Validation of altimeter data by comparison with in-situ T/S Argo profiles

2011-2015 SALP contract No 104685

Reference : CLS.DOS/NT/15-007
Nomenclature : SALP-RP-MA-EA-22406-CLS
Issue : 1rev 0
Date : January 22, 2015

Chronology Issues :		
Issue :	Date :	Reason for change :
1.0	January 2015	Creation

People involved in this issue:				
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Analyse documentaire :	
Context :	
Key words :	Altimetry, Argo Temperature and Salinity profiles, In-Situ calibration, MSL
hypertext links :	

Distribution :		
Company	Means of distribution	Names
CLS/DOS	electronic copy	G. Dibarboure V. Rosmorduc
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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 fondamental since it provides an external and independant reference. This document is the synthesis report for 2014 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, 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]).

In 2014, major efforts have been performed to better understand the physical content of the observed sea level differences, to better estimate the error of the method and to reduce the uncertainty associated with the results.

1. Concerning the data, Argo T/S profiles provide the steric Dynamic Height Anomaly (DHA) above a reference level associated with the thermohaline expansion of the water column. The associated physical content is thus different than the altimeter observations of the total height of the water column. An improvement of the method has been achieved by including the mass contribution to the sea level derived from the Gravity Recovery And Climate Experiment (GRACE) in order to compare homogeneous physical contents. In 2014, two new GRACE datasets have been used (GRGS V3 and a global mean time series provided by Chambers: Johnson and Chambers 2013, [6]). This has allowed us to better estimate the absolute altimeter MSL drift and to better characterize the associated uncertainties.
2. Concerning the method of comparison, the sensitivity to the temporal reference of the anomalies as been highlighted as well as the impact of regions of high ocean variability on the global results. The analysis of the sensitivity to the spatial and temporal sampling of the Argo profiles has been performed, as well as to the reference depth of the Argo dynamic heights. This

has contributed to better characterize the method uncertainty and to improve our confidence in the results.

3. The impact estimation of new altimeter standards or products is analyzed by comparison with the external in-situ reference. The studies concern the GDR-E and GDR-D orbit solutions and the assessment of the reprocessed SSALTO/DUACS 2014 merged products.

2. Presentation of the databases

2.1. Altimeter measurements

In this study, along-track (level 2) altimeter SSH are used from several satellite altimeters, where standards are updated compared with the Geophysical Data Record (GDR) altimeter products. Details of the SSH computation and time period for each altimeter are presented in annex 9.1. and available in the MSL part of the Archiving, Validation and Interpretation of Satellite Oceanographic website (AVISO, http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/processing-corrections.html). As the comparison with in-situ data is performed since 2004, we focus the analyses on the Envisat, Jason-1, Jason-2 and SARAL/AltiKa space missions. Sea Level Anomalies (SLA) of all altimeter missions are computed with a reference to the Mean Sea Surface (MSS) CNES/CLS 2011 model (Schaeffer et al., 2012, [14]). Concerning Envisat mission, the reprocessed (V2.1) altimeter data are used (which includes the GDR-C orbit solution). Grids of merged altimeter products (L4) can also be compared with in-situ data.

2.2. Argo in-situ measurements

The lagrangian profiling floats of the Argo program are used as a reference in this study. They provide a global monitoring of ocean temperature and salinity (T/S) data between the surface and around 2 000 dbar for most of them with a 10-day sampling and a lifetime of a few years. The objective of a global network of 3 000 operating floats has been achieved in 2007 and figure 1 displays the spatial distribution of the floats that have delivered data within the last 30 days before the mentionned date.

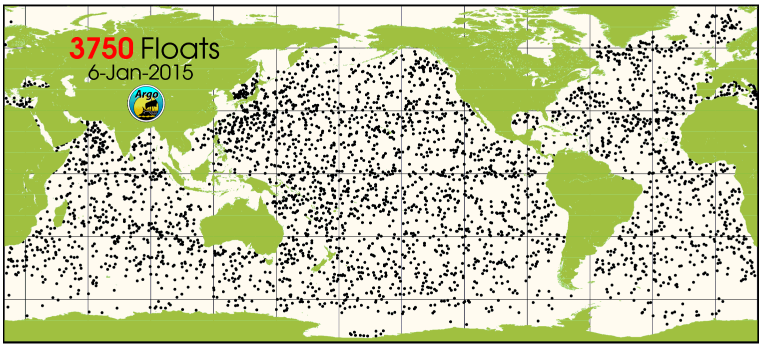

Figure 1: *Spatial distribution of the floats that have delivered data within the last 30 days before the mentionned date (Argo Information Center).*

Delayed mode and real time quality controlled (Guinehut et al., 2009: [5]) T/S profiles from the Coriolis Global Data Assembly Center (www.coriolis.eu.org) are used. Figure 2 shows spatial and temporal distribution of Argo measurements over the period 2002 - June 2014. The database has intentionnally not been updated later in 2014 so that the results of the studies have been obtained with an homogeneous in-situ reference.

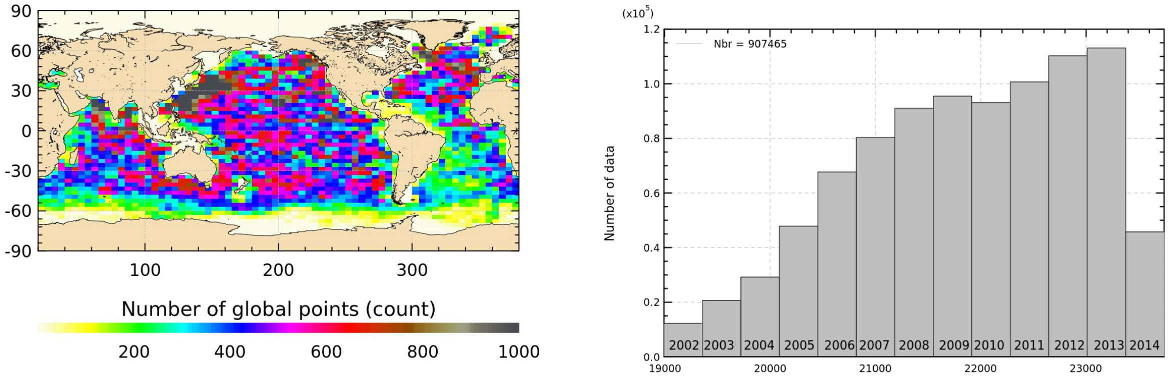

Figure 2: *Spatial (left) and temporal (right) distribution of temperature and salinity Argo profiles from 2002 to 2014.*

The vast amount of T/S profiles are available over almost the global open ocean (figure 2, left). Best sampled areas (Kurushio current, parts of the North Indian, North Atlantic and North Pacific oceans) have more than 1 000 profiles per box of 3°x5°. About 500 profiles per box are found in large parts of the global ocean, except in the South West Atlantic ocean and in the southern part of the Antarctic Circumpolar current where about 200 profiles per box are found. The number of available profiles has regularly increased since 2002 (figure 2, right) and has reached more than 100 100 per year since 2011. Nevertheless, spatial distribution has not always been high enough in some areas to produce statistically valid analyses. As discussed by Roemmich and Gilson, 2009 ([13]), figure 3 indicates that considering a threshold of two thirds of the open ocean surface covered by Argo floats (±60°), analyses should be performed with in-situ data from about mid 2004 onwards, which is done in this report. This constitues a great asset for latest altimeter missions (Jason-1, Envisat, Jason-2 and SARAL/AltiKa). It leads to a global in-situ dataset of more than 900 000 T/S profiles distributed over almost the global open ocean.

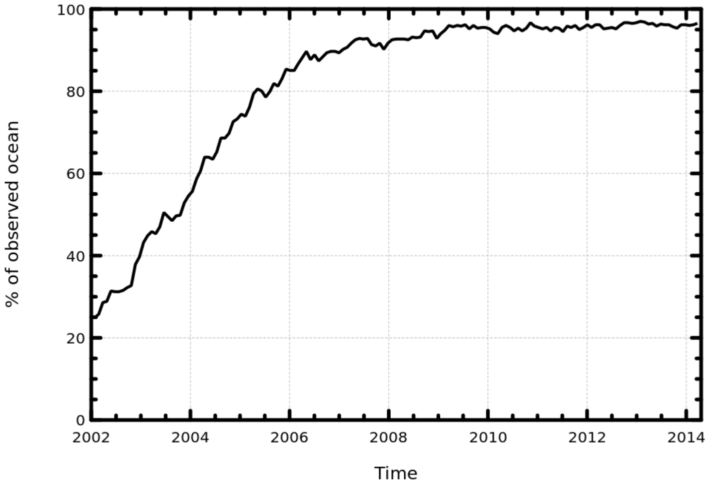

Figure 3: *Monitoring of the percentage of the ocean covered by Argo profiling floats (±60° and without inland seas).*

The associated steric Dynamic Height Anomalies (DHA) are computed using a reference level of integration of the T/S vertical profiles and a contemporaneous mean dynamic height (also called synthetic climatology). It has already been demonstrated ([9]) that the choice of the reference level results from the balance to be found between the sampling of the water column (vertical sampling) and the spatial coverage of the network (horizontal sampling). This choice may affect the results of the altimeter in-situ comparisons and some sensitivity analyses are described in this report.

2.3. GRACE measurements of the mass contribution

The physical contents of the altimeter and steric in-situ dynamic heights are different and in particular, a phase offset is observed between the two global averages due to the seasonnal distribution of the mass contribution which is missing in the Argo dataset (Chen et al, 98, [3]). This mass contribution can be derived from GRACE data in order to compare with altimetry.

We have used in the past the only dataset adapted for our analyses (global and regional comparisons) which was the GRACE mass contribution to the sea level provided by the GRGS research group (`http://grgs.obs-mip.fr/grace`). The V2 dataset (10-days grids over 2003 to August 2012) has been used and the updated V3 (monthly grids over 2003 to December 2012) has been made available. The GRGS GRACE data are not filtered and are not corrected from the post glacial rebound (Glacial Isostatic Adjustment) correction. In this report, we present the impact of using this new dataset on the altimeter quality assessment.

An additional dataset of the mass contribution to the sea level is available (http://xena.marine.usf.edu/ chambers/SatLab/Home.html). It consists in monthly global mean of the equivalent sea level (Johnson and Chambers 2013, [6]) and can thus only be used for analyses of the global altimeter sea level drift. This dataset is corrected from the GIA correction. The fact that it consists in a timeseries prevents us from regional analyses and can thus not be systematically used in the scope of our activities. In addition, this makes the technical aspect of the comparison more difficult since the processing chain is not adapted for direct comparison of global timeseries. The impact of using this dataset is presented in this report.

Note that the mass contribution is not systematically used since the mass component is not available for recent days and since relative comparison with Argo data may be sufficient to detect the impact of a new altimeter standard for instance.

3. Method of comparison

The large number of available T/S profiles constitutes an independent dataset well adapted for comparison with altimeter data over the open ocean where tide gauges distribution is not sufficient. To perform these studies, a processing sequence has been developped (in the frame of the SALP project) which aims at being regularly operated to validate all altimeter missions. In this section, we present the method of comparison of altimeter SLA with in-situ data.

Altimeter measurements are compared with in-situ dynamic height anomalies (DHA) derived from the Argo temperature and salinity profiles and with the mass contribution to the sea level derived from GRACE measurements. These are described hereafter:

1. Colocation of altimeter and GRACE data with Argo in-situ profiles
2. Validation of colocated measurements in order to exclude bad data
3. Estimate of statistics

3.1. Comparison of similar physical contents

Altimeter measurements are representative of the total elevation of the sea surface (surface to bottom), that includes barotropic and baroclinic components, whereas, DHA from profiling floats are representative of the steric elevation associated with the thermohaline expansion of the water column from the surface to the reference level of integration (i.e. baroclinic component). These data can be combined with grids of the mass contribution to the sea level from GRACE to provide an estimation of the total height of the water column so that the same physical content is compared with altimetry. Note that this mass contribution is not systematically used since relative comparison with Argo data may be sufficient to detect the impact of a new altimeter standard for instance. The deep steric contributions are not taken into account in our study but their impact on the results is discussed in this report.

As discussed in previous annual report of the activity ([8]), in-situ DHA are referenced to a mean of the Argo dynamic heights over a time period (2003-2011) different from the reference period of altimeter SLA. In order to compare both types of data with a common temporal reference, altimeter data are computed with the in-situ reference period by removing the mean of altimeter SLA over 2003-2011. The use of a common temporal reference provides more homogeneity between the two types of data and increase their correlation, which thus improves our confidence in the results (see 2011 annual report of the activity, [7]). The sensitivity of the results to this temporal reference is discussed further in this report.

3.2. Colocation of in-situ and altimeter data

The quality assessment of the altimeter SLA from a single mission is based on the along-track (L2) SLA. As the altimeter sampling is better than the in-situ coverage (a global altimeter coverage of the ocean, for Jason missions, versus a single T/S profile every ten days), grids of 10-day averaged along-track SLA are computed in order to have a sufficient spatial coverage. The quality of gridded merged (L4) products can also be estimated (SSALTO/DUACS maps for instance). Then the colocation of both types of data is made via the interpolation of these grids for each altimeter mission (bi-linearly in space and linearly in time) at the location and time of each in-situ profile. The impact of averaging the altimeter L2 data over 10 days is estimated to be weak considering that the ocean state has not changed significantly within less than 10 days. Similarly, the grids of GRACE ocean mass data are also colocated with each Argo profile.

3.3. Validation of compared altimeter and in-situ measurements

In order to exclude potential remaining spurious values and improve the correlation between both types of data (and thus increase our confidence in the results), a two steps selection is made in the processing chain over altimeter SLA and in-situ DHA:

- Selection differences between altimeter SLA and in-situ DHA lower than 0.20 m. The choice of this threshold is based on the histogramm of SLA differences (figure 4, left). The selection is written as: $|SLA_{alti} - DHA| \leq 0.20m$.
- Selection over a maximal DHA from in-situ data. According to results from global Cal/Val analyses and from analyses of the in-situ dataset, values greater than 1.5 m are not taken into account: $|SLA_{InSitu}| \leq 1.5m$

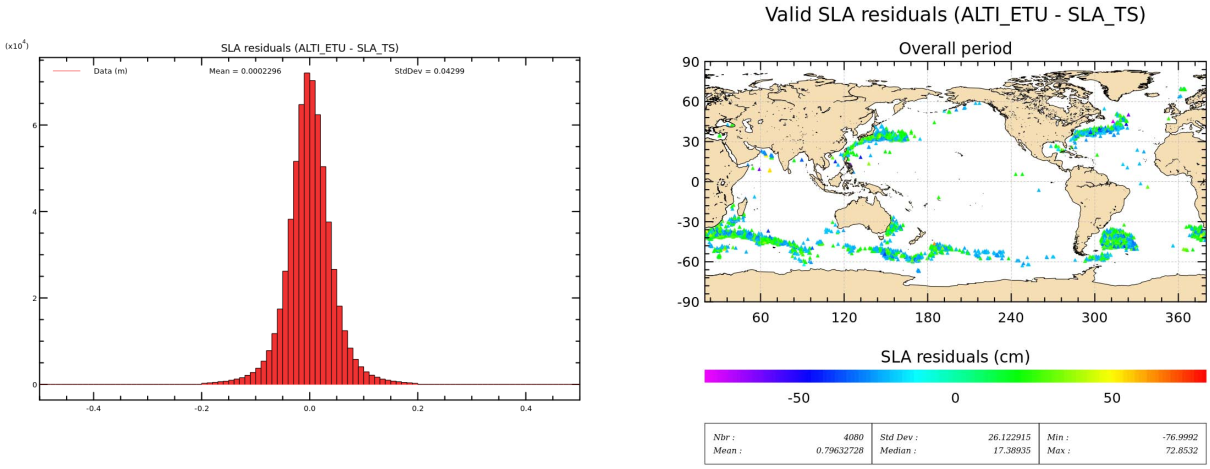

Figure 4: *Histogram of valid SLA (DUACS merged maps) - DHA differences (number of profiles according to the observed sea level differences in meters, left) and map of the invalid SLA - DHA differences (right).*

This selection excludes about 2% of the total colocated measurements of Jason-1 data and figure 4 (right) indicates that the excluded measurements are mainly located in regions of high ocean variability. They are not associated with erroneous data but their rejection is due to the colocation method itself. Thus, if this validation would not be performed, the uncertainty in these regions would be too high to produce any valid results. The exluded data are totally attributed to the first validation step (threshold on the differences) but the second validation step is kept in case of potential remaining erroneous Argo data. The correlation and rms differences between altimeter SLA and in-situ steric DHA become 0.72 and 6.3 cm respectively whereas they are 0.65 and 7.2 cm when the validation phase is not considered. Thus the results will not be significantly affected by this selection but it strongly increases our confidence in the method. Note that the sensitivity of the results to these areas of high ocean variability is discussed in the following section.

3.4. Computation of global statistics

The processing sequence uses the database of colocated altimetry and Argo profiles to generate statistics of the altimeter sea level differences compared with in-situ measurements for each altimeter mission. Then, various diagnoses are produced from these statistics in order to detect potential anomalies in altimeter data. The global dispersion of the datasets (figure 5) provides information on the correlation and coherence between both types of data and then, deeper analyses can be performed: temporal and spatial evolution of the statistics of the differences, histograms, Taylor diagrams, uncertainties estimations...

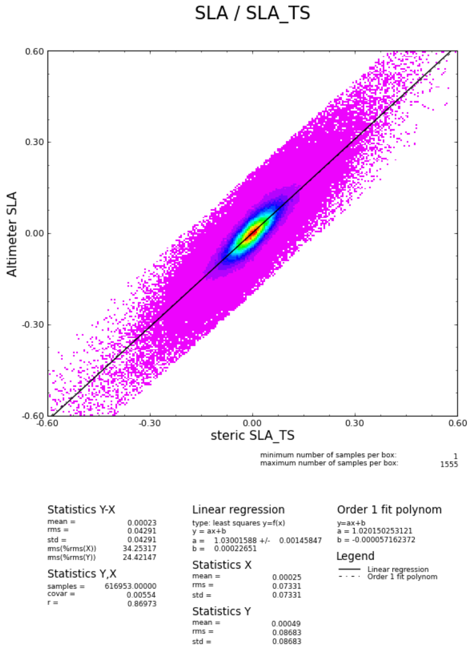

Figure 5: *Dispersion between DUACS merged maps of altimeter SLA and the steric DHA from Argo plus the mass contribution from GRACE.*

4. Impact study results

The comparison of altimeter measurements with in-situ steric heights derived from the Argo network allows the detection of altimeter drift or anomalies at global and regional scales and the assessment of new altimeter standards or products (Valladeau et al, 2012 and previous annual reports).

This document aims at determining to which extent the altimetry quality assessment is sensitive to the Argo data (sampling, processing...). Hereafter are described the results of several impact studies.

4.1. The mass contribution from GRACE: updated and new dataset

4.1.1. The GRGS dataset

The mass contribution to the sea level that is missing in the Argo observations is derived from GRACE data. As discussed in the former section, we have used the V2 dataset provided by the GRGS/LEGOS (Groupe de Recherche en Geodesie Spatiale) research group (`http://grgs.obs-mip.fr/grace`). The maps of ocean mass contribution are not filtered and they can be globally averaged in order to obtain the global ocean mass contribution to the sea level. An updated version V3 has been made available and we present here the comparison of these two versions.

The GRGS V2 dataset are 10 days-maps and is defined over the period 2003 to August 2012 whereas the GRGS V3 dataset consists in monthly maps and is defined up to December 2012. In terms of amplitude of the annual signal of the SLA - (DHA + Mass) differences, figure 6 confirms that the use of the ocean mass contribution in the altimetry versus Argo differences clearly improves the comparison of both datasets by reducing the amplitude by an order of magnitude of 10. 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. In addition, figure 6 indicates that the V3 ocean mass slightly deteriorates the amplitude of the annual signal of the differences.

The impact of using the V3 ocean mass is estimated in terms of the global correlation and rms of the differences between Jason-1 altimeter measurements and Argo + mass. Table 1 indicates that the V3 dataset significantly improves the statistics of the differences at global scales. Thus, this dataset will be used for future analyses.

SLA vs (DHA + OM)	**Correlation**	**rms of the differences**
GRGS V2	0.67	6.4 cm
GRGS V3	0.68	6.2 cm

Table 1: *Correlation and rms of the differences between Jason-1 altimeter SLA and Argo DHA referenced to 900 dbar + Ocean Mass derived from the GRGS V2 and V3*

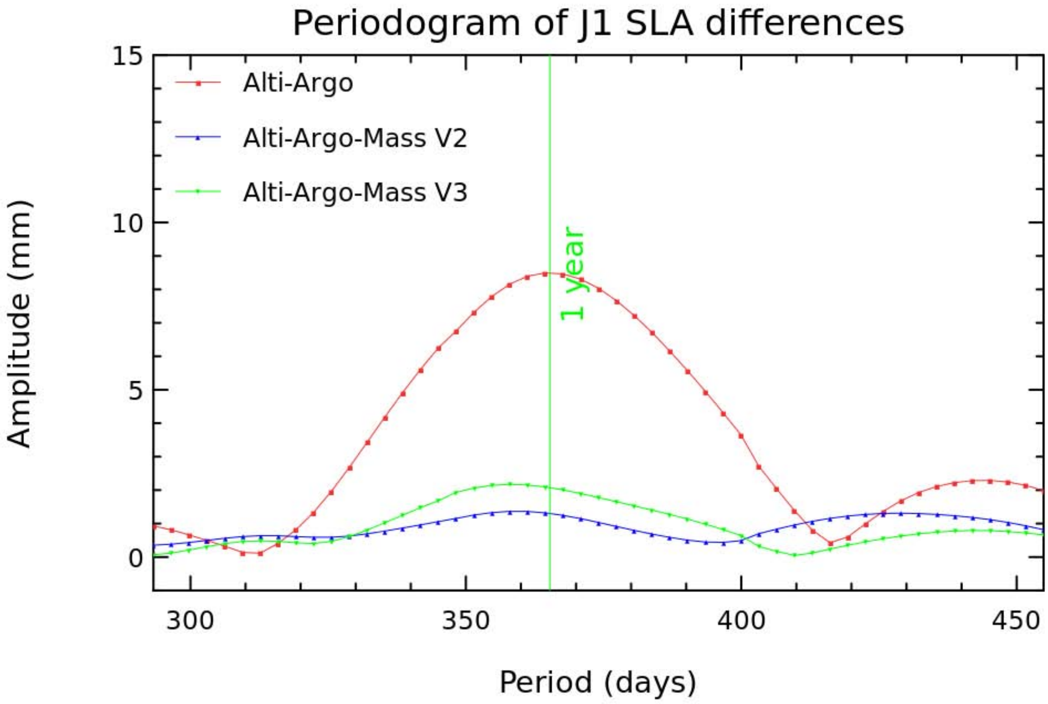

Figure 6: *Periodogram of the annual signal of the altimetry (Jason-1) - Argo - GRACE measurements with GRGS V2 (blue) and V3 (green) ocean mass datasets and without the ocean mass (red).*

4.1.2. The GRACE global mean timeseries

As mentioned in the previous section, an additional dataset of the mass contribution to the sea level is available (http://xena.marine.usf.edu/ chambers/SatLab/Home.html). It consists in monthly global mean of the equivalent sea level (Johnson and Chambers 2013, [6]) and can thus only be used for analyses of the global altimeter sea level drift. It is defined over the period 2003 to December 2013 and a GIA correction is included. The fact that it consists in a timeseries prevents us from regional analyses and can thus not be systematically used in the scope of our activities.

The impact of using these new ocean mass dataset will be discussed in the following section with the analyses of the altimeter drfit and inter-annual signals.

4.2. Sensitivity to the temporal reference of the anomalies

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 does not affect the global trend differences but it directly impacts the trend differences at regional scales (see 2011 annual report, [7]).

The detection of the evolution provided by a new altimeter standard or product in terms of global correlation between all collocated altimeter SLA and in-situ DHA may be distorted whether the temporal reference is homogeneous or not. The table 2 indicates that without a homogeneous temporal reference, the reprocessed AVISO DUACS DT 2014 product is more correlated with Argo DHA than the AVISO 2010 products. However, no difference of correlation is observed when the anomalies are computed with the same temporal reference (last column).

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

Table 2: *Correlation between all collocated altimeter SLA (AVISO DUACS delayed-time version 2010 and 2014) and in-situ DHA from Argo profiles (with a reference depth of 1900 dbar and a 2003-2011 temporal reference) without and with an homogeneous temporal reference.*

4.3. Sensitivity to the spatial and temporal sampling of Argo profiles

4.3.1. Spatial sampling

The target of a 3000 network of Argo floats has been achieved in 2007 and they now provide an almost global coverage of the open ocean. This targeted number of floats has not been determined in order to allow altimetry validation in particular. Thus a sensitivity analysis has been performed in order to illustrate the impact of a network with a reduced spatial coverage on the altimetry validation. Some results had already been shown last year (2013 annual report, [9]), indicating that reducing the number of floats strongly affects the ocean coverage by the instruments since some areas may not be sampled at all over the 2004-2012 period such as the South West Atlantic Ocean.

In terms of trend of the differences over a 8 year period, it is almost not modified with half of the floats and it is affected by up to 0.4 mm/yr when only a quarter of the floats are used.

In addition, figure 7 shows the Taylor diagram between AVISO altimeter merged products and the Argo in-situ steric heights (with the addition of the GRACE GRGS ocean mass dataset so that the physical content are homogeneous) with different subsampling of the Argo network. This diagram requires as input data the global mean altimeter and in-situ time series and it provides information on the correlation and the rms of the differences between both time series. The performance obtained with a quarter of the floats appears to be slightly deteriorated but the different points are very close to each other and as for the global trends, this confirms that the validation of altimeter measurements is not significantly affected by a reduction of the number of Argo floats and a reduced spatial coverage of the in-situ network.

4.3.2. Temporal sampling

The Argo floats provide vertical T/S profiles every 10 days. This is a good compromise in order to sample the ocean variability and to ensure a long enough life time of the floats. This temporal sampling has not been determined for satellite altimetry validation purposes in particular. For comparison, altimeter missions such as TOPEX/Jason missions provide a global coverage of the

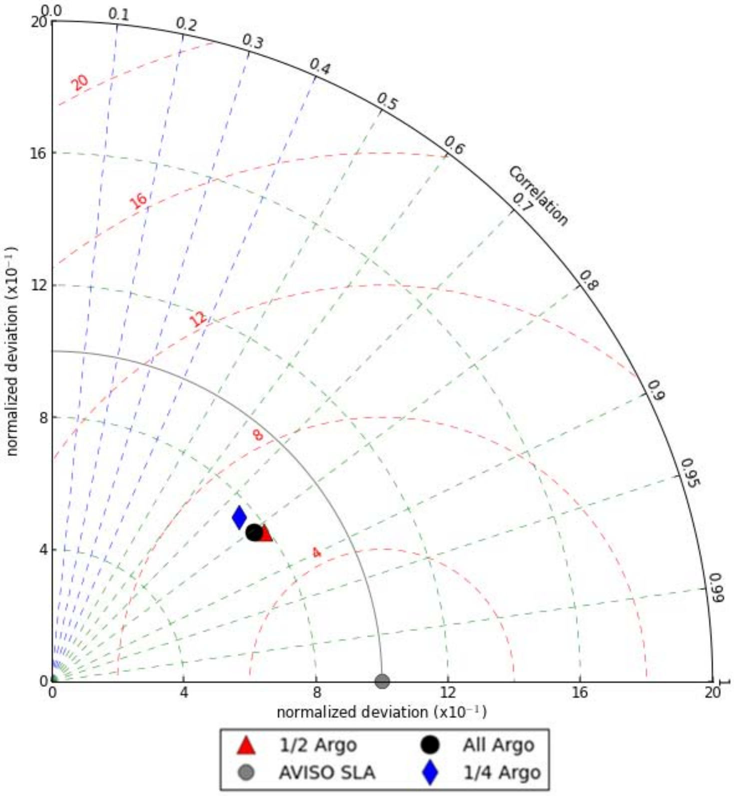

Figure 7: *Taylor diagram of the steric contributions to the sea level derived from different sub sampling of the Argo floats with the mass contribution (GRACE GRGS V2) compared with the AVISO DUACS merged altimeter SLA over the period mid 2004 to December 2012.*

ocean within the same period. We want to determine the impact of a reduced temporal sampling on the validation of altimeter products with the use of only 1 vertical profile out of 3 for each Argo floats (monthly sampling instead of 10 days).

This sensitivity study is performed in the context of the impact estimation of the GDR-D orbit solution compared with the GDR-C standard. The use of the GDR-C orbit solution for the calculation of the Jason-1 altimeter SLA leads to an East/West hemispheric bias (separated at 0°/180° longitude) in the regional distribution of the altimeter sea level trends (Valladeau et al., 2012, [15]). This has been shown to be related with the gravity field used in the orbit calculation.

This hemispheric bias is observed when computing the trend of the differences between altimeter SLA and in-situ DHA (1900 dbar) in each hemisphere (figure 8, top left): the difference of trends between each area is of -1.38 mm/yr over mid 2004-2010 with the GDR-C standard. With the use of the GDR-D orbit solution for the altimeter SLA calculation, this bias is reduced to -0.13 mm/yr (top right). This demonstrates that this updated altimeter standard improves the regional homogeneity of the altimeter SLA. However, given the uncertainty associated with these trend estimations (more than 0.5 mm/yr over this period), we are close to the limit where these both values can be distinguished with enough confidence in the results.

The goal is to assess whether the previous result is affected with a different temporal sampling of the Argo floats. The trend of the differences between the altimeter SLA and in-situ DHA is computed as before for each hemisphere with both altimeter standards but only one out of three in-situ profiles are used, which leads to a monthly sampling for all floats instead of 10 days. The East/West hemispheric trend differences become -0.98 mm/yr and 0.67 mm/yr with the GDR-C and GDR-D standards respectively (figure 8, bottom left and right respectively). The difference between these both values is greater than previsouly. However, this means that in these conditions, none of the standards allow the reduction of the hemispheric discrepancies by comparison with the in-situ independent reference (since absolute values of these trends are similar). This case of study indicates that the detection of the impact of new altimeter standard and the altimeter drift detection is clearly affected by the temporal sub sampling of the Argo floats.

However, other case of studies have been analyzed and when the difference between two altimeter products or standards is relatively small, no impact of the temporal sub sampling of the Argo floats has been found in these situations.

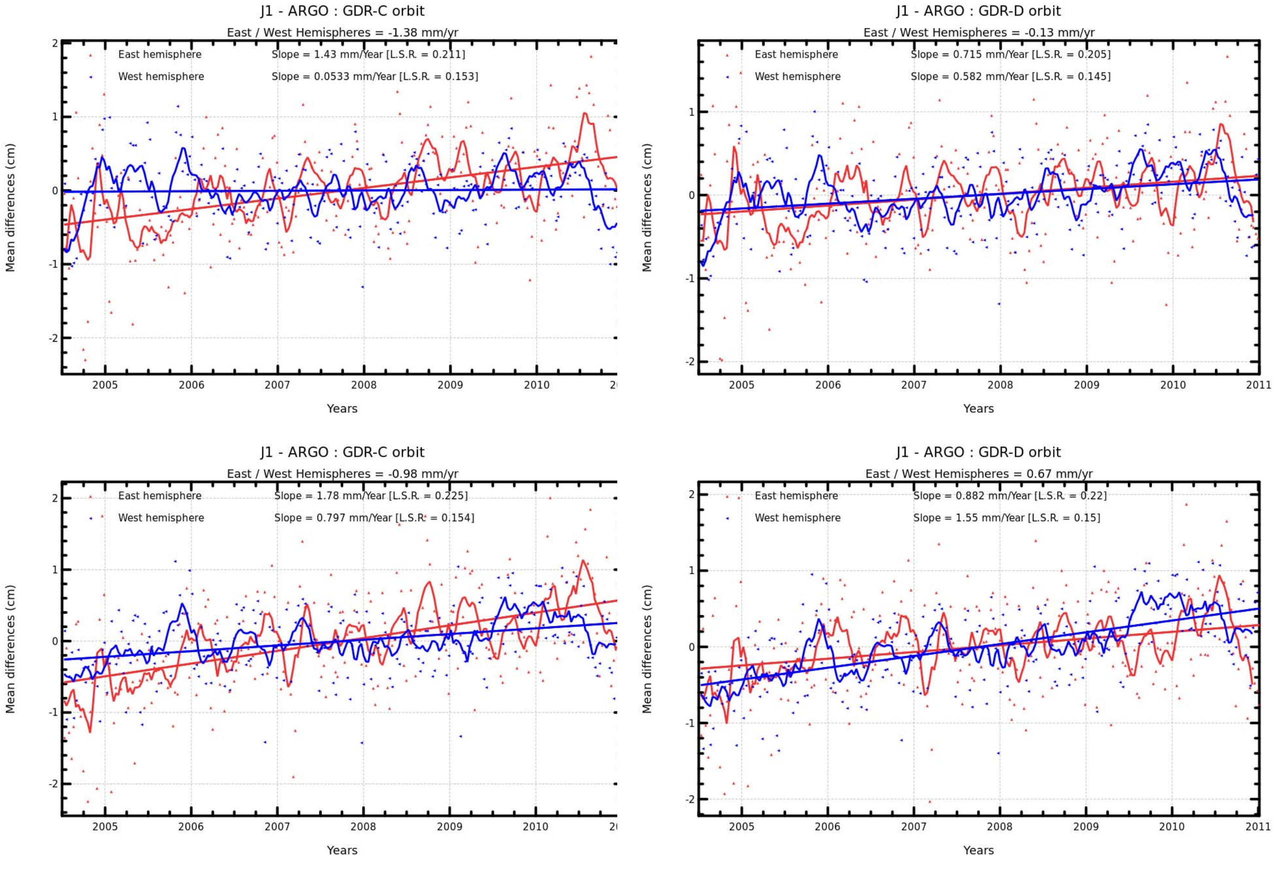

Figure 8: *SSH differences (cm) between Jason-1 altimeter data and Argo (1900dbar) in-situ measurements computed with GDR-C (left) and CNES preliminary GDR-D orbit solutions (right) with the whole Argo network (top) and with 1 profile out of 3 for each Argo floats (bottom), separating East (<180Â°, in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

4.4. Impact of the regions of high ocean variability

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The variability of the SLA - DHA differences are larger in regions of high ocean variability (figure 9, top). This is related with the method of comparison of both data and the collocation approach (interpolation of 10 days grids at the position and time of each Argo profile.

The comparison of altimeter data with Argo measurements can be performed after removing areas of ocean variability higher than a given threshold. In term of spatial coverage, the lower this threshold, the larger areas are removed. This illustrated on figure 9 which shows the spatial distribution of all SLA-DHA observations over the 2005-2013 period (left) and without areas of ocean variability higher that 100 cm^2 (right).

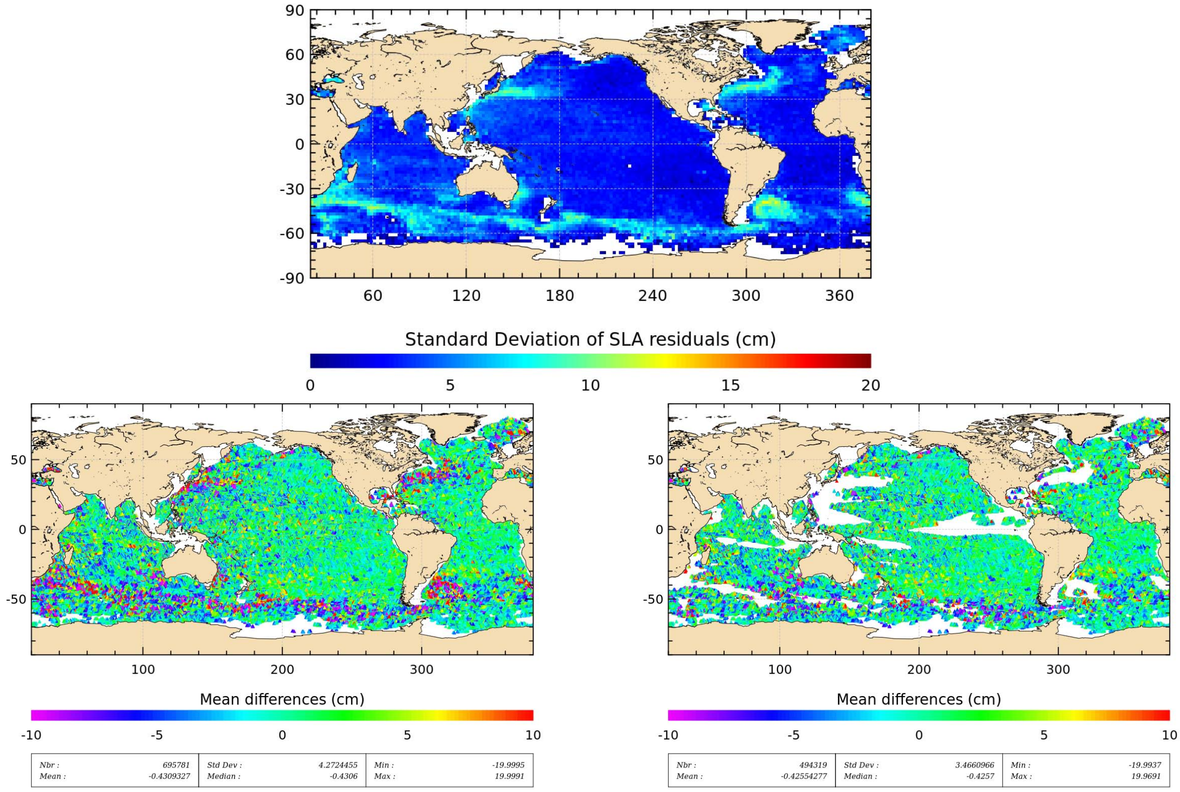


Figure 9: *Map of the standard deviation of the differences between altimeter SLA (DUACS 2014) and Argo DHA (900 dbar) over the period 2005-2013 (top). Map of the mean differences between AVISO DUACS 2014 and Argo DHA (900 dbar) with the global Argo network (left) and without areas of ocean variability > 100 cm^2 (right) over 2005-2013.*

Figure 10 indicates that the detection of altimeter drift is not affected by the exclusion of areas of high ocean variability. This is in agreement with results obtained on the sensitivity analysis of the altimeter validation to the spatial sampling of the Argo network (see 2013 annual report, [9] and the previous section).

Figure 11 (left) illustrates that the lower the threshold on the ocean variability, the larger areas are removed and thus, a lower number of observations is available. The right panel indicates that when larger areas are removed, the correlation between altimeter SLA and Argo DHA is reduced and the

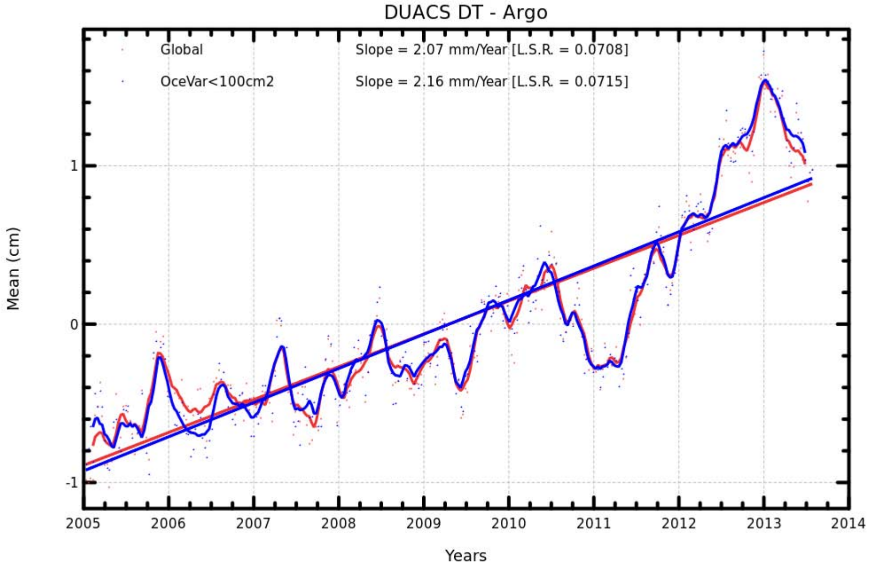


Figure 10: *Temporal evolution of the mean differences between AVISO DUACS 2014 and Argo DHA (900 dbar reference) with the global Argo network (red) and without areas of ocean variability > 100 cm2 (blue). The trends of the differences are 2.07 mm/yr and 2.16 mm/yr respectively.*

rms of the differences (expressed in percentage of the altimeter variance) is increased.

This suggests that the areas of large ocean variability significantly contribute to the global statistics computed between altimetry and Argo data. However, this does not allow us to determine whether an increased sampling of these regions by the Argo network would improve the results of altimetery validation.

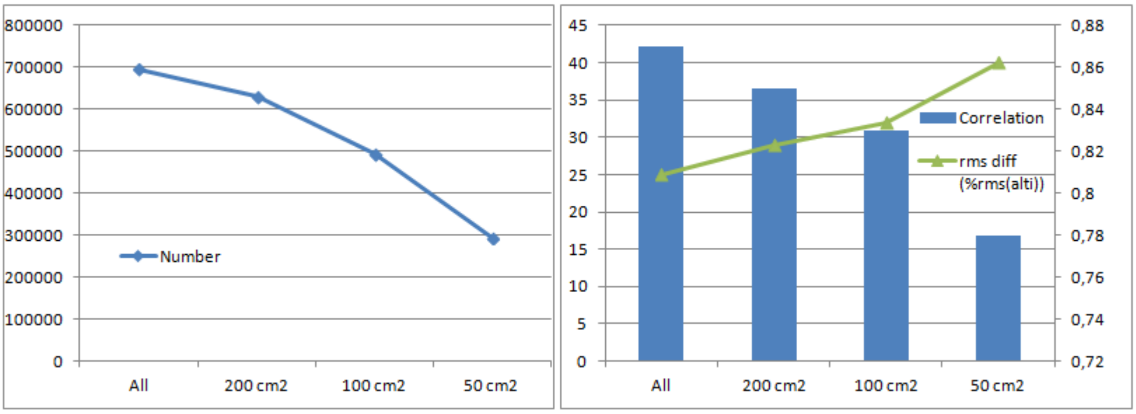


Figure 11: *Impact of excluding areas of higher ocean variability than a decreasing threshold: number of observed points (left) and correlation and rms of the differences between AVISO DUACS 2014 and Argo DHA (900 dbar reference) (right).*

4.5. Sensitivity to the reference depth of the Argo dynamic heights

The integration of the Argo T/S profiles for the computation of the in-situ steric dynamic heights requires a reference level (pressure) and,

- The deeper the reference level, the more information from the T/S profiles is taken into account,
- But the more T/S profiles are not used (those who do not reach the reference level)

Thus, we first aim at determining the impacts of a given reference depth of integration on the global Argo sampling but also on the regional Argo distribution. Secondly, we discuss of the impact on the altimeter drift detection and the sea level closure budget and then, we describe the impact of the reference level in terms of variance and detection of the difference between two altimeter products.

4.5.1. Impact on the global and regional coverage

Figure 12 (left) indicates that among the 8189 floats, most of them (3506 or 43%) have a mean maximum pressure between 1900 dbar and 2000 dbar. All the floats whose mean maximum pressure does not reach the chosen reference level will not be used. Thus, the right panel shows that:

- 6% of the floats are missed with a reference level at 900 dbar
- 21% of the floats are missed with a reference level at 1200 dbar
- 29% of the floats are missed with a reference level at 1400 dbar
- 52% of the floats are missed with a reference level at 1900 dbar

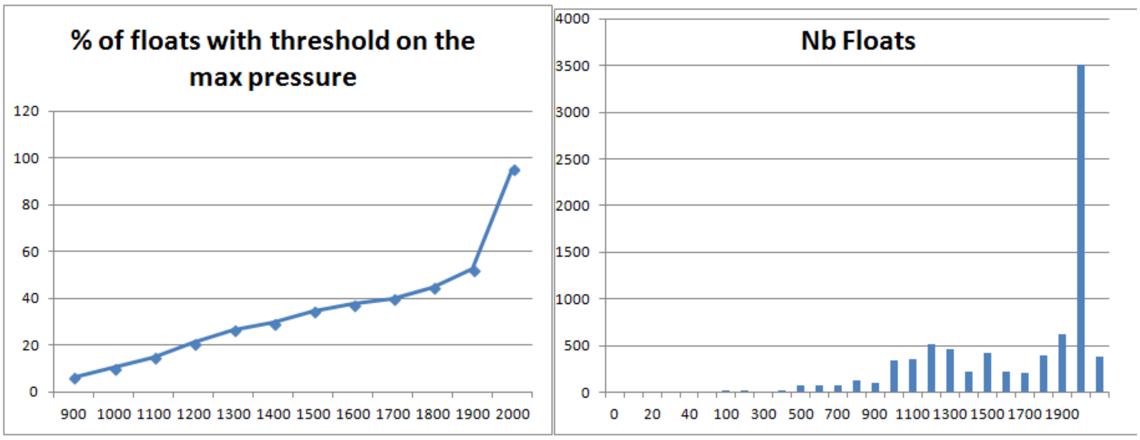
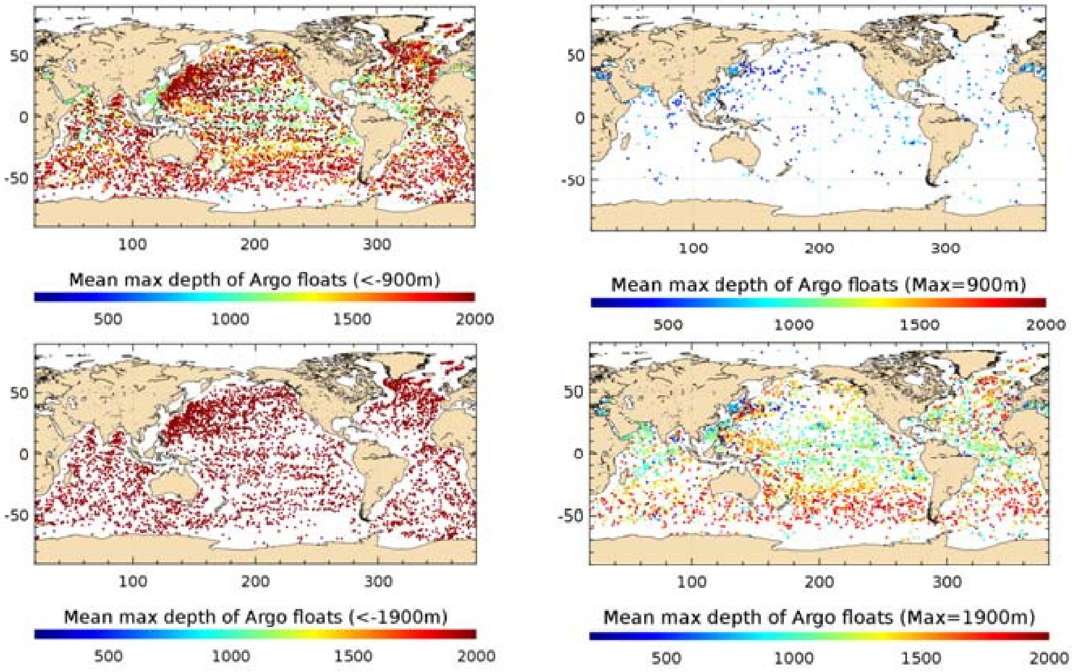


Figure 12: *Number of floats according to their mean maximum pressure over their lifetime (left) and percentage of the floats whose mean maximum pressure is smaller than a given threshold (right)*

For a given reference depth, figure 13 displays on the left maps the floats taken into account and the associated maps on the right show the floats which will not be used (mean max depth shallower than the reference). Floats with a mean maximum pressure less than 900 dbar are mainly located in the Pacific western boundary current (Kuroshio) and in the Mediterranean Sea. Floats with a mean maximum pressure between 900 dbar and 1400 dbar are mainly located at equatorial latitudes of all ocean basins. In these areas, the water column is very stratified and the steric signal is thus confined in the upper layer. Thus, with a reference depth of 1400 dbar compared with 900 dbar, the water column will be better sampled over the global ocean (which improves the retrieved steric signal) but we will miss a significant part of this steric signal at equatorial latitudes. This illustrates the balance to be found between the horizontal (shallow reference level) and vertical (deep reference level) sampling of Argo floats.


Mean max depth of Argo floats (<-900m)

Mean max depth of Argo floats (Max=900m)

Mean max depth of Argo floats (<-1900m)

Mean max depth of Argo floats (Max=1900m)

Figure 13: *Argo floats whose mean max depth is deeper than 900 dbar (top left) or 1900 dbar (bottom left) and Argo floats whose mean max depth is shallower than 900 dbar (top right) or 1900 dbar (bottom right). For a given reference depth, the left map display the floats taken into account and the associated right map show the floats which will not be used.*

When analyzing the performances of the Jason-1 mission over the 2002-2012 period, changing the reference depth from 900 dbar to 1900 dbar strongly affects the spatial coverage of the observations (figure 14): some areas as the South West Atlantic ocean are not sampled any more Ã 1900 dbar.

4.5.2. Impact on the altimeter drift detection and the sea level closure budget

The impact of the in-situ reference depth is analyzed in terms of sea level closure budget, which is provided by the global mean sea level differences between altimetry and Argo steric heights (with the addition of the GRACE GRGS V3 ocean mass contribution and corrected from the Glacial Isostatic Adjustment). This is illustrated on figure 15 for Jason-1 & 2 missions with the use of:

- All valid Argo profiles with a reference level of 900 dbar
- A reference level of 900 dbar only for valid Argo profiles whose maximum depth is deeper than 1900 dbar

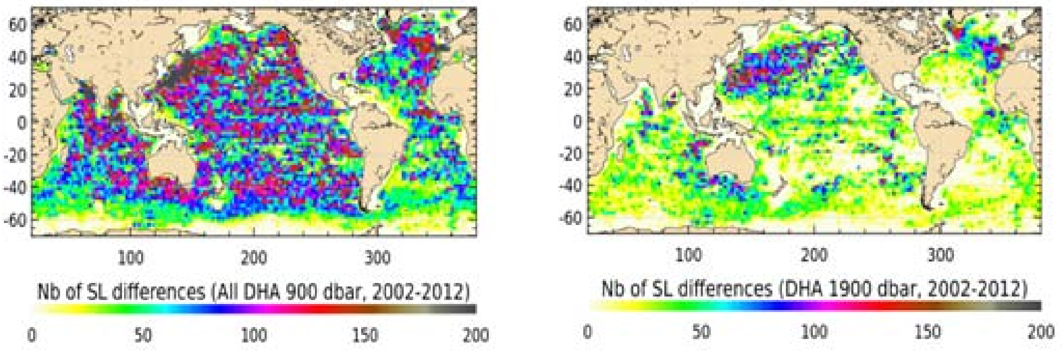


Figure 14: *Number of sea level differences between altimetry and Argo data observed in 2° × 2° boxes over 2002-2012 with all valid Argo 900 dbar (left) and 1900 dbar (right) profiles.*

- All valid Argo profiles with a reference level of 1900 dbar.

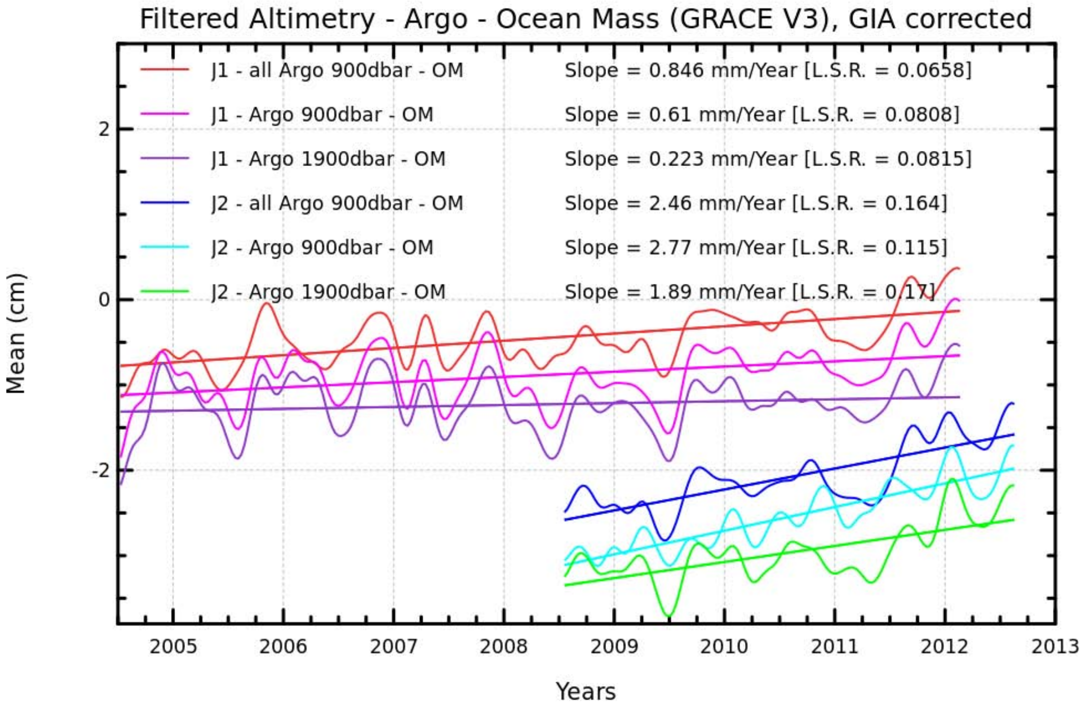


Figure 15: *Global mean sea level trends of the differences between the altimeter mean sea level (Jason-1 and Jason-2 missions) and the steric plus mass (GRACE GRGS V3) contributions to the sea level with various reference depth of integration of the Argo profiles. The altimeter and ocean mass measurements are GIA corrected.*

Among all available profiles with a 900 dbar reference depth, the selection of those whose maximum depth is deeper than 1900 dbar (impact of the horizontal sampling only) has almost no impact in terms of correlation between altimetry and in-situ data (not shown). However it affects the altimeter drift detection: 0.8 mm/yr and 0.6 mm/yr for Jason-1 over July 2004 to March 2012.

The altimeter drift detection is significantly affected by the use of 1900 dbar profiles compared with a 900 dbar reference (impact of the vertical sampling only): the Jason-1 altimeter drift is changed from 0.6 mm/yr to 0.2 mm/yr. In addition, the least squared Residual of the slope estimation is almost unchanged with this deeper reference level. This suggests that a deep reference level of integration of Argo profiles will be preferred for the detection of the altimeter drift. This illustrates that the analysis of the altimeter sea level closure budget is highly sensitive to the reference depth of integration of the Argo profiles.

Figure 15 has shown that the deep layers (900/1900 dbar) significantly contributes to the global mean sea level trends. However, figure 16 indicates that this deep contribution is not homogeneously distributed in space: the figure shows the trends of the mean differences between Jason-1 SLA and Argo DHA with 900 dbar and 1900 dbar profiles, separating the East/West hemispheres. A regional bias (0.6 mm/yr) is observed with a 900 dbar reference whereas this hemispheric discrepancy is strongly reduced (-0.1 mm/yr) with a 1900 dbar reference. This result has to be investigated for instance with a map of the trends of the in-situ steric heights computed between 900 and 1900 dbar in order to analyze in more details the spatial distribution of these sea level estimations.

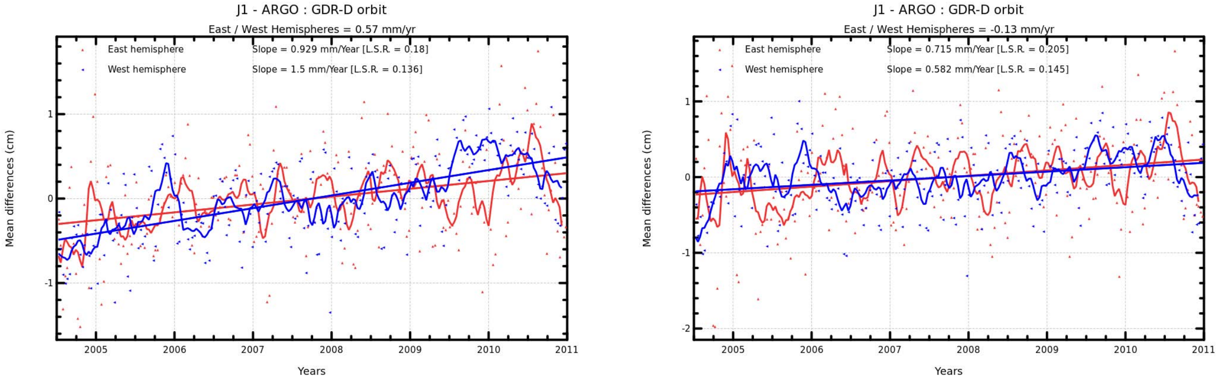


Figure 16: *SSH differences (cm) between Jason-1 altimeter data and Argo in-situ measurements computed with a 900 dbar (left) and 1900 dbar (right) reference,separating East (<180Â°, in red) and West (>180Â°, in blue) longitudes. Corresponding annual and semi-annual signals are removed. Trends of raw data are indicated and the 2-month filtered signal is added.*

4.5.3. Impact in terms of variance

The choice of the reference depth of integration of Argo profiles may affect the altimetry comparison with the in-situ measurements. Indeed, the standard deviation of the differences between altimeter SLA and Argo DHA is higher in regions of high ocean variability (figure 9, top).

We analyze the variance of the SLA - DHA differences which shows different values in the Antarctic Cirmcumpolar Current (ACC) whether the altimeter SLA is derived from mono mission or multi missions gridded products: when using 900 dbar Argo profiles (figure 17, top), adding missions reduces the altimeter / Argo consistency (blue, negative values with a mean of about -5 cm^2). On the other hand, when using 1900 dbar Argo profiles (figure 17, bottom), this tendency almost disappears in the ACC.

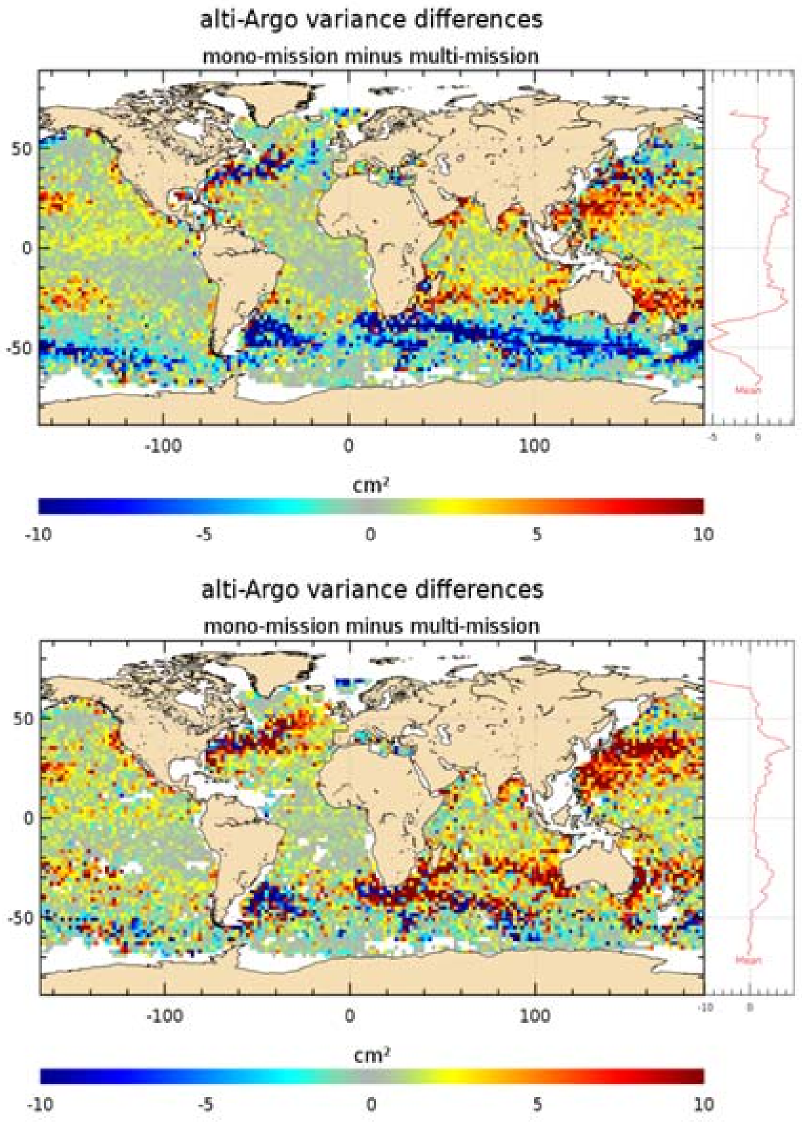


Figure 17: *Map of the difference of variance of the altimeter SLA - Argo DHA differences, using successively mono mission and multi missions grids of altimeter products with Argo 900 dabr profiles (left) and 1900 dbar profiles (right).*

This result is explained by the difference of variance of the water column as seen by altimetry or in-situ data in the ACC: figure 18 indicates that the variance of mono mission and multi missions altimeter products (collocated to Argo profiles) are very close in the ACC but the variance of the Argo steric heights referenced at 900 dbar is significantly lower (left panel). Thus with this reference level, both altimeter products can not be distinguished by comparison with Argo data. With a 1900 dbar reference level, the variance of the Argo steric heights becomes similar to the values obtained with altimeter products in the ACC (right panel) and the Argo measurements become relevant for the quality assessment of the altimeter products.

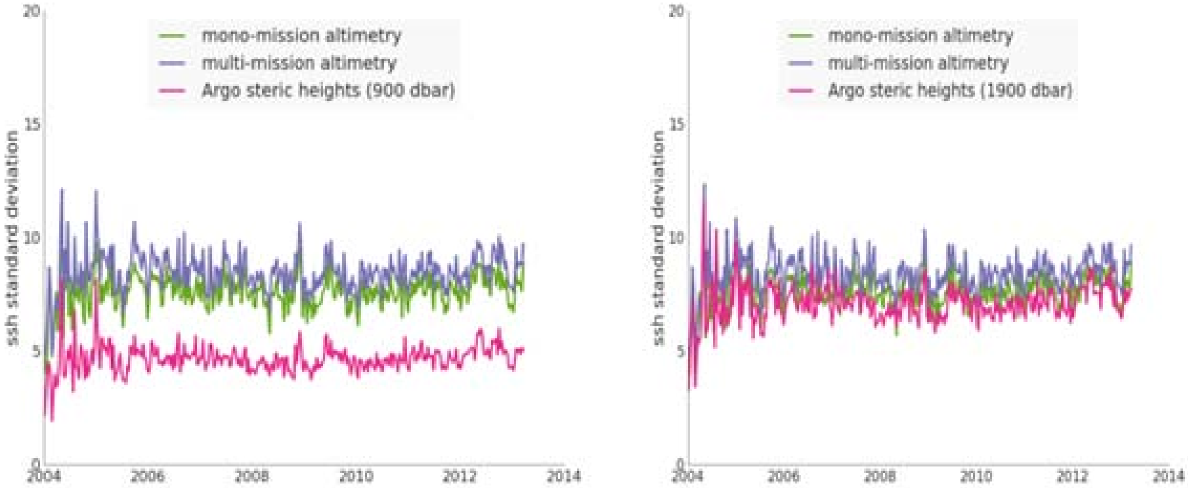


Figure 18: *Temporal evolution of the standard deviation of the altimeter SLA derived from mono mission product (green), from multi-missions product (purple) and from Argo profiles with a 900 dbar reference (left) and 1900 dbar reference (right) in the Antarctic Circumpolar Current.*

This illustrates that the Southern Ocean is a the place where the water column has to be sampled at the deepest level to estimate the steric signal. The baroclinic signal below 900m depth significantly improves the correlation between SLA and DHA and at high latitudes for mesoscale signals, the sea level variability is largely influenced by the deep baroclinic signals. According to the ocean characteristics, the analysis of the variance of the water column and thus the differences between altimetry and Argo measurements are highly sensitive to the reference depth of integration of the Argo profiles.

5. Altimeter drift

In this section, we discuss the global mean sea level trend of several altimeter missions compared with Argo+GRACE measurements and the associated inter-annual signals.

5.1. Global altimeter drifts and inter annual variability

The altimeter drift is analyzed by comparison with the sum of Argo in-situ DHA and GRACE ocean mass contribution to the sea level in order to compare similar physical content. As two different GRACE datasets are available (see previous section), we use both of them to estimate the altimeter drift. The GRGS V3 timeseries is not filtered neither corrected from the GIA effects (for the details of these effects, see the 2013 annual report, [9]), whereas the global mean timeseries of the ocean mass provided by D. Chambers (Johnson and Chambers 2013, [6]) is 2-month filtered and already corrected from the GIA.

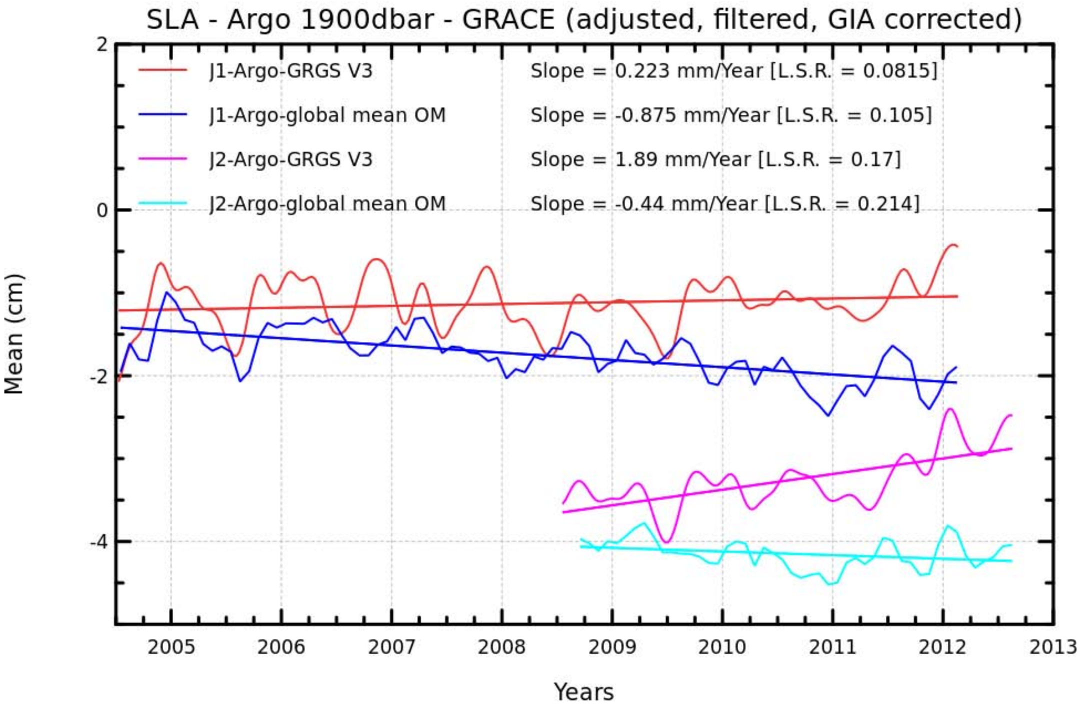


Figure 19: *Temporal evolution of the mean differences between altimeter SLA (Jason-1 & 2), Argo DHA referenced to 1900 dbar and GRACE ocean mass contribution derived from the GRGS V3 dataset and the global mean differences provided by Chambers (Johnson and Chambers 2013, [6]). Time series are filtered and GIA corrected.*

Figure 19 presents the Jason-1 and Jason-2 altimeter drifts using both GRACE datasets. Note that the Jason-1 timeseries are compared over the same period and thus stop before the end of the mission because of the length of the different GRACE datasets available. A difference of the order of 1 mm/yr is found for the Jason-1 drift computed with both GRACE measurements (+0.2 mm/yr and -0.9 mm/yr). This difference may be related with the "leakage" anomaly that is associated with areas of strong continental ice loss (mainly Greenland but also Patagonia and Antarctic peninsula). These effects are taken into account differently in the two different GRACE datasets. A selection of data only at coastal distance greater than 500 km or with a maximum threshold on the GRACE trends could help to assess whether this leakage effect has an impact on the residual altimeter drift. Over a shorter period (Jason-2 period), the difference of trends is even higher (+1.9 mm/yr and -0.4 mm/yr).

The analysis of the inter annual signals is made thanks to the detrended time series of the mean differences (figure 20) for Jason-1 with the use of the two different GRACE datsets. Similar signals can be found with both GRACE datsets, in 2005-2006 for instance but some significant differences of the order of 1 cm can be found in the observed signals at inter-annual temporal scales (in 2007-2008 for instance).

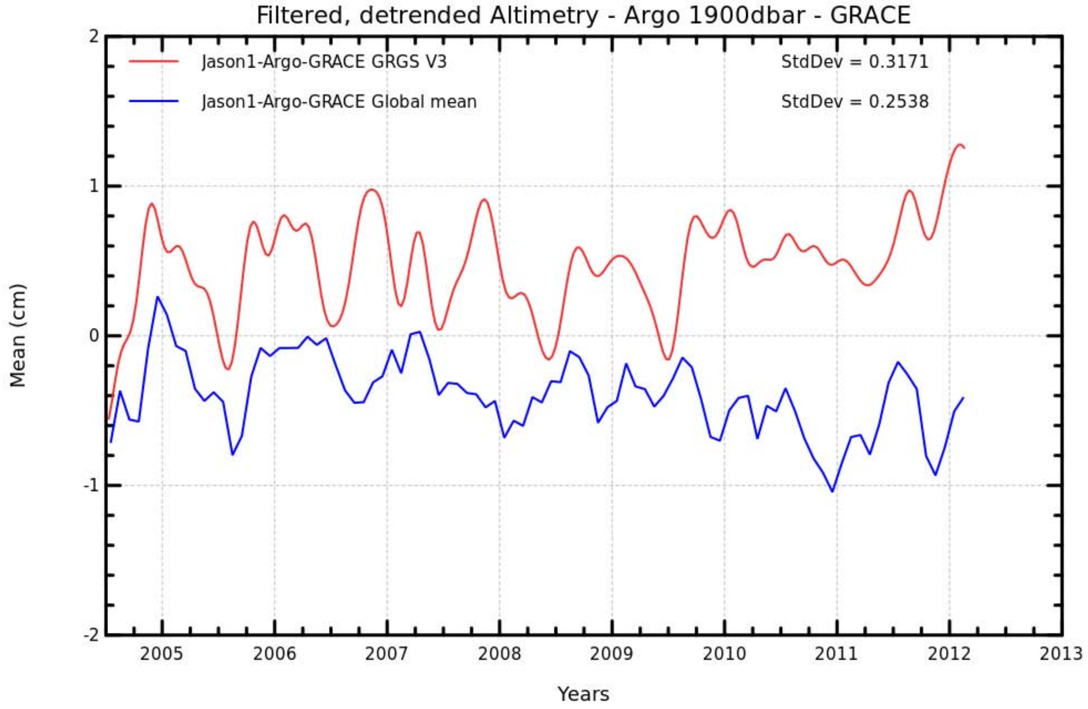


Figure 20: *Temporal evolution of the mean differences between Jason-1 altimeter SLA, Argo DHA referenced to 1900 dbar and GRACE ocean mass contribution derived from the GRGS V3 dataset and the global mean differences provided by Chambers. Time series are filtered and detrended.*

In addition, concerning the altimeter drift estimation, we have shown earlier (see the previous section), that these drifts are also strongly sensitive to the choice of the reference depth used for the computation of the Argo in-situ DHA. At last, these comparisons do not take into account the deep steric contribution (deeper than the reference level of Argo floats). The estimation of this contribution has been the subject of detailed discussions during the december 2014 CAVE (CAlibration, Validation et Expertise) in-situ meeting hold at CLS. Part of the presentations shown during this meeting are available in annex . The comparison of altimeter SLA with Argo steric DHA + the ocean mass contribution allows the estimation of the deep steric contribution (<1500m). A value of 0.3 ± 0.2 mm/yr has been estimated over the period 2005-2012 (H. B. Dieng). Note that this associated uncertainty is only a mathematical uncertainty that does not represent the total real uncertainty. Over the same period, Llovel et al., 2014 ([11]) provide an estimation of 0.0 ± 0.7 mm/yr. Over a longer period of 2003-2012, H. B. Dieng, provides an estimation of 0.55 ± 0.2 mm/yr.

The problem with the estimation of the deep steric contribution is that it requires the kwnoledge of the steric contribution from the upper ocean and a significant uncertainty remains on this estimation (see the presentation in annex , that shows the comparison of differnet datasets). Thus for the moment, it can be concluded that there is still too large uncertainties to estimate the steric deep contribution and thus to close the altimeter sea level budget.

Considering the impact of the reference depth of Argo DHA, the difference between the GRACE ocean mass datsets and the error estimation on the deep steric contribution, this suggests that the uncertainty associated with the obtained altimeter drifts (figure 19) is at least of the order of 1.0 mm/yr.

5.2. Performances of new altimeter missions

Argo measurements (DHA 1900 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 - June 2014. Table 3 indicates that over about 1 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.

Global statistics DHA 1900 dbar	**Correlation**	**rms of the differences**	**Slope of the linear regression SLA / DHA**
Jason-2	0.75	5.69 cm	0.69 m^{-1}
SARAL/AltiKa	0.74	5.70 cm	0.67 m^{-1}

Table 3: *Correlation, rms of the differences and slope of the linear regression between Jason-2 and SARAL/AltiKa altimeter SLA and Argo DHA referenced to 1900 dbar*

6. Evaluation of new altimeter standards

6.1. 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. This approach also helps us to better characterize the uncertainty associated with our method.

Various analyses of impact have been performed over the previous years concerning updated or reprocessed altimeter data for Jason-1, Jason-2 and Envisat, the use of a new MSS, the modelled or radiometric wet troposphere correction but also the quality assessment of new orbit solutions (GDR-C/D, GSFC) and new sea level merged products such as the ESA CCI dataset and so on (see previous annual reports of the activity). The criteria of improvement used for these analyses are based on the consistency (variance difference) between the updated altimeter data and the in-situ reference but also on the evolution of the correlation and of the sea level trends. According to the studied altimeter standard and the expected impact, one of these criteria will be prefered. Concerning the impact of a new orbit solution, the Argo dynamic heights are the only external reference that can be used to assess its impact. As no hemispheric bias is expected in the trend of the Argo dynamic heights, the coherence of the trend differences between two hemispheres is a strong criterion to estimate the performance of a new orbit solution (see Valladeau and Legeais 2012, [15], Couhert et al. 2014, [4]).

As already mentionned, altimeter regional sea level trends and regional trends of the mass contribution to sea level are not correlated (spatial patterns of sea level mainly depend on steric variability). Moreover high uncertainty is associated with the regional trends of ocean mass. As a result the mass contribution to the sea level is not always used when estimating the impact of new altimeter standards.

Other diagnoses should be used to estimate the impact of new altimeter standards. For instance, data could be first filtered out in the frequency band where the impact of the new standard is expected to be maximal. The regional impact could be better characterized with the maps of the correlation and rms of the differences obtained with the former and the new standards. The studies synthesized below are related to the assessment of the differences between GDR-E and GDR-D orbit solutions and of the reprocessed SSALTO/DUACS 2014 merged product.

6.2. GDR-E and GDR-D orbit solutions

The use of the GDR-E orbit solution compared with the previous GDR-D standard affects the Jason-1 altimeter SLA. In particular, an East/West hemispheric bias is observed on the difference between the map of the sea level trends computed successively with these orbit solutions (figure 21).

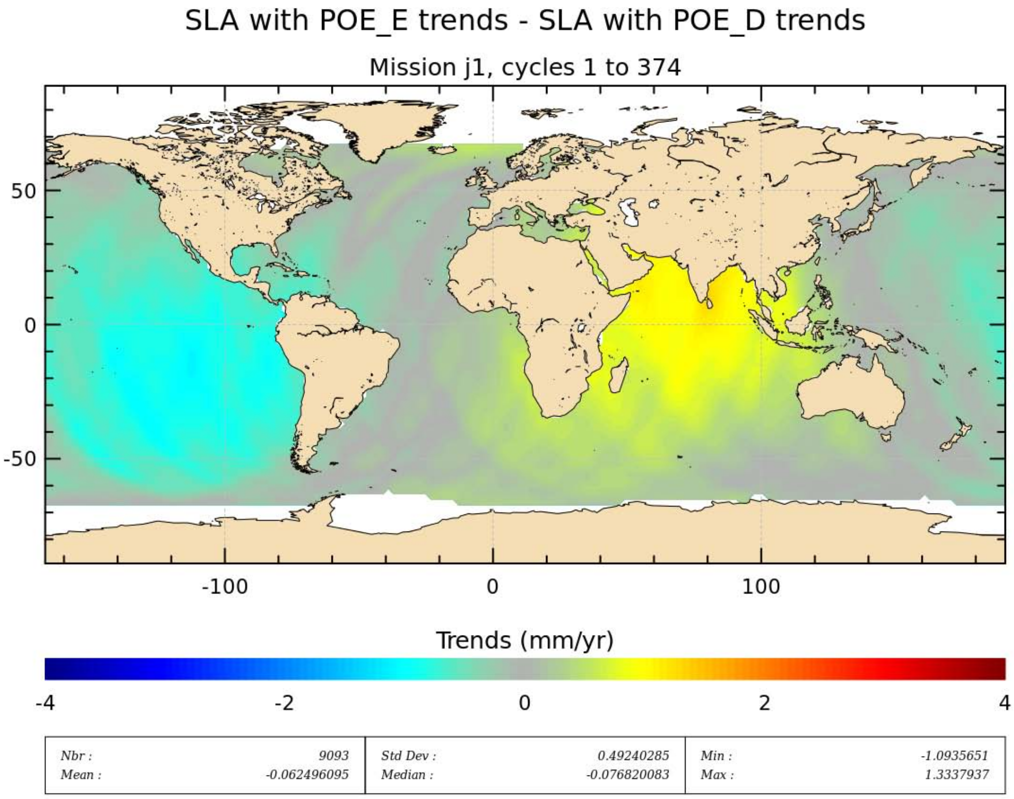


Figure 21: *Difference of maps of Jason-1 sea level trends computed successively with GDR-D and GDR-E orbit solution over 2002-2011.*

The Argo steric heights are used as an independent reference in order to determine which altimeter standard leads to the most reduced hemispheric bias. The trends of the SLA - DHA differences are computed with each orbit solution for both hemispheres and we are interested in the remaining differences. In order to better highlight the differences, we do not perform the calculation in the total ocean areas of each hemisphere but we focus on 60° × 60° boxes where the signal is the highest on figure 21. In addition, the calculations are performed with:

- All valid Argo profiles with a reference level of 900 dbar
- A reference level of 900 dbar only for valid Argo profiles whose maximum depth is deeper than 1900 dbar
- All valid Argo profiles with a reference level of 1900 dbar

This allows us to distinguish the impacts of horizontal and vertical sampling separetly and the results are shown in table 4.

East/West boxes trend differences (mm/yr)	**GDR-E**	**GDR-D**	**Difference**
All DHA 900 dbar	-0.40	-2.10	+1.8
DHA 900 dbar from 1900 dbar profiles	-0.14	-1.89	+1.7
DHA 1900 dbar	0.51	-1.25	+1.8

Table 4: *Hemispheric differences (East/West) of trends of the SLA - DHA mean differences computed with the GDR-E and GDR-D orbit solutions.*

Whatever the Argo reference level, the results suggest that the GDR-E orbit standard provides an improved estimation of the altimeter SLA by reducing the hemispheric trend discrepancies. However, given the uncertainty of the associated measurements (of the order of 1 mm/yr), we expect a difference (between results obtained with GDR-D and E) of about 2 mm/yr so that there is enough confidence in the results (right hand side column of the table). In this case, the observed differences are close to the limit whatever the Argo reference depth. Thus, even if our approach suggests that the GDR-E orbit standard provides improved altimeter SLA, the two different orbit standards can not be strictly distinguished by comparison with Argo measurements and additional external validation may be required.

6.3. Comparison of AVISO DUACS DT 2014 versus 2010

The Argo measurements are used to estimate the impact of the reprocessed AVISO/DUACS delayed-time 2014 version (AVISO Handbook, 2014, [2]) compared with the previous release. Some results have already been shown last year (see the 2013 annual report, [9]) in terms of global and regional mean sea level trend differences, annual signal and distinguising high and low frequencies of the signals. Here, we focus on the analysis of the variance of the sea level differences between altimetry and Argo measurements.

The map of the variance differences between the altimeter SLA and in-situ DHA (with a 1900 dbar reference) (figure 22) reveals a strong spatial variability of the coherence between the altimeter products and the in-situ reference, preventing us from any global conclusion.

However, in some areas such as the Bay of Bengal ($-5°S/+20°N; 80°E/95°E$), the variability of the SLA - DHA differences is lower with the AVISO 2014 altimeter products (-1 cm^2). Table 5 shows that in this area, the correlation with the Argo DHA independent reference is greater with the 2014 altimeter dataset and it provides a reduced rms of the differences (3.76 cm and 3.94 cm respectively). This indicates that at regional scales, the Argo in-situ measurements can be used to assess the impact of a new altimeter product.

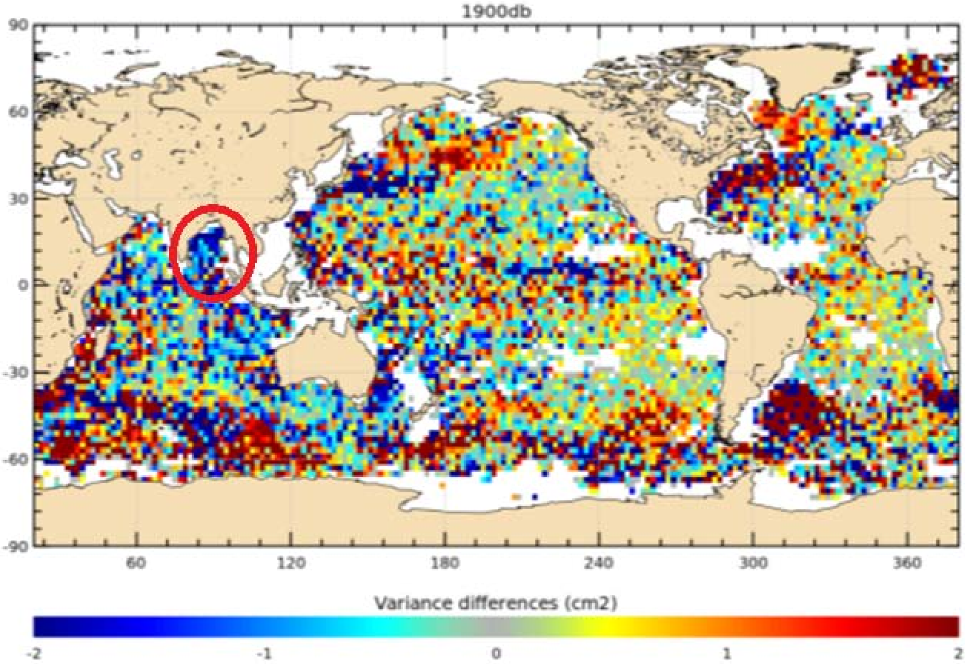


Figure 22: *Variance(AVISO/DUACS 2014 - Argo) - Variance(AVISO/DUACS 2010 - Argo) with Argo profiles referenced to 1900 dbar over 2005-2012 (cm^2). The mean in the red circle is of -1 cm^2.*

Statistic in the bay of Bengal; DHA 1900 dbar	**Correlation**	**rms of the differences (cm)**
DUACS DT 2010	0.89	3.94
DUACS DT 2014	0.90	3.76

Table 5: *Statistics in the bay of Bengal of the differences between altimetry (DUACS DT V2010 and V2014) with Argo DHA referenced to 1900 dbar.*

7. Conclusions and futures

Argo DHA can be used for the quality assessment of altimeter sea level measurements as an independent reference. This concerns the analysis of the relative mean sea level, including the detection of global and regional MSL drift and anomalies and the detection of the impact of new altimeter standards or products. Our method constitutes an essential approach for the quality assessment of the altimeter measurements. However, the improvements provided by new altimeter standards and products become more and more reduced and the searched differences may be hidden by the uncertainty of the method. In order to improve the method, we have focused the analyses on the sensitivity of the altimeter / in-situ sea level comparisons to the processing method of these data sets.

The estimation of the absolute altimeter mean sea level drift requires the additional information related to the mass contribution to the sea level that can be derived from GRACE satellite measurements. The updated GRACE GRGS V3 monthly maps have been compared with the previous version (V2) and the impact of a new global mean time series of the ocean mass contribution to the sea level has been also analyzed. Together with the steric in-situ dynamic heights from Argo, these GRACE datasets provide sea level estimations with the same physical content as the altimeter measurements. According to the dataset, a correction of the Glacial Isostatic Adjustment is required to take into account the response of the solid Earth to the last deglaciation and thus compare altimetry and GRACE homogeneously. However, we have shown that there is a strong sensitivity to these GRACE data, which affect the analysis of the altimeter mean sea level closure budget and the inter-annual variability.

In the context of the E-AIMS project, the sensitivity of the altimetry / Argo comparisons to the Argo dataset and the associated data processing have been performed. The 3000 targeted number of Argo floats had not been determined for altimetry validation purposes. We have shown that quality assessment of altimetry data is not greatly sensitive to the number of Argo floats used in the comparisons. However, estimation of some altimeter standard's impacts is sensitive to a reduction of the temporal sampling of the floats. These results indicate that the Argo community should be supported to maintain the deployment of Argo floats.

The global and regional coverage of the ocean by Argo floats are impacted by the choice of the reference level of integration of the Argo T/S profiles for the computation of the steric dynamic heights. In terms of sea level closure budget, the altimeter drift is significantly affected by this choice. In some regions such as the Southern Ocean, the comparison with the altimeter sea level requires a deep reference depth so that the variance content of the water column is similar between altimetry and in-situ data. The future evolution of the Argo network such as the deployment of deep Argo floats (4000m) should contribute to the improvement of the results.

Some additional studies have focused on the impact of the regions of high ocean variability on the method uncertainty and the sensitivity to the temporal reference of the sea level anomalies. Together with the previously mentioned analyses, this work has contributed to better characterize the uncertainty of the method and improve the confidence in the results. The main objectives of the activity have benefited from these improvements: first, the detection of the altimeter MSL drift. Secondly, the detection of the impact of new altimeter standards that are used to improve altimeter products for end-users. In particular, our approach is the only technique available to estimate the quality of new orbit solutions. This has been published in Couhert et al., 2014 ([4]). Note that the mass contribution is not systematically used since its trends are little correlated with the altimeter

MSL trends at regional scales and the associated uncertainty is relatively high. The third goal is to detect anomalies in in-situ measurements and thus qualify these data, which 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.

This work is performed in an operationnal framework which is essential to make this activity durable. Major part of the discussed results would not have been obtained with the same confidence without comparison with the results derived from global altimeter internal analyses and from the comparison with tide gauges. The synergy between these approaches is a key element to provide more and more reliable and accurate results, globally as well as regionally. 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.

In 2014, this work been presented at the OSTST meeting in Constance ([12]) and workshops have been organized in June and December 2014 with users and scientific experts of altimetry and in-situ data (CLS, CNES, LEGOS, Noveltis) 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. Part of the results (sensitivity to the Argo dataset) have been presented during E-AIMS meeting and are also available in an associated deliverable (E-AIMS WP4: impact study results and recommendations, [10]). Results related to the use of Argo data to detect orbit errors have been published in Couhert et al., 2014 ([4])) and another publication is currently in preparation synthesizing the main results of the activity over the last few years: presentation of the method, the main results, the sensitivity to the parameters and datsets and the assocated uncertainty.

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9. Annexes

9.1. Annex: Corrections applied for altimeter SSH computation

All the corrections applied on SSH for TOPEX/Poseidon, Jason-1, Jason-2 and Envisat space altimetric missions are summarized in the following table:

Orbits and corrections	TOPEX/Poseidon	Jason-1	Jason-2	Envisat
Orbit	GSFC POE (09/2008), ITRF2005+Grace	CNES POE (GDR-C standards until cycle 374, GDR-D standards from cycle 500 onwards)	CNES POE (GDR-D standards)	CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CNES/CLS 2011	MSS CNES/CLS 2011	MSS CNES/CLS 2011	MSS CNES/CLS 2011
Dry troposphere	ECMWF model computed	ECMWF model computed	ECMWF model computed	ECMWF model computed
Wet troposphere	TMR with drift correction [Scharoo et al. 2004] and empirical correction of yaw maneuvers [2005 annual validation report]	Jason-1 radiometer (JMR)	Jason-2 radiometer (AMR)	MWR (corrected from side lobes) + new corrected files
Ionosphere	Filtered dual-frequency altimeter range measurements (for TOPEX) and Doris (for Poseidon)	Filtered dual-frequency altimeter range measurements	Filtered dual-frequency altimeter range measurements	Dual-Frequency updated with S-Band SSB (< cycle 65) GIM model + global bias of 8 mm (>= cycle 65)
Sea State Bias	Non parametric SSB (for TOPEX), BM4 formula (for Poseidon)	Non parametric SSB (GDR product)	Non parametric SSB (GDR product)	Updated homogeneous to GDR-C (Labroue, 2007 [?])
Ocean and loading tides	GOT4.7 (S1 parameter is included)	GOT4.7 (S1 parameter is included)	GOT4.8	GOT4.7 (S1 parameter is included)
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971] [Cartwright and Edden, 1973]	Elastic response to tidal potential [Cartwright and Tayler, 1971] [Cartwright and Edden, 1973]	Elastic response to tidal potential [Cartwright and Tayler, 1971] [Cartwright and Edden, 1973]	Elastic response to tidal potential [Cartwright and Tayler, 1971] [Cartwright and Edden, 1973]

.../...

Orbits and corrections	TOPEX/Poseidon	Jason-1	Jason-2	Envisat
Pole tide	[Wahr,1985]	[Wahr,1985]	[Wahr,1985]	[Wahr,1985]
Combined atmospheric correction	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)
Specific corrections	Doris/Altimeter ionospheric bias, TOPEX-A/TOPEX-B bias and TOPEX/Poseidon bias	Jason-1 / T/P global MSL bias	Jason-2 / T/P global MSL bias	USO correction included in the range after V2.1 reprocessing + PTR[1]

Table 6: *Corrections applied for altimetric SSH calculation*

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[1] External corrections available on ESA website near V2.1 GDR products

9.2. Bilan du niveau moyen des mers global: contribution sterique, de masse et contribution sterique profonde.

Bilan du niveau moyen global de la mer depuis 2003 : contribution stérique (0-1500m) & de masse; Estimation de la composante stérique de l'océan profond

Habib Boubacar DIENG
Anny Cazenave , Hindumathi Palanisamy, Benoit Meyssignac
(LEGOS/CNES)

CAVE MSL N°13 CLS
05 Décembre 2014

Global Mean Sea Level (GMSL) = Steric(total) + Mass

Steric (total)= Steric(0-1500m) + Steric(>1500) + Error

Mass = Glaciers + Ice Sheets + Land Waters + Water Vapour + Snow +…

Steric(>1500) + Error =
(GMSL – Mass) - Steric(0-1500m)

Estimation of each term (altimetry era):
GMSL : Satellite altimetry
Steric: XBT, Argo; Reanalyses
Mass: GRACE; Direct estimate of each component from various observing systems & models

2 périodes d'analyse:
01/2005 - 12/2012
01/2003 - 12/2012

Données utilisées

1. GMSL : **AVISO** ; **CU** ; **NOAA** ; **GSFC** ; **CSIRO**

2. Stérique (0 – 1500 m) :

❖ Argo (2005-2012) : **Kvs & Le Traon** ; **IPRC** ; **JAMSTEC**(2003-2012) & **SCRIPPS** et **CLS** (Jean-François)

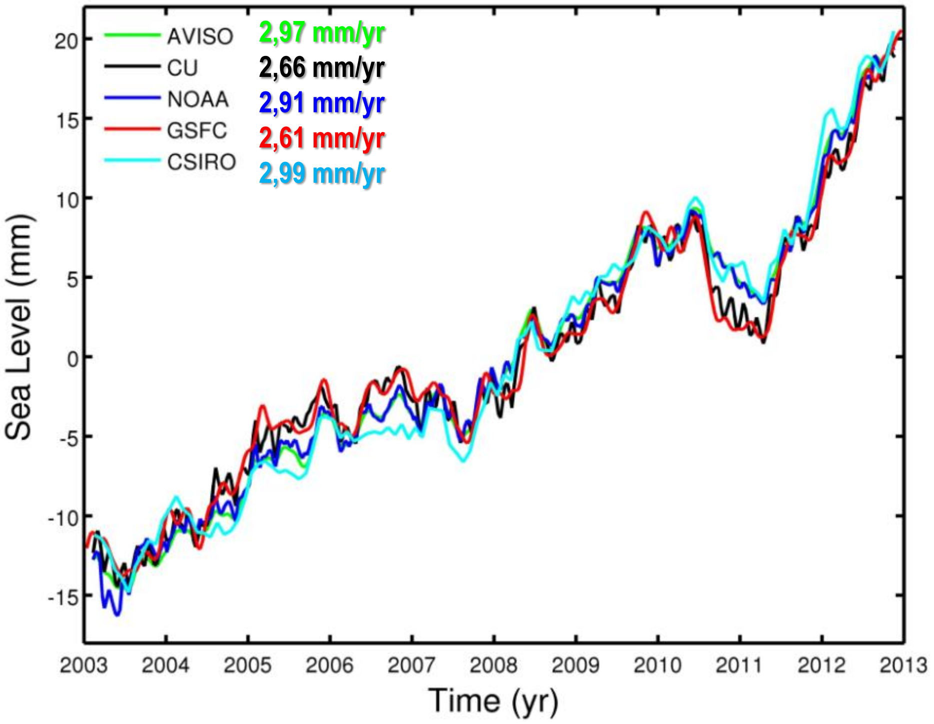
❖Autres données T/S IN SITU (2003-2012) : **IK** ; **EN4** & **NOAA**

❖Réanalyse (2003-2009) : **ORAS4** (0 – 6000 m).

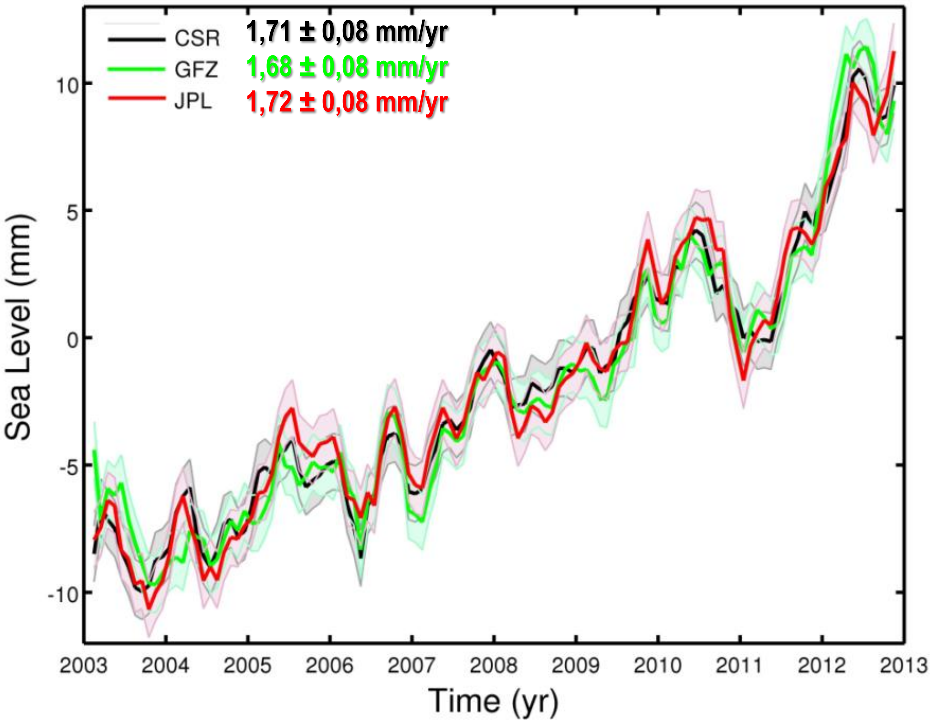
3. Variation de masse de l'océan

   GRACE (2003 – 2013) : **CSR ; GFZ ; JPL**

« 2003 - 2012 » GMSL

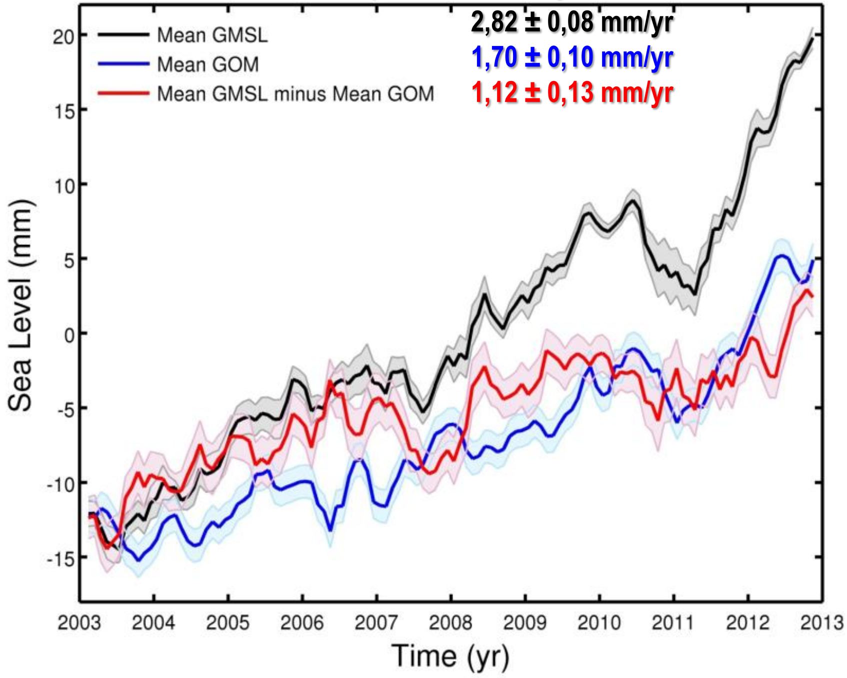


« 2003-2012 » Global Ocean Mass from GRACE



1,71 ± 0,08 mm/yr
1,68 ± 0,08 mm/yr
1,72 ± 0,08 mm/yr

2003-2012 time span : Altimetry & GRACE



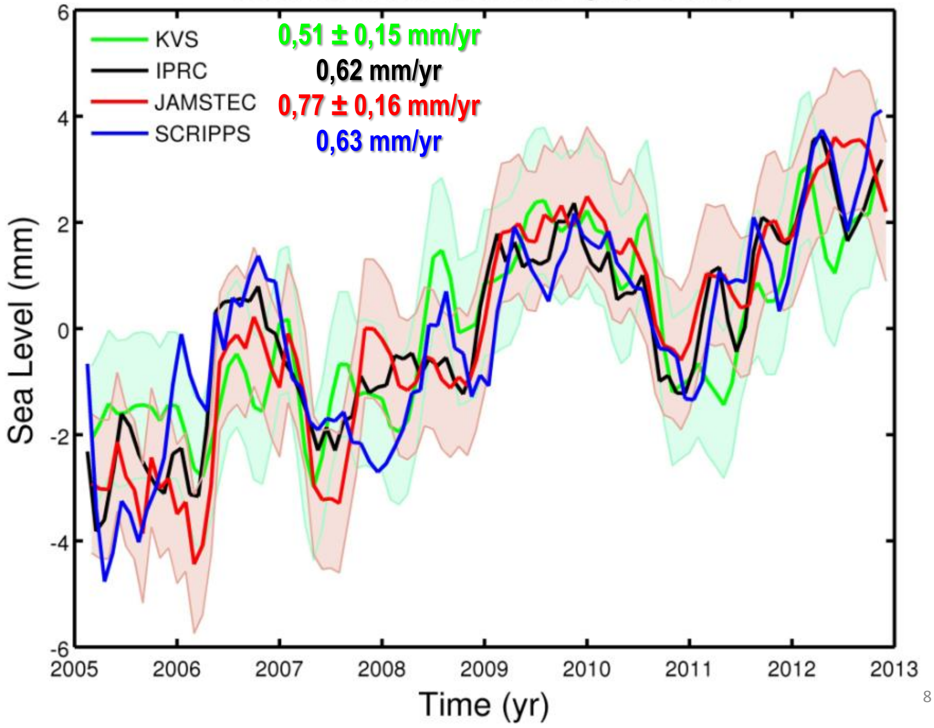
2,82 ± 0,08 mm/yr
1,70 ± 0,10 mm/yr
1,12 ± 0,13 mm/yr

GMSL: mean of AVISO, CU, NOAA, GSFC and CSIRO
GRACE: mean of CSR, JPL, GFZ (from D. Chambers website)

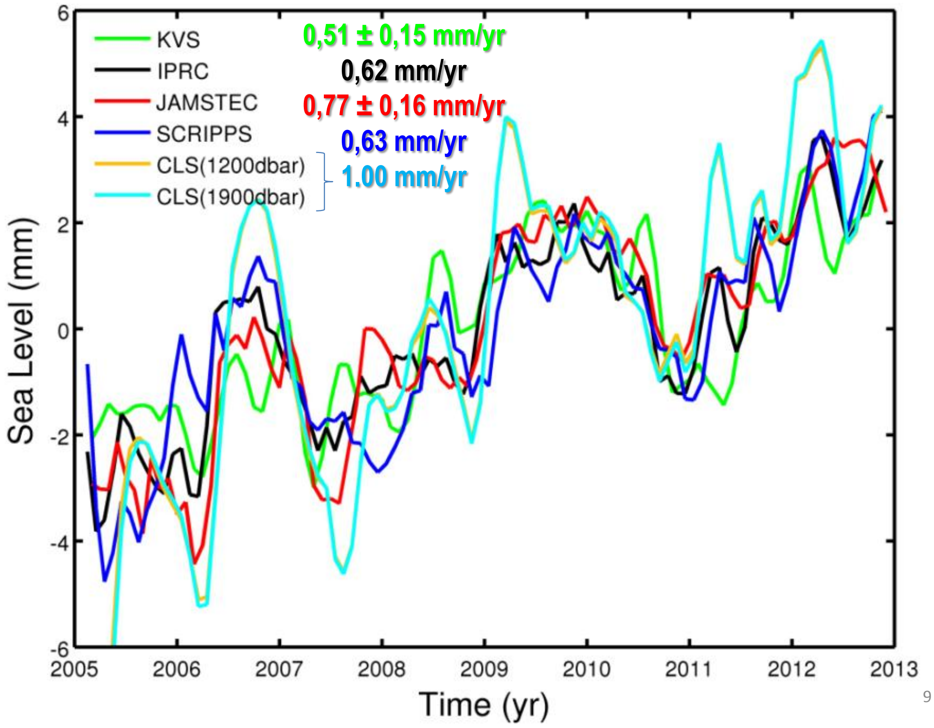
Red curve: difference 'altimetry - mass'

1. « 2005-2012 » time span (GMSL – OM) & Argo

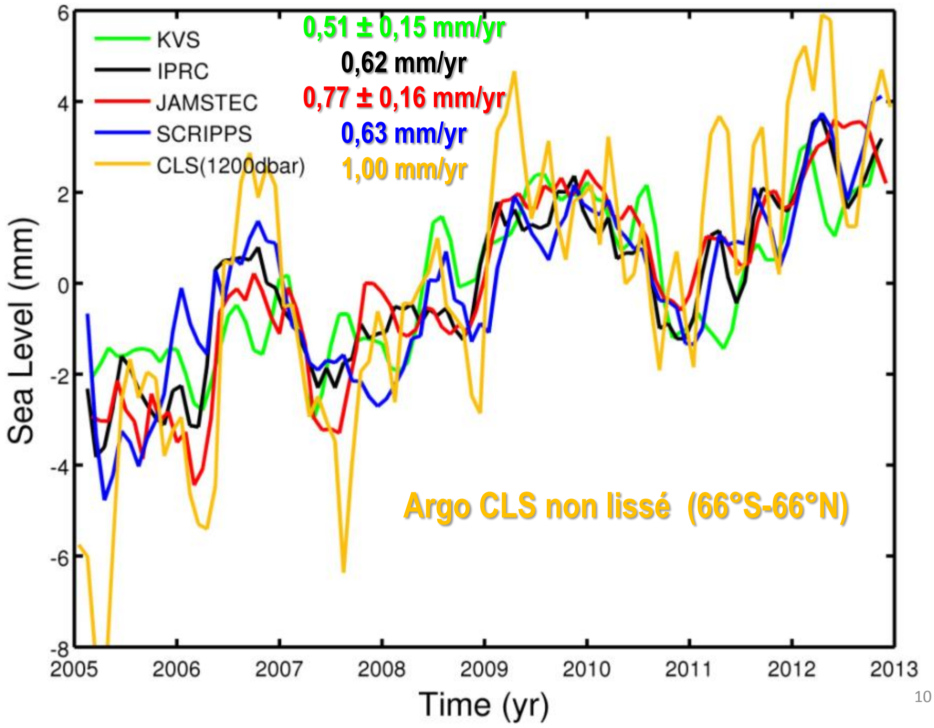
« 2005-2012 » Argo-based Steric sea level (0-1500m)



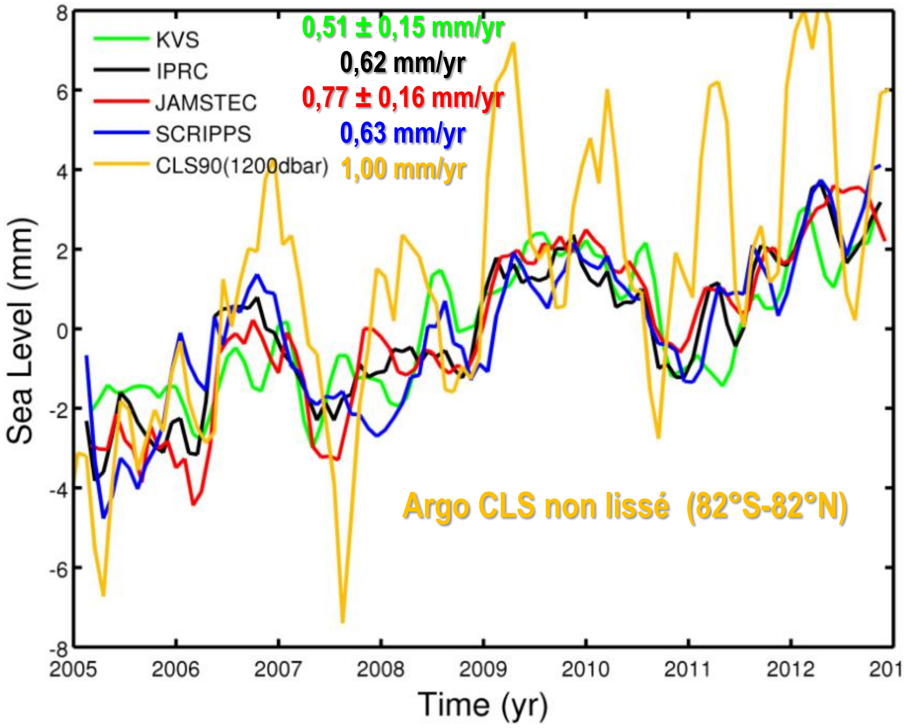
« 2005-2012 » Argo-based Steric sea level (0-1500m) & Argo CLS



« 2005-2012 » Argo-based Steric sea level (0-1500m) & Argo CLS

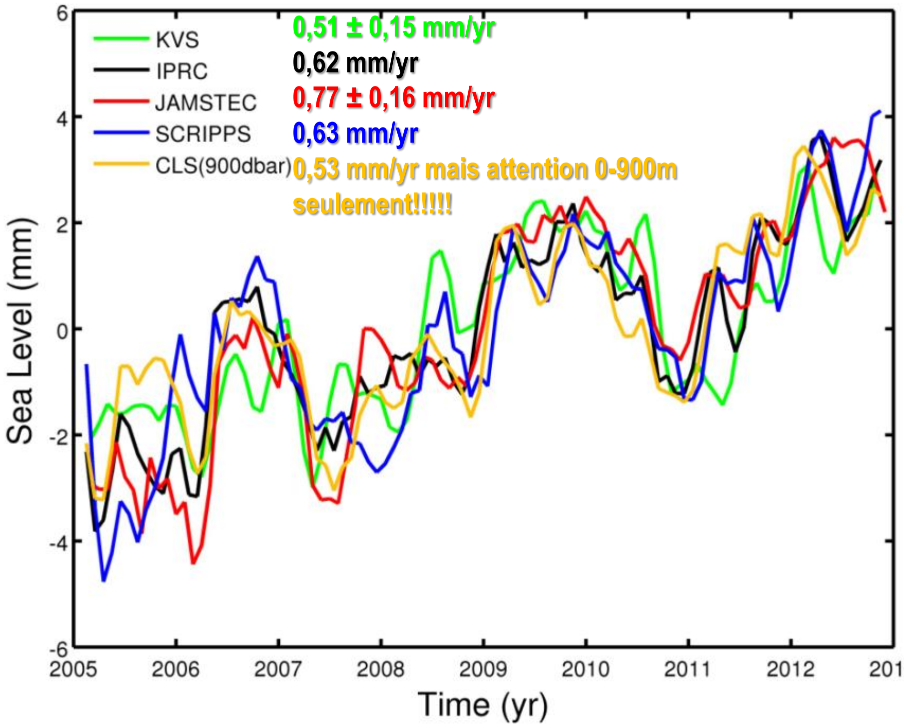


« 2005-2012 » Argo-based Steric sea level (0-1500m) & Argo CLS

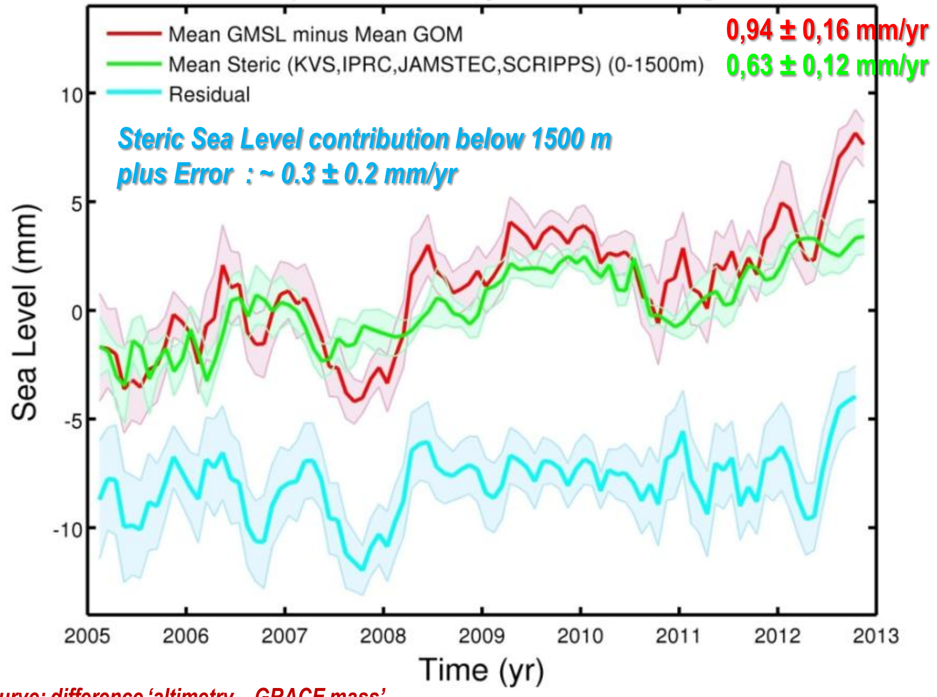


Argo CLS non lissé (82°S-82°N)

« 2005-2012 » Argo-based Steric sea level (0-1500m) & Argo CLS



2005-2012 time span : ‘Altimetry – GRACE’ , Argo & Residual



0,94 ± 0,16 mm/yr

0,63 ± 0,12 mm/yr

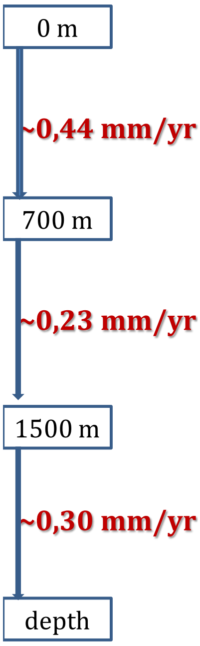
Steric Sea Level contribution below 1500 m plus Error : ~ 0.3 ± 0.2 mm/yr

Red curve: difference ‘altimetry – GRACE mass’

Argo : mean of KvS, IPRC, JAMSTEC and SCRIPPS

Blue curve: difference ‘(gmsl – gom) - Argo’

« 2005-2012 » Steric sea level (0-1500m) & (0-700m)



0 m

~0,44 mm/yr

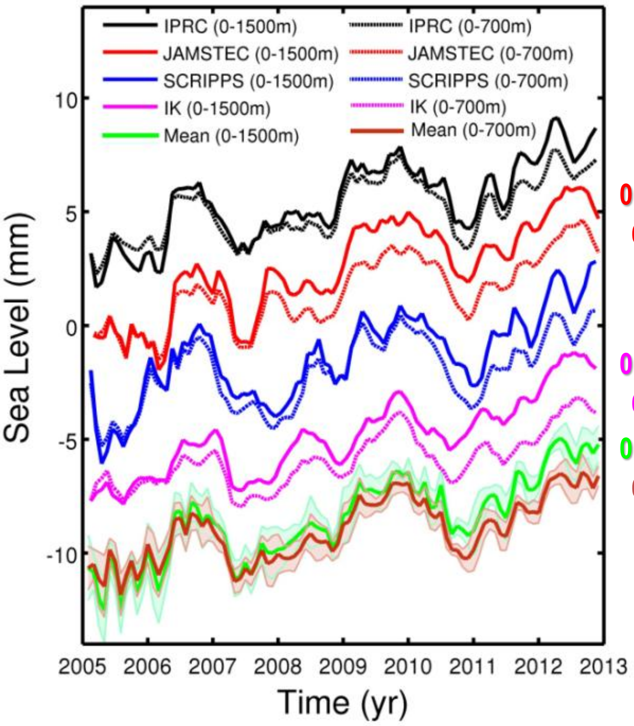
700 m

~0,23 mm/yr

1500 m

~0,30 mm/yr

depth



0,62 mm/yr

0,42 mm/yr

0,77 ± 0,16 mm/yr

0,53 ± 0,13 mm/yr

0,63 mm/yr

0,41 mm/yr

0,67 ± 0,14 mm/yr

0,40 ± 0,13 mm/yr

0,67 ± 0,10 mm/yr

0,44 ± 0,08 mm/yr

« 2005-2012 » Steric sea level (0-900dbar) & (0-1200dbar)

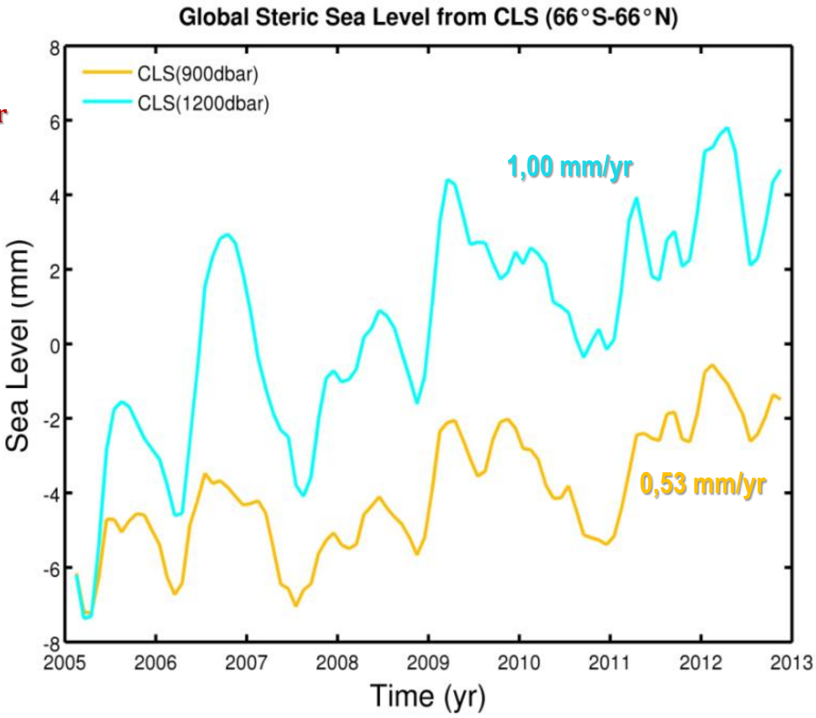
0 dbar

~0,53 mm/yr

900 dbar

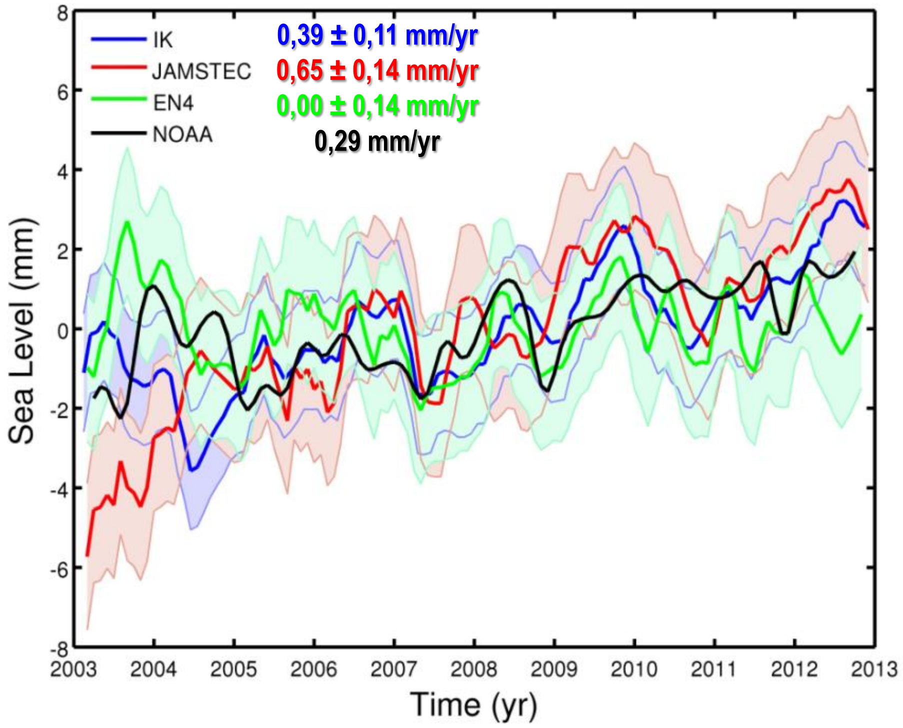
~0,47 mm/yr

1200 dbar

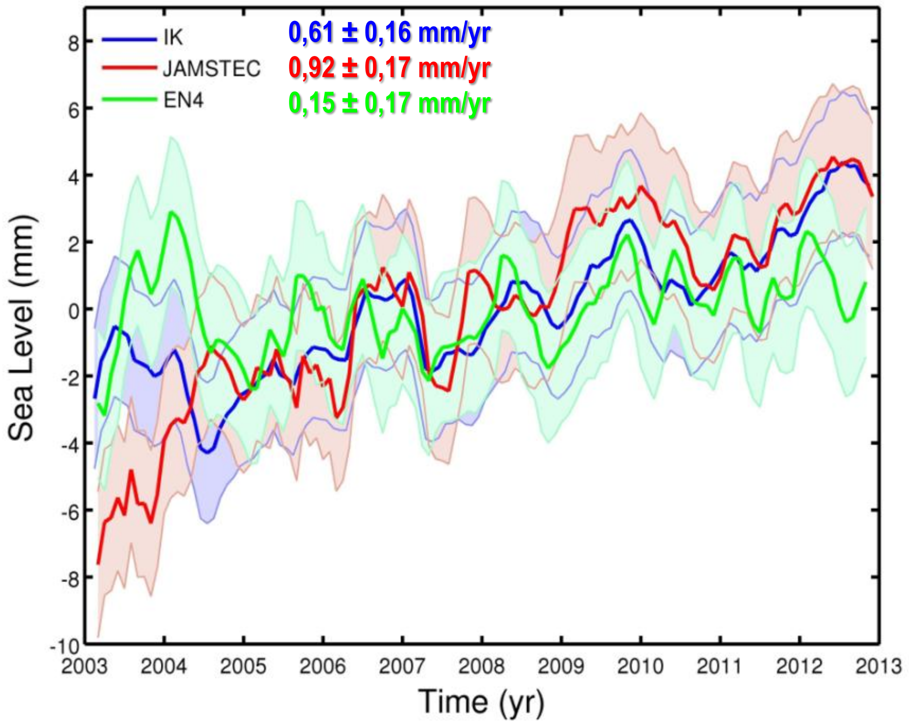


2. « 2003-2012 » time span (GMSL – OM) & GSSL

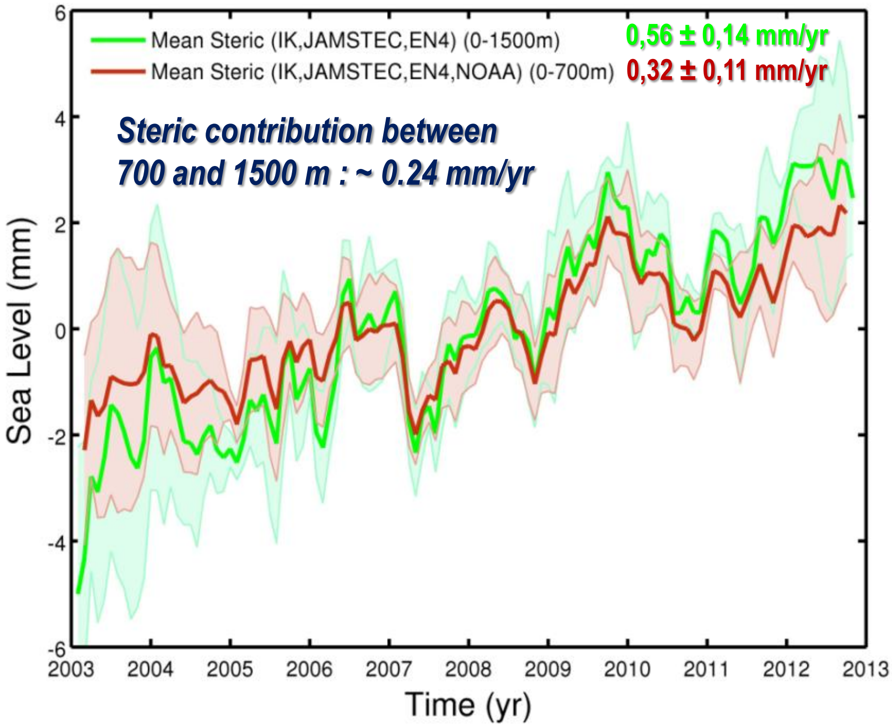
« 2003-2012 » Steric sea level (0-700m)



« 2003-2012 » Steric sea level (0-1500m)



« 2003-2012 » Steric sea level (0-700m & 0-1500m)

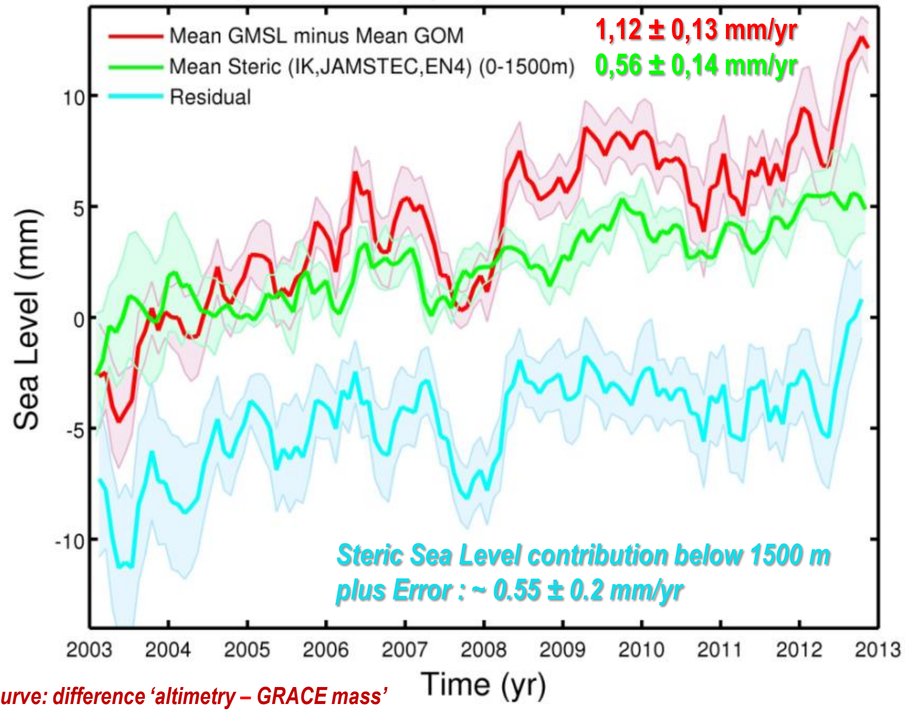


0,56 ± 0,14 mm/yr

0,32 ± 0,11 mm/yr

Steric contribution between 700 and 1500 m : ~ 0.24 mm/yr

2003-2012 time span : 'Altimetry – GRACE' , Steric & Residual



1,12 ± 0,13 mm/yr

0,56 ± 0,14 mm/yr

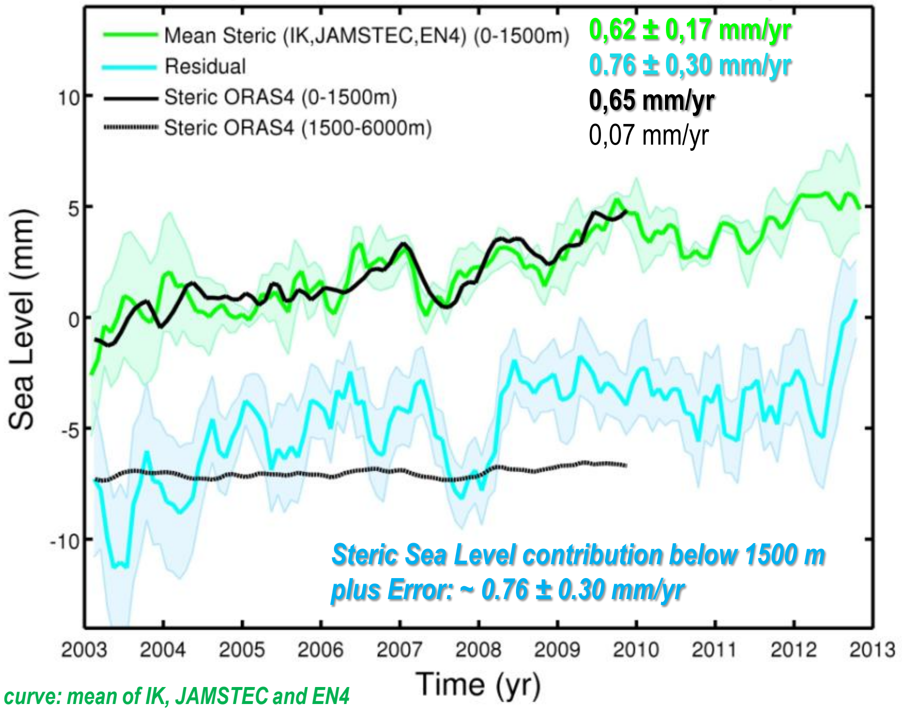
Steric Sea Level contribution below 1500 m plus Error : ~ 0.55 ± 0.2 mm/yr

Red curve: difference 'altimetry – GRACE mass'

Green curve: mean of IK, JAMSTEC and EN4

Blue curve: difference '(gmsl – gom) – GSSL In Situ'

2003-2009 time span : GSSL In Situ, Residual & ORAS4(2003-2009)



Steric Sea Level contribution below 1500 m plus Error: ~ 0.76 ± 0.30 mm/yr

Green curve: mean of IK, JAMSTEC and EN4

Black curve: ORAS4 Reanalyses 0-1500 and 1500-6000m

Blue curve: difference '(gmsl – gom) – GSSL In Situ'

TABLE OF TRENDS

66°S - 66°N		P1 : Jan 2005 - Dec 2012		P2 : Jan 2003 - Dec 2012	
GMSL (mm/yr)	AVISO	2,97		2,97	
	CU	2,57		2,66	
	NOAA	2,89		2,91	
	GSFC	2,51		2,61	
	CSIRO	3,18		2,99	
	MEAN	2,81 ± 0,11		2,82 ± 0,08	
Ocean Mass (OM) (mm/yr)	CSR	1,85 ± 0,12		1,71 ± 0,08	
	GFZ	1,94 ± 0,12		1,68 ± 0,08	
	JPL	1,81 ± 0,12		1,72 ± 0,08	
	MEAN	1,87 ± 0,11		1,70 ± 0,10	
Mean GMSL minus Mean OM		0,94 ± 0,16		1,12 ± 0,13	
		0 - 700m	0 - 1500m	0 - 700m	0 - 1500m
GSSL Argo (mm/yr)	KvS	---	0,51 ± 0,15	---	---
	IPRC	0,42	0,62	---	---
	JAMSTEC	0,53 ± 0,13	0,77 ± 0,16	0,65 ± 0,14	0,92 ± 0,17
	SCRIPPS	0,41	0,63	---	---
	MEAN	---	0,63 ± 0,12	---	---
RESIDUAL (>1500m)		---	0,29 ± 0,21	---	---
GSSL (mm/yr)	IK	0,40 ± 0,13	0,67 ± 0,14	0,39 ± 0,11	0,61 ± 0,16
	EN4	---	---	0,00 ± 0,14	0,15 ± 0,17
	NOAA	---		0,29	---
	MEAN	---	---	0,32 ± 0,11	0,56 ± 0,14
RESIDUAL (>1500m)		---	---	---	0,55 ± 0,19
Reanalyse(mm/yr)	ORAS4 (Jan2003 - Dec2009) : 0-1500m = 0,65 ; 1500-6000m = 0,07				

CONCLUSIONS:

- Jan2005 - Dec2012 time span: interesting results with Argo & GRACE with a contribution of deep ocean steric than 0,3 ± 0,2 mm/yr.
- 2003-2009 time span:
  - ○ Data EN4 with a trend than 0.00mm/yr (700m)?
  - ○ Good results with ORAS4 for the upper ocean (good agreement with GSSL In Situ on 2003-2009)

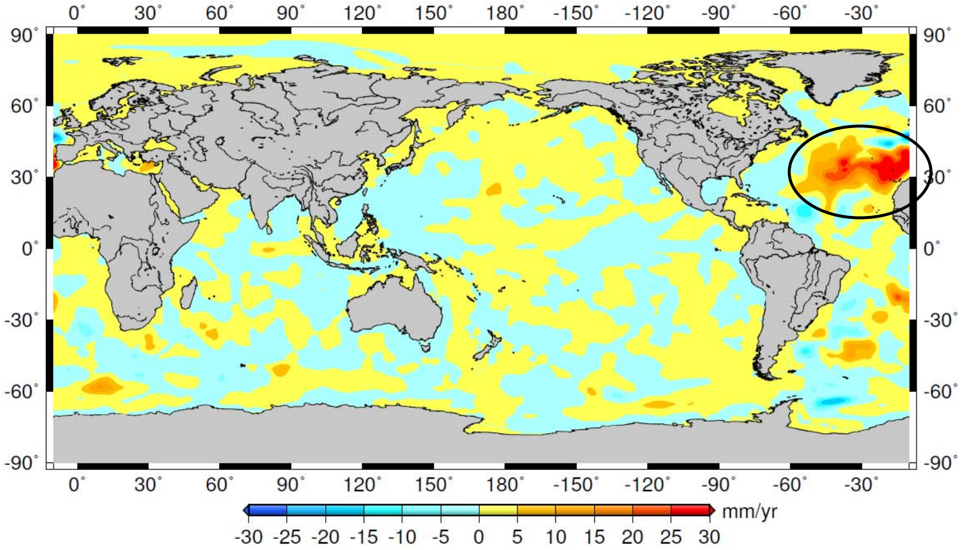
But still too large uncertainties to estimate the steric deep ocean contribution.

Priority Work to do:

- Intercompare steric sea level data sets at global and regional scales
- → understand the differences;
- → identify causes (editing, climatology, averaging method, etc.)

MERCI

« 2003-2009 » ORAS4 below 1500m



« North Atlantic » ORAS4 Steric Sea Level contribution below 1500 m : ~ 0.33 mm/yr