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1. Introduction

The calibration and validation of the altimeter sea level is usually performed by internal assessment of the mission and via inter comparison with other altimeter missions. The comparison with in-situ measurements is fundamental since it provides an external and independant reference. This document is the synthesis report for 2015 concerning altimeter and in-situ validation activities which aims at comparing altimeter data with temperature and salinity (T/S) profiles provided by lagrangian floats of the ARGO network. This activity is supported by CNES in the frame of the SALP contract for all altimeter missions. The method uses results of a study made at CLS in the frame of an IFREMER / Coriolis contract. In 2014 and 2015, some studies have been performed in the context of the Euro-Argo Improvements for the GMES Marine Services (E-AIMS) projects (sensitivity of the altimetry quality assessment to the Argo dataset).

Three objectives are achieved with the comparison of altimetry with the in-situ T/S profiles:

- To detect potential anomalies (jumps or drifts) in altimeter sea level measurements which can not be detected by comparison with other altimetric missions.
- To evaluate the quality of altimeter measurements and the improvement provided by new altimeter standards in the computation of sea level anomalies (geophysical corrections, new orbit solutions, retracking,...).
- To detect potential anomalies in in-situ data and estimate their quality.

Argo T/S profiles constitute a complementary dataset to tide gauges measurements. Indeed, although the temporal sampling is reduced (10-day profiles for a single float and hourly measurements for tide gauges), the spatial coverage of the Argo network is much larger since the global open ocean is almost completely sampled. Several results obtained through this activity are made robust thanks to the cross comparisons with several types of in-situ datasets (T/S profiles and tide gauges), which increases the quality assessment of altimeter measurements. In addition, the comparison with external and independant data enables us to contribute to the improvement of the error characterization of altimetry measurements, and especially at climate scales (Ablain et al., 2012, [1] and Ablain et al., 2015, [2]).

The results obtained with our method over the last couple of years have been published (under review) in a scientific journal (Legeais et al., 2016, Ocean Science, [6]), which constitutes a large part of this annual report. In this paper, altimeter validation activities are first illustrated with examples, showing that the method has been successfully used to detect altimeter drift and to estimate the impact of new altimeter standards (GDR-E orbit solution) or a new altimeter L4 product (SL_cci and AVISO products). The analyses provided in the examples focus on the long-term evolution of the mean sea level but also its variability, at global and regional scales with results obtained via relative and absolute comparisons thanks to the addition of the ocean mass contribution to the sea level. However, the differences between two versions of altimeter standards are getting smaller and smaller and their impact is thus more difficult to detect. It is therefore essential to characterize the errors of the method, which is illustrated in the paper with the results of sensitivity analyses to different parameters: filtering of altimeter data and collocation method but also the impact of the temporal reference period, of the ocean mass dataset, the temporal and spatial sampling of the Argo floats, the reference level of integration of the Argo profiles and the impact of the deep steric contribution. Again, different signals are addressed through these sensitivity analyses, separating the analyses of the long-term evolution of the mean sea level and its variability, at global and regional

scales and results obtained via relative and absolute comparisons with the independent dataset. This provides an estimation of the robustness of the method and the characterization of associated errors.

In addition of these published results, other analyses have been performed related to the better characterization of the uncertainty of the method and to specific analyses:

- A sensitivity analysis is performed regarding the GRACE dataset used to estimate the altimeter drift and the impact of the leakage of the continental signal on the ocean signal.
- As mentioned in the article, altimeter SLA and in-situ DHA must be anomalies over the same temporal reference and the impact of this common reference is illustrated.
- The independent Argo measurements are used to assess whether the SARAL/AltiKa mission has similar performances as Jason-2 mission.
- A new pole tide altimeter correction has been recently available and its impact on the altimeter sea level estimation compared with the reference one has been analyzed using the Argo in-situ data as a reference.

**2. "Analyses of altimetry errors using Argo and GRACE data"
(Ocean Sci., 2016)**

1 **Analyses of altimetry errors using Argo and GRACE data**

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6 **Abstract.**

7 This study presents the evaluation of the performances of satellite altimeter missions by comparing the altimeter
8 sea surface heights with in-situ dynamic heights derived from vertical temperature and salinity profiles measured
9 by Argo floats. This external assessment method contributes to altimeter Calibration and Validation analyses that
10 cover a wide range of activities. Among them, our approach focuses on the detection of altimeter drift and the
11 estimation of the impact of new altimeter standards that requires an independent reference. The methodology and
12 the Argo data used are first described and altimeter validation activities are then illustrated with some examples,
13 separating the analyses of the long-term evolution of the mean sea level and its variability, at global and regional
14 scales and results obtained via relative and absolute comparisons. The latter requires the use of the ocean mass
15 contribution to the sea level derived from GRACE measurements. Our analyses are related to different subjects
16 ranging from the estimation of the global mean sea level trend to the validation of multi-missions altimeter
17 products as well as the assessment of orbit solutions.

18 Even if this approach contributes to the altimeter quality assessment, the differences between two versions of
19 altimeter standards are getting smaller and smaller and it is thus more difficult to detect their impact. It is
20 therefore essential to characterize the errors of the method, which is illustrated with the results of sensitivity
21 analyses to different parameters. This provides an estimation of the robustness of the method and the
22 characterization of associated errors. The results also allow us to draw some recommendations to the Argo
23 community regarding the maintenance of the in-situ network.

1 **1 Introduction**

2 Since the early 1990s, several satellite missions have been equipped with altimeters allowing the estimation of
3 Sea Level Anomalies (SLA) and the monitoring of the Mean Sea Level (MSL). This contributes to understand
4 the role of the ocean in the Earth system and to assess the link with the global climate change. Altimeters are
5 available onboard several missions currently on flight (Jason-2, SARAL/AltiKa, CryoSat-2, HY-2A) and
6 providing no data anymore (TOPEX/Poseidon-T/P-, ERS-1&2, Jason-1, Envisat, Geosat Follow-On). Although
7 sea level estimates are becoming more precise, there are still some uncertainties which can be distinguished at
8 different temporal scales (long-term trend, inter annual signals and periodic signals) both at global and regional
9 scales (Ablain et al., 2015). The major sources of errors are attributed to orbit solutions, instrumental corrections
10 and some geophysical altimeter corrections such as the wet troposphere correction (Ablain et al., 2009, Couhert
11 et al., 2014; Legeais et al., 2014; Rudenko et al., 2014).

12 Quality assessment of altimeter data can be performed thanks to internal comparisons (analyses of performances
13 at crossovers points between ascending and descending tracks) and multi-mission cross calibration. A third
14 approach is to compare with independent in-situ measurements. Tide gauges are commonly used (Mitchum
15 1998, 2000; Nerem et al. 2010; Arnault et al. 2011; Bonnefond et al. 2003, Valladeau et al., 2012) but even if
16 they provide high temporal resolution measurements, the drawback is that only coastal areas are sampled and the
17 instruments are not homogeneously distributed over the coasts (hemispheric bias).

18 In this study, we use Dynamic Height Anomalies (DHA) derived from the Temperature and Salinity (T/S)
19 vertical profiles of the Argo network. The lagrangian profiling floats provide an almost global coverage of the
20 open ocean with measurements from the surface to around 2,000 dbar for most of them and the objective of a
21 global network of 3,000 operating floats has been achieved in 2007 (Roemmich and Team, 2009). The
22 consistency between these in-situ measurements and altimeter SLA has already been discussed (Guinehut et al.,
23 2006; Dhomps et al., 2011, Valladeau et al., 2012), showing that Argo DHA can be used as a reference (i) to
24 detect drifts and jumps in the altimeter sea level time series to enable an assessment of the global and regional
25 MSL trend and (ii) to assess the potential improvement provided by a new altimeter standard (e.g., orbit solution,
26 geophysical corrections) in the altimeter SLA estimation. Argo data is thus a valuable tool to assess altimeter
27 performances. However, the evolutions provided by the new algorithms allowing the sea level calculation (orbit
28 solution, instrumental corrections, geophysical corrections, mean sea surface) become more and more difficult to
29 assess (Stammer et al., 2014; Fernandes et al., 2015; Couhert et al., 2014). Hence, it is essential to determine to
30 which extent the comparison with Argo independent measurements can be used to contribute to the quality
31 assessment of these new algorithms and thus to better characterize the remaining errors of the method of
32 comparison and its sensitivity to the various parameters. The paper is organized as follow: the different datasets
33 used in our study are presented in section 2 and the details of the method of comparison of altimeter with in-situ
34 measurements are given in section 3. Some examples of altimeter validation thanks to Argo data are presented in
35 section 4 and section 5 is dedicated to the presentation of the sensitivity analyses of the method to various
36 parameters. At last, concluding remarks are provided on the method uncertainty and the results also allow us to
37 draw some recommendations for the Argo community regarding the maintenance of the in-situ network.

38 **2 Datasets**

39 **2.1 Altimetry**

1 Radar altimeters provide sea Surface height measurements which need to be referenced and corrected from
2 geophysical signals to determine SLA which can be compared with in-situ measurements. Along-track level 2
3 SSH from several satellite altimeters are used, where standards are updated compared with the geophysical Data
4 Record (GDR) altimeter products. Details of the SSH computation and time period for each altimeter are
5 available in the MSL part of the AVISO website ([http://www.aviso.oceanobs.com/en/news/ocean-
6 indicators/mean-sea-level/processing-corrections/](http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/processing-corrections/)). Sea Level Anomalies (SLA) of all altimeter missions are
7 computed with a reference to the Mean Sea surface (MSS) CNES/CLS11 model (Schaeffer et al., 2012). Grids of
8 merged altimeter products (level 4) are also compared with in-situ data.

9 **2.2 Argo**

10 In this study, we use delayed mode and real time quality-controlled T/S profiles (Guinehut et al., 2009) from the
11 Coriolis Global Data Assembly Center (www.coriolis.eu.org). Following Roemmich and Gilson (2009),
12 considering a threshold of two thirds of the surface of the global open ocean covered by Argo floats, analyses
13 should be performed with in-situ data dating only from 2005 onwards. This is a relevant reference for the latest
14 altimeter missions (Envisat, Jason-1, Jason-2 and SARAL-AIka) and results in an in-situ dataset of more than
15 10,000 floats with about 900,000 T/S profiles distributed over almost the whole open ocean. Dynamic Height
16 Anomalies (DHA) are then computed from the integration of the vertical density profiles using a reference depth
17 and a synthetic mean dynamic height. The choice of the reference level is discussed in this paper.

18 **2.3 GRACE**

19 Altimeter measurements are representative of the total elevation of the sea surface (surface to bottom), that
20 includes barotropic and baroclinic components, whereas DHA from profiling floats are representative of the
21 steric elevation associated with the thermohaline expansion of the water column from the surface to the reference
22 level of integration (i.e. baroclinic component) (Dhomps et al., 2011). However, the relative comparison between
23 altimeter SLA and in-situ DHA may be sufficient to detect an anomaly between two different missions or the
24 impact of a new altimeter standard in the SLA calculation. The analysis of the absolute altimeter drift and bias
25 requires the addition of the mass contribution to the Argo dataset so that similar physical contents can be
26 compared. This ocean mass contribution is derived from the Gravity Recovery and Climate Experiment
27 (GRACE) satellite mission. It provides a series of Earth gravity fields in the form of truncated sets of spherical
28 harmonic (Stokes) coefficients at approximately monthly intervals (Tapley et al., 2004) whose temporal
29 variations can be used to estimate changes in the ocean mass distribution. In this study, two solutions are used.
30 The monthly grids of equivalent water height from the Groupe de Recherche en Geodesie Spatiale (GRGS
31 RL03; Biancale et al., 2014). When discussing the global altimeter performances, the temporal evolution of the
32 global mean ocean mass contribution from GRACE RL05 is also used, as proposed by the University of South
33 Florida – Satellite Oceanography Laboratory (available at:
34 <http://xena.marine.usf.edu/~chambers/SatLab/Home.html>, last access: July 9th 2014) and described in Johnson
35 and Chambers, 2013.

36 **3 Method**

37 The comparison of the altimeter SLA from a single mission is based on the along-track sea level measurements.
38 As the altimeter sampling is better than the in-situ coverage (offering a global coverage of the ocean –for Jasons
39 missions– versus a single T/S profile every ten days), grids of 10-day averaged along-track SLA are interpolated
40 for each altimeter mission at the location and time of each T/S profile (bi-linearly in space and linearly in time).

1 Similarly, the quality assessment of gridded merged SLA altimeter products (L4) can be estimated after
2 collocation with the in-situ profiles.

3 In addition, the in-situ DHA are referenced to a synthetic mean Argo dynamic height calculated over the period
4 2003 to 2014. It is critical that altimeter SLA is compared relative to the same temporal reference. It affects the
5 global correlation and the regional trend differences between both types of data (see example in the paper). This
6 is performed by removing the mean of AVISO SSALTO/DUACS SLA maps for 2003-2014 (AVISO Handbook,
7 2014) from each altimeter measurements.

8 In order to improve the correlation between both types of data (and thus increase our confidence in the results),
9 outliers (corresponding to differences between altimeter SLA and in-situ DHA greater than 0.20 m) are filtered
10 out. All associated measurements are located in regions of high ocean variability, indicating that our method of
11 collocation leads to an increased error of the results in these regions. This validation step contributes to reduce
12 this error and improves the accuracy of the method. Global and regional statistics on the sea level differences are
13 then generated and various diagnoses are produced from these statistics in order to detect potential anomalies in
14 altimeter data.

15 For global analyses (trends, inter-annual and annual signals), an alternative method of comparison consists in
16 computing global mean time series of altimeter SLA and Argo DHA with the same temporal sampling and then
17 subtract the time series. This approach is discussed further in the paper.

18 **4 Altimeter Sea Level Validation**

19 In this section, the usefulness of the altimeter comparison with Argo floats is described with some examples. For
20 each of them, different spatial and temporal scales are addressed among the following via relative or absolute
21 comparisons (without or with the ocean mass contribution): the long-term evolution of the mean sea level or its
22 variability at global or regional scales.

23 **4.1 Detection of global altimeter drifts**

24 At global scale, the MSL trends of the Envisat and Jason-1 missions differ by 1.0 mm/yr over the period 2004-
25 2011 (Prandi et al., 2013). The absolute comparison of both altimeter MSLs with Argo and GRACE
26 measurements indicates that the MSL drift is greater for the Envisat than Jason-1 mission with a 1.4 mm/yr
27 difference (Fig. 1). The altimeter comparison with tide gauges measurements over the same period highlights a
28 0.9 mm/yr difference (Prandi et al., 2013) which confirms the greater drift of the Envisat mission. Thus the
29 combination of different types of in-situ data allow to detect and identify the origin of global altimeter MSL
30 trend discrepancy between two missions that cannot be addressed by internal comparison only. This Envisat drift
31 is well known and has been related with the altimeter standards and instrumental corrections used for the
32 estimation of the Envisat sea level (Ollivier et al., 2012). This is no more observed with the use of the Envisat
33 reprocessed measurements which have made both altimeter trends more homogeneous.

34 **4.2 Detection of the impact of new altimeter standards**

35 The Argo steric heights are used as a reference in order to estimate the impact of new altimeter standards used
36 for the altimeter sea level calculation. For instance, the use of the GDR-D orbit solution leads to a regional
37 East/West hemispheric bias in the spatial distribution of the Jason-1 MSL trends (Legeais et al., 2015). As Argo
38 measurements are considered to be free of this regional anomaly, the relative comparison of the MSL trends
39 differences between SLA and DHA (computed in two different East/West regions where the greatest differences
40 are observed) illustrate the strong regional discrepancy obtained with the GDR-D orbit solution (Figure 2a: 2.3

1 mm/yr). The in-situ Argo network is used to assess the impact of the updated GDR-E orbit standard in the Jason-
2 1 MSL calculation. The significant reduction of the hemispheric trend differences (Figure 2b, right: 0.1 mm/yr)
3 proves that the estimation of the altimeter SLA is improved with this new altimeter standard since the regional
4 discrepancies of the MSL trends are reduced. As discussed in Valladeau et al, 2012, the global Argo
5 measurements are the only in-situ external reference that allows us to discriminate such an impact regarding the
6 altimeter MSL.

7 **4.3 Detection of the impact of new altimeter products**

8 The independent Argo sea level estimations can also be used at global scale to distinguish two different altimeter
9 L4 merged products by relative comparison in terms of MSL variability. The Sea Level Climate Change
10 Initiative (SL_cci) project has provided climate-oriented Sea Level products (Cazenave et al., 2014; Ablain et al.,
11 2015) and we are interested in characterizing the differences between the SL_cci v1.1 ECV product and the 2014
12 SSALTO/DUACS time series (AVISO Handbook, 2014; Pujol et al., 2015). In order to isolate specific signals
13 and better discriminate the datasets, different frequencies of the differences between altimeter SLA and in-situ
14 DHA are distinguished. The correlation and the standard deviation of these differences are estimated over the
15 global ocean at different temporal scales. This is illustrated on Figure 3 using the SL_cci (triangles) and
16 SSALTO/DUACS 2014 (circles) products, thanks to the Taylor diagram formalism (Taylor, 2001). Such
17 diagram provides a way of graphically summarizing how closely different patterns match observations (in-situ
18 data: gray dot on the bottom axis). The similarity between two patterns is quantified in terms of their correlation,
19 their centered root-mean-square difference and the ratio of their variances. The statistics are indicated for the
20 total signals (in black) but also for the annual cycle (in green), high frequencies (in red) and inter annual signals
21 (in blue). The very high correlation (0.98) found between altimetry and in-situ data for the annual cycle only (in
22 green) indicates that this signal is at the origin of most of the similarities between both types of data, showing
23 that it is necessary to remove these annual variations before analyzing other frequencies. This Taylor diagram
24 reveals that both altimeter products cannot be significantly distinguished regarding the total signals (in black),
25 their annual cycle (in green) and their high frequencies (in red). At low frequencies (in blue), the SL_cci product
26 (triangle) is more in agreement with in-situ data than the SSALTO/DUACS product (circle) which is in favor of
27 a product dedicated to climate studies. However, the correlations of each altimeter data with the in-situ reference
28 are similar.

29 Furthermore, the validation of the reprocessed AVISO/DUACS 2014 products (AVISO Handbook, 2014) has
30 shown that the differences with the previous release of this product (AVISO/DUACS 2010 reprocessing) are
31 sometimes reduced for some statistics (Pujol et al., 2015). The characterization of the differences between these
32 products by relative comparison with Argo data at regional scale in terms of variance differences between SLA
33 and DHA is an additional illustration of the asset of this independent in-situ reference. Figure 4 indicates that in
34 the Bay of Bengal, the variability of the altimeter SLA minus in-situ DHA differences is reduced (-1 cm^2) with
35 the use of the new altimeter release. The statistics in this area (Table 1) indicates that the reprocessed altimeter
36 dataset provides a slightly greater correlation and a reduced rms of the differences with the in-situ reference.
37 This indicates that the Argo in-situ measurements can be used to assess the impact of a new altimeter product at
38 regional scales even in a small area.

39 **5 Sensitivity of the method**

1 This section focuses on the determination of the errors of the method of comparison of altimetry with in-situ
2 Argo data and provides sensitivity analyses of the method to different parameters. For each analysis, the impact
3 of a parameter is estimated regarding the long-term evolution of the mean sea level or its variability at global or
4 regional scales. In the following, the term “error” is considered as a quantity that would be removed if it was
5 known whereas the term “uncertainty” is associated with the confidence that can be attributed to the estimation
6 of a given parameter.

7 **5.1 Format of altimeter data**

8 As presented earlier, the assessment of a single altimeter missions is based on the collocation of each in-situ
9 profile (linearly in space and time) with grids of 10-days box-averaged along-track SLA with boxes of 1° latitude
10 x 3° longitude in order to take into account the number of altimeter tracks per cycle and also the rather zonal
11 ocean circulation because of the Coriolis force associated with the rotating effect of the Earth. The sensitivity of
12 the method to this size of boxes is estimated by comparing the results with 1°x1° grids of along-track altimeter
13 SLA. The amplitude and phase of the annual signal of the SLA – DHA differences are not affected by this
14 change of box size, neither the trend of the differences (not shown).

15 The variance of the SLA-DHA differences is computed for the time series of each Argo floats, using
16 successively the two different sizes of boxes for altimetry. The histogram of the difference of these variances for
17 all Argo floats (Figure 5) provides a mean of +1,3 cm², which indicates that averaging along-track altimeter data
18 with 1°x3° boxes makes altimeter data more coherent with in-situ Argo observations. This processing is
19 therefore chosen for the comparisons.

20 **5.2 Error of collocation**

21 The variability of the SLA – DHA differences are larger in regions of high ocean variability since the collocation
22 of altimeter and in-situ measurements is performed by interpolation of 10 days box-averaged along-track SLA at
23 the position and time of each Argo profile. Hence, the time of two co-located altimeter and in-situ measurements
24 may not be strictly the same and the associated impact may be higher in areas of high ocean variability where the
25 ocean state may change significantly within less than 10 days. Note that this effect could be reduced by
26 computing maps of altimeter measurements by optimal interpolation. However, this is very time consuming
27 since a set of grids has to be computed for a specific mission as soon as the impact of a new altimeter standard
28 has to be evaluated.

29 In order to estimate the error of the method associated with these regions of high ocean variability, the
30 comparison of altimeter data with Argo measurements could be performed after removing areas where the ocean
31 variability is higher than a given threshold. In terms of spatial coverage, the lower this threshold, the larger areas
32 are removed. The detection of altimeter drift is not affected by the exclusion of areas of high ocean variability.
33 Indeed, the 2.07 mm/yr trend of the mean differences between SSALTO/DUACS and Argo DHA (900 dbar
34 reference) is not significantly changed when areas of ocean variability higher than 100 cm² are excluded (2.16
35 mm/yr). This will be confirmed with results described later in this paper regarding the sensitivity to the spatial
36 sampling of the Argo network. Figure 6 (left) illustrates that the lower the threshold on the ocean variability, the
37 larger areas are removed and thus, a lower number of observations is available. The right panel indicates that
38 when larger areas are removed, the correlation between altimeter SLA and Argo DHA gets lower and the rms of
39 the differences (expressed in percentage of the altimeter variance) increases. This suggests that the areas of large
40 ocean variability significantly contribute to the global statistics computed between altimetry and Argo data.

1 However, this does not allow us to determine whether an increased sampling of these regions by the Argo
2 network would improve the results of altimetry validation.

3 In addition, our study focuses on the altimeter quality assessment. In particular, the estimation of the global
4 altimeter MSL drift is not considered to be significantly affected by the fact that some regions of the ocean are
5 not covered by the Argo network (e.g. the Indonesian throughflow, the Gulf of Mexico). The steric contributions
6 of such regions may be of importance for sea level closure budget studies (Dieng et al., 2015b), but similarly
7 with comparisons to tide gauges, they do not prevent from estimating the global MSL evolution.

8 **5.3 Impact of the temporal reference period**

9 When comparing both types of data, altimeter SLA and in-situ DHA should have similar physical contents and
10 in particular the same inter annual temporal reference. This does not affect the global trend differences but it
11 directly impacts the trend differences at regional scales. In addition, the detection of the evolution provided by a
12 new altimeter standard or product in terms of global correlation between all collocated altimeter SLA and in-situ
13 DHA may be distorted whether the temporal reference is homogeneous or not between both types of data. Table
14 2 indicates that without a homogeneous temporal reference, the reprocessed AVISO SSALTO/DUACS DT 2014
15 product is more correlated with Argo DHA than the previous release of these products. However, no difference
16 of correlation is observed when the anomalies are computed with the same temporal reference. This illustrates a
17 particular type of error of the method of comparison (different temporal references) that can be corrected (by
18 referencing both datasets on the same period).

19 **5.4 Impact of the GRACE data set and associated errors**

20 At regional scales and particularly in the tropical ocean, total altimeter and steric annual signals are in phase
21 (Dhomps et al., 2011, Legeais et al., 2015) but due to the spatial distribution of the ocean on the Earth and
22 seasonal hemispheric signals, the global time series are affected by a quadratic phase shift (Figure 7 and Chen et
23 al., 1998). Regarding the ocean mass contribution to the sea level, its annual signal has a larger magnitude
24 (twice) than total and steric signals and is in phase with the total altimeter global MSL. The addition of the mass
25 contribution from GRACE to the Argo dataset provides homogeneous physical content with altimeter SLA
26 (except the deep steric contribution) (Figure 7), which is required to estimate the altimeter absolute drift. In
27 addition, Figure 8 highlights that the amplitude of the annual signal of the global differences between the total
28 altimeter signal and the steric DHA is about 10 mm (in red) and it is significantly reduced when the ocean mass
29 contribution is also withdrawn (in blue). This demonstrates the relevance of this ocean mass contribution for the
30 detection of the altimeter absolute drift detection.

31 The analysis of altimeter absolute drift requires a good accuracy of the long term changes in ocean mass (trends,
32 inter-annual to decadal variations) and two important corrections have to be taken into account for such analyses.
33 The first one is the Glacial Isostatic Adjustment (GIA) which is a gravity effect. It is related to the Post Glacial
34 Rebound (Tamisiea and Mitrovica, 2011) whose oceanographers are not interested in since they rather want to
35 assess the current mass movements. The GRACE ocean measurements have to be corrected of a GIA of 1.1
36 mm/yr (Chambers et al., 2010). However, GIA does not represent the mass redistribution of continental ice to the
37 oceans, which should be corrected. Based on tests with different ice loading histories and Earth models, the GIA
38 uncertainty is estimated to be 30% (~0.3 mm/yr) (Chambers et al., 2010). The second essential ocean mass
39 correction deals with the degree 1 geocenter motion. Satellites move about the mass center of Earth but it moves
40 over time relative to the fixed geometric center and we are interested in the mass loss relative to a fixed frame

1 (i.e., the crust). In addition, the redistributions of ice from Greenland, Antarctica, and mountain glaciers affect
2 geocenter trends and although the effects offset somewhat, the uncertainty associated with this correction of
3 geocenter motion in terms of equivalent sea level is estimated to be 0.1 mm/yr (Swenson et al., 2008; Chambers
4 et al. 2007). In addition of these GIA (0.3 mm/yr) and geocenter (0.1 mm/yr) uncertainties, the global mean
5 ocean mass evolution is also affected by the harmonic coefficients fit uncertainty (0.1 mm/yr) and the leakage
6 from land to the ocean. This latter effect can be taken into account by removing a 300 km coastal band but the
7 remaining uncertainty is also of order of 0.1 mm/yr. The detection of the altimeter absolute drift is thus
8 significantly affected when introducing GRACE measurements.

9 Regarding the global altimeter drift, Figure 9 displays the temporal evolution of the differences between
10 altimetry and the sum of Argo DHA plus GRACE measurements using the grids of equivalent sea level (GRGS
11 solution, Biancale et al., 2014) and the global mean ocean mass (Johnson and Chambers, 2013). A 1 mm/yr
12 difference is observed between the altimeter drift estimated with the former (0.8 mm/yr) and the latter (-0.21
13 mm/yr) dataset. At inter annual scale, opposite temporal variations between both time series can be observed of
14 the order of several millimeters (such as during year 2008). These discrepancies are attributed to the difference
15 of processing of these datasets: the spherical harmonic coefficients are addressed differently (in particular the
16 degree 0 and 1 coefficients) and the ocean mass time series obtained with the GRGS dataset has been adjusted
17 for a -1.1 mm/yr GIA effect whereas this effect is already taken into account in the global mean ocean mass time
18 series. In addition, the so-called leakage of the continental signal over the oceans is not treated the same way.
19 Note that the method of comparison also contributes to the observed discrepancies (GRGS solution collocated to
20 Argo profiles versus global mean difference) but it is not believed to be a first order contribution to the error.
21 This illustrates that all the uncertainties mentioned above can significantly affect the estimation of the altimeter
22 absolute drift.

23 **5.5 Impact of the temporal sampling of the Argo floats**

24 The Argo floats provide vertical T/S profiles every 10 days. This is a good compromise in order to sample the
25 ocean variability and to ensure a long enough life time of the floats. For comparison, altimeter missions such as
26 Jason missions provide a global coverage of the ocean within the same period. The validation of altimeter
27 measurements by comparison with the in-situ profiles may be affected by a different temporal sampling of the
28 Argo floats. With a full sampling of the in-situ network, an East/West hemispheric bias of the regional MSL
29 trends is observed when computing the trend of the differences between altimeter Jason-1 SLA and in-situ DHA
30 in each hemisphere (Figure 10). The difference of trends between each area is of -1.38 mm/yr over mid 2004-
31 2010 with the GDR-C orbit solution (Fig. 10a) whereas it is reduced to -0.13 mm/yr with the GDR-D orbit
32 solution (Fig. 10b). This indicates that this updated altimeter standard improves the regional homogeneity of the
33 altimeter SLA but given the uncertainty associated with these trend estimations (more than 0.5 mm/yr over this
34 period), these results are close to the limit where both these values can be distinguished with enough confidence
35 in the results.

36 The goal is to assess whether this result is affected by a change the temporal sampling of the Argo floats. The
37 trend of the differences between the altimeter SLA and in-situ DHA is computed as before for each hemisphere
38 with both altimeter standards but only one out of three in-situ profiles is used which leads to a monthly sampling
39 for all floats instead of 10 days. The East/West hemispheric trend differences become -0.98 mm/yr and 0.67
40 mm/yr with the GDR-C and GDR-D standards respectively. This means that in these conditions, none of the

1 standards allow the reduction of the hemispheric discrepancies with respect to the in-situ independent reference.
2 This kind of analysis of impact of a new altimeter standard is thus sensitive to the sampling frequency of in-situ
3 floats.

4 **5.6 Impact of the spatial sampling of the Argo network**

5 The target of a network of 3000 Argo floats has been achieved in 2007 and they now provide an almost global
6 coverage of the open ocean. This targeted number of floats has not been determined in order to allow altimetry
7 validation in particular. The impact of a reduced spatial coverage of the network on the altimetry validation is
8 analyzed in terms of regional coverage, trends of the differences and coherence between both measurements.
9 Different selections of the floats have been performed and Figure 11a displays the number of valid profiles over
10 2005-2012 from all Argo floats whereas the Figure 11b shows the number of valid profiles when only 25% of
11 the floats are used (selected in the list of instruments following the increasing order of their WMO number).
12 With this selection, the spatial coverage is strongly affected and some regions are not sampled at all over the
13 period.

14 Focusing on the altimeter drift detection and in spite of this reduced spatial coverage, the global trend of the
15 differences between altimetry and Argo steric heights are not significantly modified (within 0.04 mm/yr) when
16 different sub samplings of the network are used (50% or 25% of the number of instruments). This is in
17 agreement with the lack of impact of the high ocean variability areas on the global altimeter trend estimation, as
18 described earlier. In order to have a consistent approach, the same sensitivity test has been performed as the one
19 used for the impact of the temporal sampling (see previous section). The trends of the differences between the
20 altimeter SLA and in-situ DHA are computed separating the eastern and western hemispheres using both Jason-1
21 altimeter standards but only 50% of the Argo floats are used in the comparisons. The East/West hemispheric
22 trend differences are -1.2 mm/yr and -0.1 mm/yr with the GDR-C and GDR-D altimeter standards respectively,
23 which are very similar to the differences obtained with all floats (-1.4 mm/yr and -0.1 mm/yr respectively). This
24 suggests that the reduction of the number of floats (and thus of the spatial coverage) has also no significant
25 impact on the detection of altimeter drifts at regional scale.

26 In addition, Figure 12 shows the Taylor diagram (Taylor, 2001) between AVISO SSALTO/DUACS altimeter
27 merged products and the Argo in-situ steric heights (with the addition of the GRACE GRGS ocean mass
28 contribution) with different sub sampling of the Argo network. The performance obtained with 25% of the floats
29 appears to be slightly deteriorated but the different points are very close to each other and as above for the global
30 and regional trends, this confirms that the validation of altimeter measurements is little affected by a reduction of
31 the number of Argo floats and a reduced spatial coverage of the in-situ network.

32 The reduction of the temporal and spatial sampling of the Argo floats could have been considered to have similar
33 effects but the same sensitivity analyses have been performed (impact of Jason-1 altimeter standards on the
34 regional hemispheric trend discrepancies) leading to opposite conclusions regarding the sea level trends (impact
35 versus no impact). This indicates that according to the method of sub sampling, the distribution of the in-situ
36 information (in space and time) are statistically different, leading to a different impact on the altimeter sea level
37 estimation. This will be further illustrated in the following section.

38 **5.7 Reference depth of Argo profiles**

39 The integration of the Argo T/S profiles for the computation of the in-situ steric dynamic heights requires a
40 reference level (pressure) and the deeper the reference level, the more information from the T/S profiles is taken

1 into account through the water column but the more T/S profiles are not used (those who don't reach the
2 reference level). Thus, we first aim at determining the impacts of a given reference depth of integration on the
3 global and regional Argo spatial sampling, on the estimation of the global MSL trend and in terms of sea level
4 variance.

5 **5.7.1 Impact on the global and regional coverage**

6 According to the reference pressure used to integrate the in-situ density profiles, no DHA will be computed for
7 all the floats whose mean maximum pressure does not reach this reference level. At global scale, only 6% of the
8 floats are missed with a reference level at 900 dbar but this proportion increases to 29% at 1400 dbar and 52% at
9 1900 dbar.

10 At regional scale, the floats used with a 900 dbar reference pressure provide a very homogeneous ocean
11 coverage (Figure 13a) and associated discarded floats whose reference pressure is shallower are mainly located
12 in the Pacific western boundary current, in the Mediterranean Sea and a few are found in the tropical Atlantic
13 and Eastern Pacific Ocean (Figure 13c). The map of the discarded floats with a deep reference level (1900 dbar)
14 (Figure 13d) indicates that floats with a mean max depth between 900 dbar and 1400 dbar (in light blue and
15 green) are mainly located at equatorial latitudes of all ocean basins. In these areas, the water column is very
16 stratified and the steric signal is thus confined in the upper layer. Floats reaching depths between 1400 and 1900
17 dbar (in orange and light red) are mainly found at subpolar latitudes where signals are more barotropic compared
18 to lower latitudes (Luyten et al., 1983). Floats reaching depths deeper than 1900 dbar are relatively well spread
19 out over the ocean with increasing density in the western boundary currents of the north hemisphere. Thus, with
20 a deep reference depth, the water column will be better sampled over the global ocean (which improves the
21 retrieved steric signal) but we will miss a significant part of this steric signal, especially at equatorial latitudes.
22 This illustrates the balance to be found between the horizontal (shallow reference level) and vertical (deep
23 reference level) sampling of Argo floats.

24 **5.7.2 Impact on the global MSL trend estimation**

25 An estimation of the global altimeter absolute drift is provided by the global mean sea level differences between
26 altimetry and the sum of Argo steric heights with the GRACE ocean mass contribution. This is illustrated on
27 Figure 14 with various subsets of DHA derived from the Argo network, allowing the distinction of the effect of
28 the horizontal and vertical sampling of the ocean by the floats. The altimeter drift estimated with all DHA from
29 900 dbar profiles (in red) is of 1.5 mm/yr. Among these profiles, the selection of those whose maximum depth is
30 at least 1900 dbar (impact of the horizontal sampling) has no impact in terms of global correlation between
31 altimetry and Argo measurements (0.84 in both cases). There is a relatively low impact (-0.2 mm/yr) on the
32 altimeter drift which is reduced to 1.3 mm/yr over the period (in blue). The use of all DHA from 1900 dbar
33 profiles leads to an improved correlation between altimetry and in-situ data (0.87) and the impact of this
34 increased vertical sampling on the altimeter drift detection (in green) is greater than previously (-0.4 mm/yr) and
35 leads to a 0.9 mm/yr drift. Therefore, the choice of a deep reference level for Argo DHA provides a better
36 estimation of the baroclinic signal (improved vertical sampling) which is more in agreement with the observed
37 signal by altimetry. This is in favor of an improved estimation of the absolute altimeter drift detection.

38 The use of a deep versus shallow reference level turns out to be equivalent to a reduction of the ocean coverage
39 by Argo floats (horizontal sampling). As previously discussed with the analysis of the sensitivity to the temporal
40 and spatial sampling of the floats, this kind of sub sampling associated with the reference level affects the

1 estimation of the global absolute altimeter sea level trend. The 0.6 mm/yr total difference observed between the
2 shallow and deep reference levels on Figure 14 is an estimation of one of the contributors to the error of the
3 method of comparison.

4 **5.7.3 Impact in terms of variance: altimetry multi vs mono mission**

5 We now describe two examples at global and regional scales illustrating that the comparisons of altimeter
6 measurements with Argo in-situ data in terms of variance are affected according to the reference level of
7 integration of steric heights. At global scale, the Taylor diagram of Figure 15 presents the correlation and the
8 standard deviation of the differences between altimeter multi-missions merged SLA and the Argo steric DHA.
9 With a deep reference level (1900 dbar), the altimeter (grey circle) and in-situ (black circle) time series have the
10 same standard deviation whereas a reduced variability is found with the in-situ steric measurements referenced to
11 a shallower level (900 dbar) with a 0.85 proportion compared with altimeter SLA. In addition, the correlation
12 between both types of data is also deteriorated. This has to be taken into account when assessing the impact of a
13 new altimeter standard or new product for instance.

14 At regional scales, Dhomps et al. (2011) reveal that the correlation and the regression coefficients between SLA
15 and DHA vary spatially with a latitude dependency at the first order. In particular, their Fig. 5 suggests that the
16 Southern Ocean is the place where the water column has to be sampled at the deepest level to estimate the steric
17 signal. At high latitudes, the baroclinic signal below 1000 m depth significantly improves the correlation
18 between SLA and DHA, the sea level variability being largely influenced by the deep baroclinic signals. We
19 illustrate this with Figure 16 which indicates that the variances of the differences between altimeter SLA and in-
20 situ DHA are different whether the altimeter SLA is derived from mono mission (TOPEX, Jason-1 & 2) or
21 multi-missions grids of SLA. In particular, with DHA referenced to 900 dbar (left panel), adding missions
22 reduces the altimeter / Argo consistency in the high ocean variability areas of the Antarctic Circumpolar Current
23 (ACC) (blue, negative values of -5 cm^2 on average). On the other hand, this tendency almost disappears in the
24 ACC with the use of DHA referenced to 1900 dbar (right panel). This result is explained by the difference of
25 variance of the water column as seen by altimetry or in-situ data in this region. Figure 17 indicates that the
26 variance of mono mission and multi missions altimeter products (collocated to Argo profiles) are very close to
27 each other in the ACC but the variance of the Argo steric heights referenced at 900 dbar is significantly lower.
28 Thus with this reference level, both altimeter products cannot be distinguished by comparison with Argo data.
29 With a 1900 dbar reference level, the variance of the Argo steric heights becomes similar to the values obtained
30 with altimeter products in the ACC and the Argo measurements become relevant for the quality assessment of
31 the altimeter products. This illustrates that according to the ocean characteristics, the analysis of the variance of
32 the water column and thus the differences between altimetry and Argo measurements are highly sensitive to the
33 reference depth of integration of the Argo profiles.

34 **5.8 Impact of the deep steric contribution**

35 In addition of the sensitivity to the reference depth of integration of Argo density profiles (as described in the
36 previous section), the estimation of the altimeter drift is also affected by the deep steric contribution (deeper than
37 the reference level of Argo floats) which is not taken into account in our approach. This contribution has been
38 extensively discussed in the recent years since the heat uptake in the deep ocean is suspected to explain the pause
39 in the global mean air and sea surface temperature evolution observed since the early 2000s (e. g. Trenberth and
40 Fasullo 2013; Watanabe et al. 2013; England et al. 2014). Comparing altimeter SLA with the sum of the steric

1 signal and the ocean mass contribution, Dieng et al., 2015a estimate the deep steric contribution (deeper than
2 1500 m) to be 0.3 ± 0.6 mm/yr and 0.55 ± 0.6 mm/yr over the period 2005-2012 and 2003-2012 respectively.
3 Llovel et al. (2014) provide an estimation of 0.0 ± 0.7 mm/yr over the former period. The associated
4 uncertainties include the formal error adjustment and the systematic errors associated with the observing system.
5 The problem with the estimation of the deep steric contribution is that it requires the knowledge of the steric
6 contribution from the upper ocean and the comparison of different global steric sea level datasets indicates that a
7 significant uncertainty remains on this estimation (Dieng et al., 2015a). This suggests that for the moment, there
8 are still too large errors associated with the estimation of the deep steric contribution to detect absolute altimeter
9 sea level drift with regards to climate users requirements: 0.3 mm/yr over 10-year (GCOS 2011). Note that some
10 deep profiling floats (about 4000 m) have been recently launched in the context of the Euro-Argo Improvements
11 for Marine Services (E-AIMS, 2013) which should help to better characterize the deep steric contributions and
12 assess their impact on the altimeter quality assessment. As an illustration, Figure 18 display the time series of the
13 DHA derived from the profiles of such a float drifting off the Bay of Biscay (WMO 6901632) with different
14 reference levels of integration varying from 900 dbar down to 4000 dbar together with the collocated altimeter
15 SLA (in brown). A very good coherence is globally found between all curves. A 3 cm bias is observed between
16 DHA 900 dbar and DHA 1900 dbar but also between DHA 1900 dbar and DHA 3400 dbar. The steric signal
17 deeper than this pressure seems to be much reduced since almost no bias is observed between 3400 dbar and
18 4000 dbar. In addition, the correlation between SLA and DHA significantly increases from 900 dbar (0,70) to
19 1900 dbar (0,90) and reaches up to 0,92 at 3400 dbar. Thus, the use of deep reference levels increases the
20 coherence between the in-situ and altimeter sea level estimations but regarding the altimeter drift detection, it is
21 fundamental to have enough in-situ measurements over a long period so that the in-situ sea level trend can be
22 used as a reference with enough confidence and is really representative of the global ocean.

23 **6 Conclusions**

24 The internal consistency check and the comparison with other altimeter missions cannot systematically provide
25 enough information for the quality assessment of altimeter sea level measurements. The in-situ dynamic heights
26 derived from the Argo network can be used as an independent reference for the analysis of the relative mean sea
27 level temporal evolution (including the detection of global and regional MSL drift and anomalies) but also for
28 the detection of the impact of new altimeter standards or products used to calculate the sea surface heights. Our
29 method constitutes an essential approach which has a strong synergy with results derived from the altimetry
30 comparison with tide gauges since the confrontation of both methods improves the confidence in the results. We
31 have demonstrated that it is possible to detect altimeter drifts at global and regional scales and to characterize the
32 impact of new altimeter standards. However, the improvements provided by these new standards and products
33 become more and more reduced and the searched differences may be hidden by the errors of the method. It is
34 thus necessary to better characterize the capacity of the method to distinguish the performances of two altimeter
35 products. Hence, this study focuses on the sensitivity of the altimeter / in-situ sea level comparisons to different
36 processing parameters.

37 The estimation of the absolute altimeter mean sea level drift requires the additional information related to the
38 mass contribution to the sea level that can be derived from GRACE satellite measurements. We have shown that
39 there is a strong sensitivity to the different datasets available. In addition, regarding the long term trend of the
40 global MSL, there are significant uncertainties associated with the GIA correction (0.3 mm/yr), the geocenter

1 motion (0.1 mm/yr), the fit of the harmonic coefficients (0.1 mm/yr) and the leakage from land to the ocean (0.1
2 mm/yr). The estimation of the altimeter MSL trend is thus directly affected by these uncertainties related with
3 the use of GRACE measurements.

4 Sensitivity analyses performed on the Argo network have indicated that the spatial coverage of the ocean
5 sampled by the instruments is significantly reduced as soon as a limited number of floats are used in the
6 comparisons. However, this hardly affects the global correlation between altimeter SLA and the in-situ DHA
7 plus mass contribution, neither the variance nor the trend of their differences. In addition, the 10-day temporal
8 sampling of Argo floats was not designed for satellite altimetry validation purposes. We have shown that a
9 reduced temporal sampling of the floats can prevent us from detecting the impact of a new altimeter standard.
10 The same diagnosis has been used to assess the impact of the reduction of the temporal and spatial sampling of
11 Argo floats, leading to opposite conclusions. This suggests that the resulting distributions of the in-situ profiles
12 (in space and time) are different, leading to a different impact on the regional sea level trend estimation.

13 The choice of the reference level of integration of the Argo T/S profiles for the computation of the steric
14 dynamic heights directly affects the global and regional coverage of the ocean by Argo floats. A relatively
15 deeper reference level can be assimilated to an additional sub sampling effect since it allows a better vertical
16 sampling of the water column (more in agreement with what is seen by altimetry) but this leads to a reduced
17 horizontal sampling of the ocean; the impact of the former being more than twice compared with the latter in
18 terms of altimeter MSL trends estimation over a 8 years period. In some regions such as the Southern Ocean, the
19 comparison with the altimeter sea level requires a deep reference depth so that the variance content of the water
20 column is similar between altimetry and in-situ data.

21 Considering all the sources of errors discussed in this study including the method of collocation, the impact of
22 the reference depth of Argo profiles, the uncertainty on GRACE ocean mass datasets and the error estimation on
23 the deep steric contribution, this suggests that the uncertainty associated with the obtained altimeter drifts is at
24 least of the order of 1.0 mm/yr. The future evolution of the Argo network such as the deployment of deep Argo
25 floats (4,000m) should contribute to improve the results and our approach will be an asset for the quality
26 assessment of new altimeter missions such as Sentinel-3, Jason-3 and SWOT.

27 Following the results of this study, the Argo community should be supported to maintain and improve the
28 deployment of Argo profiling floats. In particular, the temporal sampling of the Argo floats should be maintained
29 with at least the existing temporal coverage and the vertical extension of the Argo profiles should be extended to
30 deeper levels. In addition of these recommendations, enlarged network coverage at high latitudes and over
31 shallow waters, as well as an improved quality control of the data would also contribute to improve the altimeter
32 quality assessment thanks to the Argo network.

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36

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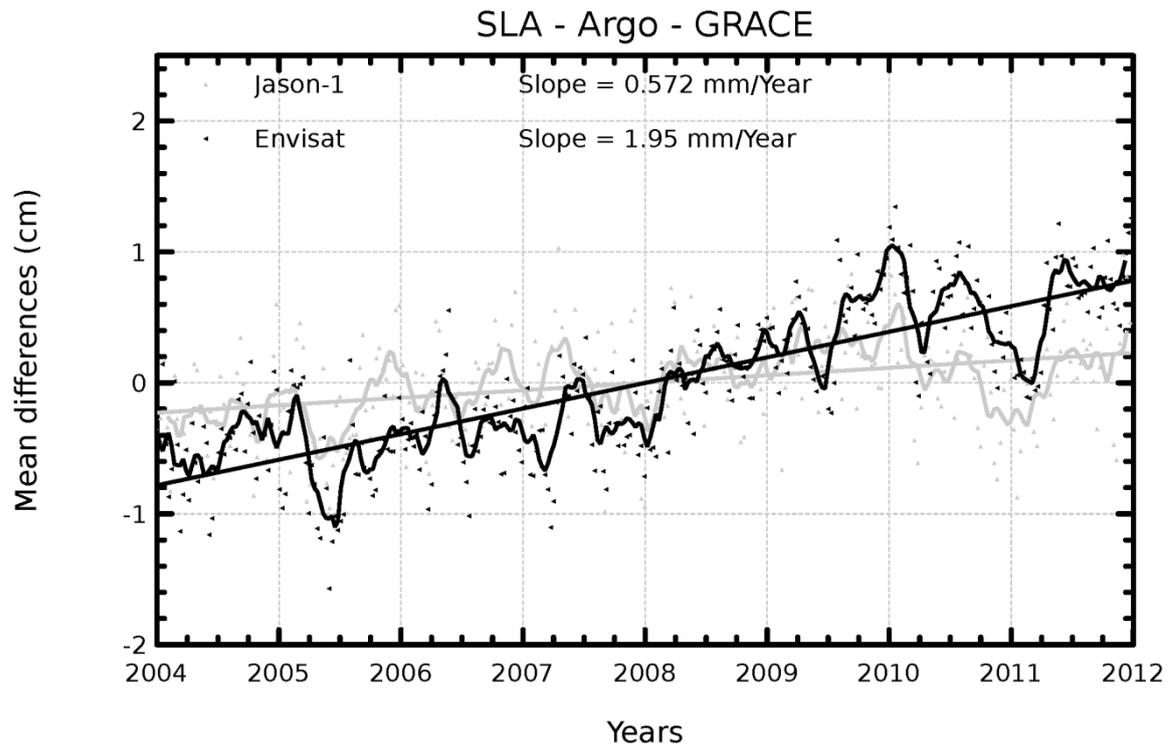
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Argo DHA 1900 dbar	Correlation	rms of the differences (cm)
SSALTO/DUACS DT 2010	0.89	3.94
SSALTO/DUACS DT 2014	0.90	3.76

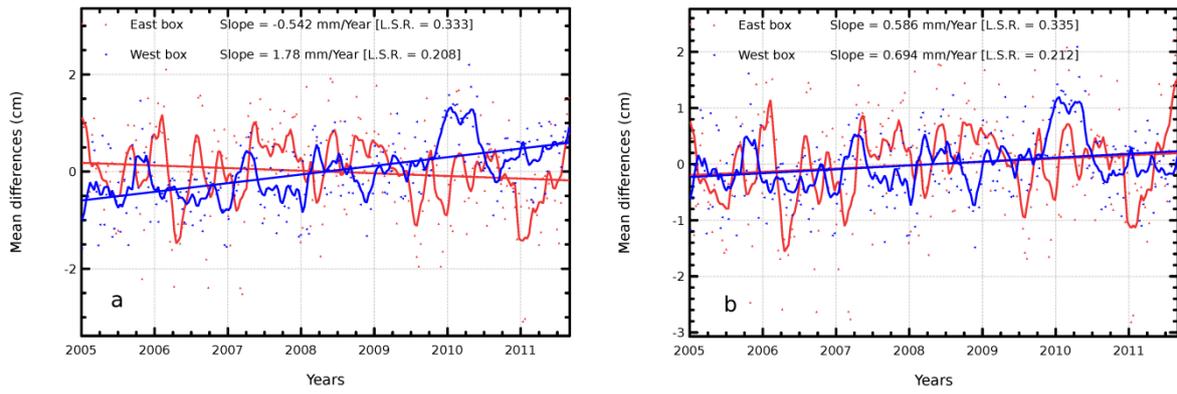
- 1 Table 1 : Statistics between altimeter products and in-situ DHA with an homogeneous reference period of the
2 altimeter SLA and in-situ DHA (2003-2011) in the Bay of Bengal (-5°S/+20°N; 80°E/95°E); Argo DHA are
3 referenced to 1900 dbar.

Global correlation	Non homogeneous temporal reference	Homogeneous temporal reference
AVISO SSALTO/DUACS 2010	0.87	0.90
AVISO SSALTO/DUACS 2014	0.90	0.90

- 1 Table 2 : Global correlation between all collocated altimeter SLA (AVISO SSALTO/DUACS 2010 and 2014)
- 2 and in-situ DHA from Argo profiles (with a reference depth of 1900 dbar and a 2003-2011 temporal reference)
- 3 without and with an homogeneous temporal reference

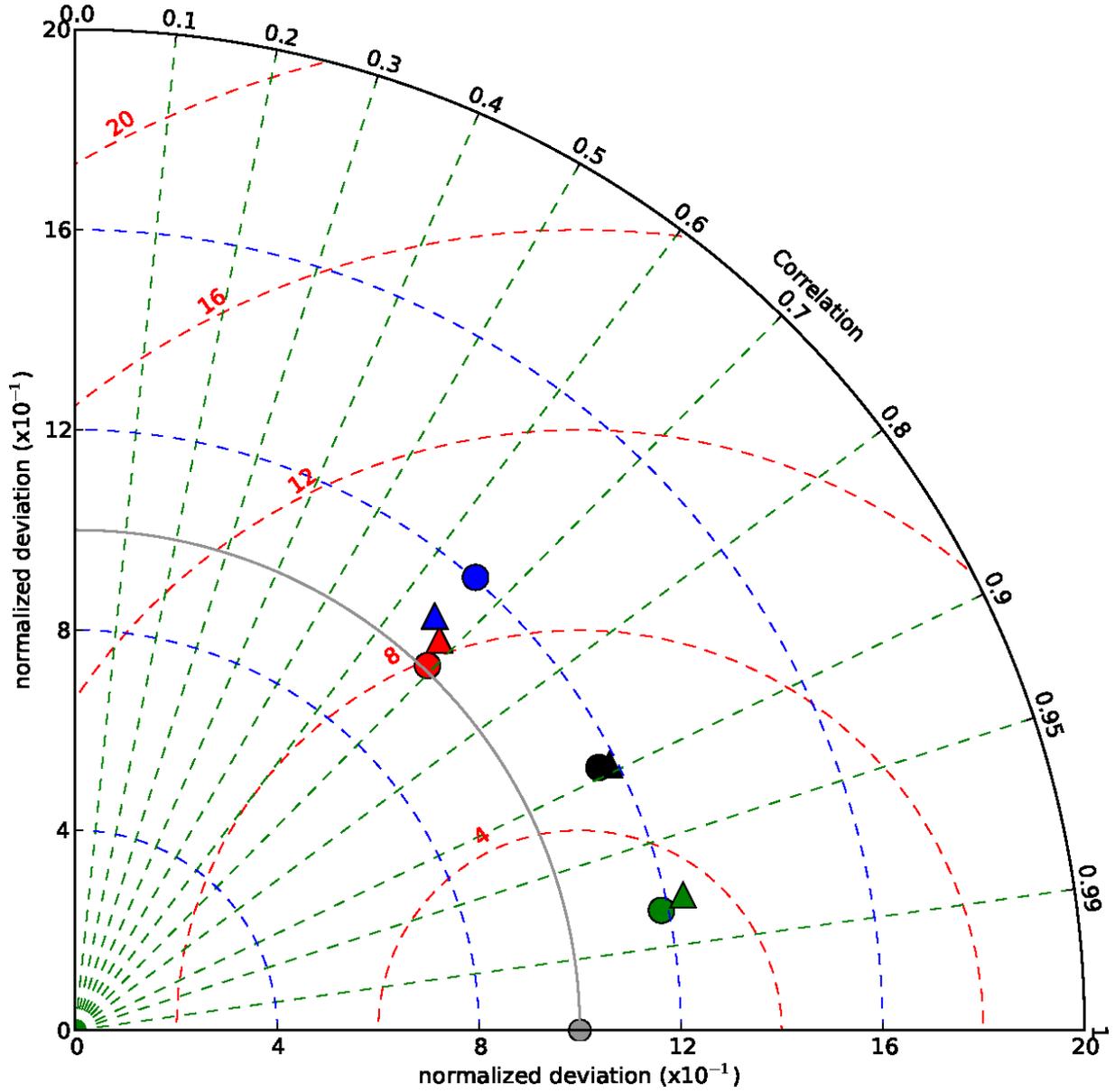


- 1
- 2 Figure 1 : Mean differences between altimetry and steric + mass contributions from Argo and GRACE
- 3 measurements for Jason1 and Envisat missions



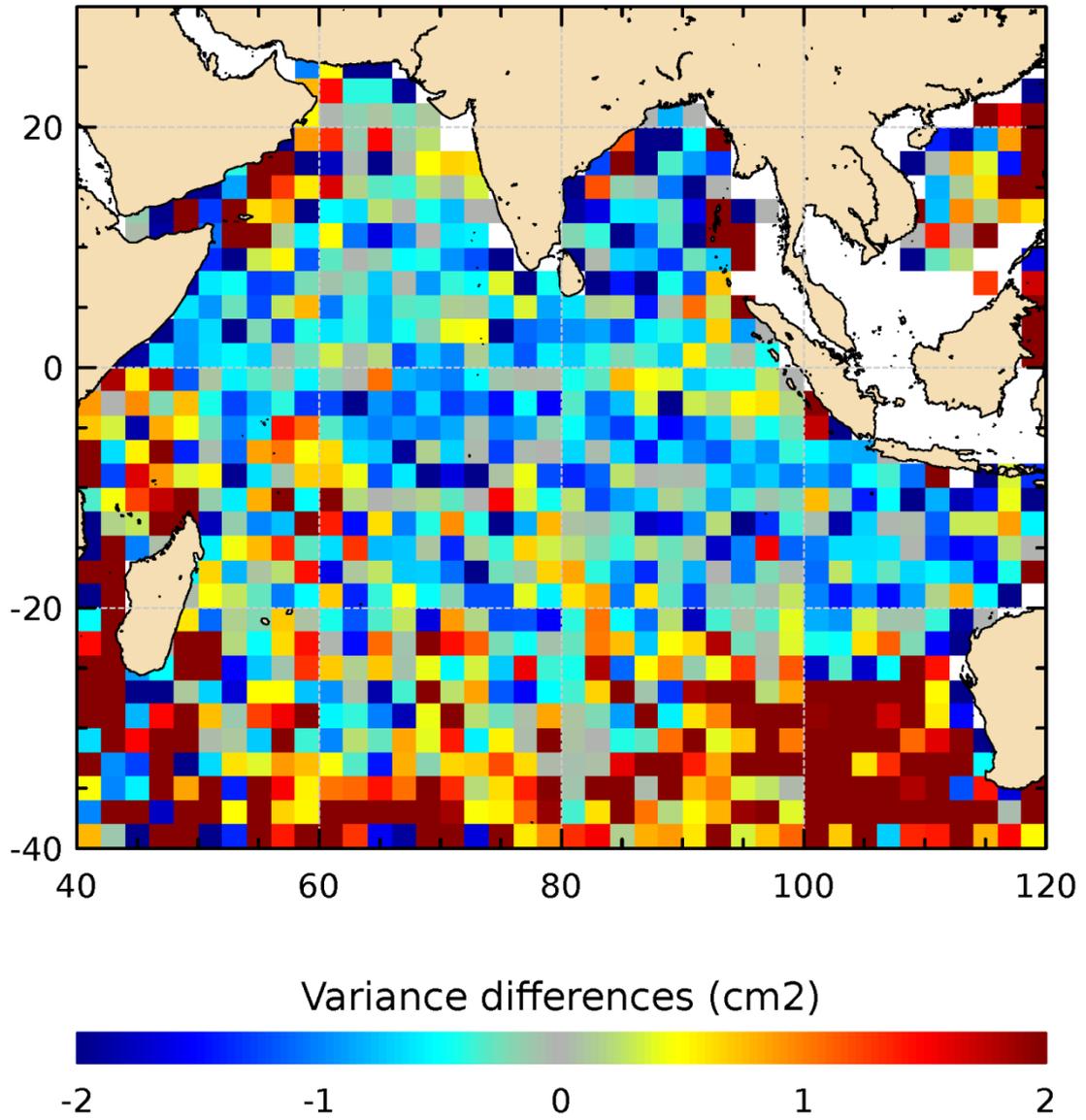
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 2 Figure 2 : SSH differences (cm) between Jason-1 altimeter data (cycles 1 to 355) and Argo in-situ measurements
 3 (900 dbar) computed with GDR-D (a) and GDR-E orbit solution (b), separating East box (Lon: 60°/120°, Lat: -
 4 30°/+30°) and West box (Lon: -150°/-190°, Lat: -50°/10°). Corresponding annual and semi-annual signals are
 5 removed. Trends of raw data are indicated and the 2-month filtered signal is added.
 6

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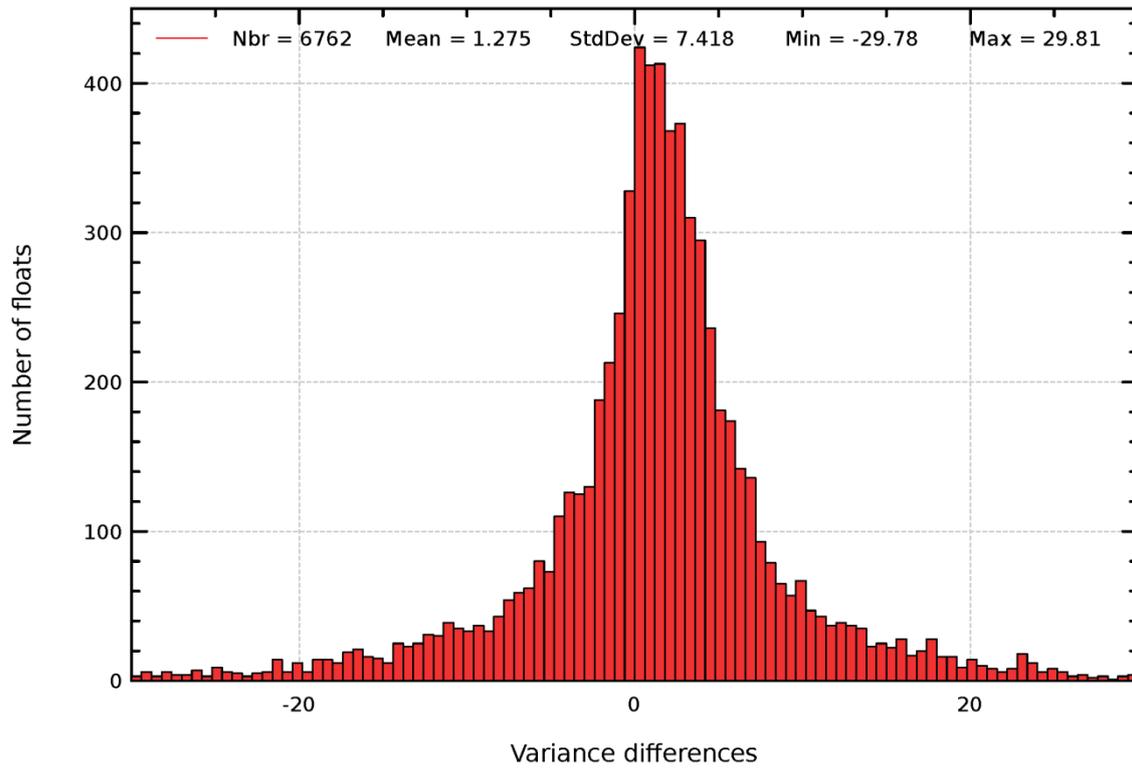


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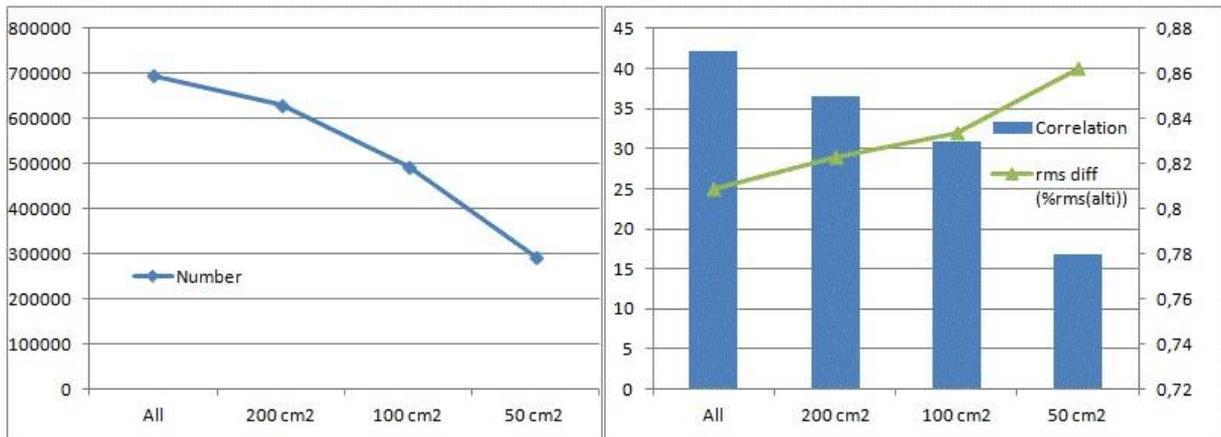
4 Figure 3 : Taylor diagram of the comparison of CCI (triangles) and AVISO SSALTO/DUACS DT (circles)
5 merged altimeter sea level products with Argo (900 dbar) and GRACE independent measurements for the global
6 data (black) and separating high frequencies (red), the annual signal (green) and the inter-annual signals (blue).



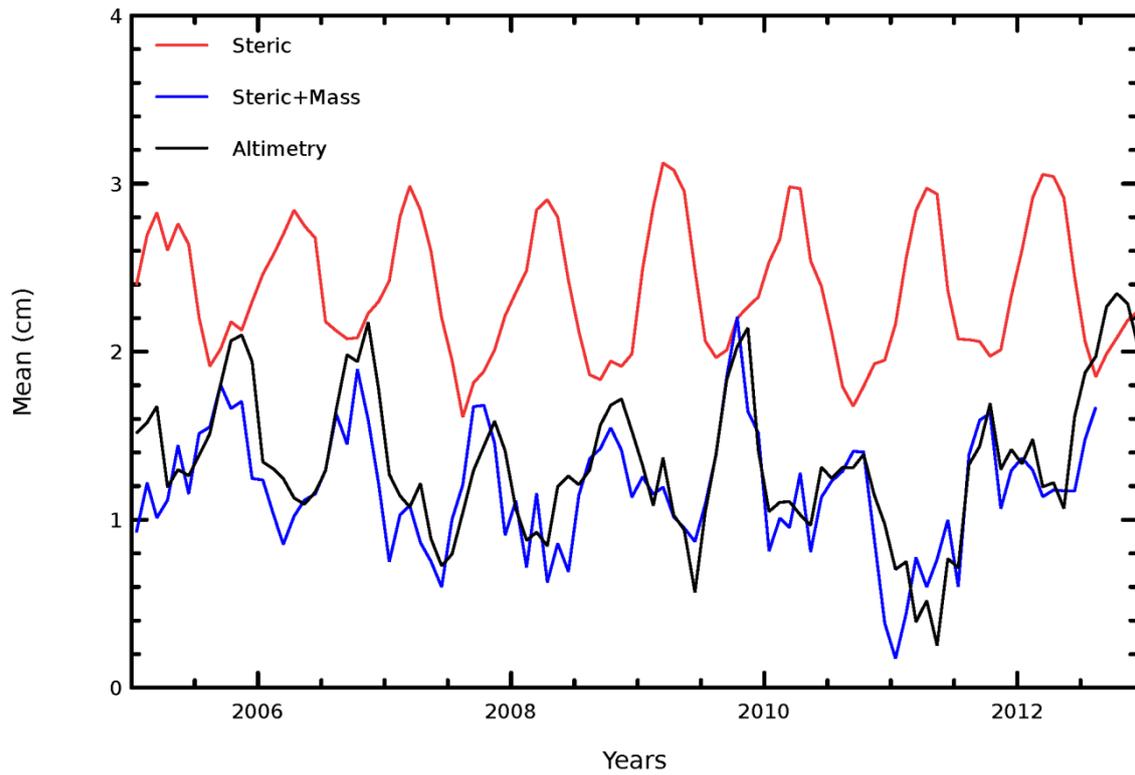
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 2 Figure 4 : Variance(DUACS 2014-Argo) – Variance(DUACS 2010-Argo) with Argo profiles referenced to 1900
 3 dbar over 2005-2012 (cm²)
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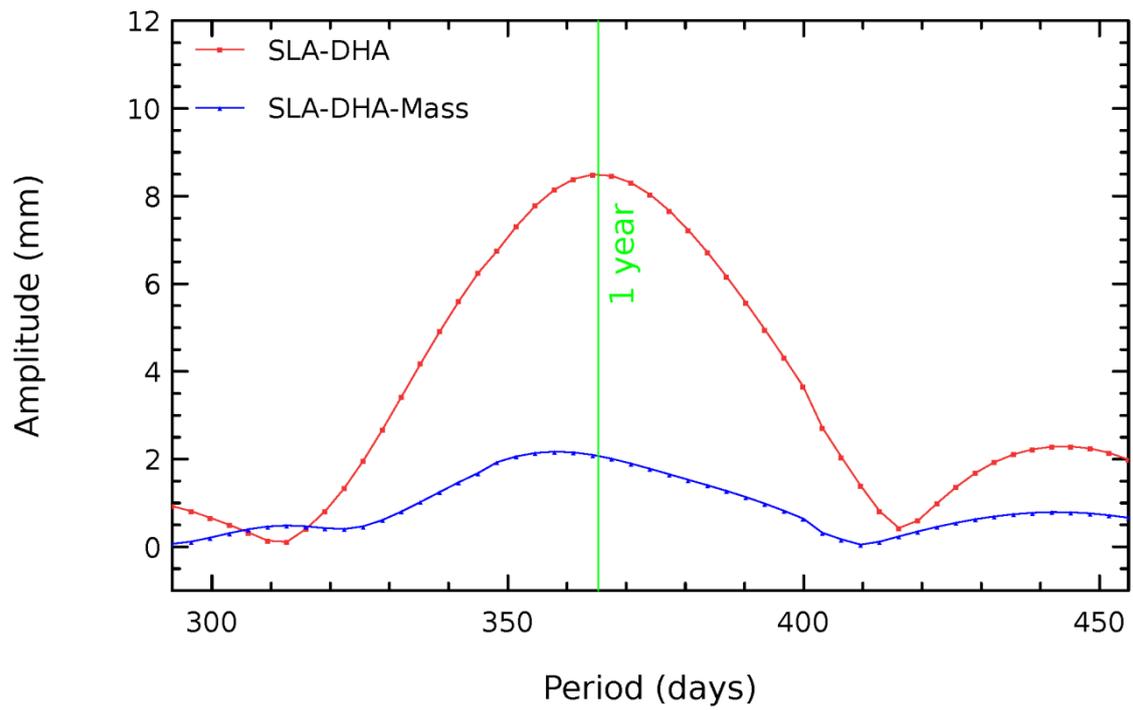
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 2 Figure 5 : Histogram of the difference of variance of the SLA-DHA differences for each Argo float using
 3 successively $1^\circ \times 1^\circ$ versus $1^\circ \times 3^\circ$ boxes ($=\text{Variance}(\text{SLA}_{1 \times 1}\text{-DHA}) - \text{Variance}(\text{SLA}_{1 \times 3}\text{-DHA})$) when
 4 averaging along-track Jason-1 altimeter SLA before collocating with Argo profiles.



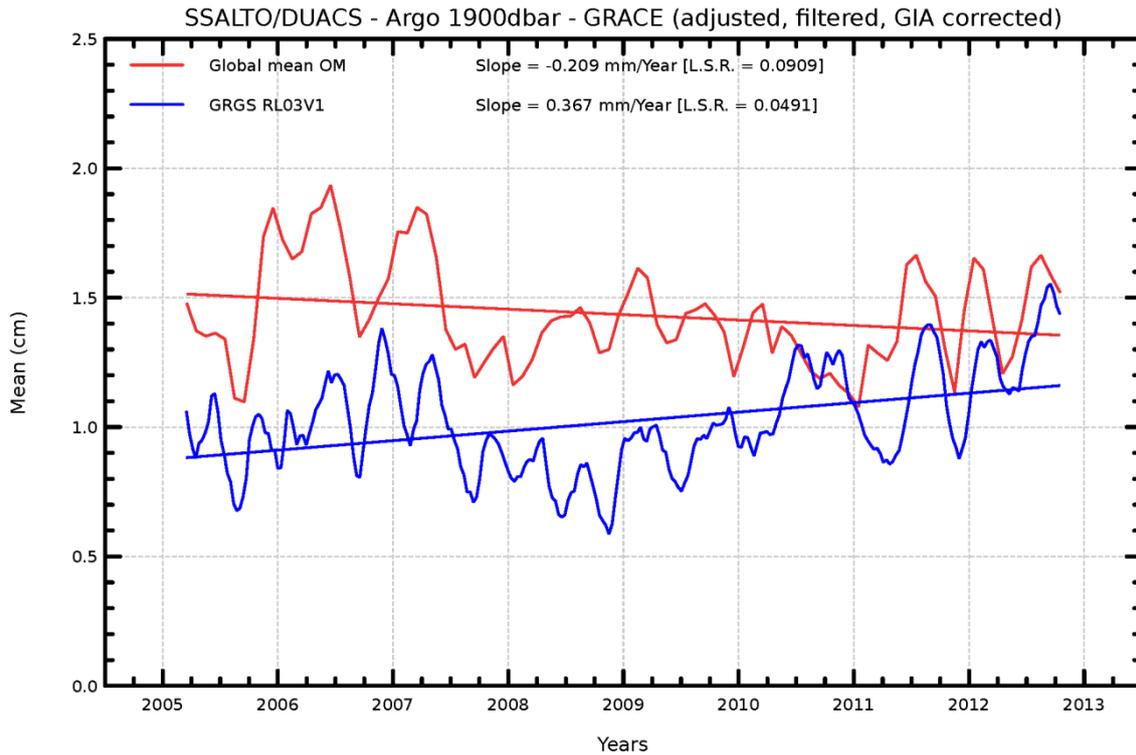
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 2 Figure 6 : Impact of excluding areas of higher ocean variability than a decreasing threshold: number of observed
 3 points (left) and correlation and rms of the differences between AVISO DUACS 2014 and Argo DHA (900 dbar
 4 reference) (right).



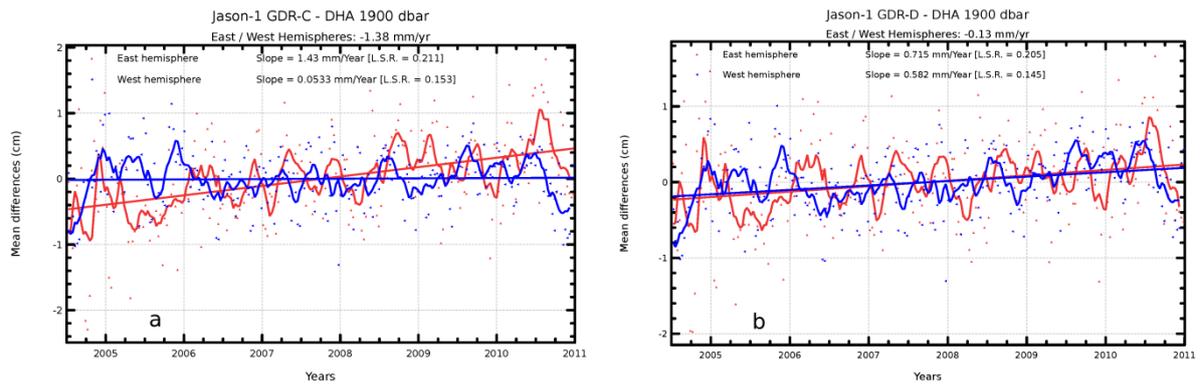
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- 2 Figure 7 : Temporal evolution of the steric DHA from Argo data (red), the summed steric + mass contributions
- 3 (blue) and the altimeter SLA (black).



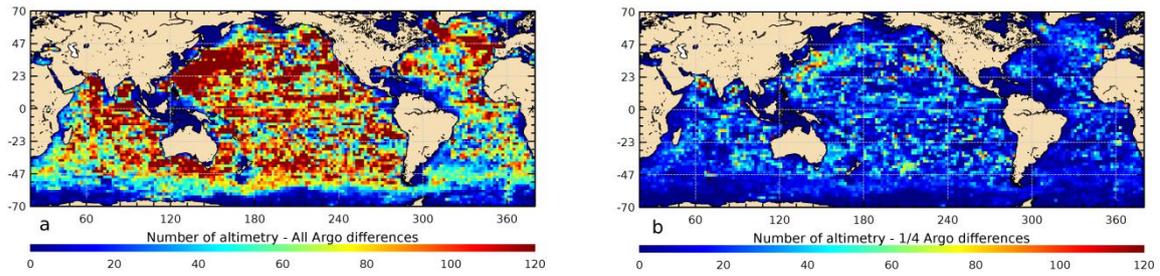
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 2 Figure 8 : Amplitude of the annual cycle of the differences between Jason-1 altimeter SLA and Argo DHA only
 3 (red) or between SLA and DHA + ocean mass (GRACE GRGS V3) (in blue).



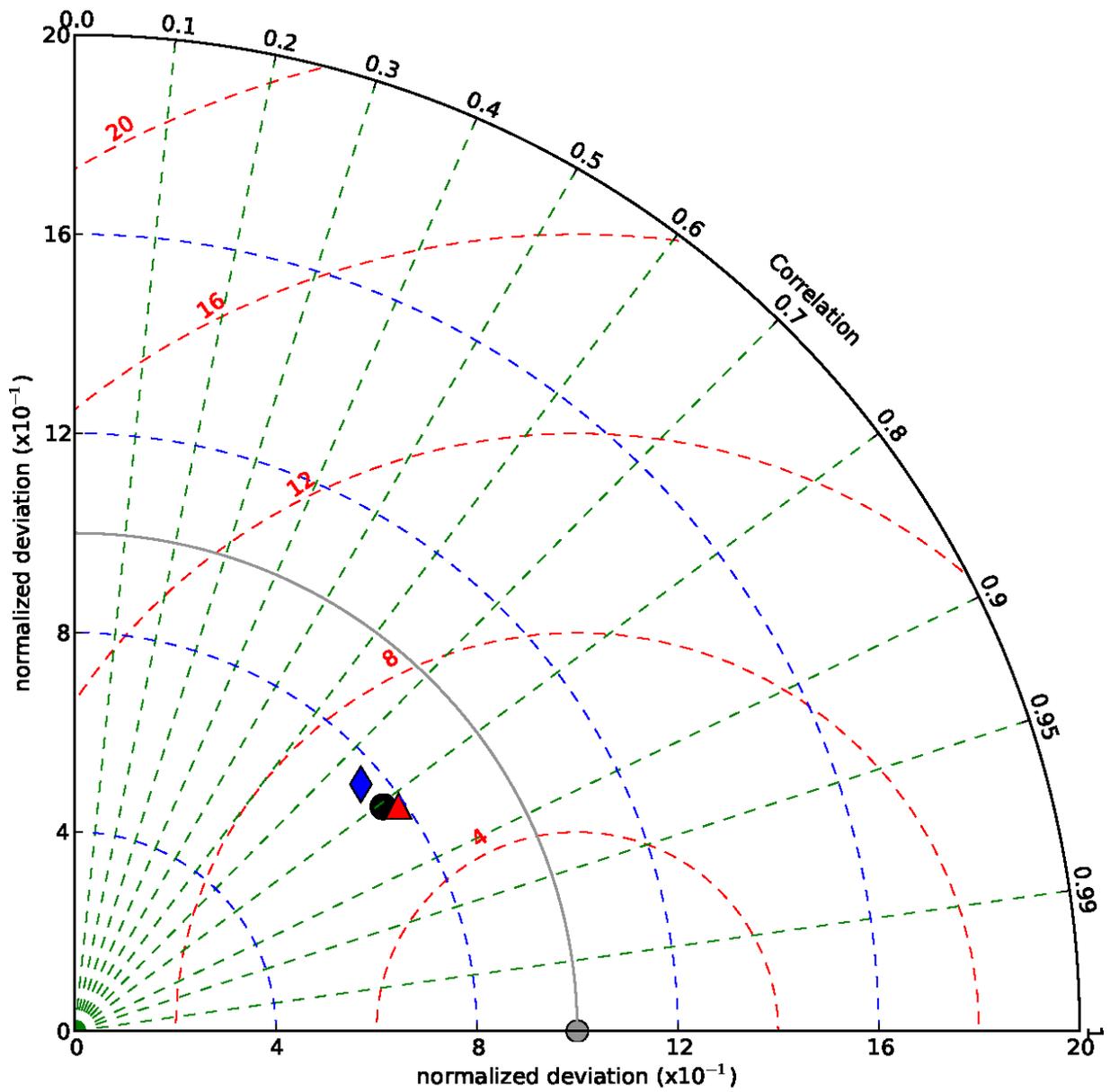
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 2 Figure 9 : Differences between SSALTO/DUACS 2014 global MSL and the sum of the Argo steric sea level
 3 (referenced to 1900 dbar) and the GRACE ocean mass contribution derived from the global mean contribution
 4 (Johnson and Chambers, 2013 in red) and the GRGS RL03v1 dataset (Biancale et al., 2014, in blue). Time series
 5 have been adjusted from annual and semi-annual signals, 3-month filtered and corrected from GIA effect. An
 6 arbitrary vertical offset has been applied to the curves for clarity.



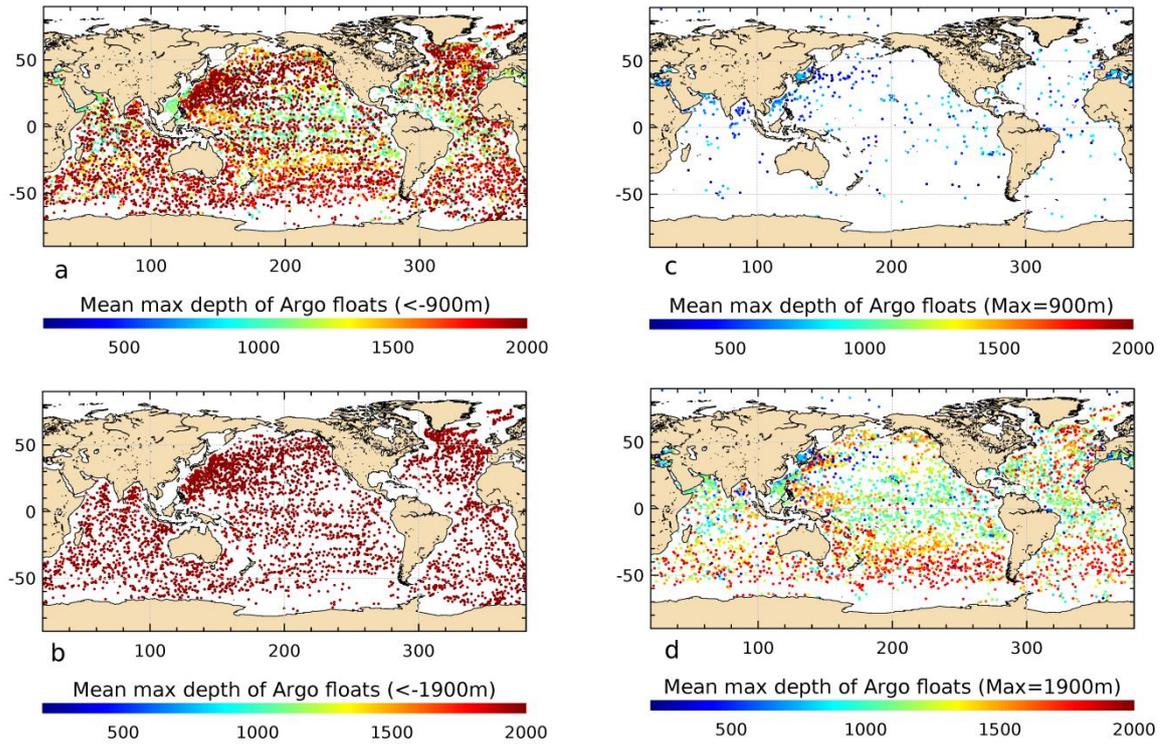
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 2 Figure 10 : SSH differences (cm) between Jason-1 altimeter data and Argo (1900dbar) in-situ measurements
 3 computed with GDR-C (a) and CNES preliminary GDR-D orbit solutions (b), separating East ($<180^\circ$, in red)
 4 and West ($>180^\circ$, in blue) longitudes. Corresponding annual and semi-annual signals are removed. Trends of raw
 5 data are indicated and the 2-month filtered signal is added.



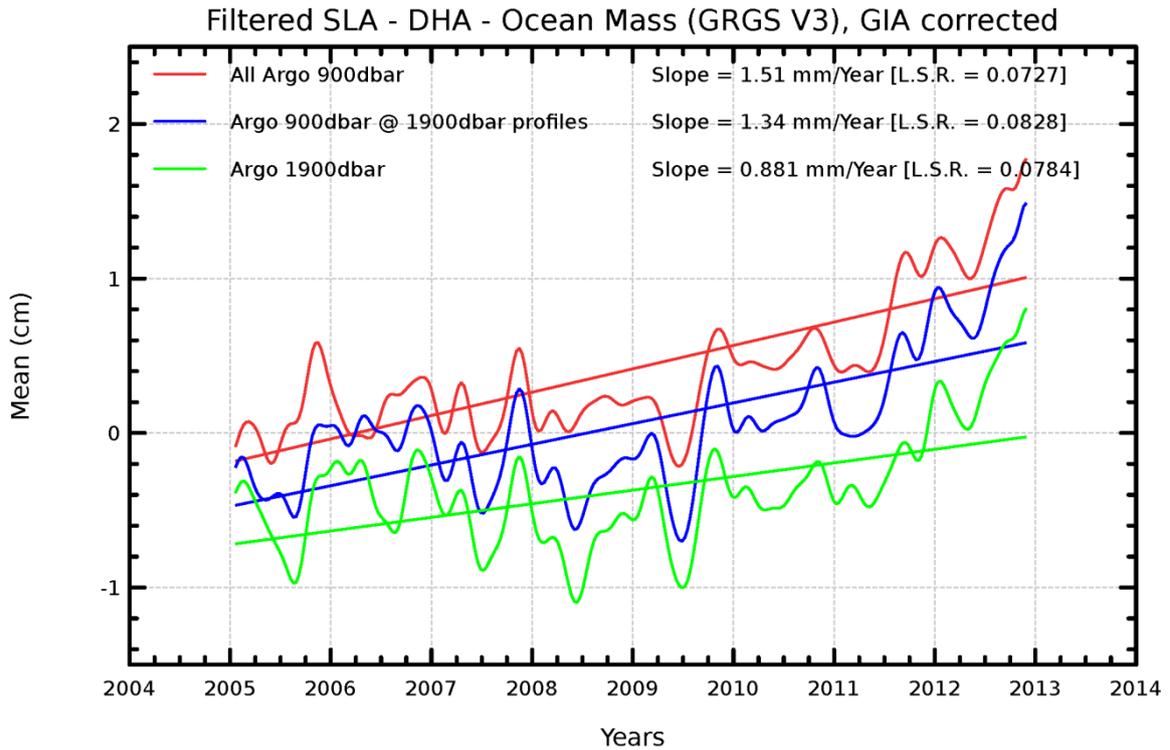
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2 Figure 11 : Number of Argo profiles per 2°x2° boxes over 2005-2012 from all Argo floats (a) and from 25% of
3 the floats (b).



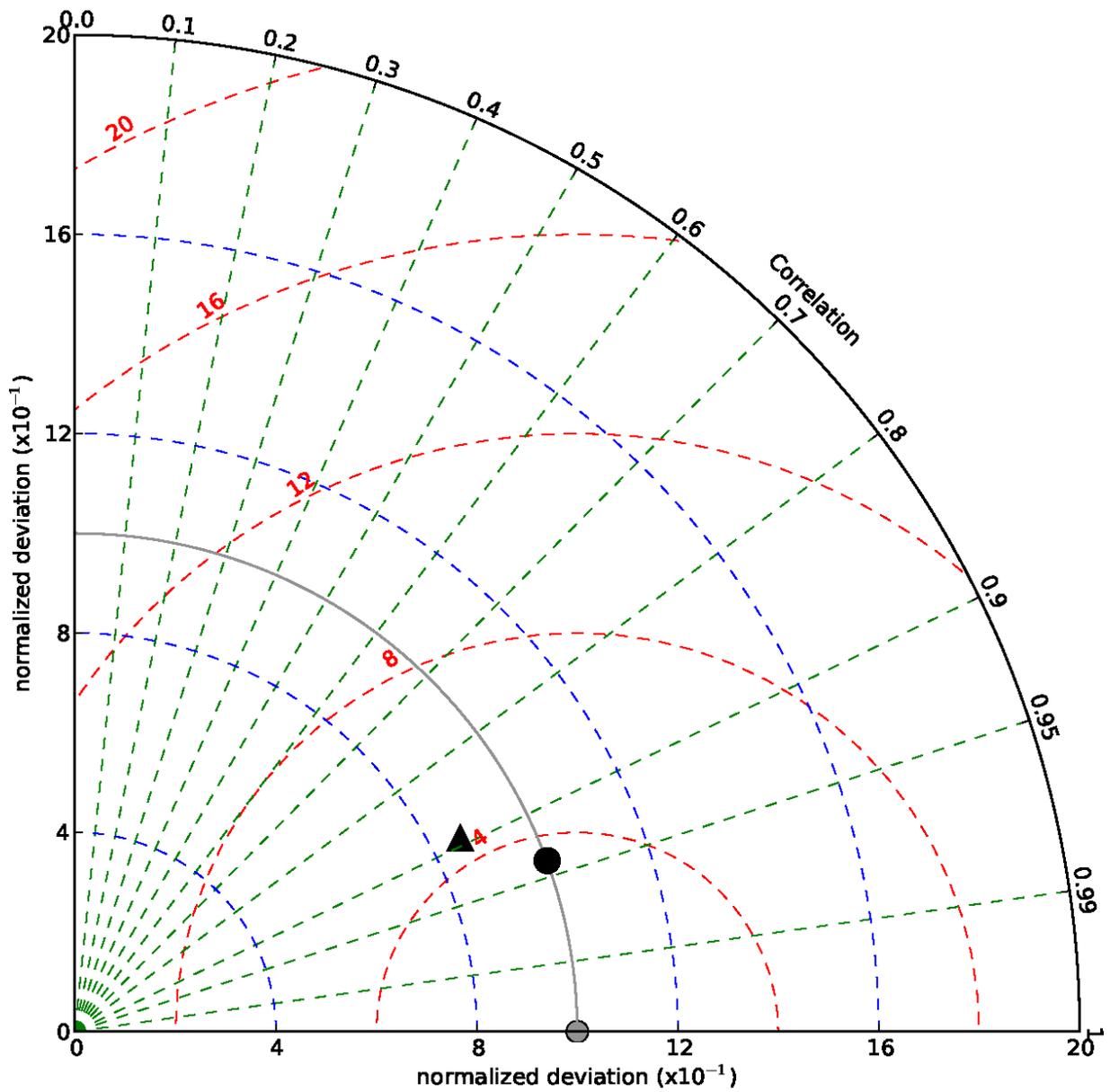
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 2 Figure 12 : Taylor diagram of the steric contributions to the sea level derived from different sub sampling of the
 3 Argo floats (DHA referenced to 900 dbar) with the mass contribution (GRACE GRGS) compared with the
 4 AVISO SSALTO/DUACS merged altimeter SLA. For each sub sampling of the in-situ dataset, the
 5 corresponding collocated altimeter measurements are used.



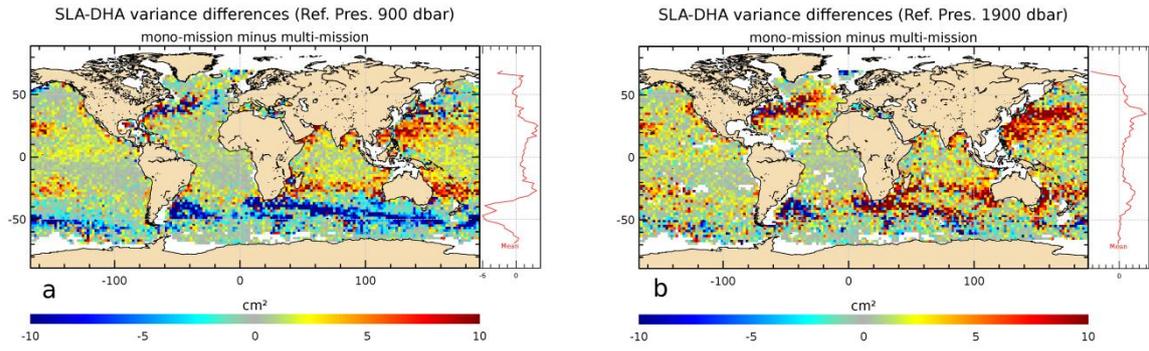
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 2 Figure 13 : Maps of the mean positions of Argo floats taken into account with a given reference depth (a,b) and
 3 the associated floats which will not be used because of their mean max depth shallower than the reference (c,d)
 4 for a 900 m (a,c) and a 1900 m (b,d) reference depth over the period 2005-2013.
 5



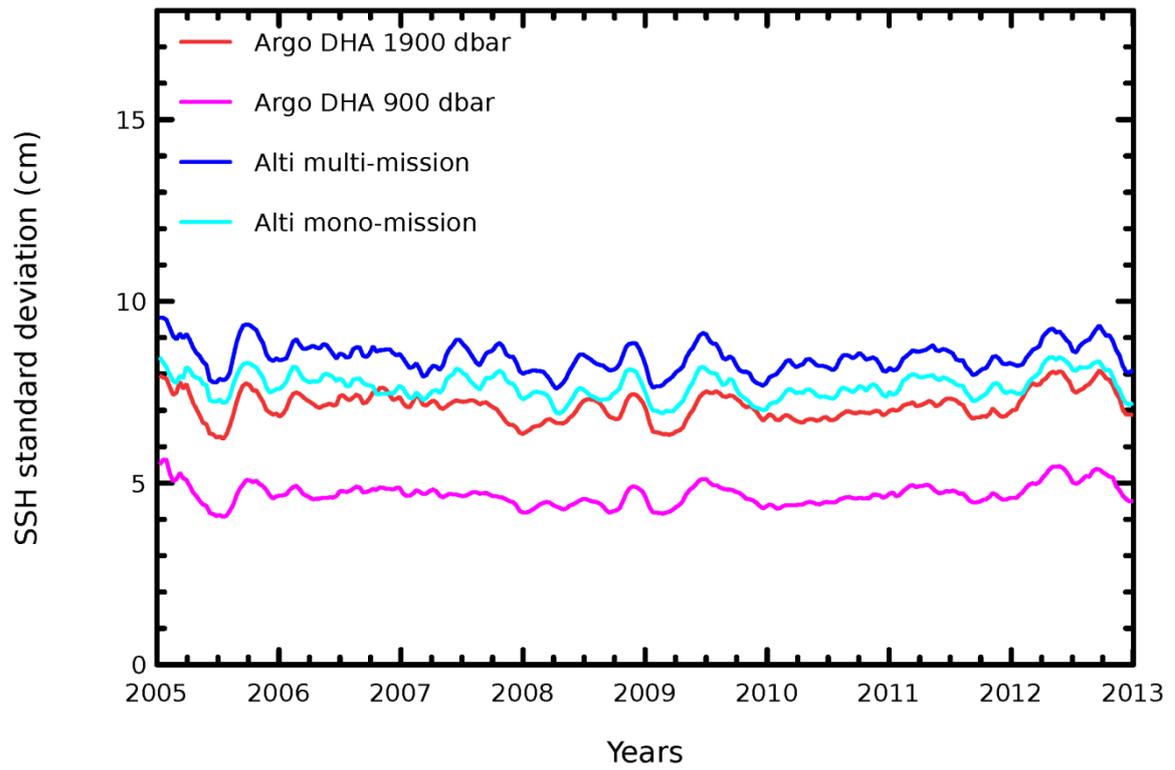
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 2 Figure 14 : Global mean sea level trends of the differences between the altimeter mean sea level (AVISO
 3 SSALTO/DUACS 2014) and the steric plus mass (GRACE GRGS RL03) contributions to the sea level with
 4 various subsets of DHA derived from the Argo network: DHA referenced to 900 dbar from all profiles reaching
 5 at least this pressure (red), DHA referenced to 900 dbar from the profiles reaching at least 1900 dbar (blue) and
 6 DHA referenced to 1900 dbar from all profiles reaching at least this pressure (green). All curves are 3-month
 7 low-pass filtered and a GIA correction is applied to altimeter (-0.3 mm/yr) and ocean mass (-1.1 mm/yr)
 8 measurements (Chambers et al., 2010; Tamisiea and Mitrovica, 2011).



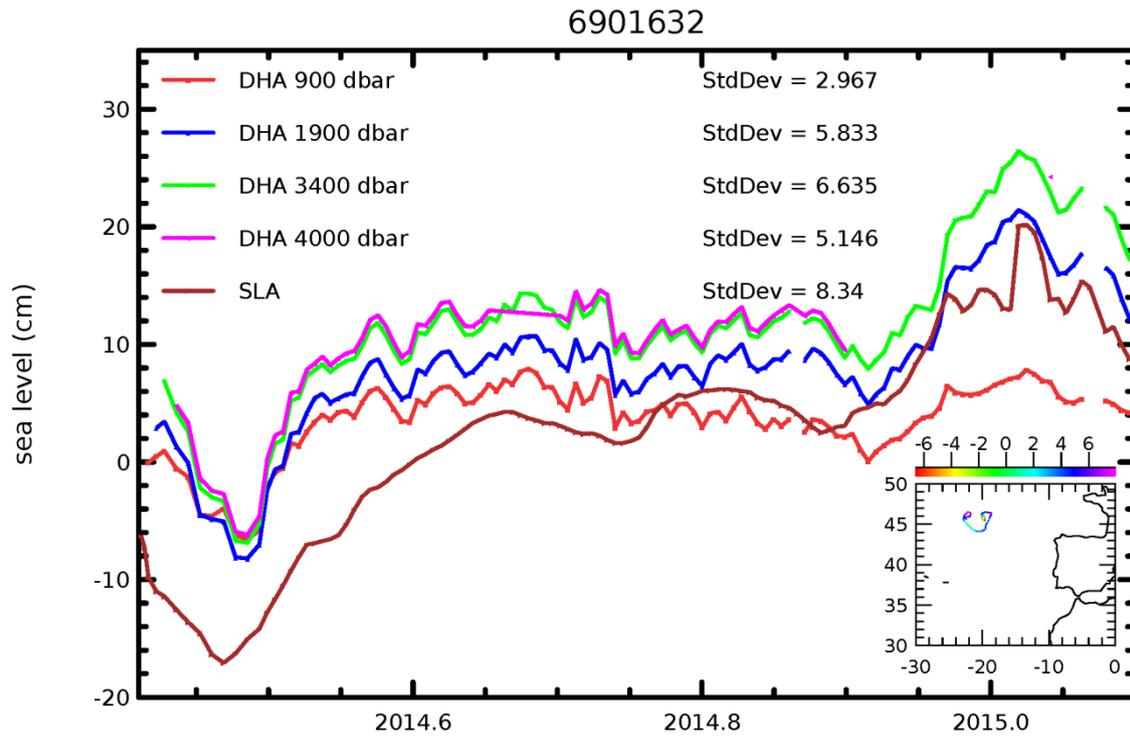
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 2 Figure 15 : Taylor diagram of the comparison of the sum of GRACE ocean mass and the steric Argo DHA with a
 3 reference level at 900 dbar (triangle) and 1900 dbar (circle) with altimetry sea level time series
 4 (SSALTO/DUACS 2014) (grey reference circle) on the x-axis over 2005-2013. The blue dotted lines indicate the
 5 normalized standard deviation (altimetry being the reference).
 6



1
 2 Figure 16 : Map of the difference of variance of the altimeter SLA – Argo DHA differences, using successively
 3 mono mission and multi missions grids of altimeter products with Argo 900 dbar profiles (a) and 1900 dbar
 4 profiles (b).



1
 2 Figure 17 : Temporal evolution of the standard deviation of the altimeter SLA derived from mono mission
 3 product (light blue), from multi-missions product (dark blue) and from Argo profiles with a 900 dbar
 4 reference (magenta) and 1900 dbar reference (red) in the Antarctic Circumpolar Current.



1
 2 Figure 18 : Time series of the DHA derived from the profiles of float WMO 6901632 with different reference
 3 levels of integration varying from 900 dbar (red), 1900 dbar (blue), 3400 dbar (green) down to 4000 dbar
 4 (magenta) together with the collocated altimeter SLA (brown).

3. Sensitivity analyses

3.1. The GRACE dataset: on the leakage of the continental signal

As mentioned in the article previously inserted, the amplitude of the annual signal of the global differences between the total altimeter signal and the steric DHA is about 10 mm (Fig. 8 of the paper) and it is significantly reduced when the ocean mass contribution is also withdrawn. The fact that almost no annual signal remains with the use of the ocean mass contribution constitutes a considerable improvement in our method of comparison and the uncertainty on the absolute trend of altimetry should be significantly reduced.

The ocean mass contribution to the sea level derived from GRACE suffers from different sources of uncertainty such as the correction of the Glacial Isostatic Adjustment (GIA), the correction of the geocenter motion, the harmonic coefficients fit uncertainty and the leakage from land to the ocean. This latter effect is due to the fact that the GRACE signal over land is about ten times greater than the ocean signal. This can be taken into account by removing measurements located at less than about 300 kilometers from the coasts. Figure 1 illustrates that with such selection of the data, the global altimeter sea level trend difference with in-situ Argo data is affected by 0.1 mm/yr over a 10 year long period. As this value is of the order of magnitude of uncertainty associated with the GRACE continental leakage (Chambers et al., 2010, [3]), further analyses are required to determine whether the coastal band should be removed or not.

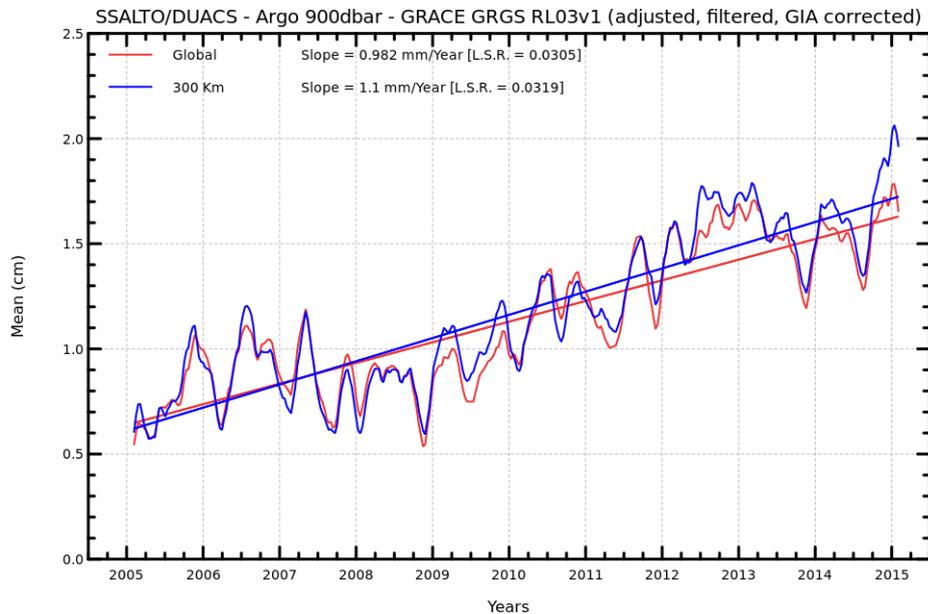


Figure 1: Temporal evolution of the differences between AVISO SSALTO/DUACS SLA, Argo DHA referenced to 900 dbar and GRACE GRGS RL03v1 with (in red) and without (in blue) measurements at less than 300 km from the coasts. Timeseries are adjusted, 2-month filtered and GIA corrected.

3.2. Common temporal reference of SLA and DHA

When comparing both types of data, altimeter SLA and in-situ DHA should have similar physical contents and in particular the same inter annual temporal reference. This means that the altimeter sea level and in-situ steric dynamic height anomalies should be computed over the same temporal reference. This does not affect the global statistics of the SLA-DHA differences (correlation, rms, trend) but it directly impacts the trend differences at regional scales by reducing the amplitude of geographically correlated patterns, as illustrated on figure 2 with the differences between AVISO and Argo measurements without and with a common temporal reference.

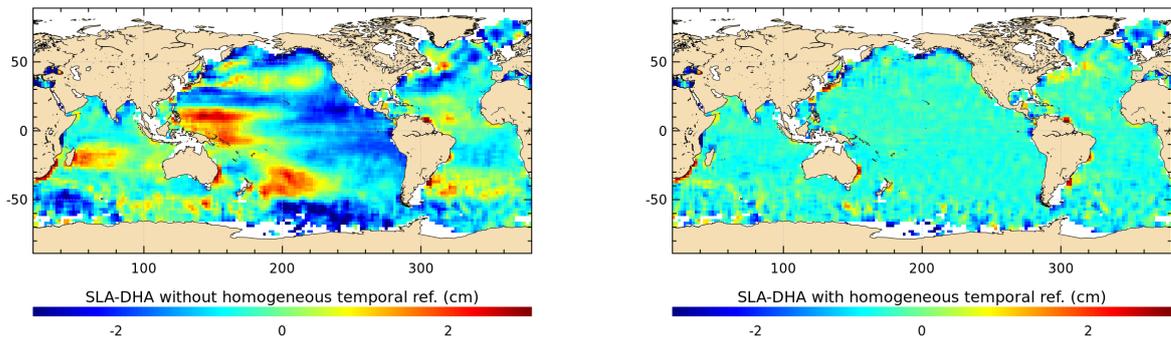


Figure 2: Map of the mean differences between AVISO SSALTO/DUACS and Argo data (900 dbar) over 2005-2015 without (left) and with (right) a common temporal reference period (2003-2014) for the estimation of the SLA and DHA anomalies.

The reference period used to compute the anomalies has been updated in 2015 and has changed from 2003-2011 to 2003-2014. This will contribute to improve the results since the reference period (2003-2014) is now more homogeneous with the temporal coverage of the dataset (2005-2015). The impact of using this longer temporal reference is illustrated on figure 3, showing the impact of using the new 2003-2014 temporal reference compared with the previous one (2003-2011). Large scale geographically correlated patterns are observed with amplitude reaching 2 centimeters. This highlights signals that can not be found any more in the SLA-DHA comparisons thanks to the new reference. This should lead to an improvement of regional analyses and in particular, this will contribute to a better impact estimation of new altimeter standards whose impact is sometimes increased at regional scales.

3.3. Performances of new altimeter missions

Argo measurements (DHA 900 dbar) are used as an independent reference to address whether the SARAL/AltiKa mission is of similar quality as Jason-2 over the period March 2013 - May 2015. Table 1 indicates that over a two-year period of SARAL/AltiKa measurements, the performances of the mission appears to be almost as good as the one of Jason-2 in terms of global correlation, rms of the differences and linear regression between SLA and DHA. This shows that the Argo in-situ network is of great interest for the quality assessment of future altimeter missions.

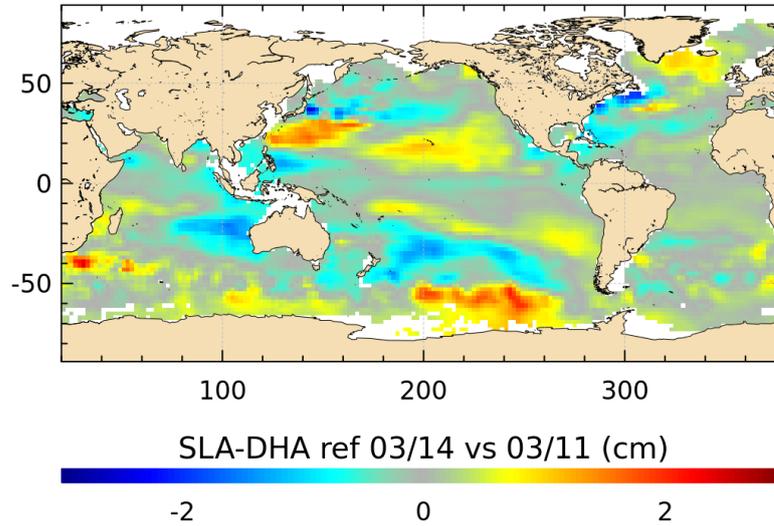


Figure 3: Map over 2005-2015 of the difference between the SLA (AVISO SSALTO/DUACS) - DHA (900 dbar) mean differences computed successively with a common temporal reference covering 2003-2014 versus 2003-2011.

Global statistics DHA 1900 dbar	Correlation	rms of the differences	Slope of the linear regression SLA / DHA
Jason-2	0.74	5.5 cm	0.76 m^{-1}
SARAL/AltiKa	0.74	5.5 cm	0.74 m^{-1}

Table 1: Correlation, rms of the differences and slope of the linear regression between Jason-2 and SARAL/AltiKa altimeter SLA and Argo DHA referenced to 900 dbar over the period March 2013 - May 2015

4. Evaluation of new altimeter standards

4.1. Overview

The impact of a new altimeter standard (orbit solution, geophysical or instrumental correction, retracking algorithm) on the sea level computed from altimetry may be estimated by comparison with in-situ measurements using successively the old and new version of the altimeter standard. Similarly, a new altimeter product can be compared with a reference one. This approach also helps us to better characterize the uncertainty associated with our method.

Several examples have been provided in Legeais et al., 2016 ([6], see in this report), such as the impact of the CNES GDR-E orbit solution compared with the GDR-D standard for the Jason-1 sea level estimation and the comparison of the ESA Sea Level Climate Change Initiative (SL_cci) ECV with the AVISO SSALTO/DUACS L4 products. Concerning the first example, it has been demonstrated that thanks to the comparison with the in-situ Argo independent reference, the GDR-E standard provides improved altimeter performances, particularly regarding the regional scale of the altimeter long term mean sea level evolution, since the large scale hemispheric discrepancies are reduced compared with the in-situ reference. In addition of these examples, the impact of using a new pole tide altimeter correction (Desai 2015) on the sea level estimation is presented in this section.

4.2. New pole tide altimeter correction

The pole tide is the response of the solid Earth and the Oceans to polar motions. The polar motion is has periodic and decadal variations (annual signal, Chandler wobble period=433 days). The mean pole location can be modelled with a bias and the use of a drift is not compulsory. The algorithms used in the models are based on tidal Love numbers.

The polar tide altimeter correction provided by Wahr (1985) is used in all GDR products since TOPEX. In this solution, the mean pole model is a bias only. A new correction (Desai, 2015) has been recently available. It accounts for self-gravitation, loading, conservation of mass, and geocenter motion (spatial dependence). In this solution, the mean pole model includes a bias and a drift (temporal dependence), which means that the computed altimeter pole tide correction does not include the effects of the Earth's displacement response to that mean pole (drift). This can be taken into account thanks to the use of a Glacial Isostatic Adjustment (GIA) model. This impact of this new correction on the altimeter sea level estimation compared with the reference one has been analyzed using the Argo in-situ data as a reference. This is illustrated on figure 4 for Jason-1 mission with a Taylor diagram, separating different temporal scales. At all scales, the sea level variance is closest to the one of the in-situ reference with the new correction. For the annual signal (in green) and the total signal to a lesser extent (in black), the correlation with the in-situ reference is improved. This demonstrates the improved quality of this new pole tide correction.

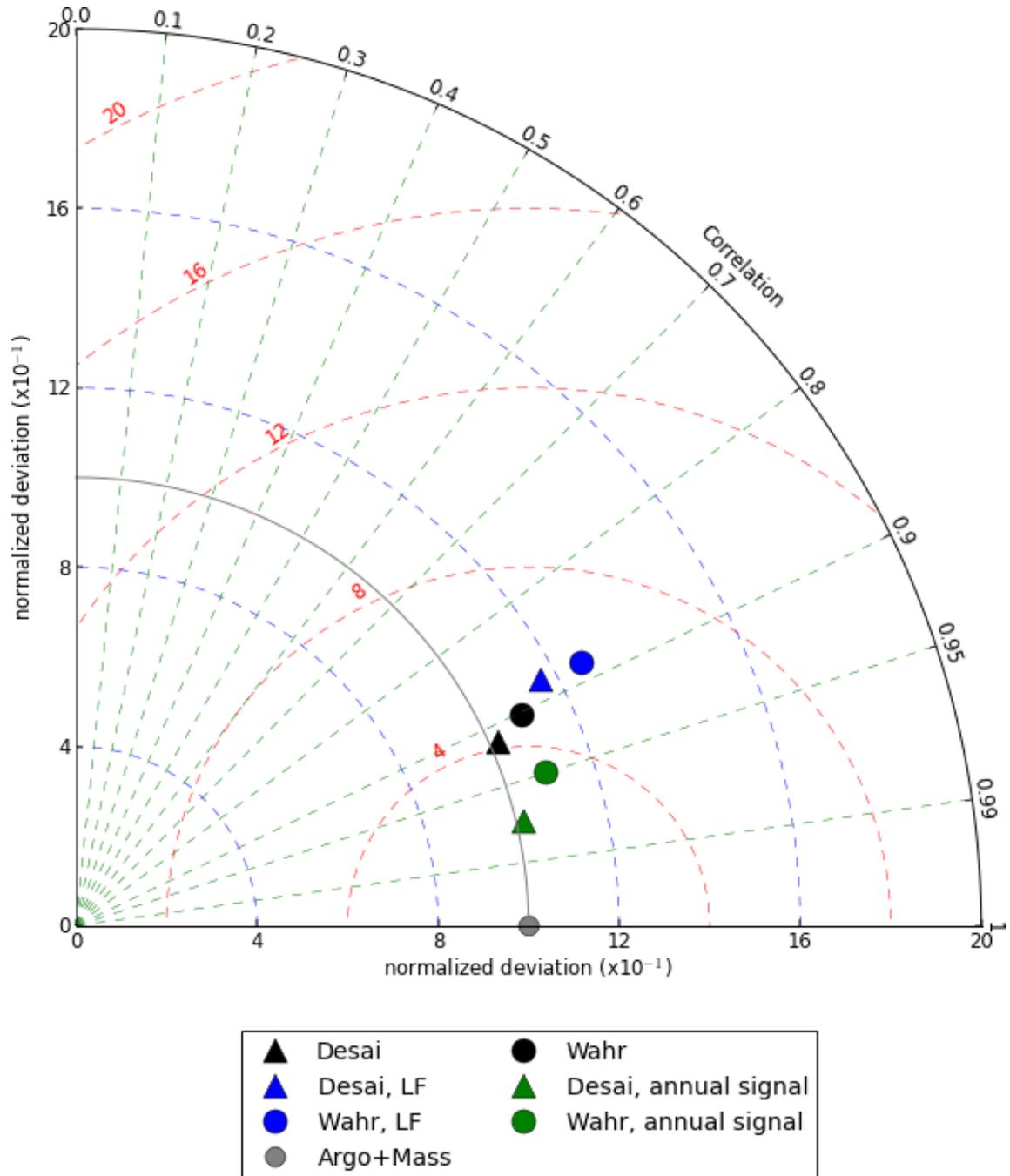


Figure 4: Taylor diagram of two pole tide altimeter corrections (Desai 2015 and Wahr 1985) compared with the sum of Argo DHA (900 dbar) and GRACE ocean mass regarding the Jason-1 altimeter sea level estimation. The comparisons are performed on the total signal (in black), the annual signal (in green) and the low frequency (in blue).

5. Conclusions and futures

The internal consistency check and the comparison with other altimeter missions cannot systematically provide enough information for the quality assessment of altimeter sea level measurements. The in-situ dynamic heights derived from the Argo network can be used as an independent reference for the analysis of the relative mean sea level temporal evolution (including the detection of global and regional MSL drift and anomalies) but also for the detection of the impact of new altimeter standards or products used to calculate the sea surface heights. Our method constitutes an essential approach which has a strong synergy with results derived from the altimetry comparison with tide gauges since the confrontation of both methods improves the confidence in the results. We have demonstrated that it is possible to detect altimeter drifts at global and regional scales and to characterize the impact of new altimeter standards (such as the new GDR-E orbit solution). However, the improvements provided by these new standards and products become more and more reduced and the searched differences may be hidden by the errors of the method. Thus, the activity has focused on better characterizing the uncertainty of the method thanks to sensitivity analyses of the method to different processing parameters.

We have demonstrated that the use of the GRACE ocean mass contribution to the sea level is a major improvement for the estimation of the absolute altimeter mean sea level drift. However, there is a strong sensitivity to the different datasets available and there are significant uncertainties associated with the processing of these GRACE datasets which affect the estimation of the altimeter MSL trend.

Sensitivity analyses performed on the Argo network have indicated that the spatial coverage of the ocean sampled by the instruments is significantly reduced as soon as a limited number of floats are used in the comparisons. However, this hardly affects the global correlation between altimeter SLA and the in-situ DHA plus mass contribution, neither the variance nor the trend of their differences. In addition, the 10-day temporal sampling of Argo floats was not designed for satellite altimetry validation purposes. We have shown that a reduced temporal sampling of the floats can prevent us from detecting the impact of a new altimeter standard.

The choice of the reference level of integration of the Argo T/S profiles for the computation of the steric dynamic heights directly affects the global and regional coverage of the ocean by Argo floats. A relatively deeper reference level allows a better vertical sampling of the water column (more in agreement with what is seen by altimetry) but it leads to a reduced horizontal sampling of the ocean; the impact of the former being more than twice compared with the latter in terms of altimeter MSL trends estimation.

Considering all the sources of errors discussed in this study including the method of collocation, the impact of the reference depth of Argo profiles, the uncertainty on GRACE ocean mass datasets and the error estimation on the deep steric contribution, this suggests that the uncertainty associated with the obtained altimeter drifts is at least of the order of 1.0 mm/yr. The future evolution of the Argo network such as the deployment of deep Argo floats (4,000m) should contribute to improve the results. And as suggested by the comparisons with SARAL/AltiKa measurements (in this report), our approach will also be an asset for the quality assessment of new altimeter missions such as Sentinel-3, Jason-3 and SWOT.

Together with the previously mentioned analyses, some additional studies have focused on the uncertainty of the GRACE measurements associated with the leakage of the continental signal over the ocean and we have illustrated the benefit of using homogeneous inter-annual reference for the computation of the anomalies. This work has contributed to improve the confidence in the results

and particularly at regional scales. The use of in-situ Argo data as a reference has been demonstrated to be a great asset for the estimation of the impact of a new altimeter standard, which has been illustrated with the next pole tide correction. In addition, our approach is the only technique available to estimate the quality of new orbit solutions (Couhert et al., 2014, [4] and Legeais et al. 2016, [6]).

An additional objective of the altimetry versus Argo comparisons is to detect anomalies in in-situ measurements and thus qualify these data. This is supported by a Coriolis project and not performed in the context of this study (Guinehut et al., 2009 [5]). Our results are strongly dependent of this validation phase since it provides reliable datasets of in-situ measurements.

In 2015, extensive communication has been made on this activity at different meetings and workshops: the EuroArgo user workshop (Brest, March 2015), the EGU meeting (Vienna, April 2015), the Sentinel-3 for Science workshop (Venice, June 2015), the Paris climate conference (Paris, July 2015), the Eumetsat Meteorological conference (Toulouse, September 2015) and the OSTST meeting (Reston, VA, October 2015). In addition, a workshop has been organized in Toulouse in June 2015 with users and scientific experts of altimetry and in-situ data (CLS, CNES, LEGOS, Noveltis, Mercator-Ocean) in order to share the points of view and discuss the methods and the results. These meetings aim at increasing the synergy on the activity.

6. References

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