Alice Carret
Laboratoire d'Etudes en Géophysique et Océanographie Spatiale (LEGOS)
OMP
14 Avenue Edouard Belin
31400 Toulouse
France
Tel : 00-33-5-61-33-26-81
Email : alice.carret@legos.obs-mip.fr

Subject : Manuscript os-2018-76 revision

14 December, 2018

Ocean Science

Dear Editor,

Please find enclosed the revised version of our manuscript entitled "Synergy between in situ and altimetry data to observe and study the Northern Current variations (NW Mediterranean Sea)" , by A. Carret and co-authors.

We are grateful that the reviewers gave us the opportunity to improve the earlier version of the manuscript. The paper has been significantly modified to take the remarks into account. In the following pages we detail the answer to the comments made by the reviewers. We have also included a marked-up manuscript version.

We hope that the revised paper is in an acceptable form now. We look forward to your decision.

Best regards,

Alice Carret.

First, we would like to thank the two reviewers for providing constructive comments that were taken into account in order to improve the manuscript. Please find below a point-by-point answer. The reviewers comments are in bold.

Reply to reviewer #1

The work presented by Carret et al compares SARAL and Jason 2 altimetry data with HF radar, vessel-mounted ADCP and glider data in the North Western Mediterranean Sea. Dataset are well presented, and a complete Section describes similitudes and differences between the dataset. Yet some important physical differences between the dataset are missing in that section. Most of the results presented are not new: it is well known that seasonal and mean average of the altimetry currents are trustable. Also, little is learnt in terms of description of the currents. On the other hand, it is presented a very interesting description of six cases where a detailed comparison between the datasets is made. I encourage the authors to push forward the analysis of the higher frequency and to clearly show when satellite altimetry works well and when does not. I hope that the below specific comments will help in that sense.

Thank you for these comments. First, we improved the description of the differences between the datasets by adding in Section 2 more informations and/or precisions on their respective physical content (details below). We also used high resolution SLA altimetry data (i.e. 20Hz for Jason-2, 40-Hz for SARAL) and added a section (new section 3.4) to compare and discuss the corresponding results with the results obtained from 1-Hz SLA data. We then insisted on the individual cases as suggested by the reviewer. However we believe that the results presented in this manuscript, even in its first submitted version, are really new. If different studies have already shown that altimetry is able to capture seasonal and mean currents, they did not (or poorly) show until what point this is true and what part of the seasonal and mean current components is missing. Past studies on coastal currents derived from altimetry are generally qualitative (as in Birol et al., 2010-2014-2015; Jébri et al, 2016) and/or based on individual case studies. Here we take advantage of a large number of data (as much as we found) and relatively long time series in order to quantify (as much as we can) what part of the current can/can't be captured by altimetry. We used a multi-platform approach in order to learn more on the causes of the differences between currents derived from altimetry and from in situ data. To our knowledge, this is not common at all since we do not know coastal altimetry studies based on such degree of integrated observation system.

P3, L 13, add a comma after “swaths”

It has been corrected.

P3, L29-30, the list of articles is non-exhaustive. Please add “eg” at the beginning of the list.

Right. It has been done.

P4, L 14: "associated to important mesoscale and sub-mesoscale variability at all time scales".Meso and sub-mesoscale have time scales associated as well. Please re-phrase.

We have removed these words. Now : "To study the contribution of altimetry amongst other types of coastal ocean measurements, the North-Western Mediterranean Sea (NWMed) represents a laboratory area. First, with a Rossby radius of only ~10 km, the region is associated to a variety of mesoscale and sub-mesoscale dynamical signals (see below)."

P6, L3-5: could you comment why the optimal spatial filtering scale that you obtained is so different for tracks that are relatively close to each other ?

We agree and have added the following sentences at the end of the paragraph: "The lower values obtained for SARAL are due to the better signal-over-noise ratio of the AltiKa altimeter, compared to Jason-2. The differences obtained between the three SARAL tracks are explained by their respective geographical locations: they represent different mesoscale features.".

P6, L7: Please justify the values used (for SARAL in the precedent paragraph you obtained values that ranged between 34km and 49km). Why you selected a fixed value?

We have added the following sentence: "Note that we have chosen a single value for the different SARAL tracks in order to have the same data processing and facilitate the comparison between the different datasets".

P6, L13: please add a short discussion (with references) to justify that the selection of the MDT. An inaccurate MDT can largely bias your results.

We agree. We chose to work with the regional MDT from Rio et al., 2014 which was validated against in situ datasets. Compared to the previous MDT from Rio et al., 2007, it has a better resolution (1/16° vs 1/8 °) and the regional circulation is better resolved (see Rio et al, 2014 but we have also done our own diagnostics). We have added the following sentences:

"The MDT product used is a regional product with an horizontal resolution of 1/16° (lower than the altimetry resolution in the along-track direction). Compared to other products, it allows a better representation of the NC in the Ligurian Sea (Rio et al., 2014)."

P6, eq 1: it should be noted that this is the across-track component of the geostrophic velocities

It has been written.

P6, L29-30: how much is "too far away" and "too short" ?

Right. Now: "The ones being too short (<60 km) or moving too far away (>15 km) from an average trajectory computed from the individual ones were discarded. "

P6, L31-P7L1: please improve sentences (for instance obs have the potential.)

We have rephrased. Now: “It represents a huge amount of observations and a large number of cases available for the comparisons with altimetry or with the other in-situ observations. "

P7, L6, a word is missing (end of the line)

We have added the word “horizontal” in the text.

P7, L8-9: Here and all over the document: Try to avoid parenthesis as much as possible

We removed these parenthesis and some others.

P7, L13, “of the second order” - > “of second order”

Done.

P7, L15, add “data” after “salinity”

Done.

P7: 15-18: please clarify that these geostrophic velocities do not represent the same physical quantity that the ones obtained from satellite altimetry

We have added the following sentence: “The difference with altimetry-derived currents is then that the barotropic component and the baroclinic component below 500m are missing.”

P8: HF-radar: please add a sentence explaining the error associated to this dataset (ie explaining where velocity components are better solved in the spatial domain covered by the antennas)

We have added the following sentence : “An assesment of this HF Radar site can be found in Sentchev et al. (2017) who found an overall good agreement between derived radial velocities and in situ ADCP, with relative errors of 1 and 9 % and root mean square (RMS) differences of 0.02 and 0.04 m/s, slightly increased, in velocity and direction, for the reconstructed total velocities, but mainly in conditions of unstationnary wind forcing. »

P9, L24: altimetry currents are not “located at the surface”. They are computed from the SSH, but the SSH topography is the result of several process, including the density changes in the whole water column. Comparison of currents from different instruments elsewhere show that satellite altimetry represents better sub-surface than surface currents. Depth of best matching depends on time and space.

It has been reworded. Now: “ We then decided to use the glider data at 34 m depth (to be coherent with the ADCP observations) and consider that it should not be a significant source of differences with altimetry currents, representing near-surface currents”

P9, L33-34: gliders provide density sections from where you can extract only the baroclinic component of the velocities. Altimeters provide SLA. When adding MDT, altimetry provides barotropic and baroclinic components. Depending on the accuracy of the geophysical corrections, altimetry data might be more or less biased by ageostrophic components. Please state more clearly the differences between gliders and altimetry data.

Done. Now: “After the addition of the MDT, the gliders and altimeters are clearly the closest in terms of current information derived. However, the glider currents are computed from hydrographic measurement profiles with a reference level of 500 m. They miss the barotropic and the deeper baroclinic geostrophic current components when altimetry and MDT allow to estimate absolute geostrophic currents representative of the horizontal density gradients integrated over the whole water column. In this study, in order to minimize (as far as possible) the differences between the current data sets, we performed a projection of the ADCP velocities to obtain the current component perpendicular to the ship transects. Concerning the gliders, estimates of depth-average currents computed following *Testor et al*., 2018 approach were added to the velocity data as an approximation of the barotropic component.”

P10, L1-4: exactly what I expressed above for comment in P9, L24.

Figure 2: representation of mean velocities for the HF radar could be improved. There, you can solve two directions. The large blue spot is not very meaningful.

We have chosen to represent only the zonal component to be closer to the information which can be derived from the other data sets. However in this area the NC is known to be almost zonal. These informations were missing in the text and have been added: “Concerning the HF radars, only the zonal current component is taken into account. Note however that in this area, since the NC is almost zonal, most of its mean and variability are captured in the corresponding statistics.” The representation of the two direction overload the figure and we have then decided not to change.

P10, L31-32: this information should be included in the legend of the Figure

This sentence has been moved in the legend of Figure 2.

Figure 4: please add monthly ticks in the x axis. Please describe how HF radar data were treated. You averaged them along the coast? If so, please discuss how much variability is lost, as the distance along the coast is not so short. →

We have added monthly ticks in the x axis and we have added the following sentence: “The HF radar data correspond to a meridional section of the zonal current component located at 6.2°E.” See also answer to the comment on Figure 2.

Figure 4f: some interannual variability is also observed. And during 2014 some noisy(?) data close to the coast are also observed. Why it is observed only during that period of time?

We have no clear explanation for the presence of the noisy HF radar data located close to the coast in 2014 (these data are processed and distributed by MOOSE) and have decided to remove these points.

Track 302 of SARAL is particularly suited to compare with the HF Radar dataset. Did you try different re-tracking procedures (ALES for example) to analyze how close to the coast the altimetry data can be improved?

No we did not try yet but it will be done in the near future. We wait for the new 20-Hz L3 ALES/X-TRACK product which should be distributed soon.

P13, L35 & P14, L1-2: please provide a clearer explanation on the criterium adopted.

Now: "The maximum NC current amplitude is defined as the average of the first decile of the velocity values for each transect and time (remember that the NC corresponds to negative current values). These values must be close in space. This strategy allows to filter large isolated current values which may not correspond to the NC. In altimetry, only a distance spanning 60 km to the coast is considered. The number of data in the first decile varies according to the data set and to the number of data in the section considered (because of the lower resolution, it always corresponds to one point in altimetry). As we can see in Figure 4d, data gaps exist in Jason 2 for some cycles. When more than 3 points are missing, the corresponding cycle is discarded from the analysis."

P14, L2-4: which velocity is seasonally averaged? Legend of Figure 5 says "maximum current amplitude" but form the text I understand that all velocities have been averaged

It has been reworded. Now: "Finally, all the maximum NC current values collected are averaged ..."

P14, L4-6, please improve sentences. →

Now: "The results derived from in-situ data are in Figure 5a and the results derived from altimetry are in Figure 5b. The glider results are on both figures because this instrument provides the currents which are the closest to altimetry in terms of physical content."

P14, L18: South of Toulon only SARAL data can be compared to HF radar data. Please add Toulon position in Figure 1

Done.

P16, L11-13. Please justify the window time scales selected. I suggest to repeat the calculation as a function of the time window. In the coastal region time scales are shorter than 22 days.

Please see the answer to the comment below (p 20, L 2-4).

P16, L19-22. Figure 6a. I wonder how the distance to the coast is measured. Figure 1 clearly shows that there are no measures of the altimeter inside the 1000m isobath, while gliders and ADCP do show measures up to the 200m isobath. Thus, I am suggesting that in Figure 6 Saral and J2 lines are not correctly placed. Orientation of J2_0009 track is quite different from Saral_887 (with respect to main direction of the isobaths).

Right. The figures are not represented as a function of the distance to the coast but of the distance to the transect-shoreline intersection point. The new sentence is: "The corresponding cross-track currents are shown in Figure 6 (by season) as a function of the distance to the point where the corresponding transect intersects the coastline."

P16, L34 to P17, L4: data are "very close in time" but then you argue that differences may be due to "one-week difference". Please say precisely what is the difference in time for each case.

All the dates are provided in Table 3 for each case and each instrument. We have added this information in the corresponding sentence. Now: "It could be due either to the differences in the dates of observations (one week from Table 3, temporal scale at which meanders develop) or to an important ageostrophic NC component."

Figure 7 looks strange: double colorbars? Double x-axis?

The figure was inserted twice. It has been corrected.

P20, L2-4 "but a quantification of the high frequency component of the coastal ocean dynamics that altimetry is able to capture would require data that are colocalized in both space and time." Completely agree. But with the dataset that you already have, you do have the possibility to quantify this quite precisely: how much is the bias that is introduced in the comparison because of non-colocalized data? Just compare, more precisely than what you have done so far, the "very close" space & time datasets with the "not very close".

Thank you for this suggestion. We have tried to investigate the bias introduced by non-colocalized data in more details and have computed the diagnostics shown below. Using all the data available, we represent in Figure 1 and in Figure 2 the differences between the maximum NC amplitudes derived from in situ datasets (gliders and ADCP) and from altimetry (J2 and SARAL) as a function of the number of days which separates two measurements. In Figure 3 and 4 we represent the differences obtained as a function of the distance of the NC core to the coast. As you can see, unfortunately, these results don't allow to draw any conclusion because there are no clear rule that appears. The explanation is not really obvious. Is it because of the high level of short scale variability in this area? Difficult to say. A high resolution numerical model would probably help to understand but it is beyond the scope of this study.

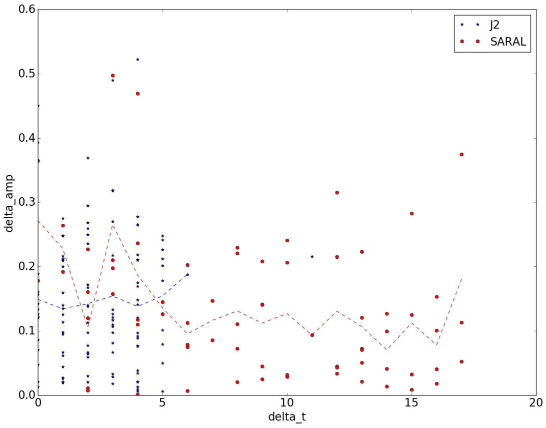


Figure 1: Differences of the maximum amplitudes the NC between the ADCP and SARAL (in red) an between the ADCP and J2 (in black) in function of time difference

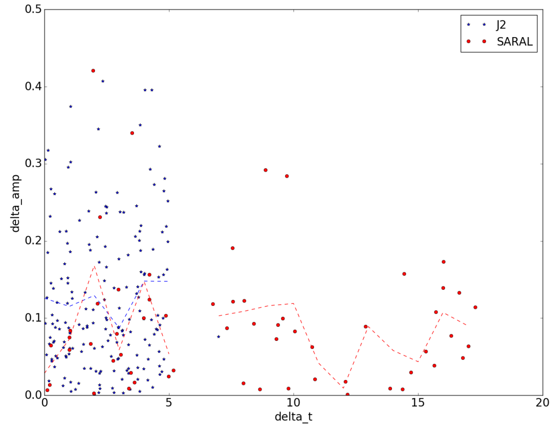


Figure 2: Differences of the maximum amplitudes of the NC between the gliders and SARAL (in red) and between the gliders and J2 (in black) in function of the time difference

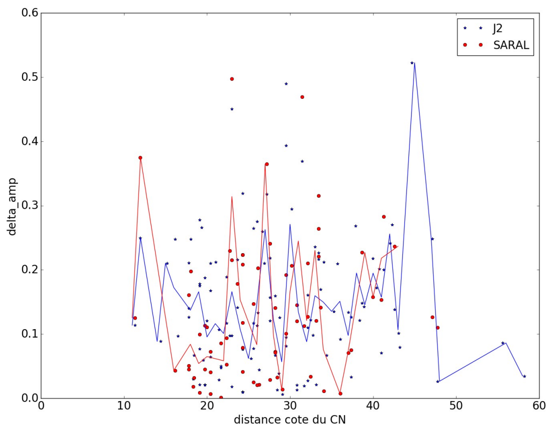


Figure 3: Differences of the maximum amplitudes the NC between the ADCP and SARAL (in red) an between the ADCP and J2 (in black) in function of NC distance to coast obtained from the ADCP

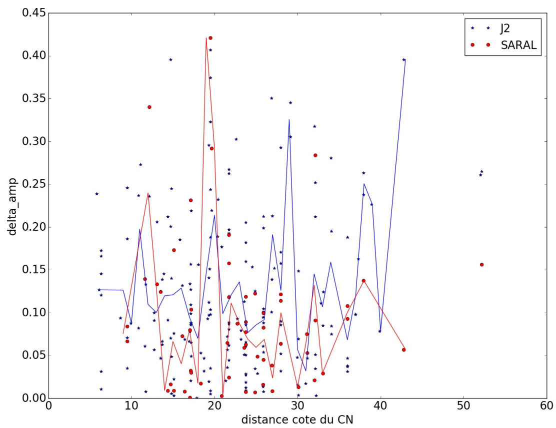


Figure 4: Differences of the maximum amplitudes of the NC between the gliders and SARAL (in red) and between the gliders and J2 (in black) in function of the NC distance to coast obtained from the gliders

Reply to reviewer #2

1) What is the novelty of this paper compared to previous papers that used the same CTOH 1 Hz along track coastal altimetry and focused on the same variability scales (i.e., mean, seasonal and inter-annual flow ?). The paper is not clearly explaining the scientific advance in terms of understanding Northern Current. I have the feeling that the paper describes data very well, but not answering scientific questions related to Northern Current dynamics. My recommendation is to reinforce the discussion (at present it looks like a summary) elaborating major findings in the context of the existing bibliography related to Northern current (from in situ, modelling, altimetry and other remote sensing studies).

We partly agree and have tried to clarify the objective of this paper relative to previous work in a new version of the introduction (see below). This paper does not focus on scientific advances concerning the NC. This is the next step but, from our point of view, the priority is still to promote the use of altimetry data for coastal circulation studies (not really used outside of the small community of coastal altimetry experts). Therefore we need to better demonstrate and quantify what can be observed by altimetry in terms of coastal current variability. In this paper we take the opportunity of a large number of data from a variety of plaforms, that are commonly used in coastal research, to perform systematic cross-comparisons. To our knowledge it is the first time that this type of work is done, and with such integrated approach. From this study we demonstrate that in average 1-Hz altimetry data (corresponding to the standard products available for the scientific community) are able to capture 50% of the NC variability. But for individual cases, this number varies a lot from one situation to the other (and not only as a function of the season). We think that these results are important. To promote the use of a given instrument, to show and quantify what can be observed and what can not is a very important issue. Note that we also decided to add high sampling rate data (see the answer to the next comment) to the analysis, even if the results are not so clear and if no consensus exists yet on the way to process these data (that means that only experimental products exist and that they are rarely used). However, this multi platform study also provides new informations on the NC system variability (even if it is not the main focus of the study). It reveals a strong NC increase in summer 2014 (not expected in this season) and the presence of an eastward current flowing ~50-80 km off the coast in the Ligurian Sea.

Anyway we think that the introduction and the objectives of the study needed indeed to be clarified relative to previous work and it has been done. We have made changes in the following paragraphs :

« To study the contribution of altimetry among other types of coastal ocean measurements, the North-Western Mediterranean Sea (NWMed) represents a laboratory area. First, with a Rossby radius of only ~10 km, the region is associated to a variety of mesoscale and sub-mesoscale dynamical signals (see below). As a result it represents a challenge for altimetry observations. Secondly, the number of in-situ observations is relatively important in this region, allowing comparison with independent data. In the NWMed, the main feature of the surface ocean circulation is the Northern Current (called NC hereafter) which is formed in the Ligurian Sea (*Taupier-Letage and Millot*, 1986) and flows cyclonically along the Italian, French and Spanish coasts. This current presents a marked seasonal variability, with a maximum amplitude from February to April (*Sammari et al*., 1995; *Millot*, 1991), and it meanders in a vast range of wavelengths (10-100 km). The mesoscale variability is higher in autumn and winter because of the larger baroclinic instability associated to strong and cold winds(*Alberola et al*., 1995; *Millot*, 1991). During the last 10 years, the NC has been intensively monitored by a variety of in situ data (moorings, research vessels, gliders, and HF radars) collected from the MOOSE integrated observing system (Mediterranean Ocean Observing System for the Environment). Despite a width of only 30-50 km, through the comparison with ADCP current data located in the Ligurian Sea, *Birol et al.*, 2010 demonstrated that reprocessed altimetry data are able to capture half of the amplitude of the seasonal NC variability. The altimetry currents have then been used to analyze the regional current variability at seasonal scale. In the Balearic Sea, the reliability of altimetry currents has been verified by direct comparison with currents derived from gliders and HF radars (*Bouffard et al.,* 2010; *Pascual et al.;* 2015; *Troupin et al*., 2015). These case studies showed that altimetry can depict current signals coherent with the other instruments. *Morrow et al*., 2017 also showed that some of the large scale eddies observed by gliders in the NWMed can be captured by altimetry, in particular by the SARAL mission. A more systematic use of altimetry in regional coastal applications requires a better quantitative assessment of its performance near coastlines, from daily to interannual time scales.

The general objective of this paper is not only to investigate the accuracy of the velocity fields derived from altimetry data next to the coast at different temporal scales , but also to define its contribution from the other coastal ocean observing systems which exist in the region (ship-mounted ADCPs, gliders and HF radars). In this study, we combine all the different available in situ data sets which provide information on currents in the Ligurian-Provençal basin and perform systematic comparisons with currents derived from altimetry at different time-scales. In particular, we analyze how the different available observing techniques capture the NC variability and the coherence/divergence/complementarity of the informations derived. From previous studies, we know that only a small part of the NC variations can be captured by conventional satellite altimetry. Here, we use both Jason-2 and SARAL/AltiKa missions to investigate the progress made from Ku-band to Ka-band altimetry. We also investigate the potential of experimental 20/40-Hz altimetry products to monitor the NC variations, relative to the conventional 1-Hz data. »

2) It is well known that the 1 Hz (7 km) sampling in the coastal zone limits the exploitation. There are many papers that show clearly that longer temporal scales are well reproduced and that the actual challenging in coastal altimetry is to dig the finer ocean scales (along track) and cross-track merging missions (there are actually six missions flying at same time). We have now SAR mode providing improved native along track spatial resolution and better signal to noise ratio. We have retracked data for

conventional missions that push resolution at 20 Hz. All these innovations are very promising to study high frequency mesoscale. For example, AltiKA has native resolution at 40 Hz, why reducing to 1 Hz ? I really recommend the authors to investigate data at higher sampling rate as this would be a really step in advance. Therefore, my position is major review as the results are not new, but potentially to become of high interest to the oceanographic community if authors re-focus the analysis on high resolution altimetry.

We fully understand this comment but here again we agree only partly. First, as explained above, we believe that it is important to promote products that are now at a mature stage for the coastal scientific community and it is the reason why we have decided to keep 1-Hz data as our focus in this study. Secondly, if different experimental high-rate datasets are generated by coastal altimetry research groups, they are still largely at an experimental stage and no consensus exists on the way they should be processed. More than the sea level (SL) estimates, the resulting current fields and then the NC characteristics, are very sensitive to the strategy followed for data processing (including both retracking and corrections), screening and filtering. Of course it is because they depend on SL gradients which computation is very sensitive to the noise and outliers which are important in high-rate coastal altimetry observations. It is illustrated in the results below. However, because we agree that it is important to gain experience on these new higher resolution datasets, we have decided to add a section 3.4 dedicated to high-sampling rate altimetry. It illustrates their potential, but as you can see below, in terms of scientific advance, the results are relatively mitigated. We have added a new Figure 7 and modified Table 4. We have also make changes in the abstract, sections 1, 2 and 4, accordingly.

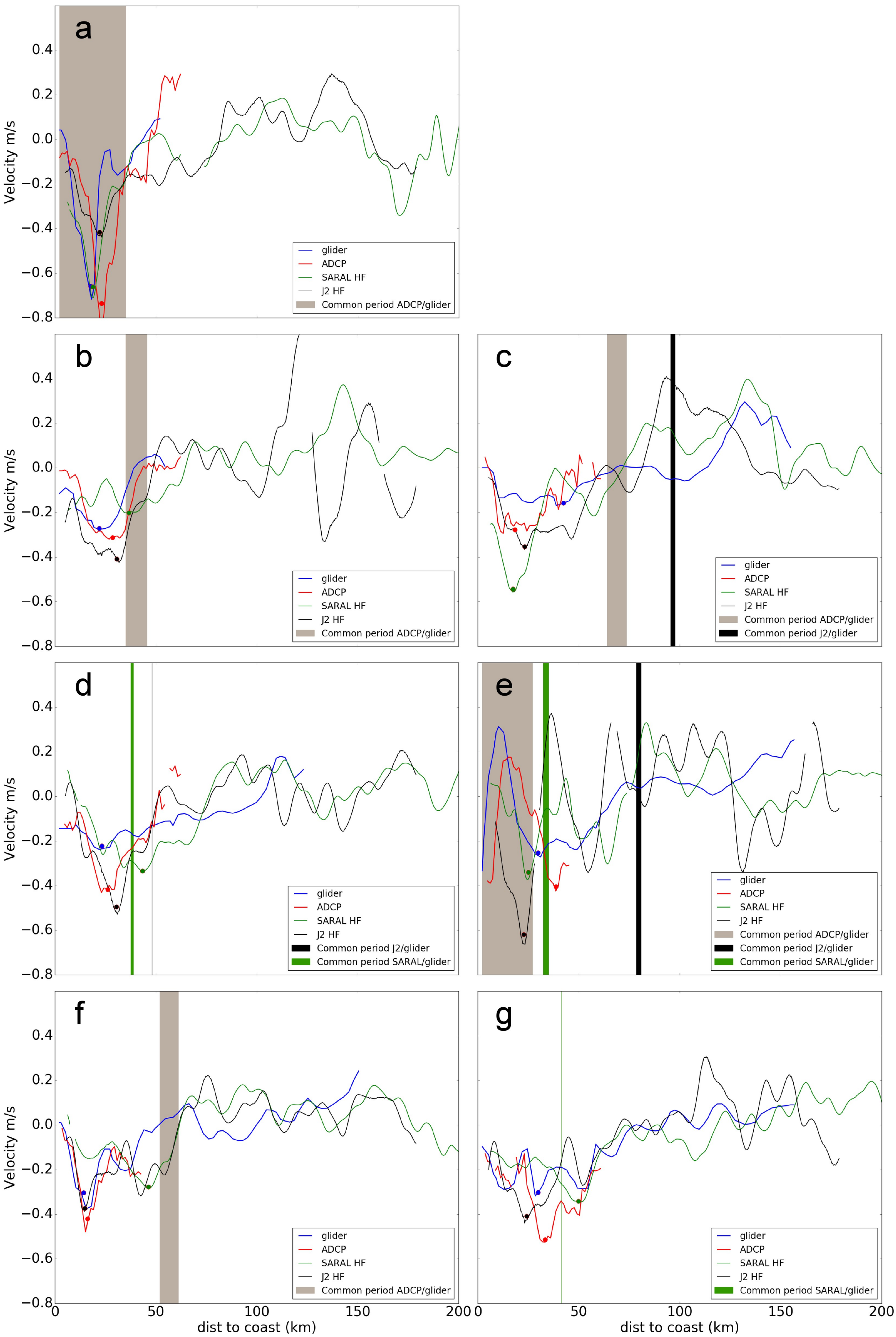
« **3.4 Can we improve the estimation of the NC characteristics with high-rate altimetry compared to 1-Hz data?**

In this section we consider the improvement that is possible to obtain in terms of current derivation with the use of high-rate altimetry measurements, compared to the conventional 1-Hz data used above. Here, we used an experimental version of high-rate X-TRACK SLA data for both Jason-2 and SARAL which original measurements are at 20-Hz and 40-Hz, respectively. Since a lot of erroneous data remained in the coastal area, we applied a 2-sigma filter on the resulting SLA fields along each individual track and cycle, in order to edit the data before filtering and computation of the current estimates (section 2.1).

In order to analyze if we can expect a better observation and understanding of the NC hydrodynamics from high-rate altimetry measurements, they have been used to compute the same diagnostics than in sections 3.1, 3.2 and 3.3. Only the results for the individual snapshots will be illustrated here (Figure 7) since, even if the major difference with the current fields derived from 1-Hz altimetry is that the larger number of coastal data allows to estimate currents closer to the coast and then to better resolve the NC flow (see Figure 7), we did not find significant differences in the NC statistics (mean current and standard deviation values) and amplitude of the seasonal cycle computed from 20/40-Hz SLA.

In Figure 7, the same color code than in Figure 6 is used while, for each case, the maximum NC current amplitude andcorresponding location are reported in Table 4 for both SARAL and Jason-2 (as in section 3.3). In case 1 (Figure 7a), the gain obtained with the use of HF data is very clear. At this date the NC vein is narrow and located near the coast. Contrary to 1-Hz solution, the NC is better resolved by both SARAL and Jason-2 high-rate altimetry. It is especially true for SARAL which NC characteristics are almost identical to the glider ones. In Jason-2, the NC core is close to the glider solution but its amplitude is ~35% lower. For cases 2 and 4 which correspond to the summer (Figure 7b and c), here again the use of high-rate altimetry allows a better observation of a NC vein but the agreement with in-situ data is not so good. Concerning SARAL, for case 2, the current estimates are suspect since a reduction of the current intensity appears at the location of the NC core in the other datasets (Figure 7b). For case 4, SARAL NC amplitude is too high (0.55 m/s vs 0.16 m/s for the glider). Jason-2 high-rate NC estimates appear closer to the in situ data than SARAL for both cases 2 and 4 but, the resulting NC characteristics do not appear better than the corresponding 1-Hz estimations, when compared to ADCP (table 4). It probably reveals that the cut-off frequency chosen in the filtering is too low. Cases 5 and 6 (Figures 7 d and e) also show some very doubtful oscillations in both SARAL and Jason-2 currents and high-rate altimetry does not improve the NC estimations. In winter, the cases 3 and 7 (Figures 7g and f, respectively) are very different. In case 7, 20-Hz Jason 2 data depicts the entire NC with current estimates much closer to in-situ data (especially the glider), compared to 1-Hz Jason 2 measurements, In case 3 they degrade/improve the NC representation (Figure 7g) if we refer to the glider/ADCP, respectively Note that this case illustrates the difficulty of the calibration of altimetry data processing algorithms with independent observations since results may differ as a function of the independent observations used. Here, 40-Hz SARAL data show a too noisy current solution .

In conclusion, as already shown in previous work (*Birol and Delebecque*, 2014; *Gomez-Enri et al*., 2016), high-rate altimetry allows to derive significantly more sea level data near the coast. Here we observe that the coastal circulation derived is better resolved in space (i.e. both in horizontal resolution and in distance to the coast of the current estimates). But the resulting current fields depend crucially on the strategy followed for data processing (including both retracking and corrections), screening and filtering. 20/40 Hz altimetry data obviously present a clear advantage for coastal studies but the production of these datasets is still at an experimental status and there is room for further improvements.”



a
b
c
d
e
f
g
Velocity m/s
dist to coast (km)
glider
ADCP
SARAL HF
J2 HF
Common period ADCP/glider
Common period J2/glider
Common period SARAL/glider

Figure 7: Cross-shore sections of currents deduced from the glider (blue), ADCP (red), SARAL (green) and J2 (blackgreen) high-rate altimetry data for the 7 individual cases identified in Table 3. Overlapping periods between the different observations are also indicated.

Specific remarks :

Pg. 3, line 1, "Radar altimeters measure the sea surface height (SSH) variations": the sentence is uncorrect. The radar altimeter transmit pulses. The system measures the time pulses take to be reflected back satellite. Time is then converted in distance,corrected for various effects and then referred to earth using orbit altitude (this is the so called SSH). Please be precise

We agree. It has been reworded for "Radar altimeters allow to estimate the sea surface height (SSH) variations along the satellite tracks at regular interval time".

Pg. 3, line 2, "ever more accurate observations": more accurate than what? Please clarify

It has been replaced by "Providing a large number of continuous and accurate observations ..."

Pg. 3, line 9, "the first global synthetic aperture radar (SAR, or Delay-Doppler) technique": the term "SAR" has to be sued properly to avoid confusion. The reader would understand the first global SAR. SAR, also known as Delay Doppler, is a new coherent processing mode of individual echoes (conventional altimetry uses incoherently processing). Please better clarify

We agree. It is now : "With the launch of Sentinel-3A, B, in February 2016 and in April 2018, the altimetry constellation was completed by the first instruments always operated at high resolution mode (commonly called Synthetic Aperture Radar or SAR) which increases the along-track data resolution."

Pg. 3, line 10, "enhanced accuracy and reduced noise": the use of the term "accuracy is wrong". Reduced noise means better precision. The other enhancement is increased native along track resolution

We have changed this sentence for : "These new altimeters provide enhanced along-track resolution and reduced noise, in comparison to the conventional nadir-looking pulse limited Ku-band instruments used since the beginning of the altimetry era"

Pg. 3, line 13, "the SWOT a new step forward": reference missing

A reference has been added : https://swot.jpl.nasa.gov/docs/SWOT_D-79084_v10Y_FINAL_REVA__06082017.pdf

Pg. 3, lines 14-15, "particularly important to monitor the sea level variations, directly related to our living environments and marine ecosystems": This sentence is too vague.

You have to better explain (in term of processes, e.g. flooding, etc.) why sea level changes are more important in the coastal zone than deep waters.

Done. Now : "In coastal ocean areas, it is particularly important to monitor the sea level variations. About 10% of the world population lives in low-elevation coastal zones (Nicholls and Cazenave, 2010) exposed to hazards such as extreme events, flooding, shoreline erosion and retreat. The latter are expected to increase due to the combined effects of sea level rise, climate change, and increasing human activities. In coastal regions in particular, we expect a lot of advances from modern altimetry instruments and processing techniques."

Pg. 3, line 16, "from these new altimetry techniques": The statement is vague. Maybe use the term "modern altimetry" to include all technical improvements (Delay Doppler processing, small footprint) as well as reprocessed conventional altimetry (retracking, new/improved corrections, etc.).

Done. See above.

Pg. 3, lines 17-18, "The strongest limitation is the modification of the radar echo in the vicinity of land": here the reader might thing that the problem is only land contamination. Indeed, there are other effects , e.g. inhomogeneity of the water surface (Brown altimetry assumes homogeneous scattering). The authors have to be more rigorous here citing proper literature

This sentence has been replaced by : "The strongest limitation is the modification of the radar echo in the vicinity of land but the sea level estimations derived are also impacted by inhomogeneity in the water surface oberved by the radar and less accurate corrections.".

Pg. 3, line 27, "new altimetry techniques are intrinsically less sensitive to the land contamination": The statement is not correct. Again the term "techniques" is not appropriate. Moreover, land contamination cannot be used in general sense., e.g. SAR mode has few effect if the track is parallel to land

This has been reworded for "Moreover, the use of new altimetry techniques provides more robust and accurate measurements closer to the coast and allows to resolve shorter spatial scales (Dufau et al., 2017; Morrow et al., 2017).".

Pg. 3, line 28, "They provide more robust and accurate measurements, ever closer to the coast": The athors have to provide figures about accuracy as function of distance with concrete examples from bibliography

We added numbers and references : « Moreover, the use of new altimetry techniques provides more robust and accurate measurements closer to the coast and allows to resolve shorter spatial scales (Dufau et al., 2017; Morrow et al., 2017). As an example, from Birol and Niño (2015), closer than 10 km to the coastline, available SARAL data is still ~60% and only ~31% for Jason-2. From Morrow et al. (2017), in summer SARAL can detect ocean scales down to 35 km wavelength, whereas the higher noise from Jason-2 blocks the observation of scales less than 50-55 km wavelength."

Pg. 3, lines 29-30, "We can easily predict that the use of altimetry in coastal studies": the reader here expects illustrating major findings from these studies (i.e. state-of-the-art)

We agree and have completed this sentence. Now : "As a result, the capability of altimetry for the monitoring of coastal ocean dynamics has already been illustrated in a number of studies. Most of them concern shelf and boundary currents (*Bouffard et al*., 2008; *Birol et. al.*, 2010; *Herbert et al*., 2011; *Jébri et al*. 2016, 2017). Some others are related to sea level applications (*Cipollini et al*., 2017a). A more complete review of coastal altimetry applications can be found in *Cipollini et al* (2017b) but we can easily predict that the use of this instrument in coastal studies will be largely extended in the next years."

Pg. 3, lines 32-33, "Coastal observations are mainly based on in situ instruments and satellite imagery (sea surface temperature and ocean color images): I don't understand this sentence. The coastal observing system is multi-sensor, multi-platform. SAR imagery is especially useful in the coastal zone due to its high spatial resolution. The sentence has to be reworded.

The sentence has been reworded. Now : « Today, observations used in coastal applications are mainly based on in-situ instruments and satellite imagery (sea surface temperature and ocean color images). »

Pg. 4, lines 1-2, "in a growing number of regions": Please provide examples

Done. Now : "In order to answer to the need for monitoring of the coastal ocean environment, in situ observing systems gather informations in a growing number of regions such as along the Australian or US coasts (http://imos.org.au/; https://maracoos.org/operations)."

Pg. 4, line 2, "in conjunction": better using in "synergy"

Done.

Pg. 4, lines 4-5, "in situ observations cover more limited areas and often provide time series that present large gaps.": please provide examples. What means gaps in time series ? are you referring to tide gauges ? buoys? Please better clarify

It has been clarified. Now: "Nonetheless, in situ observations cover more limited areas and often provide time series that present large gaps which may be several days (buoy data, HF radars) to several months (glider, ship data)."

Pg. 4, lines 6-7, "satellite imagery is often impacted by clouds and does not provide any direct information on the changes occurring in the water column.": the sentence is confusing the reader. Clouds might be a problem for optical imagery, but not for microwave sensors (e.g. scatterometry, SAR). Moreover, although satellites maps the ocean surface, it si possible to derive info in the water columns (one example is SAR detecting internal waves)

"Satellite" has been replaced by "optical".

Pg. 4, line 8, “almost-global synoptic observations”. Satellite altimetry provide global coverage. Revisting the same place depends on the mission (e.g. Cryosat is drifting in orbits and revisits the same place in along time). What about “synoptic” ? e.g.Jason takes 10 days to get a global coverage. What do you mean with “almost”? –the sentence in unclear. The reader might be confused, e.g. an optical imagery is synoptic. Infor at all pixels is at same time

We use the word “synoptic” because satellite altimetry enables to capture a regional general view of the ocean dynamics (in the sense not only local). “Almost-global” is because altimetry observations are not global: they provide observations up to a given latitude.

Pg. 4, line 11, “conjunction”: use “synergy”

Done.

Pg. 4, line 13, “ideal”: use another word (e.g. laboratory (Béthoux et al., 1999) and explain why in detail)

The word “ideal” has been replaced by “laboratory”. We have also changed the text for “To study the contribution of altimetry amongst other types of coastal ocean measurements, the North-Western Mediterranean Sea (NWMed) represents a laboratory area. First, with a Rossby radius of only ~10 km, the region is associated to a variety of mesoscale and sub-mesoscale dynamical signals (see below). As a result it represents a challenge for altimetry observations. Secondly, the number of in-situ observations is relatively important in this region, allowing comparison with independent data.”

Pg. 4, line 14, “at all time scales”; clarify which scales (i.e. range). →

We have removed these words (see above).

Pg. 4, line 20, mesoscale variability is higher in autumn and winter”: Why higher in these seasons ? please explain

Now: “The mesoscale variability is higher in autumn and winter because of the larger baroclinic instability associated to strong and cold winds (*Alberola et al.*, 1995; *Millot*, 1991).”

Pg. 4, line 25, “to partially capture”: please explain why “partially” →

This sentence has been reworded. Now: “*Birol et al.*, 2010 demonstrated that reprocessed altimetry data are able to capture half of the amplitude of the seasonal NC variability.”

Pg. 4, line 26, “to provide original aspects of the regional circulation”: please explain “original aspects”

This sentence has been reworded. Now: “The altimetry currents have then been used to analyze the regional current variability at seasonal scale.”

Pg. 4, line 27, “coherent circulation patterns”: please illustrate these patterns

This sentence has been reworded. Now: “In the Balearic Sea, the reliability of altimetry currents has been verified by direct comparison with currents derived from gliders and HF radars (*Bouffard et al.,* 2010; *Pascual et al.;* 2015; *Troupin et al*., 2015). These case studies showed that altimetry can depict current signals coherent with the other instruments.”

Pg. 4, line 29, “found similarities”: which ones?

This sentence has been reworded. Now: “*Morrow et al*., 2017 also showed that some of the large scale eddies observed by gliders in the NWMed can be captured by altimetry, in particular by the SARAL mission.”

Pg. 4, line 33, “compared to the other coastal ocean observing systems”: please specify which coastal observing systems →

This sentence is now: “The general objective of this paper is not only to investigate the accuracy of the velocity fields derived from altimetry data next to the coast at different temporal scales , but also to define its contribution from the other coastal ocean observing systems which exist in the region (ship-mounted ADCPs, gliders and HF radars). “

Pg. 4, line 34, “Ligurian Sea”: better to use Ligurian-Provencal basin, because HF radars are not in the Ligurian Sea (as it is usually defined in term of boundaries) →

Done.

Pg. 5, line 15, “The performance of SARAL is significantly better than Jason-2”: please provide references stating that with figures →

Now: “The performance of SARAL is significantly better. With a better signal-to-noise ratio, it resolves smaller spatial scales than Jason 2: ~40 km against ~50 km (Dufau et al., 2015, Verron et al., 2018).”

Pg. 5, line 19, “SARAL tracks 302, 343 and 887”: why not using also the other tracks ?

We chose tracks which are close to in situ datasets and well oriented to capture the NC. The use (and analysis) of all SARAL tracks would not provide more informations in this study and would overload all the figures and discussions.

Pg. 5, line 23, “Sea Level Anomalies (SLA) every 6-7 km: I am but surprised authors use this low along track sampling (7 km). As the novel aspect is the finer scale of ocean circulation, the authors have to use the high res altimetry (350 m) that are reprocessed using re-tracking.

Please see the answer to the main comments above. This paragraph has been changed and is now: “For both missions, because it is one of the most often used in coastal altimetry applications, we used first the X-TRACK regional product from the CTOH (doi: 10.6096/CTOH_X-TRACK_2017_02), processed with a coastal-oriented strategy (*Birol et al.*, 2017). It consists in time series of 1-Hz Sea Level Anomalies (SLA) every 6-7 km along the satellite tracks, available from 20/07/2008 to 01/10/2016 for Jason 2 (i.e. 300 cycles) and from 24/03/2013 to 12/06/2016 for SARAL (i.e. 34 cycles). In order to evaluate the skill of the elementary noisier 20/40-Hz altimetry measurements of the Jason-2/SARAL altimeters for circulation studies, relative to the conventional 1-Hz data, we have also used an experimental high-rate version of these data provided by the CTOH (see section 3.4). The processing is the same than for 1-Hz SLA, except that the high-rate SLA are computed from the 20/40-Hz range data provided in the AVISO L2 products (https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_j2.pdf and https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/SARAL_Altika_products_handbook.pdf). The resulting sea level time series are available every ~0.35 km and ~0.17 km along the satellite tracks for Jason-2 and SARAL, respectively. However, we must keep in mind that if the use high-rate altimeter measurements allows to significantly improve the spatial resolution, the resulting SLA are much noisier (see for example *Birol and Delebecque*, 2014). Considering the data availability (see below for the in-situ observations), the study period chosen is 2010-2016 for all altimetry datasets."

Pg. 6, line 2, "in Morrow et al., 2017, the data located over the continental shelf were discarded": this is further point that support the need of using high res altimetry

Please see above.

Pg. 6, lines 1-4, "We did 39 km for the SARAL track 343, 34 km for the SARAL track 887 and 67 km for Jason 2 track 222.. altimetry observations": I see that Morrow et al., 2017 used these figures come from standard along-track data at 1 Hz (7 km) discarding data in the coastal zone. They found some figures about size of structures and optimal filtering. The authors here use reprocessed along-track data at 1 Hz with no retracking applied, but with more data coverage going to the coast. They found lower figures about size of structures. I am confused as we talk about average values and sampling is not changing. Is signal-to-noise better ? you have to demonstrate, because structures can emerge from background noise only the ratio is higher . I think the scale would only change (become finer) only if authors enhance resolution of their altimeter data

The dataset used does not cover the same period and the same region than in Morrow et al.. In this study all the coastal data were discarded and all the regional spectra were averaged. Here, the computation is done track by track (and then on a mean spectrum computed from much less original samples). The computation of the mesoscale capability is very sensitive to the slope of the mean spectrum analyzed (itself very sensitive to the number of samples and the seasonal situation they capture, the way the data have been post-processed and interpolated to avoid data gaps that complicate the calculation). It explains why our results differ from those of Morrow et al 2017. If we average the results from a larger dataset we would converge to the same numbers. But individual cases may be very different from what is revealed by mean statistics. This is why we have chosen to treat in this paper a wide range of cases: from the temporal mean to individual dates.

Moreover, the author do not explain why scales vary with close tracks

The two closest SARAL tracks show almost the same mesoscale capability. The SARAL track 302 and the Jason 2 track 222 are located further so there may be mesoscale processes to take into account. The mesoscale capability corresponds to the scale for which the signal to noise ratio is greater than 1. The Jason 2 data are noisier thus it hides some scales. This explain the differences between SARAL and Jason 2.

Pg. 6, line 8, "35 km for SARAL": why do you set 35 km if tracks have different scales? Please justify

We have chosen to be consistent in the processing of the SARAL data for the different tracks in order to facilitate the comparison and discussion. Moreover, the mesoscale capability deduced from a spectral approach is a statistical result and corresponds to a mean situation (which may be biased by the number of samples analyzed and the way spectra have been computed). In some cases we may be able to observe smaller structures than expected and in some others noise will clearly remain (as shown in the individual cases). The choice of the optimal cutoff frequency does not seem obvious at all. Anyway, this section has been slightly changed to clarify. Now: "In order to have the best signal-over-noise ratio, we then filtered the data with a low-pass Loess filter, using a cut-off frequency of 35 km for SARAL. Note that we have chosen a single value for the different SARAL tracks in order to have the same data processing and facilitate the comparison between the different datasets. For Jason-2, we chose the option of using a processing as close as possible from the one of SARAL and then used a cut-off frequency of 40 km. The same low-pass filters were used for both 1-Hz and high-rate SLAs. One need then to keep in mind that noise remains in the filtered Jason 2 data."

Pg. 6, line 13, "from (Rio et al.,2014)": change to "Rio et al., (2014)" Moreover, the authors have to demonstrate that this MDT is accurate going closer to the coast as in open ocean (this product was not generated to be used in the coastal zone)

We agree. We chose to work with the regional MDT from Rio et al., 2014 which was validated against in situ datasets. Compared to the previous MDT from Rio et al., 2007, it has a better resolution (1/16 degree vs 1/8 °) and the regional circulation is better resolved (see Rio et al, 2014 but we have also done our own diagnostics). We have added the following sentences:

"The MDT product used is a regional product with an horizontal resolution of 1/16° (lower than the altimetry resolution in the along-track direction). Compared to other products, it allows a better representation of the NC in the Ligurian Sea (Rio et al., 2014)."

"(Rio et al., 2014)" has been changed for "Rio et al., (2014)".

Pg. 6, lines 29-30 "The ones being too short or moving too far away from an average trajectory": please be rigorous in stating "too short" and "too far away

Right. Now: "The ones being too short (<60 km) or moving too far away (>15 km) from an average trajectory computed from the individual ones were discarded. "

Pg. 7, line 6, "points and the was too": typo to correct

Corrected. We added the word “horizontal” in the text.

Pg. 6, lines 12-13, “compare the currents derived from these data with the currents measured or derived from the other instruments”: becareful that altimeter derived currents from altimetry are not equivalent to currents measured e.g. from ADCPs

We agree. Now: “In order to estimate currents as close as possible to the currents measured or derived from the other instruments (see below), ...”.

Pg. 8, line 17, “HF radar is roughly 60x40”: is this the area covered? How much is accuracy of currents? Please discuss bibliography

The HF radars section has been developed. Now : “The HF radars data used here, which are also part of the MOOSE network (Zakardjian and Quentin, 2018), targets the area off the coast of Toulon as a key zone conditioning the behaviour of the North Current just upstream of the Gulf of Lions due to a sharp bathymetry and several islands thet deviate a stronger NC southwestward, significant cross-shelf exchanges correlated to the strongnorth-westerlies present in the region (Mistral, Tramontane) as well as a marked mesoscale variability of the NC (e.g., Guihou et al., 2013). The system consists in two HF (16 MHz) Wellen Radar (WERA) instruments installed near Toulon in monostatic (Cap Sicié station) and bistatic (Cap Bénat/Proquerolles island stations) 8-antenna configurations (see Quentin et al., 2013, 2014 for details). The systems are working with a 50 kHz bandwidth, resulting in a 3 km range resolution, a direction finding method based on MUSIC (Lipa et al., 2006, Molcard et al., 2009) allowing a 2 degree azimuthal resolution and with a time integration of 20 minutes. The radial velocities maps are means over a 1 hour time window and cartesian total velocities are then reconstructed on a regular 2 x 2 km grid. An assesment of this HF Radar site can be found in Sentchev et al. (2017) who found an overall good agreement between derived radial velocities and in situ ADCP, with relative errors of 1 and 9 % and root mean square (RMS) differences of 0.02 and 0.04 m/s, slightly increased, in velocity and direction, for the reconstructed total velocities, but mainly in conditions of unstationnary wind forcing. The MOOSE HF radar data base used here is made of daily (one diurnal lunar period of 25h), averaged surface currents computed from the re-processed hourly total velocity data (QC level L3B, i.e., velocity threshold and Geometric Dilution of Precision – GDOP - tests passed) with additional cleaning of residual RFI outliers using outlier-removal algorithm based on the number of L3B valid data, variance and mean over a one intertial period window (17h at 43°N). The data are hence hence tides and inertial oscillation filtered. The time series starts in May 2012 and ends in September 2014 with a total of 732 days of available data. The size of the area covered by total velocities after the GDOP test is roughly 60x40 km and it is located about 170 kmwestward of the glider and ADCP observations (as well as of the altimetry tracks we have chosen to focus on in this study).”

Pg. 9, lines 4-5, “to altimetry data still remains limited in the 10- 15 km coastal band” The statement is wrong. With reprocessed high res altimetry tat adopts retracking one can go closer to the coast.

We changed into “to 1Hz-altimetry data”. However, if more altimetry data are now available thanks to efforts done in retracking and reprocessing, 1) their uncertainty is larger (and remain unknown) and 2) they are still available only for some expert users (because only experimental data sets exist, usually at level 2 or level 2P, covering only one or a few missions, or a few areas or a few years). So we really believe that for most users altimetry data still remains limited in the 10- 15 km coastal band.

Pg. 9, line 19, “HF radars and altimeters observe the ocean surface”: altimetry provides geostrophic currents that are derived from SLA where tides and atmospheric effects (wind and pressure) are removed. HF radar provides the real total current at surface. . Also gliders provide only the baroclinic component of currents. ADCP measure currents at differet layers. Authors have to discuss in detail these differences.

The differences are explained in details in the the next section (“physical content”) and in in the data description.

Pg. 9, lines 33-34, “the gliders and altimeters are clearly the closest in terms of current information derived.”. I don’t agree. Gliders miss the barotropic component due to atmospheric effects that in the coastal zone is not negligible

Part of the barotropic component is also removed from altimetry through the DAC correction (e.g. the barotropic response to the HF wind fluctuations). Moreover, in the glider data, an estimate of depth-average currents was added to the velocity data as an estimation of the barotropic component. So we really think that the question of the details of the differences between altimetry and glider is a complex issue and goes beyond the scope of this paper. We think that in this region ageostrophic motions are very important and that among all the platforms analyzed in this study, gliders and altimetry are the closest in terms of current information derived. However we agree that we needed to be clearer in the text and made a number of changes in section 2.2.d “physical content” accordingly. Now:

“Moreover, the different instruments do not capture the same physical content. The ADCP and the HF radars measure both the total instantaneous velocities when the gliders and altimeters allow to derive only the geostrophic current component perpendicular to the satellite or glider track (i.e. excluding the ageostrophic parts such as wind-driven surface current, tidal currents, internal waves, etc…, and the current component parallel to the track). Unlike the other current data sources used here, altimetry gives only access to current anomalies. But the addition of a synthetic MDT allows to overcome this difficulty if its quality is good enough to derive a reliable mean velocity field. After the addition of the MDT, the gliders and altimeters are clearly the closest in terms of current information derived. However, the glider currents are computed from hydrographic measurement profiles with a reference level of 500 m. They miss the barotropic and the deeper baroclinic geostrophic current componentss when altimetry and MDT allow to estimate absolute geostrophic currents representative of the horizontal density gradients integrated over the whole water column. In this study, in order to minimize (as far as possible) the differences between the current data sets, we performed a projection of the ADCP velocities to obtain the current component perpendicular to the ship transects.

Concerning the gliders , estimates of depth-average currents computed following *Testor et al*., 2018 approach were added to the velocity data as an estimation of the barotropic component."

Pg. 10, line 22, "from March 2013 to October 2014": I am not sure this is a good approach. Mean flows have sense if you average by month, season or annual.

We agree but the period which is common for all the types of observations is really limited and we have chosen to have a maximum of samples to compute the statistics. Our objective here is to quantify the differences between the currents derived from the different platforms and not to discuss the seasonal or annual variability.

Pg. 11, lines 1-2, "Fig. 2, where one can notice a very good consistency of the mean currents derived from all the different instruments."

Pg. 11, lines 32-33, "HF radars (∼-0.44 m/s) than in altimetry (∼-0.29 m/s)": Why this difference ? please explain.

Right. We added the following sentence: "This difference is probably due to the ageostrophic motions captured by the HF radars but not by altimetry, and to the differences in the data resolution."

Pg. 12, line 1, "we observe values of 0.12-0.2 m/s": Mean values are around 0.3 m/s and variability is of same order of magnitude (more or less). Is this picture confirmed by bibliography ?

Very few NC studies use altimetry data but in Birol et al., 2010, values between 0.1 and 0.2 m/s were found. It is due to the too low resolution of the data that capture only one part of the NC variability (explained below in the text). From this work we demonstrate that 1-Hz altimetry data (corresponding to the standard products available for the scientific community) are able to capture 50% of the variability of the geostrophic NC component.

Pg. 13, lines 29-30, "The maximum NC current amplitude is defined as the average of the first decile of the velocity values for each transect and time": please justify this definition

We agree and added an explanation. Now: "The maximum NC current amplitude is defined as the average of the first decile of the velocity values for each transect and time (remember that the NC corresponds to negative current values). These values must be close in space. This strategy allows to filter large isolated current values which may not correspond to the NC."

Synergy between in situ and altimetry data to observe and study the Northern Current variations (NW Mediterranean Sea).

Alice Carret[1], Florence Birol[1], Claude Estournel[2], Bruno Zakardjian[3] and Pierre Testor[4]

(1) LEGOS, Université de Toulouse-CNES-CNRS-IRD, OMP, 14 Av. E. Belin, 31400 Toulouse, France
(2) L.A. Université de Toulouse-CNRS, OMP, 14 Av. E. Belin, 31400 Toulouse, France
(3) Université de Toulon, CNRS/INSU, IRD, Mediterranean Institute of Oceanography (MIO), UM 110, 83957 La Garde, France
(4) LOCEAN, Sorbonne Université-CNRS-IRD-MNHN, Paris, France

Abstract

During the last 15 years, substantial progress has been achieved in altimetry data processing, providing now data with enough accuracy to illustrate the potential of these observations for coastal applications. In parallel, new altimetry techniques improve the data quality by reducing the land contamination and by enhancing the signal-to-noise ratio. Satellite altimetry provides ~~ever~~ more robust and accurate measurements ever closer to the coast and resolve ~~ever~~ shorter ocean signals. An important issue is now to learn how to use altimetry data in conjunction with the other coastal observing techniques.

Here, we ~~demonstrate the ability of satellite altimetry to observe part of the Northern Current variability. We~~ cross-compare and combine the coastal currents provided by large data sets of ship-mounted ADCPs, gliders, HF radars and altimetry. We analyze how the different available observing techniques, with a particular focus on altimetry, capture the Northern current variability at different time-scales. We also study the coherence/divergence/complementarity of the informations derived from the different instruments considered. Two generation of altimetry missions and both 1-Hz and high-rate measurements are used: Jason 2 (nadir Ku-band radar) and SARAL/AltiKa (nadir Ka-band altimetry); their performances are compared.

In terms of mean speed of the Northern Current, a very good spatial continuity and coherence is observed at regional scale, showing the complementarity between all the types of current measurements. In terms of current variability, there is still a good spatial coherence but the Northern Current amplitude derived from altimetry, glider, ADCP and HF radar data differ, mainly because of differences in their respective spatial and temporal resolutions.~~of the seasonal variations is underestimated by ~50% in altimetry, compared to both gliders and ADCPs, because of a too low spatial resolution~~. If we consider the seasonal variations, 1-Hz

altimetry captures ~60% and ~55% of the continental slope current amplitude observed by the gliders and by the ADCPs, respectively. For individual dates this number varies a lot as a function of the distance to the coast and width of the Northern Current. Compared to Jason 2, the SARAL~~/AltiKa~~ altimeter data tend to give estimations of the NC characteristics that are closer to in situ data in a number of cases. The much noisier high-rate altimetry data appear to be more difficult to analyze but they provide current estimates that are generally closer to the other types of current measurements. A~~Satellite a~~ltimetry obviously provides a synoptic view of the Northern Current circulation system and variability which helps to interpret the other current observations. Its regular sampling allows the observation of many features that may be missed by in situ measurements.

1. Introduction

Radar altimeters allow to estimate ~~measure~~ the sea surface height (SSH) variations along the satellite tracks at regular interval time. Providing a large number of continuous and ~~ever more~~ accurate observations of the global oceans since more than 25 years, they have progressively evolved into one of the fundamental instruments for many scientific and operational oceanographic applications (Morrow and Le Traon, 2012). The SARAL mission and its first AltiKa Ka-band frequency radar, launched in 2013, has still improved the performance of satellite altimetry (Bonnefond et al., 2018). With the launch of Sentinel-3A, B, in February 2016 and in April 2018, the altimetry constellation was completed by the first instruments always operated at high resolution mode (commonly called Synthetic Aperture Radar or SAR) ~~the first global synthetic aperture radar (SAR, or Delay-Doppler) technique which increases the along-track data resolution~~. These new altimeters provide enhanced along-track resolution ~~accuracy~~ and reduced noise, in comparison ~~compared~~ to the conventional nadir-looking pulse limited Ku-band instruments used since the beginning of the altimetry era. In 2021, the SWOT mission, with its SAR interferometer in Ka-band measuring SSH over 120-km wide swaths will be a new step forward.

In coastal ocean areas, ~~where~~ it is particularly important to monitor the sea level variations. About 10% of the world population lives in low-elevation coastal zones (Nicholls and Cazenave, 2010) exposed to hazards such as extreme events, flooding, shoreline erosion and retreat. The latter are expected to increase due to the combined effects of sea level rise, climate change, and increasing human activities.~~, directly related to our living environments and marine ecosystems,~~ In coastal regions in particular, we expect a lot of advances from these ~~new~~modern altimetry instruments and processing techniques. Indeed, conventional satellite altimetry missions have not been designed for the observation of the coastal ~~ocean~~dynamics. The strongest limitation is the modification of the radar echo in the vicinity of land but the sea level estimations derived are also impacted by inhomogeneity in the water surface observed by the radar and by less accurate corrections. Coastal altimetry measurements are much more difficult to interpret and need a dedicated processing and specific corrections (Gommenginger et al., 2011; Cipollini et al., 2017a). The data resolution is also too low to capture the fine scales of the coastal ocean dynamics. As a consequence, most altimetry data collected in coastal zones over the last 25 years have been discarded in altimetry products and/or poorly ~~un~~exploited. A lot of efforts has been done during the last 15 years in the altimetry community to overcome these difficulties and substantial progress has been achieved on the data processing side (Roblou et al., 2011; Passaro et al., 2014; Valladeau et al., 2015; Cipollini et al., 2017a), starting to provide data with enough accuracy to illustrate the potential of altimetry for coastal applications (Passaro et al., 2016; Birol et al., 2017; Morrow et al., 2017). Moreover, the use of new altimetry techniques~~ are intrinsically less sensitive to the land contamination. They~~ provide more robust and accurate measurements, ~~ever~~ closer to the coast and allows to resolve~~ ever~~ shorter spatial scales ~~ocean features~~ (Dufau et al., 2016; Morrow et al., 2017). As an example, from Birol and Niño (2015), closer than 10 km to the coastline, available SARAL data is still ~60% and only ~31% for Jason-2. From Morrow et al. (2017), in summer, SARAL can detect ocean scales down to 35 km wavelength, whereas the higher noise from Jason-2 blocks the observation of scales less than 50-55 km wavelength. As a result, the capability of altimetry for the monitoring of coastal ocean dynamics has already been illustrated in a number of studies. Most of them concern shelf and boundary currents (Bouffard et al., 2008; Birol et. al., 2010; Herbert et al., 2011; Jébri et al. 2016, 2017). Some others are related to sea level applications (Cipollini et al., 2017a). A more complete review of coastal altimetry applications can be found in Cipollini et al (2017b) and we can easily predict that the use of this instrument in coastal studies will be largely extended in the next years.~~. We can easily predict that the use of altimetry in coastal studies (Pascual and Gomis, 2003; Bouffard et al., 2008; Birol et al., 2010; JÃ©bri et al., 2016, 2017) will be largely extended in the next years.~~

Today, ~~coastal observations~~ observations used in coastal applications are mainly based on in situ instruments and satellite imagery(sea surface temperature and ocean color images). In order to answer to the need for monitoring of the coastal ocean environment, in situ observing systems gather informations in a growing number of regions such as along the Australian or US coasts (http://imos.org.au/; https://portal.secoora.org/; http://www.nanoos.org/; see also Liu et al., 2015). The different techniques are often used in ~~conjunction~~synergy, measuring different ocean state parameters on different time and spatial scales. Compared to altimetry, their spatial and/or temporal resolution is much more adapted to detect the coastal ocean variability. Nonetheless, in situ observations cover more limited areas and often provide time series that present large gaps. Moreover, ~~satellite~~optical imagery is often impacted by clouds and does not provide any direct information on the changes occurring in the water column. The large advantage of satellite altimetry, and the reason of its success in the deep ocean, is that it offers almost-global and synoptic observations of the sea level, a geophysical parameter which can be related to the ocean circulation and many other dynamical features (eddies, waves, sea water changes, ...). An important issue is now to learn how to use altimetric data in conjunction with the other coastal observing techniques.

To study the contribution of altimetry amongst other types of coastal ocean measurements, the North-Western Mediterranean Sea (NWMed) represents a laboratory~~n ideal~~ area. First w~~W~~ith a Rossby radius of ~10 km, the region is associated to a variety of mesoscale and sub-mesoscale dynamical signals (see below). As a result it represents a challenge for altimetry ~~it is associated to important mesoscale and sub-mesoscale variability at all time scales, representing a challenge for observing systems~~. Secondly, the number of in situ observations is relatively important in this region, allowing comparison with independent data. In the NWMed, ~~T~~the main feature of the surface ocean circulation is the Northern Current (called NC hereafter) which is formed in the Ligurian Sea (Taupier-Letage and Millot, 1986) and flows cyclonically along the Italian, French and Spanish coasts. This current presents a marked seasonal variability, with a maximum amplitude from February to April (Sammari et al., 1995; Millot, 1991), and it meanders in a vast range of wavelengths (10-100 km). The mesoscale variability is higher in autumn and winter because of the larger baroclinic instability associated to strong and cold winds (Alberola et al., 1995; Millot, 1991). During the last 10 years, the NC has been intensively monitored by a variety of in situ data (moorings, research vessels, gliders, and HF radars) collected from the MOOSE integrated observing system (Mediterranean Ocean Observing System for the Environment). Despite a width of only 30-50 km, through the comparison with ADCP current data located in the Ligurian Sea, Birol et al., 2010 demonstrated that reprocessed altimetry data are able to ~~partially~~ capture half of the amplitude of the ~~the~~ seasonal NC variability ~~of the NC and to provide original aspects of the regional circulation~~. The altimetry currents have then been used to analyze the regional current variability at seasonal scale. In the Balearic Sea~~sub-basin~~, the reliability of altimetry currents has been verified by direct comparison with currents derived from gliders and HF radars (-Bouffard et al., 2010, Pascual et al., 2015 and Troupin et al., 2015)These case studies showed that altimetry can depict current signals coherent with the other instruments. ~~showed that coherent circulation patterns could be obtained from altimetry data, in comparison with glider and HF radar data~~. Morrow et al., 2017 also showed that some of the large scale eddies observed by gliders in the NWMed can be captured by altimetry ~~also found similarities between currents measured by gliders and surface currents derived from the most recent altimetry missions~~. A more systematic use of altimetry in regional coastal applications requires a better quantitative assessment of its performance near coastlines, from daily to interannual time scales.

The general objective of this paper is not only to investigate the accuracy of the velocity fields derived from altimetry data next to the coast at different temporal scales ~~to demonstrate the ability of satellite altimetry to observe and understand the NWMed ocean dynamics, and~~ but also to define its contribution compared to the other coastal ocean observing systems which exist in the region (ship-mounted ADCPs, gliders and HF radars). In this study, we combine all the different available in situ data sets which provide information on currents in the ~~Ligurian Sea~~Ligurian-Provençal basin ~~(ship-mounted ADCPs, gliders and HF radars)~~ and perform systematic comparisons with currents derived from altimetry at different time-scales. In particular, we analyze how the different available observing techniques capture the NC variability and the coherence/divergence/complementarity of the informations derived. From previous studies, we know that only a small part of the NC variations can be captured by conventional satellite altimetry. Here, we use both Jason-2 and SARAL/AltiKa missions to investigate the progress made from Ku-band to Ka-band altimetry. We also investigate the potential of experimental 20/40-Hz altimetry products to monitor the NC variations, relative to the conventional 1-Hz data.

In this paper, section~~Sect.~~ 2 presents the datasets used and the corresponding data processing. It is followed by the intercomparison between the currents derived from altimetry and from the different in situ datasets, with the analysis of the NC variations observed at different time scales by the different instruments (section~~Sect. 3~~). Section 4 concludes the paper.

2. Data and methodology

2.1. Satellite Altimetry

~~In this study, w~~We use two altimetry missions with distinct characteristics: Jason 2 and SARAL/AltiKA. Jason 2 was launched in June 2008 and provides long time series of data with a 10-day repeat observation cycle. The performance of SARAL is significantly better. With a better signal-to-noise ratio, it resolves smaller spatial scales than Jason 2: ~40 km against ~50 km (Dufau et al., 2016, Verron et al., 2018). However the corresponding time series started only in February 2013 and have a 35-day repeat observation cycle, a priori not really adapted to the monitoring of the coastal ocean variability. ~~but the corresponding time series started only in February 2013 and have a 35-day repeat observation cycle,a priori not really adapted to the monitoring of the coastal ocean variability.~~ On the other hand, SARAL orbit leads to a smaller distance between tracks, compared to Jason-2 (Fig. 1). Here we focus only on the SARAL tracks 302, 343 and 887 and on the Jason 2 track 222, providing the closest data from the in situ observations.

For both missions, because it is one of the most often used in coastal altimetry applications, we used the X-TRACK regional product from the CTOH (doi:10.6096/CTOH_X-TRACK_2017_02), processed with a coastal-oriented strategy (Birol et al., 2017). It consists in time series of Sea Level Anomalies (SLA) every 6-7 km along the satellite tracks, available from 20/07/2008 to 01/10/2016 for Jason 2 (i.e. 300 cycles) and from 24/03/2013 to 12/06/2016 for SARAL (i.e. 34 cycles). In order to evaluate the skill of the elementary noisier 20/40-Hz altimetry measurements of the Jason-2/SARAL altimeters for circulation studies, relative to the conventional 1-Hz data, we have also used an experimental high-rate version of these data provided by the CTOH (section 3.4). The processing is the same than for 1-Hz SLA, except that the high-rate SLA are computed from the 20/40-Hz range data provided in the AVISO L2 products (https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_j2.pdf and https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/SARAL_Altika_products_handbook.pdf). The resulting sea level time series are available every ~0.29 km and ~0.19 km along the satellite tracks for Jason-2 and SARAL, respectively. However, we must keep in mind that if the use of high-rate altimeter measurements allows to significantly improve the spatial resolution, the resulting SLA are much noisier (see for example Birol and Delebecque, 2014). Considering the data availability (see below for the in situ observations), the study period chosen is 2010-2016 for all altimetry datasets.

Jason 2 altimeter is designed as “conventional altimetry” as it operates in the Ku-band frequency. SARAL altimeter operates in the Ka-band, allowing a better performance in terms of spatial resolution (the radar footprint is smaller) and measurement noise. Morrow et al. (2017) analyzed the “mesoscale capability” (defined as the wavelength where the noise is larger than the signal, which varies spatially as shown by Dufau et al., 2016) of these two altimeters in the NWMed using a statistical method (Xu and Fu, 2012). It allows to have an estimate of the size of the structures which can be theoretically detected by each altimeter (in average) and to define the optimal dataspatial filtering. Here, we did the same computation for each of the 4 tracks used in this study, using all the data available unlike ~~(~~in Morrow et al., 2017, where the data located over the continental shelf were discarded~~)~~. We obtained 49 km for the SARAL track 302, 39 km for the SARAL track 343, 34 km for the SARAL track 887 and 67 km for the Jason 2 track 222, which is coherent with the results of Morrow et al., (2017) who obtained 39 km for SARAL and 55 km for Jason-2 without the coastal altimetry observations. It suggests that the quality of near-shore altimetry SLA remains good. The lower values obtained for SARAL are due to the better signal-over-noise ratio of the AltiKa altimeter compared to Jason-2. The differences obtained between the three SARAL tracks are explained by their respective geographical locations. They capture different mesoscale features.

In order to have the best signal-over-noise ratio, we then filtered the data with a low-pass Loess filter, using a cut-off frequency of 35 km for SARAL. Note that we have chosen a single value for the different SARAL tracks in order to have the same data processing and facilitate the comparison between the different datasets. For Jason-2, we chose the option of using a processing as close as possible from the one of SARAL and then used a cut-off frequency of 40 km. One need then to keep in mind that noise remains in the filtered Jason 2 data.

Altimetry only provides sea level anomalies relative to a temporal mean. In order to estimate currents as close as possible to the currents measured or derived from the other instruments (see below)~~be able to compare the currents derived from these data with the currents measured or derived from the other instruments (see below)~~, we added the regional Mean Dynamic Topography (MDT) from ~~(~~Rio et al., (2014) to the altimetric SLA and computed the surface velocities (u) from the total sea level gradients observed between consecutive points along the track, assuming that the fluid is in geostrophic balance:

$$u = \frac{-g}{f}\frac{\Delta(SLA+MDT)}{\Delta x} \quad \text{, where} \qquad (1)$$

f is the Coriolis parameter, g the gravitational constant and Δx the distance between the points.

Only the across-track component of the geostrophic currents can be derived. The MDT product used is a regional product with an horizontal resolution of 1/16° (i.e. lower than altimetry resolution in the along-track direction). Compared to other MDT products, it allows a better representation of the NC in the Ligurian sea (Rio et al., 2014).

2.2. In situ measurements

2.2.a) Glider data

Gliders have been deployed in the NWMed since 2005. However, it is only since 2009 that they are regularly operating as part of the MOOSE network (http://www.moose-network.fr/?page_id=272). In particular, on the Nice-Calvi line (Fig. 1, pink line), 36 deployments were undertaken between 2009 and 2016. Some of them have already been analyzed in different studies, with different scientific objectives (Piterbarg et al., 2014 focused on the frontal variability, Bosse et al., 2015 investigated the submesoscale anticyclones, Niewiadomska et al., 2008 analyzed physical- biogeochemical coupling mechanisms). Each glider deployment encompassing several transects, the database includes 204 sections; 192 of them are between 2010 and 2016. The ones being too short (<60 km) or moving too far away (>15 km) from an average trajectory computed from the individual ones were discarded. Finally, 173 glider transects along this line were used in this study. It represents a huge amount of observations and a large number of cases available for the comparisons with altimetry or with the other in situ observations. ~~a large potential of comparisons with altimetry or other in situ observations~~.

The campaigns were sliced into ascending (from Calvi to Nice) and descending (from Nice to Calvi) transects and the data were projected on a reference track. We assume that one dive or one ascent represents one vertical profile. In practice, data were discarded when the latitude was not monotonically varying or when the angular deviation between 2 consecutive points and the was too strong (i.e. larger than 3 standard deviations away from a mean angle). Then the data were gridded with a 4 km horizontal bin size along the reference track. ~~(~~4 km corresponds to the average distance between two successive profiles.

During their mission, gliders measure temperature and salinity ~~(among other parameters)~~ from the surface down to 1000 meters (or less if the bottom is shallower, or if commanded to dive shallower). To avoid noise (mainly due to aliased internal waves), temperature and salinity data have to be filtered. A butterworth filter of the second order (Durand et al., 2017) was applied. Different cut-off frequencies have been tested and we finally chose 15 km to avoid noise without removing small-scale variations (as in Bosse et al., 2017). From the temperature and salinity we computed the density and then the geostrophic velocity component perpendicular to the reference track using the thermal wind equation. These velocities are referenced to 500m, corresponding to the depth reached by all gliders. The difference with altimetry-derived currents is then that the barotropic component and the baroclinic component below 500 m are missing.

2.2.b) ADCP data

Since 1997, the TETHYS II RV collected a large number of ADCP current measurements during frequent repeated cruises between the French coast (Nice) and the Dyfamed/Boussole site (43°25 N ; 7°52E). The corresponding ship transect is much shorter than the Nice-Calvi glider line (Fig. 1), but samples the NC at about the same location. From 1997 to 2014 a 150 kHz ADCP was used, with a vertical bin length of 4m. In 2015, it was replaced by a 75 kHz

ADCP, providing data with a 8 m vertical resolution. The first valid measurement is located at 8/18 m depth for the first/second ADCP. Processed and validated data were obtained from the INSU-DT data center (http://www.dt.insu.cnrs.fr/spip.php?article35). A total of 513 vertical sections of horizontal currents in earth geographical coordinates are provided from November 1997 to March 2017. This number is reduced to 218 during the period 2010-2016. We only used the ADCP transects with a very precise heading which leaves us with 151 sections. Following the same strategy as for glider data, the data were gridded with a 2 km horizontal bin size along a reference transect (from the French coast to DYFAMED site, yellow line on Fig. 1). Ship tracks located outside the chosen grid bins, incomplete transects, as well as data associated to a ship direction which deviates too much from the referencetrajectory (generally corresponding to ship stations) were eliminated. For each cruise, we have onereturn trip (sometimes two). After a visual inspection of each individual transect to check the coherence of the currents measured during the same day, the data have been averaged per bin, to have one daily-averaged transect. It finally leads to a total of 134 selected current sections. In this study, we focused on the 34m-depth cell, as it is less influenced by surface instrumental errors.

2.2.c) HF radars

The HF radars data used here (orange zone on Figure 1), are also part of the MOOSE network (Zakardjian and Quentin, 2018). They target the area off the coast of Toulon as a key zone conditioning the behaviour of the NC just upstream of the Gulf of Lions. Due to a sharp bathymetry and several islands that deviate the NC southwestward, significant mesoscale variability and cross-shelf exchanges exist in this area (Guihou et al., 2013), correlated to the strong north-westerlies winds (Mistral, Tramontane). The system consists in two HF (16 MHz) Wellen Radar (WERA) instruments installed near Toulon in monostatic (Cap Sicié station) and bistatic (Cap Bénat/Proquerolles island stations) 8-antenna configurations (see Quentin et al., 2013, 2014 for details). They work with a 50 kHz bandwidth, resulting in a 3 km range resolution, a direction finding method based on MUSIC (multiple signal classification algorithm, see Lipa et al., 2006, Molcard et al., 2009) allowing a 2 degree azimuthal resolution and with a time integration of 20 minutes. The radial velocity maps are averaged over a 1 hour time window and cartesian total velocities are then reconstructed on a regular 2 x 2 km grid. More details on this HF Radar site can be found in Sentchev et al. (2017) who found an overall good agreement between derived radial velocities and in situ ADCP, with relative errors of 1 and 9 % and root mean square (RMS) differences of 0.02 and 0.04 m/s, slightly increased, in velocity and direction, for the reconstructed total velocities, but mainly in conditions of unstationnary wind forcing. The MOOSE HF radar data base used here is made of daily (one diurnal lunar period of 25h), averaged surface currents computed from the re-processed hourly total velocity data (QC level L3B, i.e., velocity threshold and Geometric Dilution of Precision - GDOP - tests passed) with additional cleaning of residual RFI (Radio Frequency Interference) outliers using outlier-removal algorithm based on the number of L3B valid data, variance and mean over an inertial period window (17 h at 43°N). The data are then filtered from tides and inertial oscillations. The time series starts in May 2012 and ends in September 2014 with a total of 732 days of available data. The size of the area covered by total velocities after the GDOP test is roughly 60x40 km and it is located about 170 km westward of the glider and ADCP observations.

~~The HF radars are also part of the MOOSE network (http://www.moose-network.fr/?page_id=270). The site (indicated in green on Fig. 1) has been chosen to monitor the coastal circulation. There, the bathymetry is very sharp and islands deviate a stronger NC southward. As a consequence, its position and intensity become highly variable, depending on seasonal and wind conditions (Guihou et al., 2013). The system consists in 2 Wellen Radar (WERA) instruments installed near Toulon to monitor seasonal and high frequency variability of the NC. They provide hourly surface current observations. Inertial currents have been filtered. We used edited and daily averaged data provided by MOOSE. The time series starts in May 2012 and ends in September 2014. Due to gaps, only 732 days of data are available. The size of the area covered by the HF radar is roughly 60x40 km and it is located about 170 km westward of the glider and ADCP observations (as well as of the altimetry tracks we have chosen to focus on in this study).~~

2.2.d) Differences between the currents derived from the different observational techniques

In this study, we extensively compare the currents derived from the four different techniques described above with the objective to better understand how they can optimally complement each other for the observation and study of the variability of the NC circulation system. However, we must first have in mind the intrinsic characteristics of each type of current observation and the differences between the data sets.

- **Spatial and temporal sampling**

First, the locations of the different types of observations do not coincide with each other, and their temporal and spatial sampling is also very different. After processing, current values are obtained every 2 km along the ship ADCP track, every 4 km along the glider line, in a 3 km resolution grid for the HF radar and every 5-6 km / 7-8 km ~~f~~ along the satellite track for 1 Hz ~~or~~ Jason 2 / SARAL altimetry and every 0.29 km / 0.19 km for HF Jason 2 / SARAL altimetry, respectively. Moreover, each instrument is characterized by specific measurement errors (and then specific signal to noise ratio) and a filtering has to be applied on the glider and altimetry data, still limiting the wavelengths of the current which can be resolved (see above and in Table 1). We have also to keep in mind instrumental limitations concerning the area which can be monitored. The ship ADCPs, the HF radars and the gliders have a higher spatial resolution than altimetry but a much more limited spatial coverage. We have also to consider that the access to altimetry data still remains limited in the 10- 15 km coastal band. As the NC fluctuates in both location and width (and at both seasonal and much higher frequencies as shown by Albérola et al., 1995), it can make a large difference in the ability of the instrument considered to capture this current flowing along the continental slope, often located very close to the coastline (Fig. 2).

Concerning the temporal sampling, the HF radars and the altimetry provide current observations at regular interval: every day for the HF radar product used here, every 10 days for Jason 2 and every 35 days for SARAL. The glider and ADCP data are available between 0 and 9 times per month and between 0 and 5 times per month, respectively. These unevenly spaced time series make the corresponding data analysis more complex since it can produce significant biases in the distribution of the NC properties (as for example its seasonal variations, see Table 2). It will also be influenced by the period of observations available: from about 2 years for the HF radar to more than 6 years for the ADCP, glider and Jason-2 data (see Table 1).

- **Vertical sampling**

The depth of the current measurement also varies for the different instruments: HF radars and altimeters observe the ocean surface when ADCP and gliders provide vertical sections of measurements. Using both the glider and the ADCP data, we compared the currents computed at different depths (18, 34 and 50 m) and did not find significant differences (less than 5 cm/s for the mean NC core velocity and around 2-3 cm/s for the corresponding STD value). We then decided to use the glider data at 34 m depth (to be coherent with the ADCP observations) and consider that it should not be a significant source of differences with altimetry currents, representing near-surface currents~~located at the surface~~.

- **Physical content**

Moreover, the different instruments do not capture the same physical content. The ADCP and the HF radars measure both the total instantaneous velocities when the gliders and altimeters allow to derive only the geostrophic current component perpendicular to the satellite or glider track (i.e. excluding the ageostrophic parts such as wind-driven surface current, tidal currents, internal waves, etc..., and the current component parallel to the track). Unlike the other current data sources used here, altimetry gives only access to current anomalies. But the addition of a synthetic MDT allows to overcome this difficulty if its quality is good enough to derive a reliable mean velocity field. After the addition of the MDT, the gliders and altimeters are clearly the closest in terms of current information derived. However, the glider currents are computed from hydrographic measurement profiles with a reference level of 500 m. They miss the barotropic and the deeper baroclinic geostrophic current components when altimetry and MDT allow to estimate absolute geostrophic currents representative of the horizontal density gradients integrated over the whole water column ~~(missing the deeper current component), when altimetry currents are derived from sea level measurements (representative of the horizontal density gradients integrated over the whole water column).~~ In this study, in order to minimize (as far as possible) the differences between the current data sets, we performed a projection of the ADCP velocities to obtain the current component perpendicular to the ship transects. Concerning the gliders~~ data~~, estimates of depth-average currents computed following Testor et al., 2018 approach were added to the velocity data as an estimation of the barotropic component~~ were added to the geostrophic velocities (computed by comparing dead reckoning navigation and GPS fixes at the surface between two surfacing, see Testor et al., 2018 for further information)~~.

All the differences mentioned above are summarized in Table 1. If the data appear complementary in terms of space-time coverage and resolution, we can anticipate that their respective characteristics make their comparison and combination an issue. It is what will be analyzed in details in Sect. 3.

3. Results

Note first that all the results below are obtained from 1-Hz standard altimetry measurements, except in section 3.4 which is dedicated to the analysis of the potential of 20/40-Hz altimetry data for coastal circulation studies.

3.1. Mean flow and spatial variability: a regional view

From Fig. 1, we can expect that the different observations mentioned above allow to efficiently detect different characteristics of the NC (intensity, position) along its axis, and the variability of these characteristics. In order to have a first general view of how the different velocity fields compare, we have computed their time-average and their standard deviation values at each point of observation for a common period of time: from March 2013 to October 2014. We need to keep in mind that it corresponds to very different sample sizes: 33 ADCP sections, 8 glider transects, 484 days of HF radar measurements and 54-56 and 16 current data for Jason 2 and SARAL satellite altimetry, respectively. Glider / HF radar observations will then have the lowest / highest significance in terms of statistics. Concerning the HF radars, only the zonal current component is taken into account. Note however that in this area, since the NC is almost zonal, most of its mean and variability are captured in the corresponding statistics. Figure 2 shows the resulting map of the mean current and its standard deviation is in Fig. 3. Here, we choose to not represent the results for all the SARAL tracks in order to not overload the figures. Both the regional map (Fig. 2a and 3a) and a zoom in the northern Ligurian Sea (Fig. 2b and 3b), where the largest number of current observations are located, are shown.

~~Current values are positive (negative) to the right (left) of the ship, glider or satellite tracks (when oriented to the north). Therefore~~From~~, from~~ Fig. 1 (see the circulation scheme), we expect negative/~~(~~positive~~)~~ current values along the northern / ~~(~~southern~~)~~ branch of the cyclonic NC current system. It corresponds to what is observed in Fig. 2, where one can notice a very good consistency of the mean currents derived from all the different instruments. Putting together all the pieces of information, the regional structure of the circulation emerges. As already shown in Birol et al. (2010), in the Tyrrhenian Sea, the northwestward Tyrrhenian Current (TC) is well observed at the northern end of Jason 2 track 161. Further north, the NC is formed by the merging of the Eastern Corsica Current (ECC), captured just east of Corsica by the Jason 2 track 085, and of the Western Corsica Current (WCC), well captured by both the gliders and the SARAL track 343. The WCC appears however more extended towards the open sea in the SARAL data, compared to the glider. The NC is then strongly constrained by the bathymetry and follows the continental slope along the coasts of Italy, France and Spain. It can be continuously followed from the SARAL track 343 to the Jason 2 track 070, through the ADCP, glider and HF radar observations. Mean NC velocities larger than -0.3 m/s are observed in the Ligurian Sea (by ADCPs, and altimetry) and off Toulon (by the HF radars and altimetry). Then the continental slope current slows down offshore the Gulf of Lion (the Jason 2 track 146 gives a mean current value of ~-0.15 m/s) and its flow is almost divided by three in the Balearic Sea (~-0.10 m/s). Further south, around

40.5°N around 5-6°E and then between 42°N and 42.5°N around 7-8°E, an eastward flow, probably associated to the Balearic Front which closes the cyclonic circulation south of the Northwestern Mediterranean basin, is captured by the Jason 2 tracks 146, 009, 222 and the SARAL tracks 302 and 887 (from west to east). Around 8°E, it slightly deviates to the southeast before joining the WCC.

If we focus on the northern Ligurian Sea (Fig. 2b), the cross-track direction of Jason 2 track 009 is not well oriented compared to the local axis of the NC. In this area, the continental shelf is very narrow and as a consequence the NC is very close to the coast: altimetry struggles to observe the corresponding flow. However, the Jason 2 track 009 and SARAL track 887 still capture a westward current at their northern end. Considering altimetry, Jason 2 track 222, located further southwestward, appears better oriented to monitor the NC. In this area, despite the difference in the number of data samples, the altimetry, ADCP and glider mean current values are very close (between -0,24 and -0,32 m/s for all of them). The width of the NC tends to vary from one instrument to the other. With the gliders it appears slightly narrower than with the ADCP and altimetry (i.e. SARAL track 887). Note also that the ADCPs and gliders, which provide more nearshore information, show a positive or almost null flow very close to the coast, not observed by altimetry (which stop further offshore). Still further West, the altimetry and HF radars also capture a coherent mean NC flow, but with larger values in HF radars (~-0.44 m/s) than in altimetry (~-0.28~~9~~ m/s). This difference is probably due to the ageostrophic motions captured by the HF radars but not by altimetry, and to the differences in the data resolution.

Figure 3 represents the associated current variability, as captured by the different types of observations. Not surprisingly, in all datasets, larger standard deviation values generally coincidewith the NC system. In altimetry, we observe values of 0.12-0.2 m/s at the northern ends of the Jason 2 tracks 161, 085, 044, 222, 146 and 070 (the signal at the end of track 146 does not correspond to the NC) and of SARAL tracks 302, 343 and 887. If we focus on Fig. 3b, on Jason 2 track 222, we first see clearly the coastal current variations associated to the NC flow (see also Fig. 2b). However, the NC is not fully resolved by altimetry: observations stop at ~10 km from land (the more coastal observations have been discarded during the processing, probably due to large data errors). This is even more true for the Jason 2 track 009 (the last data point available is associated to a large suspicious current value) and the SARAL tracks 887 and 302. We have to keep in mind that in this area, where the narrow NC flow is very close to the coastline (its core is in the range 10-40 km from land, Piterbarg et al., 2014), its observation by altimetry is very challenging. In comparison, the ADCP, glider and HF radar data allow to observe the NC current variability much closer to the coast (our datasets stop at 2.5 km, 3.5 km and 3-7 km from land, respectively). But they all differ in the current variance captured. Concerning the ADCPs and gliders, observing the NC at the same location, the ADCPs show larger standard deviation values (~0.13 m/s) almost all along the transect when the gliders show much lower values in the open ocean (~0.05 m/s), increasing on the shelf break to values very close to the ones observed on Jason 2 track 222 (~0.15~~2~~- 0.20~~15~~ m/s). Further west, the HF radars show the largest current variance south of Toulon, with values around 0.23 m/s located on the continental shelf break. In comparison, the corresponding NC variance captured by the SARAL track 302 is only half of that. Further south, off Corsica, the gliders show very low variability (roughly half of the values corresponding to the NC), indicating a WCC flow which is very stable in time (as shown in Astraldi and Gasparini, 1992).

Considering the intrinsic and important differences between the different current datasets (Sect. 2.2.d), these first statistical results are encouraging. They give a coherent picture of the regional circulation, with, except for the HF radars which capture a faster current flow, about the same NC average velocity values. The NC variability is also clearly captured by the different data sets all along its path, but with significant differences in terms of amplitude. Note that when we recompute the standard deviations using a larger period of time (not shown), ADCP and glider tend to converge toward the same cross-shore profile than the one derived from Jason 2 track 222 (with a maximum which is about 0.03 m/s larger for the in situ observations). We can then conclude that this diagnostic is largely influenced by the number of data samples considered as well as by the period of time covered by the measurements.

In order to better understand the differences in variability captured by the various data sets, we analyze the time-space diagrams of the currents derived from ADCP, HF radar, glider and altimetry data over the period considered (Fig. 4). We focus on the first 60 km off the French coast and,concerning altimetry, on SARAL tracks 302 and 887 and on Jason 2 track 222. The HF radar data correspond to a meridional section of the zonal current component located at 6.2°E. The NC is clearly detected in all data but Fig. 4 displays large variations at different timescales (see also Font et al. 1995; Sammari et al., 1995; Albérola et al., 1995) that make the data temporal sampling resolution a very sensitive question if we want to study this current system. The number of glider transects is low and concentrated in 2013 and the unevenly spaced ADCP sections miss a large number of events (spring 2013, winter and summer 2014 are poorly sampled). The HF radar provides a very good temporal sampling according to the one needed to capture the high-frequency NC current variations but it monitors only its section located in the vicinity of Toulon. Altimetry provides then a good complementary information. Despite its relatively low spatial resolution and the intrinsic difficulties when approaching the land, it detects seasonal changes coherent with the ones observed in the other data sets as well as much shorter period changes. Note that if the SARAL mission capabilities are expected to be particularly adapted for fine-scale oceanography and coastal applications (Verron et al., 2018), in our case study its 35-day period appears to be a strong limitation to monitor the highly fluctuating NC flow. This particular point will be further analysed in Sect. 3.3. In the next section, we concentrate on the seasonal variability observed in the different data sets, as it is known to be the dominant signal of the NC system at regional scale (Alberola et al., 1995; Sammari et al., 1995; Crepon et al., 1982; Birol et al., 2010).

3.2. The seasonal variability of the NC flow captured by the different instruments

Here we compare the monthly climatology (i.e. the mean value for each month of the year) of the maximum NC current amplitude computed from the different current data sets (ADCP, glider, HF radar and altimetry). This time, we use all the data available during the period 01/01/2010 - 31/12/2016 (note that the HF radar data are only available over the period 2012-2014). Concerning altimetry, we consider only Jason 2 since we have 2-4 samples per month for SARAL, which is not enough to compute meaningful statistics (see Table 2). For each data sample available, the current profiles along the Jason 2 track 222, the ADCP and glider reference transects and a meridional HF radar section located at 6.2°E, are analyzed. The maximum NC current amplitude is defined as the average of the first decile of the velocity values for each transect and time (remember that the NC corresponds to negative current values). These values must be close in space. This strategy allows to filter large isolated current values which may not correspond to the NC. In altimetry, only a distance spanning 60 km to the coast is considered. The number of data in the first decile varies according to the data set and to the number of data in the section considered. ~~(b~~Because of the lower resolution, it always corresponds to one point in altimetry~~)~~. As we can see in Fig. 4d, data gaps exist in Jason 2 for some cycles. When ~~it is larger than 3 points~~ more than 3 points are missing, the corresponding cycle is discarded from the analysis. ~~We also make sure that the velocities detected correspond to the NC by adding a criterion on the distance allowed between the data points selected in the first decile.~~ Finally, all the maximum NC current values ~~information~~ collected are averaged as a function of month and data set and synthesized in monthly climatologies represented in the Fig. 5a,b. The results derived from in situ data are in Figure 5a and the results derived from altimetry are in Figure 5b. The glider results are on both figures because this instrument provides the currents which are the closest to altimetry in terms of physical content. ~~For reasons of clarity, results from in situ data are shown in Fig. 5a and results from altimetry are in Fig. 5b, with the glider ones again because this instrument provides the currents which are the closest to altimetry in terms of physical content.~~ For each month, the standard deviation computed from all the NC amplitude values available is also indicated.

Table 2 lists the temporal distribution of the number of samples included in the calculation as a function of month (in brackets). The data density is much more important than in Sect. 3.1 and the corresponding statistics more robust. It appears relatively stable for Jason 2 altimetry and more heterogeneous for the other observations. The number of in situ data per month is strongly variable (especially for the ADCP and to a lesser extent for the glider) and varies also a lot from one year to the other (24 ADCP transects are available in 2015 and only 7 in 2012 and 2014, when the glider dataset has a large gap in 2014). As a consequence, the results will be only discussed in terms of seasonal tendencies.

In Fig. 5a and b, except altimetry, all the climatologies show a clear and coherent seasonal cycle of the NC amplitude, with a stronger/lower flow in winter/summer. As already seen in the previous section, compared to the other data sets, the HF radars capture a faster NC south of Toulon. Higher NC velocities are expected in this location (Ourmières et al., 2011). The corresponding amplitude of the seasonal variations is 0.32 m/s (with a minimum of -0.34 m/s in August and a maximum of -0.66 m/s in February, values also found by Guihou et al., 2013 in this area). In comparison, further East in the northern Ligurian Sea, the peak-to-peak amplitude of the seasonal cycle is slightly lower for the ADCPs than for the HF radars, and associated to a lower mean flow (with a minimum of ~- 0.27 m/s in August and a maximum of -0.54 m/s in January). Note however that the value observed in January may be less robust (or at least poorly representative of a mean monthly situation) since it is computed only with 3 data samples. Concerning the gliders, the peak-to-peak amplitude variation is ~25~~0~~% lower than for the ADCPs, with a minimum of ~-0.25 m/s in August/September and a maximum of -0.46 m/s in December. Since these instruments measure velocities at very close locations, the differences may be mainly due to ageostrophic currents. The Jason 2 climatology displays significantly different results with a series of maxima (~-0.46~~37~~ m/s in February and November) and minima (~-0.35~~27~~ m/s in May and October).

For~~To~~ further analysis~~ze these results~~, we consider~~ing~~ the dispersion of individual current values for each month (Fig. 5a,b, envelopes around the curves).~~;~~ W~~w~~e observe significantly different date-to-date variability for each month (between 0.03 and 0.15 m/s for the glider and ADCP, between 0.12 m/s and 0.20 m/s for the HF radar and between 0.08~~7~~ and 0.17~~016~~ m/s for altimetry). It indicates that the seasonal NC cycle observed in Fig. 5 is modulated by a strong mesoscale and/or year-to-year variability, and it seems to be especially true during intermediate seasons. The dispersion curve of Jason 2 generally follows the other ones except in July and September, when it shows large peaks of variability.

Deeper inspection in the corresponding current data set reveals that it is due to much larger NC amplitudes observed during these months in 2014 and 2015. The corresponding NC current intensifications are clearly observed in Fig. 4d in July and September 2014. Unfortunately, no glider transect is available during these periods (Fig. 4c) and we have only one ADCP section which does not show a NC flow increase (Fig. 4b). However, the HF radar currents (Fig. 4f) tend to support that the NC intensification captured by Jason 2 is realistic and not due to altimetry errors.~~ (note that o~~One profile of SARAL track 887 is available in July 2014 and ~~that~~ it observes the same feature, Fig. 4a~~)~~. Since we did not find evidence of summer NC intensification in the previous years, we decided to recompute the seasonal cycle of the NC amplitude using only the data available during the first 6 year-period of Jason-2 (i.e. 2008-2014). We did the same for the ADCPs and gliders, but very few glider data and no ADCP currents are available before 2010 (HF radar currents have not been considered because of the too short length of the time series). The resulting curves are shown in Fig. 5c and a clear seasonal cycle is now also observed in the climatology derived from Jason 2, with a summer/winter decrease/increase of the NC flow. Note that it is also coherent with the results of Birol et al. (2010) who used a combination of the T/P and Jason-1 altimeter missions to obtain a current time series over the 1993-2007 time period. The amplitudes of the seasonal variations computed during this new period of time are now around 0.29 m/s, 0.27 m/s ~~(i.e. close to the ones derived from Fig. 5a)~~ and 0.1~~3~~6 m/s for the ADCP, glider and

Jason2 altimetry data, respectively. Fig. 5c highlights that the summer velocities measured by the different instruments are relatively close on average. During winter and especially spring, the differences become significant in both amplitude and phase.

Two physical processes can explain the seasonality of the differences between the different types of current measurements. First, the stronger mesoscale variability associated to the NC during these seasons makes the space and time sampling of the current measurements a critical issue for the study of this current system. Second, the strong Tramontane and Mistral winds are more frequent in winter and are decreasing in amplitude from the Gulf of Lion to the Ligurian Sea. This could explain (i) that the differences between the glider and the ADCP current measurements, very close in location, are more important during winter and spring, when the non geostrophic dynamics (in particular the Ekman flow produced by the strong winds) is expected to be the more important and (ii) the strong currents observed by the HF radar in Toulon. The closest seasonal variations to the ones observed by altimetry are found for the glider. It is not surprising since the currents derivedfrom this instrument are also the closest in terms of physical content (see Sect. 2.2.d). The amplitude of the seasonal variations of the NC captured by the Jason2 track 222 along the French coast is ~55-60~~0~~% of the amplitude captured by the glider~~ (which i~~. It is a good result if we consider the spatial resolution of altimetry data and the width and very coastal location of this current).

3.3. Individual snapshots

To learn more about the similarities and differences between the currents derived from the different instruments, as well as their causes, we now analyze the observations at particular dates. In order to minimize, ~~(~~as far as possible,~~)~~ the differences due to distances in space and time between observations, we focus here on the region near Nice (i.e. on the ADCP and glider data, as well as on the SARAL track 887 and the Jason 2 track 222), and consider only observations that are close in time. For each day of the 2010-2016 study period, we used a time window for each data set (5 days for Jason 2, 10 days for the glider and ADCP data and 22 days for SARAL) and selected only the dates for which we had the four types of observations available. We obtained 7 cases which are reported in Table 3. The corresponding cross-track currents are shown in Fig. 6 (by season) as a function of the distance to the coast. For each case and each data set, we have computed the maximum NC current amplitude (following the same method than in Sect. 3.2) and the corresponding location (expressed in distance to the coast). The results are provided in Table 4.

Figure 6 highlights very different NC situations. Here, the largest coastal current velocities are observed in spring and not in winter as expected from Sect. 3.2. Case 1 (Fig. 6a), the only one in this season, shows (by far) the strongest NC amplitudes in ADCP and glider data (< -0.6 m/s), associated to a narrow flow located within the 30 km coastal band. It corresponds to a difficult study case for altimetry which is still able to depict the NC, but with a too large current vein which amplitude is less than half of what is observed in the in situ observations. Cases 2 and 4 (Fig. 6b,c) are in summer. The NC is broader and its velocity is around -0.3 m/s in all data sets (except in the glider of case 4, see below). This time, altimetry successfully captures the NC amplitude; the location of its core is also good in case 4 but not in case 2 (it is too far/close to the coast for SARAL~~/Jason 2~~). In case 4, altimetry and ADCP currents are very close but, for a reason which is unclear (it may be due to a a NC meander or eddy captured by the glider and not by the other instruments), the glider represents a significant slower flow located further south. Cases 5 and 6 (Fig. 6d,e) correspond both to autumn situations but they highlight very different coastal current patterns. In case 5, the glider and SARAL data (corresponding to the same day) are very coherent: they show a relatively weak NC flow (~-0.2 m/s) which core is ~30 km to the coast. Jason 2 observations (very close in time to SARAL and the glider data) show a larger current located slightly further south (~6 km). The ADCP represents a NC vein at the same location than in the glider and SARAL but with a much stronger amplitude. It could be due either to the differences in the dates of observations (one week, temporal scale at which meanders develop) or to an important ageostrophic NC component. In case 6, a lack of data for Jason 2 can be observed which lead to question the realism of the current estimates close to the coast ~~Jason 2 does not provide data close enough to the coast to observe the NC~~. However, the glider, the ADCP and SARAL data show a broad NC located further offshore than in the other cases (its core is located ~ 40 km offshore in ADCP and glider data). As in case 5, the glider and SARAL data provide NC amplitudes and location that are relatively close and the ADCP data give a larger NC maximum. A particular feature in this autumn situation is the succession of very strong and narrow southwestward and then northeastward flows observed in the first 20 km coastal band in both ADCP and glider currents (but not in SARAL which does not get close enough to the coast). It is probably associated to an eddy or meander sticked on the northern anticyclonic side of the NC (eddies were documented at this location in Casella et al., 2011). Finally, cases 3 and 7~~6~~ (Fig. 6f, g) correspond to winter situations and, as for the autumn, they are very different. In case 3, we observe a broad NC with a core located around 30 km to the coast. The glider exhibit current oscillations along its transect but all current data sets show a coherent representation of the NC, even if the ADCP data provide larger velocities. In case 7, the glider and ADCP capture a narrow NC located ~20 km off the coast also observed by altimetry but with some differences: in Jason 2 the NC flow is not entirely captured ~~flow is slightly broader~~ and in SARAL it is located further offshore. It may be due to rapid variations of the NC between the different dates of observations (12 days between the ADCP and SARAL).

Beyond the large variations of the NC characteristics from one case to the other, an interesting feature in Fig. 6 is the presence of an eastward flow located south of the NC (100-150 km to the coast) in altimetry data in different cases (cases 4, 5 and 6 in particular). The ADCP transect is too short to capture this current vein and it is not observed in the glider data (located further east compared to SARAL track 887 and Jason 2 track 222) which rather depict the WCC on the southern edge of its section. To our knowledge, the corresponding offshore eastward flow is not documented in the literature but its signature seems also be observed in Fig. 2a and 3a (around 42.5°N in SARAL, and around 42.8°N in Jason2). It will be further discussed in the section 3.5 ~~next section~~.

Finally, what is illustrated in Fig. 6 is that, because of the large short-term changes in the NC circulation system, each snapshot of observations differs significantly from the corresponding seasonal tendency. It highlights the strong interest of long-term and regular altimetry data to study the persistent components of the NC circulation system, as well as its seasonal variations and possible longer-term changes.

3.4 Can we improve the estimation of the NC characteristics with high-rate altimetry compared to 1-Hz data?

In this section we consider the improvement that is possible to obtain in terms of current derivation with the use of high-rate altimetry measurements, compared to the conventional 1-Hz data used above. But if research coastal altimetry products, calibrated and validated and covering different regions and missions, are now available at 1-Hz, it is not the case for high-rate altimetry products. Even if some studies have shown the better performance of 20/40-Hz altimeter measurements to observe the coastal circulation (Birol and Delebecque, 2014; Gomez-Enri et al., 2016) they are much noisier and no consensus exists yet concerning their (post-)processing. Here, we used an experimental version of high-rate X-TRACK SLA data for both Jason-2 and SARAL which original measurements are at 20-Hz and 40-Hz, respectively. Since a lot of erroneous data remained in the coastal area, we applied a 2-sigma filter on the resulting SLA fields along each individual track and cycle, in order to edit the data before filtering and then computation of the current estimates (section 2.1).

In order to analyze if we can expect a better observation and understanding of the NC hydrodynamics from high-rate altimetry measurements, they have been used to compute the same diagnostics than in sections 3.1, 3.2 and 3.3. Only the results for the individual snapshots will be illustrated here (Figure 7) since, even if the major difference with the current fields derived from 1-Hz altimetry is that the larger number of coastal data allows to estimate currents closer to the coast and then to better resolve the NC flow (see Figure 7), we did not find significant differences in the NC statistics (mean current and standard deviation values) and amplitude of the seasonal cycle computed from 20/40-Hz SLA, compared to the 1-Hz solutions.

In Figure 7, the same color code than in Figure 6 is used. For each case, the maximum NC current amplitude and corresponding location are reported in Table 4 for both SARAL and Jason-2 (as in section 3.3). In case 1 (Figure 7a), the gain obtained with the use of HF data is very clear. A this date the NC vein is narrow and located near the coast. Contrary to 1-Hz solution, the NC is better resolved by both SARAL and Jason-2 high-rate altimetry. It is especially true for SARAL with NC characteristics that are almost identical to the ones derived from the gliders. In Jason-2, the NC core is also close to the glider solution but its amplitude is ~35% lower. For cases 2 and 4 which correspond to the summer (Figure 7b and c), here again the use of high-rate altimetry allows a better observation of a NC vein but the agreement with in situ data is not so good. Concerning SARAL, for case 2, the current estimates are suspect since a reduction of the current intensity appears at the location of the NC core in the other datasets (Figure 7b). For case 4, SARAL NC amplitude is too high (0.55 m/s vs 0.16 m/s for the glider). Jason-2 high-rate NC estimates appear closer to the in situ data than SARAL for both cases 2 and 4 but the resulting NC characteristics do not appear better than the corresponding 1-Hz estimations, when compared to ADCP (Table 4). It probably reveals that the cut-off frequency chosen in the filtering is too low. Cases 5 and 6 (Figures 7 d and e) also show some very doubtful oscillations in both SARAL and Jason-2 currents and high-rate altimetry does not improve the NC estimations. In winter, the cases 3 and 7 (Figures 7g and f, respectively) are very different. In case 7, 20-Hz Jason 2 data depicts the entire NC with current estimates much closer to in situ data (especially the glider), compared to 1-Hz Jason-2 measurements. In case 7 they degrade / improve the NC representation (Figure 7g) if we refer to the glider / ADCP, respectively. Note that this case illustrates the difficulty of the calibration of altimetry data processing algorithms with independent observations since results may differ as a function of the independent observations used. Here, 40-Hz SARAL data show a too noisy current solution.

As already shown in previous work (Birol and Delebecque, 2014; Gomez-Enri et al., 2016), high-rate altimetry allows to derive significantly more sea level data near the coast. Here we observe that the coastal circulation derived is better resolved in space (i.e. both in horizontal resolution and in distance to the coast of the current estimates). But the resulting current fields depend crucially on the strategy followed for data processing (including both retracking and corrections), screening and filtering.

3.4. The seasonal variability of the regional surface circulation observed by altimetry

Here we use only 1-Hz altimetry data. In order to separate the seasonal component of the surface circulation from the mesoscale variations, along each pass of Jason 2 and SARAL located in the area of interest, we have computed a seasonal "climatology" of the cross-track surface geostrophic currents captured by these two altimetry missions (Fig. 8~~7~~). It was done by simply averaging the corresponding seasonal velocity values for the common 3-year period (April 2013 -April 2016). Note that this type of analysis can be already found in Birol et al. (2010) with a much longer period of altimetry data, but with Jason measurements only (the need to use multi-mission observations was incidentally pointed out in this study). Here, the combination with SARAL data largely improves the spatial resolution of the regional circulation, enabling to capture the main current veins at much more locations along their path (see Fig. 9 of Birol et al., 2010 for comparison).

In Fig. 8~~7~~, all the structures of the standard circulation scheme of the NW Mediterranean Sea (Fig. 1) are observed: the NC, the WCC, the Balearic Current, the Balearic Front and the TC. What can also be noticed first is the very good coherence and complementarity between the SARAL and Jason 2 climatologies, especially at crossover points (even if differences in the current captured are expected, due to the differences in the track's orientation). The seasonal variations of the regional circulation system already discussed in details in Birol et al. (2010) are confirmed from this different and shorter period of altimetry observations. In particular, if a stronger and unique southwestward flow is observed along the Italian, French and Spanish coasts from autumn to spring, it is not so clear during summer. During this season, the NC does not seem to continue west of 4°E to reach the Balearic Sea. Instead, it may recirculate eastward offshore Cape Creus.

More generally, compared to Birol et al. (2010), the better spatial coverage obtained by combining both SARAL and Jason 2 reveals a circulation scheme that could be much more complex than the one classically proposed in the literature. In summer and autumn (Fig. 8a,d), between 3Â°E and 9Â°E, individual eastward current veins are observed between the NC and the Balearic Front, suggesting that recirculations may exist along its path during these seasons. One of them corresponds to the eastward current branch mentioned in Sect. 3.3. Note however that this seasonal analysis is based only on 3 years of observations and could be biased by particular features occuring during 2015. Further investigation based on numerical modeling is clearly needed. This is the next step of this study. But, here again, altimetry appears clearly as a very good tool to first validate the model results.

4. Discussion and conclusion

The characteristics of the dynamics as well as the diverse arrays of in situ instrumentation in the NWMed offers the possibility to evaluate in details the complementarity between different types of measurements, ~~including the ones derived from space observations,~~ to monitor the coastal ocean circulation. ~~The NC system in particular is an interesting target since it is a permanent and coherent current system, associated to a large variability (in both space and time), regularly monitored by a variety of observation tools.~~ In this study, the systematic comparison of the NC characteristics~~ (using first statistics, focusing then on seasonal tendencies and finally on individual cases) derived from the different current data sets provide insights into the causes of their differences as well as into the biases in the NC estimations that these differences may cause. In this contribution, we have seen that t~~

The HF radars provide a good ~~synoptic and~~ daily view of the NC but only for a small area (60x40 km) and the slope current can be hidden by a strong Ekman component as they observe only the surface layer. The ship-mounted ADCP permits to see the vertical NC structure at very high resolution and up to the coast but the measurements may contain unsteady ageostrophic current components such as inertial oscillations (Petrenko et al., 2008). Since they can be operated on a routine basis only in a few number of places, we have only one regular section crossing the NC off the French coast (and it is relatively short). It is also the case of gliders which horizontal resolution and temporal sampling is lower than that of the ADCP and the HF radars but which provide much longer sections of observations (and also more generally the possibility to measure a large number of physical and biological ocean parameters). Alongtrack altimetry provides a reasonably good monitoring of surface currents in both space and time but its spatial resolution (section 2.1) does not allow to resolve all the mesoscale and sub-mesoscale signals associated to the NC. However, the missing NC component can be partly quantified using the other current observations. If we consider a reasonably long time series of observations including enough data samples for each instrument (see section 3.2), in the northern Ligurian Sea, the average NC value derived from altimetry is -0.3m/s and is coherent with the estimations derived from the other instruments. Concerning the amplitude of its seasonal variations, it is underestimated by ~40-45% compared to both the glider (closest instrument in terms of physical content of current estimations) and the ADCP (the highest resolution current data set). For individual dates this number varies a lot as a function of the distance to the coast and width of the NC (from a correct NC amplitude estimation to no NC observation). A quantification of the high frequency component of the coastal ocean dynamics that altimetry is able to capture would require data that are colocalized in both space and time.~~In this context, the added value of using all these different current measurements in conjunction appears clearly.~~

The present cross-comparison exercise allows to confirm that the standard 1-Hz along track altimetry products derived from Ku-band radars provide meaningful estimations of the NC (as already shown in Birol et al., 2010 and Birol and Delebecque, 2014). The new Ka-band SARAL altimeter data tend to give estimations of the NC characteristics that are closer to in situ data in a number of cases but its 35-day cycle is clearly a strong limitation for the study of this coastal current system. The use of 20-40Hz altimetry measurements improves significantly the number of near-coastal sea level data and then the resolution of the NC. However, the currents derived are still relatively noisy, meaning that their (post-)processing strategy is still at an experimental stage and needs to be improved.~~present day alongtrack altimetry products provide meaningful estimations of the NC (as already shown in Birol et al., 2010 and Birol and Delebecque, 2014). If the spatial resolution allowed by satellite altimeters limits the current component which can be captured, the missing variability can be quantified using the other current observations. If we consider a reasonably long time series of observations including enough data samples for each instrument (see Sect. 3.2), in the northern Ligurian Sea, the average NC value derived from altimetry (-0.3m/s) is coherent with the one derived from the other instruments. But the amplitude of its seasonal variations is underestimated by ~50% compared to both the glider (closest instrument in terms of physical content of current estimations) and the ADCP (the highest resolution current data set). It means that in this case the seasonal cycle of the non-geostrophic current component is very low. However, for individual dates this number varies alot as a function of the distance to the coast and width of the NC (from a correct NC amplitude estimation to no NC observation) but a quantification of the high frequency component of the coastal ocean dynamics that altimetry is able to capture would require data that are colocalized in both space and time. Compared to Jason 2, the SARAL altimeter data tend to give estimations of the NC characteristics that are closer to in situ data in a number of cases but its 35-day cycle is clearly a strong limitation for the study of this coastal current system. Despite this problem of spatial resolution, altimetry obviously provides a synoptic view of the circulation system and variability which helps to interpret the other current observations as well as analyze their limitations. It also reveals~~

~~features that are not (to our knowledge) documented in the literature and that are not (or poorly) captured by the currents derived from the other instruments. It is the case of possible NC recirculation branches and of the summer NC increase in 2014 and 2015.~~

Not surprisingly, one conclusion of this study is that the data resolution and sampling is clearly an issue to capture the large range of frequencies found in the NWMed coastal ocean (and we can easily assume that it is true for many other coastal ocean areas). In particular, the temporal data coverage is a large source of differences between the NC statistics computed from the different observing systems. A second cause of differences in the estimations of the NC characteristics appears to be due to ageostrophic flow, principally the Ekman and inertial currents, measured by the ADCP and HF radars but not represented in the glider (even if they are partially included through the correction of the depth-average currents) and altimeter-derived geostrophic currents. Clearly, a multi-data combined approach is the unique way to obtain a complete picture of a dynamical system as complex as the NC and altimetry is one component of the observing system needed.

Finally, it is important to note that improved altimetry data processing and corrections as well as technical innovations lead to an ever increasing number of coastal data ever closer to the coastline. It raises the question of the calibration and validation of these new data against independent in situ observations. How can we robustly quantify the evolution of the new processing and products? We benefit from the long experience of nadir altimetry technology, widely based on tide gauges sea level observations taken as an independent reference. However a full understanding and exploitation of the new performances allowed by the Ka-band, SAR and SAR-in altimetry techniques requires new methods and validation means. We advocate that only a combination of in situ instruments providing regular cross-shore informations along altimetry tracks will allow to understand and exploit the full capability of altimetry in coastal observing systems and guide its evolution. Beyond the case study presented here, such cross-comparison exercises between altimetry and different types of in situ observing systems allows to identify how they can be combined for advanced altimetry validation purposes.

Acknowledgements.

This study was done with the financial support of the Region Occitanie and the CNES through their PhD funding programs. The ship-mounted ADCP data were kindly provided by the DT-INSU who did the acquisition, management and processing. Altimetry data used in this study were developed, validated, and distributed by the CTOH/LEGOS, France.Glider data were collected and made freely available by the Coriolis project (http://www.coriolis.eu.org) and programs that contribute. We would like to acknowledge the staff of the French National Pool of Gliders (DT-INSU/CNRS - CETSM/Ifremer) for the sustained gliders deployments carried out in the framework of MOOSE. Support was provided by the French ‘‘Chantier Méditerranée’’ MISTRALS program (HyMeX and MERMeX components) and by the EU projects FP7 GROOM (grant agreement 284321), FP7 PERSEUS (grant agreement 287600), FP7 JERICO (grant agreement 262584), and the COST Action

ES0904 ‘‘EGO’’ (Everyone’s Gliding Observatories). HF radar data were funded as part of the French MOOSE Mediterranean observing system program.

References

Alberola, C., C. Millot, and J. Font. 1995. On the seasonal and mesoscale variabilities of the Northern Current during the PRIMO-0 experiment in the western Mediterranean-sea. *Oceanologica Acta*, 18(2):163–192,.

Astraldi, M., and G. P. Gasparini. 1992. The seasonal characteristics of the circulation in the north Mediterranean basin and their relationship with the atmospheric-climatic conditions. *Journal of Geophysical Research: Oceans*, 97(C6):9531–9540, https://doi.org/10.1029/92JC00114.

Birol, F., and C. Delebecque. 2014. Using high sampling rate (10/20Hz) altimeter data for the observation of coastal surface currents: A case study over the northwestern Mediterranean Sea. *Journal of Marine Systems*, 129:318–333, **https://doi.org/10.1016/j.jmarsys.2013.07.009**.

Birol, F. and F. Niño. 2015. Ku– and Ka-band Altimeter Data in the Northwestern Mediterranean Sea: Impact on the Observation of the Coastal Ocean Variability. Marine Geodesy, 38, 313-327, https://doi.org/10.1080/01490419.2015.1034814

Birol, F., M. Cancet, and C. Estournel. 2010. Aspects of the seasonal variability of the Northern Current (NW Mediterranean Sea) observed by altimetry. *Journal of Marine Systems*, 81(4):297–311, https://doi.org/10.1016/j.jmarsys.2010.01.005.

Birol, F., N. Fuller, F. Lyard, M. Cancet, F. Niño, C. Delebecque, S. Fleury, F. Toublanc, A. Melet, M. Saraceno, and F. Léger. 2017. Coastal applications from nadir altimetry: Example of the X-TRACK regional products. *Advances in Space Research*, 59(4):936–953, https://doi.org/10.1016/j.asr.2016.11.005.

Bonnefond, P., J. Verron, J. Aublanc, K. N. Babu, M. Bergé-Nguyen, M. Cancet, A. Chaudhary, J. F. Créteaux, F. Frappart, B. J. Haines, O. Laurain, A. Ollivier, J. C. Poisson, P. Prandi R. Sharma, P. Thibaut, C. Watson. 2018. The Benefits of the Ka-Band as Evidenced from the SARAL/AltiKa Altimetric Mission: Quality Assessment and Unique Characteristics of AltiKa Data. *Remote Sensing* 10 (83) , https://doi:10.3390/rs10010083

Bosse A., P. Testor, N. Mayot, L. Prieur, F. D'Ortenzio, L. Mortier, H. Le Goff, C. Gourcuff, L. Coppola, H. Lavigne, P. Raimbault. 2017. A submesoscale coherent vortex in the Ligurian Sea: From dynamical barriers to biological implications. *Journal of Geophysical Research: Oceans* 122(8) 6196-6217, https://doi:10.1002/2016JC012634

Bosse, A., P. Testor, L. Mortier, L. Prieur, V. Taillandier, F. d’Ortenzio, and L. Coppola. 2015. Spreading of Levantine Intermediate Waters by submesoscale coherent vortices in the northwestern Mediterranean Sea as observed with gliders. *Journal of Geophysical Research: Oceans*, 120(3):1599–1622, https://doi.org/10.1002/2014JC010263.

Bouffard, J., A. Pascual, S. Ruiz, Y. Faugère, and J. Tintoré. 2010. Coastal and mesoscale dynamics characterization using altimetry and gliders: A case study in the Balearic Sea. *Journal of Geophysical Research: Oceans*, 115(C10):C10029, https://doi.org/10.1029/2009JC006087.

Bouffard J., S. Vignudelli, P. Cipollini, Y. Menard. 2008. Exploiting the potential of an improved multimission altimetric data set over the coastal ocean. *Geophysical Research Letters*, 35(10). 10.1029/2008GL033488

Casella, E., A. Molcard, and A. Provenzale. 2011. Mesoscale vortices in the Ligurian Sea and their effect on coastal upwelling processes. *Journal of Marine Systems*, 88(1):12–19, https://doi.org/10.1016/j.jmarsys.2011.02.019.

Cipollini P., F. M. Calafat, S. Jevrejeva, A. Melet, P. Prandi. 2017. Monitoring Sea Level in the Coastal Zone with Satellite Altimetry and Tide Gauges. *Surveys in Geophysics* 38(1), 33-57

Cipollini P., J. Benveniste, F. Birol, J. Fernandes, E. Obligis, M. Passaro, P.T. Strub, P. Thibaut, G. Valladeau, S. Vignudelli and J. Wilkin, 2017b. Satellite altimetry in coastal regions. CRC Book, Chapter 12.

Crépon M., L. Wald, J. M. Monget. 1982. Low-frequency waves in the Ligurian Sea during December 1977. *Journal of Geophysical Research*. 87(C1) 595-600. 10.1029/JC087iC01p00595

Dufau C., M. Orsztynowicz, G. Dibarboure, R. Morrow, P. Y. Le Traon. 2016. Mesoscale resolution capability of altimetry: Present and future. *Journal of Geophysical Research: Oceans*, 121(7) 4910-4927 https://doi.org/10.1002/2015JC010904

Durand, F., F. Marin, J.-L. Fuda, and T. Terre. 2017. The East Caledonian Current: A Case Example for the Intercomparison between AltiKa and In Situ Measurements in a Boundary Current. *Marine Geodesy*, 40(1):1–22, https://doi.org/10.1080/01490419.2016.1258375.

Font J., E. Garcialadona, E. G. Gorriz. 1995. The seasonality of mesoscale motion in the northern current of the western Mediterranean – several years of evidence. Oceanologica Acta 18(2) 207-219

Gòmez-Enri, J., Cipollini, P., Passaro, M., Vignudelli, S., Tejedor, B., & Coca, J. 2016 Coastal Altimetry Products in the Strait of Gibraltar. IEEE Transactions on Geoscience and Remote Sensing, 54 (9), 5455-5466.

Gommenginger C., P. Thibaut, L Fenoglio-Marc, G. Quartly, X. Deng, J. Gomez-Enri, P. Challenor, Y. Gao. 2011. Retracking Altimeter Waveforms Near the Coasts. *Coastal Altimetry* 61-101

Guihou, K., J. Marmain, Y. Ourmières, A. Molcard, B. Zakardjian, and P. Forget. 2013. A case study of the mesoscale dynamics in the North-Western Mediterranean Sea: a combined data–model approach. *Ocean Dynamics*, 63(7):793–808, **https://doi.org/10.1007/s10236-013-0619-z**.

Herbert, G., N. Ayoub, P. Marsaleix, F. Lyard. 2011. Signature of the coastal circulation variability in altimetric data in the southern Bay of Biscay during winter and fall 2004. Journal of Marine Systems, 88 (2), 139-158, https://doi.org/10.1016/j.jmarsys.2011.03.004

Jébri F., F. Birol, B. Zakardjian, J. Bouffard, C. Sammari. 2016. Exploiting coastal altimetry to improve the surface circulation scheme over the central Mediterranean Sea. *Journal of Geophysical Research: Oceans* 121(7) 4888-4909, 10.1002/2016JC011961

Jébri F., B. Zakardjian, F. Birol, J. Bouffard, L. Jullion, C. Sammari. 2017. Interannual Variations of Surface Currents and Transports in the Sicily Channel Derived From Coastal Altimetry. *Journal of Geophysical Research: Oceans* 122(11) 8330-8353. 10.1002/2017JC012836

Lipa, B, Nyden, B. Ulman, D. S., & Terrill E. 2006. SeaSonde Radial Velocities: Derivation and Internal Consistency, IEEE Journal of Oceanic Engineering, vol. 31, 850-861.

Liu, Y., H. Kerkering, and R.H., Weisberg (Editors) 2015, Coastal Ocean Observing Systems, 461 PP., ISBN 978-0-12-802022-7, Elsevier (Academic Press), London, UK.

Millot, C. 1991. Mesoscale and seasonal variabilities of the circulation in the western Mediterranean. *Dynamics of Atmospheres and Oceans*, 15(3):179–214, **https://doi.org/10.1016/0377-0265(91)90020-G**.

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

Morrow, R., and P.-Y. Le Traon. 2012. Recent advances in observing mesoscale ocean dynamics with satellite altimetry. *Advances in Space Research*, 50(8):1062–1076, https://doi.org/10.1016/j.asr.2011.09.033.

Morrow, R., A. Carret, F. Birol, F. Nino, G. Valladeau, F. Boy, C. Bachelier, and B. Zakardjian. 2017. Observability of fine-scale ocean dynamics in the northwestern Mediterranean Sea. *Ocean Science*, 13(1):13–29, https://doi.org/10.5194/os-13-13-2017.

Niewiadomska, K., H. Claustre, L. Prieur, and F. d'Ortenzio. 2008. Submesoscale physical-biogeochemical coupling across the Ligurian current (northwestern Mediterranean) using a bio-optical glider. *Limnology and Oceanography*, 53(5):2210,.

Ourmières, Y., B. Zakardjian, K. Béranger, and C. Langlais. 2011. Assessment of a NEMO-based downscaling experiment for the North-Western Mediterranean region: Impacts on the Northern Current and comparison with ADCP data and altimetry products. *Ocean Modelling*, 39(3–4):386–404, https://doi.org/10.1016/j.ocemod.2011.06.002.

Pascual, A., A. Lana, C. Troupin, S. Ruiz, Y. Faugère, R. Escudier, and J. Tintoré. 2015. Assessing SARAL/AltiKa Data in the Coastal Zone: Comparisons with HF Radar Observations. *Marine Geodesy*, 38(sup1):260–276, https://doi.org/10.1080/01490419.2015.1019656.

~~Pascual A. and D. Gomis. 2003. Use of Surface Data to Estimate Geostrophic Transport. *Journal of Atmospheric and Oceanic Technology* 20, 912-926~~

Passaro M., P. Cipollini, S. Vignudelli, G. D. Quartly, H. M. Snaith. 2014. ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry. Remote Sensing of Environment, 145, 173-189

Passaro, M., S. Dinardo, G. D. Quartly, H. M. Snaith, J. Benveniste, P. Cipollini, B. Lucas. 2016. Cross-calibrating ALES Envisat and CryoSat-2 Delay–Doppler: A coastal altimetry study in the

Indonesian Seas. *Advances in Space Research* 58(3), 289-303, http://dx.doi.org/10.1016/j.asr.2016.04.011

Petrenko A., C. Dufau and C. Estournel, 2008. Barotropic eastward currents in the western Gulf of Lion, north-western Mediterranean Sea, during stratified conditions. *Journal of Marine Systems*, 74(1-2), 406-428.

Piterbarg, L., V. Taillandier, and A. Griffa. 2014. Investigating frontal variability from repeated glider transects in the Ligurian Current (North West Mediterranean Sea). *Journal of Marine Systems*, 129:381–395, **https://doi.org/10.1016/j.jmarsys.2013.08.003**.

Quentin C., Y. Barbin, L. Bellomo, P. Forget, J Gagelli., S. Grosdidier, C.-A. Guerin, K Guihou., J. Marmain, A. Molcard, B. Zakardjian, P. Guterman, K. Bernardet, 2013. HF radar in French Mediterranean Sea: an element of MOOSE Mediterranean Ocean Observing System on Environment. OCOSS'2013 Proceedings, vol. p.25-30, hal-00906439

Quentin C., Y. Barbin, L. Bellomo, P. Forget, D. Lallarino, J. Marmain, A. Molcard, B. Zakardjian, P.,Guterman, K. Bernardet, 2014. High Frequency Surface Wave Radar in the French Mediterranean Sea: an element of the Mediterranean Ocean Observing System for the Environment. In Buch E, Antoniou Y, Eparkhina D, Nolan G (Eds.), Operational Oceanography for Sustainable Blue Growth. Proceedings of the Seventh EuroGOOS International Conference. 28-30 October 2014, Lisbon, Portugal. ISBN 978-2-9601883-1-8

Rio, M.-H., A. Pascual, P.-M. Poulain, M. Menna, B. Barceló, and J. Tintoré. 2014. Computation of a new mean dynamic topography for the Mediterranean Sea from model outputs, altimeter measurements and oceanographic in situ data. *Ocean Sciences*, 10(4):731–744, https://doi.org/10.5194/os-10-731-2014.

Roblou L., J. Lamouroux, J. Bouffard, F. Lyard, M. Le Hénaff, A. Lombard, P. Marsaleix, P. De Mey, F. Birol. 2011. Post-processing altimeter data towards coastal applications and integration into coastal models. *Coastal Altimetry*, 217-246

Sammari, C., C. Millot, and L. Prieur. 1995. Aspects of Seasonal and Mesoscale Variabilities of the Northern Current in the Western Mediterranean-Sea Inferred from the PROLIG-2 and PROS-6 Experiments. *Deep-Sea Research Part I-Oceanographic Research Papers*, 42(6):893–917, **https://doi.org/10.1016/0967-0637(95)00031-Z**.

Sentchev A., Forget P., Fraunie P., 2017. Surface current dynamics under sea breeze conditions observed by simultaneous HF radar, ADCP and drifter measurements.

Taupier-Letage, I., and C. Millot. 1986. General hydrodynamical features in the Ligurian Sea inferred from the DYOME experiment. *Oceanologica Acta*, 9(2):119–131,.

Testor, P., A. Bosse, L. Houpert, F. Margirier, L. Mortier, H. Legoff, D. Dausse, M. Labaste, J. Karstensen, D. Hayes, A. Olita, A. Ribotti, K. Schroeder, J. Chiggiato, R. Onken, E. Heslop, B. Mourre, F. d'Ortenzio, N. Mayot, H. Lavigne, O. de Fommervault, L. Coppola, L. Prieur, V. Taillandier, XD. De Madron, F. Bourrin, G. Many, P. Damien, C. Estournel, P. Marsaleix, I. Taupier-Letage, P. Raimbault, R. Waldman, M. N. Bouin, H. Giordani, G. Caniaux, S. Somot, V. Ducrocq, P. Conan (2018). Multiscale observations of deep convection in the northwestern Mediterranean Sea during winter 2012–2013 using multiple platforms. *Journal of Geophysical Research: Oceans*, 123(3) 1745-1776. https://doi.org/10.1002/2016JC012671

Troupin, C., A. Pascual, G. Valladeau, I. Pujol, A. Lana, E. Heslop, S. Ruiz, M. Torner, N. Picot, and J. Tintoré. 2015. Illustration of the emerging capabilities of SARAL/AltiKa in the coastal zone using a multi-platform approach. *Advances in Space Research*, 55(1):51–59, https://doi.org/10.1016/j.asr.2014.09.011.

Valladeau, G., P. Thibaut, B. Picard, J. C. Poisson, N. Tran, N. Picot, A. Guillot. 2015. Using SARAL/AltiKa to improve Ka-band altimeter measurements for coastal zones, hydrology and ice: The PEACHI prototype. *Marine Geodesy*, 38(sup1), 124-142, http://dx.doi.org/10.1080/01490419.2015.1020176.

Verron, J., P. Bonnefond, L. Aouf, F. Birol, S. A. Bhowmick, S. Calmant, T. Conchy, J.-F. Crétaux, G. Dibarboure, A. K. Dubey, Y. Faugère, K. Guerreiro, P. K. Gupta, M. Hamon, F. Jebri, R. Kumar, R. Morrow, A. Pascual, M. I. Pujol, E. Rémy, F. Rémy, W. H. F. Smith, J. Tournadre, and O. Vergara. 2018. The benefits of the Ka-band as evidenced from SARAL/AltiKa altimetric mission. Part 2: scientific applications. 2018. *Remote Sensing* 10(2), 163 https://doi.org/10.3390/rs10020163

Xu, Y., and L.-L. Fu. 2012. The Effects of Altimeter Instrument Noise on the Estimation of the Wavenumber Spectrum of Sea Surface Height. *Journal of Physical Oceanography*, 42(12):2229–2233, https://doi.org/10.1175/JPO-D-12-0106.1.

Zakardjian Bruno, Quentin Céline. 2018. MOOSE HF radar daily averaged surface currents from MEDTLN site (Toulon NW Med). SEANOE. https://doi.org/10.17882/56500

Instrument	Physical content	Depth	Spatial resolution	Temporal resolution	First and last dates in the data record	Number of sections selected	Filtering
HF radars	Absolute surface current	surface	3 km	daily	May 2012 - September 2014	732	No
ADCP	Vertical section of absolute current	34 m chosen for this study	1.3 km	unevenly spaced : 1 day to 6 months between consecutive data	May 2010 - November 2016	134	No
Gliders	Vertical section of geostrophic current (baroclinic component above 1000 m + additional correction)	34 m chosen for this study	4 km	unevenly spaced : 1 day to 1 year between consecutive data	June 2010 - September 2016	173	15 km
Jason 2	Surface geostrophic current	Near surface	5.75 km	~ 10 days	January 2010 - October 2016	246	40 km
SARAL	Surface geostrophic current	Near surface	7.38 km	35 days	April 2013 - May 2016	34	35 km

Table 1: Main characteristics of the different current data sets used in this study.

Instrument	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
radars	62 (60)	56 (55)	62 (62)	60 (60)	93 (70)	90 (90)	93 (91)	93 (52)	90 (70)	62 (35)	60 (29)	62 (53)
ADCP	6 (3)	20 (11)	18 (5)	20 (10)	15 (8)	25 (9)	18 (11)	24 (15)	20 (12)	11 (6)	24 (15)	17 (8)
Gliders	6 (6)	20 (20)	12 (10)	12 (12)	10 (10)	28 (23)	26 (22)	14 (14)	10 (9)	17 (15)	17 (14)	20 (16)
Jason 2	22 (19)	20 (20)	21 (20)	20 (18)	21 (21)	21 (20)	22 (21)	22 (21)	20 (17)	19 (19)	18 (17)	19 (19)
Saral	3	3	2	3	4	4	2	2	3	3	3	2

Table 2: Number of data sample per month for each current dataset during the period 01/01/2010 - 31/12/2016. The number of data selected for the climatology computation is indicated in brackets.

	Date of observations				
	Glider	ADCP	SARAL altimetry (track 887)	Jason 2 altimetry (track 222)	Temporal window
Case 1 (Figure 6a): April 2013	11-13/04/2013	11/04/2013	14/04/2013	11/04/2013	4 days
Case 2 (Figure 6b): July 2013	12-14/07/2013	13/07/2013	28/07/2013	09/07/2013	20 days
Case 3 (Figure 6g): February 2015	6-15/02/2015	09/02/2015	08/02/2015	04/02/2015	12 days
Case 4 (Figure 6c): September 2015	18-26/09/2015	22/09/2015	06/09/2015	20/09/2015	21 days
Case 5 (Figure 6d): October 2015	06-11/10/2015	17/10/2015	11/10/2015	10/10/2015	12 days
Case 6 (Figure 6e): November 2015	13-21/11/2015	12/11/2015	15/11/2015	18/11/2015	10 days
Case 7 (Figure 6f): February 2016	1-9/02/2016	05/02/2016	24/01/2016	27/01/2016	17 days

Table 3: List of the cases of relative colocatisation in time between the glider, ADCP and atimetry current data, and corresponding dates of observations.

	Maximum NC value and distance to the coast of this maximum					
	Glider	ADCP	Saral altimetry (track 887)		Jason 2 altimetry (track 222)	
			1 Hz	40 Hz	1 Hz	20 Hz
Case 1	18 km -0.66 m/s	23 km -0.74 m/s	21 km -0.29m/s	19 km -0.66 m/s	19 km -0.34 m/s	22 km -0.42 m/s
Case 2	22 km -0.27 m/s	28 km -0.31 m/s	50 km -0.30 m/s	37 km -0.20 m/s	24 km -0.39 m/s	31 km -0.41 m/s
Case 3	30 km -0.30 m/s	33 km -0.51 m/s	29 km -0.26 m/s	50 km -0.34 m/s	24 km -0.34 m/s	24 km -0.41 m/s
Case 4	42km -0.16 m/s	18 km -0.28 m/s	21 km -0.31 m/s	17 km -0.55 m/s	19 km -0.37 m/s	23 km -0.35 m/s
Case 5	23 km -0.22 m/s	26 km -0.42 m/s	21 km -0.23 m/s	43 km -0.33 m/s	30 km -0.53 m/s	31 km -0.49 m/s
Case 6	30 km -0.25 m/s	39 km -0.40 m/s	29 km -0.26 m/s	25 km -0.34 m/s	19 km -0.26 m/s	23 km -0.62 m/s
Case 7	14 km -0.30 m/s	16 km -0.42 m/s	43 km -0.44 m/s	46 km -0.28 m/s	10 km -0.54 m/s	15 km -0.37 m/s

Table 4: Maximum NC current value deduced from the glider, ADCP and atimetry current data for the 7 individual cases listed in Table 3.

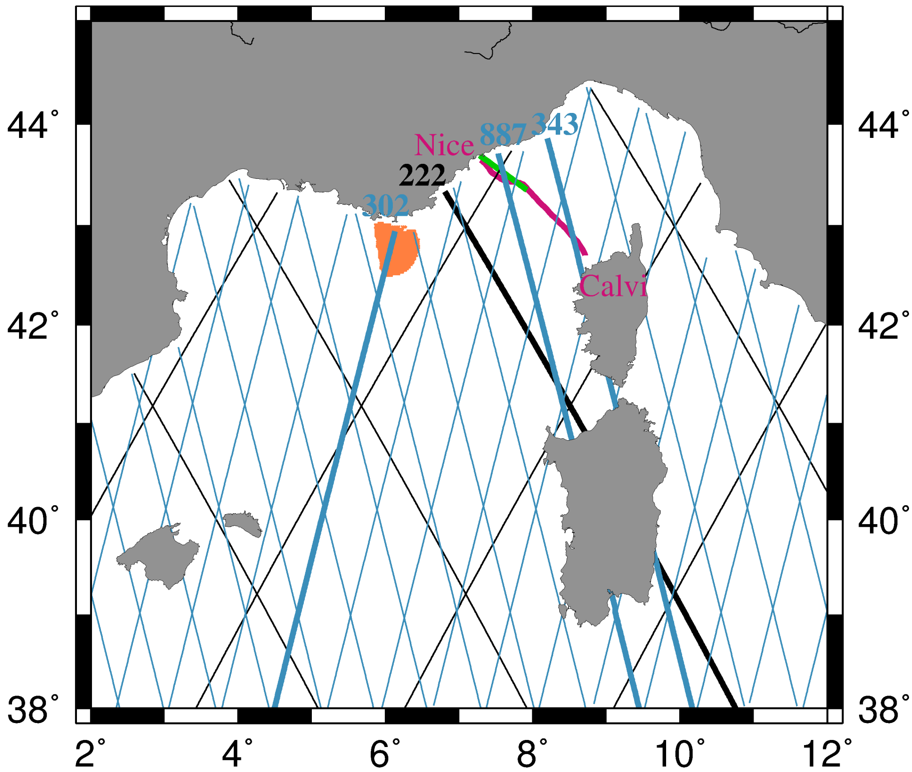


Figure 5: Study area and data distribution. Jason 2 and SARAL tracks in the study area are represented by the black and blue lines, respectively. The satellite tracks used in the study are indicated in bold. The green region corresponds to the HF radar coverage. The Nice-Calvi glider line is in pink and the Thetys ADCP transect is in yellow. A map of the schematic regional circulation is presented at the upper left hand corner.

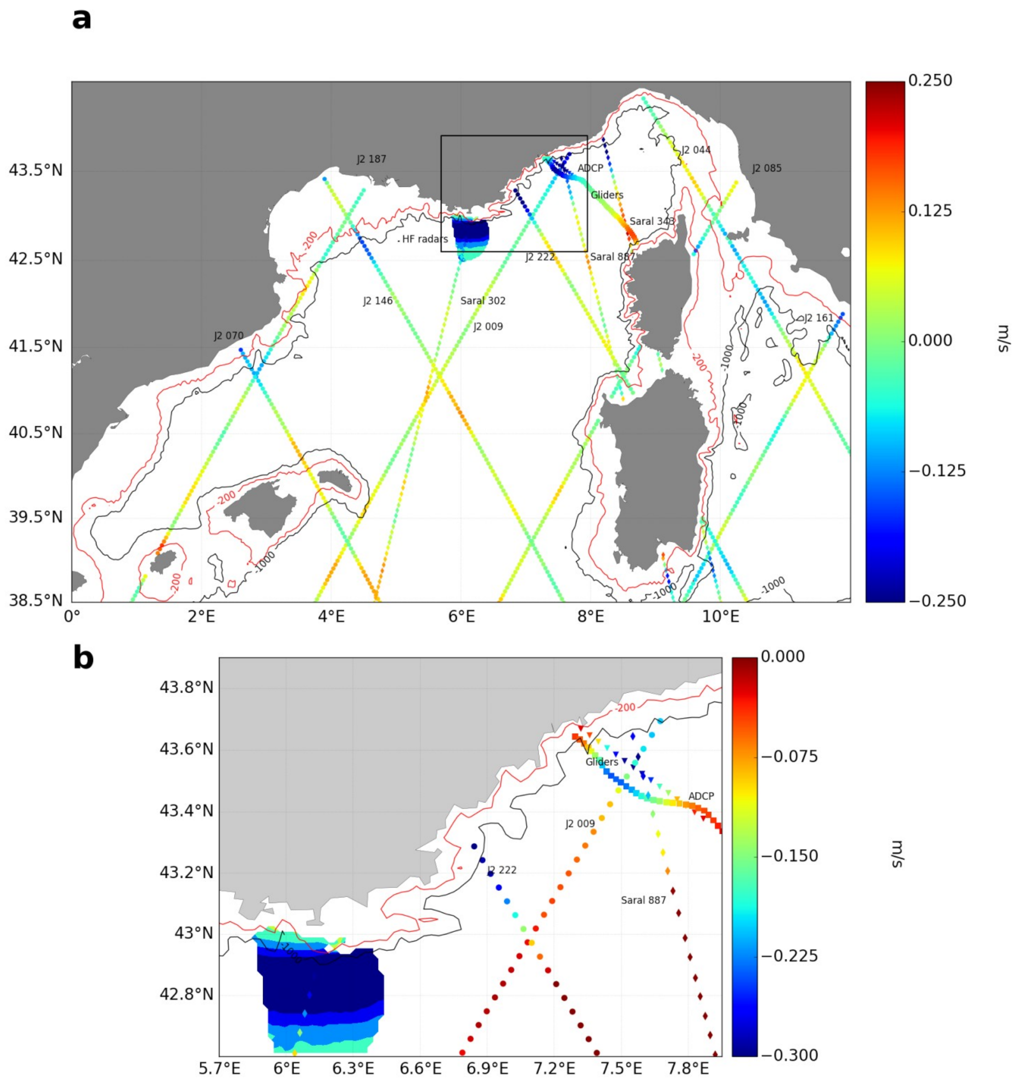


Figure 6: a) Map of the mean current values derived from ADCP, glider, HF radar and altimetry data over the period 03/2013 – 10/2014. b) Zoom in the northern Ligurian Sea (black rectangle indicated in Figure 2a). The 200-m (red line) and 1000-m (black line) are also shown.

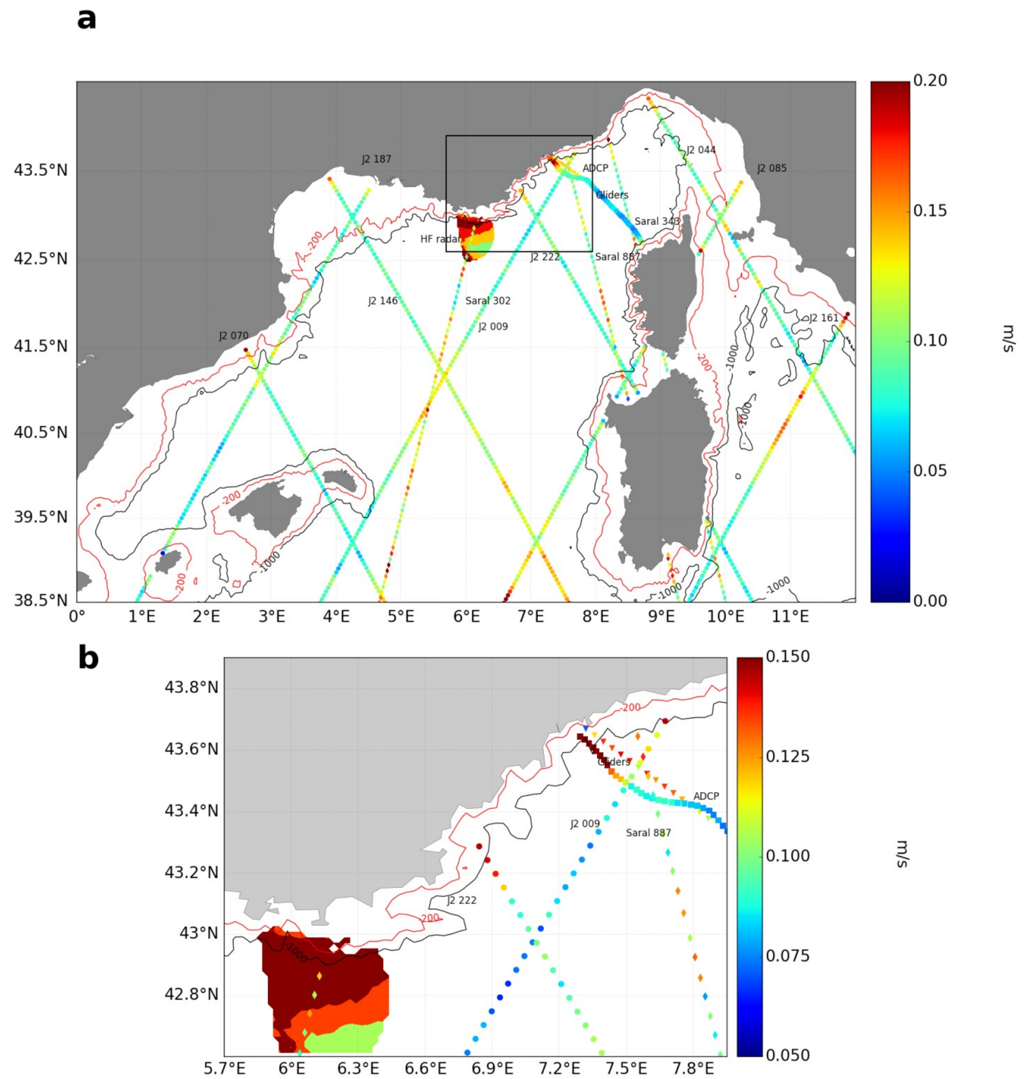


Figure 7: a) Map of the standard deviations of the velocities derived from ADCP, glider, HF radar and altimetry data over the period 03/2013 – 10/2014. b) Zoom in the northern Ligurian Sea (black rectangle indicated in Figure 3a). The 200-m (red line) and 1000-m (black line) are also shown

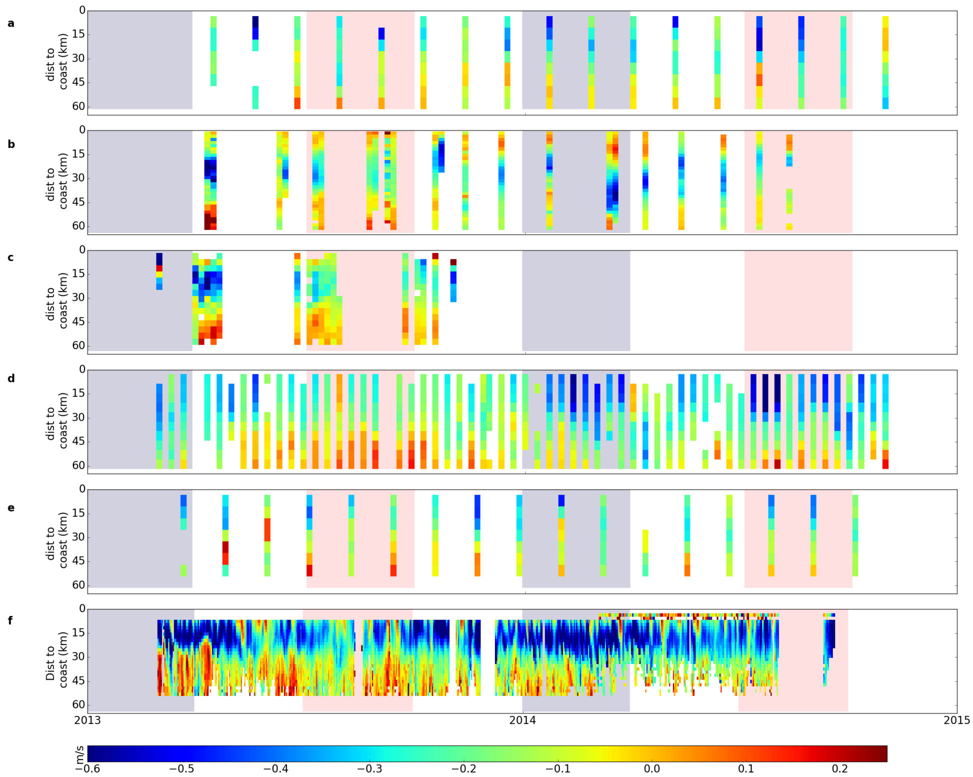


Figure 8: Time-space diagrams of the current velocities derived from a) SARAL track 887 b) ADCP, c) Gliders, d) Jason 2 track 222, e) SARAL track 302 and f) HF radars between March 2013 and October 2014. The pink and purple areas in the background of the diagrams correspond to the summer and winter seasons, respectively.

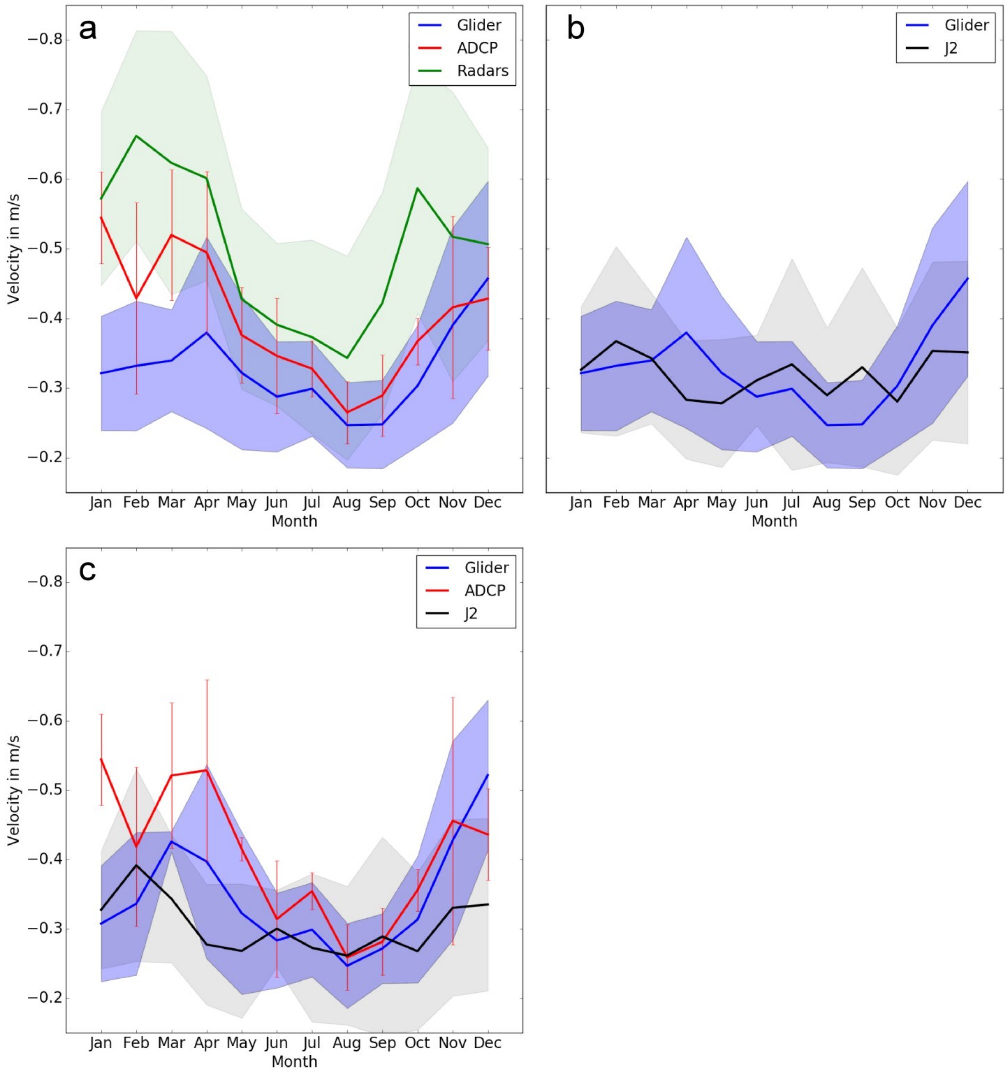


Figure 9:Seasonal variations of the maximum current amplitude derived from the a) HF radars (green line), ADCP (red line), gliders (blue line), and b) Jason 2 (black line) and glider (blue line) observations available over the period 01/01/2010 - 31/12/2016. c) Same than a) and b) but computed over the period July 2008 to June 2014 and only for the gliders, ADCP and Jason 2. For all the curves the monthly standard deviation of the maximum current amplitude derived from the corresponding instrument is also indicated (curve envelopes and error bars).

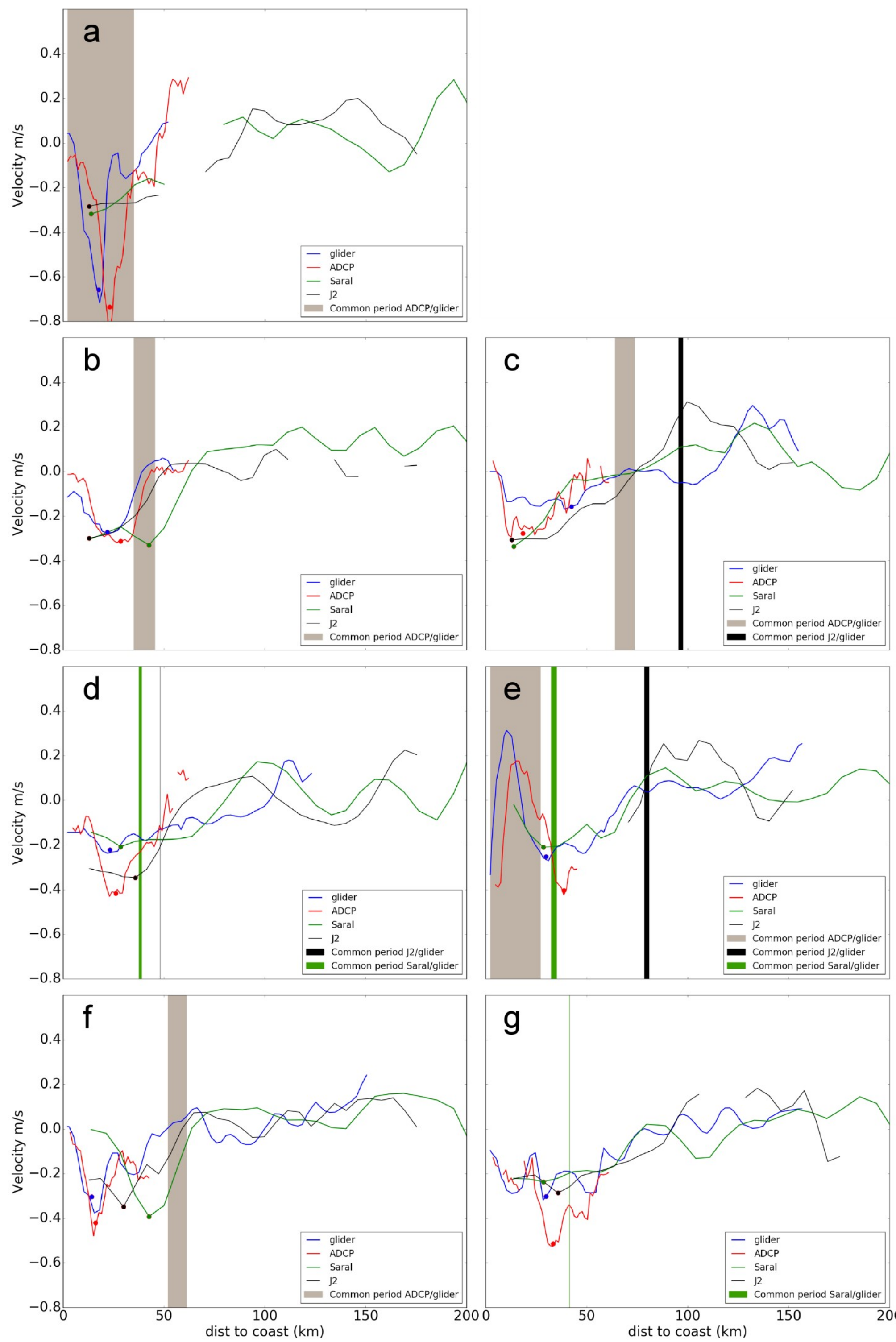


Figure 10: Cross-shore sections of currents deduced from the glider (blue), ADCP (red), SARAL (green) and J2 (black) altimetry data for the 7 individual cases identified in Table 3. Overlapping periods between the different observations are also indicated.

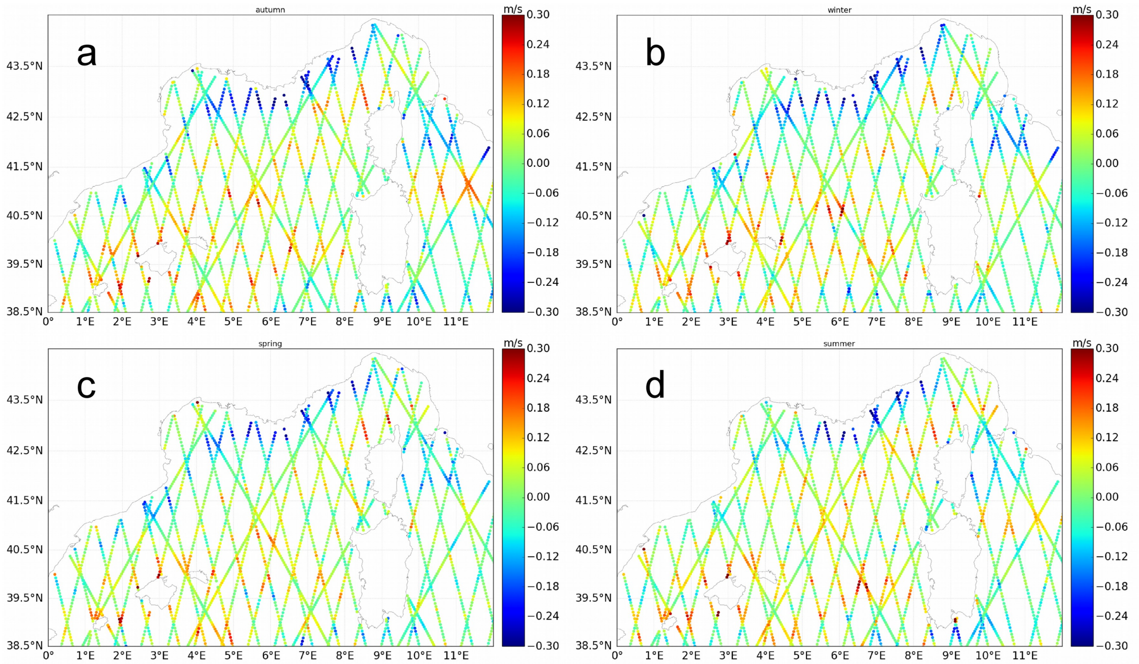


Figure 11: Seasonal climatology maps of cross-track geostrophic currents (in m/s) derived from Jason 2 and SARAL/AltiKa altimeter data over the period April 2013 – April 2016.