

# AUTHOR'S RESPONSE

Note that all the locations of the changes mentioned herein after correspond to the locations in the “clean” manuscript, not the marked-up version.

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## **Anonymous Referee #1**

HF radar and coastal altimetry-derived surface currents are quantitatively compared first at certain locations and then along the altimetry ground tracks in the southeastern Bay of Biscay during multiple years from 2009 to 2015. The two data sets are further used to describe the mesoscale dynamics of the Iberian Poleward Current and eddies in the region. It is demonstrated that a combination of different coastal ocean observing systems may provide a better understanding of the coastal ocean processes. Despite the limitations of the ocean observation techniques, the results are encouraging. Also, the topic is interesting and the paper is informative. I would recommend it be accepted for publication after minor revision.

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**Dear reviewer,**

**First of all, thank you for showing the technical errors. They really help to improve the manuscript and we have addressed all of the into the text. Thank you for your specific comments as well. We did not realize that we had not mentioned the confidence level of the correlations, which is 90%. We have also included it as explained below.**

**Best regards,**

**Ivan Manso**

Comments are enumerated

AR = author's response

AC = author's changes in manuscript

1. Correlation coefficient is used to quantify the comparison between two time series without any statistical significance test. It is important to mention whether a correlation is statistically significant or not, because a high correlation coefficient may not be meaningful at all without a significance test.

AR: We considered the significance (90%), therefore, all the results shown in the manuscript are significant. However, it was not mentioned in the text. Thank you for this comment.

AC: We have added this information at page 8, line 15

2. “correlation coefficients” are simply written as “correlations” in many cases, which should be clearly specified.

AR: We have specified it.

AC: Page 8, line 14.

3. Throughout the manuscript, two decimal places are used for ocean current velocities. In my opinion, one decimal digit would be enough. This is because the accuracy of HF radar current measurement is about several cm/s, and the errors in altimetry-derived currents are even larger.

AR: We have changed the values, using only one decimal place throughout all the manuscript.

4. Page 1, Line 9, “resolution” should be “resolutions”.

AR: Done.

AC: Page 1, line 9.

5. Page 1, Line 20, “higher” should be changed to “larger”.

AR: The sentence has been rephrased and therefore this adjective has been removed.

6. Page 1, Line 25, “in” should be changed to “by”.

AR: Done.

AC: Page 1, line 24.

7. Page 2, Lines 1-2, it would be good to refer to a recent book in this topic (Liu et al., 2015).

AR: Done.

AC: Page 2, line 1.

8. Page 2, Line 17, “resolution” should be “resolutions”.

AR: Done.

AC: Page 2, line 17.

9. Page 2, Line 17, “of” should be removed.

AR: Sorry, but we have not found any ‘of’ in that point.

10. Page 5, Line 6, the single sentence paragraph should be combined with the previous paragraph.

AR: We have rephrased and moved this sentence to page 4, line 30.

11. Page 5, Line 14, the single sentence paragraph should be combined with the previous paragraph.

AR: Done.

AC: Page 5, Line 18.

12. Page 5, Line 23, “except” should be changed to “except for”.

AR: Done.

AC: Page 5, line 27.

13. Page 7, Line 27, what value is used for  $C_D$ ?

AR: The value we used was the one proposed by Large and Pond (1981) which depends on the velocity of the wind ( $U_{10}$ ):

$$C_D = 1.2 \times 10^{-3} \quad \text{for } 4 < U_{10} < 11 \text{ m s}^{-1}$$
$$C_D = 10^{-3} (0.49 + 0.065 U_{10}) \quad \text{for } 11 < U_{10} < 25 \text{ m s}^{-1}$$

Note that we have considered  $1.2 \times 10^{-3}$  for every value smaller than  $11 \text{ m s}^{-1}$  and  $10^{-3} (0.49 + 0.065 U_{10})$  for larger values.

AC: We have added the reference to Large and Pond (1981) at page 8, line 1.

14. Page 9, Line 28, “the higher is the correlation, the smaller is the difference...” should be changed to “the higher the correlation, the smaller the difference...”. Both “is” should be removed from the sentence.

AR: Done.

AC: Page 9, line 29.

15. Page 14, Line 27, “Altimetry has also its own limitations” should be changed to Altimetry also has its own limitations”.

AR: Done.

AC: Page 14, line 30.

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**Anonymous Referee #2**

the paper focuses on the validation of two different altimetry products and aims at demonstrating the complementary with high-frequency radar observations of surface currents in the bay of Biscay. the manuscript has a few flaws, that should be accounted for properly before it is accepted for publication. details are given below for the Authors and the Editorial Board.

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**Dear reviewer,**

**Thank you for your thorough reading of the text and the exhaustive review. Your fruitful comments have improved the article.**

**Best regards,**

**Ivan Manso**

Comments are enumerated

AR = author's response

AC = author's changes in manuscript

**Abstract:**

1. define "surface currents"

AR: Done.

AC: Page 1, Line 8.

2. correct the spatial and temporal resolution: depending on the HFR system, they can be as low as 300m to 12km, 5 min to 3 hours; same corrections apply within the text.

AR: Done.

AC: Page 1, Line 9.

3. line 20: what variability is the Author referring to? why is it so? it would be useful to have these details in the abstract

AR: The line has been rephrased (see comment 6) and this variability it is not mentioned any more.

4. line 25: is this correlation increase statistically significant? is there a real benefit in including a simplified Ekman current model to the data, given the amount of processing the dataset already go through?

AR: Thank you for this comment, the significance of the correlation is 90%, but we forgot to mention it in the text, therefore, it has been added at page 8, line 15. With regard to the addition of the Ekman current model, it is true that the qualitative benefit is not high, but apart from providing a moderate benefit it is methodologically interesting and gives way to a better analysis.

5. check grammar and break sentences to improve readability (mainly within the manuscript)

AR: done.

6. lines 20-25: I personally would rephrase this sentence in order to focus on benefits first and limitations after; for instance, something like: "Both HFR and altimetry capture the main oceanographic features in the region (the IPC and the mesoscale eddies), however performances reduce in the areas closer to shore because of ....", or similar.

AR: Rephrased.

AC: Page 1, Lines 20-24.

### Introduction:

7. page2, line4: references to Jerico and Jerico-Next should be added

AR: Done.

AC: Page 2, Line 2.

8. page2, line6: cit: "...best possible quality indicators..." of what?

AR: This sentence has been rephrased.

AC: Page 2, Line 6.

9. page2, line19: definition of "HF" is missing; the guess is, it means High-Frequency spectral components, but it confuses with the acronym HFR

AR: Changed to high-frequency.

AC: Page 2, Line 19.

10. page2, line20: HFR do not measure "inertial waves" but can resolve "inertial currents" if the proper grid resolution is set up

AR: Thank you, it was a mistake. It has been corrected.

AC: Page 2, Line 20.

11. page3, line 12: missing network after HFR

AR: Done.

AC: Page 3, Line 11.

12. page3, line 15-18: one of the major motivations of this present work - that is, the comparison of the two products - is not stressed out properly in my opinion; this is actually te added value to this manuscript.

AR: Rephrased.

AC: Page 2, Lines 17-19.

### Section 2.1.1

13. radial velocities are not measured directly; they are derived from the inversion of the 1st order scatter from Bragg-matching waves

AR: We have changed 'measure' to 'infer'.

AC: Page 3, Line 24.

14. operational range is usually frequency and bandwidth dependent; low-frequency systems have usually narrower bandwidths thus boosting range but with inversely-proportional range resolution - 40KHz bandwidth should provide a radial range resolution of \_3.7km, not 5km as stated.

AR: It is true; however, the range cell and angular resolutions are set to 5 km and 5° respectively.

AC: We have added this clarification in page 3, line 31.

15. "noise to signal ratio" should be the opposite: signal to noise ratio.

AR: Done.

AC: Page 4, Line 1.

16. is it the RT HFR product being used, or the reprocessed DM data set used instead?

AR: The DM one.

17. "receipt antenna pattern" should be "receive antenna pattern"

AR: Done.

AC: Page 4, Line 2.

18. bi-annual calibration: performed every two years, or twice per year?

AR: It has been performed at least every two years.

AC: We have clarified it at page 4, line 2.

19. Page 4, lines 5-13: this section is confusing. Gurgel (1994) and Lipa and Barrick (1983) proposed the unweighted least-square fit for the WERA and the Codar systems. The first does a 1-1 match of radials from two stations, the second uses a spatial search radius. The OMA analysis has nothing to do with this. OMA was developed by Kaplan and Lekien (2007). My understanding is the following: radials in polar coordinate systems from the two separate stations were mapped to currents on a cartesian grid using the HFR\_Progs Matlab package; then, an OMA analysis was performed for gap-filling purposes. Since the results of the conventional least-squares approach were similar to the OMA output, it was decided to use the OMA products for the following analysis. If that is the case, there is at least one motivation for me to ask 1, if there is any quantitative comparison between the OMA and the LS fit with any other data set (see for instance Cosoli et al., 2015, who tested the EOF interpolation versus the conventional LS fit in the Malta Channel); 2, to have at least a map of the comparison metrics between the OMA - LS fit products. The reason being: OMA is fitting a limited number of modes which will inevitably lose some observed structures, and most likely adds some spurious structure that needs to be accounted for properly.

AR: Thank you for the in-depth revision of this part. The whole paragraph has been checked and rewritten to allow more clear explanations. Indeed, this is not the first time we used both LS fit and OMA for total current retrieval. Quantitative comparison between both methods have been performed in Solabarrieta et al. 2016, from a Lagrangian perspective and in Hernandez-Carrasco (this same issue- see <https://www.ocean-sci-discuss.net/os-2018-26/>).

(Solabarrieta, L., Frolov, S., Cook, M., Paduan, J., Rubio, A., González, M., Mader, J., and Charria, G.: Skill Assessment of HF Radar-Derived Products for Lagrangian Simulations in the Bay of Biscay, Journal of Atmospheric and Oceanic Technology, 33, 2585–2597, <https://doi.org/10.1175/JTECH-D-16-0045.1>, 2016.)

AC: page 4, lines 5-12.

Section 2.1.2

20. page4, lines28-32: details should be provided about this data processing approach, especially in relation to the spatial filtering approach. References should be added to the Loess filter because it needs to be understood properly in order to avoid biases at ranges from the coastline within the filter spatial cut-off length. if the filtered products are used to derive the along-track geostrophic currents, I would expect a systematic bias between HFR and satellite in the coastal regions; this would explain for instance the biases documented in Figure 5 for the first 4-5 bins; also, it would most likely explain why correlation is maximised between km 40 and 50 (3rd panels, figure 5 a and b) - page5, lines1:5: same considerations as above apply to this dataset.

AR: We have bias if we have systematic errors in SLA at the coast which are not filtered by the data editing process and then extrapolated offshore by the filter. This is true for both CTOH and CMEMS products even if the filters and cut off frequency (and then area where errors are extrapolated) are not the same. And indeed, we know that the accuracy of altimetry data is lower in the 20-30 km coastal band, so it might be a source of differences between altimetry and HFR data. But the larger the oceanic signal (larger signal-over-noise ratio), the lower this effect will be observed anyway. Additionally, note that SLA errors approaching the coast are not usually systematic as they are mainly due to several sources (signal perturbations in altimeter/radiometer footprint, SSB, tidal & DAC corrections) which vary from one cycle to another.

AC: An explanation with regard to this has been added in page 5, lines 8-12. The reference to the Loess filter has been added in page 5 line 3 (Cleveland, W.S. and Devlin, S.J.: Locally Weighted Regression: An Approach to Regression Analysis by Local Fitting, JASA, 83, 596-610,1988).

Section 2.2

21. page5, lines17-24: while the moving-average filter is probably fine in removing the low-frequency components from the HFR data set, it would be useful to have also some quantitative results of the sensitivity study about the 2, 5, 10, 15 d windows. How was the phase shift introduced by the MA process handled, for instance?

AR: These are the results of the sensitivity tests carried out for the pointwise comparison, in terms of correlation, where the 10-d window seems to be the most reasonable choice:

<u>CTOH</u>	<u>CMEMS</u>
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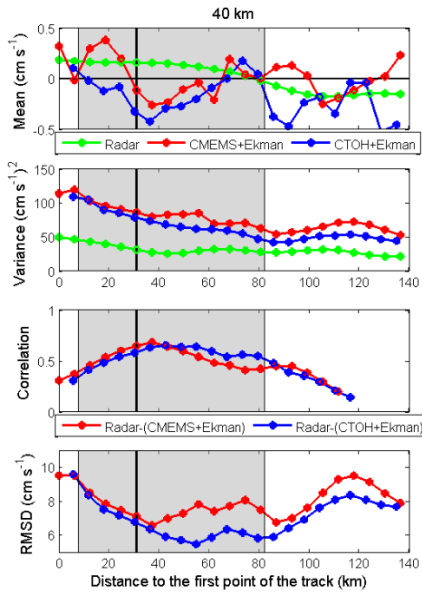
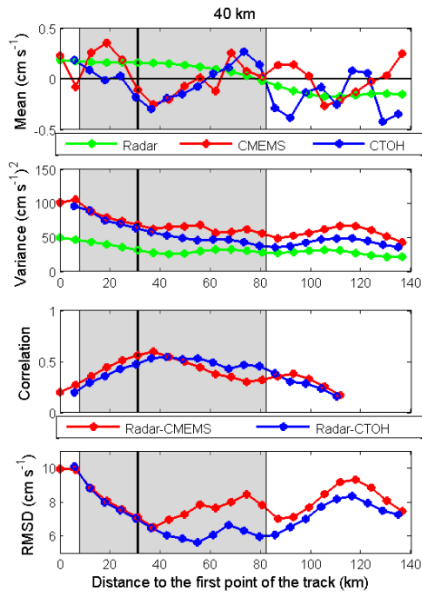
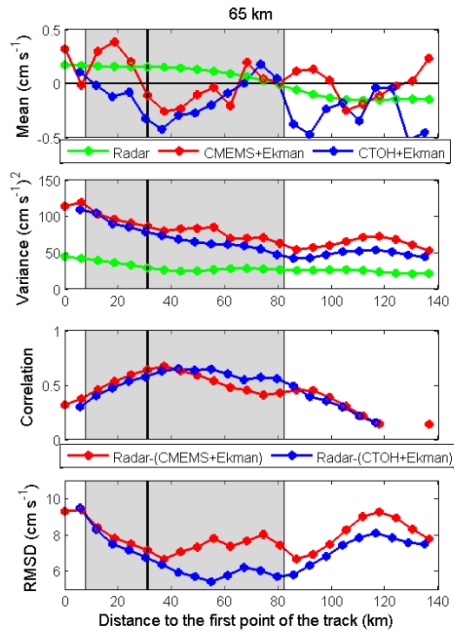
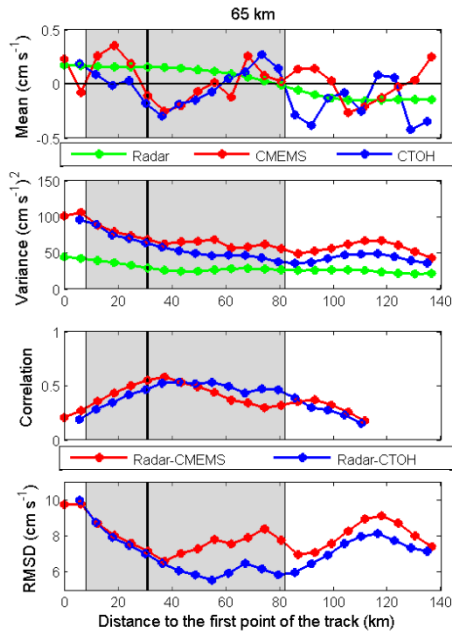
Point E:	Point W:	Point E:	Point W:
2 days $\rightarrow r=0.37$	2 days $\rightarrow r=0.59$	2 days $\rightarrow r=0.45$	2 days $\rightarrow r=0.53$
5 days $\rightarrow r=0.42$	5 days $\rightarrow r=0.60$	5 days $\rightarrow r=0.51$	5 days $\rightarrow r=0.60$
10 days $\rightarrow r=0.48$	10 days $\rightarrow r=0.64$	10 days $\rightarrow r=0.53$	10 days $\rightarrow r=0.60$
15 days $\rightarrow r=0.50$	15 days $\rightarrow r=0.59$	15 days $\rightarrow r=0.54$	15 days $\rightarrow r=0.54$

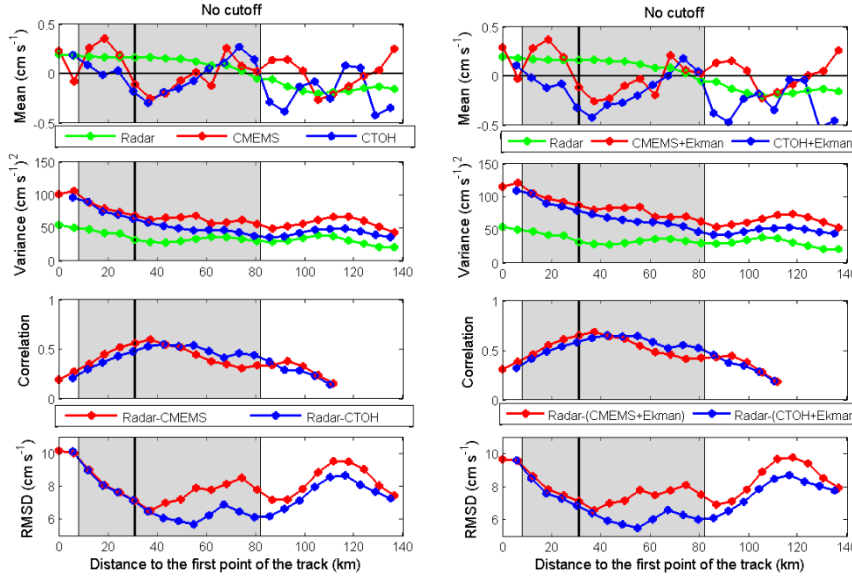
With regard to the phase shift, there is not such an effect because the data used in the MA is always the original. That is, the filtered data is not used in the MA. Therefore, it is independent of doing it forward or backward.

22. Given the spatial smoothing the altimetry data goes through, I believe a similar thing should be done for the HFR data set, so that to avoid any processing bias.

AR: Although the radar data was already smoother than the altimetry one, we have applied two spatial filters to the radar data for the along-track comparison in order to see which the effects of this filtering are. In the cases where the Ekman currents are used, they are also spatially filtered. In the next table the correlations between altimetry and HFR are shown at the two points related to this comparison. The no cutoff results are the same results of the Table 1 (in the text), however more decimal numbers are used to show which are the effects of the filtering. The correlations scarcely change and in some cases are even lower than the original ones, therefore the spatial filtering does not improve the analysis. As it can be seen in the figures below, the results do not change neither along the track. The mean values and the std of the radar are a bit lower as we use bigger cutoffs, however, as it has been said the difference is almost imperceptible. Therefore, we are not going to make any change in the analysis in this sense.

Cutoff	$r(AC_G)$		$r(AC_G + AC_E)$	
	$E_T$	$Max_T$	$E_T$	$Max_T$
65 km	CTOH: 0.5210 CMEMS: 0.5476	CTOH: 0.5317 CMEMS: 0.5783	CTOH: 0.6249 CMEMS: 0.6339	CTOH: 0.6447 CMEMS: 0.6694
40 km	CTOH: 0.5294 CMEMS: 0.56	CTOH: 0.5421 CMEMS: 0.5927	CTOH: 0.6284 CMEMS: 0.6447	CTOH: 0.6503 CMEMS: 0.6794
No cutoff (values of the table)	CTOH: 0.5261 CMEMS: 0.5572	CTOH: 0.5452 CMEMS: 0.5951	CTOH: 0.6223 CMEMS: 0.6462	CTOH: 0.6472 CMEMS: 0.6824





23. page 6: I there is something wrong with eqtn. 3; this applies to a standard orthogonal Cartesian x-y plane with x axis pointing eastwards, y axis pointing northwards and z axis pointing to the opposite direction of gravity; not clear in the text if the geostrophic velocities are computed in this coordinate system. assuming it is so, however, the derivative should be computed along y if one wants the across-track velocity, not x:  $u = -g/f * DSLA/Dy$ .

AR: It is mentioned in page 6 line 12 that x is the along-track distance. Therefore, we are in a rotated plane with respect to the usual coordinate system (where x axis points eastwards and y axis points northwards). For both altimetry tracks (213 and 248) the y axis has a positive westward component and since we assume eastward direction as the positive one (it is the direction of the main currents in the area) we add the minus symbol (considering the -y direction as the positive one) to achieve this.

24. page 6, lines18-31: more details are needed in regard to this. I assume that the comparison is performed after projecting the geostrophic currents in the direction of the radar stations, so to have a "true" comparison between the radial currents. That would be fine if the radars was error-free, which is not the case. Usually, the direction-finding radars suffer from systematic and unpredictable errors in the determination of the incoming signal, which results in statistically significant bearing offsets (see Emery et al., 2004, for additional details). I think this analysis should be extended to a few more angular sectors or the potential limitations properly acknowledged in the text.

AR: The point of this method is to compare currents in across-track direction. If we extend our analysis to a few more angular sectors we would be adding currents that are not in such direction. Actually, as mentioned in the text, 3 radials are already considered to compute the across-track currents in each point (E and W). Another possibility would be to use additional altimeter tracks but the only one in the HFR footprint area in addition to that of Jason altimeter would be that of Sentinel, so

it would be difficult to evaluate if the different correlation obtained in both tracks would be due to offsets in the bearing or to differences among SLA data from these two altimeter products.

25. page 7, eqtn. 5: the bulk-flux formula described here has no references-it should be added; is the stress computed at the standard 10-m height? what formulation is used for the drag coefficient? is it wind speed dependent or independent?

AR: With regard to the drag coefficient, the value we used was the one proposed by Large and Pond (1981) which depends on the velocity of the wind at the standard 10-m height ( $U_{10}$ ):

$$\begin{aligned} C_D &= 1.2 \times 10^{-3} & \text{for } 4 < U_{10} < 11 \text{ m s}^{-1} \\ C_D &= 10^{-3} (0.49 + 0.065 U_{10}) & \text{for } 11 < U_{10} < 25 \text{ m s}^{-1} \end{aligned}$$

Note that we have considered  $1.2 \times 10^{-3}$  for every value smaller than  $11 \text{ m s}^{-1}$  and  $10^{-3} (0.49 + 0.065 U_{10})$  for larger values.

AC: We have added Large and Pond (1981) reference at page 8, line 1. A reference (Stewart, R.H.: Introduction to Physical Oceanography, Texas A & M University, 2004) has been added regarding the bulk-flux formula (eq. 5) at page 7, line 28.

26. page 8, lines 7-8: HF again I suspect stays for "high-frequency"; so, the Ekman currents are computed then low-pass filtered with the same 10-d moving average filter. same considerations as before apply also to this product - a spatial filtering should also be applied.

AR: Same answer of the comment 22.

### Section 3

27. I would like to see the actual 95%-99% CL to correlation and statistics; are changes in correlation statistically significant?

AR: Same answer of comment 4.

28. based on Table1, the high standard deviations do compensate for any changes in mean values, and as such I would be cautious in interpreting similar variations.

AR: You are right.

AC: A clarification has been added at page 11, line 13.

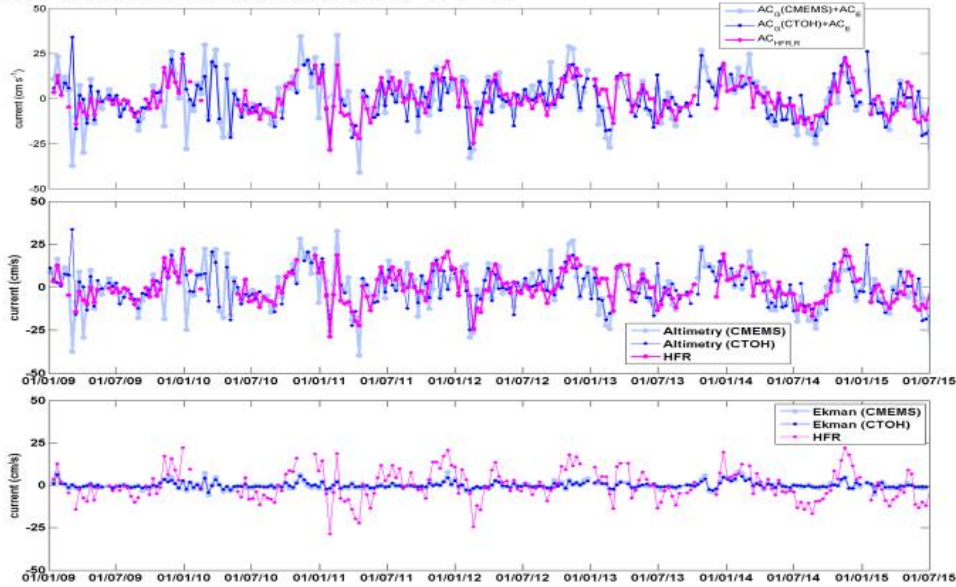
29. it is stated that in general adding the Ekman currents decreases rmsd but adds variability; it would be interesting to see a plot of these terms and try understand if the added variability reflects in the intrinsic variability of the Ekman term.

AR: The Ekman component is in good agreement with HFR and altimetry series, thus when it is added to the altimetry it strengthens its effects, and consequently increases the variability. See next figures:

## Ekman current addition: in E



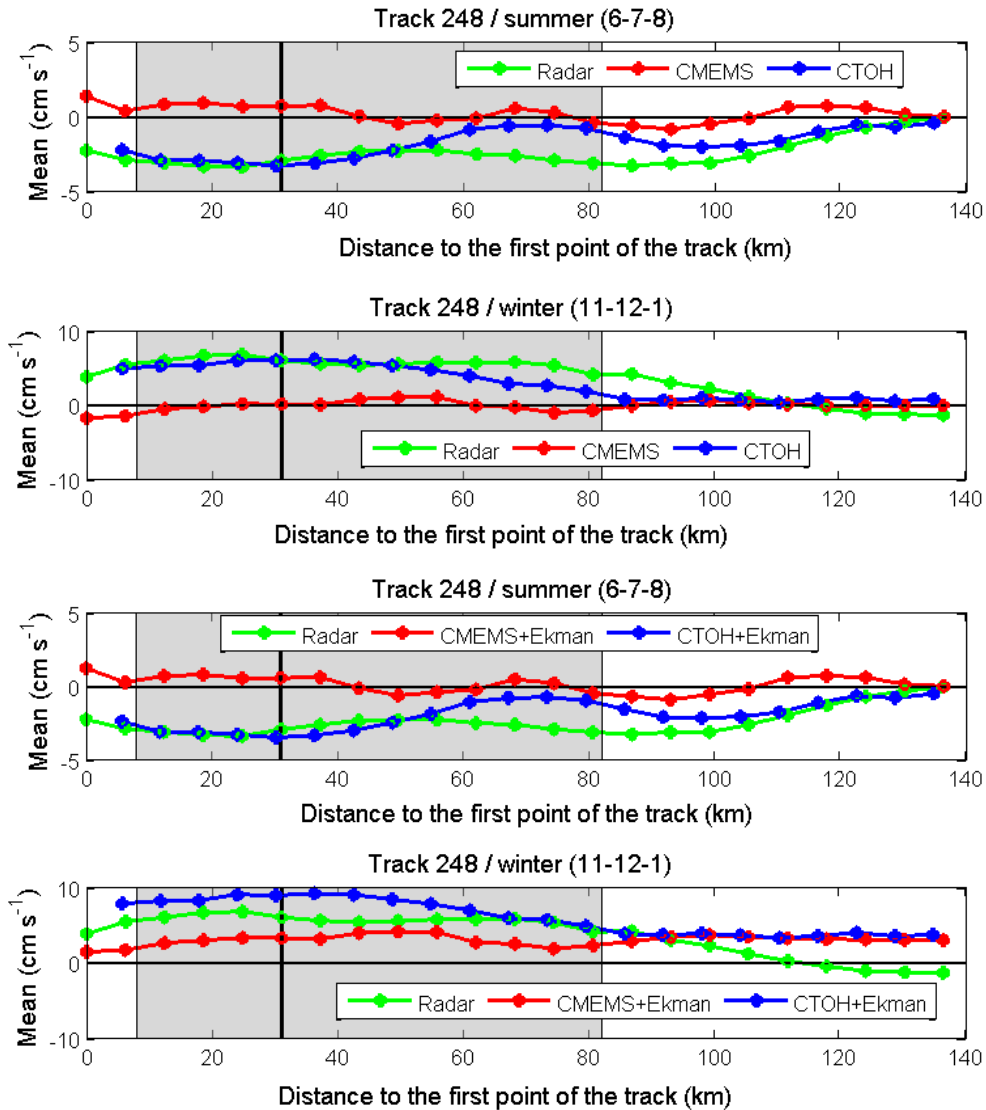
## Ekman current addition: in W



30. Figure 5 needsome additional analysis and comments: interestingly, HFR-altimetry correlation is maximised at around 40-60 km which is comparable to the size of the altimetry spatial filtering widow; the HFR dataset shows an inversion at the edge of the grey-marked area (which corresponds to the 1000m isobath); but neither the CMEMS or the CTOH products follow that pattern. why is it so? what are the sources of a similar disagreement?

AR: Although the correlation is maximized at around 40-60 km it already starts decreasing before the 1000 m isobath is reached. In addition, when the analysis with the spatially filtered radar data was carried out (see figures at comment 22), the pattern of the correlation did not change.

With regard to the inversion at the edge of the slope, it is mentioned in the text that the mean values of the currents are really small and that they are very close to zero. Therefore, the differences that are shown in figure 5 are subtle. Additionally, this greater variability of the altimetry data agrees with what it has been mentioned and shown throughout the manuscript: a larger variability in the altimetry data set. The tendency that the HFR data set shows is expectable (westward currents in winter and eastward currents in summer) and it agrees with the altimetry data if we carry out a seasonal analysis (see figures below). It can be observed that the mean value is going to be close to zero, and if we consider the spring and autumn data, we finally obtain the results of Figure 5.



31. While in general there is an agreement between the mesoscale patterns (Figure 8 for insytance), comparison is poor in the region close to shoreline where the altimetry products are often in opposite direction to the HFR data. In this sense, it would be interesting: 1, to investigate a bit further the assumptions of geostrophic balance in the boundary regions; 2, try to merge the altimetry and HFR data so to correct and in this way maximise the two products

AR: Thank you for these comments. Since they are interesting work lines for the future, we have added them in the discussion.

AC: Page 15, Lines 2-4.

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### **List of relevant changes:**

In general, there are not any major changes in the manuscript, since there are not any changes in the analyses made. Most of the changes are improvements in the writing. These are the most relevant ones:

- Page 1, Line 8: Definition of the surface currents.
- Page 1, Line 9: Specification of HFR resolution.
- Page 1, Lines 20-24: Rephrased sentence.
- Page 2, Line 1: Added reference (with its corresponding change in the reference section).
- Page 3, Line 31: Rephrased sentence.
- Page 4, Lines 4-7: Rephrased sentence.
- Page 5, Lines 8-12: An explanation about the sources of differences between radar and altimetry near the coast has been added.
- Page 7, Line 28: Added reference (with its corresponding change in the reference section).
- Page 8, Line 1: Added reference (with its corresponding change in the reference section).
- Page 8, Line 15: Specification of the minimum confidence levels considered for the correlations.
- Page 11, Line 12-13: Explanation that the high std values compensate changes in the mean values.
- Page 15, Lines 2-4: Addition of a future work line proposed by the reviewer 2.
- Page 21, Line 10: Explanation for the blank space in Table 1 in Max<sub>T</sub> point.
- Throughout the manuscript: The use of one decimal for currents and statistical results as proposed by reviewer 1.

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### **Marked-up version of the manuscript:**



# Joint analysis of coastal altimetry and HF radar data: observability of seasonal and mesoscale ocean dynamics in the Bay of Biscay

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**Abstract.** Coastal HF radar systems provide operational measurements of coastal surface currents (within 1-3 m depth) with high spatial (~300 m-510 km) and temporal (<=1 hour-hourly) sampling resolutions while the near-continuous altimetry missions afford, from 1993 to nowadays, information of geostrophic currents in the global ocean with typical along-track and temporal sampling resolutions of >7 km and >9 days, respectively. During the last years, the altimetry community has made a step forward in improving these data in the coastal area, where the data present lower quality than in the open ocean. The combination of HF radar and altimetry measurements arises as a promising strategy to improve the continuous monitoring of the coastal area (e.g. by expanding the measurements made by HF radars to adjacent areas covered by the altimetry, or by validating/confirming improvements brought by specific coastal algorithms or new altimeter missions). A first step towards this combination is the comparison of both data sets in the overlapping areas.

In this study, a HF radar system and two Jason-2 satellite altimetry products with different processing (CTOH and CMEMS) are compared over the period from 1 January 2009 to 24 July 2015. The results provide an evaluation of the performance of different coastal altimetry data sets within the study area and a better understanding of the ocean variability contained in the HF radar and both altimetry data sets. The variability of the radar and altimetry measurements is higher near the coast, and both observing systems detect the main mesoscale processes within the study area (the Iberian Poleward Current and the mesoscale eddies), which are the main mesoscale processes within the study area. The highest correlations between radar and altimetry (up to 0.64) take place in the slope, where the Iberian Poleward Current represents a significant part of the mesoscale variability of the circulation. Besides, the use of an Ekman model, to add the wind-induced current component to the altimetry-derived geostrophic currents, increases the agreement between both data sets (increasing the correlation by around 10 %).

## 1 Introduction

Ocean dynamics result from a combination of processes of different time and space scales. However, and mainly due to technical limitations, this complexity cannot be captured by the existing observational systems if each observing technique they are is analysed individually since each observing technique is they are designed for resolving certain scales. Nowadays,

there is a growing tendency to combine different observing systems for a more complete description and understanding of the ocean dynamics. Current observatories are designed to monitor, in an operational way, the ocean environment to support the human activities concentrated in the coast (Liu et al., 2015). In ~~recent~~~~the last~~ years, a great effort has been focused on the development and improvement of these platforms. ~~In the framework of~~ European projects such as JERICO (2007-2013) and JERICO-NEXT (2014-ongoing, [www.jerico-ri.eu](http://www.jerico-ri.eu)) ~~have it has progress~~~~worked~~ has been made on the one hand, on the improvement and creation of coastal observatory networks, and on the other hand, on the applications of these observatories for addressing European marine policyies. As an example, the latter project aims to integrate the emerging methodology and technology, ~~in order to~~ proceed towards the automated monitoring at high temporal and spatial resolution of wider areas, ~~for~~ providing~~de~~ the best possible ~~quality indicators~~~~data and products necessary to the implementation of~~~~for~~ the European Marine Strategy Framework Directive. For this purpose, there is an ongoing research on assessing the interconnection among physics, biogeochemistry and biology, at different spatial and temporal scales. In addition to the development of coastal observatories, there are global initiatives, as the GLOBCURRENT project (2014-2017; <http://www.globcurrent.org/>), aimed to advance in the evaluation of the synergy of satellite sensors and in situ data for the quantitative estimation of ocean surface currents (e.g. Rio et al., 2014).

Among the different methodologies to retrieve surface currents, two of them are particularly interesting due to their high potential complementarity: satellite altimetry and HF radar (HFR) systems. The former technique consists in a constellation of altimeters onboard satellites measuring the global sea level with a revisit period higher than a week and a track distance around tens of kilometres. These continuous sea level series are today close to complete 25 years of data, resolving the ocean dynamics from mesoscale to near climate scale. HFRs are designed to measure the local ocean surface dynamics with a high time and space resolutions. However, altimetry and HFR do not capture exactly the same dynamics. Altimetry detects surface currents that are in geostrophic equilibrium (~~by~~ excluding the direct response of the surface layer to the wind and then part of the ~~high-frequency~~~~HF~~ variations~~);~~); whereas HFRs measure surface total currents, i.e. ~~the~~ geostrophic and ageostrophic components (like wind-driven-currents ~~and~~ inertial ~~waves~~currents, or the wave-induced Stokes drift ~~;~~(e.g. Graber et al., 1997; Law, 2001; Ardhuin et al., 2009)).

Besides the effort made for collecting data from different platforms, methods for combining these data are under development. Recent studies focused on the evaluation of the ~~capabilities~~~~performance~~ of altimetry using HFR, concluded that HFR offers a way to improve the validation of altimetry products for coastal areas (Chavanne and Klein, 2010; Liu et al., 2012; Pascual et al., 2015; Troupin et al., 2015; Roestler et al., 2013). One of the most extended approaches found in the literature to study the synergy between altimetry and HFR data consists ~~in~~ the comparison of the total across-track currents in the along-track direction (e.g. Morrow et al., 2017; Troupin et al., 2015; Pascual et al., 2015). The combination of HFR and altimetry could help to potentiate their strengths by for example, expanding the spatial and temporal coverage of the HFR systems or evaluating and correcting~~of~~ the altimetric signal near ~~the~~ coast.

In this study, we focus on the south-eastern Bay of Biscay (SE-BoB), which is characterized by ~~the presence of~~ canyons (e.g. Capbreton canyon), ~~by an~~ abrupt changes in the orientation of the coast, ~~and~~ by a narrow shelf and slope ~~and the presence of~~

canyons (e.g. Capbreton Canyon). The ~~characteristic~~ winter surface circulation in the SE-BoB is mainly related to the Iberian Poleward Current (IPC), ~~which~~ that affects the upper 300 m of the water column. In winter, the IPC flows over the slope, advecting warm surface waters (Le Cann and Serpete, 2009; Charria et al., 2013) eastwards along the Spanish coast and northwards along the French coast (Fig. 1). In summer, the flow is reversed being three times weaker than in winter (Solabarrieta et al., 2014). Overlaid to the density-driven slope circulation, wind-induced currents are the main drivers of the surface circulation ~~at the surface~~ in the area (e.g. Lazure, 1997, Solabarrieta et al., 2015). During autumn and winter, ~~south-~~ ~~westerly~~SW winds dominate and generate northward and eastward drift over the shelf. The wind regime changes to the NE during spring, when it causes sea currents ~~turning~~ toward the W-SW along the Spanish coast. The summer situation is similar to that of spring, but the weakness of the winds and the greater variability of the direction of the general drift make currents more variable (González et al., 2004; Lazure, 1997; Solabarrieta et al., 2015). In addition to these processes, mesoscale eddies in the SE-BoB are generated, mainly during winter, by the interaction of the IPC with the abrupt bathymetry (Pingree and Le Cann, 1992) (Fig. 1). The combination of these processes makes the SE-BoB an area of interesting complexity.

The existence of a long historical time series of surface current ~~fields~~ from a long-range HFR system in the area provides, ~~in turn~~, an invaluable opportunity to explore the benefit of a combined analysis of satellite and land-based remote sensing ocean currents. This HFR network (two sites, see Fig. 1) is part of

~~The~~ coastal observatory of the SE-BoB, ~~is also~~ composed by a network of oceano-meteorological coastal stations, ~~and~~ two slope buoys ~~and a HFR network (two sites, see Fig. 1)~~. The performance of this system and its potential for the study of ~~the~~ ocean processes and of transport patterns in the area have already been demonstrated by previous works (e.g. Solabarrieta et al., 2015; Rubio et al., 2018). With regard to the ~~usefulness of altimetry for describing ocean dynamics in the BoB~~, several studies have ~~been undertaken~~ ~~proven its suitability~~ to study ~~regional~~ processes that goes from mesoscale (Dussurget et al., 2011; Herbert et al., 2011; Caballero et al., 2008b, 2014, 2016) to climate scale (e.g. Pingree, 2005).

The main objectives of this study are first, to obtain a diagnosis of the agreement of the surface currents measured by ~~altimetry and HFR both methodologies~~ over the SE-BoB; and secondly, to evaluate the observability of certain mesoscale processes by ~~the altimetry and HFR both measuring systems~~.

## 2 Data and methods

### 2.1 Data

#### 2.1.1 HFR data

HFRs are remote sensing instruments that send radio waves to the ~~surface-ocean~~ surface and use the signal backscattered by the ~~surface-ocean~~ waves to ~~measure-infer~~ the radial velocity of the surface current (toward or away from each HFR antenna). They can measure ~~ocean~~ surface currents over wide areas (reaching distances from the coast over 100 km) with high spatial (1-5 km) and temporal ( $\leq 1$  h) resolution. In this study, surface currents were obtained by means of two long-range HFR

antennas, ~~owned by the Directorate of Emergency Attention and Meteorology of the Basque Government Security Department.~~

The ~~SE-BoB-HFR-se~~ antennas emit at a central frequency of 4.5 MHz and ~~with~~ a 40-kHz bandwidth. They are located at Matxitxako and Higer Capes (Fig. 1) and provide operational data since 2009 (with some interruptions mostly due to maintenance stops or malfunctioning related with severe atmospheric conditions). The averaged Doppler backscatter spectrum obtained from the received signal (in a window of 3 h) is processed to obtain hourly radial currents using the MUSIC algorithm (Schmidt, 1986). The coverage of radial data is up to 150 km, ~~and the range cell and the angular resolutions are set to 5 km and 5°, respectively with a 5 km range cell resolution and 5° angular resolution.~~ Radial data are quality controlled using advanced procedures based on velocity and variance thresholds, ~~noise to signal?????signal to noise~~ ratios and radial total coverage. Since ~~the~~ deployment of the HFR system, the receiving ~~eeipt~~ antenna pattern of the two HFR sites has been calibrated at least ~~every two years~~ ~~biannually~~. A more detailed description of the system, and of the HFR data validation exercises ~~in the study area~~ are provided by Solabarrieta et al. (2014, 2015 and 2016) and Rubio et al. (2011 and 2018).

To obtain total currents gridded into a 5 km resolution regular orthogonal mesh, a least mean square algorithm (spatial interpolation radius of 10 km) was applied, ~~by using the HFR\_Progs Matlab package (https://cencalarchive.org/~cocmpmb/COCMPwiki/), based on Gurgel (1994) and Lipa and Barrick (1983).~~ Then, using the same grid, radial velocities were processed with HFR\_Progs to generate spatially gap-filled Open Mode Analysis (OMA) total currents (Kaplan and Lekien, 2007). ~~The OMA was applied by using the HFR\_Progs Matlab package (https://cencalarchive.org/~cocmpmb/COCMPwiki/), based on Gurgel (1994) and Lipa and Barrick (1983).~~ 85 OMA modes, built setting a minimum spatial scale of 20 km, were used to generate hourly total fields. A first analysis of the comparisons between HFR and altimetry showed that the results obtained using total currents generated by least mean square and OMA were very similar. Thus, only results using OMA currents are presented in this work.

The typical spatial scales resolved by the HFRs ~~mainly~~ depend on the resolution of the data; and thus, mainly on the operation frequency of the systems (Rubio et al., 2017). For the SE-BoB, the spatial scales resolved are typically of O(15-20) km.

### 2.1.2 Altimetry data

The basic principle of the altimetry technology is to send a radar signal to the sea surface and then to measure the ~~reflected~~ return echo ~~reflected by the sea surface~~. The time needed for the signal to go and come back determines the distance between the altimeter and the sea surface (called the range). A physically-based model (Brown, 1977) is adjusted to the resulting signal, called waveform, providing different parameters, among which the range. ~~In order to~~ ~~For~~ ~~reducinge~~ the measurement noise, the result is averaged, and the final data rate is classically (and in our case) of 1 Hz (i.e. one data every ~7 km along the satellite track).

~~The sea surface height (SSH) is obtained b~~ By subtracting the range to the satellite orbit altitude (with respect to the ~~ellipsoid~~ reference ~~ellipsoid level~~) and by applying several corrections (e.g. tropospheric and ionospheric effects on the radar wave, sea surface bias, ~~---~~), ~~the sea surface height (SSH) is obtained:~~ (SSH = orbit - range — corrections). To retrieve the total geostrophic currents, in balance with the SSH gradients, the surface height ~~has to~~ ~~must~~ be referenced to the geoid; ~~this height#~~ is called

Dynamic Topography (DT). However, since geoids are not known with enough accuracy, only geostrophic anomaly currents can be accurately derived from Sea Level Anomaly (SLA). The SLA is referenced data, which are referenced to a temporal mean-average (Le Traon et al., 2003) by subtracting a mean profile to the SSH: ( $SLA = SSH - \langle SSH \rangle$ ). For more information about the SLA and the reference surfaces, the reader is referred to <https://www.aviso.altimetry.fr/en/techniques/altimetry/principle/basic-principle.html>.

The two different along-track SLA time series used herein come from Jason-2 altimeter's 248 and 213 tracks, from cycle 18 to 259 and have a revisit period of ~10 days (d). Track 248 covers the HFR footprint area, whereas track 213 only crosses a small area at the NW of the HFR total currents coverage (Fig. 1); therefore, track 213 is only useful for the comparison with HFR radial data.

One of the altimetry data sets used in this study is the CTOH-XTRACK product (<http://ctoh.legos.obs-mip.fr/products/coastal-products/coastal-products-1/sla-1hz>), which provides SLA data specifically processed for coastal areas. The filtered version of the product was used, meaning that a 40 km cut-off spatial Loess filter (Cleveland and Devlin, 1988) was also applied in order to reduce the remaining noise in the along-track SLA.

For the same Jason-2 altimeter measurements, a differently processed data set was also used in order to assess possible discrepancies between the two altimetric products. This product is a preliminary version of the 2018 update of the reprocessed global ocean along-track Level 3 data product provided by the Copernicus Marine Environment Monitoring Service (CMEMS). As for the CTOH-XTRACK product, the filtered version was used data filtered with a 65 km cut-off spatial Lanczos filter in order to reduce noise (Pujol et al., 2016) whereas used.

Note that that on the one hand, the accuracy of altimetry data is lower in the 20-30 km coastal band, so it might be a source of differences between altimetry and HFR data; and that on the other hand, But the the larger the oceanic signal (larger signal to noise ratio), the lower this effect will be observed. In the SE-BoB area, part of the slope (characteristically by been narrow) is located within the 20-30 km coastal band, and therefore the altimetry data will be affected by this inaccuracy in this area. , this means that within the mentioned coastal band this effect will be lower for the slope area points. track 248 covers the HFR footprint area, whereas track 213 only crosses a small area at the NW of the HFR total currents coverage (Fig. 1); therefore, track 213 is only useful for the comparison with HFR radial data.

### 2.1.3 Wind data and SST images

Hourly wind data from the Weather Research and Forecasting model (WRF, [http://mandeo.meteogalicia.es/thredds/catalogos/WRF\\_2D/catalog.html](http://mandeo.meteogalicia.es/thredds/catalogos/WRF_2D/catalog.html)) were provided by the meteorological agency of Galicia (MeteoGalicia). This model, with a native resolution of 12 km, reproduces with a reasonable accuracy the offshore wind fields of the SE-BoB (Ferrer et al., 2010). In this study, the WRF gridded field was interpolated to the Jason-2 along-track points.

Due to the cloudy weather in the SE-BoB, the most proper infrared sea surface temperature (SST) images were selected one by one from the AVHRR sensor series of 1 km resolution to process Level 2 SST maps.

## 2.2 Methods

Since the time resolution of the altimetry ( $\approx 7\sim 10$  d) is lower than that of the HFR (hourly), the HFR currents data were filtered using a low-pass filter, based on a 10-day running average. The objective was to remove the high-frequency (HF) signals contained in the data (see for instance Solabarrieta et al., 2014) and part of the ageostrophic signals to make HFR data closer to the measurements from altimetry data. Several tests were carried out to determine the sensibility of the results to the temporal window chosen for the filter. For that purpose, 2, 5, 10 and 15 d low-pass filters were tested, and the resulting currents were compared to those derived from the SLA. The 10-d filtered HFR currents provided the highest correlation with the altimetry data. It is worth noting that the 10-d running average filtered out a significant part of the wind-induced currents, except for the low-frequency (LF) Ekman component.

Since from the altimetry data used here we can only obtain sea surface anomaly currents, as explained in Sect. 2.1.2, the comparisons with the radar data were carried out in terms of anomaly. In order to obtain the HFR anomaly currents ( $AC_{HFR}$ ), the temporal average of the HFR currents for the study period was subtracted to the series of low-pass HFR currents (Eq. (1)). Then, to obtain SLA relative to the same period, the average SLA for the study period was subtracted to the SLA series (Eq. (2)).

$$AC_{HFR} = V - \langle V \rangle_{t1-t2} \quad (1)$$

$$SLA' = SLA - \langle SLA \rangle_{t1-t2} \quad (2)$$

Hence, the time referenced  $SLA'$  and  $AC_{HFR}$  anomalies were obtained as suggested in Pujol et al. (2016), where  $t1 = 1$  January 2009 and  $t2 = 24$  July 2015. Hereafter, when referring to the  $AC_{HFR}$  HFR current anomalies computed using Eq. (1), we will use  $AC_{HFR,R}$  to refer to current anomalies computed directly from the radial HFR components and  $AC_{HFR,T}$  to refer to current anomalies computed from total OMA HFR currents.

For the altimetry velocity, across-track geostrophic anomaly currents ( $AC_G$ ) were inferred by means of the finite difference geostrophic velocity equation (Eq. (3)),

$$AC_G = -\frac{g}{f} \frac{\Delta SLA'}{\Delta x} \quad (3)$$

where  $g$  is the acceleration of gravity,  $f$  is the Coriolis parameter,  $x$  is the along-track distance, and  $SLA'$  is the time referenced SLA and  $AC_G$  is the geostrophic current anomaly.  $AC_G$  wereas estimated along the altimeter track by a 3 point central difference operator.

For the statistical comparison between  $AC_G$  and  $AC_{HFR}$ , two different strategies were used. The first and simplest approach is the comparison of HFR radial across-track currents with altimetry across-track currents in two given points (Sect. 2.2.1), which permits the direct use of radial HFR currents. The second approach is the along-track comparison (Sect. 2.2.2) of total OMA HFR and altimetry across-track currents, which provides additional information on the spatial variability of the agreement

between both data sets. Finally, **in order** to take into account the LF Ekman component that remains in the low-pass filtered HFR data, a **simple** model for the computation of this component was used (Sect. 2.2.3).

### 2.2.1 Pointwise comparison

This method, previously **applied in** Liu et al. (2012), consists in a direct comparison between HFR and altimetry data in a certain point, where one of the HFR radial directions (red lines in Fig. 2) crosses the altimeter track perpendicularly. This approximation allows to directly use the radar radial currents, which are in the same direction than the across-track  $AC_G$ . This method was applied for Jason-2 **altimetersatellite**'s 213 and 248 tracks shown in Fig. 1, by using the corresponding  $AC_{HFR,R}$  measured by the Matxitxako antenna in two points: point E on the track 248 and point W on the track 213 (Fig. 2). Note that the radials from Higer station were not used, since they did not provide any orthogonal radial direction for track 248 and were too gappy for the track 213 due to the large distance between this track and the antenna. Point E is located near the Capbreton Canyon at 43.75° N, 2.05° W, 46.86 km far from the coast and in a depth of 500 m (on the slope); whereas, point W is located at 43.80° N, 3.58° W, 40.73 km far from the coast and in a depth of 3000 m (on the abyssal plain). It is worth noting that using directly radial currents, additional errors that propagate in the combination from HFR radials into HFR OMA currents are avoided.

In order to make the computations more robust to the potential absence of HFR or altimetry data in the points W and E, nearby points were considered to obtain the across-track currents (Fig. 2). With regard to  $AC_{HFR,R}$ , radial directions of  $\pm 5^\circ$  (blue lines), away from the orthogonal radial direction (red line) were also considered. For each of them, the points in a range of  $\pm 5$  km from the track (blue crosses for the adjacent radials and red crosses for the central radial) were selected. Then, the across-track  $AC_{HFR,R}$  in our point was obtained by firstly averaging the values for each radial, so that only three values along the track were obtained (green crosses). Finally, the three values were again averaged to get the corresponding across-track  $AC_{HFR,R}$  (black dot).

**Finally, Then,** the  $AC_G$  in the three along-track points considered for the HFR case (green crosses) were averaged to obtain the  $AC_G$  in the central point (E and W). This permitted to ensure a similar spatial smoothing for both data sets. It must be mentioned that at point W and for CTOH altimetry product, the points were located between the along-track HFR points, so instead of considering three along-track points, two points on each side of the central point (W) were selected.

### 2.2.2 Along-track current comparison

In order to assess the variability of the comparison between HFR and altimetry from the coast to the open ocean, the comparison between the across-track  $AC_{HFR,T}$  and  $AC_G$  along the 248 track was performed. For that purpose, the  $AC_{HFR,T}$  currents were interpolated into the along-track altimetry points, and they were rotated to the across-track direction.  ~~$AC_G$  were obtained by means of the finite difference geostrophic velocity equation (Eq. (3)) and by means of a 3 point central difference operator, like in the pointwise comparison.~~ Then, an average with its adjacent two points on each side was carried out. As in the previous



case, this permitted to ensure a similar spatial smoothing for both data sets. The sensitivity to the number of adjacent points considered was tested, and this approach was the one that provided the best adjustment to the HFR data.

### 2.2.3 Ekman currents

Ekman currents were estimated to find out which was their contribution to LF currents in the area, and to evaluate how this component contributed to part of the differences observed between HFR and altimetry. Three different ways to calculate Ekman currents were tested to infer which one provided the best results in the comparisons: the rule of thumb that states that the surface currents are 3 % of the wind velocity, Ekman equations for the surface (Ekman, 1905) and the model M1 proposed in Rio and Hernandez (2003). Finally, the M1 model offered the best results:

$$\vec{u}_{ek} = \frac{b\vec{\tau}}{\sqrt{f}} e^{i\theta} \quad (4)$$

where  $f$  is the Coriolis parameter,  $\vec{u}_{ek}$  is the Ekman currents vector (meridional and zonal components),  $b$  is the amplitude parameter,  $\theta$  is the phase parameter and  $\vec{\tau}$  is the wind stress vector (meridional and zonal components) that was obtained by means of the bulk-flux formula (Stewart, 2004):

$$\vec{\tau} = \rho_{air} C_d |\vec{w}| \vec{w} \quad (5)$$

where  $\rho_{air}$  is the density of the air ( $1.22 \text{ kg m}^{-3}$ ),  $\vec{w}$  is the wind vector and  $C_d$  the drag coefficient proposed by Large and Pond (1981).  $b$  and  $\theta$  were acquired adjusting the model (by a least square fit) to the real data in the study area. These parameter values were taken from Caballero et al. (2008a), where from the fit of wind stress measurements and drifter-derived currents of the Bay of Biscay to Eq. (4) the following results were obtained:  $b=4.45 \cdot 10^{-3} \text{ m}^2 \text{ kg}^{-1} \text{ s}^{1/2}$  and  $\theta=-23.68^\circ$ . Once the parameters were obtained,  $\vec{u}_{ek}$  was estimated using the wind data series described in Sect. 2.1.3.

Ekman currents initially computed in the locations of the WFR model nodes were interpolated and rotated (from zonal and meridional directions to along-track and across-track directions). For the pointwise comparison, they were interpolated in E, W and in their adjacent points, and rotated to obtain the across-track component. After, they were averaged so that finally, the across-track Ekman current velocity was obtained in each point (E and W). In the along-track current comparison, they were interpolated to the altimetry along-track points and after rotated to get the across-track component. Ekman currents were also 10-d running averaged to remove the HF Ekman signal.

For the comparisons with  $AC_{HFR}$ , Ekman anomaly currents ( $AC_E$ ) were obtained by subtracting the average value of the study period like in Eq. (1) and (2). Then, they were added to  $AC_G$  and this is indicated as  $AC_G+AC_E$  on Table 1.

The results of all the comparisons described above are presented in terms of the correlation coefficient or correlation ( $r$ ) (with a confidence level of 100% and 90% for the pointwise comparison and the along-track current comparison, respectively) and the root mean square difference (RMSD) between the across-track currents measured by each system. In addition, the mean and the standard deviation ( $std$ ) of such currents the across-track currents measured by each system were also analysed. All these parameters were computed for the study period. Since the HFR radials are used in the



pointwise comparison, the crossing points are called  $E_R$  and  $W_R$ . In the along-track comparison, the point E is precisely across-track currents are compared along all the track. However, one of those along-track points. Therefore, is the point E and considering that the corresponding statistical parameters are the ones that use the rotated  $AC_{HFR,T}$  are used in this comparison, the point is named  $E_T$ . The  $Max_T$  points along the track are the points where  $r$  is maximum in the along-track current comparison (point  $2.10^\circ$  W,  $43.82^\circ$  N for CTOH and point  $2.09^\circ$  W,  $43.80^\circ$  N for CMEMS); are also called  $Max_T$  the rotated  $AC_{HFR,T}$  were also used in these points. All these points and their statistics are displayed in Table 1, as well as in Figs. 3, 4 and 5, and they are also discussed in the next section. Moreover, in Fig. 5, apart from the results of  $E_T$  and  $Max_T$ , the results for all the track 248 are also shown.

Note that the HFR-altimetry comparisons were carried out for CMEMS and CTOH data sets and that each comparison was also made with and without adding  $AC_E$ .

### 3 Results and discussion

#### 3.1 Statistical results

Table 1 provides an overview of the statistical results of the HFR and altimetry data sets is-comparison in the points  $E_R$  and  $W_R$  for the pointwise method and in the points  $E_T$  and  $Max_T$  for the along-track method. Despite the differences between the two measuring systems, the comparison between  $AC_{HFR}$  and  $AC_G$  ( $AC_G + AC_E$ ) shows maximum correlations of 0.64 (0.70). Table 1 provides an overview of the statistical results of this comparison in the points  $E_R$  and  $W_R$  for the pointwise method and in the points  $E_T$  and  $Max_T$  for the along track method.

Concerning the pointwise comparisons between  $AC_G$  and  $AC_{HFR,R}$  it can be observed that  $r$  depends on the location, as well as on the SLA-product altimetry product considered. In any case, the addition of  $AC_E$  increases  $r$  by 6-11 % for both SLA-product altimetry products; from 0.53 and 0.48 to 0.64 and 0.59 in  $E_R$ , and from 0.61 and 0.64 to 0.67 and 0.70 in  $W_R$ , for CMEMS and CTOH, respectively. The RMSD also decreases between 0.249-0.44  $\text{cm s}^{-1}$ . Therefore, in general terms, the addition of  $AC_E$  decreases the differences between  $AC_{HFR,R}$  and  $AC_G$ . However, it adds variability; the  $std$  for  $AC_G + AC_E$  increases 0.769-1.04  $\text{cm s}^{-1}$ . It should be pointed out that the  $std$  of  $AC_{HFR,R}$  is lower than the  $std$  of  $AC_G$  (where CMEMS's variability is higher than CTOH's), probably due to the filtering of because HF signals may have been better filtered for the applied to the radar due to the 10 day running average temporal filter or because the finite difference operator that estimates the geostrophic velocity from  $SLA'$  increases the variability. The same effect was observed in Liu et al. (2012) and in Verron et al. (2018). Nevertheless, however, although the addition of  $AC_E$  it increases even more the variability-the addition of  $AC_E$ , it clearly improves the results.

Fig. 3 displays the time series of  $AC_{HFR,R}$  and  $AC_G + AC_E$  in the points  $E_R$  and  $W_R$ . In general, there is a global agreement between the three series ( $AC_G$  (CTOH) +  $AC_E$ ,  $AC_G$  (CMEMS) +  $AC_E$ ,  $AC_{HFR,R}$ ), and all the data sets observe-are observing the same variability. Although in Fig. 3 it is difficult to detect-observe any differences between locations and data sets, the lowest

RMSD is observed in  $E_R$  for CMEMS  $AC_G$  (RMSD= 7.14 cm s<sup>-1</sup>), while the RMSD rises up to 8.95 cm s<sup>-1</sup> in  $W_R$  for CTOH. A larger variability in  $W_R$  is ~~shown~~observed in Table 1, ~~which and it~~ is also noticeable in Figs. 3a and 3c.

In terms of correlation, the results suggest a higher agreement in  $W_R$  (0.67 and 0.70 for CMEMS and CTOH respectively) than in  $E_R$  (0.64 and 0.59 for CMEMS and CTOH respectively). This could be explained by the fact that point  $W_R$  is located in a deeper area, more influenced by the IPC that flows over the slope. The IPC shows lower variability in point  ~~$W_R$ - $E_R$~~  than in point  $E_R$   $W_R$ , where the signal of the slope current is ~~more~~less persistent. ~~Indeed, point  $E_R$  is located near the Capbreton Canyon, an abrupt bathymetry area where the coast also changes of orientation.~~ These spatial differences agree to what was observed in the area by Rubio et al. (2009), from the analysis of the ADCP time series of two buoys located over the slope in locations comparable to points E and W. These authors suggest that while there is a clear along-slope transport with intense mesoscale variability at Matxitxako buoy (slightly east from point W), at Donostia buoy (close to point E) ~~the influence of the slope circulation was less significant and stronger stratification was observed.~~ The lower current velocities and lower vertical coherence observed at Donostia buoy during winter could be linked to the complex bathymetry, which might force the IPC to flow over deeper grounds in the area. This could also explain why the addition of  $AC_E$  increases more  $r$  in  $E_R$  (by 11 %) than in  $W_R$  (by 5-6 %), where the circulation has a stronger geostrophic component.

With regard ~~to~~the performances of the two ~~SLA-product~~altimetry products ~~are compared~~, it must be highlighted that CTOH shows higher (lower)  $r$  (RMSD) in  $W_R$ , while CMEMS shows higher (lower)  $r$  (RMSD) in  $E_R$ . However, the differences are small and do not permit to discuss on their relative accuracy ~~of the two SLA-products.~~

In  $E_R$  ( $W_R$ ) when  $r$  is ~~bigger~~higher for CMEMS (CTOH) than for CTOH (CMEMS), the RMSD is lower in the former. Therefore, the higher ~~is~~the correlation, the smaller ~~is~~the difference between  $AC_G$  and  $AC_{HFR,R}$ . However, the difference of the RMSD in each point (i.e. between the RMSD value of each altimetry product with the radar) is not related to the difference in  $r$ .

Figs. 3b and 3d also show the residuals between  $AC_G$  and  $AC_{HFR,R}$  for each altimetry product. It can be observed that in  $W_R$  (Fig. 3d) the residuals' amplitudes are larger for CMEMS than for CTOH, agreeing with the higher RMSD value observed for the CMEMS  $AC_G$ . In  $E_R$  the similar RMSD values observed for both ~~SLA-product~~altimetry products ~~are in agreement~~agree with the similar amplitudes of the residuals in Fig. 3b.

The IPC winter intensification is visible in all data sets, being stronger in  $AC_G$  for both ~~SLA-product~~altimetry products. There are some remarkable intensifications, for instance in November 2014, ~~where when~~ a strong peak is shown in all the series and where the  ~~$AC_{HFR,R}$  HFR-current~~ signal is higher in  $W_R$  than in  $E_R$  (see black arrows in Figs. 3a and 3c), approaching more to the  $AC_G$ . There is another remarkable intensification in winter 2009, when the IPC shows a pronounced peak (see black arrows in Figs. 3a and 3c), especially in  $E_R$ , where CTOH is very similar to  ~~$AC_{HFR,R}$  HFR~~. ~~This~~ intensification ~~is not so clear~~ in point  $W_R$  ~~is not so clear~~, but it is still noticeable comparing with the rest of the period. Equatorward slope current intensifications can be also observed through the whole period, as for instance in May 2011, where the peak is more prominent in  $W_R$  than in  $E_R$  (and even more for CMEMS) (see black arrows in Figs. 3a and 3c).

Since the presence of a stronger IPC signal is expected to improve the correlation between HFR and SLA data sets, and the IPC shows marked seasonality, a monthly analysis has been carried out (Fig. 4). Every monthly value of every statistical parameter shown in the figure, has been computed ~~taking into account~~ considering all the available data for that month during all the study period.

5 It can be observed that in terms of monthly mean currents, the three ~~time~~ series have the same tendency and that in general there is low discrepancy among them. No significant differences in terms of monthly patterns are observed among the two ~~SLA-altimetry~~ products. The winter poleward current intensification is patent from October to January with a maximum in November (ranging for all ~~dataset~~ data sets from 7.54 to 13.436 cm s<sup>-1</sup> in E<sub>R</sub> and from 11.73 to 14.879 cm s<sup>-1</sup> in W<sub>R</sub>). In E<sub>R</sub>, the current intensification is still perceptible in February, whereas in W<sub>R</sub> there is a little increase in March in the  $AC_G$ , but not in the  $AC_{HFR,R}$  ~~currents~~. From March to September the mean is maintained around zero, with a slight decrease reaching the minimum in September (ranging from -7.30 to -3.986 cm s<sup>-1</sup> in E<sub>R</sub> for all ~~dataset~~ data sets and from -5.437 to -3.56 cm s<sup>-1</sup> in W<sub>R</sub>) and showing an equatorward weak mean slope current for that period. The addition of  $AC_E$  slightly strengthens the intensity of the slope currents for both poleward and equatorward directions. This can be explained by the general wind patterns of the area, which are in agreement with the main geostrophic regime in the study area, although winter south-westerlies are stronger than the summer north-easterlies (Herbert et al., 2011).

15 Fig. 4 shows, as it has been mentioned previously, lower *std* values for the  $AC_{HFR,R}$  along all the period. ~~These values are slightly~~ ~~whereas~~ increased by the addition of  $AC_E$  ~~increases it slightly~~, especially in winter when winds are stronger. In point E<sub>R</sub>, the tendency of the *std* is similar to that of the mean, being slightly higher in January, and then stable (with small oscillations) until September. In the last three months of the year it is increased. Therefore, there is a higher variability in late autumn and winter, probably due to the slope current intensification and the ~~effect of the wind (as mentioned before)~~ stronger winds.

20 In point W<sub>R</sub>, the highest variability takes place in the first 4 months of the year. This increase is coherent with the intensification of the slope current and the development of an anticyclonic structure in March and especially in April near Torrelavega ~~C~~ Canyon (Caballero et al., 2014). Afterwards, the variability is practically maintained, with little oscillations and an increase in CMEMS data.

25 Regarding the RMSD, the patterns are similar to those of the *std* of the  $AC_G$  but with variability. In general, the addition of  $AC_E$  improves the results by a slight decrease of the RMSD. The major differences between  $AC_G$  and  $AC_G + AC_E$  time series, are observed in February and April in point E<sub>R</sub>. This can be clearly seen in the normalized RMSD, which measures the value of the RMSD with respect of the values of the  $AC_{HFR,R}$ .

30 The same statistical parameters, ~~in addition to the correlation~~, computed along the track 248 are shown in Fig. 5 in order to study the spatial variability in the comparison between  $AC_{HFR,T}$  and  $AC_G$ . Temporal statistics considering all the study period for each point of the track are plotted as a function of the distance to the first point of the track.

The  $AC_{HFR,T}$  shows mean values close to zero along all the track, with low variability. Currents are oriented poleward over the shelf and upper slope, over grounds shallower than 1000 m, (i.e. until the point where the track leaves the slope current area). From there on, the mean is oriented equatorward. The mean  $AC_G$  are also close to zero, however, they show larger variability changing between positive and negative values along the track, and with a lack of agreement between both ~~SLA~~ ~~product~~ altimetry products in some points. Nevertheless, it should be pointed out that in any case the mean anomaly currents are very weak and that the high  $std$  values compensate changes in the mean values. The addition of  $AC_E$  does not cause any spatial variation and it barely changes the values.

With regard to the variability, it is higher close to the coast. For  $AC_G$ , it softly decreases as it gets away from the first point of the track, until the 1000 m isobath of the slope is reached (where the grey area ends in the figure). From there on, it is kept almost constant with a slight local maximum at around 120 km from the first point. For the  $AC_{HFR,T}$ , the variability decreases until the point  $E_T$  is reached (where the Capbreton canyon area is left) and after, it is also almost constant with two maximums at around 60 km and 105 km from the first point.

It can be once again observed that the addition of the  $AC_E$  slightly increases the variability (Fig. 5), that the variability of  $AC_{HFR}$  is lower than the one of  $AC_G$  and that CMEMS's variability is higher than CTOH's. Moreover, in Fig. 5, all these results are proved for all the track instead of for some certain points.

The highest  $r$  is observed between 200 and 1000 m isobaths of the slope, where the IPC signal is the strongest, and thus the geostrophic component measured by the HFR is also stronger. In the points furthest from the coast the  $r$  decreases. This can be linked to the absence of a strong and persistent geostrophic component and a higher noise to signal ratio for the HFR data (which increases as we get away from the antennas).

The maximum (minimum) values of  $r$  (RMSD) take place at around 37 and 45 km from the first point of the track for CMEMS and CTOH, respectively ( $Max_T$  points). These values could be explained by the fact that those points are located in the middle of the slope, where the slope current is stronger and where they are out of the Capbreton canyon area. At the same time, in that area, the slope current direction is nearly orthogonal to the track, so that the across-track component is stronger. For CTOH, the values around the maximum are relatively high, that is why the maximum is not a prominent peak. The same happens for CMEMS, but with a sharper peak and higher value (see Table 1). The addition of  $AC_E$  increases the  $r$  by 8-10 % as it can be seen in the table (for  $E_T$  and  $Max_T$  points).

In general, the addition of  $AC_E$  slightly increases (decreases) the  $r$  (RMSD), along all the track. This fact is not perceptible in the figure, where it seems that the addition of  $AC_E$  does not make any difference, but it can be observed in the values of the Table 1, except in the point  $W_T-E_T$  for CMEMS data where it does not change.

### 3.2 Observability of mesoscale processes in HFR and altimetry data sets

In order to provide a complementary insight into the synergies and differences between HFR and altimeter data, in this section the observability of different processes detected by HFR and altimetry is qualitatively analysed. Since the data are spatially

filtered (for  $AC_G$ ) or time filtered (for  $AC_{HFR}$  and  $AC_E$ ), the detectable processes are mesoscale, seasonal and interannual processes, such as mesoscale eddies and the IPC. Only CMEMS data is used for this analysis, since the statistical results are very similar for both ~~SLA-product~~ altimetry products and CMEMS data have less data gaps in the period and study area, which is more suitable for monitoring ocean processes.

### 5 3.2.1 Observability of the IPC

Along-track values of  $SLA'$ ,  $AC_E$  and across-track  $AC_{HFR,T}$  for all the study period are shown in Fig. 6. The highest ~~SLA'~~  $SLA'$  values are observed during late autumn and winter, whereas the lowest ones are observed in spring and summer, specially from March to July (Fig. 6a). This is coherent with the contribution of the main driving factor of the seasonal SLA variability in the area, the steric effect. It was observed in Caballero et al. (2008b) that the maximum amplitude of sea level ~~in the BoB~~ is reached in October ~~in the BoB~~, whilst the minimum takes place in April.  $AC_E$  shows a poleward seasonality with intensifications mainly in autumn and winter (usually from November to February), and weaker equatorward currents in spring and summer (usually from March to October) (Fig. 6b). This fact agrees with the general wind pattern in the area. Along-track ~~SLA'~~  $SLA'$  gradients indicate winter slope current intensifications (IPC) mostly from November to January and from the coast to the 1000 m isobath, approximately. The poleward intensification in winter 2014/2015 is the most remarkable, which was already observed in Rubio et al. (2018). ~~On the other hand,~~ in spring and summer the gradients are weaker and even suggest equatorward currents along all the track.

The IPC intensifications are also detected by the  $AC_{HFR,T}$  in late autumn and winter, mainly in the nearest points to the coast between the 200 and 1000 m isobaths (Fig. 6c). In spring and summer, although there are also some poleward current pulses, they are weaker. During this period, equatorward current pulses are also observed. From the joint analysis of  $SLA'$  and  $AC_{HFR,T}$  data series, four main IPC events can be detected along the study period (Figs. 6a and 6c).

More details on these events are provided in Fig. 7, where ~~four~~ selected HFR total currents ~~fields~~ (obtained from OMA as explained in Sect. 2.1.1) snapshots are shown. Although each event is ~~represented~~ for a specific date, they last around 2-3 weeks (not shown), being the dates displayed in the figure representative of all the period. Note that the SST maps do not show ~~exactly the same~~ the same date as HFR snapshots and  $SLA'$  data, due to the limitations of this technique under cloudy conditions. For the four events, HFR total currents show a typical IPC spatial pattern, with poleward circulation along the slope intensified between the 200 and 1000 m isobaths (Solabarrieta et al., 2015). The poleward patterns observed by the HFR agree with the  $AC_G$  observed along the altimetry track, which show poleward currents intensified over the slope. In the four events, the SST images show intensifications along the slope that are related to an increase of 0.5-1 °C along ~~the~~ time (not shown), which is the increase in temperature that typically correspond to the slope current intensification in the study area (Esnaola et al., 2013). The spatial extension of the warm water masses and the IPC along the French shelf/slope depends on the event, and ~~it~~ determines the area where ~~it is observed~~ the highest agreement between the  $AC_G$  and HFR total currents ~~is observed~~. During the IPC event of November 2009, the warm water tongue is closer to the coast. In this event, the strongest agreement between

$AC_G$  and HFR total currents is observed over the slope, while they disagree in the north-western area of the domain. Otherwise during December 2010, the warm water extends over adjacent offshore areas, and so it does the area presenting the strongest agreement between HFR and altimeter. In three of the four events, the  $AC_G$  and HFR total currents show lower fit over the shelf. These observations corroborate the results obtained in Sect. 3.1, where the best statistical results are obtained for the data pairs inside the slope area (Fig. 5).

The relationship between the IPC and the NAO in the study area was described in Garcia-Soto et al. (2002, 2004). They concluded that for strong IPC years, January water warmings (as a signal of the IPC) were related with negative NAO index values in the previous months (November, December). On the other hand, the Eastern Atlantic (EA) is also considered another possible factor of the IPC intensification, with positive EA values related to current intensifications. For the four events studied here, the relationship between the IPC intensification and those indexes are shown in Table 2. In general, the NAO (EA) indexes are negatively (positively) related to the IPC in strong intensification periods; however, this relation is not always fulfilled (see for instance the event on January 2011, where positive NAO and negative EA index are observed). Moreover, the intensity of the currents is not related to the amplitude of the index, reaching the same conclusion as Le Cann and Serpette (2009) and Le Hénaff et al. (2011).

### 3.2.2 Observability of mesoscale eddies

~~As in the previous section,~~ Fig. 8 shows four examples of eddies detected by the HFR and the altimeter. Although the effect ~~in terms of statistical results~~ of the presence of mesoscale eddies, in terms of statistical results has not been explored, there is a qualitative agreement between  $AC_G$  and HFR total currents when eddies are observed in the area covered by the two measuring systems (even if the eddy core is not crossed by the altimeter track). This happens when either the eddies cross the track of the altimeter or when the size of the eddies is large enough to be observable by the altimetry. Across-track  $AC_G$  are generally in agreement with the HFR current fields, mainly in terms of current directions. For example, on ~~the~~ 15 September 2012 the altimeter crosses a small anticyclone located ~~in the French slope,~~ to the north of the Capbreton canyon head. The maximum  $SLA'$  and minimum  $AC_G$  near the core of the eddy and the patterns of the  $SLA'$  and  $AC_G$  north and southwards of the core agree with the structure detected by the HFR. An eddy with a similar diameter and located near the same area, is observed on ~~the~~ 15 February 2015. In this case the eddy is cyclonic, and though the HFR and altimetry currents in the area occupied by the structure agree, this is not the case in the rest of the track. ~~Also, d~~ During winter, on ~~the~~ 15 March 2014, a cyclone is detected by both ~~dataset~~ data sets near the head of the Capbreton canyon, in addition to another cyclone in the north-western part of the domain. Finally, on ~~the~~ 7 December 2014, an anticyclone, more energetic than all the former eddies, is observed over the Capbreton canyon. This anticyclone was analysed by Rubio et al. (2018), showing that it had an important role in the offshore transport of coastal waters. North of this eddy, the altimetry and the HFR detect a cyclonic circulation, but in this case, it is not clear from the HFR total current fields that the structure is an eddy.

## 4 Summary and conclusions

In this study, we have investigated the synergies and differences between land-based HFR and satellite altimetry, two remote sensing techniques that provide measurements of the ocean surface currents at different temporal and spatial scales. A general agreement between HFR and altimetry has been observed in the study area, with correlations ranging up to 0.7. The comparisons have been carried out in terms of time anomaly of currents, following different approaches with radial and total OMA HFR data, ~~and~~ ~~in~~ all cases the addition of the LF Ekman component ( $AC_E$ ) to the geostrophic component ( $AC_G$ ) has improved the results.

The best agreement between both data sets is observed in the slope area, mainly between 200 and 1000 m isobaths, where the surface circulation is dominated by a more energetic geostrophic component. In the coastal area, the agreement between both data sets is lower, ~~and~~  $AC_G$  has higher variability than  $AC_{HFR}$ , ~~which~~ ~~This~~ can be explained by ~~the~~ error propagation in the finite difference operator that estimates the geostrophic velocity from  $SLA'$  or by a more effective filtering of HF signals in the radar data (where HF signals ~~are correctly sampled and~~ can be efficiently removed using a running average temporal filter).

In terms of monthly mean currents, north-eastward currents are observed in all data sets in late autumn and in winter, while weaker north-eastward and south-westward currents are observed in spring and summer. In the winter period, higher variability is also observed in points E and W, ~~possibly related~~ ~~probably linked~~ to a more energetic slope current regime. Additionally, high variability is observed in point W in March-April, probably linked to an anticyclonic structure near Torrelavega ~~c~~Canyon. Four IPC events have been isolated and described further by means of additional SST data. From this analysis we conclude that during the IPC intensifications, the qualitative agreement between  $AC_G$  and HFR total currents is high, ~~and~~ well related to the SST anomalies. ~~In addition, Moreover,~~ a relationship between strong IPC events with negative (positive) NAO (EA) indexes in the previous months has been detected for three of the four events. ~~On the other hand, A~~although the effect in terms of statistical results of the presence of mesoscale eddies has not been explored, there is a qualitative agreement between  $AC_G$  and HFR ~~total~~ currents when eddies are observed in the area.

The low correlation between HFR and altimetry observed in some areas and periods can be due to several factors. ~~It is worth noting that It must be kept in mind that~~ both technologies are based on different physical approaches to ~~observe-measure the surface-ocean~~ currents, at different spatial and temporal scales, and work under different physical assumptions. Besides, the quality of the radar data is expected to decrease in the furthest points from the antennas and varies in function of the angle formed by the radial current components used for total current estimations (affecting the along-track comparison). Altimetry ~~has~~ also ~~has~~ its own limitations and might have errors in the data editing procedure or in the corrections.

Future work should be oriented to a better understanding of the relationship of the surface circulation and the dynamics of the subsurface layers, ~~throughby~~ means of the combination of remote observations with data in the water column. ~~Since the comparison near the shoreline is inconsistent, another future work line could be the investigation of the assumptions of geostrophic balance in the coastal area and the merge of altimetry and radar measurements in-order-to~~ improve both products.



In addition, further comparison with HFR data and higher resolution **coastal** altimetry products would enable a better understanding of the differences between both observing systems.

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**Table 1.** Statistics of different points for the study period.  $r$  is the correlation parameter and RMSD is the root mean square difference of the velocity anomalies between HFR and altimetry for different altimetry products (i.e. CMEMS and CTOH). The mean and the standard deviation ( $std$ ) are also estimated for each data set. E and W are the points where HFR radial velocities are orthogonal to the tracks 248 and 213 respectively (see Fig. 1). E<sub>T</sub> means that the parameters are estimated in the point E but instead of using the HFR radial velocity anomalies, using the HFR current velocity anomaly fields rotated to across track direction. That HFR data has also been used for Max<sub>T</sub> which is the track point where the correlation  $r$  is maximum (point 2.10° W, 43.82° N for CTOH and point 2.09° W, 43.80° N for CMEMS). RAD refers to HFR data, which really means radial anomaly current for E<sub>R</sub> and W<sub>R</sub>, and across-track rotated OMA anomaly currents for E<sub>T</sub> and Max<sub>T</sub>. There is not data in Max<sub>T</sub> because it is different for each altimetry product.

		$r$		RMSD (cm s <sup>-1</sup> )		mean $\pm$ $std$ (cm s <sup>-1</sup> )		
		CMEMS	CTOH	CMEMS	CTOH	CMEMS	CTOH	RAD
E <sub>R</sub>	$AC_G$	0.53	0.48	7.437	7.55	0.35 $\pm$ 8.766	-0.106 $\pm$ 8.53	0.11 $\pm$ 5.94
	$AC_G + AC_E$	0.64	0.59	7.14	7.436	0.35 $\pm$ 9.67	-0.21 $\pm$ 9.438	
W <sub>R</sub>	$AC_G$	0.61	0.64	9.24	7.83	-0.217 $\pm$ 11.90	0.25 $\pm$ 9.988	0.03 $\pm$ 9.30
	$AC_G + AC_E$	0.67	0.70	8.95	7.42	-0.118 $\pm$ 12.89	0.219 $\pm$ 10.657	
E <sub>T</sub>	$AC_G$	0.56	0.53	7.15	6.51	-0.11 $\pm$ 8.25	-0.30 $\pm$ 7.659	0.216 $\pm$ 5.45
	$AC_G + AC_E$	0.65	0.62	7.15	6.43	-0.12 $\pm$ 9.31	-0.42 $\pm$ 8.56	
Max <sub>T</sub>	$AC_G$	0.60	0.55	6.54	6.11	-0.25 $\pm$ 7.987	-0.219 $\pm$ 7.25	-
	$AC_G + AC_E$	0.68	0.65	6.60	6.0597	-0.326 $\pm$ 8.95	-0.30 $\pm$ 8.327	

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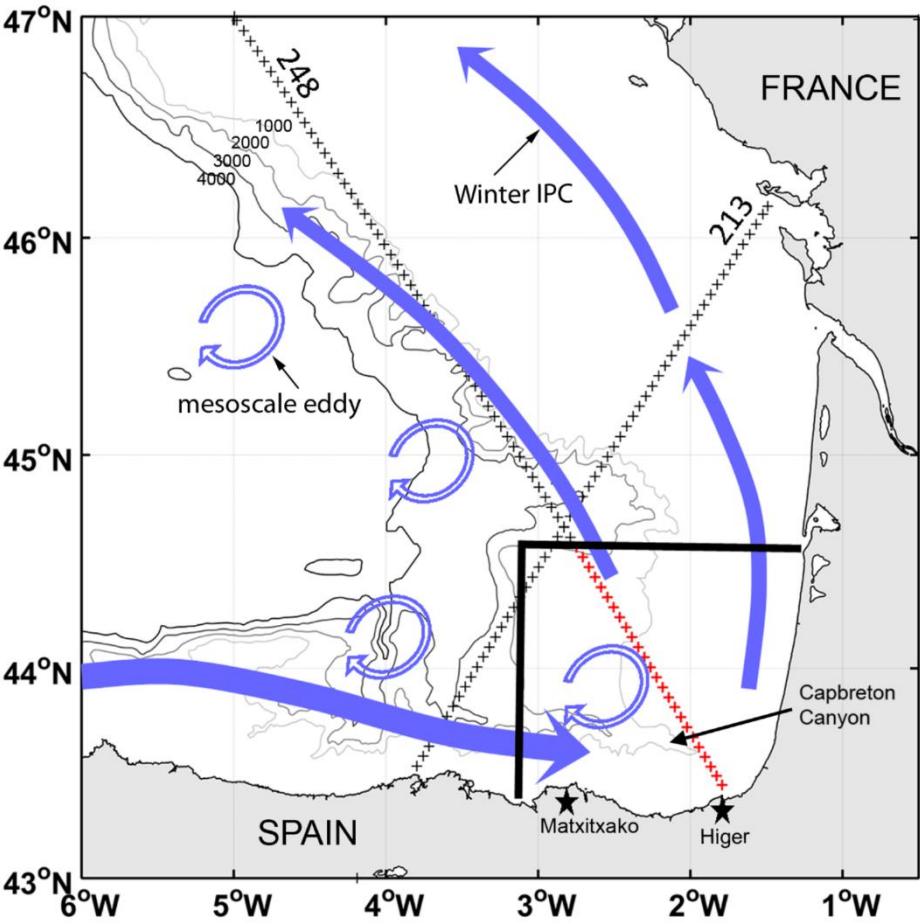
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**Table 2.** NAO and EA indexes in the previous two months of the events. m-2 means two months before the event whereas the m-1 means one month before.

Event	NAO		EA	
	m-2	m-1	m-2	m-1
November 2009	1.62	-0.61	0.59	0.96
January 2011	-1.84	-1.8	0.24	-0.49
January 2014	0.81	0.79	0.09	1.3
November 2014	1.72	-0.87	0.2	1.02

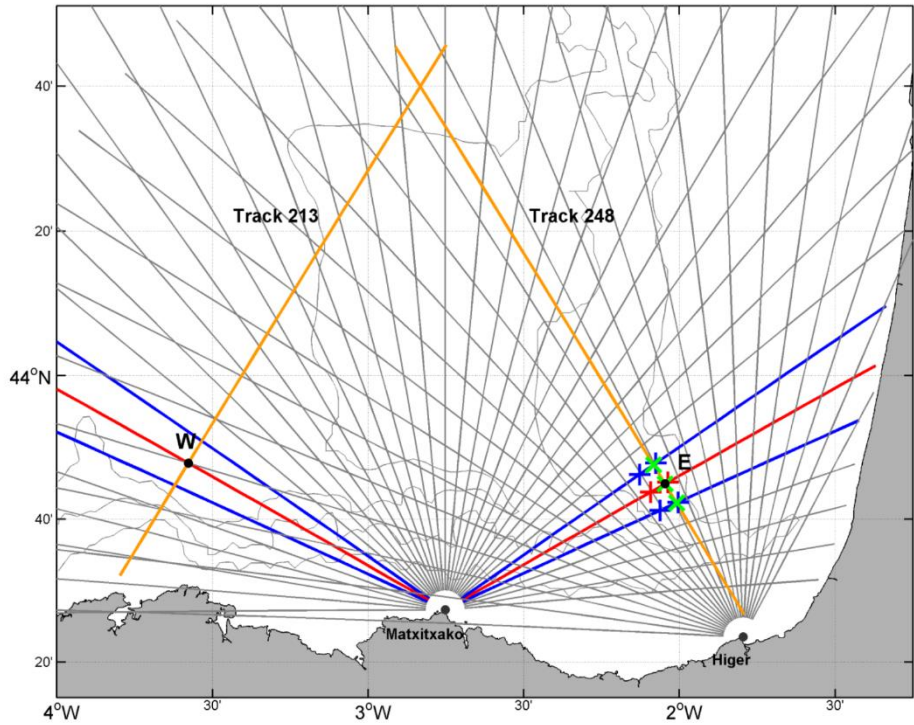
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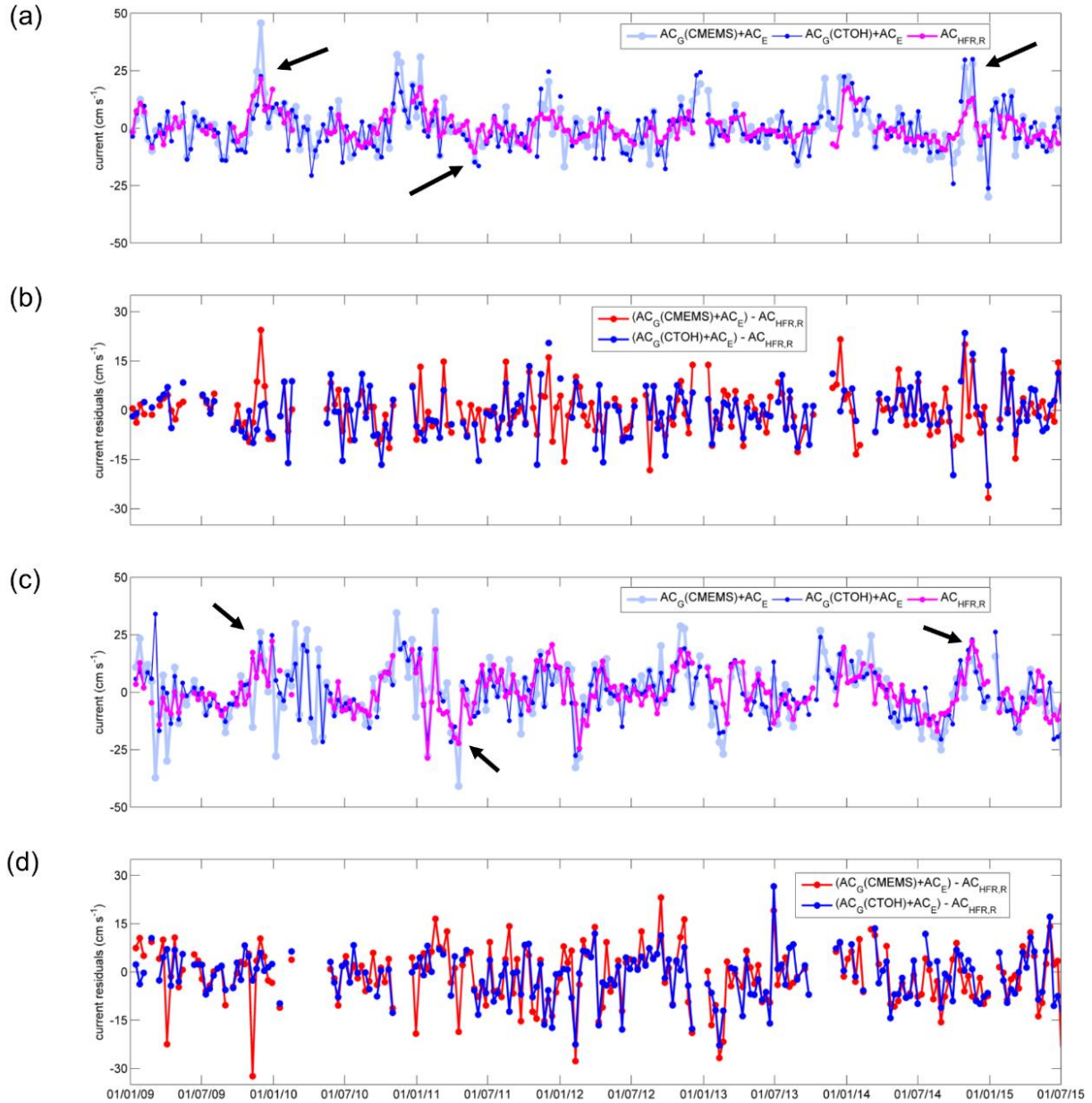


**Figure 1.** Study area, observational systems and main characteristics of the ocean circulation (Figure modified from Rubio et al. (2018)). The winter IPC is represented by blue solid arrows, whereas the blue hollow arrows show the mesoscale eddy regime (although only anticyclonic arrows are represented, eddies of anticyclonic and cyclonic polarity are observed in different locations along the slope). The bold black lines delimit the HFR total currents footprint. The black stars represent the HFR stations: Matxitxako (left) and Higer (right). Jason-2 tracks 213 and 248 are represented by black crosses and the part of the track used in this study is marked in red. Grey lines: 1000, 3000, and 4000 m isobaths.

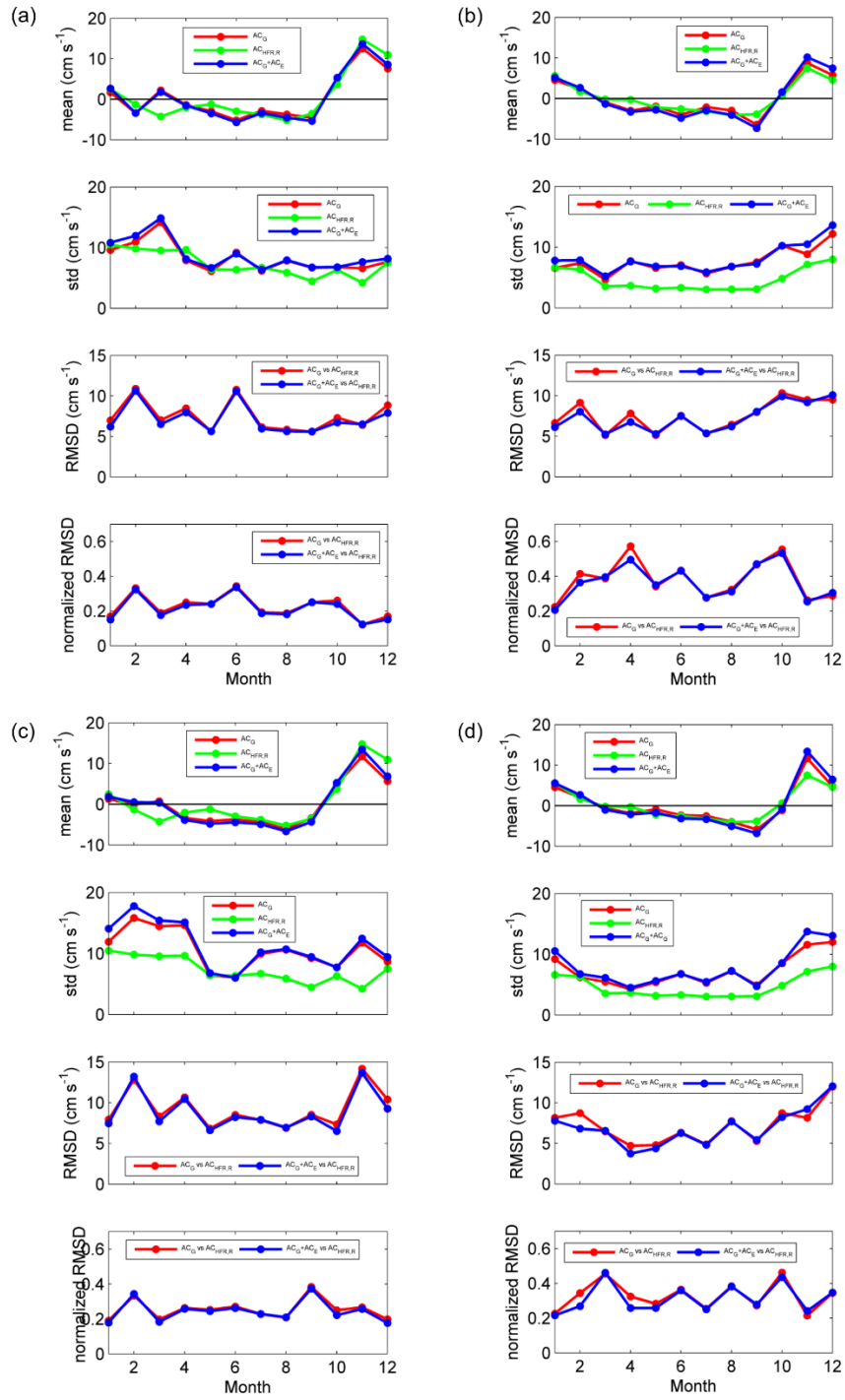




**Figure 2.** Schematic view of the pointwise comparison and of the data used for this approximation. Jason-2's 213 and 248 tracks are depicted by orange lines. The HFR radial directions from both sites are represented by grey lines and the selected radial directions (from Matxitxako site) for the pointwise comparison are plotted in red (i.e. the central radial orthogonal to the track) and in blue (the adjacent radials). ~~Points E and W;~~ Points E and W are those along both tracks, where each of the HFR radial directions are orthogonal to the Jason-2's tracks directions. At point E, the blue and red crosses show the selected points of HFR radial directions where radial currents are averaged in a first step to obtain the corresponding values on the track (green crosses). Then, the along-track green crosses are averaged to obtain the corresponding HFR current values in the point at issue (the same process is carried out for point W, but it is not represented in the figure). Grey lines: 200, 1000, and 2000 m isobaths.

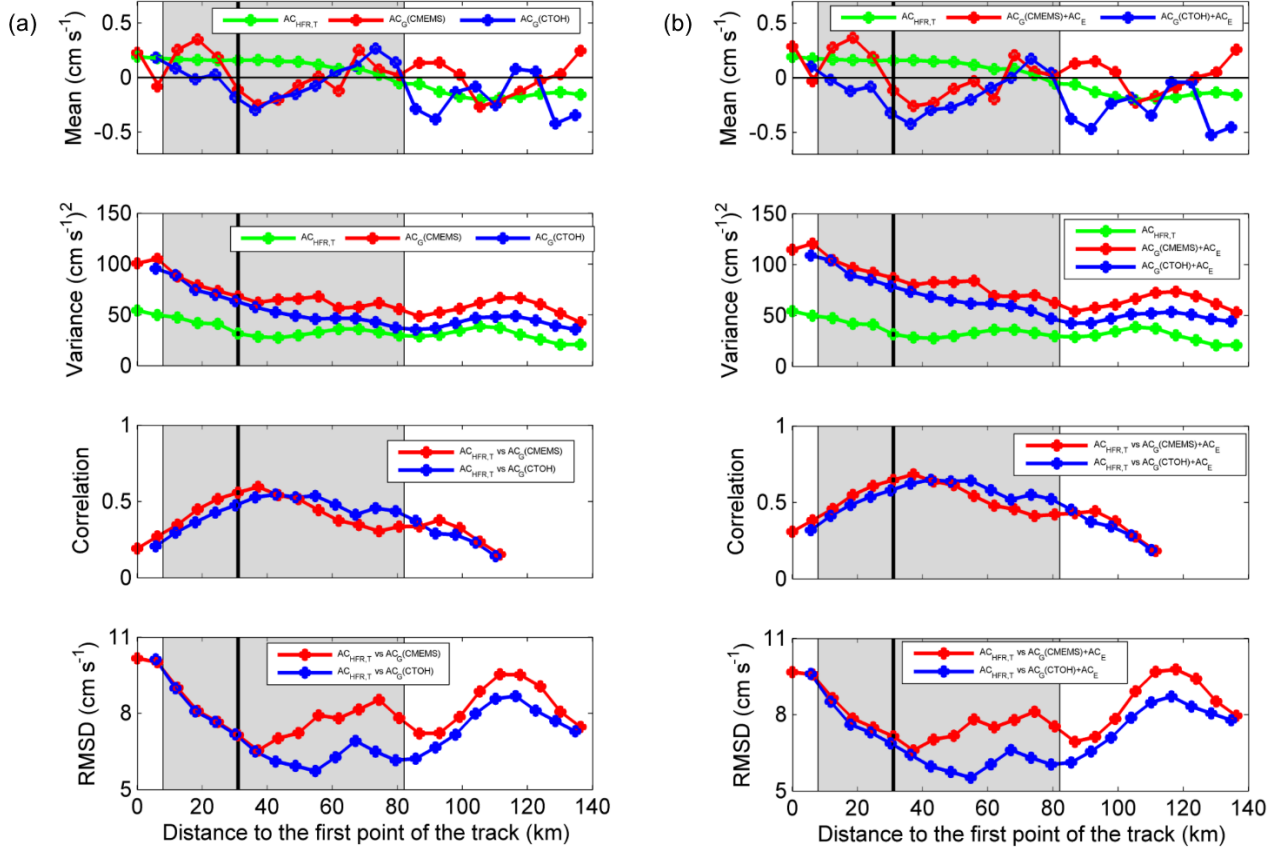


**Figure 3.** Across-track currents measured by altimetry+Ekman and HFR radials. (a) CTOH, CMEMS and HFR data sets in point  $E_R$ . (b) CTOH-HFR and CMEMS-HFR residuals in point  $E_R$ . (c) CTOH, CMEMS and HFR data sets in point  $W_R$ . (d) CTOH-HFR and CMEMS-HFR residuals in point  $W_R$ . Black arrows depict the slope current intensifications mentioned in the text.



**Figure 4.** Monthly statistical parameters of the comparison between  $AC_G (+AC_E)$  and  $AC_{HFR,R}$  in the points  $E_R$  and  $W_R$  for both altimetry products: (a) CTOH  $AC_G$  in point  $W_R$ , (b) CTOH  $AC_G$  in point  $E_R$ , (c) CMEMS  $AC_G$  in point  $W_R$ , (d) CMEMS  $AC_G$  in point  $E_R$ . The normalized RMSD is the quotient between the RMSD and the values of the corresponding  $AC_{HFR,R}$ .

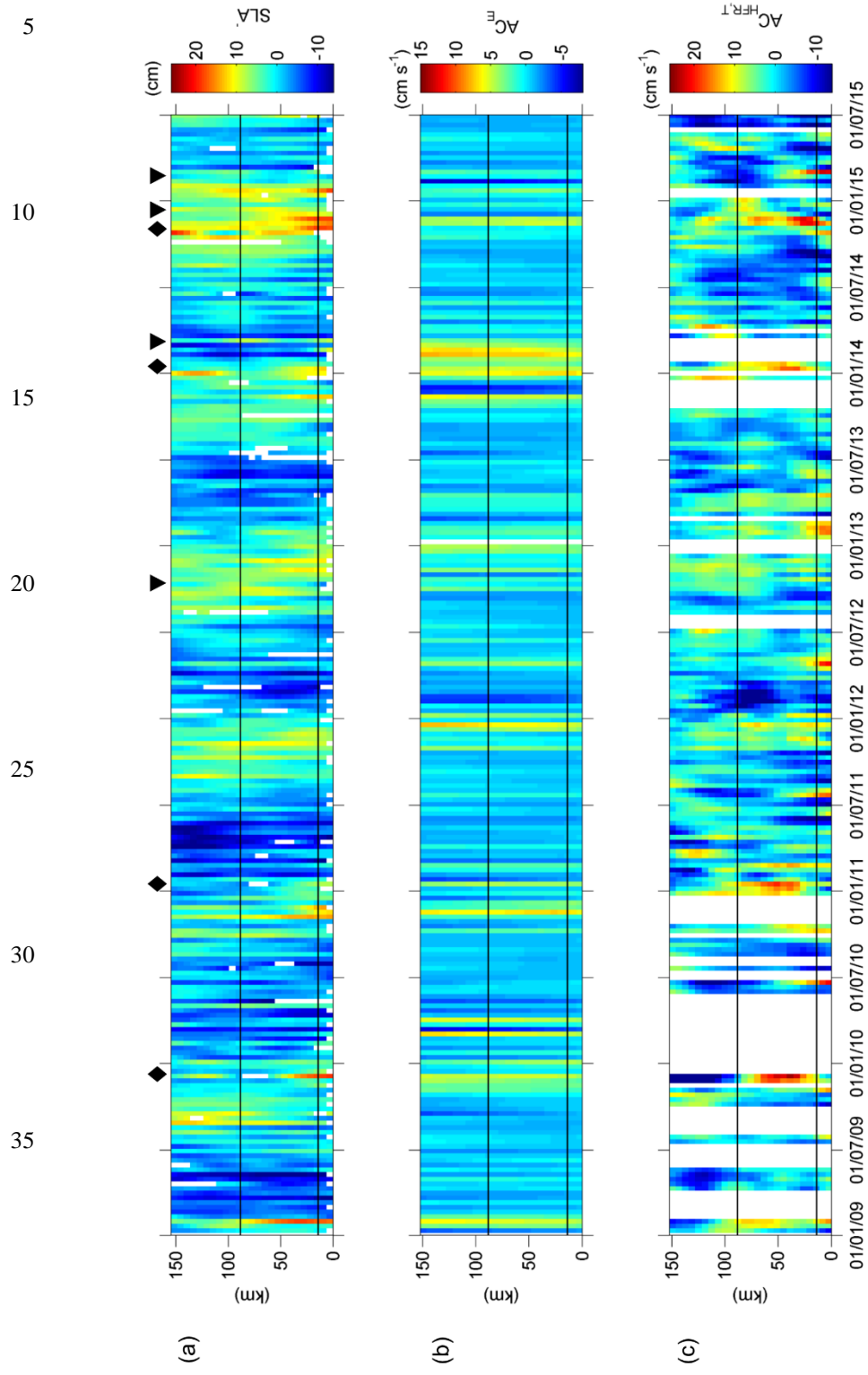
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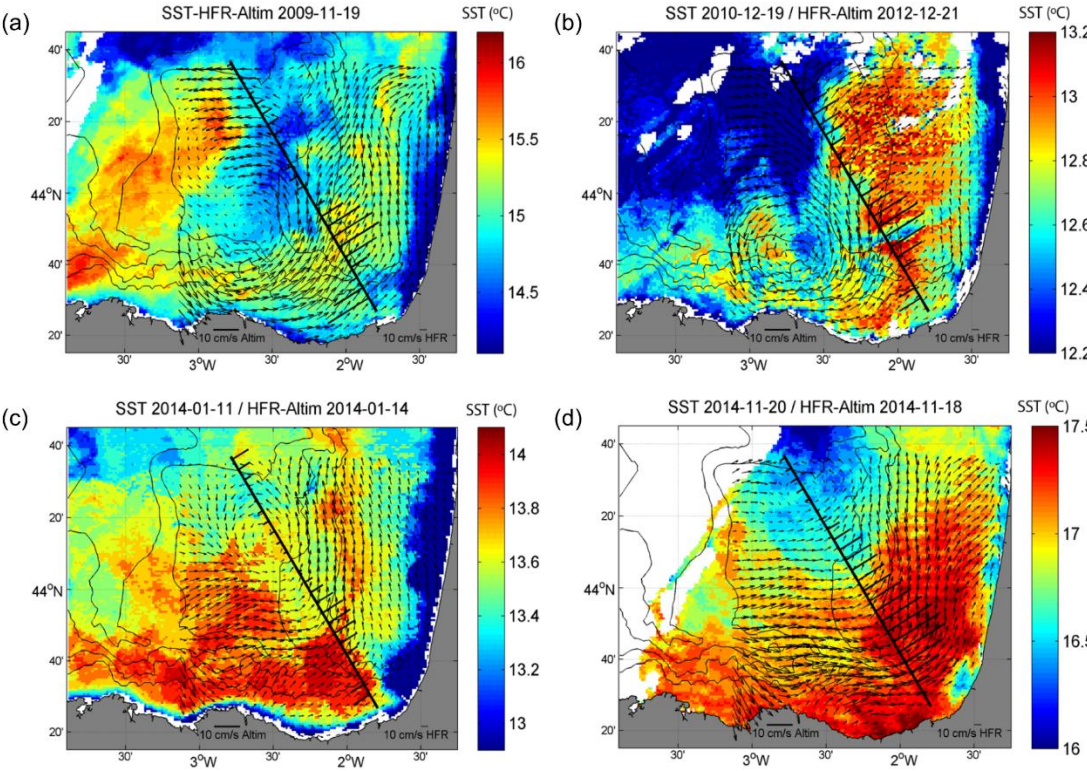
**Figure 5.** Mean and variance along the track 248 of the different data sets ( $AC_{HFR,T}$ ,  $AC_G$  (CTOH) and  $AC_G$  (CMEMS)) and correlation and RMSD between  $AC_G$  and  $AC_{HFR,T}$ . (a)  $AC_{HFR,T}$  vs  $AC_G$ , (b)  $AC_{HFR,T}$  vs  $AC_G + AC_E$ . The grey coloured area corresponds to the slope between 200 m and 1000 m isobaths. The black line is the location of the point E and the first point of the track is around 11 km away from the coast. Correlation values are not plotted for confidence levels under 90 % (i.e. in the points along the track with a distance from the first point beyond 120 km). Note that the first point is different for CTOH and CMEMS (which are around 10.5 km and 13 km away from the coast respectively) and that the spacing between the points is slightly different. Moreover, the first point in CTOH is removed because it is an outlier. The radar points are the same as CMEMS points.

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**Fig. 6.** Time evolution from 1 January 2009 to 1 July 2015 along the track 248 (y axis shows distance to the first point of the track in km) of: (a) CMEMS SLA' (cm), (b)  $AC_E$  ( $\text{cm s}^{-1}$ ) and (c)  $AC_{HFR.T}$  ( $\text{cm s}^{-1}$ ). The distance from the first point of the track to the coast is around 6 km. The horizontal black lines delimit the slope area between the 200 and 1000 m isobaths. The black diamonds depict the IPC intensification signals whereas the black inverted triangles show the eddy events, all mentioned in the text.

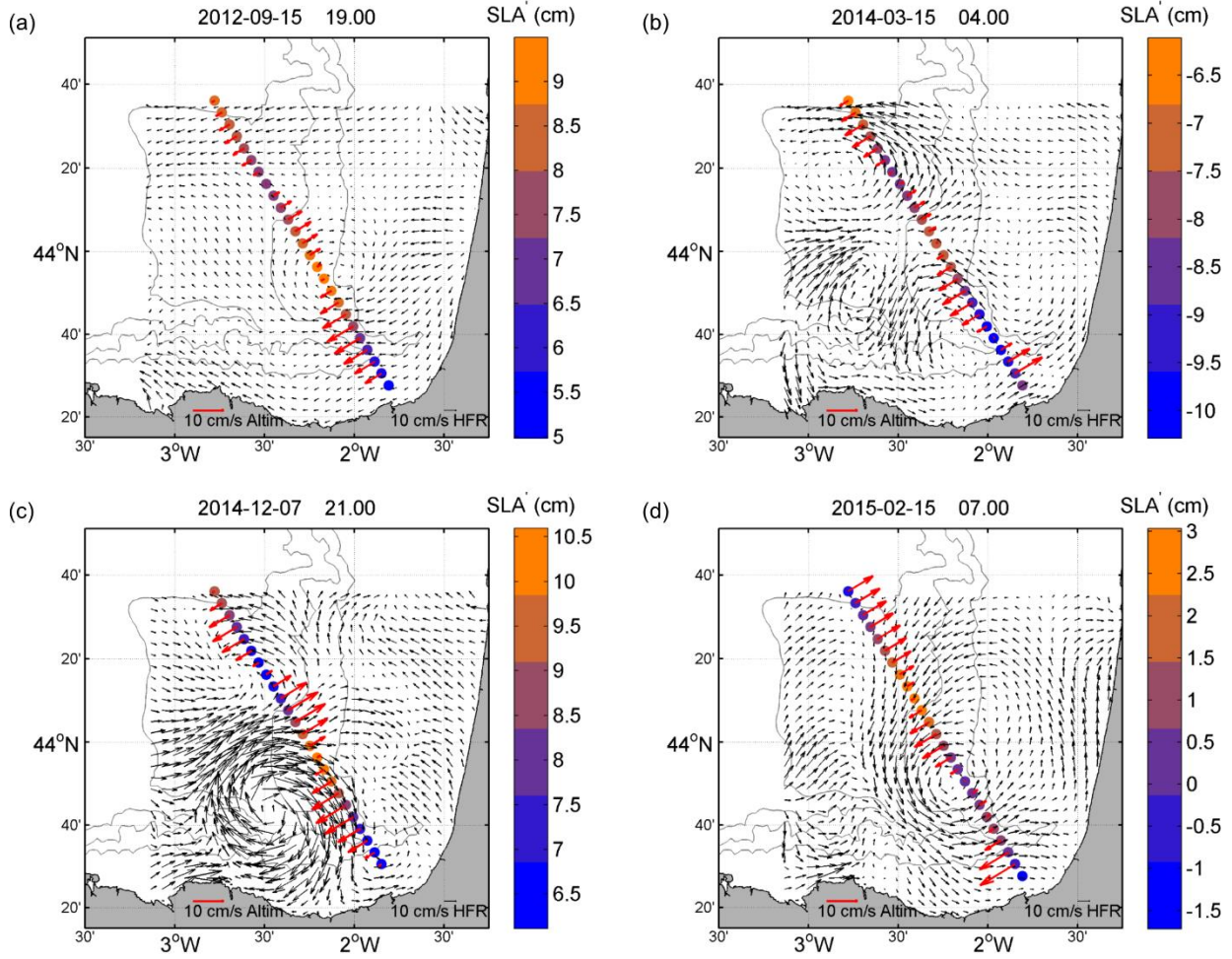




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**Figure 7.** Snapshots showing four slope current intensification events observed by HFR, altimetry and SST (see the dates of the events depicted in Fig. 6) in November 2009 (top left), December 2010-January 2011 (top right), January 2014 (bottom left) and November 2014 (bottom right). The small arrows depict the HFR current fields (not rotated) whereas the thick ones indicate the across-track  $AC_G$ . The black line shows the altimeter's track. The colormap depicts the sea surface temperature (°C) with values referenced in each colour palette. Note that the dates corresponding to the data are not equal for SST or for HFR and  $AC_G$  (specified in each picture's title).



**Figure 8.** Four mesoscale eddies observed in the study area. The dots show the points of the track 248 of the CMEMS database. SLA' (cm) values are indicated in the colour palette. Black arrows depict the HFR current fields. Red arrows correspond to across-track  $AC_G$  derived from the SLA' values in the dots. Grey lines: 200, 1000, and 2000 m isobaths. Note that the scale of the arrows is not the same in all the subplots.