

# Evaluating the surface circulation in Ebro Delta (NE Spain) with quality-controlled High Frequency radar measurements

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## Abstract

Ebro River Delta is a relevant marine protected area in the western Mediterranean. In order to promote the conservation of its ecosystem and support operational decision making in this sensitive area, a three site standard-range (13.5 MHz) CODAR SeaSonde High Frequency (HF) radar was deployed in December 2013. The main goal of this work is to explore basic features of the sea surface circulation in Ebro estuary as derived from reliable HF radar surface current measurements. To this aim, a combined quality control methodology was applied: firstly, one year-long (2014) real-time web monitoring of nonvelocity-based diagnostic parameters was conducted to infer both radar site status and HF radar system performance. Signal-to-noise ratio at the monopole exhibited a consistent monthly evolution although some abrupt decreases (below 10 dB), occasionally detected in June for one of the radar sites, impacted negatively on the spatiotemporal coverage of total current vectors. It seemed to be sporadic episodes since radar site overall performance was found to be robust during 2014. Secondly, a validation of HF radar data with independent *in situ* observations from a moored current meter was attempted for May-October 2014. The accuracy assessment of radial and total vectors revealed a consistently high agreement. The directional accuracy of the HF radar was rated at better than 8°. The correlation coefficient and RMSE values emerged in the ranges [0.58-0.83] and [4.02-18.31] cm·s<sup>-1</sup>, respectively. The analysis of the monthly averaged current maps for 2014 showed that the HF radar properly represented basic oceanographic features previously reported, namely: the predominant southwestward flow, the coastal clockwise eddy confined south of Ebro Delta mouth or the Ebro River impulsive-type freshwater discharge. The EOF analysis related the flow response to local wind forcing and confirmed that the surface current field evolved in space and time according to three significantly dominant modes of variability.

## 1 **1. Introduction.**

2 The circulation in Ebro continental margin (NE Spain, Fig. 1 - a) is mainly thermohaline  
3 and characterized by a quasi-permanent barotropic shelf-slope jet, which flows  
4 southwestwards and is named 'the North current', only altered by clockwise inertial  
5 oscillations and some short periods of current reversals. This relatively low-intensity  
6 current flow ( $10 \text{ cm}\cdot\text{s}^{-1}$ ) is in geostrophic balance with the so-called Catalan front, which is  
7 a permanent density front associated with strong salinity gradients maintained by the Ebro  
8 River runoff (Font *et al.*, 1988a).

9 The marine circulation near the delta, although dominated by the alongshore large-scale  
10 dynamics, presents a complex structure strongly influenced by the topography, the  
11 seasonality of the remarkable Ebro River discharges (Font *et al.*, 1988b), the changing wind  
12 conditions and the water column thermal stratification (Salat *et al.*, 2002). Nonetheless, the  
13 tidal influence in the continental shelf currents field is very weak as expected for a  
14 microtidal and low-energy environment (Jimenez *et al.*, 2002).

15 Since the Ebro River Delta is one of the most relevant marine protected areas in the  
16 western Mediterranean in terms of biodiversity, an important monitoring activity is  
17 performed to manage this deltaic coastal region and promote the conservation of its  
18 ecosystem. In order to support marine domain awareness and operational decision making  
19 in this sensitive area, a network of 13.5 MHz CODAR SeaSonde High Frequency (HF)  
20 radar systems has been deployed (Fig. 1 - b). HF radar has been steadily gaining  
21 recognition as an efficient land-based remote sensing instrument for mapping surface  
22 currents at high spatial and temporal resolutions in near real time. This technology presents  
23 a broad range of practical applications, encompassing management (SAR operations, oil  
24 spill emergencies), commercial (vessel tracking, ocean energy production) and research  
25 (ecology, water quality, fisheries) uses. Other emerging uses include the validation of  
26 operational ocean forecasting systems or assimilation into numerical coastal circulation  
27 models (Marmain *et al.*, 2014; Stanev *et al.*, 2015).

28 As a consequence, there is a growing demand for quality-controlled HF radar surface  
29 current measurements. Since HF radar estimations are subject to many potential  
30 uncertainties (namely: power-line disturbances, radio frequency interferences, ionosphere  
31 clutter, ship echoes, antenna pattern distortions or environmental noise - see Kohut and  
32 Glenn, 2003), many efforts have been recently devoted to identify occasional non-realistic  
33 radar current vectors. Such artefacts (defined as spikes, spurious values or corrupted data)  
34 are generally detected at the outer edges of the radar domain and flagged in accordance  
35 with a pre-defined protocol. An individual quality control (QC) index, based on an integer  
36 number derived from a battery of tests, should be assigned for each and every single radar  
37 grid-cell to indicate the quality level of each measured value (Gomez *et al.*, 2015).

38 The artefacts can be subsequently eliminated from the data stream in real time (Cosoli *et*  
39 *al.*, 2012b) or offline (Liu *et al.*, 2014). Other approaches are focused, in addition, on  
40 replacing noisy values with more reliable estimates (Wyatt *et al.*, 2015) by using open-  
41 boundary model analysis (Kaplan and Lekien, 2007) or statistical mapping (Barrick *et al.*,  
42 2012). However, the main drawback lies with the potential removal of accurate data when  
43 the discriminating algorithm is based on tight thresholds. Some fine-tuning, based on the  
44 specific local conditions of the system, is thus required to have the right trade-off between

1 confirmed outlier identification and false alarm rate, maximizing the benefit of the  
2 applications of these methods (Gomez *et al.*, 2014).

3 Whereas some quality indexes are assigned according to velocity-based QC schemes,  
4 other approaches intend to use nonvelocity-based metrics related to the characteristics of  
5 the received signal in order to implement advanced quality controls and reduce the  
6 systematic errors in radar current estimates (Kirincich *et al.*, 2002). One of the radial  
7 metrics that offers the most potential benefits as reliability indicator is the Signal-to-Noise  
8 Ratio of sea-echo at the monopole (SNR3), since it has been previously proved to be a valid  
9 proxy for both radar site status and onset of HF radar system malfunction (Cosoli *et al.*,  
10 2012b; Roarty *et al.*, 2012). Complementarily, a big jump in the average state over time in  
11 antenna parameters (*e.g.* amplitude corrections for loops 1 and 2 to the monopole, AMP1  
12 and AMP2, respectively) may indicate an antenna problem and should be investigated  
13 (COS, 2005).

14 In this context, a number of previous works have focused on defining optimum threshold  
15 levels since there is still no worldwide consensus. Atwater and Heron (2011) showed that a  
16 simple thresholding of SNR3 is a good starting point, although a 20 dB limit constitutes a  
17 too severe QC criterion with a resulting detrimental impact on coverage area. Values of  
18 SNR3 below 10 dB have been proved to be closely linked to a significant decrease of the  
19 Multiple Signal Characterization (MUSIC) direction-finding algorithm skill (De Paolo and  
20 Terril, 2007). As MUSIC is employed to resolve ocean surface current structure (Schmidt,  
21 1986), limitations in its performance are related to potentially suspect velocity outputs.  
22 Furthermore, different combinations of dynamic thresholds cutoffs have been analyzed to  
23 quantify the potential for error reduction (De Paolo *et al.*, 2015). Since the question still  
24 remains open, further researches are currently underway to shed light on it.

25 In addition, the credibility of HF radar data has been previously tested in extensive  
26 validation studies, including direct comparisons of HF radar-derived surface currents  
27 against independent in situ sensors like moored ADCP's, point-wise current meters – PCM  
28 hereinafter-, drifters or similar (Graber *et al.*, 1997; Kaplan *et al.*, 2005; Cosoli *et al.*, 2010;  
29 Solabarrieta *et al.*, 2014). Accordingly, a number of accuracy assessment exercises have  
30 been performed with the HF coastal radar network operated by Puertos del Estado (Fig. 1 –  
31 a) -PdE hereinafter- in order to quantify and lower uncertainties in radar current  
32 measurements (Alfonso *et al.*, 2006; Lorente *et al.*, 2014, 2015a and 2015b).

33 Correlation coefficients (CORR) and root mean squared errors (RMSE) have been  
34 previously found to be in the ranges [0.32-0.92] and [6-30 cm·s<sup>-1</sup>], respectively (Kohut and  
35 Glenn 2003; Paduan *et al.*, 2006; Chapman and Graber, 1997). Relative HF radar velocity  
36 errors can vary dramatically with the radar transmission frequency, sensor type and location  
37 within the sampled domain, as well as the data processing scheme used (Rypina *et al.*,  
38 2014; Kirincich *et al.*, 2012). In this frame, the instrumental noise and sub-grid scale  
39 current variability have been reported to yield noise levels of 4-6 cm·s<sup>-1</sup> (Emery *et al.*,  
40 2004; Ohlmann *et al.*, 2007; De Paolo *et al.*, 2015).

41 The main goal of this work is to explore basic features of the sea surface circulation in  
42 Ebro River estuary as derived from reliable and accurate HF radar surface current  
43 measurements. To this aim, a combined QC methodology is firstly applied: one year-long  
44 real-time web monitoring of nonvelocity-based diagnostic parameters and offline validation

1 of HF radar-derived current data with *in situ* observations from a PCM installed in a buoy  
2 moored within the radar domain (B1, Fig. 1 - b). This integrated approach is used during  
3 2014 in order to infer both radar site status and HF radar system overall performance and  
4 also to provide upper bounds on both radial and total radar current measurement accuracy  
5 (Lorente *et al.*, 2015c). Once HF radar data quality is estimated, Ebro Delta HF radar  
6 capabilities in reproducing well-known circulation features are investigated through the  
7 exploration of monthly averaged flow patterns and dominant modes of variability both in  
8 time and space (Cosoli *et al.*, 2012a and 2013; Kovacevik *et al.*, 2004). Lastly, the relative  
9 contribution of local wind as forcing mechanism is evaluated.

10 This paper is organized as follows: sections 2 and 3 outline the specific instrumentation  
11 and methods used in this study, respectively, followed in section 4 by a detailed discussion  
12 of the results. Finally, main conclusions are summarized in section 5.

## 14 **2. Instrumentation.**

### 15 **2.1. HF radar.**

16 A CODAR SeaSonde standard-range HF radar system was deployed at Ebro Delta in  
17 December 2013 within the frame of RIADE (Redes de Indicadores Ambientales del Delta  
18 del Ebro) project. The HF radar network consists of an array of three remote shore-based  
19 sites: Salou, Vinaroz and Alfacada. They will hereafter be referred to by their four letter  
20 site codes: SALO, VINA and ALFA, respectively (Fig. 1 - b).

21 The HF radar technology, founded on principle of Bragg scattering of the  
22 electromagnetic radiation over a rough sea (Crombie, 1955), infer the radial current  
23 component from the Doppler-shift of radio waves back-scattered by surface gravity waves  
24 of half their electromagnetic wavelength. Each single radar site is configured to estimate  
25 radial currents moving toward or away from the receive antenna. Since the speed of the  
26 wave is easily derived from linear wave theory, the velocity of the underlying ocean surface  
27 currents can be computed by subtraction. The distance to the backscattered signal is  
28 determined by range-gating the returns and the angle of origin is inferred, in the case of  
29 CODAR SeaSonde radars, by a direction-finding process (Barrick and Lipa, 1986) using  
30 three collocated receive antennas (two orthogonal crossed loops and a single monopole)  
31 and the MUSIC algorithm (Schmidt, 1986).

32 Each site is operating at a nominal frequency of 13.5 MHz with a 90 KHz bandwidth,  
33 providing hourly radial measurements with a cut-off filter of  $100 \text{ cm} \cdot \text{s}^{-1}$  and representative  
34 of current velocities in the upper first meter of the water column. Only calibrated  
35 (measured) antenna beam patterns (hereinafter APM) were employed by the manufacturer  
36 supplied software to process radial data used in the present study, with the aim of  
37 maximizing HF radar usefulness for operational applications (Lipa *et al.*, 2006; Kohut and  
38 Glenn, 2003). In regions of overlapping coverage from two or more sites, radial current  
39 measurements are geometrically combined using a least-square fit technique (Barrick and  
40 Lipa, 1986) with the averaging radius set to 6 km in order to estimate hourly averaged total  
41 current vectors on a predefined Cartesian regular grid with  $3 \times 3$  km horizontal resolution.  
42 The maximum horizontal range is set to 80 km and the angular resolution is  $5^\circ$ .



1 HF radar-derived data used in this study have been collected from 1 January to 31  
2 December 2014 (Fig. 1 - c). During this period the three sites were simultaneously  
3 operational and radar coverage was as its maximum extent. Temporal data coverage was  
4 quantified by computing the percent of total possible vector returns at each radar grid point  
5 (Fig. 1 - b). Percent coverage decreases rapidly near the outer edges of the domain where  
6 error levels are higher due to poor intersecting beam geometry (Chapman and Graber,  
7 1997) and quantified by larger Geometric Dilution of Precision (GDOP, Chapman *et al.*,  
8 1997). GDOP is an unit-less coefficient of uncertainty that characterizes how radar  
9 geometry may impact on measurement accuracy and position determination errors, owing  
10 to the angle at which the radials intersect and also to uncertainties in the radial vectors  
11 geometrically combined (Levanon, 2000; Trujillo *et al.*, 2004).

12 With the aim of screening out radar grid points where data are less reliable, a threshold  
13 on percent coverage has been imposed. Only time series of zonal and meridional surface  
14 currents at grid points with percent coverage greater than 50% over the 2014 annual record  
15 have been considered in this study. The selected coverage area present associated GDOP  
16 values of 1.5 or less.

## 17

## 18 **2.2. Buoy B1.**

19 The domain of Ebro Delta HF radar array includes an ocean Seawatch buoy deployed  
20 since August 2004 in the eastern waters of the Iberian Peninsula: Tarragona buoy (40.68°N,  
21 1.47°E, 688 meters depth), hereafter referred to as B1 (Fig. 1 - b). This buoy is equipped  
22 with an acoustic point-wise current meter manufactured by Falmouth Scientific Inc.,  
23 providing quality-controlled hourly averaged current velocity vectors at a nominal depth of  
24 three meters. A wind speed and direction sensor manufactured by R. M. Young Company  
25 measures hourly wind data at a nominal height of 3 meters. It should be noted that current  
26 and wind records are only available from 1 May to 31 October, 2014 (Fig. 1 - c). B1  
27 suffered from brief communication outages during this period and subsequent short gaps  
28 (2-3 h) in data time series have been linearly interpolated.

## 29

## 30 **3. Methods.**

### 31 **3.1. Online Quality Control of HF radar measurements.**

32 In order to ensure the reliability of the HF radar products delivered, maintenance and  
33 Quality Control (QC) procedures must be performed at various stages on the data  
34 generation pipeline. The manufacturer software package integrates a set of QC routines and  
35 thresholding techniques in the data processing chain (*e.g.*, limits for maximum vector  
36 magnitude and maximum GDOP).

37 This section presents a simplistic approach based on additional data quality checks at the  
38 post-processing stage and devoted to examine a variety of nonvelocity-based diagnostic  
39 parameters provided by the manufacturer (CODAR Ocean Sensors -COS-) and listed in  
40 Table 1. Such indicators include hardware, antenna, radial and total parameters, employed  
41 here as diagnostic tools for evaluating HF radar integrity and health (Roarty *et al.*, 2012,  
42 Emery and Washburn, 2007). A dedicated online website has been developed to  
43 operationally monitor in real time radar site status since anomalous values, inconsistencies

1 or sharp fluctuations in the indicators might be related to potential malfunctions. This  
2 automated quality control web tool runs in background with a cron job, being updated on an  
3 hourly basis.

4 One year-long (2014) real-time monitoring has been performed in order to inspect the  
5 temporal evolution and consistency of the aforementioned parameters, obtain estimates of  
6 their standard ranges and evaluate Ebro Delta radar site performance according to them  
7 (Lorente *et al.*, 2015a). Abrupt or gradual degradation and failures can be easily detected,  
8 triggering alerts for troubleshooting when defined thresholds (initially set to two standard  
9 deviations above/below the mean) are persistently exceeded. Particular emphasis has been  
10 devoted to SNR3 and the number of radial vectors provided.

11 Finally, automated quality checks have been implemented at the second level within the  
12 hierarchy defined for QC procedures, referred to total vectors. Temporal and spatial  
13 coverage of Ebro Delta radar system are separately analyzed on a monthly basis and later  
14 confronted to each other to check if HF radar systems operate within tolerance ranges,  
15 fulfilling the recommended level of data provision: 80% of the spatial region over the 80%  
16 of the time (Roarty *et al.*, 2012).

### 18 **3.2. HF radar validation.**

19 Since the Ebro Delta HF radar footprint overlooks of a moored PCM within its spatial  
20 coverage, an accuracy assessment of radar surface currents is performed for a 6-month  
21 period May-October 2014 of concurrent radar-PCM measurements (Fig. 1 - c). The present  
22 section builds on previous investigations devoted to the determination of measurements  
23 errors, the evaluation of direction-finding capabilities and the angular distribution of radial  
24 velocity uncertainties (Emery *et al.*, 2004; Paduan *et al.*, 2006; Cosoli *et al.*, 2010; De  
25 Paolo and Terrill, 2007).

26 To this aim, the radar radial arc geographically closest to B1 buoy location has been  
27 selected for each HF radar site and radial current vectors estimated at each arc point have  
28 been compared with the radial projection of PCM velocities. The B1-HF radar comparative  
29 analysis allows the computation of statistical parameters (*e.g.*, CORR and RMSE) as a  
30 function of the angle comprised between B1 and the arc grid point position. In absence of  
31 direction-finding errors (DF), maximum CORR and minimum RMSE values should be  
32 found over the arc point closest to B1 location. In presence of DF, the bearing offset is thus  
33 expressed as the angular difference between the arc point with maximum correlation and  
34 the buoy location.

35 Radial current time series have been filtered to remove all tidal, diurnal and inertial  
36 fluctuations (the inertial period is 18.4 h at B1 location latitude) from the velocity data.  
37 Filtered time series, obtained after applying a 10<sup>th</sup> order digital low-pass Butterworth filter  
38 with a cut-off period of 30 h (Emery and Thomson, 2001), have been compared to evaluate  
39 the discrepancies in subinertial currents.

40 Complementarily, HF radar total vector hourly estimations at the grid point closest to B1  
41 location (HFR1, 1.48°E 40.69°N, Fig. 1 - b) have been compared with PCM velocities to  
42 provide upper bounds on the radar current measurement accuracy. Comparisons have been  
43 undertaken using zonal (U) and meridional (V) components in order to evaluate the

1 agreement between both instruments by means of the computation of a set of statistical  
2 metrics – RMSE, scalar and complex correlations and best linear fit of scatter plots.  
3 Monthly results have been summarized with Taylor diagrams (Taylor, 2001), which  
4 provide a concise statistical summary of the agreement between both datasets.

5 Finally, rotatory spectral analyses (Gonella, 1972) have been performed for HF radar-  
6 derived total vectors at HFR1 location and for current data from B1 in order to identify the  
7 dominant modes of temporal variability. To ensure the continuity of the data record, small  
8 gaps detected (not larger than 6 h) in time series have been linearly interpolated. Spectra  
9 have been calculated by dividing time series into successive six day segments, with a 50%  
10 overlap and a Hanning window (Emery and Thompson, 2001), and subsequently averaged  
11 to provide some smoothing. Confidence levels for spectra densities have been derived  
12 assuming a chi-squared distribution for the variance.

### 14 **3.3. Characterization of the surface circulation field**

15 Maps of the Eulerian mean current field have been constructed at monthly time scale  
16 from the raw (unfiltered) radar time series on a subsampled grid with the aim of assessing  
17 the surface current dynamics in Ebro Delta. Additionally, a complex Empirical Orthogonal  
18 Function (EOF) decomposition (Kundu and Allen, 1976) has been used to infer the driving  
19 forces and spatiotemporal scales behind the variability of sea surface currents (Kaihatu *et*  
20 *al.*, 1998). This method, which reduces the components of the vector field to a complex  
21 scalar, has become widespread in order to extract the dominant modes of variability. The  
22 representative spatial patterns (or EOF modes) and their corresponding temporal  
23 coefficients or principal components (PCs, which describe the evolution of the modes) are  
24 determined by using the singular value decomposition of the covariance matrix. Each  
25 statistically significant EOF mode explains a limited portion of the total surface current  
26 variance.

27 EOF analysis has been applied to radar current velocity dataset using again the raw  
28 (unfiltered) hourly time series for the entire year 2014. Main spatial modes obtained for HF  
29 radar have been interpreted in terms of physical processes related to the detected spatially  
30 coherent structures. Since EOFs are purely statistical, each EOF mode's statistical  
31 significance must be evaluated. Several rules of thumb have been previously proposed  
32 indicating when an EOF is likely to be subject to large sampling fluctuations. In the present  
33 work, error estimates based on temporal decorrelation scales have been calculated  
34 according to North et al. (1982):

$$35 \quad \delta(\lambda_i) = \lambda_i * (2/N)^{\frac{1}{2}} \quad [1]$$

36 Where  $\delta_i$  is the eigenvalue for mode  $i$ , and  $N$  is the number of degrees of freedom  
37 determined using a conservative two-day decorrelation time-scale, following Münchow and  
38 Chant (2000). If the confidence intervals from the error estimates of any modes overlap, the  
39 modes may be non-orthogonal and can not be considered distinct and uncorrelated.  
40 Consequently, such modes are excluded from the EOF analysis and hence only the first  
41 previous modes can be considered to contain a significant portion of the total variance and  
42 to properly reproduce the observed surface current fields.

1 Finally, hourly wind vector dataset registered at B1 buoy has been also decomposed into  
2 principal components in order to infer the main axis of variability. Particular emphasis has  
3 been placed on the relationship between wind and radar-derived current EOF modes of  
4 variability in order to derive a better statistical insight.

## 5 6 **4. Results and discussion**

### 7 **4.1. Annual Quality Control**

8 Box plots of SNR3 for each radar site (Fig. 2 – a, b, c) exhibit a consistent monthly  
9 evolution, with a median (central mark) above 40 dB. However, a number of sharp  
10 decreases can be occasionally observed in VINA site for the month of June (Fig. 2 - c),  
11 exceeding the previously reported threshold of 10 dB (De Paolo and Terril, 2007).

12 The annual time series of hourly SNR3 values for VINA site (Fig. 2 - d) reveals that the  
13 thresholds proposed in the present work (two standard deviations above/below the mean,  
14 represented by bold blue dotted lines) were abruptly exceeded several times in June. SNR3  
15 reached extremely low values, leading to a drastic reduction in the radar spatial coverage  
16 presumably related to an inherent limitation of MUSIC algorithm, namely, the extraction of  
17 a maximum of two bearing solutions for a given range cell and a given radial current  
18 velocity. In this context, poor SNR3 values associated with potential interferences or  
19 environmental noise can lead to ambiguities in the estimation of the direction of arrival  
20 (DOA) function performed by MUSIC algorithm. Such ambiguities, based on the existence  
21 of more than two bearing solutions, eventually produce gaps in HF radar spatial coverage  
22 since additional solutions are excluded.

23 Consequently, the number of radial vectors (NRV) provided by VINA lowered  
24 significantly in June (Fig. 2 - e). Leaving aside the regular high frequency fluctuations due  
25 to the day/night cycle, NRV was several times below 500 and even equal to zero, indicating  
26 a poorer than expected performance of VINA site during this month. Nonetheless, it  
27 appears to be a sporadic episode, maybe related to radio-wave interferences, since VINA  
28 presented a stable performance during the second semester of 2014.

29 The quality checks implemented at total vectors level allow an overall evaluation of  
30 Ebro Delta HF radar system performance on a monthly basis (Fig. 3). A comparative  
31 analysis for February and June confirms the degraded performance during the latter. Data  
32 availability generally exceeded 80% in time over the majority of the radar footprint in  
33 February, with an abrupt decrease at the periphery of the radar range (Fig. 3 - a). By  
34 contrast, it only outreached the 50% in June, with a smoother transition at the outer edges  
35 of the domain (Fig. 3 – b). The evolution of the spatial coverage was rather consistent in  
36 February, with sporadic decreases below 50% (Fig. 3 - c). On the contrary, an irregular  
37 performance is detected in June as a consequence of both ALFA site outage (1-8 June) and  
38 VINA irregular behavior (Fig. 3 - d). The first factor yielded a dramatic and persistent drop  
39 in the areal coverage, lower than 20% most of the time. The second led to a significant,  
40 albeit occasional, reduction in the radar spatial domain (below 50%), which can be  
41 observed from 8 to 30 June 2014.

42 Finally, the temporal and spatial coverage have been confronted to each other (Fig. 3 –  
43 e, f). Ebro Delta radar system was closer to fulfill the required 80%-80% level of data

1 provision in February (Roarty *et al.*, 2012), with a 64% of the areal domain (referred to its  
2 maximum extent) available the 80% of the time. By contrast, the radar system barely  
3 reached the 35% of spatial coverage for the 80% of the time in June. Despite this  
4 occasional degradation, radar sites overall performance and their day-to-day operation have  
5 been found to be robust and within tolerance ranges. One year of continuous operation  
6 revealed three sites up and operational in excess of 95% of the time, with sporadic  
7 interruptions that introduced short-duration gaps in time and space (Fig. 1 - c).

8 It is noteworthy that the described methodology, at this preliminary development stage,  
9 is not able to remove suspicious values or outliers from the data stream in real time like  
10 Cosoli *et al.* (2012b) but only to detect anomalies and categorize them in order to create a  
11 historic database of flagged radial files similar to Roarty *et al.* (2012) for a later offline  
12 reprocessing of total vector maps when one (or more) radar site(s) is (are) considered to be  
13 working abnormally.

14 In this context, the hourly radial vectors provided by VINA site in June that did not  
15 satisfy the proposed QC control have been discarded from the analyses performed in the  
16 next sections and the associated total vector maps have been accordingly reprocessed  
17 offline. Future efforts should be devoted to improve radial data quality in real-time prior to  
18 the vector combination process and also to assign meaningful quality descriptor flags for  
19 each grid point data in total current fields.

## 21 4.2. Buoy-radar comparison results

22 The evaluation of direction-finding capabilities revealed the existence of small bearing  
23 errors (hereafter  $\Delta\alpha$ ) in radar radial estimations, ranging between  $2^\circ$ - $8^\circ$  (Fig. 4) and in  
24 accordance with the typical values previously reported (Emery *et al.*, 2004; Paduan *et al.*,  
25 2006). Comparison of unfiltered hourly radial currents estimated by B1 and SALO site  
26 (Fig. 4 - b) shows maximum CORR in a grid point (denoted by vertical solid red line)  
27 angularly close to B1 location (vertical dotted black line): 0.79, with associated RMSE of  
28  $10.95 \text{ cm}\cdot\text{s}^{-1}$  and  $\Delta\alpha$  of  $3.74^\circ$  in the counter-clockwise direction. VINA site (Fig. 4 - c)  
29 presents a lower bearing offset ( $\Delta\alpha = 1.82^\circ$ ) but also lower (higher) CORR (RMSE) value  
30 of 0.58 ( $13.31 \text{ cm}\cdot\text{s}^{-1}$ ). It is worth mentioning that minimum RMSE values are also placed  
31 on the vicinity of the correlation peaks. The VINA site exhibits the largest pointing error  
32 ( $\Delta\alpha = 7.82^\circ$ ) and the poorest agreement with moored radial estimations as CORR is 0.58  
33 and RMSE is fairly above  $18 \text{ cm}\cdot\text{s}^{-1}$  (Fig. 4 - d).

34 Hourly time series of low-pass filtered radial currents measured by B1 and those  
35 estimated in the closest range arc point (“best match-angle”) by each HF radar site are  
36 presented in Fig. 5. Metrics derived from the accuracy assessment highlight the consistently  
37 high agreement between SALO radar site and B1 estimations, with a CORR and RMSE  
38 values of 0.80 and  $5.58 \text{ cm}\cdot\text{s}^{-1}$ , respectively (Fig. 5 - a). Results derived from the best linear  
39 fit reveal a slope close to 1 and an intercept up to  $-0.82 \text{ cm}\cdot\text{s}^{-1}$ . The concordance between  
40 ALFA site and B1 is moderately good, with acceptable pairs of values CORR-RMSE and  
41 slope-intercept:  $[0.63\text{-}6.91] \text{ cm}\cdot\text{s}^{-1}$  and  $[0.73\text{-}1.92] \text{ cm}\cdot\text{s}^{-1}$ , respectively (Fig. 5 - b). VINA  
42 site data show lower agreement with *in situ* measurements (Fig. 5 - c) as reflected by a  
43 lower (higher) CORR (RMSE) value of 0.56 ( $7.76 \text{ cm}\cdot\text{s}^{-1}$ ). This might be partially  
44 attributable to the long site-buoy distance (*i.e.*, the radar signal is weaker) and to the limited

1 radar data availability due to day/night coverage fluctuations (*i.e.*, the data return is more  
2 than three times lower, with only 986 hourly observations available).

3 Ancillary validation works with radial measurements like internal self-consistency  
4 checks have not been performed due to Ebro Delta radar sites' geometry. Radar-to-radar  
5 comparisons along the overwater baselines (Paduan *et al.*, 2006; Yoshikawa *et al.*, 2006;  
6 Atwater and Heron, 2010), although valuable to explore quantitatively intrinsic  
7 uncertainties in radial velocities, are not feasible since they are positioned over land or near  
8 the coastline.

9 Statistical metrics derived from filtered hourly time series comparison of zonal (U) and  
10 meridional (V) components of total vectors estimated by B1 and HFR1 for the 6-month  
11 period are presented in Fig. 6. Results reveal a good agreement for both components  
12 (CORR above 0.74), in accordance with results reported in the literature (Cosoli *et al.*,  
13 2010; Kaplan *et al.*, 2005). RMSE is significantly higher for the zonal component than the  
14 meridional: 12.69 versus 4.02  $\text{cm}\cdot\text{s}^{-1}$  (Fig. 6 – a, b). The disparity of uncertainty levels  
15 between the east and north component vectors comes for the geometry of the radar vector  
16 combination and the prevalent south-southwestward current flow. This presumably might  
17 lead to less (more) precise radial vectors provided by ALFA (SALO) radar site since radial  
18 measurements are proved to be more accurate when the dominant current flow moves in the  
19 same direction (Robinson *et al.*, 2011). Since ALFA (SALO) site contributed mainly to the  
20 HF radar zonal (meridional) current assessment in B1 nearby region, a strong relationship  
21 between radial and total vector uncertainties has been evidenced.

22 The scatter plots (not shown) and the associated best linear fits show that HF radar  
23 slightly underestimates total current velocities registered by B1 since the slopes are below  
24 1: 0.71 and 0.67 for U and V components, respectively. The time-averaged complex  
25 correlation coefficient between B1 and HFR1 currents at zero lag is 0.77. The related phase  
26 is  $8.65^\circ$ , indicating that the former are, on average, slightly right shifted since the veering  
27 angle gives the average counter-clockwise turning of the second vector with respect to the  
28 first vector (Kundu, 1976).

29 The monthly mean current values were computed to characterize the main features of the  
30 flow in this region. The descriptive statistics reveal predominant negative values for the  
31 zonal speed (Fig. 6 - c) and a quasi-permanent average flow in the N-S direction (Fig. 6 -  
32 d). There is no evidence of a seasonal signal in both zonal and meridional velocity  
33 components of radar and B1 surface currents. Therefore, both instruments exhibit similar  
34 monthly mean values and variability, capturing the well-known southwestward  
35 thermohaline flow and identifying episodic but intense current reversals, as those observed  
36 by mid-September (Fig. 6 – a, b).

37 The monthly comparison of total vectors, performed on the unfiltered time series,  
38 provide a variety of metrics that are concisely summarized in a Taylor diagram (Taylor,  
39 2001), shown in Fig. 7. The diagram compares both data sets by combining information  
40 about their relative standard deviations, centered RMSE and CORR, synthetizing the  
41 statistical information of how closely the radar measurements at HFR1 grid point match  
42 with B1 velocities. As it can be seen, the cluster of points that show best agreement (*i.e.*,  
43 are closest to their corresponding reference point, labeled with blue squares) are those  
44 corresponding to the period May-September (red squares, sequentially numbered 1-5). The

1 reported correlation coefficient, standard deviation and RMSE values emerge in the ranges  
2 of [0.72-0.83], [10.96-14.18 cm·s<sup>-1</sup>] and [7.48-8.75 cm·s<sup>-1</sup>], respectively, for both zonal and  
3 meridional velocity components (Fig. 7 – a, b). However, HF radar is less accurate by the  
4 last month of the analyzed period, since metrics computed for October (red square 6) reflect  
5 lower (higher) CORR (RMSE) values: 0.50-0.58 (10.92-11.03).

6 Instrument-to-instrument comparisons present intrinsic limitations since both devices  
7 operate differently and at distinct nominal depths. A fraction of observed radar-B1  
8 differences can thus be explained in terms of different sampling strategies on disparate time  
9 and space scales (Ohlmann *et al.*, 2007). In this context, many of the uncertainties  
10 associated with HF radar technology are geometric in nature. Apart from the instrumental  
11 noise, other sources of potential errors in vector currents might be the sub-grid horizontal  
12 shear, the geophysical variability within the water column (Graber *et al.*, 1997) and some  
13 specific processes, namely, the Stokes drift, the Ekman drift and baroclinity (Paduan *et al.*,  
14 2006).

15 Spectral analyses have been computed for a 6-month period May-October 2014 (warm  
16 stratified season) to examine power spectral discrepancies in the frequency domain between  
17 both instruments. B1 and HFR1 current time series present qualitatively similar  
18 characteristics, capturing properly the dominant features within the diurnal and inertial  
19 bands, related to significantly prevalent clockwise (CW) rotatory motions (solid lines, Fig.  
20 8). Relevant polarized peaks are evident for both datasets, although their amplitudes are  
21 slightly larger for radar currents (solid red line). The inertial peak is the most pronounced,  
22 pointing out the adjustment of the stratified fluid to the wind driven currents and,  
23 subsequently, the importance of local wind as forcing mechanism (addressed in section  
24 4.3.2). Offshore oscillations in this frequency band are a common feature in ocean  
25 circulation and their presence in the study area has been previously documented (Font *et al.*,  
26 1990). By contrast, the counter-clockwise component (CCW, dotted lines) is much less  
27 energetic (especially in the case of B1 current estimations) and is where the main radar-B1  
28 differences in variance distribution can be found. Finally, a drop of energy and later  
29 flattening about 2 cpd are common for the CW components of both B1 and radar spectra,  
30 although the latter presents larger energy at that frequency band. Radar surface estimations  
31 are influenced by energetic high-frequency processes related to air-sea interaction like  
32 highly variable and strong wind gusts, which are not fully contained in sub-surface current  
33 estimations provided by the current meter.

### 35 **4.3. Dominant features of the surface flow**

#### 36 **4.3.1. Monthly averaged current patterns**

37 The sequence of monthly averaged current maps in Fig. 9 shows that some of the main  
38 circulation features in Ebro Delta remain rather invariant throughout most part of the year,  
39 like the southwestward slope jet, associated with the highest velocities detected (above 30  
40 cm·s<sup>-1</sup>). The current speed diminishes toward coastal areas, except in the vicinity of ALFA  
41 radar site, where the signal of Ebro River impulsive-type freshwater outflow is clearly  
42 evidenced during winter and spring (Fig. 9 - a, b, f). As a consequence of the remarkable  
43 seasonal variability of Ebro discharge rates, the estuarine plume loses intensity during the

1 warm season (Fig. 9 - c), becoming barely noticeable in late summer and early autumn (Fig.  
2 9 – d, e), until the beginning of the following hydrological cycle (Fig. 9 - f).

3 It is noteworthy the weakening of the southwestward slope jet during the central part of  
4 the year, in agreement with reported short periods of current reversals (Font *et al.*, 1990).  
5 The jet is intensified in October, perhaps as a result of the observed increase of the  
6 mesoscale activity (Font *et al.*, 1995), reaching ultimately a peak strength in December. By  
7 the end of 2014, the monthly spatial patterns become rather uniform, revealing the  
8 acceleration of the jet (with a spatial propagation of maximum velocities, exceeding 40  
9  $\text{cm}\cdot\text{s}^{-1}$ ) on the eastern region of the radar domain and also the presence of two small-scale  
10 coastal meanders (Fig. 9 - e, f).

11 A coastal anticyclonic eddy can also be observed in radar data, confined south of Ebro  
12 Delta mouth (Fig. 9 – a, b, c). This hydrodynamic feature has been well-documented in  
13 previous studies (Font *et al.*, 1990; Salat *et al.*, 2002), which stated the interaction of the  
14 buoyancy-driven flow with the topography as triggering source of this clockwise gyre,  
15 eventually reinforcing the shelf/slope front that drives the general circulation to the south-  
16 southwest. In addition, persistent and high-intensity NW wind jets (called ‘mistral’ winds),  
17 dominant during the October-May cold season and channeled by the narrow Ebro Valley,  
18 have been reported to introduce negative vorticity in the flow south of the Ebro Delta and  
19 reinforce the long-time preservation of this small-scale eddy (Garcia and Ballester, 1984;  
20 Espino *et al.*, 1998). Notwithstanding, this coastal clockwise rotation is eventually absent  
21 from September (not shown) to December monthly averaged current maps.

22 During the transition month of August, a large anticyclonic recirculation cell is  
23 evidenced, detached from the shore and located on the center of radar domain (Fig. 9 - d).  
24 This current pattern is dominated by the interaction of the cross-shelf flow on the southern  
25 inner shelf with topographic obstacles, giving rise to a shift to the right of the coastal flow.  
26 The subsequent northeastward reversal of the inshore flow is scarcely influenced by Ebro  
27 River freshwater discharge as it reaches the lowest value at this stage of the year.

#### 29 **4.3.2. Empirical orthogonal function (EOF) analysis**

30 The mean and EOFs of hourly surface currents have been calculated for the entire 2014  
31 (Fig. 10). The long-term mean flow (Fig. 10 - a) captures the main circulation features  
32 previously reported about ‘the North Current’, characterized by a quasi-permanent shelf-  
33 slope jet oriented southwestward and a remarkable Ebro River impulsive-type freshwater  
34 discharge (located in front of ALFA site). The buoyancy input introduced by large estuarine  
35 outflows, together with topographic effects, lead to the development of the aforementioned  
36 anticyclonic coastal eddy on the southern side of the delta.

37 Since the EOF analysis has been performed on the unfiltered data set containing relevant  
38 high-frequency spatiotemporal variability, the first three EOFs cumulatively account only  
39 for the 46.1% of the total variance (26.1%, 15.3% and 4.7%, respectively). Only the first  
40 three EOF modes are statistically significant according to the mode selection rule and  
41 truncation criterion suggested by North *et al.* (1982). The first, second and third modes are  
42 distinct and uncorrelated; however, the fourth mode is not since its error bars overlap with  
43 those of mode 5 (not shown). Therefore, higher order modes will not be further addressed



1 here as they represent a combination of unresolved high-frequency motions or noise (Cosoli  
2 *et al.*, 2012a).

3 The first dominant EOF mode (Fig. 10 - b) represents a spatially uniform pattern, rather  
4 similar to the annual averaged current map, with a prevailing alongshore shelf-slope jet  
5 flowing mainly southwestward, basically capturing the thermohaline Catalan front. The  
6 second EOF (Fig. 10 - c) shows a homogeneous spatial structure, perpendicular to the first  
7 mode, with a well-defined offshore-directed flow. The spatial pattern of EOF3 (Fig. 10 - d)  
8 adds some complexity to the basic uniform flows represented by the first two modes, since  
9 it introduces curvature to the current field by means of a large, albeit weak, anticyclonic  
10 recirculation cell (flow divergence) in the central (southern) region of the radar domain.

11 Temporal variation in the strength of these three EOF modes is represented by their  
12 corresponding principal components, shown in Fig. 11. EOF1 is predominantly positive  
13 except during the summertime, when the quasi-permanent flow to the SW is altered by  
14 clockwise inertial oscillations (positive EOF3) and some periods of current reversals, with  
15 maximum occurrence during the stratified warm season as reported by Font *et al.* (1990).  
16 Nevertheless, EOF1 becomes again strongly positive during the autumn, reaching a peak by  
17 mid-December, in clear agreement with the strengthened shelf-slope jet flowing  
18 southwestwards shown in Fig. 9 - f. The temporal structure of EOF2 reveals a principal  
19 offshore-directed flow through January-May period and also in late December, coincident  
20 with the cold season (October-May) which is characterized by both energetic Mistral winds  
21 and Ebro River high discharge rates. Lastly, EOF3 adds clockwise curvature most part of  
22 the year (February-September and November). The evident enhancement of the  
23 anticyclonic gyre in August (positive EOF3), combined with the onshore-directed flow  
24 (negative EOF2) and the reversal of the main current flow (negative EOF1) during that time  
25 period, gave rise to a complex circulation scheme, rather similar to the monthly averaged  
26 pattern represented in Fig. 9 - d.

27 In order to define the prevalent wind directions registered at B1, the major and minor  
28 variance axes have been determined (Fig. 12 - a). The results show that the main variability  
29 occurs along a direction  $99^\circ$  azimuth containing the 54% of the total energy. This is the  
30 EOF1 mode, largely aligned with persistent and intense northwesterly mistral winds  
31 channeled by the narrow Ebro Valley (Font, 1990). The orthogonal EOF2 mode is oriented  
32  $9^\circ$  clockwise from north and holds the remaining 46% of the variance, capturing mainly the  
33 influence of alongshore winds.

34 Linear correlation coefficients have been computed between the principal components  
35 related to the two main wind EOF modes of variability and radar-derived EOF2, since the  
36 cross-shelf circulation shown in Fig. 10-c might be presumably driven by strong local  
37 winds. The high correlation between the filtered principal components can be readily seen  
38 in Fig. 12 (b-c), with a value of 0.47 (0.67) for wind-PC1 (PC2) and radar-PC2,  
39 respectively. The results underline that the surface current variability in Ebro Delta can be  
40 influenced by wind action, in accordance with Espino *et al.* (1998), who demonstrated such  
41 relationship when winds are strong and steady enough. The higher agreement between both  
42 wind-radar PC2 appears to be consistent with Ekman transport to the right of the wind  
43 direction. By contrast, northwesterly mistral wind events (PC1) are expected to enforce the  
44 prevalent offshore-directed circulation regime (radar EOF2) by increasing the mean speed  
45 of the flow.

1 Equally, the influence of local wind forcing on HF radar EOF1 mode has been assessed  
2 (but not shown), with a correlation coefficient of 0.52 (-0.28) for wind PC1 (PC2). This  
3 finding highlights the impact of mistral winds on the predominant southwestward flow, by  
4 inducing an Ekman veering.

## 6 **5. Concluding remarks and future work**

7 Since the acquisition of high-quality surface current data remains as a priority for HF  
8 radar operators and the research community, a combined quality control (QC) methodology  
9 has been applied for a three site standard-range (13.5 MHz) CODAR SeaSonde HF radar  
10 network deployed at Ebro Delta (NE Spain). This integrated approach consists of one year-  
11 long (2014) real-time web monitoring of nonvelocity-based diagnostic parameters,  
12 coordinated with a 6-month (May-October 2014) validation of HF radar data (at both the  
13 radial and total vector levels) with independent *in situ* observations from a point-wise  
14 current meter installed in B1 buoy, moored within the radar footprint.

15 The overall stable and accurate performance of Ebro Delta HF radar during 2014,  
16 derived from the combined QC-validation approach, suggests that sites were functioning  
17 properly and that their APMs were correctly performed and integrated in the data  
18 processing. This provides ground truth to examine future radar performances.

19 The analysis of the monthly averaged spatial patterns of the velocity field shows that the  
20 HF radar properly represents basic oceanographic features and recurrent circulation patterns  
21 previously observed in the study area, namely: the predominant southwestward flow, the  
22 coastal clockwise eddy confined south of Ebro Delta mouth or the Ebro River impulsive-  
23 type freshwater discharge. It is also noteworthy that this study has been performed in a low-  
24 energy shelf where the surface currents are generally weaker than most of those referenced  
25 herein (Lorente *et al.*, 2014). The EOF analysis related the flow response to local winds and  
26 confirmed that the surface current field evolved in space and time according to three  
27 dominant modes of variability, which significantly account for the 46.1% of the variance.

28 Regarding Ebro Delta study area, active and planned efforts are devoted to an extensive  
29 description of a variety of marine processes impacting on the evolution and reshape of the  
30 nearshore deltaic area: the wave action eroding exposed wetlands, the sediment transport,  
31 the freshwater discharges and buoyancy fluxes (which further complicate water motions in  
32 the Ebro Estuary) and ultimately the major influence of local wind forcing.

33 Future works should include the use of verified HF radar data for the rigorous skill  
34 assessment of operational ocean circulation systems currently running in Ebro estuarine  
35 region like IBI (Iberia–Biscay–Ireland) regional system (Sotillo *et al.*, 2015), implemented  
36 within the frame of MyOcean projects and the Copernicus Marine Environmental  
37 Monitoring Service (CMEMS). A combined observational and modeling approach would  
38 provide a comprehensive characterization of the coastal circulation and benefit from the  
39 complementary nature of both systems. HF radar observations improve the model  
40 description by resolving low scale processes in areas with significant topographic gradients,  
41 whereas model outputs provide a 3-D quantitative picture with vertical resolution that  
42 completes the surface radar-derived information when the quality data or the  
43 spatiotemporal coverage are poorer.

1 This integrated strategy might complement and optimize the intense monitoring activity  
2 performed around the deltaic coastline through the timely and seamless delivery of high-  
3 quality operational products, devoted to support wise decision-making and mitigate  
4 anthropogenic hazards in the marine environment. Such products could also provide  
5 paramount information on biological connectivity between Ebro Delta marine protected  
6 area and other relevant ecological regions in the western Mediterranean Sea.  
7

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15

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<b>SITE STATUS</b>		
<b>Type</b>	<b>Parameter</b>	<b>Description</b>
Receiver	MTMP, RTMP	Chassis and board temperatures.
Transmitter	XPHT, XAHT	Chassis and amplifier temperatures.
Transmitter	XAFW, XARW	Forward and reflected powers.
Antenna	SNR1, SNR2, SNR3	Signal-to-Noise ratio at loop 1, loop 2 and the monopole.
Antenna	AMP1, AMP2	Calculated amplitude corrections for loops 1 and 2 to the monopole.
Radial	Number radials / u.t, Range and bearing	Abrupt decrease can be related to a potential malfunction
<b>SYSTEM STATUS</b>		
<b>Parameter</b>		<b>Description</b>
Temporal coverage		Data availability (%): areas of poor data return (<50%) are discarded from any analysis.
Evolution of spatial coverage		Monitoring of fluctuations due to day/night cycle. Identification of time-steps of sharp decrease in spatial coverage.
Spatial coverage–VS–Temporal coverage		Verification of the 80%-80% recommended level of data provision.
COS uncertainty metrics (standard deviation of U/V, covariance U/V)		Useful resource, based on fluctuations in the data themselves.

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4 **Table 1.** Diagnosed parameters used to operationally monitor Ebro Delta HF radar status in  
5 real time. The HF radar system's performance is routinely evaluated through the analysis of  
6 the below listed indicators on different frequencies (daily / weekly / monthly).

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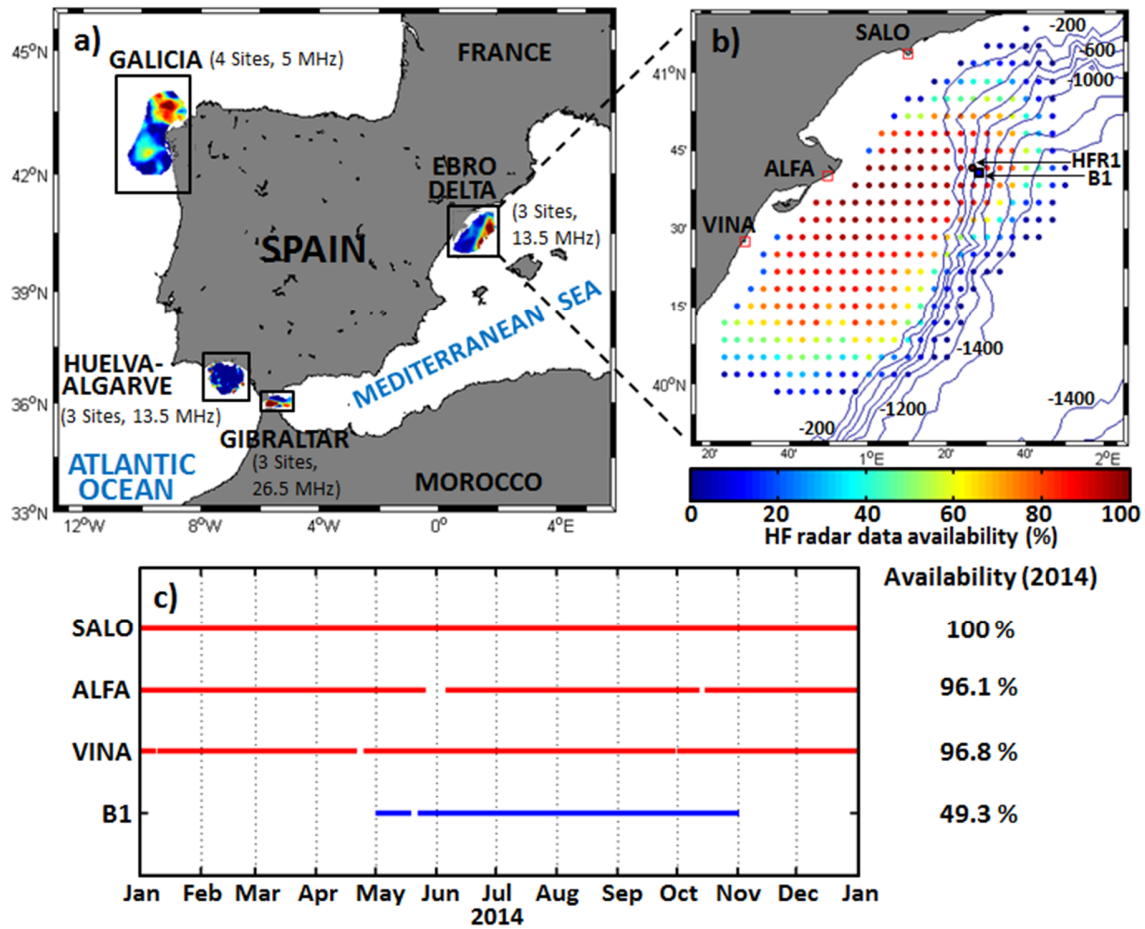
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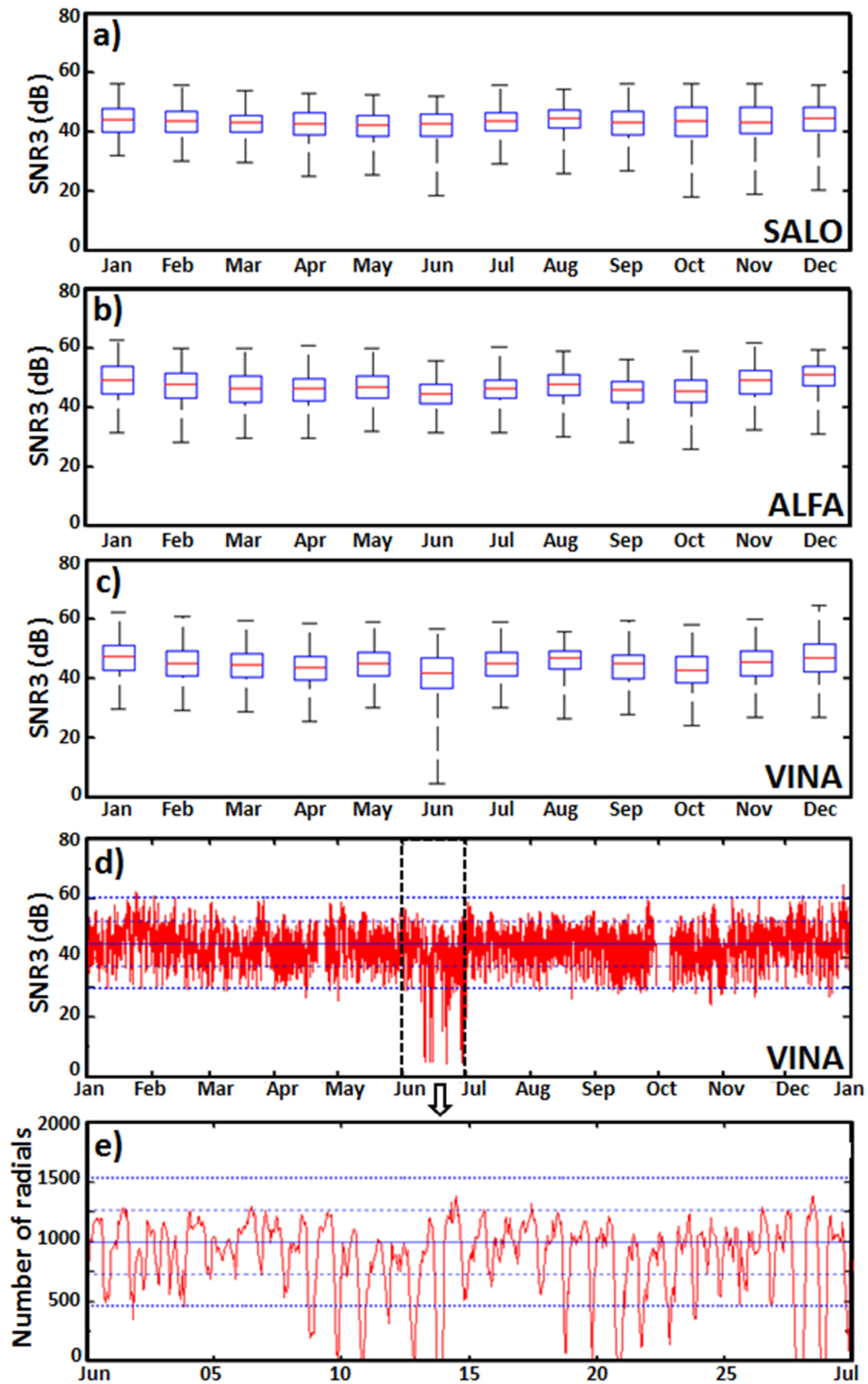
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3 **Figure 1.** (a) HF coastal radar network currently operated by Puertos del Estado (b) HF  
4 radar deployed at the Ebro Delta, composed by three sites: Salou (SALO), Alfacada  
5 (ALFA) and Vinaroz (VINA). Colored dots denote the temporal coverage in percent of HF  
6 radar surface current total vectors for the entire year 2014. Isobath depths are labeled every  
7 200 m. Location of Tarragona buoy (B1) is marked with filled blue squares. HFR1 denotes  
8 the radar grid point closest to B1 position. (c) Time lines of HF radar sites (red) and B1  
9 buoy (blue) current data availability for 2014.



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2 **Figure 2.** Annual quality control of Ebro Delta radar sites, SALO (a), ALFA (b) and VINA  
3 (c), based on monthly boxplots of Signal-to-Noise Ratio at the monopole (SNR3) for 2014.  
4 On each box, the central mark is the median, the edges of the box are the 25<sup>th</sup> and 75<sup>th</sup>  
5 percentiles, and the whiskers extend to the most extreme data points.

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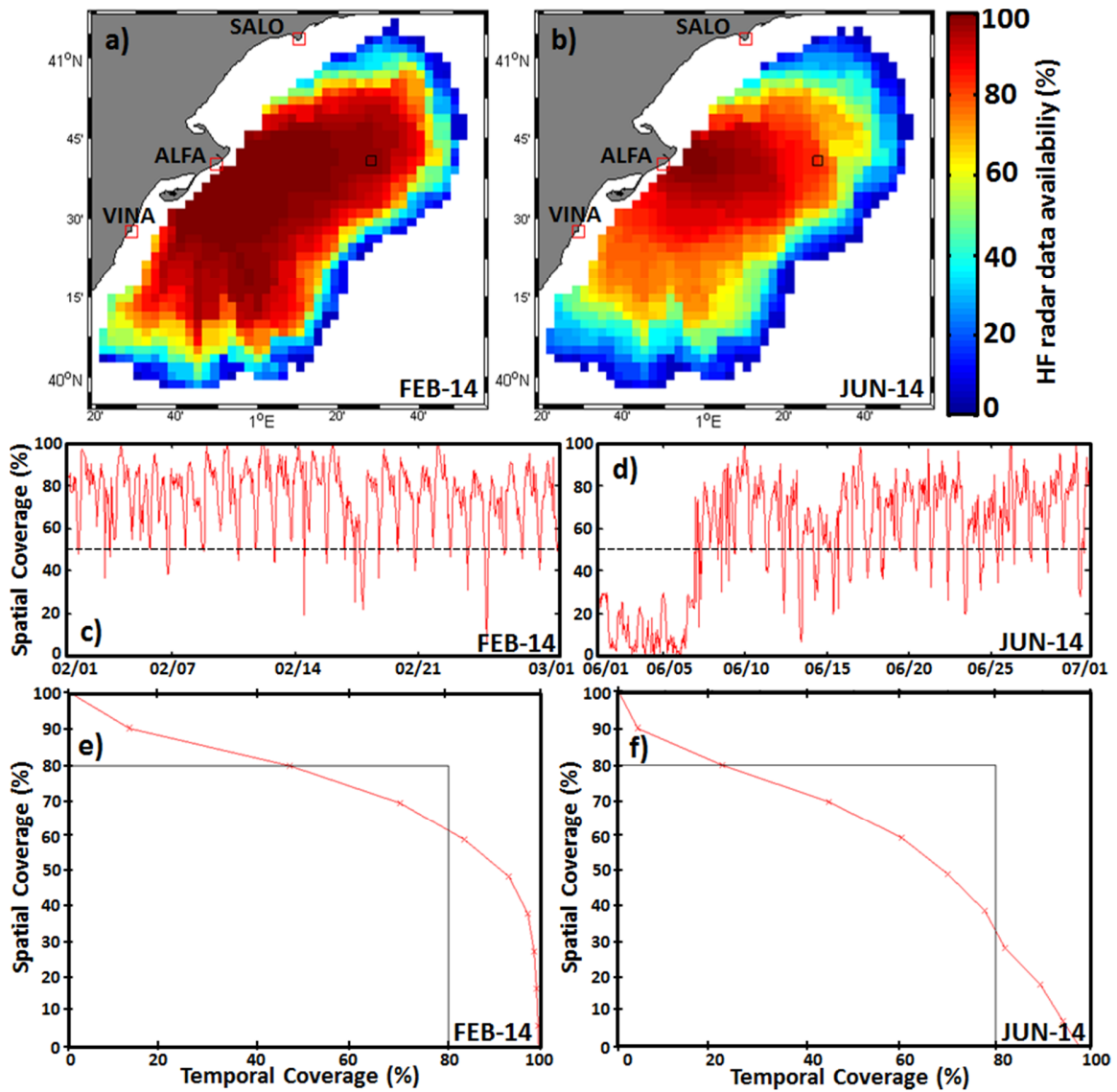
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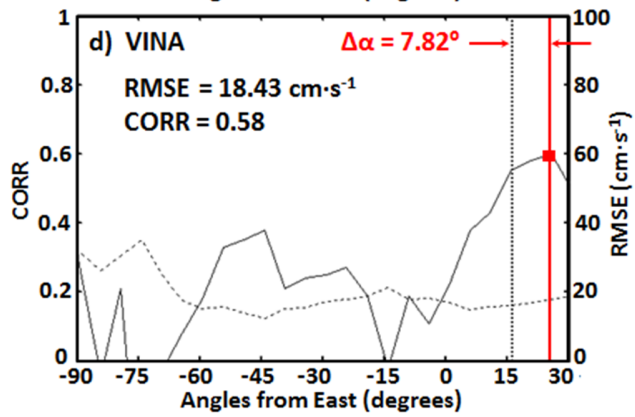
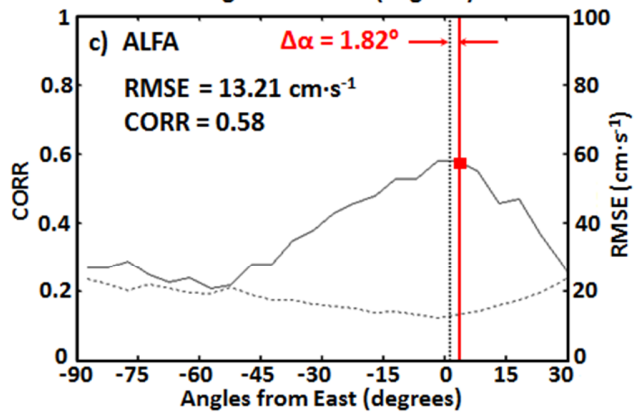
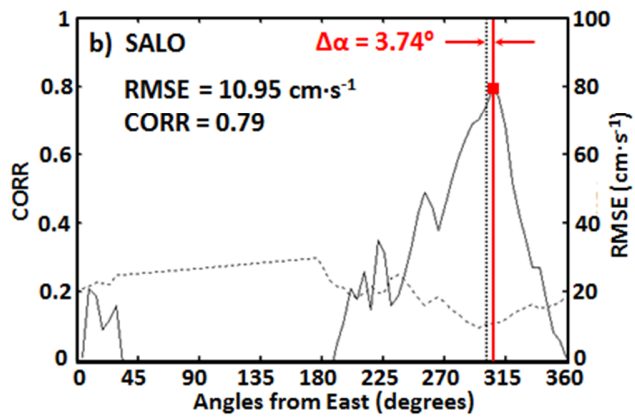
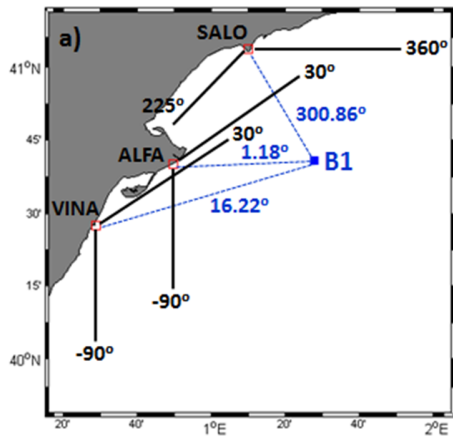


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2 **Figure 3.** Evaluation of Ebro Delta HF radar system performance on a monthly basis:  
 3 February (left) and June (right), 2014. A comparative analysis is carried out for the radar  
 4 data availability (a-b), the temporal evolution of the spatial coverage (c-d) and the  
 5 relationship between both the spatial and temporal coverage (e-f). The black square  
 6 represented in (a-b) denotes B1 buoy location.

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1 **Figure 4.** (a) Angular position of Ebro Delta HF radar sites respect to B1 buoy location.  
2 Angle values are measured counter-clockwise from East, indicating arc limits and buoy  
3 direction. (b-d) Correlation (solid line) and RMSE (dashed line) between unfiltered radial  
4 currents estimated by B1 buoy and those measured by three HF radar sites, SALO (b),  
5 ALFA (c), and VINA (d), using calibrated antenna patterns for a 6-month period May-  
6 October 2014. Vertical dotted line represents the angular position of B1. Vertical red solid  
7 line denotes the angular position of maximum correlation (CORR), which is gathered with  
8 the associated RMSE and bearing offset ( $\Delta\alpha$ ) values.

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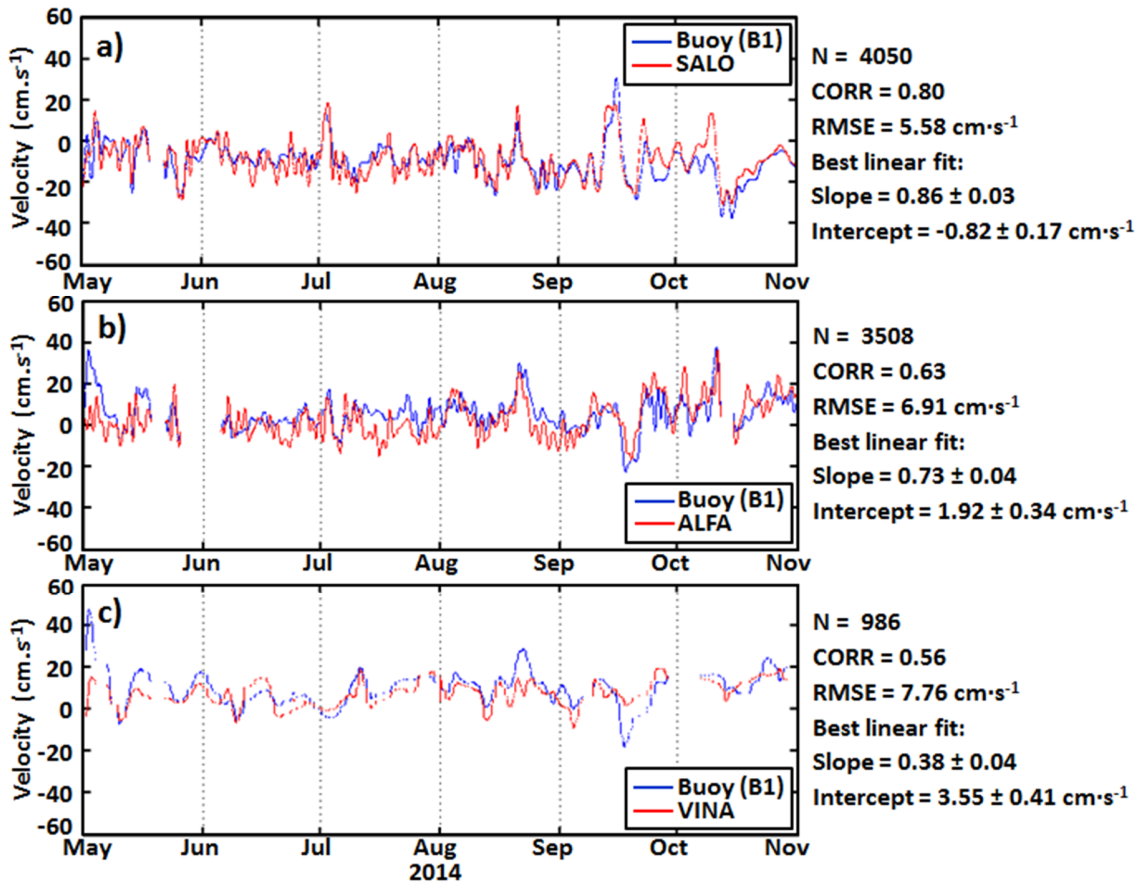
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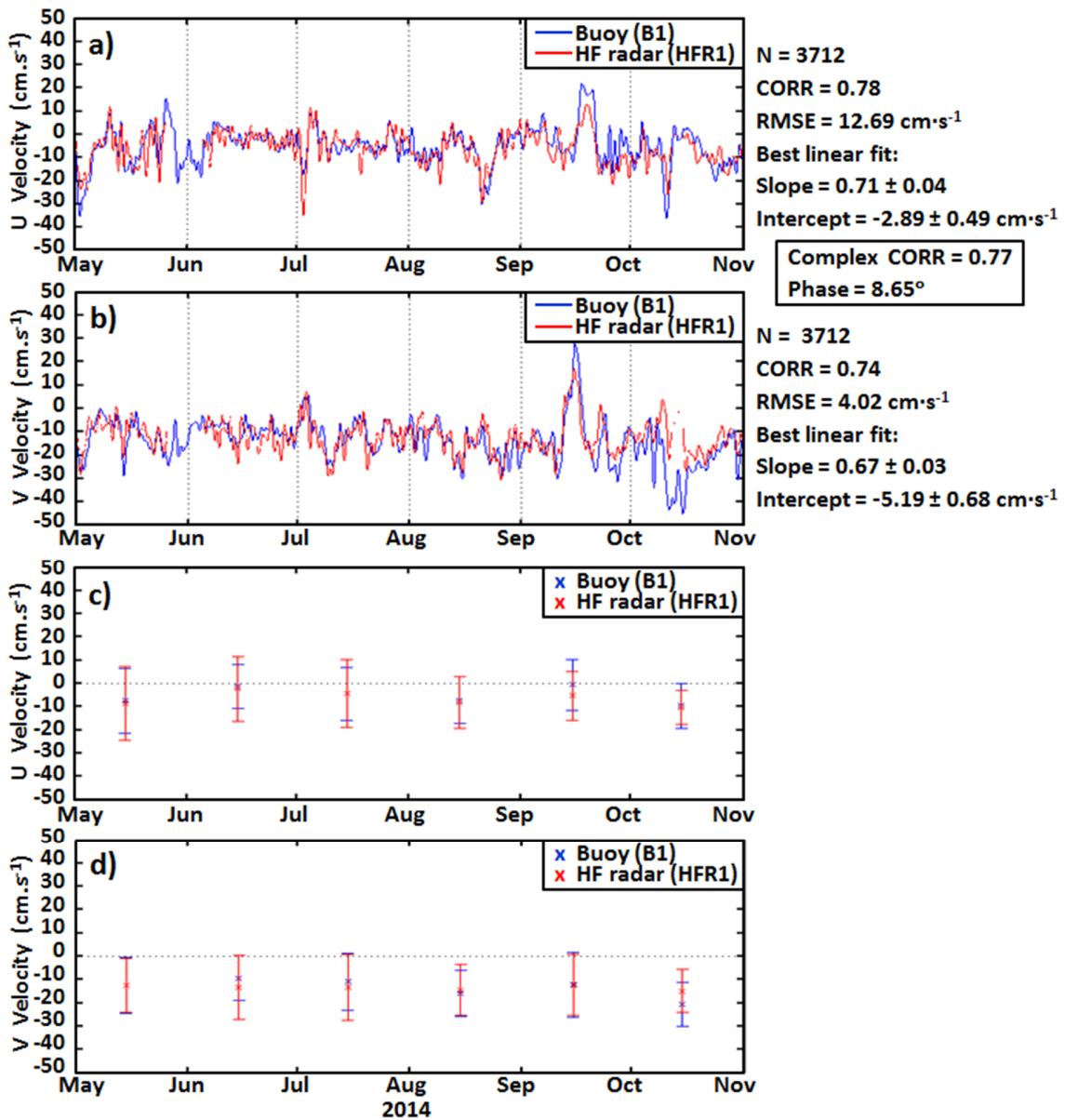
2 **Figure 5.** Comparison of low-pass filtered hourly time series (cut-off period of 30 h) of  
 3 radial currents measured by B1 buoy (blue line) and HF radar sites (red lines): (a) SALO,  
 4 (b) ALFA and (c) VINA in the range arc point closest to B1 location for a 6-month period  
 5 May-October 2014, using calibrated antenna patterns. N, slope and intercept represent the  
 6 number of hourly radial current observations and the results derived from the best linear  
 7 fits, respectively.

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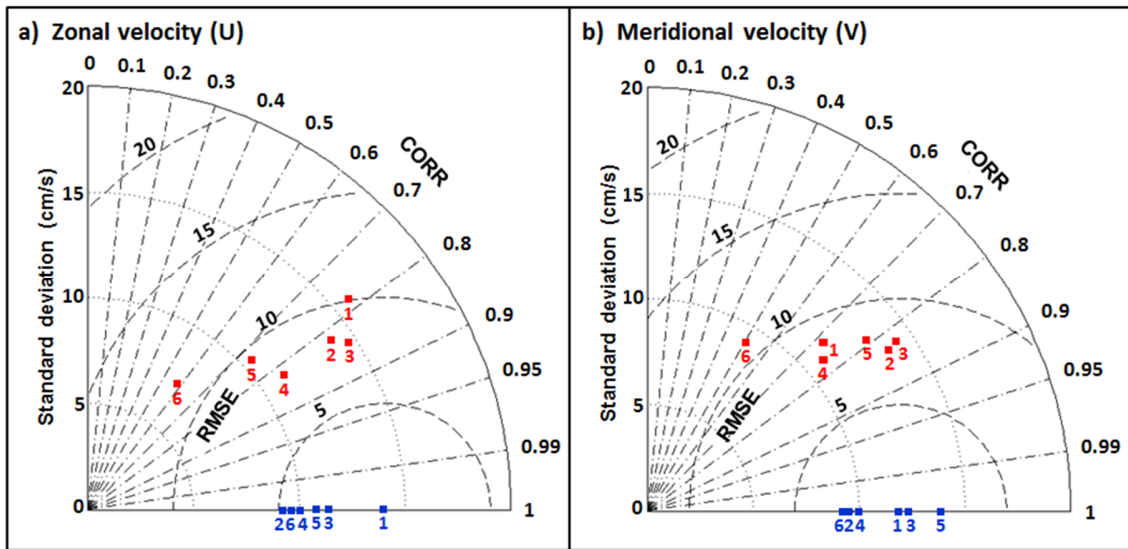
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2 **Figure 6.** Low-pass filtered (cut-off period of 30 h) hourly time series of zonal (a) and  
3 meridional (b) components of total currents measured by B1 buoy (blue line) and HF radar  
4 at the closest grid point HFR1 (red line), for a 6-month period May-October 2014. Mean  
5 zonal (c) and meridional (d) current velocities, averaged over individual months for both  
6 HF radar and B1 measurements, with one standard deviation (error bars represent the 95%  
7 confidence interval).





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2 **Figure 7.** Taylor diagrams, based on the law of cosines, provide a concise statistical  
 3 summary of how closely unfiltered hourly radar estimations (red filled squares) match with  
 4 B1 observations (blue filled squares), considered here as the reference points of perfect  
 5 agreement. Taylor diagrams for zonal (a) and meridional (b) velocity components gather  
 6 the monthly statistical metrics derived from HF radar – B1 comparison. Sequential numbers  
 7 refer to individual months of the analyzed period May-October 2014 (1: May; 6: October).

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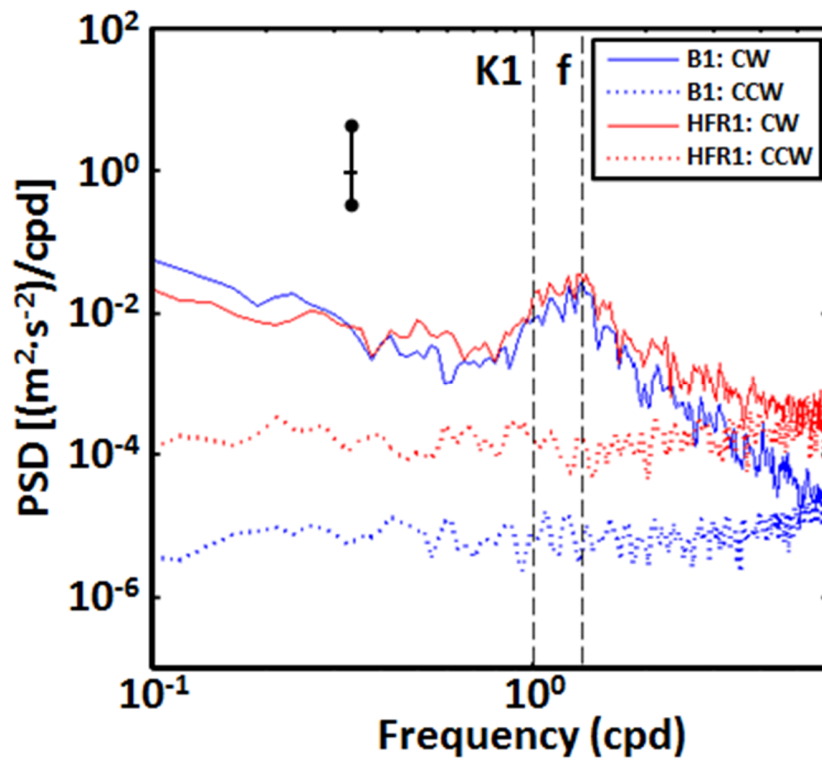
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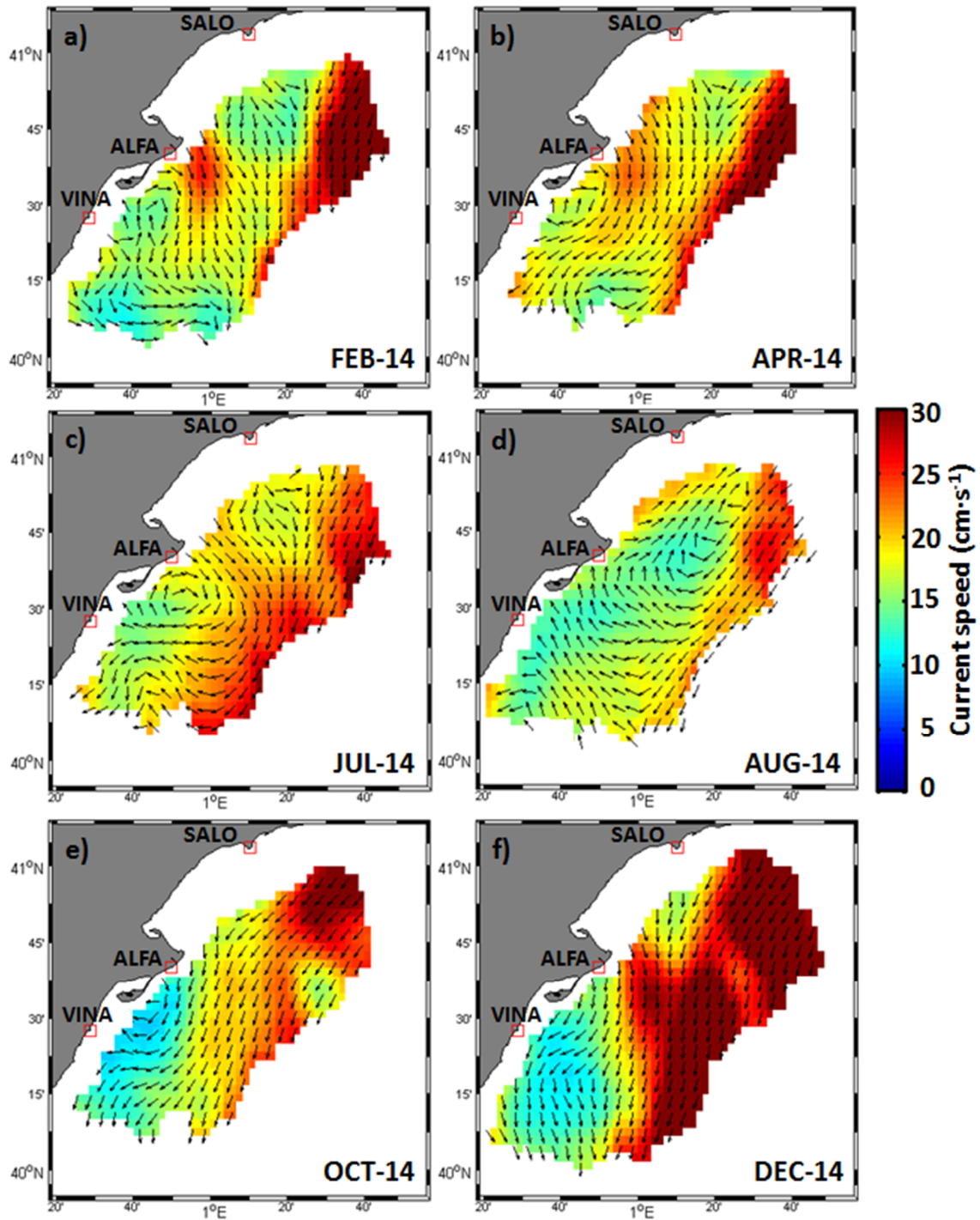
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2 **Figure 8.** Spectral density of the rotary auto-spectra of B1 buoy (blue) and HF radar at the  
 3 closest grid point HFR1 (red), performed for a 6-month period May-October 2014 of  
 4 concurrent records. Clockwise (counter-clockwise) components are represented by solid  
 5 (dotted) lines. Vertical dashed lines indicate the frequencies of the diurnal constituent ( $K_1$ )  
 6 and the inertial oscillations (f). Error bars indicate the 95% confidence interval.

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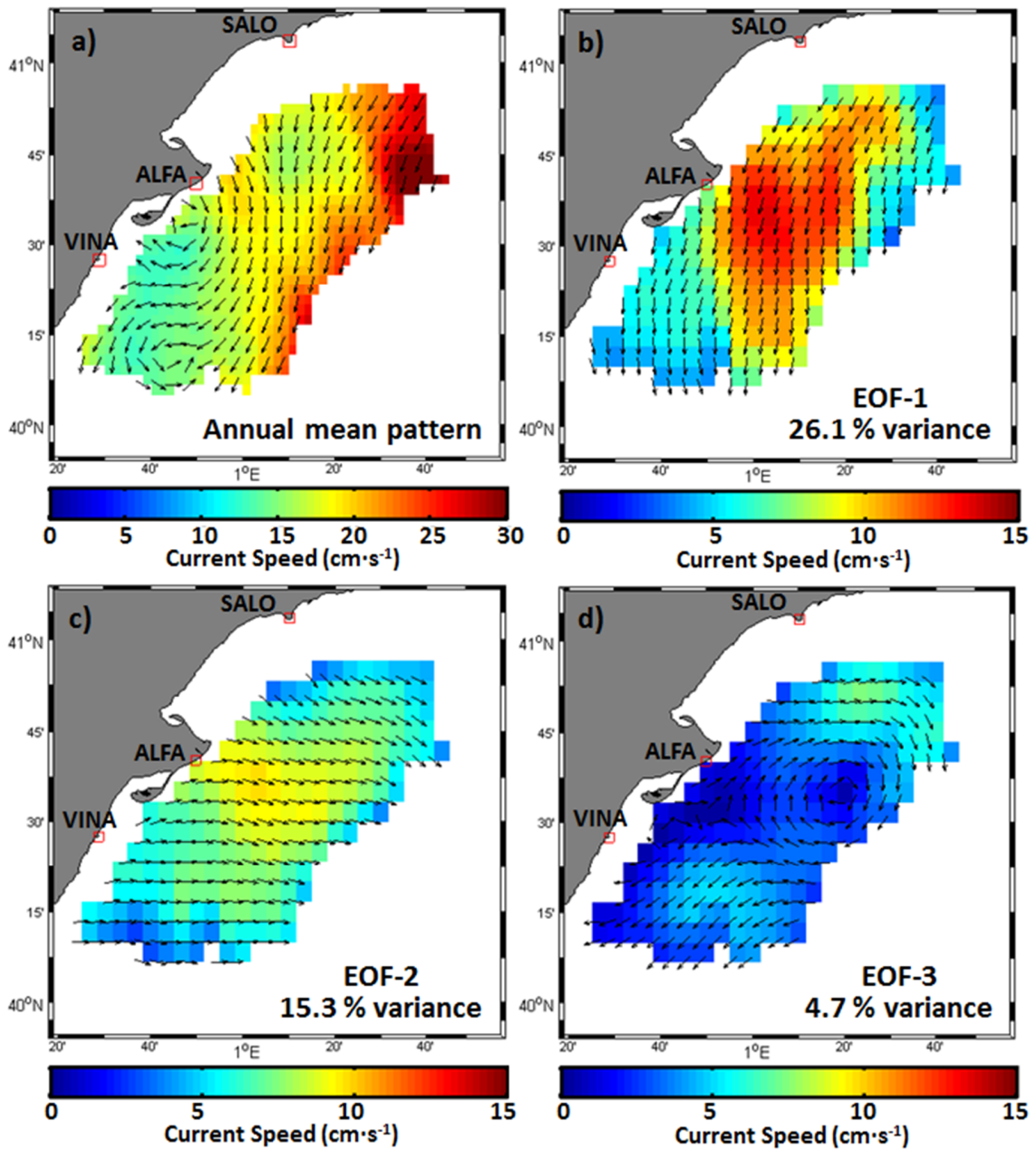
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2 **Figure 9.** Monthly averaged surface velocity fields, based on unfiltered hourly HF radar  
 3 current data, for (a) February, (b) April, (c) July, (d) August, (e) October, and (f) December  
 4 2014. The study area is not uniformly covered since only radar grid points satisfying a  
 5 minimum data return of 50% over the monthly record have been considered. Only one grid  
 6 point of every two is plotted for visualization reasons.

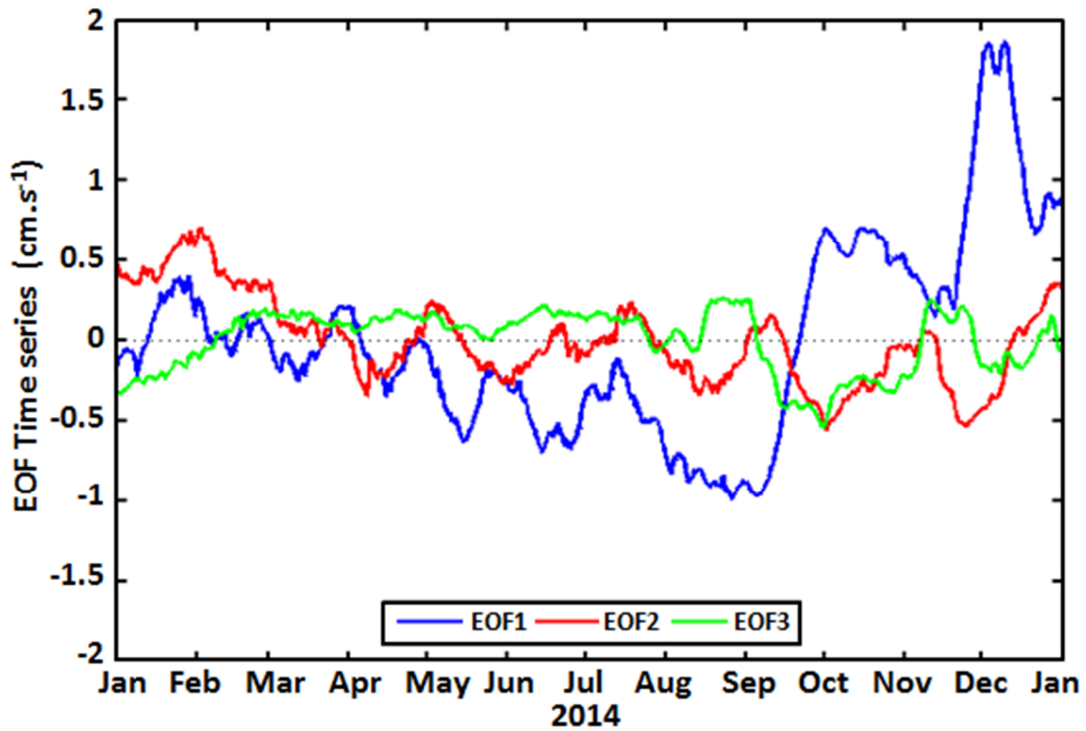
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3 **Figure 10.** Spatial patterns of the (a) annual mean velocity field and (b) first, (c) second  
4 and (d) third EOF dominant modes of unfiltered hourly radar surface currents for 2014.  
5 Current vectors were plotted in every second grid point for clarity. Variance explained is  
6 indicated in the lower right corner of the corresponding panel.

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2 **Figure 11.** Time coefficients of the first (blue), second (red) and third (green) EOF modes  
 3 of hourly radar current data set evaluated for the entire year 2014. Time series have been  
 4 filtered with a 20 day running mean.

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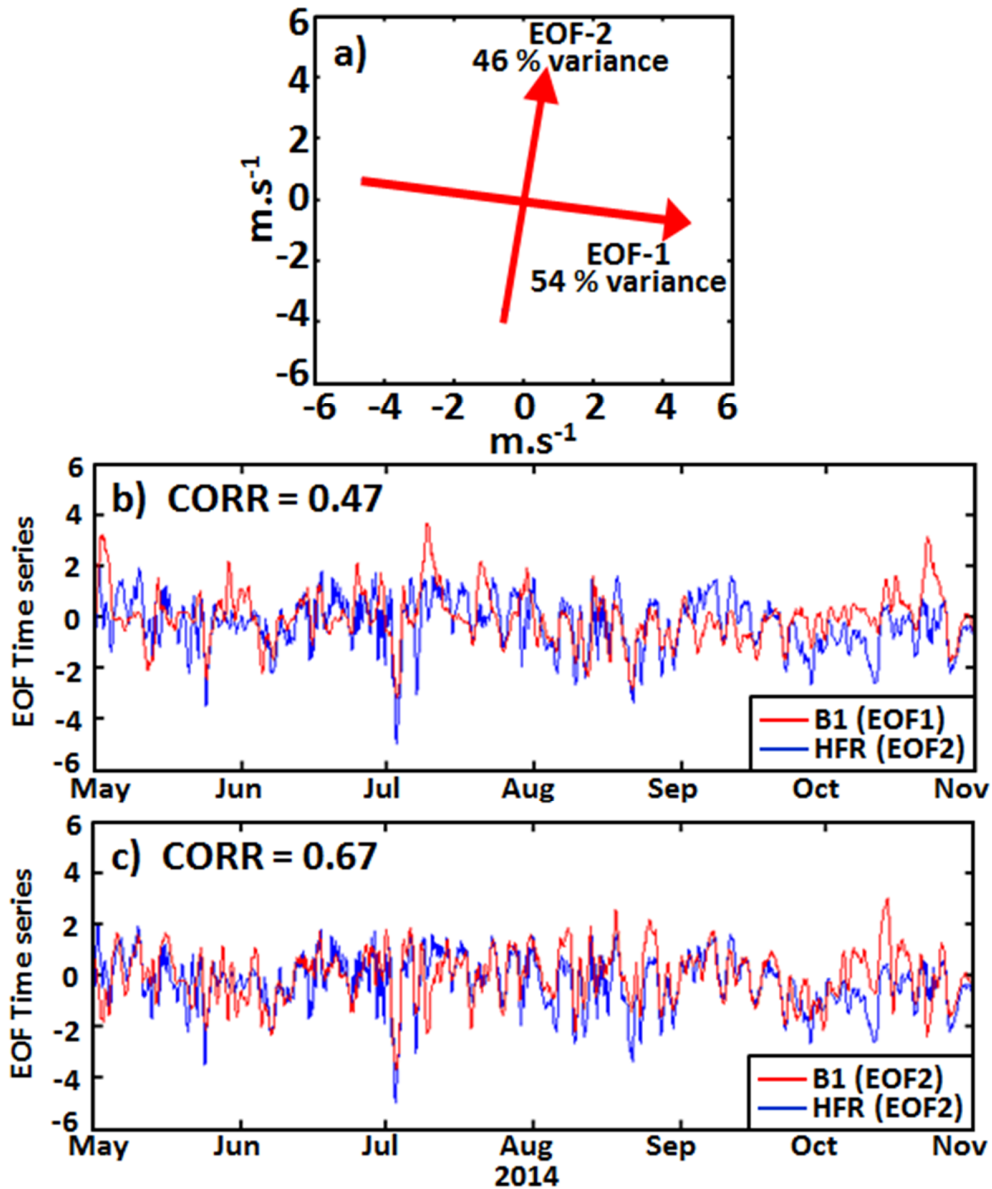
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2 **Figure 12.** (a) Main axes of variability for hourly wind data registered at B1 buoy. (b)  
 3 Principal components of the first EOF mode of wind (m/s, in red) and the second EOF  
 4 mode of radar currents (cm/s, in blue). (c) Principal components of the second EOF mode  
 5 of wind (red) and the second EOF mode of radar currents (blue). The amplitudes have been  
 6 normalized by their respective standard deviations and filtered with a 1 day running mean.