

## **OS62015-111: Author's response following the review process**

Dear editorial board,

First, I would like to thank the two reviewers of my manuscript for their comments. I think they will contribute to improve the quality of the paper and to make it easier to read.

Following the open discussion of my manuscript, I have posted Author Comments (AC1 and AC2) to the two Referee comments (RC1 and RC2). I have provided a point by point response to all referee's comments and listed in details what will be modified in the manuscript.

I now provide the updated abstract and manuscript in line with the Author Comments #1 and #2 with a marked-up version showing the changes made (track changes from MS Word). The structure of the document has been simplified (as suggested by referee 1) so that the most important aspects of the paper are introduced as soon as possible.

Two figures have been removed (1 and 4), the content of figure 9 (now figure 7) has been reprocessed (as suggested by referee 1) and the legend and labels of figure 10 (now figure 8) have been made easier to read (as requested by referee 2).

In addition, as suggested by both referees, the manuscript suffers from English grammatical errors and I would like to ask you if it is possible to perform a copy-editing of the manuscript so that its quality will be improved?

Let me know if this is possible.

Best regards,  
Jean-François Legeais

# Analyses of altimetry errors using Argo and GRACE data

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## Abstract.

This study presents the evaluation of the performances of satellite altimeter missions by comparing the altimeter sea surface heights with in-situ dynamic heights derived from vertical temperature and salinity profiles measured by Argo floats. The two objectives of this approach are the detection of altimeter drift and the estimation of the impact of new altimeter standards that requires an independent reference. This external assessment method contributes to altimeter Calibration and Validation analyses that cover a wide range of activities. Among them, ~~our approach focuses on the detection of altimeter drift and the estimation of the impact of new altimeter standards that requires an independent reference. several examples are given to illustrate the usefulness of this approach~~The methodology and the Argo data used are first described and altimeter validation activities are then ~~illustrated with some examples~~, 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. The latter requires the use of the ocean mass contribution to the sea level derived from GRACE measurements. Our analyses ~~cover~~are related to different subjects ranging from the estimation of the global mean sea level trend, to the validation of multi-missions altimeter products as well as the assessment of orbit solutions.

Even if this approach contributes to the altimeter quality assessment, the differences between two versions of altimeter standards are getting smaller and smaller and it is thus more difficult to detect their impact. It is therefore essential to characterize the errors of the method, which is illustrated with the results of sensitivity analyses to different parameters. This includes the format of the altimeter data, the method of collocation, the temporal reference period and the processing of the ocean mass solutions from GRACE. We also assess the impact of the temporal and spatial sampling of Argo floats, the choice of the reference depth of the in-situ profiles and the importance of the deep steric contribution. These analyses This provides an estimation of the robustness of the method and the characterization of associated errors. The results also allow us to draw some recommendations to the Argo 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  
4 understanding the role of the ocean in the Earth system and to assess the link with the global climate change.  
5 Altimeters are available onboard several missions currently on flight (Jason-2 [& 3](#), SARAL/AltiKa, CryoSat-2,  
6 [Sentinel-3](#), HY-2A) and providing no data anymore (TOPEX/Poseidon-T/P-, ERS-1&2, Jason-1, Envisat, Geosat  
7 Follow-On). Although sea level estimates are becoming more precise, there are still some uncertainties which  
8 can be distinguished at different temporal scales (long-term trend, inter annual signals and periodic signals) both  
9 at global and regional scales (Ablain et al., 2015). The major sources of errors are attributed to orbit solutions,  
10 instrumental corrections and some geophysical altimeter corrections such as the wet troposphere correction  
11 (Ablain et al., 2009, Couhert 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). [Taking  
22 advantage of the consistency between these in-situ measurements and altimeter SLA \(Guinehut et al., 2006;  
23 Dhomps et al., 2011\), several examples illustrate the usefulness of the comparison between these data in order to  
24 reach two major objectives in terms of calibration and validation of altimeter data.](#)

25 [The first objective deals with the detection of drifts and jumps in the altimeter sea level time series. For instance,  
26 at global scale, the MSL trends of the Envisat and Jason-1 missions differ by 1.0 mm/yr over the period 2004-  
27 2011 \(Prandi et al., 2013\). The absolute comparison of both altimeter MSLs with Argo and GRACE  
28 measurements indicates that the MSL drift is greater for the Envisat than Jason-1 mission with a 1.4 mm/yr  
29 difference, which is confirmed by the 0.9 mm/yr difference provided by the altimeter comparison with tide  
30 gauges measurements over the same period \(Prandi et al., 2013\). The use of in-situ data as a reference allows the  
31 detection and identification of the origin of global altimeter MSL trend discrepancy between two missions that  
32 cannot be addressed by internal comparison only. Note that this Envisat drift is well known \(Ollivier et al., 2012\)  
33 and is no more observed with the use of the Envisat reprocessed measurements which have made both altimeter  
34 trends more homogeneous.](#)

35 [The second objective is to assess the potential improvement provided by a new altimeter standard \(e.g., orbit  
36 solution, geophysical corrections\) in the SLA estimation \(or new altimeter product\), regarding the long-term  
37 evolution of the mean sea level or its variability, at global or regional scales, thanks to relative or absolute  
38 comparisons. A first example is provided by the regional East/West hemispheric bias observed in the spatial  
39 distribution of the Jason-1 MSL trends with the use of the GDR-D orbit solution \(Legeais et al., 2015\). As Argo  
40 measurements are considered to be free of this regional anomaly, the relative comparison of the MSL trends](#)

1 differences between SLA and DHA (computed in two different East/West regions where the greatest differences  
2 are observed) illustrate the strong regional discrepancy obtained with the GDR-D orbit solution (Figure 1a: 2.3  
3 mm/yr). The use of the updated GDR-E orbit solution in the Jason-1 MSL calculation leads to a significant  
4 reduction of the regional discrepancies of the MSL trends (Figure 1b, right: 0.1 mm/yr), which demonstrates the  
5 better quality of this new altimeter standard. As discussed in Valladeau et al, 2012, the global Argo  
6 measurements are the only in-situ external reference that allows us to discriminate such an impact regarding the  
7 altimeter MSL. Secondly, the independent Argo sea level estimations can be used at global scale, by relative  
8 comparison and in terms of MSL variability to distinguish two different altimeter products such as the climate-  
9 oriented SL\_cci v1.1 ECV product (Cazenave et al., 2014a; Ablain et al., 2015) and the 2014 SSALTO/DUACS  
10 time series (AVISO Handbook, 2014; Pujol et al., 2015). This is illustrated on Figure 2 (with triangles and  
11 circles respectively) thanks to the Taylor Diagram formalism (Taylor, 2001). Different frequencies of the  
12 differences between SLA and DHA are distinguished (total signals in black, annual cycle in green, high  
13 frequencies in red and inter annual signals in blue) and such diagram provides a way of graphically summarizing  
14 how closely different signals match observations (in-situ data: gray dot on the bottom axis) in terms of their  
15 correlation, their centered root-mean-square difference and the ratio of their variances. Both altimeter products  
16 have an annual cycle highly correlated with the in-situ reference (in green), that has to be removed before  
17 analyzing others signals. The diagram reveals that the products cannot be significantly distinguished regarding  
18 the total signals (in black), their annual cycle (in green) and their high frequencies (in red). At low frequencies  
19 (in blue), the SL\_cci product (triangle) is more in agreement with in-situ data than the SSALTO/DUACS product  
20 (circle). As the quality of climate products is rather addressed at these low frequencies (inter-annual and long-  
21 term evolution of the sea level), this highlights the better relevance of the SL\_cci products for climate studies.  
22 However, the correlations of each altimeter data with the in-situ reference are similar.  
23 Furthermore, the differences between the reprocessed AVISO/DUACS 2014 product (AVISO Handbook, 2014)  
24 and its previous release (2010 reprocessing) are sometimes reduced and difficult to characterize (Pujol et al.,  
25 2015). The relative comparison of these datasets with Argo measurements shows that in the Bay of Bengal, the  
26 use of the new altimeter release leads to a reduced variability ( $-1 \text{ cm}^2$ ) of the SLA minus DHA differences (not  
27 shown) and a slightly greater correlation and a reduced rms of the differences with the in-situ reference (see  
28 Table 1).  
29 All these illustrations clearly demonstrate that the Argo in-situ measurements are a valuable tool to detect  
30 altimeter drift and to assess the impact of a new altimeter standard or product, regarding the long-term evolution  
31 of the mean sea level or its variability, at global or regional scales. However, the evolutions provided by the new  
32 algorithms allowing the sea level calculation (orbit solution, instrumental corrections, geophysical corrections,  
33 mean sea surface) become more and more difficult to assess (Stammer et al., 2014; Fernandes et al., 2015;  
34 Couhert et al., 2014). Hence, it is essential to determine to which extent the comparison with Argo independent  
35 measurements can be used to contribute to the quality assessment of these new algorithms and thus to better  
36 characterize the remaining errors of the method of comparison and its sensitivity to the various parameters. The  
37 consistency between these in-situ measurements and altimeter SLA has already been discussed (Guinehut et al.,  
38 2006; Dhomps et al., 2011, Valladeau et al., 2012), showing that Argo DHA can be used as a reference (i) to  
39 detect drifts and jumps in the altimeter sea level time series to enable an assessment of the global and regional  
40 MSL trend and (ii) to assess the potential improvement provided by a new altimeter standard (e.g., orbit solution,

1 ~~geophysical corrections) in the altimeter SLA estimation. Argo data is thus a valuable tool to assess altimeter~~  
2 ~~performances. However, the evolutions provided by the new algorithms allowing the sea level calculation (orbit~~  
3 ~~solution, instrumental corrections, geophysical corrections, mean sea surface) become more and more difficult to~~  
4 ~~assess (Stammer et al., 2014; Fernandes et al., 2015; Couhert et al., 2014). Hence, it is essential to determine to~~  
5 ~~which extent the comparison with Argo independent measurements can be used to contribute to the quality~~  
6 ~~assessment of these new algorithms and thus to better characterize the remaining errors of the method of~~  
7 ~~comparison and its sensitivity to the various parameters. Following the description of~~  
8 ~~the paper is organized as~~  
9 ~~follow: the different datasets used in our study are presented in (section 2), and the details of the method of~~  
10 ~~comparison of altimeter with in situ measurements are given in section 3. Some examples of altimeter validation~~  
11 ~~thanks to Argo data are presented in section 4 and sensitivity analyses of the method to different parameters are~~  
12 ~~presented. This includes the format of the altimeter data, the method of collocation, the temporal reference~~  
13 ~~period and the processing of the ocean mass solutions from GRACE. We also assess the impact of the temporal~~  
14 ~~and spatial sampling of Argo floats, the choice of the reference depth of the in-situ profiles and the importance of~~  
15 ~~the deep steric contribution. Section 5 is dedicated to the presentation of the sensitivity analyses of the method to~~  
16 ~~various parameters.~~ At last, concluding remarks are provided on the method uncertainty and the results also  
17 allow us to draw some recommendations for the Argo community regarding the maintenance of the in-situ  
18 network.

## 18 **2 Datasets**

### 19 **2.1 Altimetry**

20 Radar altimeters provide sea Surface height measurements which need to be referenced and corrected from  
21 geophysical signals to determine SLA which can be compared with in-situ measurements. Along-track level 2  
22 SSH from several satellite altimeters are used, where standards are updated compared with the geophysical Data  
23 Record (GDR) altimeter products. Details of the SSH computation and time period for each altimeter are  
24 available in the MSL part of the AVISO website ([http://www.aviso.oceanobs.com/en/news/ocean-](http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/processing-corrections/)  
25 [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  
26 computed with a reference to the Mean Sea surface (MSS) CNES/CLS11 model (Schaeffer et al., 2012). Grids of  
27 merged altimeter products (level 4) are also compared with in-situ data.

### 28 **2.2 Argo**

29 In this study, we use delayed mode and real time quality-controlled T/S profiles (Guinehut et al., 2009) from the  
30 Coriolis Global Data Assembly Center ([www.coriolis.eu.org](http://www.coriolis.eu.org)). Following Roemmich and Gilson (2009),  
31 considering a threshold of two thirds of the surface of the global open ocean covered by Argo floats, analyses  
32 should be performed with in-situ data dating only from 2005 onwards. This is a relevant reference for the latest  
33 altimeter missions (Envisat, Jason-1, Jason-2, ~~Jason-3, and~~ SARAL-AltiKa ~~and Sentinel-3~~) and results in an in-  
34 situ dataset of more than 10,000 floats with about 900,000 T/S profiles distributed over almost the whole open  
35 ocean. ~~Dynamic Height Anomalies (DHA) are computed as follows: dynamic heights are first computed from~~  
36 ~~the integration of the Argo pressure, temperature and salinity vertical profiles using a reference depth. In order to~~  
37 ~~calculate anomalies of dynamic heights consistent with altimeter SLA, a mean dynamic height is used as a~~  
38 ~~reference. It is estimated through a synthetic climatology approach (Guinehut et al., 2006): the technique consists~~  
39 ~~in combining altimeter SLA with simultaneous in-situ dynamic height to estimate the mean dynamic height.~~  
40 ~~Dynamic Height Anomalies (DHA) are then computed from the integration of the vertical density profiles using~~

~~a reference depth and a synthetic mean dynamic height.~~ The choice of the reference level is discussed in this paper.

### 2.3 GRACE

Altimeter measurements are representative of the total elevation of the sea surface (surface to bottom), that includes barotropic and baroclinic components. DHA from Argo profiling floats are representative of the steric elevation associated with the ~~thermohaline~~ expansion and contraction of the water column from the surface to the reference level of integration (i.e. baroclinic component) (Dhompas et al., 2011). ~~However, the relative comparison between altimeter SLA and in-situ DHA may be sufficient to detect an anomaly between two different missions or the impact of a new altimeter standard in the SLA calculation. The analysis of the absolute altimeter drift and bias requires the addition of the mass contribution to the Argo dataset so that similar physical contents can be compared. This ocean mass contribution~~ As described in the previous section, the relative comparison between altimeter SLA and in-situ DHA is sufficient to detect an anomaly between two different altimeter missions or the impact of a new altimeter standard in the SLA calculation. However, the analysis of the absolute altimeter drift and bias requires the addition of the ocean mass contribution to the sea level which is not included in the in-situ measurements. This contribution is derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. It provides a series of Earth gravity fields in the form of truncated sets of spherical harmonic (~~Stokes~~SH) coefficients (Stokes) at approximately monthly intervals (Tapley et al., 2004), whose ~~Their~~ temporal variations can be used to estimate changes in the ocean mass distribution in terms of equivalent water thickness (Chambers et al., 2004; Llovel et al., 2014; Ponte et al., 2007). As the total mass of the Earth is assumed to be unchanged, the time-variable mean ocean mass is related with the exchanges of water mass with the continents and the atmosphere. These exchanges significantly contribute to the inter annual evolution of the global MSL (Fasullo et al., 2013; Cazenave et al., 2014b). In this study, two ocean mass solutions are used: ~~T~~ the monthly grids of equivalent water height from the Groupe de Recherche en Geodesie Spatiale (GRGS RL03v1; Biancale et al., 2014) and ~~When discussing the global altimeter performances, the temporal evolution of the global mean ocean mass contribution time series from GRACE RL05 is also used,~~ as provided ~~posed~~ by the University of South Florida – Satellite Oceanography Laboratory (available at: <http://xena.marine.usf.edu/~chambers/SatLab/Home.html>, last access: July 9<sup>th</sup> 2014) and described in Johnson and Chambers, 2013.

### 3 Method

~~The comparison of the altimeter SLA from a single mission is based on the along track sea level measurements. As the altimeter sampling is better than the in-situ coverage (offering a global coverage of the ocean for Jasons missions versus a single T/S profile every ten days), grids of 10-day averaged along track SLA are interpolated for each altimeter mission at the location and time of each T/S profile (bi-linearly in space and linearly in time). Similarly, the quality assessment of gridded merged SLA altimeter products (L4) can be estimated after collocation with the in-situ profiles.~~

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

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

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

#### 11 **4 Altimeter Sea Level Validation**

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

##### 16 **4.1 Detection of global altimeter drifts**

17 At global scale, the MSL trends of the Envisat and Jason 1 missions differ by 1.0 mm/yr over the period 2004-  
18 2011 (Prandi et al., 2013). The absolute comparison of both altimeter MSLs with Argo and GRACE  
19 measurements indicates that the MSL drift is greater for the Envisat than Jason 1 mission with a 1.4 mm/yr  
20 difference (Fig. 1). The altimeter comparison with tide gauges measurements over the same period highlights a  
21 0.9 mm/yr difference (Prandi et al., 2013) which confirms the greater drift of the Envisat mission. Thus the  
22 combination of different types of in situ data allow to detect and identify the origin of global altimeter MSL  
23 trend discrepancy between two missions that cannot be addressed by internal comparison only. This Envisat drift  
24 is well known and has been related with the altimeter standards and instrumental corrections used for the  
25 estimation of the Envisat sea level (Ollivier et al., 2012). This is no more observed with the use of the Envisat  
26 reprocessed measurements which have made both altimeter trends more homogeneous.

##### 27 **4.2 Detection of the impact of new altimeter standards**

28 The Argo steric heights are used as a reference in order to estimate the impact of new altimeter standards used  
29 for the altimeter sea level calculation. For instance, the use of the GDR D orbit solution leads to a regional  
30 East/West hemispheric bias in the spatial distribution of the Jason 1 MSL trends (Legeais et al., 2015). As Argo  
31 measurements are considered to be free of this regional anomaly, the relative comparison of the MSL trends  
32 differences between SLA and DHA (computed in two different East/West regions where the greatest differences  
33 are observed) illustrate the strong regional discrepancy obtained with the GDR D orbit solution (Figure 1 Fig. 2a:  
34 2.3 mm/yr). The in situ Argo network is used to assess the impact of the updated GDR E orbit standard in the  
35 Jason 1 MSL calculation. The significant reduction of the hemispheric trend differences (Figure 1 Fig. 2b, right:  
36 0.1 mm/yr) proves that the estimation of the altimeter SLA is improved with this new altimeter standard since  
37 the regional discrepancies of the MSL trends are reduced. As discussed in Valladeau et al, 2012, the global Argo  
38 measurements are the only in situ external reference that allows us to discriminate such an impact regarding the  
39 altimeter MSL.

##### 40 **4.3 Detection of the impact of new altimeter products**

1 The independent Argo sea level estimations can also be used at global scale to distinguish two different altimeter  
2 L4 merged products by relative comparison in terms of MSL variability. The Sea Level Climate Change  
3 Initiative (SL\_cci) project has provided climate oriented Sea Level products (Cazenave et al., 2014; Ablain et al.,  
4 2015) and we are interested in characterizing the differences between the SL\_cci v1.1 ECV product and the 2014  
5 SSALTO/DUACS time series (AVISO Handbook, 2014; Pujol et al., 2015). In order to isolate specific signals  
6 and better discriminate the datasets, different frequencies of the differences between altimeter SLA and in situ  
7 DHA are distinguished. The correlation and the standard deviation of these differences are estimated over the  
8 global ocean at different temporal scales. This is illustrated on Figure 2 Fig. 3 using the SL\_cci (triangles) and  
9 SSALTO/DUACS 2014 (circles) products, thanks to the Taylor diagram formalism (Taylor, 2001). Such  
10 diagram provides a way of graphically summarizing how closely different patterns match observations (in situ  
11 data: gray dot on the bottom axis). The similarity between two patterns is quantified in terms of their correlation,  
12 their centered root mean square difference and the ratio of their variances. The statistics are indicated for the  
13 total signals (in black) but also for the annual cycle (in green), high frequencies (in red) and inter-annual signals  
14 (in blue). The very high correlation (0.98) found between altimetry and in situ data for the annual cycle only (in  
15 green) indicates that this signal is at the origin of most of the similarities between both types of data, showing  
16 that it is necessary to remove these annual variations before analyzing other frequencies. This Taylor diagram  
17 reveals that both altimeter products cannot be significantly distinguished regarding the total signals (in black),  
18 their annual cycle (in green) and their high frequencies (in red). At low frequencies (in blue), the SL\_cci product  
19 (triangle) is more in agreement with in situ data than the SSALTO/DUACS product (circle) which is in favor of  
20 a product dedicated to climate studies. However, the correlations of each altimeter data with the in situ reference  
21 are similar.

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

### 32 **5.3 Sensitivity of the method**

33 This section focuses on the determination of the errors of the method of comparison of altimetry with *in situ*  
34 Argo and GRACE data and provides sensitivity analyses of the method to different parameters. For each  
35 analysis, the impact of a parameter is estimated regarding the long-term evolution of the mean sea level or its  
36 variability at global or regional scales. In the following, the term “error” is considered as a quantity that would  
37 be removed if it was known whereas the term “uncertainty” is associated with the confidence that can be  
38 attributed to the estimation of a given parameter. The fit uncertainty provided with the long term trend  
39 estimations can be considered as a standard error: the confidence interval is one standard deviation of the  
40 statistical distribution of the trend estimators. In addition, comparisons of altimeter SLA with in-situ DHA suffer



1 from systematic errors. However, their realizations are the same when the SLA – DHA differences are analyzed  
2 by relative comparisons (for instance with the use of a new and reference altimeter standards in the SLA  
3 calculation or successively in two different hemispheres). In this case, these errors cancel each other, which  
4 make possible the detection of some trend differences.

### 5 **5.1 Format of altimeter data**

6 The altimeter sampling provides a global coverage of the ocean within 10 days (for Jasons missions) whereas in-  
7 situ Argo floats provides only one profile over this period. Thus, the quality assessment of a single altimeter  
8 mission is performed after computing grids of 10-days box-averaged along-track SLA which are then  
9 interpolated at the location and time of each T/S profile (bi-linearly in space and linearly in time). The size of the  
10 boxes has been chosen. As presented earlier, the assessment of a single altimeter missions is based on the  
11 collocation of each in-situ profile (linearly in space and time) with grids of 10 days box averaged along track  
12 SLA with boxes of 1° latitude x 3° longitude in order to take into account the number of altimeter tracks per  
13 cycle and also the rather zonal ocean circulation because of the Coriolis force associated with the rotating effect  
14 of the Earth. The sensitivity of the method to this size of boxes is estimated by comparing the results with 1°x1°  
15 grids of along-track altimeter SLA. The amplitude and phase of the annual signal of the SLA – DHA differences  
16 are not affected by this change of box size, neither the trend of the differences (not shown).

17 The variance of the SLA-DHA differences is computed for the time series of each Argo floats, using  
18 successively the two different sizes of boxes for altimetry. The histogram of the difference of these variances for  
19 all Argo floats (Figure 3Fig-5) provides a mean of +1,3 cm<sup>2</sup>, which indicates that averaging along-track  
20 altimeter data with 1°x3° boxes makes altimeter data more coherent with in-situ Argo observations. This  
21 processing is therefore chosen for the comparisons.

### 22 **5.2 Error of collocation**

23 In order to improve the correlation between both types of data (and thus increase the accuracy of the results),  
24 outliers (corresponding to differences between altimeter SLA and in-situ DHA greater than 0.20 m) are filtered  
25 out. All associated measurements are located in regions of high ocean variability, which is expected given the  
26 method of collocation of both types of data. In these regions, the time of two co-located altimeter and in-situ  
27 measurements may not be strictly the same and the associated impact may be higher as the ocean state may  
28 change significantly within less than 10 days. The variability of the SLA – DHA differences are larger in regions  
29 of high ocean variability since the collocation of altimeter and in-situ measurements is performed by  
30 interpolation of 10 days box averaged along track SLA at the position and time of each Argo profile. Hence, the  
31 time of two co-located altimeter and in-situ measurements may not be strictly the same and the associated impact  
32 may be higher in areas of high ocean variability where the ocean state may change significantly within less than  
33 10 days.–Note that this effect could be reduced by computing maps of altimeter measurements by optimal  
34 interpolation. However, this is very time consuming since a set of grids has to be computed for a specific mission  
35 as soon as the impact of a new altimeter standard has to be evaluated.

36 In order to estimate the error of the method associated with these regions of high ocean variability, the  
37 comparison of altimeter data with Argo measurements could be performed after removing areas where the ocean  
38 variability is higher than a given threshold. In terms of spatial coverage, the lower this threshold, the larger areas  
39 are removed. The detection of altimeter drift is not affected by the exclusion of areas of high ocean variability.  
40 Indeed, the 2.07 mm/yr trend of the mean differences between SSALTO/DUACS and Argo DHA (900 dbar

1 reference) is not significantly changed when areas of ocean variability higher than 100 cm<sup>2</sup> are excluded (2.16  
2 mm/yr). This will be confirmed with results described later in this paper regarding the sensitivity to the spatial  
3 sampling of the Argo network. ~~Figure 4~~Figure-6 (left) illustrates that the lower the threshold on the ocean  
4 variability, the larger areas are removed and thus, a lower number of observations is available. The right panel  
5 indicates that when larger areas are removed, the correlation between altimeter SLA and Argo DHA gets lower  
6 and the rms of the differences (expressed in percentage of the altimeter variance) increases. This indicates that  
7 contrary to the trend of the SLA-DHA differences which is less sensitive, the global statistics computed between  
8 altimetry and Argo data are significantly affected by the areas of large ocean variability. This suggests that the  
9 areas of large ocean variability significantly contribute to the global statistics computed between altimetry and  
10 Argo data. However, this does not allow us to determine whether an increased sampling of these regions by the  
11 Argo network would improve the results of altimetry validation.

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

### 17 **5.3 Impact of the temporal reference period**

18 When comparing altimeter SLA and in-situ DHA, both types of data, it is critical that both types of data  
19 altimeter SLA and in-situ DHA should have similar physical contents and in particular the same inter annual  
20 temporal reference. The in-situ DHA are referenced to a synthetic mean Argo dynamic height calculated over the  
21 period 2003-2014 and the temporal reference of the altimeter SLA is adapted to this period by removing the  
22 mean of AVISO SSALTO/DUACS SLA maps (AVISO Handbook, 2014) over 2003-2014 from each altimeter  
23 measurements. The homogenization of the temporal references. This does not affect the global trend differences  
24 but it directly impacts the trend differences at regional scales. In addition, the detection of the evolution provided  
25 by a new altimeter standard or product in terms of global correlation between all collocated altimeter SLA and  
26 in-situ DHA may be distorted whether the temporal reference is homogeneous or not between both types of data.  
27 Table 2Table-2 indicates that without a homogeneous temporal reference, the reprocessed AVISO  
28 SSALTO/DUACS DT 2014 product is more correlated with Argo DHA than the previous release of these  
29 products. However, no difference of correlation is observed when the anomalies are computed with the same  
30 temporal reference. This illustrates a particular type of error of the method of comparison (different temporal  
31 references) that can be corrected (by referencing both datasets on the same period).

### 32 **5.4 Impact of the GRACE data set and associated errors**

33 At regional scales and particularly in the tropical ocean, total altimeter and steric annual signals are in phase  
34 (Dhomps et al., 2011, Legeais et al., 2015) but due to the spatial distribution of the ocean on the Earth and  
35 seasonal hemispheric signals, the global time series are affected by a quadratic phase shift (Figure 5Fig-7 and  
36 Chen et al., 1998). Regarding the ocean mass contribution to the sea level, its annual signal has a larger  
37 magnitude (twice) than total and steric signals and is in phase with the total altimeter global MSL. ~~The addition~~  
38 ~~of the mass contribution from GRACE to the Argo dataset provides homogeneous physical content with~~  
39 ~~altimeter SLA (except the deep steric contribution) (Figure 5~~Fig. 7), which is required to estimate the altimeter  
40 ~~absolute drift.~~ In addition, Figure 6Figure-8 highlights that the amplitude of the annual signal of the global

1 differences between the total altimeter signal and the steric DHA is about 10 mm (in red) and it is significantly  
2 reduced when the ocean mass contribution is also withdrawn (in blue). Thus, the addition of the mass  
3 contribution from GRACE to the Argo dataset provides homogeneous physical content with altimeter SLA  
4 (except the deep steric contribution) and makes possible This demonstrates the relevance of this ocean mass  
5 contribution for the detection of the altimeter absolute drift-detection.  
6 Such detection The analysis of altimeter absolute drift requires a good accuracy of the long term changes in  
7 ocean mass (trends, inter-annual to decadal variations) and two important corrections have to be taken into  
8 account ~~for such analyses~~. The first one is the Glacial Isostatic Adjustment (GIA) which is a gravity effect. It is  
9 related to the Post Glacial Rebound (Tamisiea and Mitrovica, 2011) whose oceanographers are not interested in  
10 since they rather want to assess the current mass movements. ~~The GRACE ocean measurements have to be~~  
11 ~~corrected of a GIA of 1.1 mm/yr (Chambers et al., 2010). However, GIA does not represent the mass~~  
12 ~~redistribution of continental ice to the oceans, which should be corrected.~~ Based on tests with different ice  
13 loading histories and Earth models, the GIA uncertainty is estimated to be ~~30% (-about 0.3 mm/yr)~~ (Chambers  
14 et al., 2010; 2016). The second essential ocean mass correction deals with the degree 1 geocenter motion.  
15 Satellites move about the mass center of Earth but it moves over time relative to the fixed geometric center and  
16 we are interested in the mass loss relative to a fixed frame (i.e., the crust). In addition, the redistributions of ice  
17 from Greenland, Antarctica, and mountain glaciers affect geocenter trends and although the effects offset  
18 somewhat, the uncertainty associated with this correction of geocenter motion in terms of equivalent sea level is  
19 estimated to be 0.1 mm/yr (Swenson et al., 2008; Chambers et al. 2007). In addition of these GIA (0.3 mm/yr)  
20 and geocenter (0.1 mm/yr) uncertainties, the global mean ocean mass evolution is also affected by the harmonic  
21 SH coefficients fit uncertainty (0.1 mm/yr) and the leakage from land to the ocean. This latter effect can be taken  
22 into account by removing a 300 km coastal band but the remaining uncertainty is also of the order of 0.1 mm/yr.  
23 The detection of the altimeter absolute drift is thus significantly affected when introducing GRACE  
24 measurements.

25 Regarding the global altimeter drift, ~~Figure 7~~Figure 9 displays the temporal evolution of the global mean  
26 differences between altimetry and the sum of Argo DHA plus GRACE measurements. The differences between  
27 the SLA grids collocated with Argo profiles are first computed and then, two different ocean mass solutions are  
28 subtracted, using the grids of equivalent sea level (GRGS solution, Biancale et al., 2014) and tFor the global  
29 mean ocean mass time series (Johnson and Chambers, 2013; in red), the impact of the continental leakage and  
30 the GIA correction are already taken into account.global mean ocean mass (Johnson and Chambers, 2013).  
31 Regarding the GRGS solution (Biancale et al., 2014; in blue), the monthly maps of equivalent sea level are  
32 averaged over the global ocean with a mask over the 300 km coastal band and a GIA correction is applied, based  
33 on the mean (over the same area) of the ICE5G/VM2 model (Geruo et al., 2013). A 0.24 mm/yr difference is  
34 observed between the altimeter drift estimated with the former (-0.20-8 mm/yr) and the latter (-0.240.0 mm/yr)  
35 ocean mass dataset. In spite of the different processing of the SH coefficients and the different GIA corrections  
36 applied to both dataset, these altimeter drifts are considered to be undistinguishable given the previously  
37 described sources of uncertainties associated with the GRACE measurements. At inter annual time scale, similar  
38 evolutions are observed for instance over 2005-2007 but in the mean time, differences of the order of several  
39 millimeters can be found opposite temporal variations between both time series can be observed of the order of  
40 several millimeters (such as during year in 2008-2009 and in 2012). These discrepancies are attributed to the

1 difference of processing of these datasets. Furthermore, in these calculations, the spatial coverage of the Argo  
2 and GRACE solutions are not exactly the same (marginal seas, high latitudes) and in these regions, the  
3 discrepancies between both ocean mass solutions may contribute to the inter annual differences observed on  
4 Figure 7.: the spherical harmonic coefficients are addressed differently (in particular the degree 0 and 1  
5 coefficients) and the ocean mass time series obtained with the GRGS dataset has been adjusted for a 1.1 mm/yr  
6 GIA effect whereas this effect is already taken into account in the global mean ocean mass time series. In  
7 addition, the so-called leakage of the continental signal over the oceans is not treated the same way. Note that the  
8 method of comparison also contributes to the observed discrepancies (GRGS solution collocated to Argo profiles  
9 versus global mean difference) but it is not believed to be a first order contribution to the error. This illustrates  
10 that the estimation of the altimeter absolute drift is possible thanks to the combined used of Argo and GRACE  
11 data but it is affected by significant uncertainties related to the estimation of the different ocean mass  
12 solutions, all the uncertainties mentioned above can significantly affect the estimation of the altimeter absolute  
13 drift.

#### 14 5.5 Impact of the temporal sampling of the Argo floats

15 The Argo floats provide vertical T/S profiles every 10 days. This is a good compromise in order to sample the  
16 ocean variability and to ensure a long enough life time of the floats. For comparison, altimeter missions such as  
17 Jason missions provide a global coverage of the ocean within the same period. The validation of altimeter  
18 measurements by comparison with the in-situ profiles may be affected by a different temporal sampling of the  
19 Argo floats. With a full sampling of the in-situ network, an East/West hemispheric bias of the regional MSL  
20 trends is observed when computing the trend of the differences between altimeter Jason-1 SLA and in-situ DHA  
21 in each hemisphere (Figure 8Fig-10). The difference of trends between each area is of -1.38 mm/yr over mid  
22 2004-2010 with the GDR-C orbit solution (Fig. 10a) whereas it is reduced to -0.13 mm/yr with the GDR-D orbit  
23 solution (Fig. 10b). This indicates that this updated altimeter standard improves the regional homogeneity of the  
24 altimeter SLA but given the uncertainty associated with these trend estimations (more than 0.5 mm/yr over this  
25 period), these results are close to the limit where both these values can be distinguished with enough confidence  
26 in the results.

27 The goal is to assess whether this result is affected by a change the temporal sampling of the Argo floats. The  
28 trend of the differences between the altimeter SLA and in-situ DHA is computed as before for each hemisphere  
29 with both altimeter standards but only one out of three in-situ profiles is used which leads to a monthly sampling  
30 for all floats instead of 10 days. The East/West hemispheric trend differences become -0.98 mm/yr and 0.67  
31 mm/yr with the GDR-C and GDR-D standards respectively. This means that in these conditions, none of the  
32 standards allow the reduction of the hemispheric discrepancies with respect to the in-situ independent reference.  
33 This kind of analysis of impact of a new altimeter standard is thus sensitive to the sampling frequency of in-situ  
34 floats.

#### 35 5.6 Impact of the spatial sampling of the Argo network

36 The target of a network of 3000 Argo floats has been achieved in 2007 and they now provide an almost global  
37 coverage of the open ocean. This targeted number of floats has not been determined in order to allow altimetry  
38 validation in particular. The impact of a reduced spatial coverage of the network on the altimetry validation is  
39 analyzed in terms of regional coverage, trends of the differences and coherence between both measurements.  
40 Different selections of the floats have been performed and Figure 9Figure-11a displays the number of valid

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1 | profiles over 2005-2012 from all Argo floats whereas ~~the Figure 11b-9b~~ shows the number of valid profiles  
2 | when only 25% of the floats are used (selected in the list of instruments following the increasing order of their  
3 | WMO number). With this selection, the spatial coverage is strongly affected and some regions are not sampled at  
4 | all over the period.

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

17 | In addition, ~~Figure 10~~~~Figure 12~~ shows the Taylor diagram (Taylor, 2001) between AVISO SSALTO/DUACS  
18 | altimeter merged products and the Argo in-situ steric heights (with the addition of the GRACE GRGS ocean  
19 | mass contribution) with different sub sampling of the Argo network. The performance obtained with 25% of the  
20 | floats appears to be slightly deteriorated but the different points are very close to each other and as above for the  
21 | global and regional trends, this confirms that the validation of altimeter measurements is little affected by a  
22 | reduction of the number of Argo floats and a reduced spatial coverage of the in-situ network.

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

## 29 | **5.7 Reference depth of Argo profiles**

30 | The integration of the Argo T/S profiles for the computation of the in-situ steric dynamic heights requires a  
31 | reference level (pressure). ~~As all floats do not reach the same depth, the steric signal will be well sampled~~  
32 | ~~through the water column with a deep reference level but the shallower floats will not be used. On the opposite,~~  
33 | ~~more floats will be used with a shallow reference level but the vertical steric signal will be less sampled and the~~  
34 | ~~deeper the reference level, the more information from the T/S profiles is taken into account through the water~~  
35 | ~~column but the more T/S profiles are not used (those who don't reach the reference level).~~ Thus, we first aim at  
36 | determining the impacts of a given reference depth of integration on the global and regional Argo spatial  
37 | sampling, on the estimation of the global MSL trend and in terms of sea level variance.

### 38 | **5.7.1 Impact on the global and regional coverage**

39 | ~~For a given reference level of integration of the vertical density profiles, only the floats reaching at least this~~  
40 | ~~level will be used to compute the associated DHA whereas shallower floats will not be included in the~~

1 calculation. As an illustration, at According to the reference pressure used to integrate the in-situ density profiles,  
2 no DHA will be computed for all the floats whose mean maximum pressure does not reach this reference level.

3 At global scale, only 6% of the floats are missed with a reference level at 900 dbar but this proportion increases  
4 to 29% at 1400 dbar and 52% at 1900 dbar.

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

### 19 5.7.2 Impact on the global MSL trend estimation

20 An estimation of the global altimeter absolute drift is provided by the global mean sea level differences between  
21 altimetry and the sum of Argo steric heights with the GRACE ocean mass contribution. This is illustrated on  
22 Figure 12Fig-14 with various subsets of DHA derived from the Argo network, allowing the distinction of the  
23 effect of the horizontal and vertical sampling of the ocean by the floats. The altimeter drift estimated with all  
24 DHA from 900 dbar profiles (in red) is of 1.5 mm/yr. Among these profiles, the selection of those whose  
25 maximum depth is at least 1900 dbar (impact of the horizontal sampling) has no impact in terms of global  
26 correlation between altimetry and Argo measurements (0.84 in both cases). There is a relatively low impact (-0.2  
27 mm/yr) on the altimeter drift which is reduced to 1.3 mm/yr over the period (in blue). The use of all DHA from  
28 1900 dbar profiles leads to an improved correlation between altimetry and in-situ data (0.87) and the impact of  
29 this increased vertical sampling on the altimeter drift detection (in green) is greater than previously (-0.4 mm/yr)  
30 and leads to a 0.9 mm/yr drift. Therefore, the choice of a deep reference level for Argo DHA provides a better  
31 estimation of the baroclinic signal (improved vertical sampling) which is more in agreement with the observed  
32 signal by altimetry. This is in favor of an improved estimation of the absolute altimeter drift detection.

33 The use of a deep versus shallow reference level turns out to be equivalent to a reduction of the ocean coverage  
34 by Argo floats (horizontal sampling). As previously discussed with the analysis of the sensitivity to the temporal  
35 and spatial sampling of the floats, this kind of sub sampling associated with the reference level affects the  
36 estimation of the global absolute altimeter sea level trend. The 0.6 mm/yr total difference observed between the  
37 shallow and deep reference levels on Figure 12Fig-14 is an estimation of one of the contributors to the error of  
38 the method of comparison.

### 39 5.7.3 Impact in terms of variance: altimetry multi vs mono mission

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1 We now describe two examples at global and regional scales illustrating that the comparisons of altimeter  
2 measurements with Argo in-situ data in terms of variance are affected according to the reference level of  
3 integration of steric heights. At global scale, the Taylor diagram of [Figure 13](#)~~Fig. 15~~ presents the correlation and  
4 the standard deviation of the differences between altimeter multi-missions merged SLA and the Argo steric  
5 DHA. With a deep reference level (1900 dbar), the altimeter (grey circle) and in-situ (black circle) time series  
6 have the same standard deviation whereas a reduced variability is found with the in-situ steric measurements  
7 referenced to a shallower level (900 dbar, [black triangle](#)). [This reduced vertical sampling of the water column](#)  
8 [leads to a decrease of the DHA standard deviation by a 0.85 factor at global scale. with a 0.85 proportion](#)  
9 [compared with altimeter SLA.](#) In addition, the correlation between both types of data is also deteriorated. This  
10 has to be taken into account when assessing the impact of a new altimeter standard or new product for instance.  
11 At regional scales, Dhomps et al. (2011) reveal that the correlation and the regression coefficients between SLA  
12 and DHA vary spatially with a latitude dependency at the first order. In particular, their Fig. 5 suggests that the  
13 Southern Ocean is the place where the water column has to be sampled at the deepest level to estimate the steric  
14 signal. At high latitudes, the baroclinic signal below 1000 m depth significantly improves the correlation  
15 between SLA and DHA, the sea level variability being largely influenced by the deep baroclinic signals. We  
16 illustrate this with [Figure 14](#)~~Fig. 16~~ which indicates that the variances of the differences between altimeter SLA  
17 and in-situ DHA are different whether the altimeter SLA is derived from mono mission (TOPEX, Jason-1 & 2)  
18 or multi-missions grids of SLA. In particular, with DHA referenced to 900 dbar (left panel), adding missions  
19 reduces the altimeter / Argo consistency in the high ocean variability areas of the Antarctic Circumpolar Current  
20 (ACC) (blue, negative values of  $-5 \text{ cm}^2$  on average). On the other hand, this tendency almost disappears in the  
21 ACC with the use of DHA referenced to 1900 dbar (right panel). This result is explained by the difference of  
22 variance of the water column as seen by altimetry or in-situ data in this region. [Figure 15](#)~~Figure 17~~ indicates that  
23 the variance of mono mission and multi missions altimeter products (collocated to Argo profiles) are very close  
24 to each other in the ACC but the variance of the Argo steric heights referenced at 900 dbar is significantly lower.  
25 Thus with this reference level, both altimeter products cannot be distinguished by comparison with Argo data.  
26 With a 1900 dbar reference level, the variance of the Argo steric heights becomes similar to the values obtained  
27 with altimeter products in the ACC and the Argo measurements become relevant for the quality assessment of  
28 the altimeter products. This illustrates that according to the ocean characteristics, the analysis of the variance of  
29 the water column and thus the differences between altimetry and Argo measurements are highly sensitive to the  
30 reference depth of integration of the Argo profiles.

### 31 **5.8 Impact of the deep steric contribution**

32 In addition of the sensitivity to the reference depth of integration of Argo density profiles (as described in the  
33 previous section), the estimation of the altimeter drift is also affected by the deep steric contribution (deeper than  
34 the reference level of Argo floats) which is not taken into account in our approach. This contribution has been  
35 extensively discussed in the recent years since the heat uptake in the deep ocean is suspected to explain the pause  
36 in the global mean air and sea surface temperature evolution observed since the early 2000s (e. g. Trenberth and  
37 Fasullo 2013; Watanabe et al. 2013; England et al. 2014). Comparing altimeter SLA with the sum of the steric  
38 signal and the ocean mass contribution, Dieng et al., 2015a estimate the deep steric contribution (deeper than  
39 1500 m) to be  $0.3 \pm 0.6 \text{ mm/yr}$  and  $0.55 \pm 0.6 \text{ mm/yr}$  over the period 2005-2012 and 2003-2012 respectively.  
40 Llovel et al. (2014) provide an estimation of  $0.0 \pm 0.7 \text{ mm/yr}$  over the former period. The associated

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

## 20 **6 Conclusions**

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

34 The estimation of the absolute altimeter mean sea level drift requires the additional information related to the  
35 mass contribution to the sea level that can be derived from GRACE satellite measurements. ~~We have shown that~~  
36 ~~there is a strong sensitivity to the different datasets available. In addition, regarding the long term trend of the~~  
37 ~~global MSL, there are s~~Significant uncertainties ~~are~~ associated with ~~this dataset, ranging from~~ the GIA correction  
38 (0.3 mm/yr), ~~to~~ the geocenter motion (0.1 mm/yr), the fit of the ~~harmonic-SH~~ coefficients (0.1 mm/yr) and the  
39 leakage from land to the ocean (0.1 mm/yr). The estimation of the altimeter MSL ~~trend-drift~~ is thus directly  
40 affected by these uncertainties ~~related with the use of GRACE measurements.~~



1 Sensitivity analyses performed on the Argo network have indicated that the spatial coverage of the ocean  
2 sampled by the instruments is significantly reduced as soon as a limited number of floats are used in the  
3 comparisons. However, this hardly affects the global correlation between altimeter SLA and the in-situ DHA  
4 plus mass contribution, neither the variance nor the trend of their differences. In addition, the 10-day temporal  
5 sampling of Argo floats was not designed for satellite altimetry validation purposes. We have shown that a  
6 reduced temporal sampling of the floats can prevent us from detecting the impact of a new altimeter standard.  
7 The same diagnosis has been used to assess the impact of the reduction of the temporal and spatial sampling of  
8 Argo floats, leading to opposite conclusions. This suggests that the resulting distributions of the in-situ profiles  
9 (in space and time) are different, leading to a different impact on the regional sea level trend estimation.  
10 The choice of the reference level of integration of the Argo T/S profiles for the computation of the steric  
11 dynamic heights directly affects the global and regional coverage of the ocean by Argo floats. A relatively  
12 deeper reference level can be assimilated to an additional sub sampling effect since it allows a better vertical  
13 sampling of the water column (more in agreement with what is seen by altimetry) but this leads to a reduced  
14 horizontal sampling of the ocean; the impact of the former being more than twice compared with the latter in  
15 terms of altimeter MSL trends estimation over a 8 years period. In some regions such as the Southern Ocean, the  
16 comparison with the altimeter sea level requires a deep reference depth so that the variance content of the water  
17 column is similar between altimetry and in-situ data.

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

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

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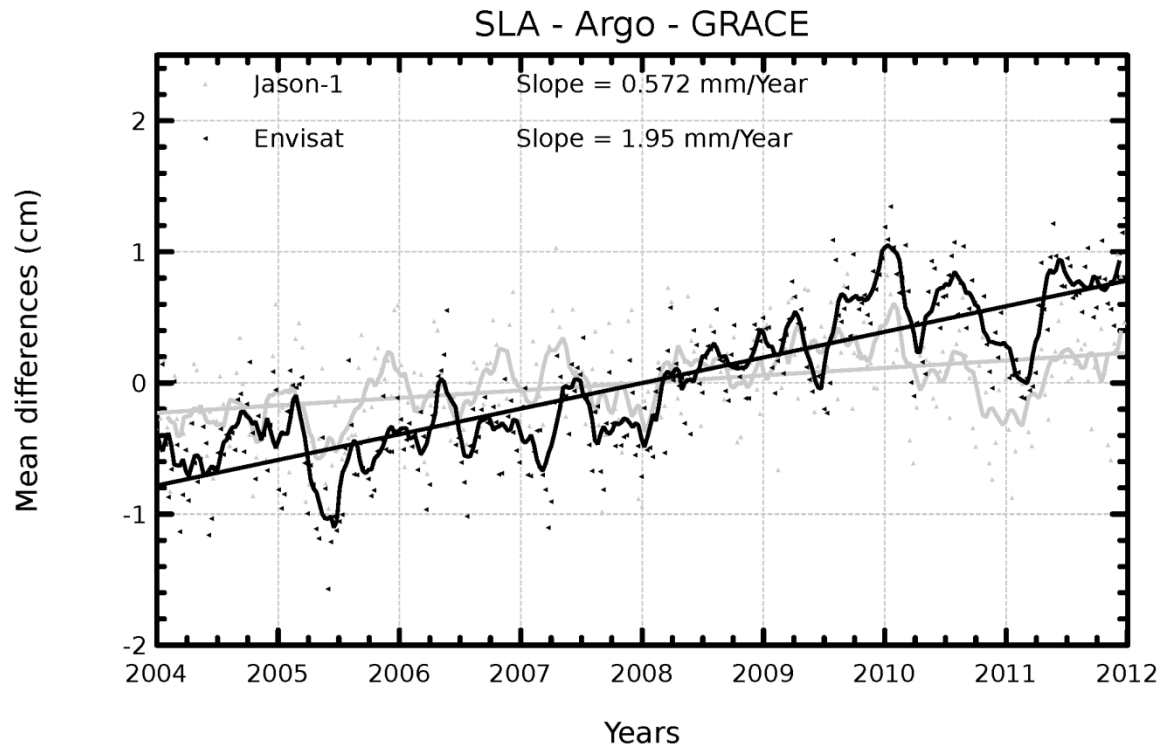
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- 7

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

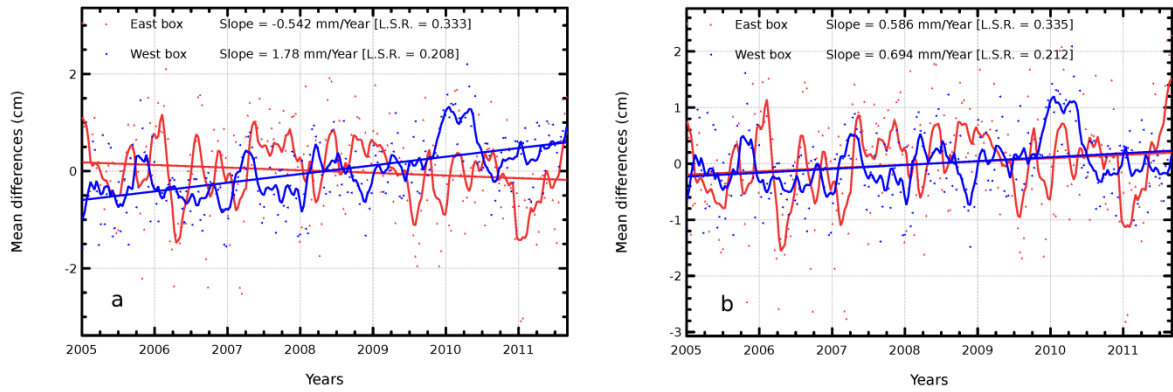
<b>Global correlation</b>	<b>Non homogeneous temporal reference</b>	<b>Homogeneous temporal reference</b>
AVISO SSALTO/DUACS 2010	0.87	0.90
AVISO SSALTO/DUACS 2014	0.90	0.90

- 1 | Table 2 : Global correlation (with a 95% confidence interval) between all collocated altimeter SLA (AVISO
- 2 | SSALTO/DUACS 2010 and 2014) and in-situ DHA from Argo profiles (with a reference depth of 1900 dbar and
- 3 | a 2003-2011 temporal reference) without and with an homogeneous temporal reference



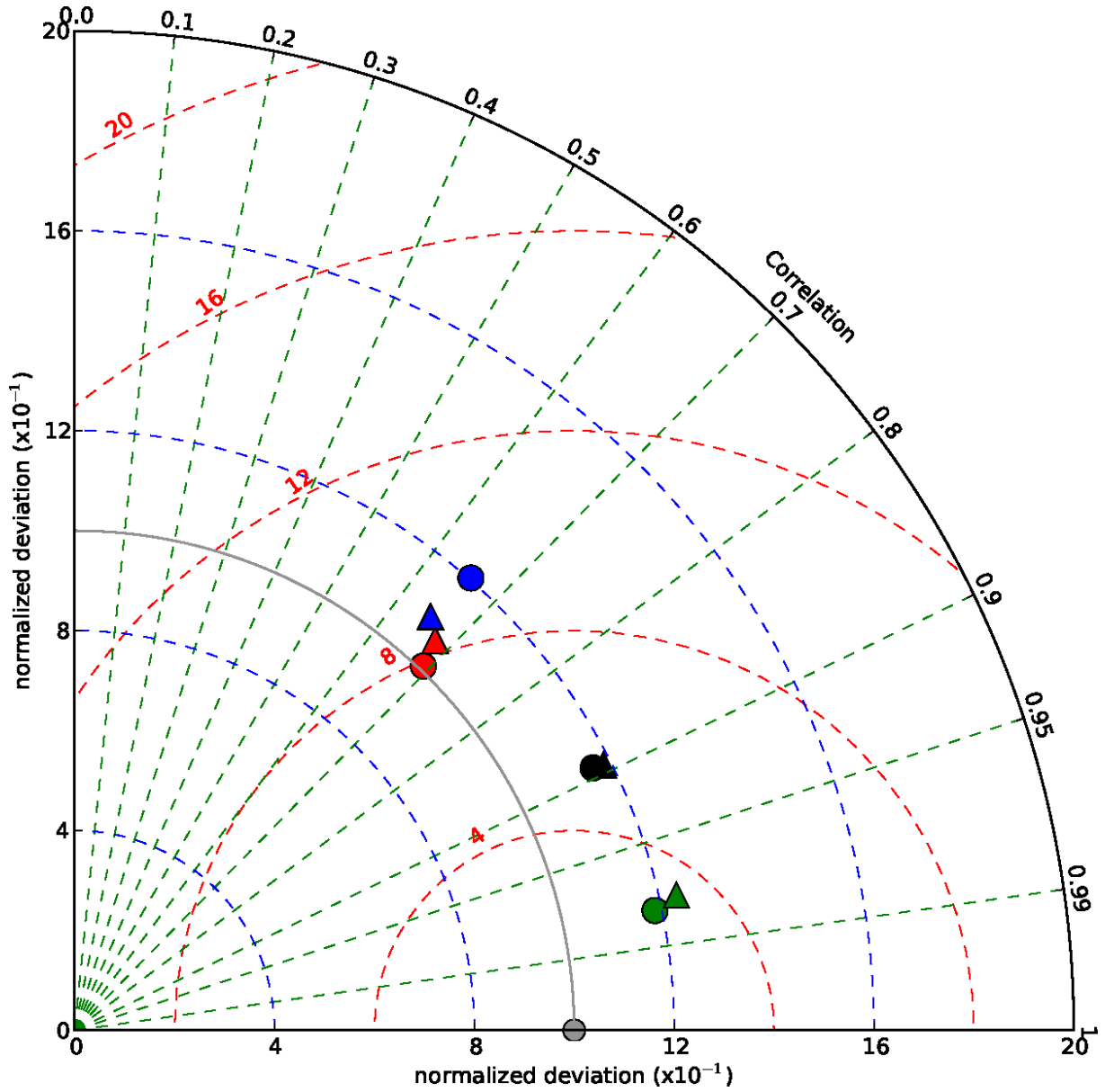
1 .  
2 ~~Figure 1: Mean differences between altimetry and steric + mass contributions from Argo and GRACE~~  
3 ~~measurements for Jason1 and Envisat missions~~





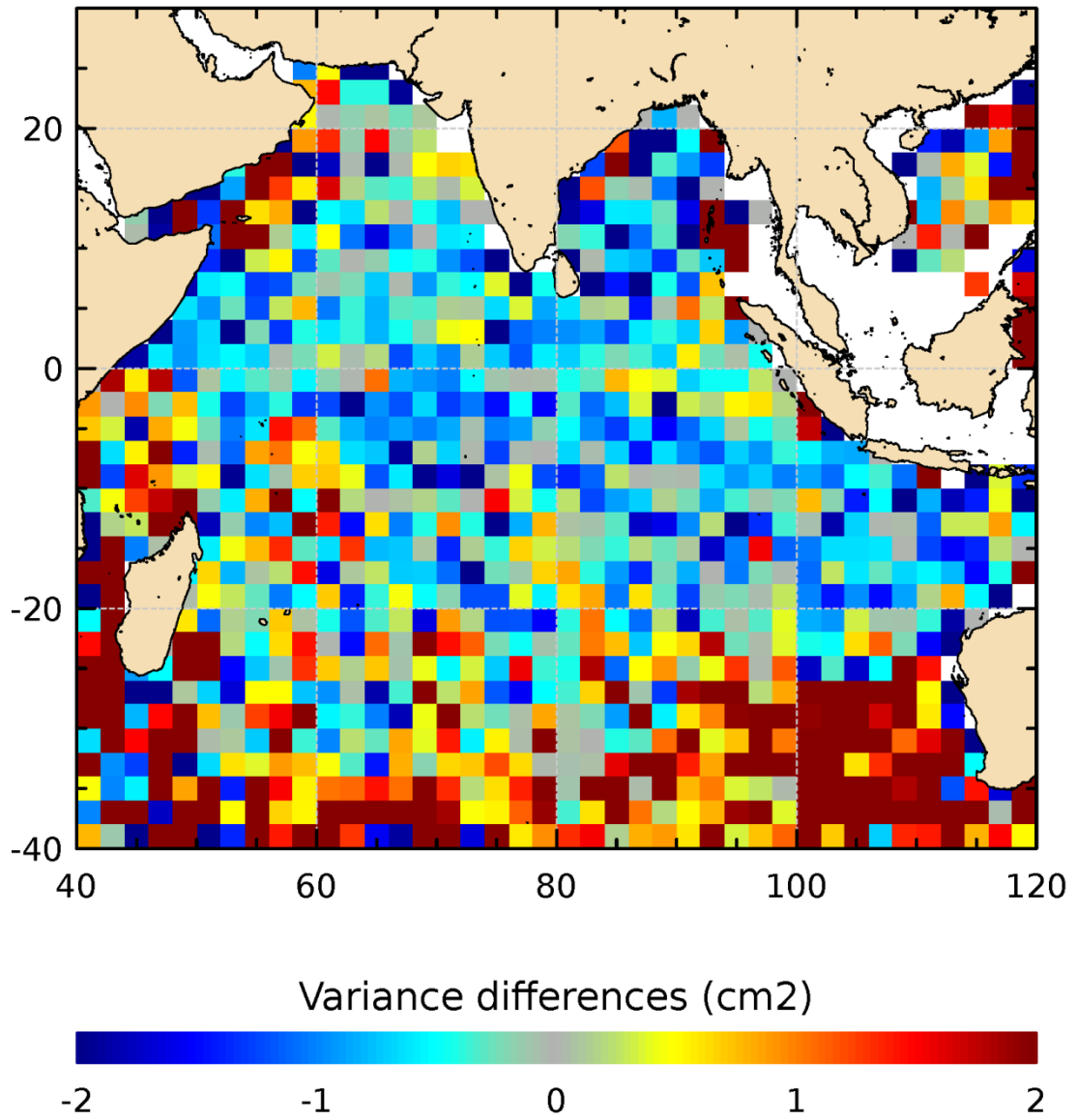
1  
 2 | Figure 12: SSH differences (cm) between Jason-1 altimeter data (cycles 1 to 355) and Argo in-situ  
 3 | measurements (900 dbar) computed with GDR-D (a) and GDR-E orbit solution (b), separating East box (Lon:  
 4 | 60°/120°, Lat: -30°/+30°, in red) and West box (Lon: -150°/-190°, Lat: -50°/10°, in blue). Corresponding annual  
 5 | and semi-annual signals are removed. Trends of raw data (dots) are indicated and the 2-month filtered signal is  
 6 | added (curves).  
 7

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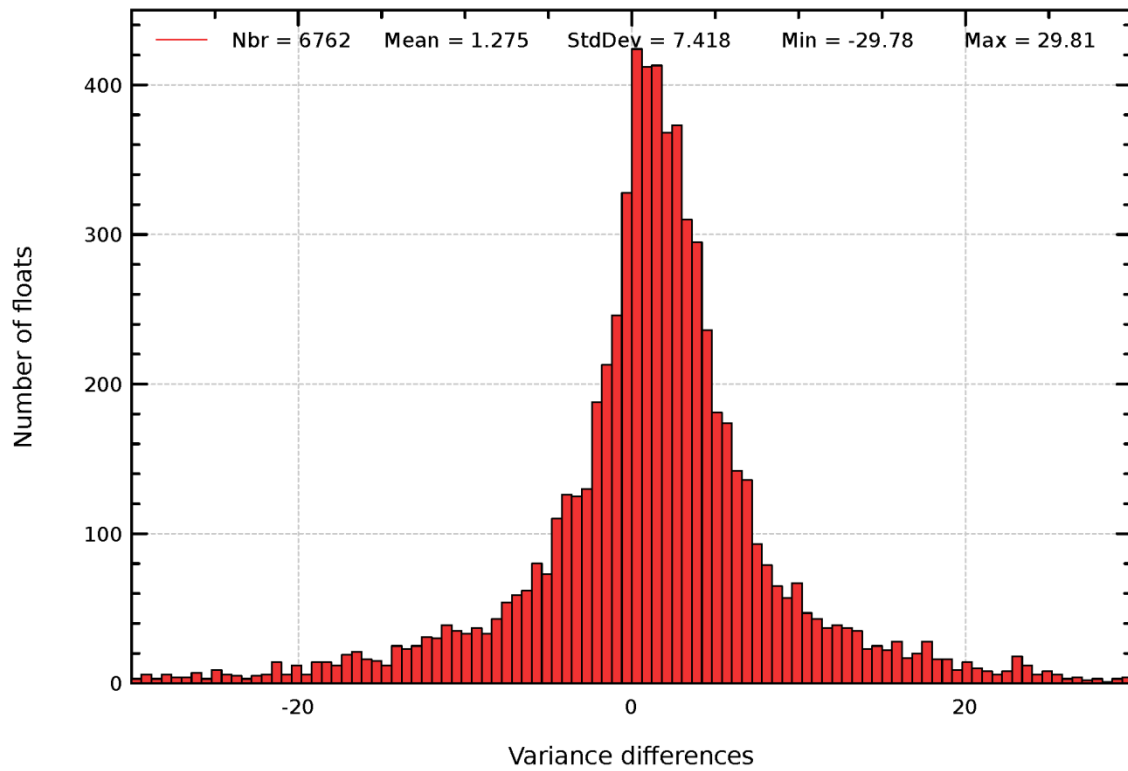


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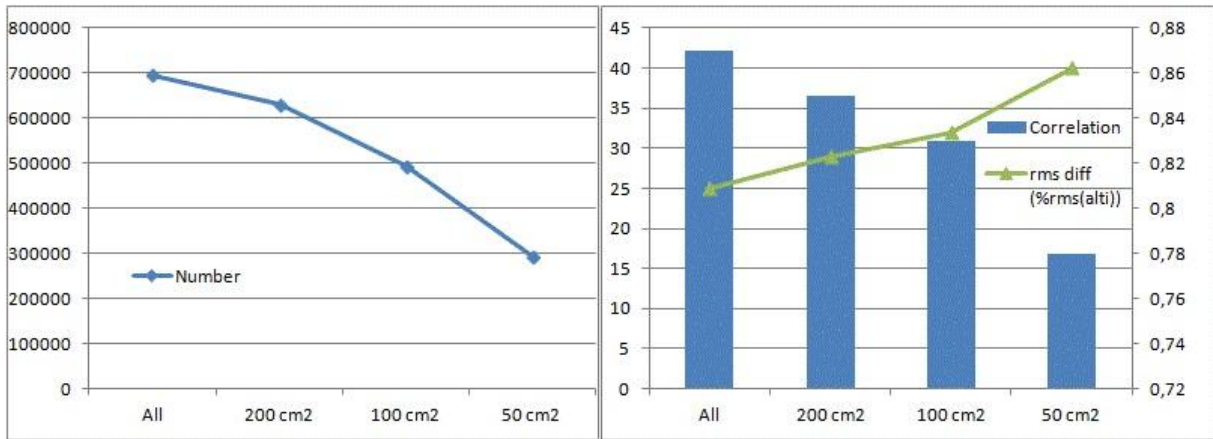
4 | Figure 23: Taylor diagram of the comparison of CCI (triangles) and AVISO SSALTO/DUACS DT (circles)  
5 merged altimeter sea level products with Argo (900 dbar) and GRACE independent measurements for the global  
6 data (black) and separating high frequencies (red), the annual signal (green) and the inter-annual signals (blue).



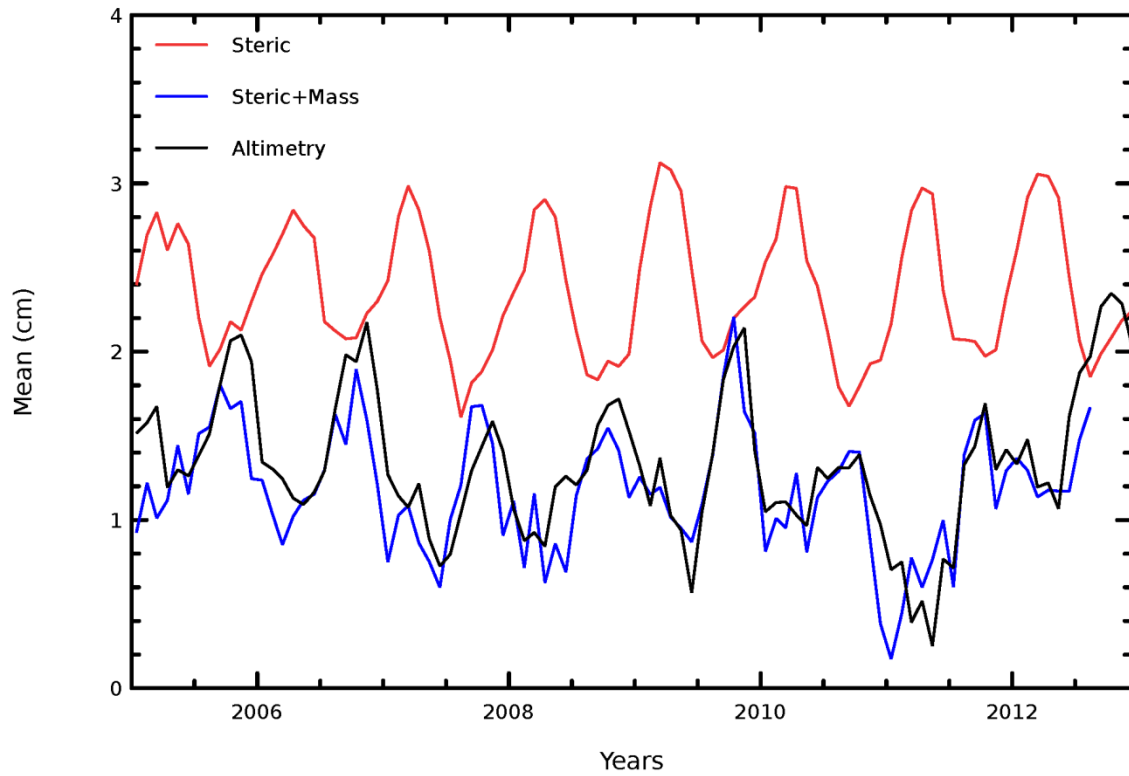
1 .  
 2 Figure 4 : Variance(DUACS 2014 Argo) — Variance(DUACS 2010 Argo) with Argo profiles referenced to 1900  
 3 dbar over 2005-2012 (cm<sup>2</sup>)  
 4



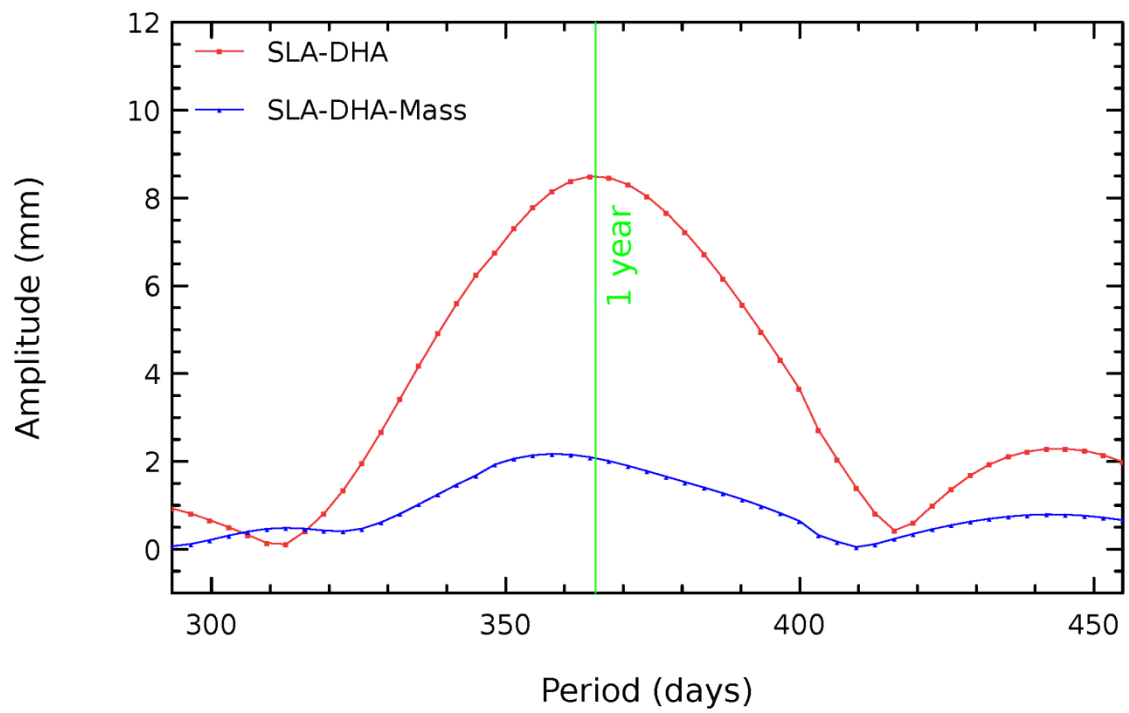
1  
 2 | Figure 35: Histogram of the difference of variance of the SLA-DHA differences for each Argo float using  
 3 | successively  $1^\circ \times 1^\circ$  versus  $1^\circ \times 3^\circ$  boxes ( $=\text{Variance}(\text{SLA}_{1 \times 1} - \text{DHA}) - \text{Variance}(\text{SLA}_{1 \times 3} - \text{DHA})$ ) when  
 4 | averaging along-track Jason-1 altimeter SLA before collocating with Argo profiles.



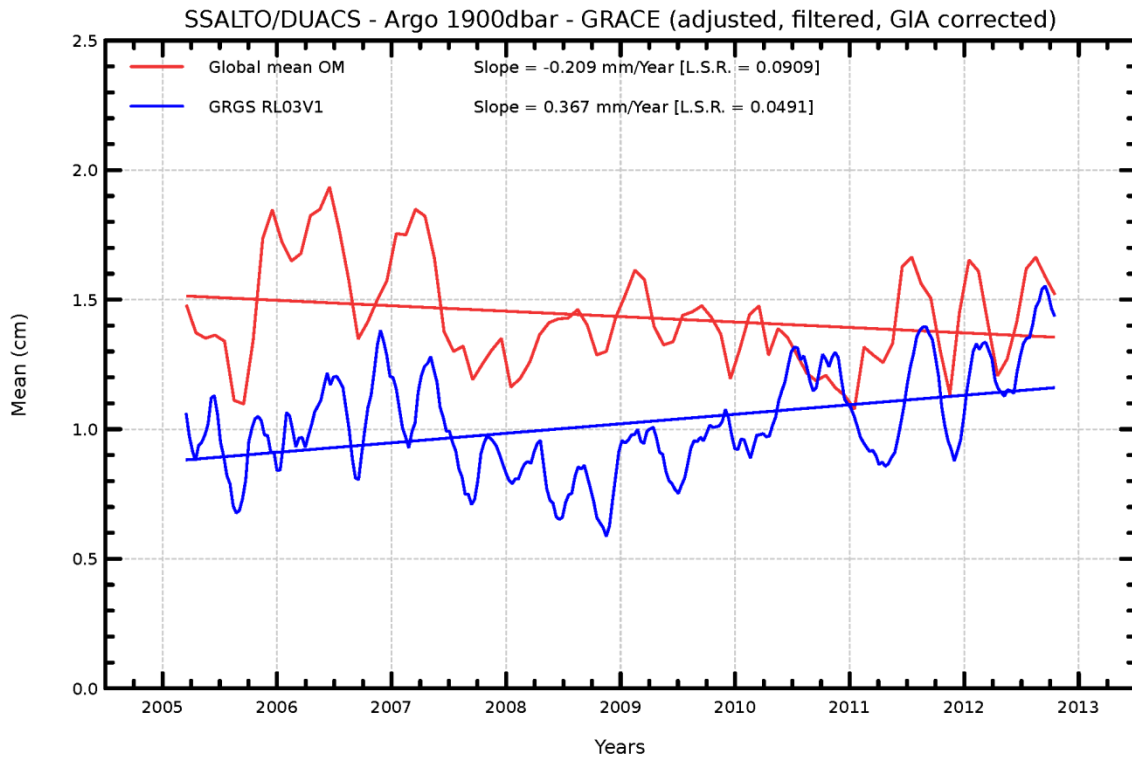
1  
 2 | Figure 46: Impact of excluding areas of higher ocean variability than a decreasing threshold: number of  
 3 | observed points (left) and correlation and rms of the differences between AVISO DUACS 2014 and Argo DHA  
 4 | (900 dbar reference) (right).



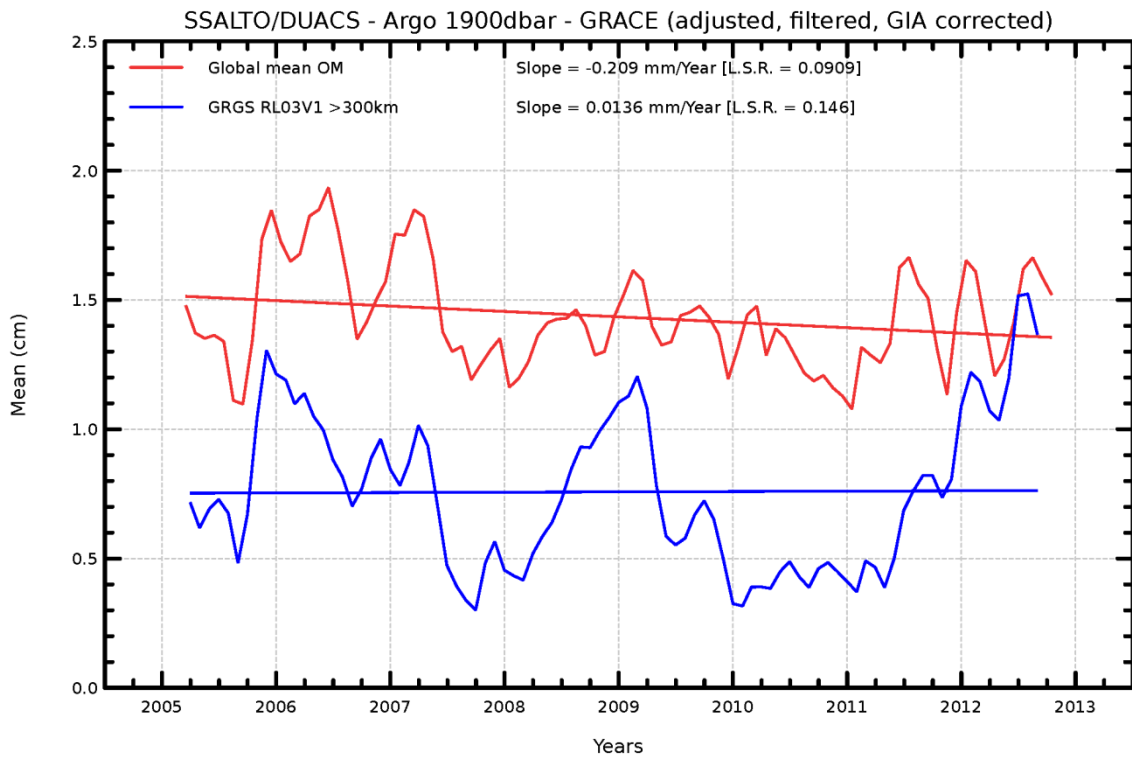
1  
 2 | Figure 57 : Temporal evolution of the steric DHA from Argo data (red), the summed steric + mass contributions  
 3 (blue) and the altimeter SLA (black).



1  
 2 | Figure 68 : 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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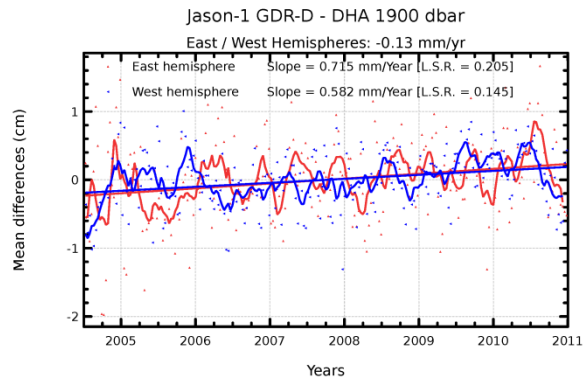
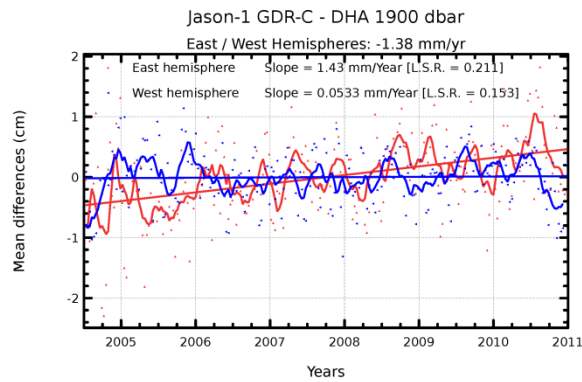
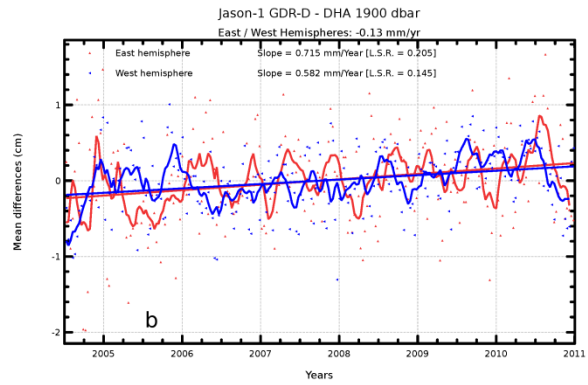
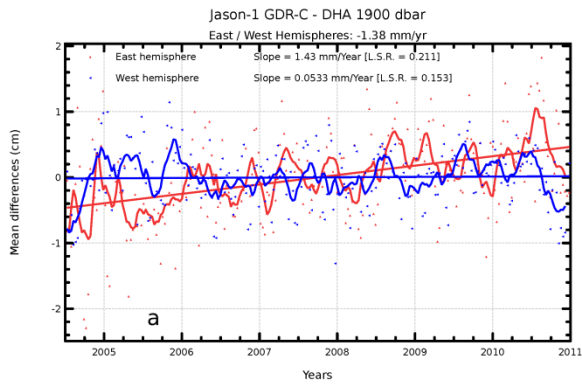


2

3 Figure 79: Differences between SSALTO/DUACS 2014 global MSL and the sum of the Argo steric sea level  
 4 (referenced to 1900 dbar) and the GRACE ocean mass contribution derived from the global mean contribution  
 5 (Johnson and Chambers, 2013 in red) and the GRGS RL03v1 dataset (Biancale et al., 2014, in blue). The GRGS  
 6 grids have been averaged over the ocean with a mask over the 300 km coastal band and corrected for GIA effect  
 7 using the mean over the same area of the Geruo et al., 2013 model. Time series have been adjusted from a annual



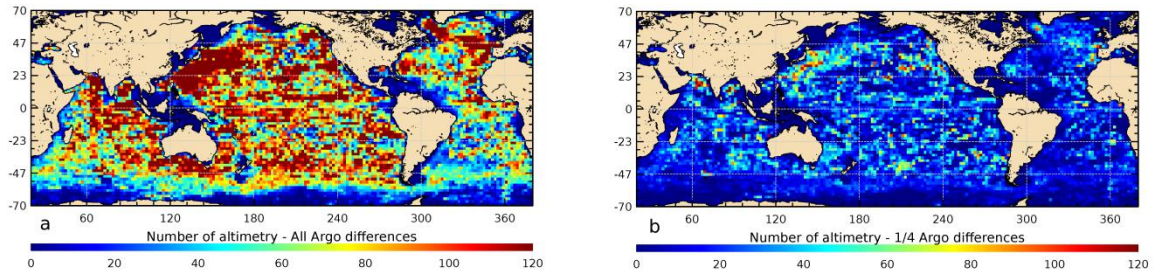
- 1 | and semi-annual signals ~~have been adjusted and, 3-month filtered and corrected from GIA effect. An an~~
- 2 | arbitrary vertical offset has been applied to the curves for clarity.



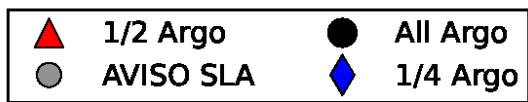
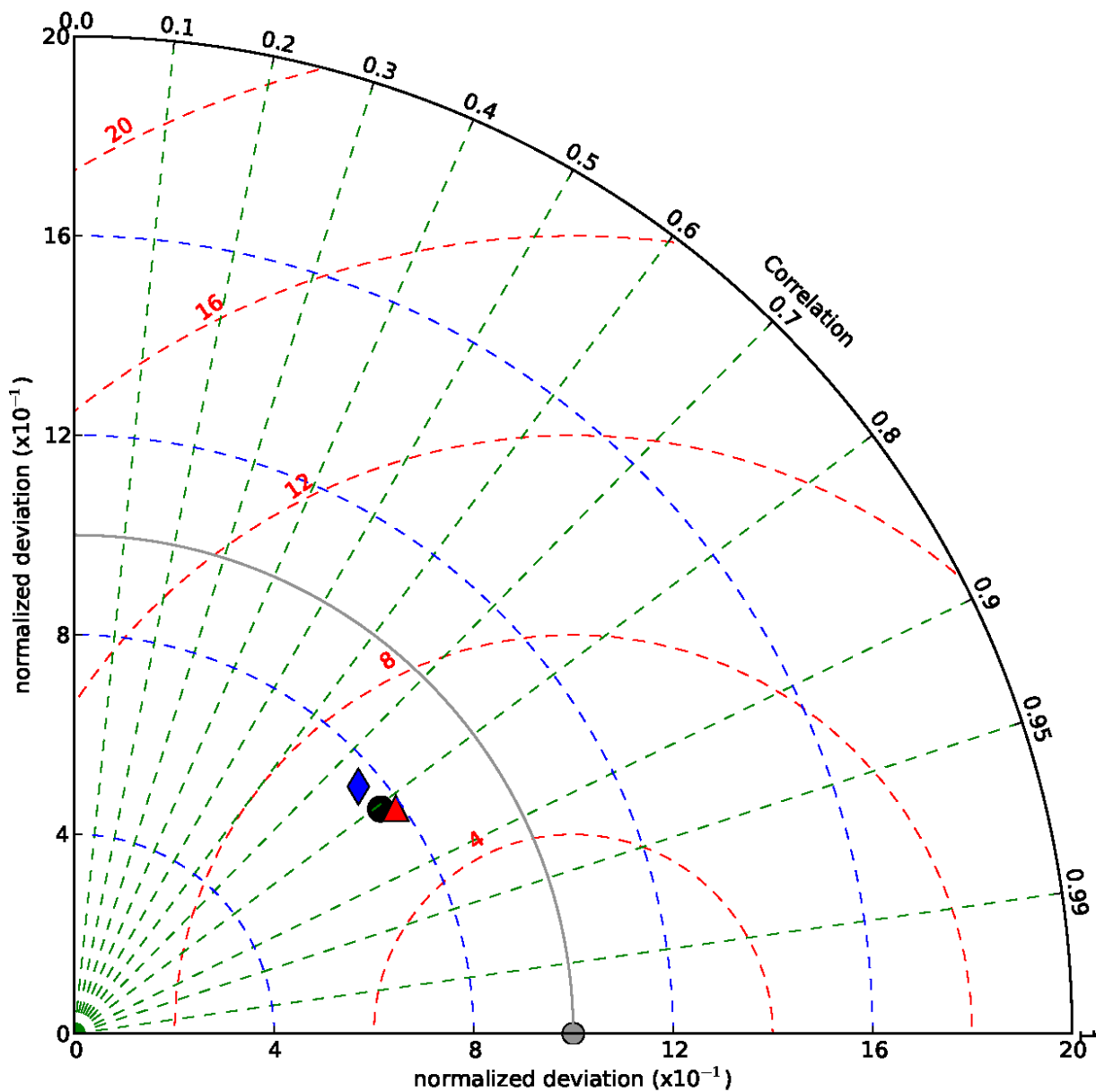
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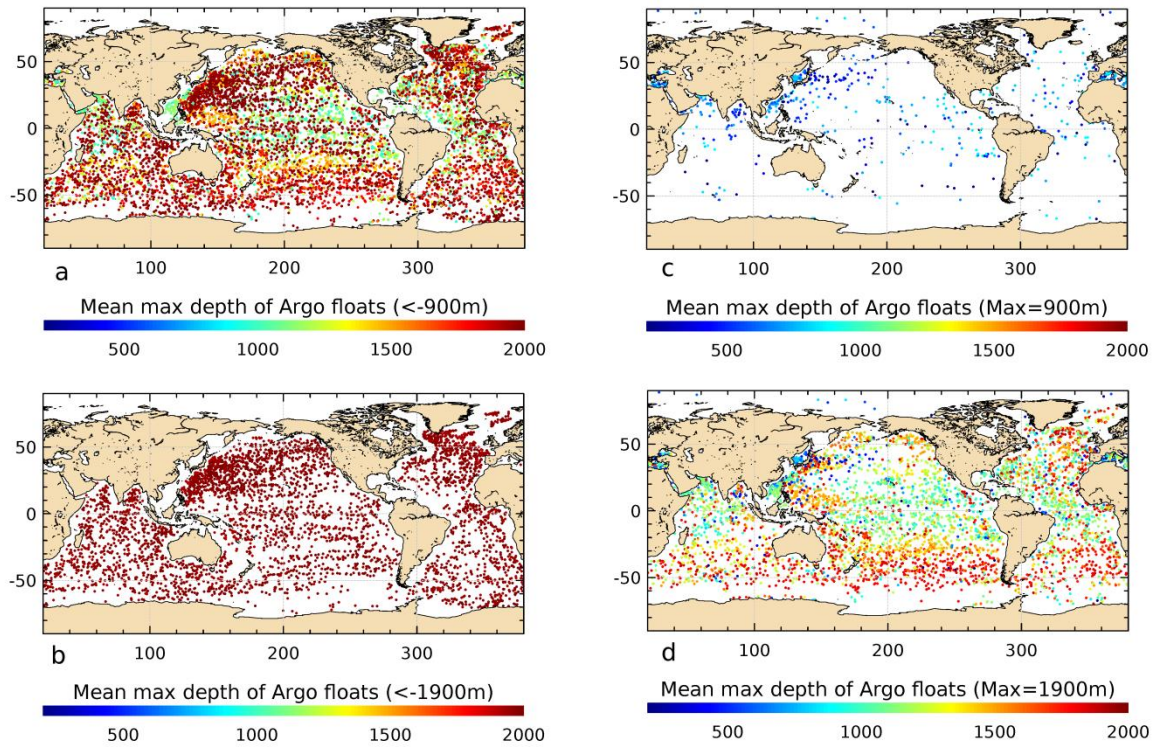
3 Figure 8-10 : SSH differences (cm) between Jason-1 altimeter data and Argo (1900dbar) in-situ measurements  
 4 computed with GDR-C (left) and CNES preliminary GDR-D orbit solutions (right), separating East (<180°, in  
 5 red) and West (>180°, in blue) longitudes. Corresponding annual and semi-annual signals are removed. Trends  
 6 of raw data are indicated and the 2-month filtered signal is added.



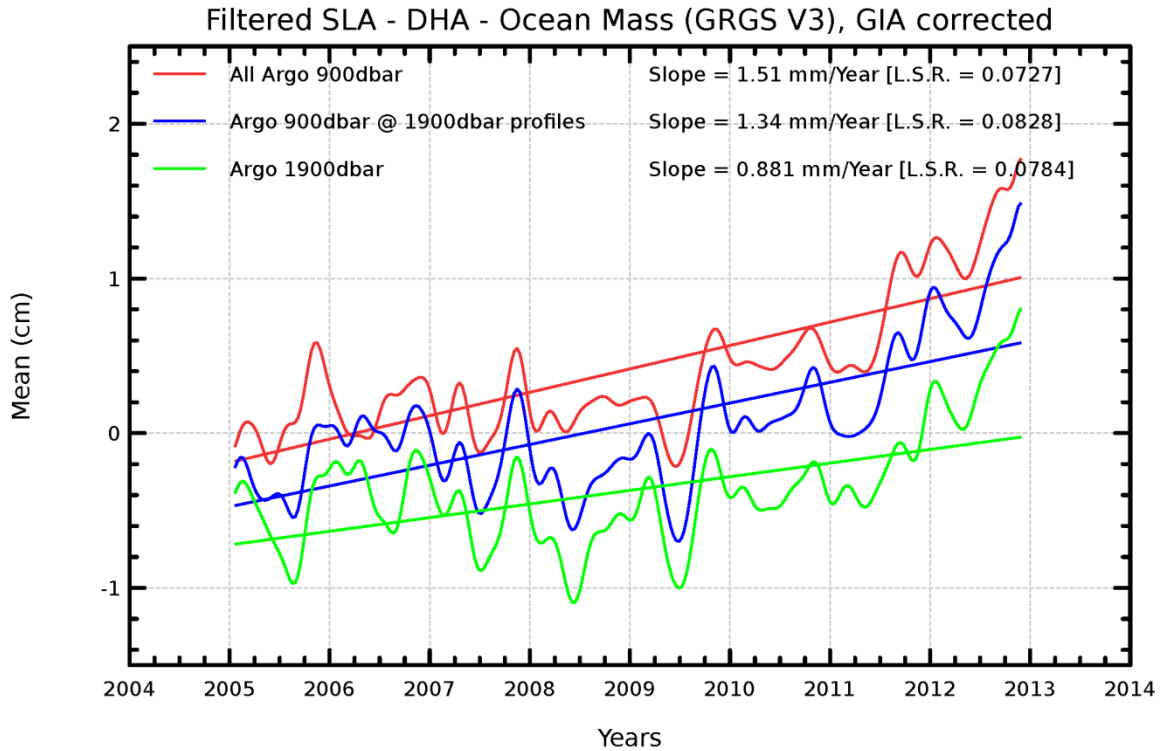
1  
 2 | Figure 914 : Number of Argo profiles per  $2^\circ \times 2^\circ$  boxes over 2005-2012 from all Argo floats (a) and from 25% of  
 3 | the floats (b).



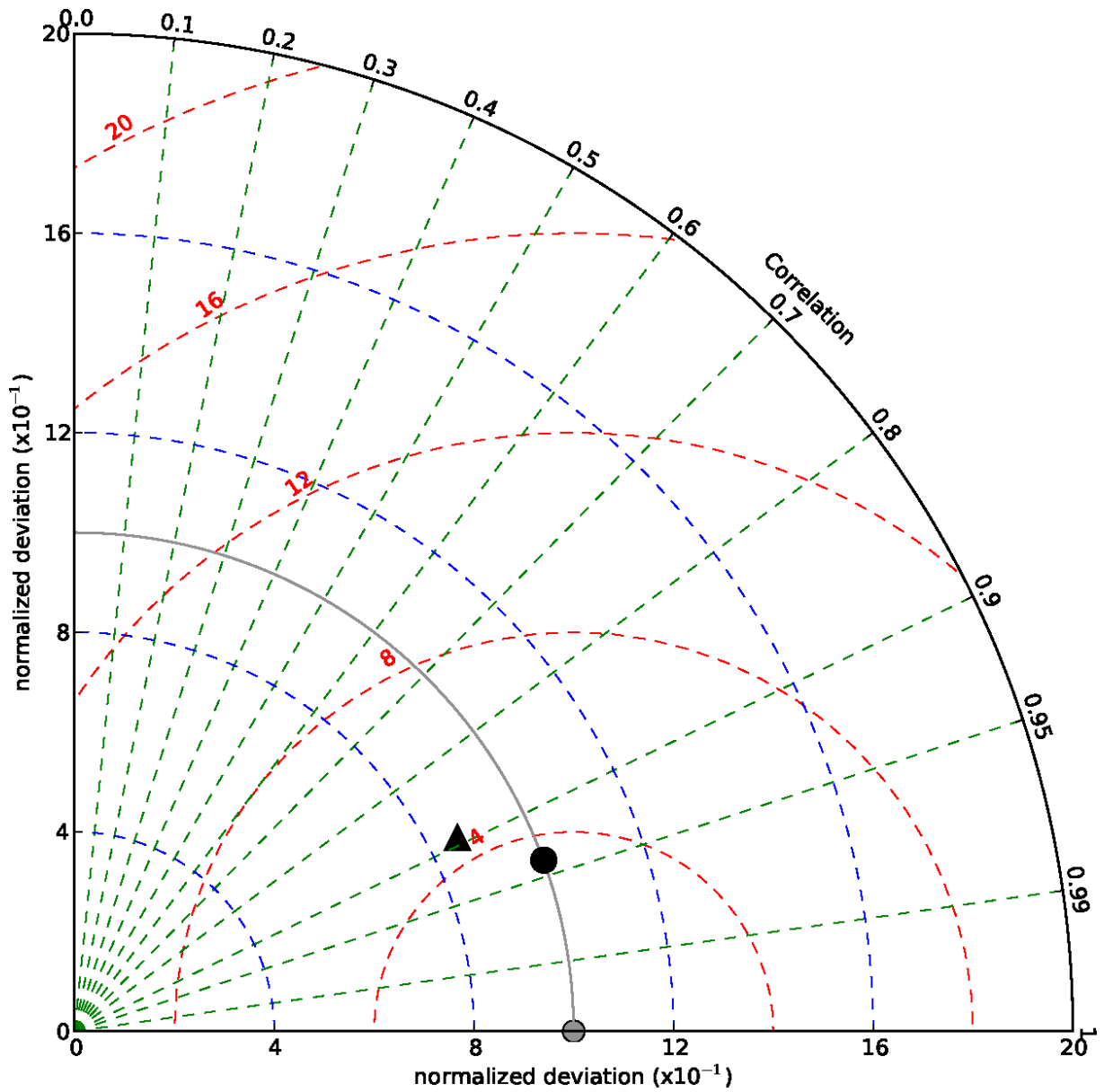
1  
 2 | Figure 1012 : Taylor diagram of the steric contributions to the sea level derived from different sub sampling of  
 3 the Argo floats (DHA referenced to 900 dbar) with the mass contribution (GRACE GRGS) compared with the  
 4 AVISO SSALTO/DUACS merged altimeter SLA. For each sub sampling of the in-situ dataset, the  
 5 corresponding collocated altimeter measurements are used.



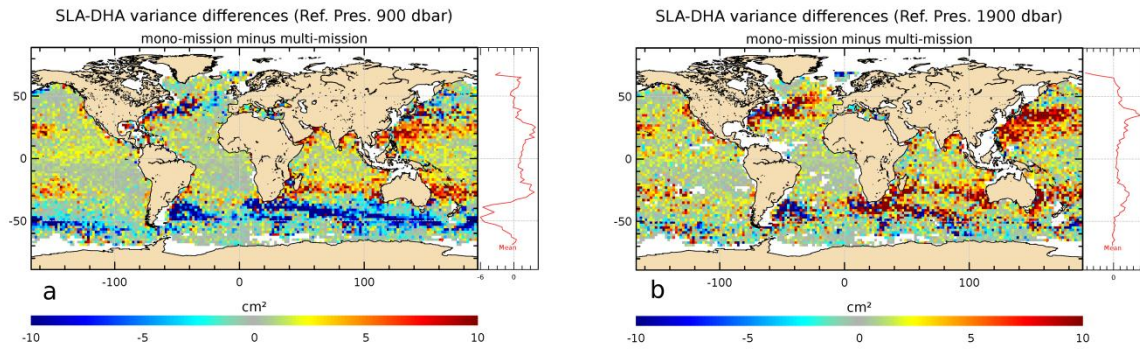
1  
2 | Figure 1143 : Maps of the mean positions of Argo floats taken into account with a given reference depth (a,b)  
3 and the associated floats which will not be used because of their mean max depth shallower than the reference  
4 (c,d) for a 900 m (a,c) and a 1900 m (b,d) reference depth over the period 2005-2013.  
5



1  
2 | Figure [1214](#): 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 [maps collocated with Argo profiles](#))  
4 | contributions to the sea level with various subsets of DHA derived from the Argo network: DHA referenced to  
5 | 900 dbar from all profiles reaching at least this pressure (red), DHA referenced to 900 dbar from the profiles  
6 | reaching at least 1900 dbar (blue) and DHA referenced to 1900 dbar from all profiles reaching at least this  
7 | pressure (green). All curves are 3-month low-pass filtered and a GIA correction is applied to altimeter (-0.3  
8 | mm/yr) and ocean mass (-1.1 mm/yr) measurements (Chambers et al., 2010; Tamisiea and Mitrovia, 2011).

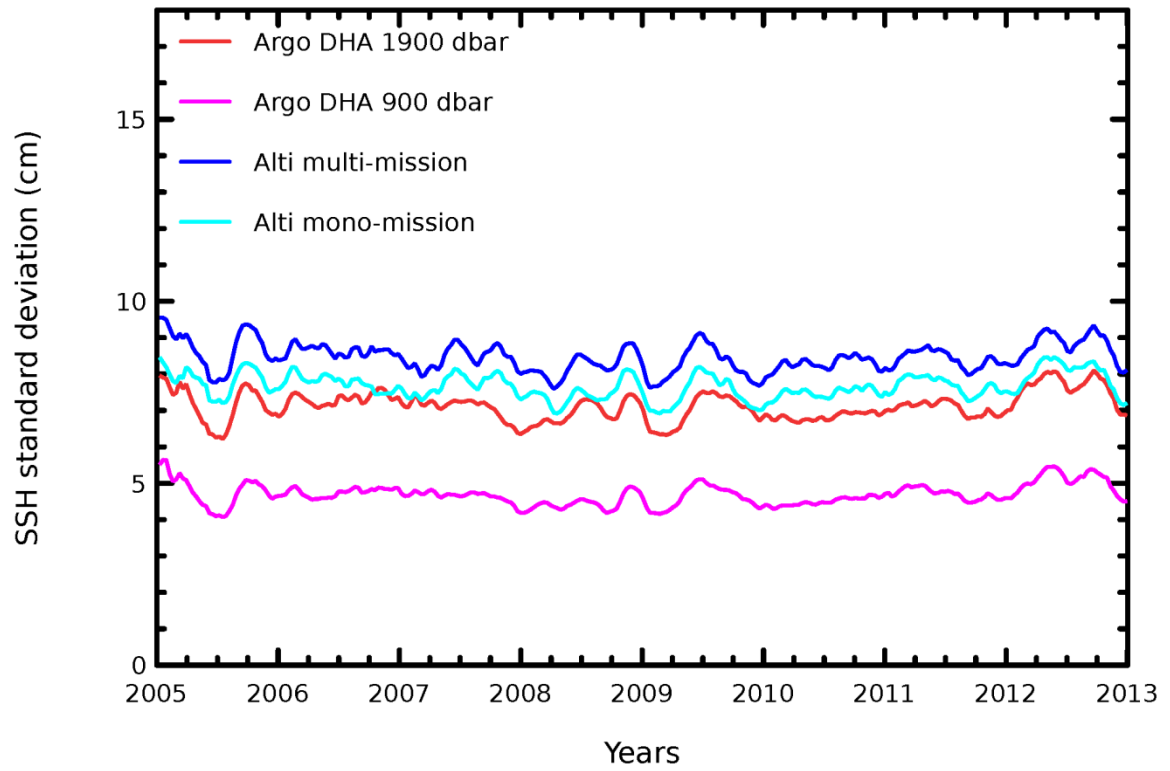


1  
 2 | Figure 1345 : Taylor diagram of the comparison of the sum of GRACE ocean mass and the steric Argo DHA  
 3 with a reference level at 900 dbar (triangle) and 1900 dbar (circle) with altimeter sea level time series  
 4 (SSALTO/DUACS 2014) (grey reference circle) on the x-axis over 2005-2013. The blue dotted lines indicate the  
 5 normalized standard deviation (altimetry being the reference).  
 6

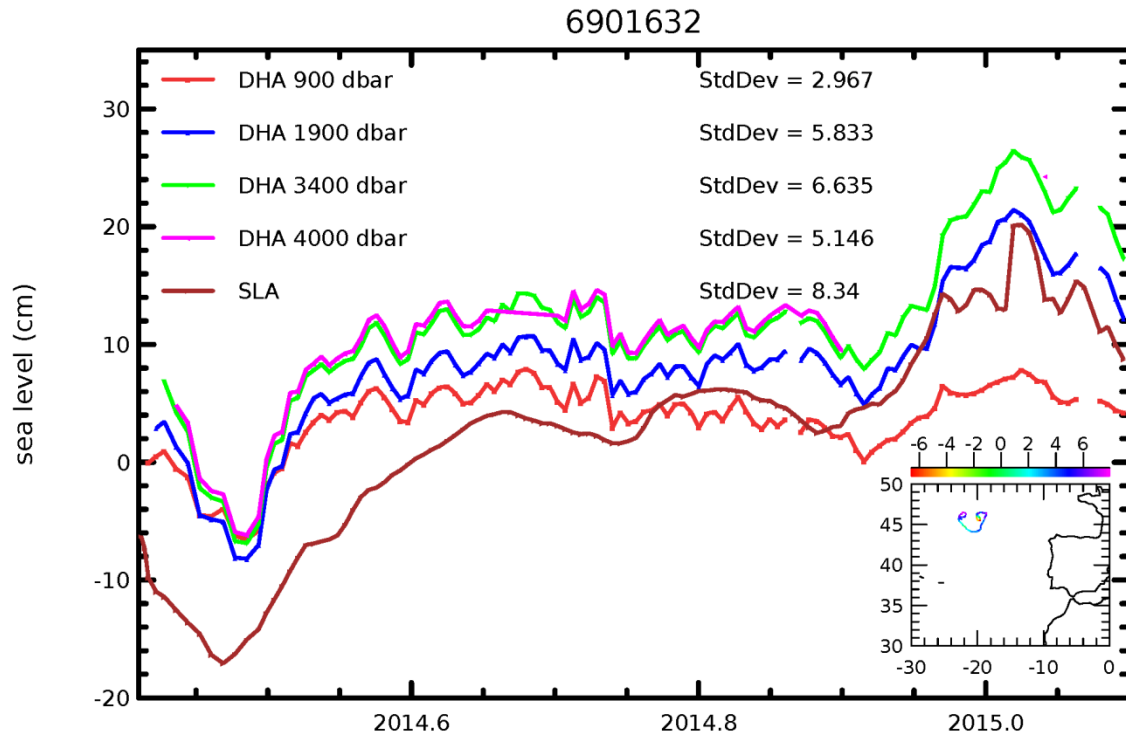


1  
 2 | Figure 1446: Map of the difference of variance of the altimeter SLA – Argo DHA differences, using  
 3 | successively mono mission and multi missions grids of altimeter products with Argo 900 dbar profiles (a) and  
 4 | 1900 dbar profiles (b).





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 2 | Figure 15-17: 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 reference  
 4 | (magenta) and 1900 dbar reference (red) in the Antarctic Circumpolar Current.



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 2 | Figure 1618 : 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).