were also used, for different periods in winter and spring 2018 and 2019. There drifters consist in a spherical float and a cylindrical hole-sock drogue centered at a nominal depth of 15m.

Table 7.- Drifters used for experiments in Biscay Bay.

Drifter n#	Drifters in Biscay Bay	Analyzed period
1	SASEMAR summer drifter 2018	17/09/2018-19/09/2018
2	SASEMAR winter drifter 2019	12/02/2019-14/02/2019
3	CMEMS/DB4401627	07/06/2018-13/06/2018

4	CMEMS/DB6203505	30/04/2018-03/05/2018
5	CMEMS/DB4101612	10/02/2019-29/03/2019

Five different models were assessed (Table 8): four models from CMEMS (GLO, IBI, NWS, MED) and one model from the Spanish Port System (coastal model for Bilbao Port - SAMOA. In addition, **HF radar** datasets have also been evaluated.

Table 8.- Models and HF radar datasets used for experiments in Biscay Bay.

Models/HF radar	Temporal resolution	Spatial resolution
CMEMS-IBI-MFC	hourly	~2km
CMEMS-GLO-MFC	hourly	~8km
CMEMS-MED-MFC	hourly	~4km
CMEMS-NWS-MFC	hourly	~1.5km
PUERTOS-SAMOA-Bilbao	hourly	~350m
HF radar - SE Biscay Bay (OMA totals)	hourly	~5km

Figures 11 and 12 show the skill assessment results over the entire region and the Bilbao subregion. Averaged SS values are given for each target source in Table 9.

Summary of the results:

On average over the whole region (Table 9), SS values range from 0.21 to 0.25, being **HFR** the one that **shows the best performance**. However, SS are low in the regions of the HF radar two-station baseline and at the outer edges of the domain, areas where the HF Radar currents are known to have a higher observational error. Among the models, **CMEMS-IBI-MFC** shows the best performance because of high SS in the region of Bilbao. It is worth noting that this result matches the information provided by the SAR operators from the MRCC Bilbao, who reported that, based on their professional expertise, from the models available, the CMEMS-IBI-MFC gave the best results in reproducing the drifter track.

In general, **the SS values are higher** for the **Bilbao subregion** with values ranging between 0.23 to 0.29. In this case, two models (CMEMS-MED-MFC and CMEMS-IBI-MFC) are performing as well as the HF Radar, being the **best scores obtained with the CMEMS-NWS-MFC**. Not surprisingly, CMEMS-MED-MFC presents the lowest SS for the Biscay area, as this model is not relevant in this area (i.e. no tides, close to its open boundaries). However, it presents better results in the Bilbao subregion. PUERTOS-SAMOA's performances are better than the CMEMS-GLO-MFC, but worse than the rest of the models, being not able to improve the performance of its parent model (CMEMS-IBI-MFC), probably due to its bad performance close to the open boundaries.

What can be observed in the figures is that there are **better SSs over the Spanish shelf**, compared with the open waters. Indeed, if we perform the average of the SS over the shelf (defined by the area of bottom depths shallower than 200m west of 2ºW) we obtain a mean SS of 0.273, while out of this area SS is 0.196. This is because the **drifter trajectories** over the shelf **followed the large-scale pathway of the IPC,** which is **generally better represented in the models**, while the drifters in the northern part of the domain were trapped in the **SWODDIES**, being these features **less predictable in time and space**.

Table 9.- Result of experiments in Biscay Bay. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the Bilbao region for all drifters
CMEMS-GLO-MFC	0.220	0.233
CMEMS-MED-MFC	0.214	0.283
CMEMS-IBI-MFC	0.233	0.282
CMEMS-NWS-MFC	0.212	**0.296**
HFR - SE Biscay Bay	**0.248**	0.283
SAMOA-Bilbao	-	0.274

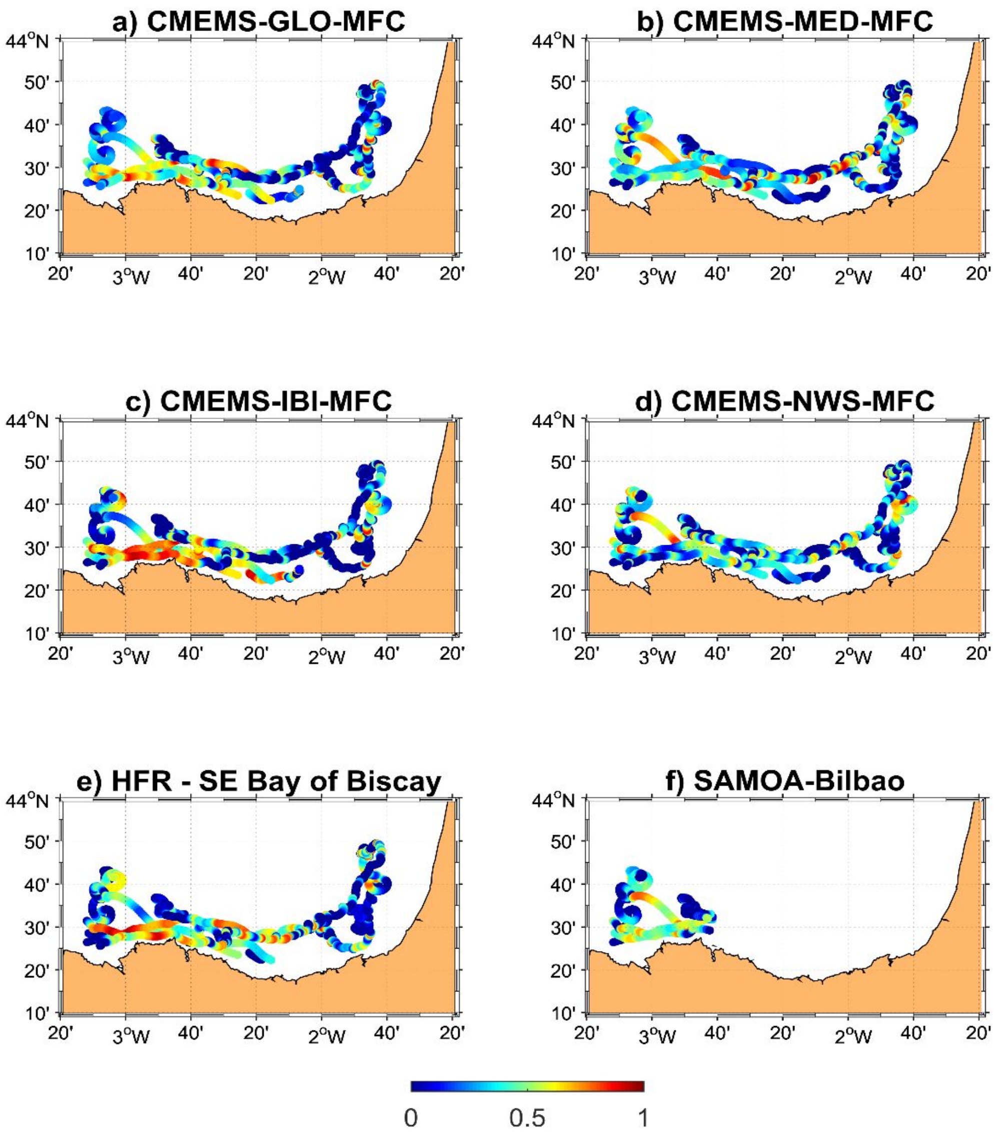

Figure 11: Map of the SE Bay of Biscay showing the spatial distribution of Skill Scores for the datasets indicated in each figure title (note the different spatial domain covered by SAMOA).

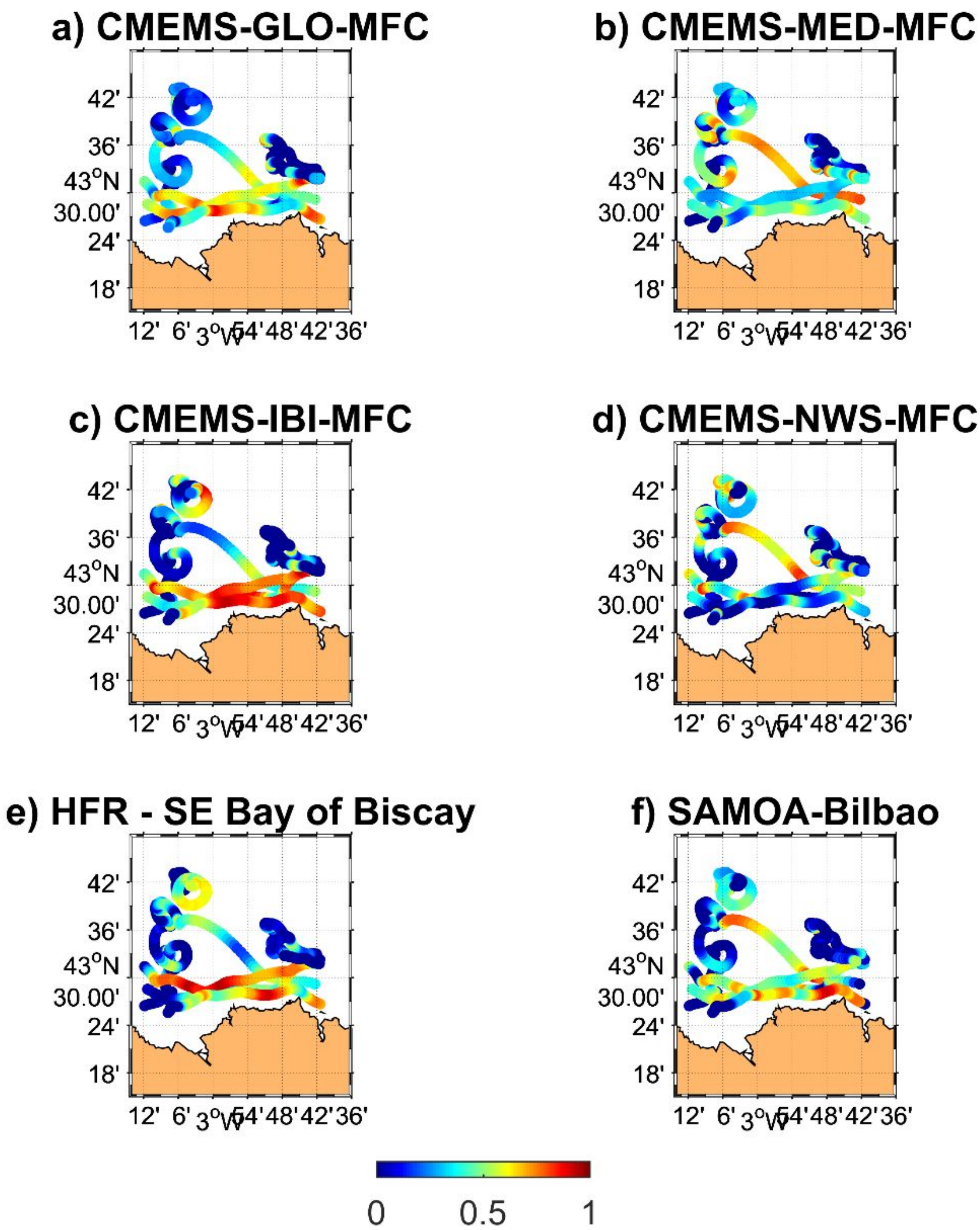

Figure 12: Map of the Bilbao region (SE Bay of Biscay) showing the spatial distribution of Skill Scores for the datasets indicated in each figure title.

When analyzing the performances of the models and HF radar data **for each drifter** we observe **high variability** (Table 9). For instance, most of the models and the HF radar present very low SS for drifters #2 and #3 while, **all perform much better for drifter #4**. Also, during the summer, none of the models are able to reproduce the entire eddy-like trajectory of the drifter #1, with CMEMS-IBI-MFC and HFR from the NIBSH region presenting the higher SS on average. This suggests that the **performances can be very different depending on the prevailing dynamic conditions in the analyzed periods and buoy locations**.

Table 9.- Skill Score averaged for each drifter available in Biscay Bay, inside the HFR footprint coverage. The highest SS for each drifter is indicated in bold.

Dataset	SS averaged over the whole region for each of the available drifters					SS averaged over the Bilbao region for each of the available drifters			
Source / drifter	#1	#2	#3	#4	#5	#1	#3	#4	#5
CMEMS-GLO-MFC	0.186	0.234	0.252	0.453	0.206	0.186	0.227	0.525	0.258
CMEMS-MED-MFC	0.275	0.040	**0.352**	0.322	0.217	0.275	**0.331**	0.378	0.252
CMEMS-IBI-MFC	0.303	**0.411**	0.172	**0.587**	0.157	0.303	0.135	**0.639**	0.298
CMEMS-NWS-MFC	**0.403**	0.030	0.210	0.271	0.205	**0.403**	0.198	0.267	0.223
HFR - Biscay Bay	0.291	-*	0.229	0.371	**0.242**	0.291	0.206	0.406	0.305
SAMOA-Bilbao	-	-	-	-	-	0.329	0.184	0.438	**0.310**

2.3. Results in the Alboran Sea.

The Strait-of-Gibraltar is one of the most singular spots of the oceans, where exchanges between Atlantic and Mediterranean basins occur. The mean circulation through the Strait is composed of **two counter flowing currents**. In the **upper layer fresher Atlantic water** flows east toward the Mediterranean and, in the **lower layer, saltier and denser Mediterranean water** flows westward to the Atlantic. In the **Alboran Sea**, the surface **circulation is dominated** by the meanders of the **Atlantic jet** (Fig. 13): the **Western Alboran Gyre** (WAG), which is permanent throughout the year, and the **Eastern Alboran Gyre** (EAG), which shows some seasonality (Renault et al. 2012). **More eastward**, the circulation is dominated by the **Algerian Current** (AC) flowing along the African coat. This current is highly energetic and present large and intense anticyclonic eddies that detach from the coast (Escudier et al. 2016b).

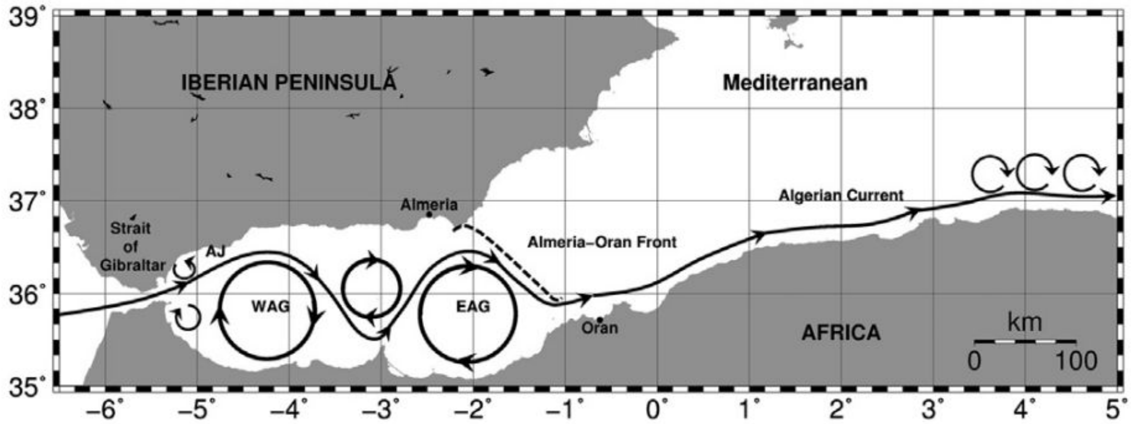

Figure 13: Scheme of the surface circulation in the Alboran Sea and the Algerian Basin. Features such as the Atlantic Jet (AJ), Western and Eastern Alboran Gyres (WAG and EAG, respectively) and the Almeria-Oran Front together with the Algerian Current are depicted. *From Sotillo et al. 2016.*

In total **114 drifters** were found in this region, but **only 23 inside HFR coverage**, as detailed in tables 10 and 11:

Table 10.- Drifters in Alboran Sea used for experiments in the Alboran Sea.

Year	Drifters in Alboran Sea	Analyzed period
2014	35 mostly CODE drifters from MEDESS-GIB experiment	09/09/2014-30/11/2014
2018	18 drifters (12 CODE and 6 SVP) from COSMO experiment	19/02/2018-30/04/2018
2019	58 SVP drifters from CMEMS (CALYPSO campaign)	01/03/2019-30/04/2019

Table 11.- Drifters inside HF radar coverage used for experiments in the Alboran Sea.

Year	Drifters inside HF radar coverage	Analyzed period
2014	20 CODE drifters from MEDESS-GIB experiment	09/09/2014-13/09/2014
2015	3 drifters (2 ODI and 1 SVP) from CMEMS	04/12/2015-09/12/2015

In addition to the CODE and ODI drifter types, already described in section 2.1, SVP drifters were used. The MetOcean Surface Velocity Program (SVP) drifting buoy is a Lagrangian current-following drifter, designed to track water currents 15 metres below the ocean surface.

Five different models were assessed, plus the **HFR data** of the Strait of Gibraltar (Table 12). Before 2016, the reanalysis of the CMEMS models are used instead of hindcast since hindcast are only available starting from 2016.

Table 12.- Models and HF radar datasets used for experiments in the Alboran Sea.

Models	Temporal resolution	Spatial resolution
CMEMS-IBI-MFC	Before 2016: daily After 2016: hourly	Before 2016: ~8km After 2016: ~2km
CMEMS-GLO-MFC	Before 2016: daily After 2016: hourly	~8km

CMEMS-MED-MFC	Before 2016: daily After 2016: hourly	Before 2016: ~6km After 2016: ~4km
SOCIB-WMOP	3-hourly	~2km
PUERTOS-SAMPA	Hourly	~300-500m
HF radar - Gibraltar (OMA totals)	Hourly	~1km

In total 5 experiments were performed:

2014a : MEDESS-GIB experiment (35 drifters)
2014b : MEDESS-GIB drifters inside HFR coverage (20 drifters)
2015 : CMEMS drifters inside HFR coverage (3 drifters)
2018 : COSMO experiment (18 drifters)
2019 : CALYPSO experiment (58 drifters)

Summary of the results:

On average over the whole region, CMEMS-GLO-MFC shows the best performance in 2014a (Fig. 14 and Table 13) and 2019 (Fig. 18 and Table 17), while CMEMS-MED-MFC shows the best performance in 2018 (Fig. 17 and Table 16). It is surprising that the **models with the highest resolutions do not show better performance** than the lower-resolution ones, probably because the drifters generally followed the **large-scale circulation features of the Alboran Sea** (e.g. Western Alboran Gyres and Algerian current), which are relatively **well represented in large-scale models**. All models have some **troubles in reproducing the quasi-permanent EAG gyre** (Fig. 14, 17, 18), particularly those with coarser resolution. This also highlights the fact that the models could have some issues by assimilating altimetry to improve their solutions.

On average over the region of the PUERTOS-SAMPA model, different **regional models** show the best performance for each one of the experiments, as follows: SOCIB-WMOP in 2014a (Fig. 14 and Table 13), CMEMS-MED-MFC in 2018 (Fig. 17 and Table 16), and CMEMS-IBI-MFC in 2019 (Fig. 18 and Table 17). In these experiments, the highest resolution model PUERTOS-SAMPA always shows a low performance, because it does not properly represent the dynamic of the Western Alboran Gyre during the periods considered. However, in the experiments where only the **Gibraltar Strait region** was considered (experiments 2014b, Fig. 15 and Table 14; and 2015, Fig. 16 and Table 15), PUERTOS-SAMPA shows SS values higher (e.g. experiment 2014b) or similar to other models.

In the experiments where HFR data have been included (experiments 2014b; Fig. 15 and Table 14 and 2015 Fig. 16 and Table 15), **HFR always shows the best performance**, suggesting that HFR data should be used instead of numerical models for backtracking purposes. However, the SS in all experiments appear to be very **scenario-specific and region-dependent,** so more drifters in the HFR coverage during different periods are needed in order to be able to make a robust conclusion.

Results for the 2014a experiment:

On 9 September 2015, 35 drifters were deployed in the Strait of Gibraltar in the frame of the MEDESS-GIB experiment (Sotillo et al. 2016). The purpose of this experiment was to characterize the surface circulation in the Alboran Sea and the Algerian basin. During the first weeks, all drifters followed the northern branch of the Western Alboran Gyre (WAG) and the Eastern Alboran Gure (EAG). Then, part of the drifters recirculated in the southern branch of the EAG, while others followed the Algerian Current. Once in the Algerian basin, most of the drifters get trapped in the anticyclonic eddies of the Algerian current.

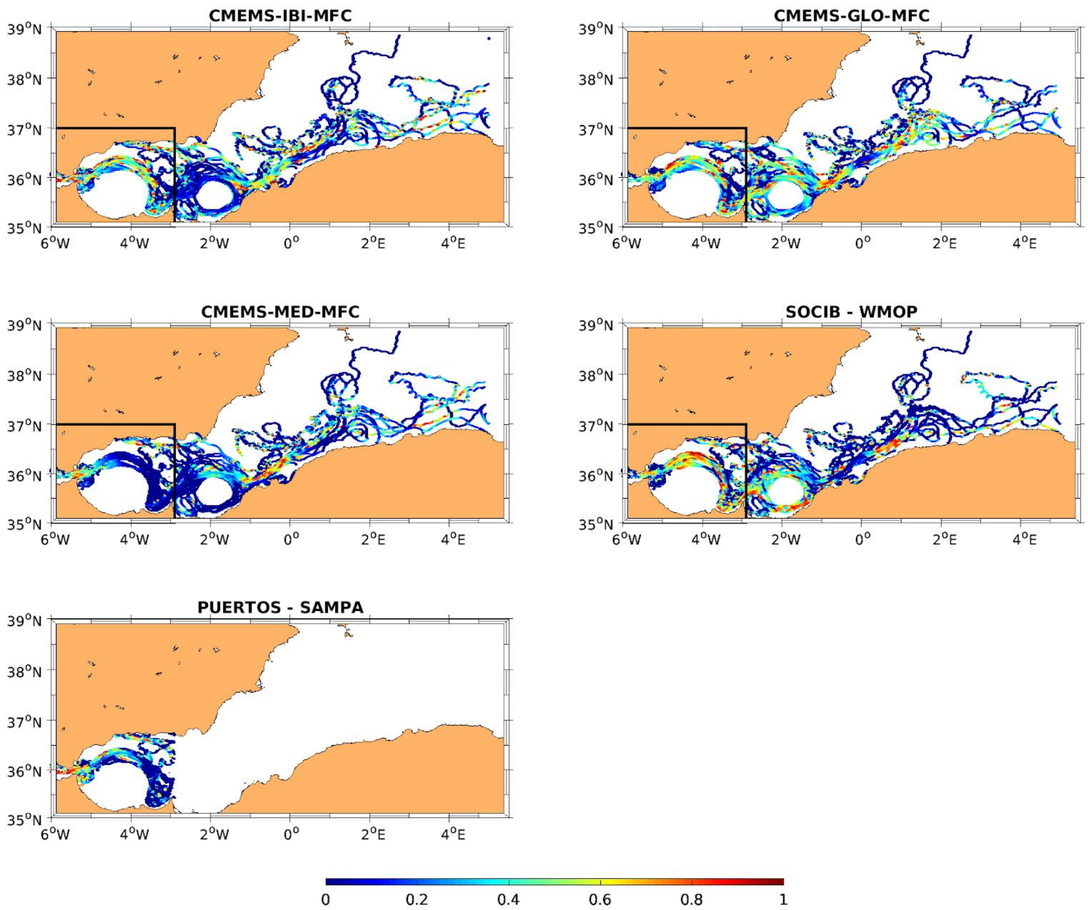

Figure 14: Map of the Alboran Sea showing the spatial distribution of Skill Scores for 2014a experiment and the models indicated in each figure title. Black line boxes show the bounding box of the PUERTOS-SAMPA model.

Table 13.- Results of 2014a experiments in the Alboran Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the PUERTOS-SAMPA domain for all drifters
CMEMS-GLO-MFC	**0.246**	0.240
CMEMS-MED-MFC	0.168	0.136
CMEMS-IBI-MFC	0.217	0.240
SOCIB - WMOP	0.210	**0.259**
PUERTOS-SAMPA	-	0.151

In this experiment, **CMEMS-GLO-MFC shows the best SS on average over the entire region**, closely followed by CMEMS-IBI-MFC and SOCIB-WMOP, because the drifters followed the large-scale meanders of the Atlantic jet that are well represented in these models (not shown). Indeed, the highest SS values are found in the Western Alboran Gyre (WAG), the Eastern Alboran gyre (EAG), and in the Algerian current along the North African coast.

When considering only the PUERTOS-SAMPA domain (WAG region), SOCIB-WMOP shows the best performance (also followed by the CMEMS-GLO-MFC and CMEMS-IBI-MFC), because very high values are found in the northern part of the WAG, suggesting that WMOP better represent the WAG than the other models during this period. Although of much higher resolution, the PUERTOS-SAMPA model shows lower performance because it does not properly represent the extension of the WAG during the period of the experiment (not shown).

Results for the 2014b experiment:

Here, we only consider the 20 drifters from the MEDESS-GIB that were deployed in the HFR domain of Gibraltar and remained in the domain for more than 6 hours. The period of this experiment corresponds to the first 4 days of the MEDESS-GIB experiment. Part of the drifters were deployed in the Strait of Gibraltar and moved eastward with the Atlantic inflow. Once in the Mediterranean basin, some of them moved southward, while others moved northward. The other drifters were deployed in the eastern part of the Algeciras bay and got trapped in mesoscale circulation features.

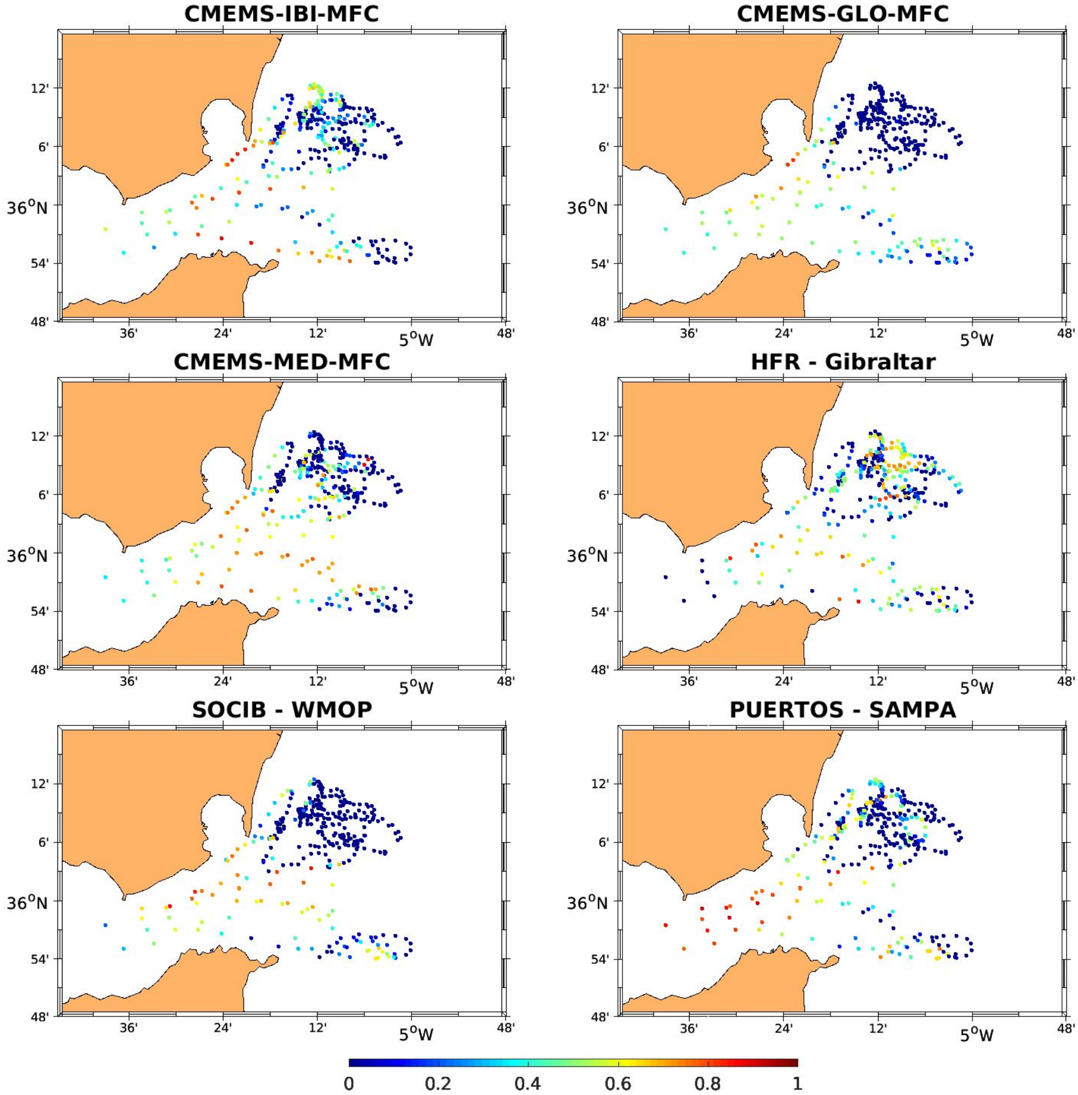

Figure 15: Map of Gibraltar showing the spatial distribution of Skill Scores for 2014b experiment and the datasets indicated in each figure title.

Table 14.- Results of 2014b experiments in the Alboran Sea. The highest SS value is in bold.

Dataset	SS averaged over the whole HFR region for all available drifters
CMEMS-GLO-MFC	0.118
CMEMS-MED-MFC	0.227
CMEMS-IBI-MFC	0.239
SOCIB - WMOP	0.134
HFR - Gibraltar	**0.340**
PUERTOS-SAMPA	0.226

In this experiment, **HFR shows the best SS value**, followed by CMEMS-IBI-MFC, while SOCIB-WMOP and CMEMS-GLO-MFC show the lowest SS values because they do not represent well the Atlantic jet during this period (they show an unrealistic northeastward trajectory; not shown). **PUERTOS-SAMPA shows the highest SS within the Strait of Gibraltar**, but it does not represent well the dynamics in the eastern part of the Algeciras bay (i.e. eastern part of the domain).

Results for the 2015 experiment:

Here, we consider the CMEMS drifters that got into the Gibraltar HFR footprint area. Three drifters were deployed in the Strait of Gibraltar on December 4th 2015 and stayed inside the HFR coverage area until December 9th 2015.

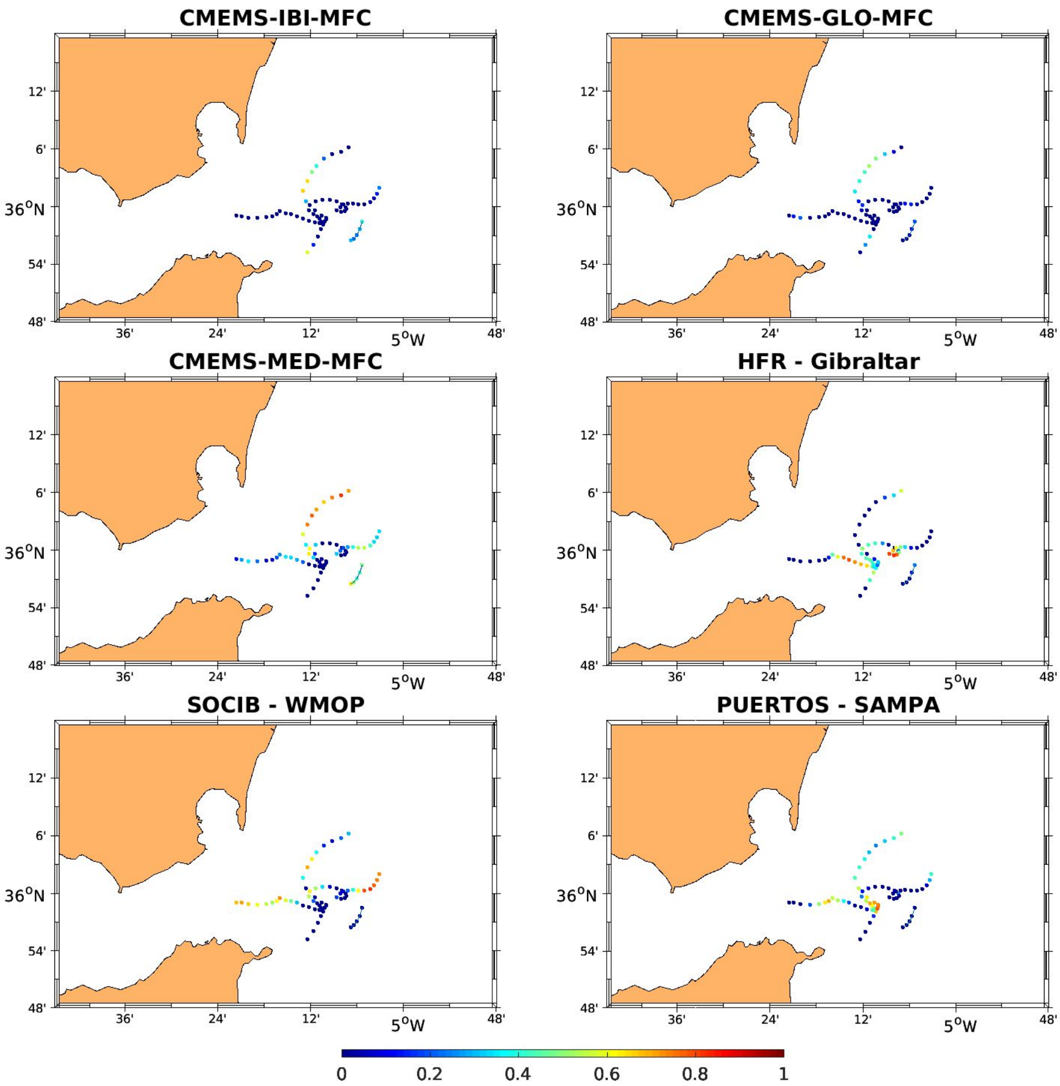

Figure 16: Map of Gibraltar strait showing the spatial distribution of Skill Scores for 2015 experiment and the models indicated in each figure title.

Table 15.- Results of 2015 experiments in the Alboran Sea. The highest SS value is in bold.

Dataset	SS averaged over the whole HFR region for all available drifters
CMEMS-GLO-MFC	0.071
CMEMS-MED-MFC	0.264
CMEMS-IBI-MFC	0.082
SOCIB - WMOP	0.260
HFR - Gibraltar	**0.280**
PUERTOS-SAMPA	0.252

In this experiment, **HFR shows the best SS value**, followed by CMEMS-MED-MFC model, while CMEMS-IBI-MFC and CMEMS-GLO-MFC show very low values because they overestimate the intensity of the Atlantic jet (not shown).

Results for the 2018 experiment:

On 19 February 2018, 18 drifters were deployed in the Alboran Sea in the frame of the COSMO project. During the first two weeks, all drifters went southeastwards in the Western Alboran Gyre (WAG). Then, all drifters became trapped in the Eastern Alboran Gure (EAG). Part of the drifters recirculated in the southern branch of the EAG, while others followed the Algerian Current. Once in the Algerian basin, most of the drifters followed the coastal shelf, being trapped sometimes in the anticyclonic eddies of the Algerian current.

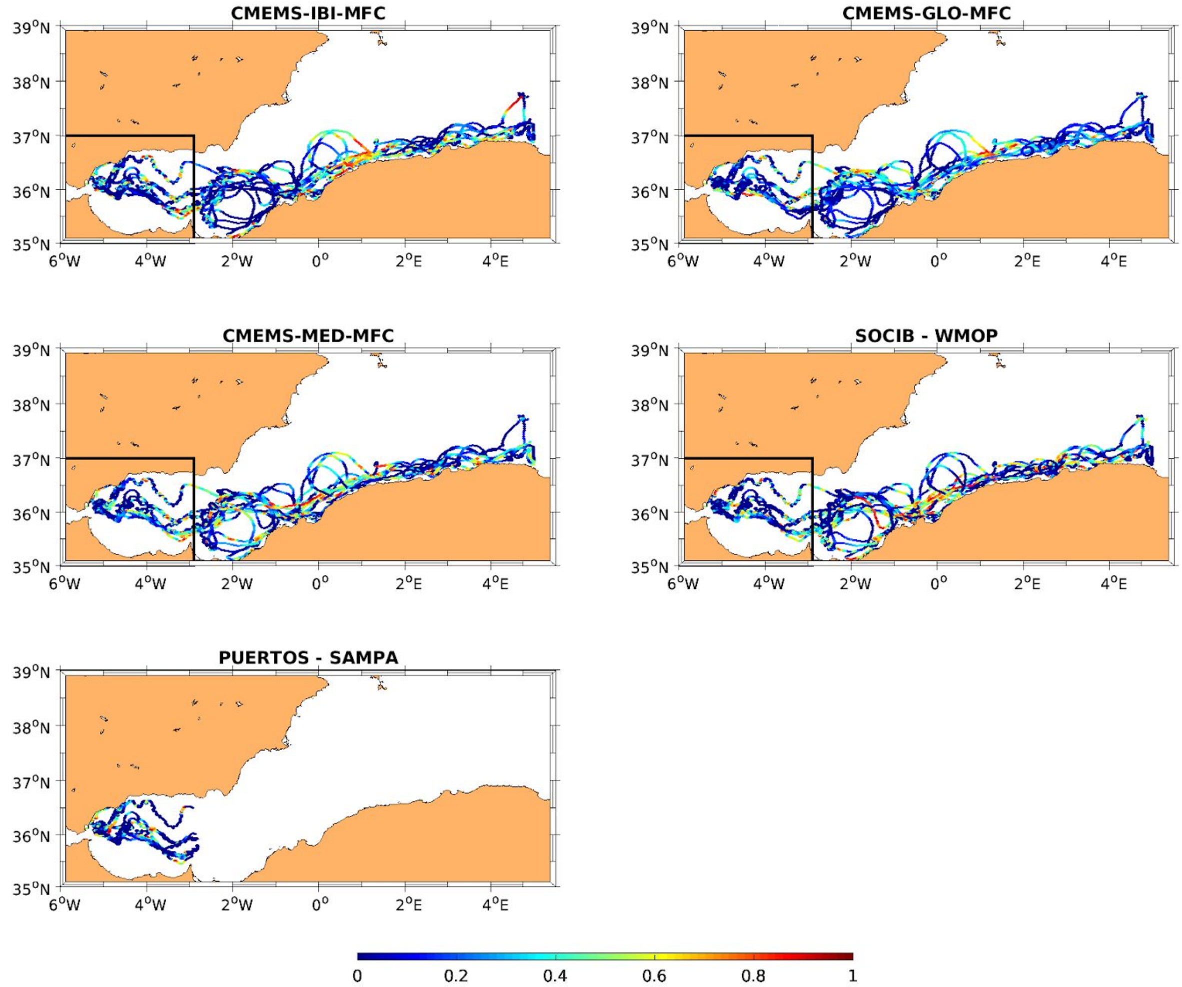

Figure 17: Map of the Alboran Sea showing the spatial distribution of Skill Scores for 2018 experiment and the datasets indicated in each figure title. Black line boxes show the bounding box of the PUERTOS-SAMPA model.

Table 16.- Results of 2018 experiments in the Alboran Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the PUERTOS-SAMPA domain for all drifters
CMEMS-GLO-MFC	0.166	0.129
CMEMS-MED-MFC	**0.177**	**0.153**
CMEMS-IBI-MFC	0.166	0.144
SOCIB - WMOP	0.169	0.128
PUERTOS-SAMPA	-	0.108

In this experiment, **CMEMS-MED-MFC shows the highest SS value over both domains, the whole and the PUERTOS-SAMPA ones.** However, none of the models show good performance in predicting the drifter trajectories, probably because none of the models is able to reproduce the turbulent eddy-like trajectories of the drifters. PUERTOS-SAMPA shows the lowest performance, because the Western Alboran Gyre is too weak in this model (not shown).

Results for the 2019 experiment:

From March 27th to April 9th 2019, 58 drifters were deployed in the Alboran Sea tracked until April 30th in the context of the CALYPSO campaign. During the first week, most drifters were trapped in the northern branch of the Western Alboran Gyre (WAG) and went eastward and southward. The drifter deployed in the northern part of the Alboran Sea also went southward along the eastern branch of the WAG. Then, the drifters followed the African coast, until reaching the Eastern Alboran Gyre (EAG), between 1W and 0W. Most of the drifters recirculated in the southern branch of the EAG, while a few followed the Algerian Current.

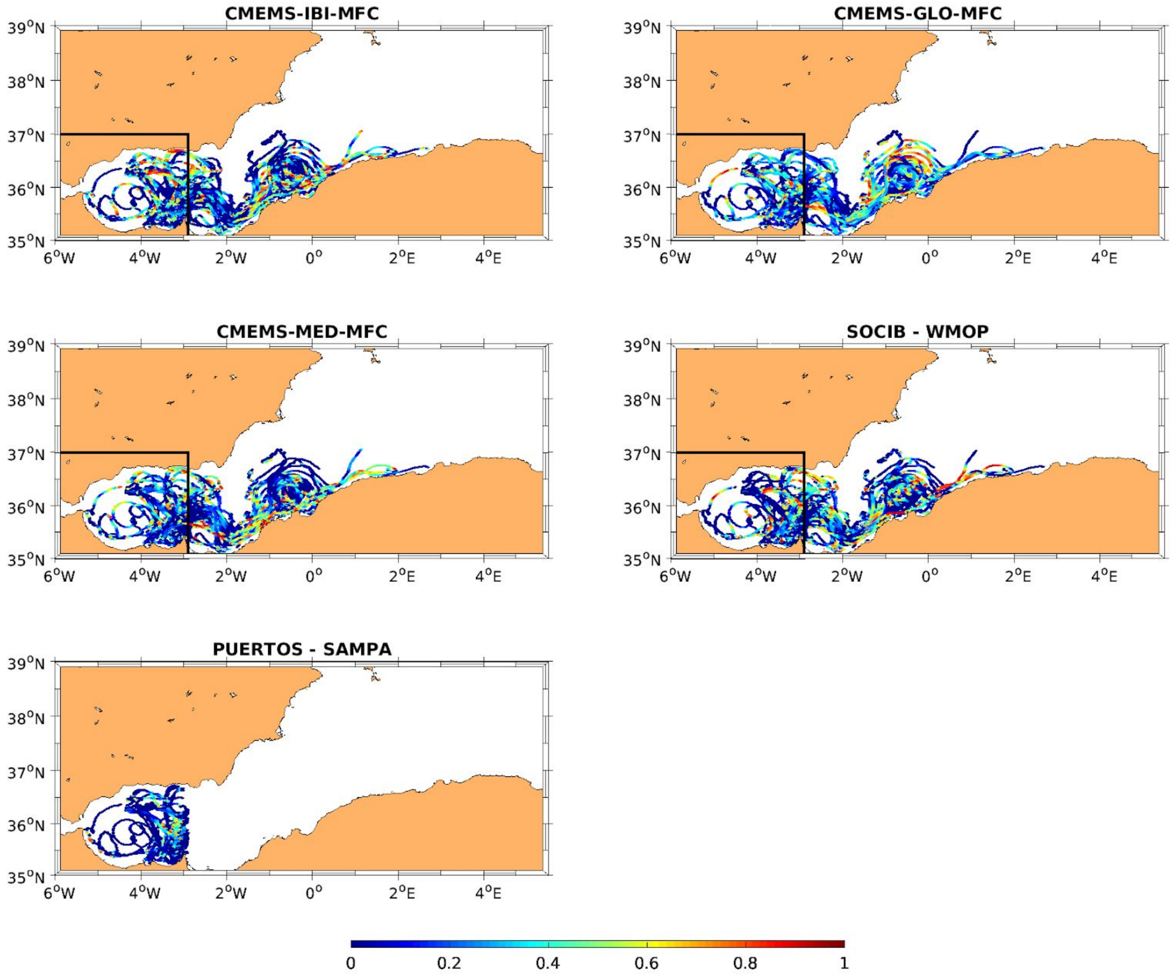

Figure 18: Map of the Alboran Sea showing the spatial distribution of Skill Scores for 2019 experiment and the datasets indicated in each figure title. Black line boxes show the bounding box of the PUERTOS-SAMPA model.

Table 17.- Results of 2019 experiments in the Alboran Sea. The highest SS values are in bold.

Dataset	SS averaged over the whole region for all drifters	SS averaged over the PUERTOS-SAMPA domain for all drifters
CMEMS-GLO-MFC	**0.200**	0.135
CMEMS-MED-MFC	0.174	0.127
CMEMS-IBI-MFC	0.176	**0.147**
SOCIB - WMOP	0.160	0.124
PUERTOS-SAMPA	-	0.103

In this experiment, **CMEMS-GLO-MFC shows the best performance on averaged over the whole domain**, essentially because the highest SS are found in the region 1W-0W where the drifters followed the EAG, which is well represented by CMEMS-GLO-MFC during this period (not shown).

Over the PUERTOS-SAMPA domain, CMEMS-IBI-MFC shows the best performance, because all drifters are concentrated in an area where this model performs the best during this period. In the Strait of Gibraltar, PUERTOS-SAMPA do not show a good performance, because it does not properly represent the WAG (not shown).

Test at 15m depth:

Since some buoys considered here have a drogue at 15m nominal depth (SVP-type drifters), we examined if the SS was increasing when comparing the trajectories with 15m-depth currents instead of with surface currents. No significant changes are observed in the SS results when comparing with currents at 15m (Fig. 26 and Table 24). Values of SS slightly decrease at 15 m depth in most of the cases with the exception of the value obtained for the CMEMS-GLO-MFC for the PUERTOS-SAMPA domain. It is simply because the currents during this period were very similar at the surface and at 15m depth (not shown), particularly in the case of the global model in contrast to the regional model SOCIB-WMOP. The same occurs during the period of 2019 (not shown).

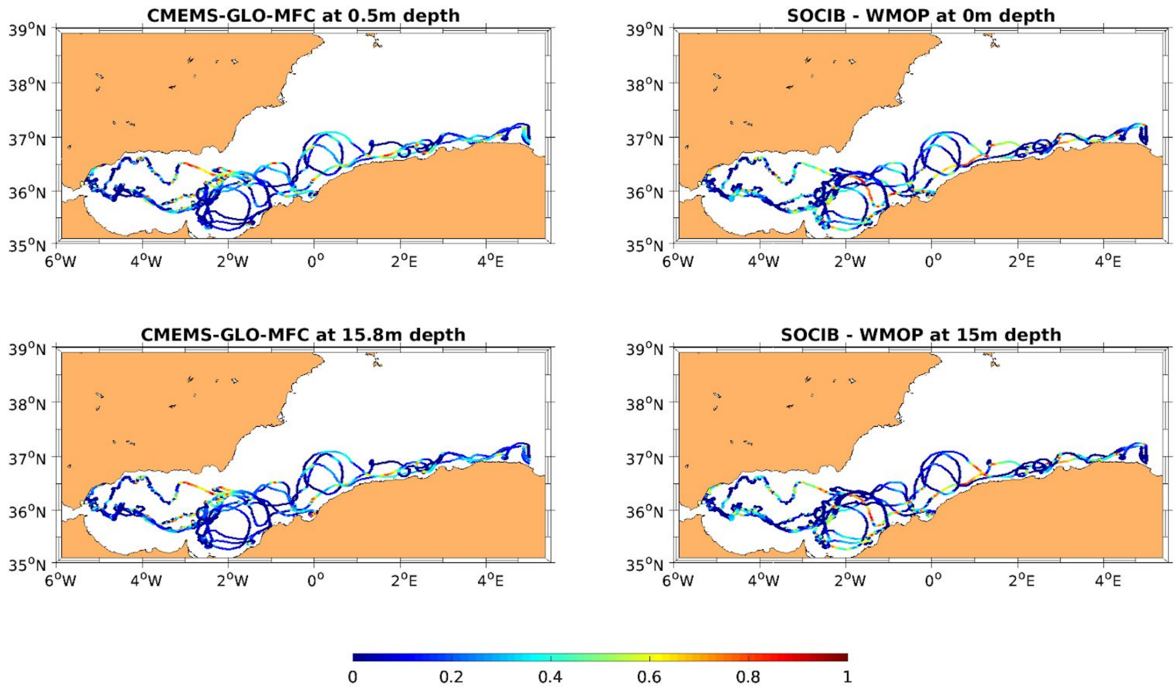

Figure 19: Map of the Alboran Sea showing the spatial distribution of Skill Scores for the 6 SVP-drifters of 2018 experiment for (left panels) CMEMS-GLO and (right panels) SOCIB-WMOP when comparing the drifter trajectories with (upper panels) surface currents and (lower panels) ~15m-depth currents.

Table 18.- Results of the 6 SVP-drifters in 2018 in the Alboran Sea.

Dataset	**SS averaged over the whole region for all drifters**		**SS averaged over the PUERTOS-SAMPA domain for all drifters**	
Depth	**surface**	**15m**	**surface**	**15m**
CMEMS-GLO-MFC	0.151	0.146	0.128	0.130
SOCIB - WMOP	0.137	0.128	0.123	0.123

2.4. Results in the Galicia coast.

The Galicia coast is located at the northwestern corner of the Iberian peninsula, where the coastal orientation changes. This region is characterized by a **very strong seasonality** (Fig. 20). During **autumn-winter**, the warm density-driven Iberian Poleward Current (**IPC**) **is intense**. Due to the abrupt changes of topography, the IPC shows a turbulent character, with **eddies and smaller scale instabilities** typically being generated in the shear regions (Peliz et al., 2003b). During **spring-summer**, the **IPC is weak**, and northeasterly winds drive an offshore Ekman transport, forcing an upwelling along the coast. This leads to filaments structures associated with strong offshore currents that extend more than 200 km offshore. A portion of the water transported off shelf recirculated back to the shelf (Barton et al. 2001), leading to complex mesoscale patterns.

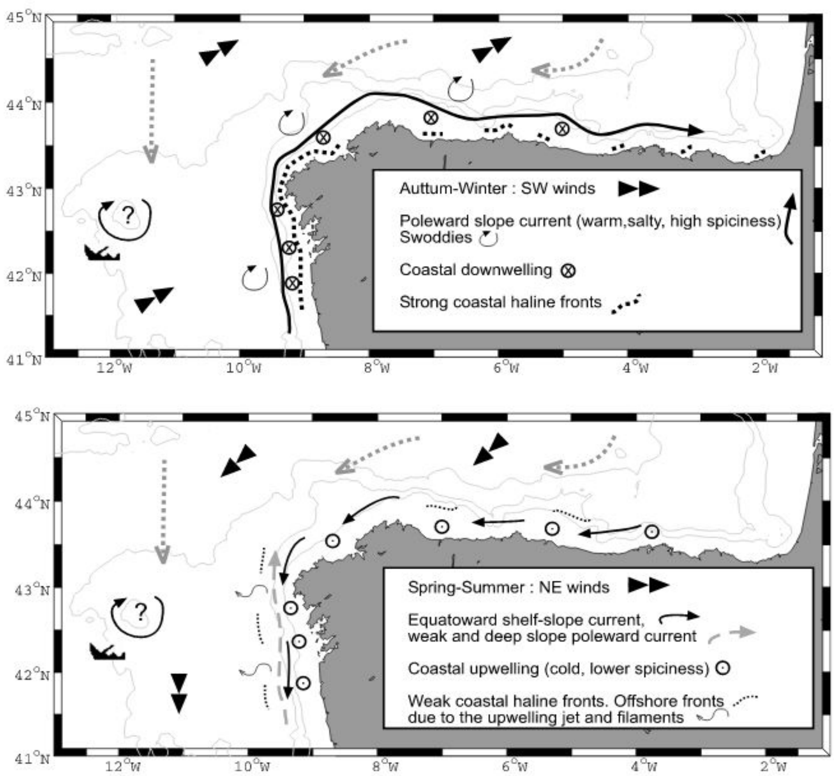

Figure 20: Map of the Northwest of Spain showing the main characteristics of the oceanic circulation and winds in (upper panel) autumn-winter and (lower panel) spring-summer. ***From Ruiz-Villarreal et al. 2006.***

In total **3 SVP drifters** from CMEMS were found in this region, for a period of several days in 2018 and 2019 (Table 19). These drifters consist in a spherical float and a cylindrical hole-sock drogue centered at a nominal depth of 15m:

Table 19.- Drifters used for experiments in Galicia.

Drifter n#	Drifters in Galicia Coast	Analyzed period
1	CMEMS/DB4101606	09/03/2019-17/05/2019
2	CMEMS/DB4401613	26/12/2018-09/01/2019
3	CMEMS/DB6200558	01/01/2018-18/01/2018

Four CMEMS models were assessed (GLO, IBI, NWS, MED) (Table 20). In this case, the model from the Spanish Port System (coastal model for FERROL Port – SAMOA-FER), could not be assessed since no drifter was available inside the model domain. In addition to the model data, OMA data from the 3-antenna HF radar system of Galicia were assessed.

Table 20.- Models and HF radar datasets used for experiments in Galicia.

Models	Temporal resolution	Spatial resolution
CMEMS-IBI-MFC	hourly	~2km
CMEMS-GLO-MFC	hourly	~8km
CMEMS-MED-MFC	hourly	~4km
CMEMS-NWS-MFC	hourly	~1.5km
HF radar - Galicia (OMA totals)	hourly	~6km

Fig. 21 shows the skill assessment results over the entire region.

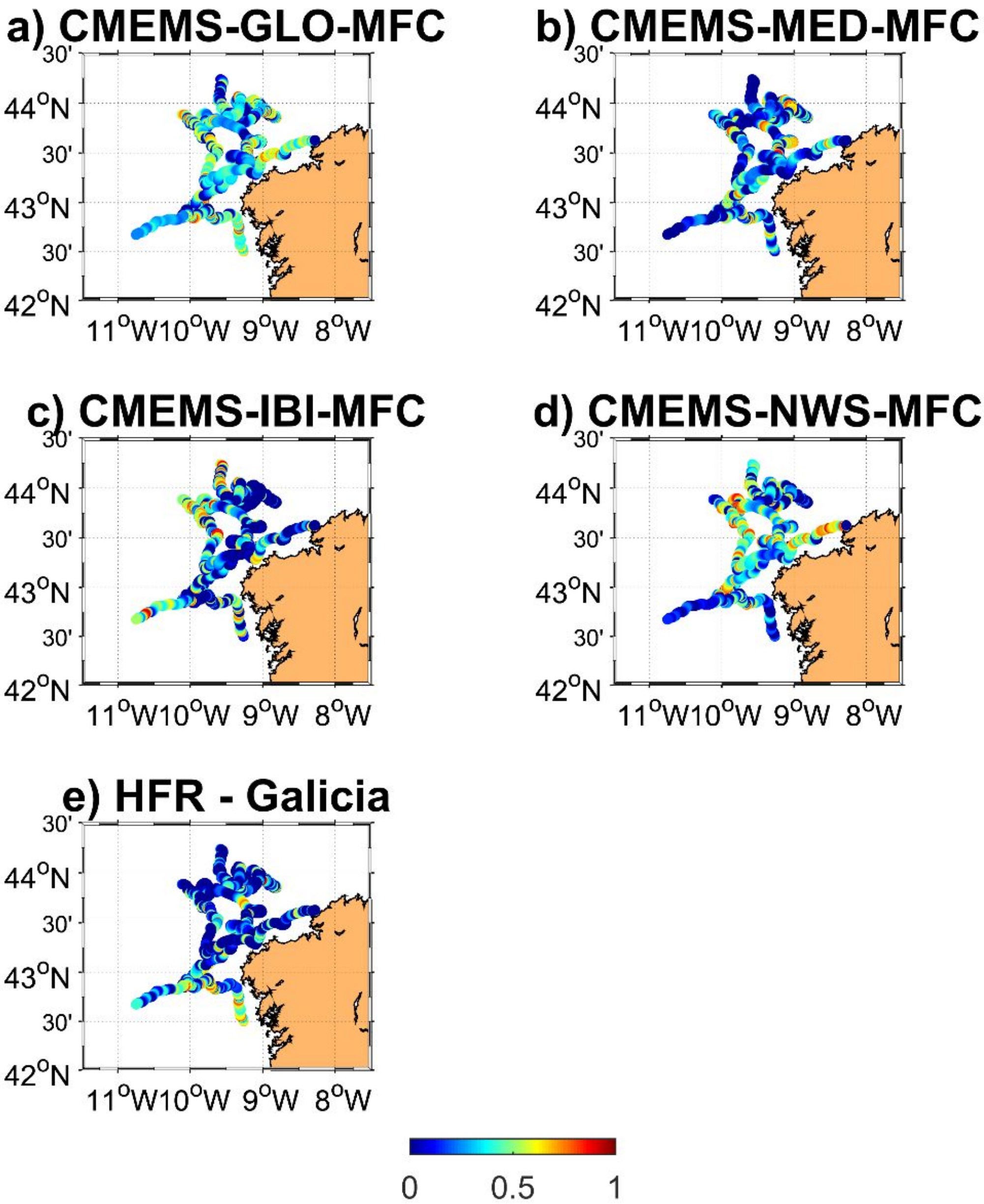

Figure 21: Map of Galicia area showing the spatial distribution of Skill Scores for the datasets indicated in each figure title.

On average over the whole domain (Table 21), SS values range from 0.162 to 0.258, being the **CMEMS-GLO-MFC** the one that shows **the best performance**, followed by the CMEMS-NWS-MFC model. It is surprising that in this region the two products with the highest resolutions (i.e. HFR and CMEMS-IBI-MFC) show the lowest SSs, even lower than CMEMS-MED-MFC; which, like in the Biscay region, is not expected to be really performant due to its characteristics not adapted for this area (i.e. no tides, close to its open boundaries). One possible explanation for this result is the fact that the **three buoys evaluated are drogued** at a nominal depth of 15 m and that the vertical shear in the area results in very different dynamics at the surface and at 15m. The **vertical shear** would **better simulated in the higher resolution**

models and account for differences between surface currents (the ones extracted from the models and the HFR) and currents at 15m (the ones sampled by the drifters). Most of the data available are in the period march-may (drifter #1), where stratification conditions begin (and also the period of more intense/frequent coastal upwelling).

Table 21.- Result of experiments in Galicia. The highest SS value is in bold.

Dataset	SS averaged over the whole region for all drifters
CMEMS-GLO-MFC	**0.258**
CMEMS-MED-MFC	0.198
CMEMS-IBI-MFC	0.162
CMEMS-NWS-MFC	0.254
HFR - Galicia	0.167

When analyzing the performances of the models and HFR data drifter per drifter (Table 22) we can observe a **lot of variability**. While **HFR** is providing the **best SS for drifter #2 (in winter),** CMEMS-GLO-MFC and CMEMS-NWS-MFC are showing the best performances for drifters #1 (spring) and #3 (winter), respectively. This suggests again that the **performances can be very different depending on the periods and drifter locations**. However, no clear spatial or temporal patterns can be observed with this regard due to the relatively reduced number of trajectories available for comparisons in the area.

Table 22.- Averaged SS for each drifter available in Galicia, inside the HFR footprint coverage. The highest SS for each drifter is indicated in bold.

Dataset	SS averaged over the whole region for each of the available drifters		
Source / drifter	#1	#2	#3
CMEMS-GLO-MFC	**0.234**	0.281	0.339
CMEMS-MED-MFC	0.199	0.202	0.191
CMEMS-IBI-MFC	0.127	0.189	0.282
CMEMS-NWS-MFC	0.221	0.201	**0.430**
HFR - Galicia	0.150	**0.299**	0.125[2]

[2] For this period there are gaps in HF radial files so very likely OMA reconstruction contains high errors.

3. Validation of the service outcomes.

In this section we **compare the results** of the model performance (i.e. **Skill Score -SS-**) obtained during the experiments **against the results provided by the IBISAR service**. By using the service, we select the bounding box and the period of the experiment and Skill Assessment functionality computes the SS, following the same methodology. The reader is requested to refer to the IBISAR tutorial video available at the webpage to check how to use it. We do not expect a perfect match between the experiment's results and the service's outcomes, since the formers were done with simulated trajectories from the COSMO lagrangian model, while the service uses OpenMap Java Geo toolkit (https://github.com/OpenMap-java/openmap/blob/master/src/openmap/com/bbn/openmap/geo/Geo.java). However, we expect that the uncertainties due to the trajectory model used (as shown for 3 different models in Fig. 11) do not impact the skill assessment ranking but the absolute values.

Unfortunately, we cannot make a straight comparison of all the experiments performed because the service only contains the partial SS of 2018-2019 considering the drifters available in CMEMS, and do not provide results for the drifters deployed in the context of the experiments carried out in 2014, 2015, 2016, or 2018, which belong to complementary databases. For this reason, we are only presenting comparison with the CMEMS drifters of 2019. Among the experiments performed, the CMEMS drifters available in 2019 are:

- **Drifter 4101612** in Biscay Bay from 10/02/2019 to 29/03/2019
- **Drifter 4101606** in Galicia from 09/03/2019 to 17/05/2019
- **Drifter 4401613** in Galicia from 01/01/2019 to 09/01/2019
- **58 drifters** in the Alboran Sea from 25/03/2019 to 30/04/2019

Tables 29, 30, 31 and 32 provide the SS obtained from these drifters by the experiments and the service for comparison.

Table 29.- Skill Score comparison between experiments and service for drifter 4101612.

Dataset	SS averaged over the whole region for 4101612 drifter		SS averaged over the Bilbao region for 4101612 drifter	
	Experiments	**Service**	**Experiments**	**Service**
CMEMS-GLO-MFC	0.206	0.202	0.258	**0.303**
CMEMS-MED-MFC	0.217	**0.244***	0.252	0.274*
CMEMS-IBI-MFC	0.157	0.148	0.298	0.210
CMEMS-NWS-MFC	0.160	0.224	0.223	0.268
HFR-Biscay Bay	**0.242**	X	0.305	X
PUERTOS-SAMOA	-	-	**0.310**	0.255

X = no SS provided *computation based on a subset of the total available data

Table 30.- Skill Score comparison between experiments and service for drifter 4101606.

Dataset	SS averaged over the whole region for 4101606 drifter	
	Experiments	Service
CMEMS-GLO-MFC	**0.234**	0.234
CMEMS-MED-MFC	0.199	0.172*
CMEMS-IBI-MFC	0.127	0.128
CMEMS-NWS-MFC	0.221	0.237
HFR-Galicia	0.150	**0.288***

*computation based on a subset of the total available data

Table 31.- Skill Score comparison between experiments and service for drifter 4401613.

Dataset	SS averaged over the whole region for 4401613 drifter	
	Experiments	Service
CMEMS-GLO-MFC	0.281	0.251
CMEMS-MED-MFC	0.202	X
CMEMS-IBI-MFC	0.189	0.154
CMEMS-NWS-MFC	0.201	0.181
HFR-Galicia	**0.299**	**0.276***

X = no SS provided *computation based on a subset of the total available data

Table 32.- Skill Score comparison between experiments and service for the 58 drifters of 2019 experiments in Alboran Sea (GIBST)

Dataset	SS averaged over the whole region for all drifters		SS averaged over the PUERTOS-SAMPA domain for all drifters	
	Experiments	Service	Experiments	Service
CMEMS-GLO-MFC	**0.200**	**0.202***	0.135	0.164*
CMEMS-MED-MFC	0.174	0.190*	0.127	0.140*
CMEMS-IBI-MFC	0.176	0.179*	**0.147**	**0.169***
SOCIB - WMOP	0.160	0.173*	0.124	0.153*
PUERTOS-SAMPA	-	-	0.103	0.115*

X = no SS provided *computation based on a subset of the total available data

Due to some technical issues (e.g. continuous migration of the different forecast systems to a newer version; transfer of the data product to a new server or provision of the information in new data format; discontinuous and patchy data from third party data providers), there are **gaps in the calculations**, and the SS is not provided in some cases.

When **comparing the results of one drifter alone**, the **experiments and the service provide different results**, except for drifter 4401613 (Table 31), which shows similar results in terms of ranking, although the SS values are different. However, when **comparing a large set of drifters** available over the same period (the 58 drifters of 2019 experiment in Alboran Sea available during a period of one month, Table 32), **the experiment and the service provide very similar results** in terms of model performance ranking, although the SS values are also different. This highlights the fact that the **more observations available**, the **more statistically stable** are the SS results, and the **more robust is the methodology**, despite some gaps in the calculation.

However, if the calculation is not complete, the average Skill Score is based on a **smaller number of observations than it should be**. If there are a lot of drifters, this would average out the value of the Skill Score, as seen before. But if there is a **small amount of drifters** (as it is generally the case), this **can strongly impact the average Skill Score value** and therefore the model ranking.

4. General conclusions from all experiments.

- **Global forecast system performs well:** coarser resolution models show a good behaviour where the average pattern follows major large-scale circulation features (e.g. the Alboran Sea anticyclonic gyres; Algerian Current; Balearic Current; the intense IPC in Galicia during winter season), being the CMEMS-GLO-MFC model also able to reproduce the intense mesoscale activity in some cases (e.g. in the Balearic Sea in 2016 and 2018).

- **However, downscaling is needed in specific regions:** to reproduce intense sub-mesoscale activity (e.g. in the Balearic Sea during the analyzed period in 2014 where the regional model SOCIB-WMOP showed the best performance; in the Bay of Biscay where the regional model for the Iberian-Biscay-Irish regional seas showed the best performance; in the Alboran Sea where the regional models outperforms the global one in the region of the model PUERTOS-SAMPA; in the narrower section of the Strait of Gibraltar where the high-resolution regional model PUERTOS-SAMPA performs better).

- **Coastal high resolution models do not generally provide the highest skill scores:** a first interpretation is that the skill score is on average more favourable to coarser resolution models with less energetic dynamics due to the double-penalty errors affecting the comparison of high-resolution simulations with point-wise observations (e.g. Mourre et al., 2018). Moreover, data assimilation would also certainly be needed in the coastal models to improve the representation of the main currents and eddies.

- **Modelling performance are strongly region-dependant and scenario-specific:** the Skill Score metrics shows that all models show skill, but none on a consistent basis, depending on the region and on the analyzed period. This highlights the need for a service like **IBISAR** to maintain an up-to-date skill evaluation of all models available. It also highlights the necessity of specific drifter deployments in case of emergencies to evaluate the models under the most relevant conditions in near-real time.

- **SS values are higher in very intense large-scale dynamic areas**, better reproduced by models and better observed by the HFRs (i.e. due to higher signal-to-noise ratio): e.g. the shelf region of the Biscay Bay as obtained for buoy

#5 in the Bilbao Region; the eastern part of the Ibiza Channel as shown in the 2016 experiment; the Galicia region as shown for drifter #3 deployed in winter conditions.

- **HFR observations outperform models:** HFR data is observation, and in most cases it has proved to be better than models in following the trajectory of ocean surface drifters, demonstrating the potential of HFR currents for backtracking purposes. However, HFR derived trajectories do not perfectly match the drifter observations because there are areas with high observational errors (i.e. along the baseline between the two HFR stations and at the domain outer-edge), and because HFR OMA data used are not systematically quality-controlled and may contain significant errors for some areas and/or periods. It must also be considered the strong smoothing character of the OMA analysis, which can remove small features from the velocity field (Kaplan and Lekien, 2007; Hernández-Carrasco et al., 2018). Improved results could be expected if the quality indicators provided by the OMA method and included in the output files as quality flags for the different variables were used by the Lagrangian model to improve the Lagrangian trajectories.

- **HFR short-term current predictions are required:** being aware of the need of short-term currents forecasting for emergency responses and having proved the very effective capabilities of the HFR currents for backtracking purposes the development of forecasting algorithms to use HFR data to make short-term surface current predictions is required. The results to demonstrate the effectiveness of short term predictions (STP) of surface currents from the latest HFR field to plan response activities so far are very promising (Zelenke 2005, Frolov et al. 2011, Barrick et al., 2012, Orfila et al. 2015, Solabarrieta et al., 2016, Vilibić et al, 2016, Abascal et al., 2017, Ren et al., 2019). However, there is still work to be done in this research area both in developing new approaches and in providing standardized data and metadata of STP on an operational basis.

- **More feedback is expected:** despite all the valuable contributions compiled from several experts (e.g. from SASEMAR- Bilbao, SASEMAR-Castellón, INTECMAR) from the different pilot regions, we have not been able to gather feedback to support our results, since their findings are mostly based on the use of other models and from other periods. However, this exchange of results highlights the importance of **win-win collaboration** with diverse organizations and particularly with the target-users. Thus, we expect to continue exchanging the results aiming to compile more feedback through the direct use of the **IBISAR** service.

5. Limitations of the methodology.

In this section, we provide some recommendations in the use and interpretation of the results, based on the limitations of the methodology.

- **Results are very scenario-dependant:** the Skill Score evaluates one point at one time, so the results are very scenario-specifics. In the context of SAR applications, this suggests that the evaluation of model predictions from past-scenarios should be taken with a lot of caution, since the calculations of SS for past performance does not guarantee the quality or accuracy of any model to compare with the others in nowcast sense. However, with more experiments of this type covering different periods during the year, we will hopefully be able to highlight tendencies, if there are any. The use of the service with specific drifter deployments in the place and time of emergencies is strongly encouraged to get the most reliable outcomes in near-real time.

- **Be careful with averages:** the average Skill Score for a specific region of interest is computed from the available drifters in this region. Therefore, if all available drifters concentrate in the same area, the model performance is being assessed only in this area.

- **Pay attention to the number of available drifters:** the robustness of the method depends on the number of available drifters in the region of interest. Since there is a lack of drifter observations in some areas (especially coastal risk-prones regions), drifters launched in the context of maritime emergencies should be integrated in CMEMS to allow the assessment of the models in near real-time (if CMEMS drifters are not available in the area of interest).

- **The Skill Score is only one measure of performance**: it does not gauge all aspects of model performance. Combining multiple Skill Score metrics may be useful in the future (Liu and Weisberg, 2011).

- **None of the models should be rejected:** Skill Score should be interpreted as a quality indicator (i.e. quality flag) of the model forecast but none of the models should be rejected under the only consideration of the metrics. The service can have gaps in the calculations, and sometimes models without adequate forcing or resolution can show better performance. The Skill Score is a decision-support tool but previous experience of SAR operators and prior knowledge of the ocean circulation in the area of interest are crucial to finally select the model. Also, it must be kept into consideration that the evolution of the prediction systems may affect their individual performance over time.

- **IBISAR only evaluates surface currents:** Skill assessment should be applied to different layer depths of the current predictions, considering also the possibility to include wind-forcing, depending on the emergency case (e.g. man overboard, floating object or oil spills).

- **Skill Score values depend on the forecast length.** The service and all experiments performed to evaluate the model skill at predicting the drift of satellite-tracked Lagrangian buoys in **IBISAR** consider a forecast time of 6 hours. This forecast horizon has been selected because as highlighted by Liu and Wesiberg (2011), such model assessment made over relatively short time scales (e.g. tidal to synoptic weather) are useful for assessing applications to oil spill trajectories (Abascal et al., 2009), search and rescue (Smith et al., 1998; Jordi et al., 2006) and river plume spreading (McCabe et al., 2009). Additionally, it also corresponds to the usual operational time framework of the safety agencies (e.g. USCG). However, the Skill Score tends to increase with the forecast length (see Fig. 22). This is because the Skill Score evaluates different dynamical scales in function of the forecast length. Further investigation is needed in order to improve the methodology and determine which forecast length is appropriate for which purpose. In all cases, users should be aware that the Skill Scores given by the service represent an average over the 6 hours of forecast, and that the Skill Score after 2 or 3 hours can be smaller (if the prediction is bad at the beginning and then get closer to the real drifter) or higher (if the prediction is good at the beginning and then draw away). The **forecast length** could be something to be **implemented as a user-dependent parameter** in **IBISAR**, in order to be adapted to the needs of the emergency (e.g. oil spill or man overboard).

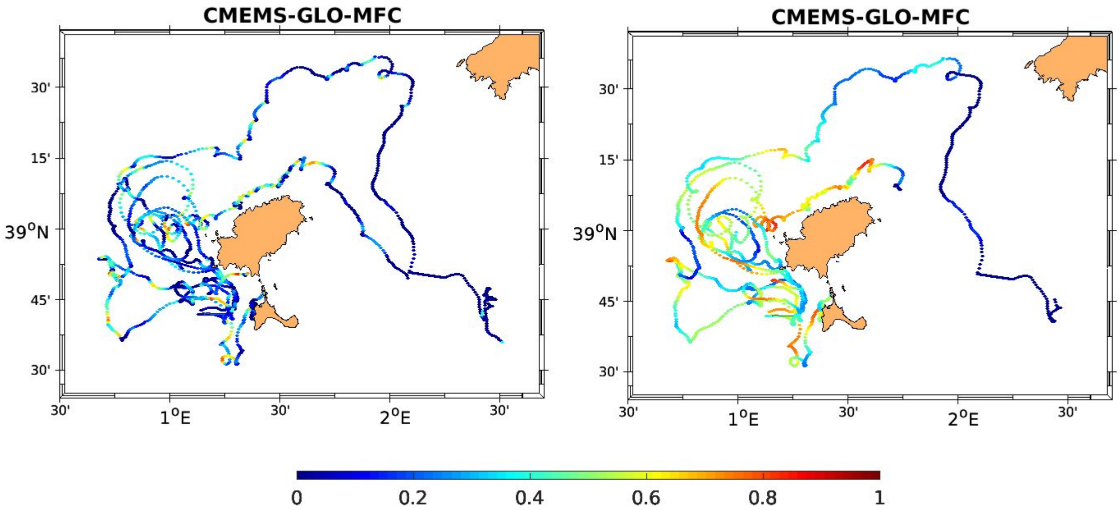

Figure 22: Map of Ibiza and Mallorca channels showing the spatial distribution of Skill Scores of CMEMS-GLO-MFC computed after (left) 6 hours and (right) 72 hours of simulation.

Despite the number of limitations of the methodology at this time, we hope that, now that the service will be in place, feedback provided during further and expected **interactions between scientists and users** will finally lead to an improvement of the methodology, which again will lead to a significant enhancement of the IBISAR service.

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