CalVal In-Situ altimetry / Argo TS profiles

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

for Jason-1, Envisat and Jason-2

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CLS - 8-10 Rue Hermès - Parc Technologique du Canal - 31520 Ramonville St-Agne - FRANCE
Telephone 33 5 61 39 47 00 / Fax 33 5 61 75 10 14

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People involved in this issue:				
	AUTHORS	**COMPANY**	**DATE**	**INITIALS**
WRITTEN BY	J.F. Legeais M. Ablain	CLS CLS		
CHECKED BY	S. D'Alessio	CLS		
APPROVED BY	JP. Dumont M. Ablain	CLS CLS		
APPLICATION AUTHORISED BY				

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CLS/DOS	electronic copy	G. DIBARBOURE V. ROSMORDUC J. DORANDEU
CNES	electronic copy	thierry.guinle@cnes.fr nicolas.picot@cnes.fr aqgp_rs@cnes.fr dominique.chermain@cnes.fr delphine.vergnoux@cnes.fr

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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 2011 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 and by ESA for Envisat mission. The method uses results of a study made at CLS in the frame of an IFREMER / Coriolis contract.

Three objectives are achieved with the comparison of altimetry with in-situ measurements as 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 altimetric measurements and the improvement brought by new altimeter standards in the computation of sea level anomalies (geophysical corrections, new orbit, retracking,...).
- To detect potential anomalies in in-situ data and estimate their quality.

Argo T/S profiles constitutes 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 such as T/S profiles enables us to contribute to the improvement of the global error budget estimate of the altimetric measurements (cf 2.11 topic of the SLOOP project, [10] and OSTST presentation, [11]).

Contrary to tide gauges measurements which are (almost) directly comparable with altimetry, T/S profiles only provide steric Dynamic Height Anomaly (DHA) above a reference level (chosen as 900 meters). As altimetry provides the height of the total water column, a specific process is required to compare similar physical contents. Results obtained up to this year have been computed with extrapolated in-situ DHA over the total water column with regression coefficients. Nevertheless, the confidence in the absolute altimeter MSL drift is strongly limited with this approach (see 2010 annual report [13]) and relative comparisons with the steric in-situ DHA only are preferred. This approach has been used in 2011 to detect altimeter anomalies and estimate the impact of a new altimeter standard. In particular, the regional MSL trend discrepancies observed between Jason-1 and Envisat are discussed as well as the impact estimation of the new altimeter standard used to correct this anomaly and the quality of Envisat reprocessed data is also analyzed. In order to improve the estimation of absolute altimeter drift, several evolutions of the method of comparison have been performed and Gravity Recovery And Climate Experiment (GRACE) data have been used to take into account the mass contribution to close the sea level budget. In 2011, the activity has focused on the estimation of the performance of this new method compared with results from the previous one.

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 raw Geophysical Data Record (GDR) altimeter products. Details of the SSH computation and time period for each altimeter are presented in annex 8.2. and available in the MSL part of the Archiving, Validation and Interpretation of Satellite Oceanographic website (AVISO, http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/processing-corrections/index.html). As the comparison with in-situ data is performed since 2004, we focus the analyses on the end of Topex/Poseidon, Envisat, Jason-1 and Jason-2 space missions. SLA for the whole altimeter missions are computed with a reference to the Mean Sea Surface (MSS) CLS2001 model (Hernandez and Schaeffer, 2001). Concerning Envisat mission, some level-1 processing heterogeneities remain in the data and the orbit solution has been updated with GDR-C standards. This makes Envisat SSH homogeneous enough to be compared with Jason-1 sea level. The remaining heterogeneities, directly impacting the assessment of the MSL trend, are expected to be improved and even corrected in the reprocessed data (which are discussed in this report). Envisat data are subsampled over 10 days (usual cycles are longer) in order to be consistent with results from Jason missions.

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. 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. The associated Dynamic Height Anomalies are computed with a reference to 900 dbar ($\sim$ 900 m), chosen for sampling reasons.

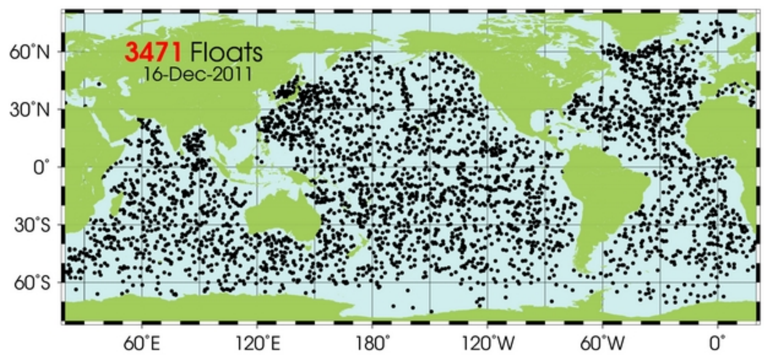

Figure 1: *Spatial distribution of the floats that have delivered data within the last 30 days before the mentionned date.*

In this study, we use delayed mode and real time quality controlled (Guinehut et al., 2009: [9]) T/S profiles from the Coriolis Global Data Assembly Center (www.coriolis.eu.org). Note that the delayed mode data concerns only two thirds of the dataset. Figure 2 shows spatial and temporal distribution of Argo measurements over the period 2002 - September 2011 (last update of the in-situ database).

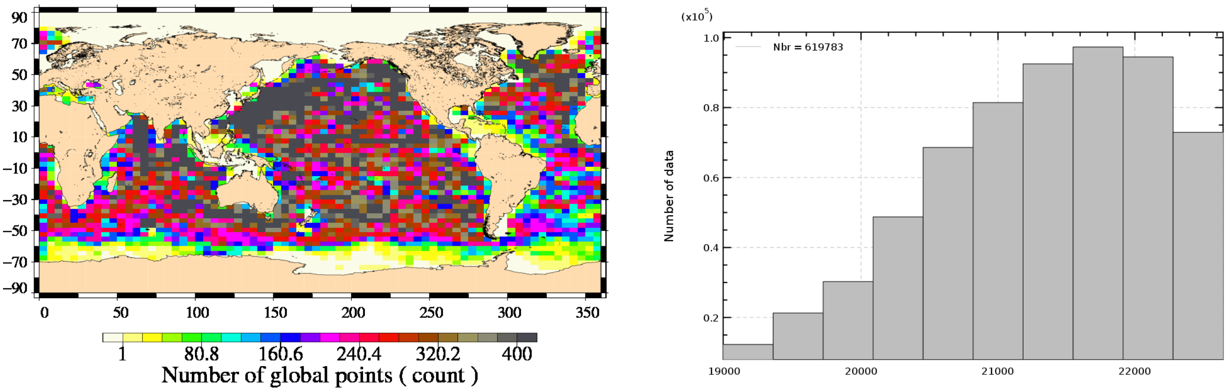

Figure 2: *Spatial (left) and temporal (right) distribution of temperature and salinity Argo profiles. Each bar of the histogramm indicates the number of profiles per year from 2002 to 2011.*

The vast amount of T/S profiles are available over almost the global open ocean (figure 2, left). Best sampled areas (Kurushio current, north Indian Ocean) have more than 400 profiles per box of 3°x5°. But no more than about 20 profiles per boxes are available in the southern ocean. The number of available profiles has regularly increased since 2002 (figure 2, right) and reaches almost 100 000 per year since 2008 (in 2011, data are used until September). Nevertheless, spatial distribution has not always been high enough in some areas to produce statistically valid analyses. As discussed by Roemmich and Gilson, 2009 ([22]), 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 mid 2004 onwards, which is done in this report. This consitues a great asset for latest altimeter missions (Jason-1, Envisat et Jason-2). It leads to an in-situ dataset of 600 000 T/S profiles distributed over almost the global open ocean.

The vast amount of available T/S profiles constitutes an independant dataset well adapted for comparison with altimeter data over the open ocean where tide gauges distribution is insufficient. To perform these studies, a processing sequence has been developped (in the frame of the SALP project) which aims at being regularly operated in order to have an efficient tool to validate all altimeter missions.

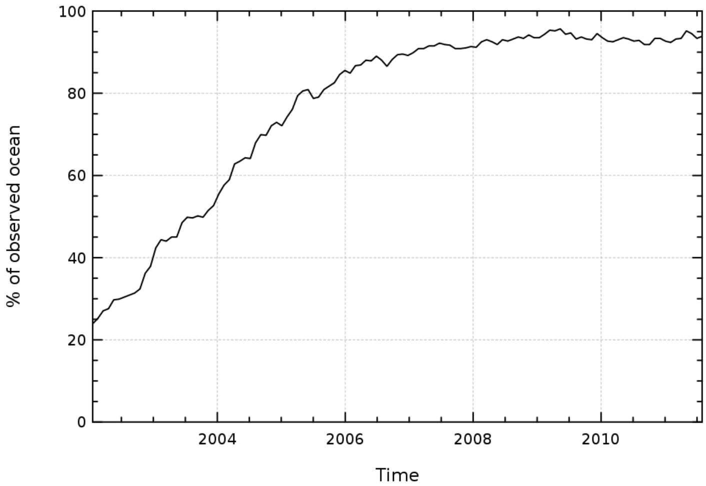

Figure 3: *Monitoring of the percentage of the ocean covered by Argo profiling floats (±60° and without inland seas).*

3. Description and evolution of the CalVal processing chain Altimetry / in-situ Argo

We first present the method of comparison which has been used up to this year. Then evolutions of this method is discussed.

3.1. Description of the processing sequence

3.1.1. Overview

Altimeter measurements are compared with in-situ dynamic height anomalies (DHA) and annex 8.1. provides a schematic view describing the different steps of the processing sequence. These are described hereafter:

1. Assessment of in-situ DHA: a regression coefficients grid (static over the studied period) is used to extrapolate the steric part to the total water column in order to compare similar physical contents with altimeter measurements
2. Colocation of in-situ and altimeter data
3. Validation of colocated in-situ and altimeter measurements in order to exclude bad data
4. Estimate of global statistics

3.1.2. Comparison of similar physical contents

Altimeter measurements are representative of the barotrope elevation of the sea surface (surface to bottom) wheras DHA from profiling floats are representative of the steric elevation associated with the thermohaline expansion of the water column from the surface to 900dbar. We use a grid of regression coefficients to extrapolate in-situ steric heights over the total water column and compare both types of data with similar physical contents (Guinehut, 2002: [8]). The estimate of the grid of regression coefficients is based on the following steps:

- Extraction of Temperature profiles only or Temperature and Salinity profiles from Coriolis database
- When only temperature profiles are available, interpolation of salinity profiles via a θ/S diagramm or a climatologic relationship S(z) depending on the area
- Estimate of dynamic heights from T/S profiles referenced to 900dbar level
- Interpolation of altimeter SLA in space and time over in-situ data (bilinear in space and linear in time)
- Computation of the regression coefficients between colocated in-situ DHA and altimeter SLA

Coefficients are estimated on a 2° resolution grid using available observations in a 2° latitude by 10° longitude box. Figure 4 displays values higher than 0.8 at low latitudes which decrease below 0.4 at 60° north and in the southern ocean. Spatial distribution mainly depends on vertical stratification and Coriolis parameter. At high latitudes where stratification is weak and Coriolis parameter high, vertical coupling is significant and dynamic is mainly barotropic. On the contrary at low latitudes where stratification is strong and Coriolis parameter is weak, vertical coupling is reduced and the ocean circulation is mainly baroclinic.

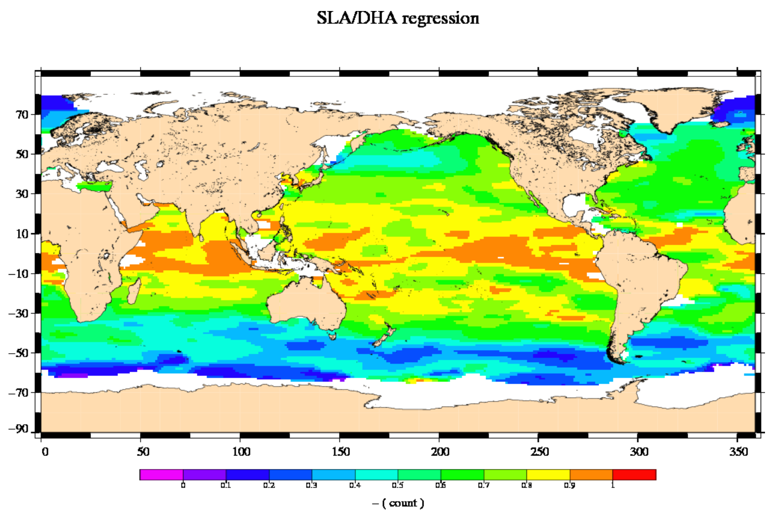

Figure 4: *Cartography of the regression coefficients between altimetry and in-situ T/S profiles between the surface and 900 dbar (about 900m)*

With this method, we compare both types of data with the same physical content. This approach is based on a linear relationship between total and steric parts of the water column which may not be strictly the case over the global ocean. Temporal variation of the relationship is not taken into account. The use of seasonnal maps of this coefficient has a negligeable impact on the long-term drift of the altimetry - in-situ differences (Dhomps PhD thesis: [7]) but the Mean Sea Level monitoring could be improved by the use of annual grids. Indeed temporal evolution of the MSL associated with mass and steric contributions (sum gives total MSL) are estimated to be linear and in phase in our case whereas it is not true over the studied period (Chen et al. 1998: [6]). In addition the computation of new regression coefficients with the same altimeter standards than the one used for the analyses should improve the accuracy of the results.

As discussed in the 2010 annual report of the activity ([13]), in-situ DHA are referenced to a mean of the Argo dynamic heights over a time period 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 2003-2008. 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. As explained in the following section, both the reference period and the method to reference the data have benefited from evolutions in 2011.

3.1.3. Colocation of in-situ and altimeter data

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. 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 this chosen altimeter temporal average is estimated to be weak considering that the ocean state has not changed significantly within less than 10 days.

3.1.4. 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 and in-situ SLA:

- Selection over the difference between altimeter SLA and in-situ DHA over the total water column. The choice of the threshold is based on the histogramm of SLA differences (figure 5) and is selected at 30cm. The selection is written as: $|SLA_{alti} - SLA_{InSituExtrapol.}| \leq 0.30m$.

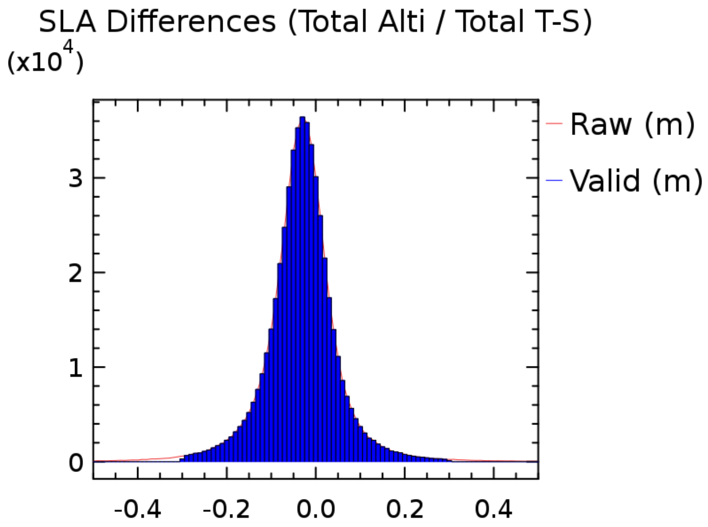

Figure 5: *Histogram of raw and validated Jason-1 SLA - in-situ DHA differences*

- 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: $|SLA_{InSitu}| \leq 1.5m$

Concerning the current dataset, this selection excludes 1.6% of the total colocated measurements, which is totally attributed to the first step of this validation phase. The correlation and rms differences between altimeter SLA and in-situ steric DHA become 0.72 and 6.3 cm respectively whereas they reach 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.

3.1.5. Computation of global statistics

The processing sequence uses the altimetry / in-situ database to generate statistics of the sea level differences between the colocated data for each altimeter mission. Then, various diagnoses are produced from these statistics in order to detect potential anomalies in altimeter data.

3.2. Evolution of the processing sequence in 2011

According to the objectives described in previous annual report (see [13]) some improvements have been performed in 2011 concerning both types of data but also within the method itself.

3.2.1. Altimeter database

No major update has been performed since last year concerning altimeter measurements.

3.2.2. In-situ T/S database

In our study, we mirror the operational database at a given date in order to avoid being impacted by potential evolutions. Results presented in the following section have been computed until September 2011.

3.2.3. Improving altimeter and Argo profiles comparison

In 2010, we have pointed out that the use of a grid of regression coefficients to extrapolate in-situ DHA and compare similar physical contents with altimetry generates a strong uncertainty of 1 to 2 mm/yr on the estimation of the absolute altimeter MSL drifts, which is much higher than the ~0.5 mm/yr signal we are looking for. It provides non homogeneous absolute altimeter MSL drifts compared with the one obtained with tide gauges over the same period. Nevertheless the relative difference obtained for instance between Jason-1 and Envisat missions are similar with both methods of comparison. Several improvements have been proposed in order to reduce the uncertainty on absolute slopes.

- **Homogeneous temporal reference for anomalies**

As previously explained, the use of a common temporal reference to compute both types of anomalies (SLA and DHA) is necessary to provide consistent results from the comparisons. For instance, it strongly reduces the amplitude of regional biases as depicted by figure 6. But the absolute slope of the sea level differences is also affected. As the coherence of altimetry and in-situ measurements is improved, more confidence is attributed to updated values.

Until last year, the in-situ reference period has been 2003-2008 and altimeter data have computed by removing the mean of altimeter SLA over this period. This average of SLA may be computed with the data from the currently studied altimeter mission or with multi altimeters merged products from the AVISO/DUACS SLA maps. This latter solution can be an asset in order to calibrate altimeter missions whose time period is not sufficient as for Jason-2. It also provides consistent results between all altimeter missions which is adapted for the cross compararison of the associated results. According to the chosen solution, this will affect the statistics of the sea level differences

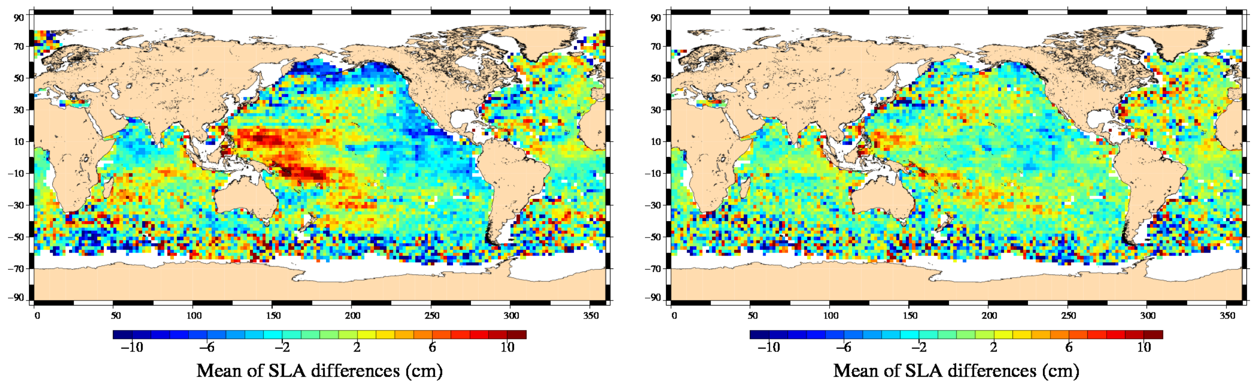

Figure 6: *Map of the mean altimetry vs Argo differences for Envisat without (left) and with (right) common temporal reference (2003-2008) for the estimation of anomalies (SLA and DHA)*

Mean SLA	**Merged DUACS SLA**		**Mono mission SLA**	
	Correlation	rms of differences	Correlation	rms of differences
SLA / DHA	0.718	6.3 cm	0.724	5.6 cm

Table 1: *Correlation and rms differences between Jason-1 altimeter SLA and in-situ DHA according to the method of averaging the SLA for the estimation of a common temporal reference*

between altimeter and in-situ data. As displayed in table 1, the correlation is not changed significantly and the coherence between both types of data is slightly improved when the mean SLA over the temporal reference period is computed with the currently studied altimeter data. As it is not possible to average the SLA of recent altimeters (such as Jason-2) from 2003 and as the methods aims at detecting the potential relative differences between altimeters, an homogeneous reference for all missions is prefered and the average of merged DUACS SLA is chosen to compute the sea level differences with the same temporal reference.

In addition, in 2011, the in-situ reference period has been increased of one year and DHA are now referenced to 2003-2009. Thus, the altimeter SLA is now referenced to this updated period.

- **Impact of the evolutions**

Taking into account these evolutions of the method together with the increase of the databases (+ 1.3 yr), updated altimeter MSL trends have been computed and are displayed on figure 7 for Jason-1 and Envisat missions. The altimeter MSL trends are of 0.4 mm/yr and -0.9 mm/yr for Jason-1 and Envisat mission respectively whereas the corresponding results of last year (with a shorter period of study) were 0.8 mm/yr and 0.0 mm/yr. The Jason-1 versus envisat MSL trend difference has not changed significantly (1.1 mm/yr versus 0.8 mm/yr) but there is a pronounced sensitivity of the absolute drift to the evolutions of the method. Even if this approach is sufficient to detect relative altimeter anomalies (cf 2010 annual report), the remaining uncertainty on the absolute drifts is greater than the searched signal and is associated with the way the different physical contents are compared between both types of data.

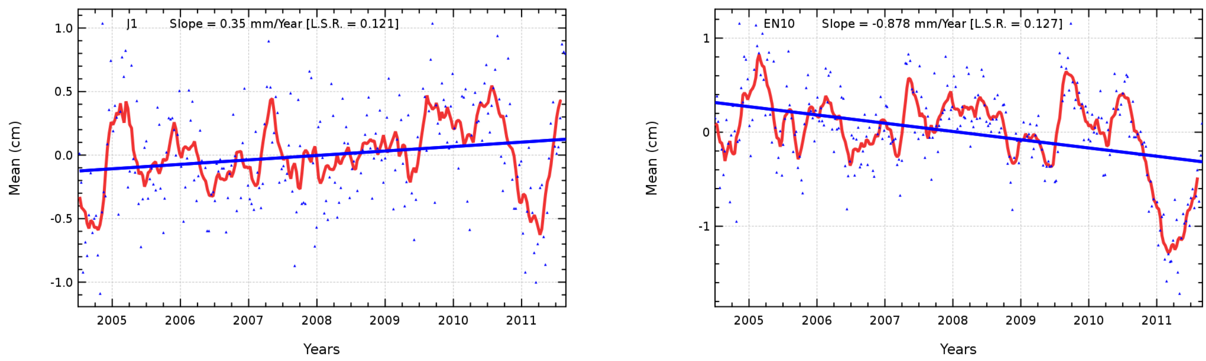

Figure 7: *Monitoring of the sea level differences between altimeter and in-situ data for Jason-1 (left) and Envisat (right) missions after removing semi-annual and annual signals from the corresponding timeserie with the associated 2 months filtered signals.*

- **Towards a different approach**

The use of regression coefficients to extrapolate the steric content of in-situ data impacts the MSL trend estimation. For instance, figure 8 illustrates that the use of the regression coefficients is not adapted in the case of a specific float located in the Mozambic canal (coefficients of ∼0.7). Indeed, it indicates that the variance of the steric signal is greater than the colocated altimeter SLA over the total water column (7.7 cm versus 5.6 cm).

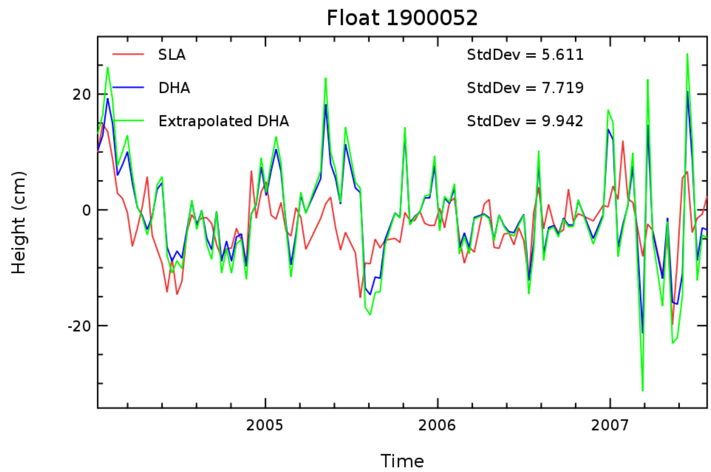

Figure 8: *Monitoring of the Jason-1 SLA, in-situ DHA from float 1900052 located around Mozambic canal and the extrapolated DHA over the total water column with regression coefficients of about 0.7.*

It suggests that the steric and mass contributions (sum with steric gives total sea level) are in phase opposition in this area leading to a total variance signal of less amplitude. The variance of the extrapolated DHA is thus greater than for DHA only (by construction) showing that the method is not adapted to compare similar physical contents. Moreover, it has been shown (2010 annual report: [13]) that the spatial restriction (via a threshold on the regression coefficents; see

	Correlation	rms of differences
SLA to steric content / DHA	0.75	5.2 cm
SLA / DHA	0.72	6.3 cm
SLA / DHA to total content	0.69	8.1 cm

Table 2: *Impact of using regression coefficents to compare similar physical contents in terms of correlation and rms differences between SLA (Jason-1) and in-situ data (with the validation flag of the method).*

figure 4) of the sea level comparison to regions where altimetry and in-situ instruments measure similar signals has no significant impact on the amplitude, phase and drift of the sea level differences.

The analysis of the correlation and the rms differences between altimeter SLA and in-situ DHA when extrapolating the latter or not illustrates the impact of the use of the regression coefficients. Historically, they have been firstly used to extract the steric content from altimeter data and compare them to the in-situ DHA which is better in terms of correlation and rms differences between both types of data (table 2, 1^{st} versus 2^{nd} lines). In order to calibrate altimeter data, the extrapolation of in-situ steric DHA over the total water column has been prefered but table 2 indicates that the quality of the results is deteriorated (3^{rd} versus 2^{nd} lines). Note that these statistics are greatly improved (correlation of 0.85 and rms differences of 4.4 cm for SLA/DHA comparison) when the DUACS merged multi missions products is used to compute the altimeter SLA. Since our method mainly aims at calibrating the altimeter signal itself (on the total water column) for each single mission, the regression coefficients should not be used with our method of comparison. The following section describes a new approach to calibrate altimeter SLA.

3.2.4. Use of the mass contribution to the sea level with GRACE data

In order to calibrate the altimeter data for each space mission, they must be compared with a reference with a consistent physical content. The use of a static grid of regression coefficients does not takes into account the inter annual evolution of the mass contribution which is not in phase with the steric signal (Chen et al. 1998: [6]). Rather than extrapolating the steric content of Argo T/S profiles, we propose to improve the accuracy of the absolute altimeter MSL trend by adding the steric signal to the mass contribution to the sea level derived from the Gravity Recovery and Climate Experiment (GRACE) data.

Two available datasets of the mass contribution to the sea level are available (Chambers, 2006: [4]) (http://grace.jpl.nasa.gov/data/GRACEMONTHLYMASSGRIDSOCEAN/): (i) GRACE product from the Center for Space Reasearch (CSR, Univ. Texas) computed by Don Chambers (Univ. of South Florida) version RL4.0. Data are computed on a 1°x1° spatial grid resolution and a post glacial rebound signal has been removed according to the model of Paulson et al., 2007 ([18]). Data are gaussian filtered with a 300km half width and are available from August 2002 until May 2011 with a monthly temporal sampling. (ii) Projection of the first set onto the empirical orthogonal functions of an ocean model for circulation and tides, reconstructing the first 10 modes (Chambers and Willis, 2010: [5]) available over the period February 2003 / May 2011. Grace signal which is inconsistent with the physical model is thus filtered out. This reconstructed dataset better fits altimeter SSH corrected for steric effects using Argo floats data. Both datasets have been analyzed but as results are more consistent with altimetry corrected for the steric signals, we only discuss results obtained with the second reconstructed mass dataset. Equivalent sea level values represent anomalies referenced to the 2003/03-2010/02 time period.

The monitoring of the mass contribution to the mean sea level displays a trend of 1.0 mm/yr (with annual and semi-annual signals removed) (figure 9, left). But the spatial distribution of this trend (figure 9, right) varies from ±5 mm/yr.

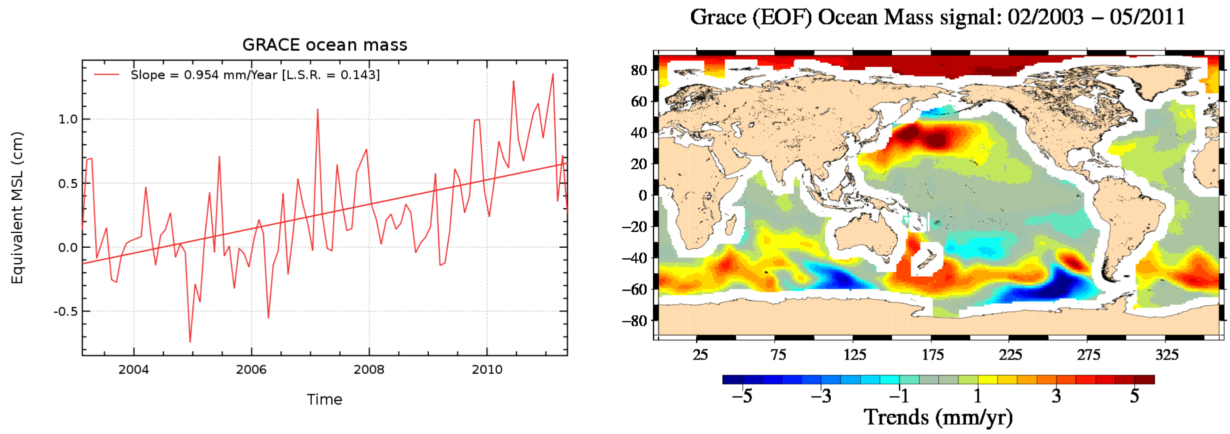

Figure 9: *Monitoring (left) and spatial distribution (right) of the trend of the mass contribution to the equivalent MSL from GRACE reconstructed data.*

- **Comparison of altimeter SLA with Argo and GRACE**

Preliminary analysis of the datasets is performed by computing their dispersion (figure 10). The correlation between altimeter SLA and summed DHA from Argo with the mass signal is of 0.73 and the rms differences of 6.3 cm. These statistics are much improved compared with the situation where SLA is compared with the extrapolated DHA with regression coefficients (cf. table 2) but no significant change is detected when SLA is compared with DHA only.

The variance differences of the altimeter SLA (Jason-1) corrected from the steric and mass signals versus the steric signal only is computed in order to detect the best coherence between altimeter measurements and external and independent data. This corresponds to:

$$VAR(SLA - DHA - Mass) - VAR(SLA - DHA)$$

This is estimated as an histogram of the number of timeseries associated with each Argo float (figure 11, left). The mean variance difference is of -2.2 cm^2 which means that the altimeter SLA is more coherent with steric DHA and mass signal rather than with the steric signal only. The spatial distribution of these variance differences (figure 11, right) indicates a mean value (box averaged) of -1.2 cm^2 with increased reduced variance observed in the Kuroshio current, the south eastern Pacific ocean and in the Indian ocean. Nevertheless, the spatial distribution of the mass signal is significantly reduced compared with the altimeter and Argo distributions in particular in regions of

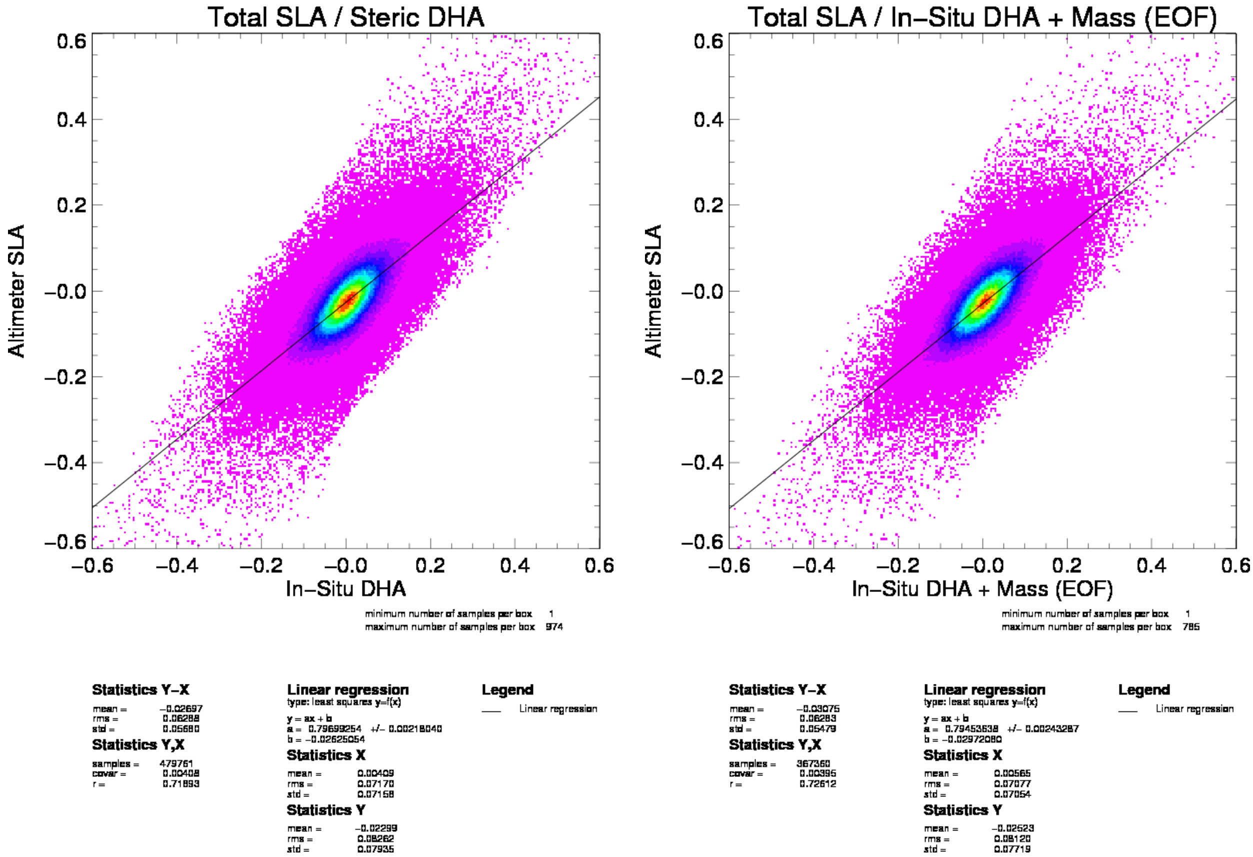

Figure 10: *Dispersion between altimeter SLA (Jason-1) and DHA from Argo (left) and DHA + mass contribution from GRACE reconstructed (right).*

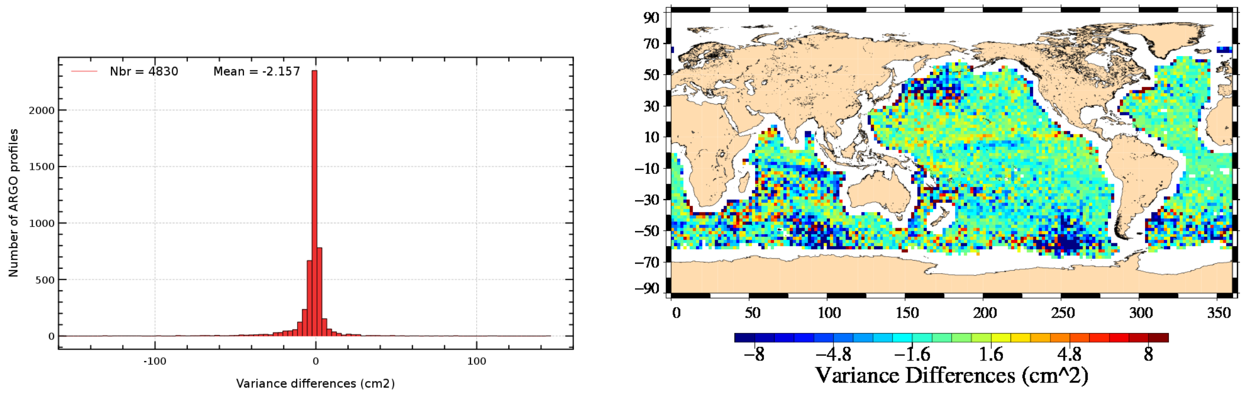

Figure 11: *Histogramm and spatial distribution of the variance differences of the altimeter SLA (Jason-1) corrected from the steric and mass signals versus SLA - DHA.*

high ocean variability (Gulf Stream, Aghulas retroflexion, Confluence zone) and at high latitudes, which largely contributes to the obtained reduced variance. Indeed, similar analyses processed with pure GRACE data (not projected on the EOFs of an ocean model) provides measurements much closer to the coast (and thus in regions of high ocean variability) and the associated variance difference is slightly positive (+2.1 cm^2). Considering the calibration of altimetry in the open ocean, this turns in favour of the use of the mass contribution from reconstructed GRACE data added with Argo.

The temporal evolution of the altimeter SLA (Jason-1) and the mass contribution to the sea level display strong annual signals with similar magnitude (±1 cm) (figure 12, left) whereas the magnitude of the steric DHA is smaller with less pronounced annual signal. A slightly different behaviour of the steric DHA is detected from 2008 onwards compared with two others signals. Nevertheless, a strong correlation is observed between the altimeter SLA and the summed DHA and mass signal (figure 12, right; red and blue curves). In opposition, the evolution of the in-situ DHA extrapolated with the regression coefficients (green curve) displays a signal in phase opposition with the SLA signal.

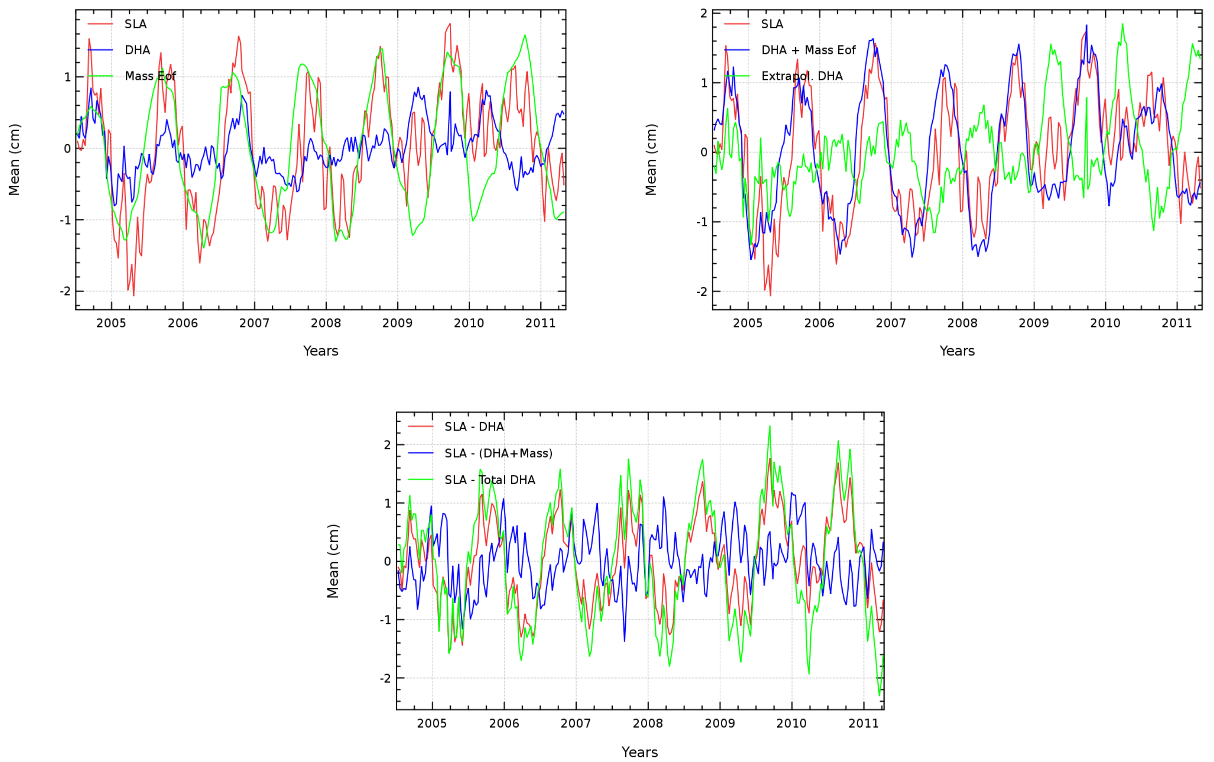

Figure 12: *Altimeter SLA (Jason-1), steric DHA from Argo and mass contribution from GRACE reconstructed (left). Comparison of altimeter SLA (Jason-1) with summed DHA and mass contribution and with extrapolated DHA) (right). Altimeter SLA residuals (Jason-1) with three different methods (bottom). Annual and semi-annual signals are included.*

Regarding the altimeter residuals with different methods (figure 12, bottom), the comparison with steric DHA (in red) or extrapolated DHA (in green) provides very similar signals. The magnitude of the annual signal obtained with these both methods (red and green) is increased compared with the use of the summed DHA and mass signals (in blue). This clearly demonstrates that part of the signal is missing when altimeter SLA is compared with Argo data only and that their extrapolation with the regression coefficients does not provide the physical content of the missing signal. It demonstrates that the combined steric DHA with the GRACE mass signal should be used to assess the altimeter residuals.

- **Analysis of the altimeter residuals drift**

Now that the datasets have been analyzed, the altimeter residuals drifts are estimated over the studied period (figure 13) for Jason-1 (left) and Envisat (right) missions. For both missions, the highest altimeter MSL drift is obtained with the steric DHA only (in red) and in spite of strong discrepancies between raw differences (figure 12, bottom), the altimeter residual drifts obtained with the extrapolated DHA (former method) and with the use of the mass contribution become very similar (0.3 mm/yr and 0.2 mm/yr respectively for Jason-1). As the correlation and coherence between both types of data are improved with the new method (0.73 and 6.3 cm versus 0.69 and 8.1 cm), more confidence is thus expected in the trend obtained with the new method using the mass contribution. In order to estimate the precision of the observed drifts, results are compared with those from global Cal/Val analyses and comparison with in-situ tide gauges over the same period. Table 3 indicates that high confidence is attributed with the in-situ tide gauges method since by relative comparison, the Jason-1 - Envisat trends difference is the same as the one from global Cal/Val analyses (1.5 mm/yr). As the precision of the value derived from the tide gauges comparison is estimated to be 0.5 mm/yr, the precision on the drift obtained with the new method is estimated to reach at least 0.5 mm/yr (since the observed drift difference is of 0.5 mm/yr). In addition, values obtained with our new method is higher than the tide gauges method by 1.0 mm/yr for Jason-1 and 2.0 mm/yr for Envisat (table 3). But we consider that absolute altimeter drifts obtained with both in-situ comparison methods can not be strictly compared since tide gauges measure the coastal ocean and Argo profiles are located in the open ocean. Thus, an estimation of the precision on the altimeter drift obtained by comparison with steric DHA and GRACE mass contribution could be of 0.5 mm/yr to 1.0 mm/yr according to the studied regions.

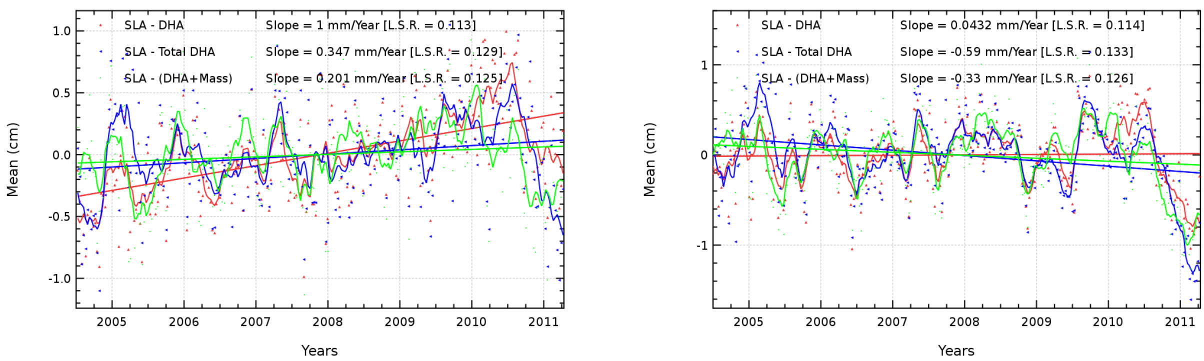

Figure 13: *Difference between altimeter SLA from Jason-1 (left) and Envisat (right) and DHA from Argo (red), extrapolated DHA with regression coefficients (blue) and DHA + mass contribution from GRACE reconstructed (green). Annual and semi-annual signals are removed and data are 2-month filtered.*

- **Analysis of the inter annual evolution of the altimeter residuals**

Even with annual and semi-annual signal removed (figure 13), inter-annual variations of the altimeter residuals are observed for both missions with several millimeters amplitude. In particular, a decrease of the residuals is detected over the last 6 months of year 2010 with 6 mm and 11 mm

Drift (mm/yr)	**Jason-1**	**Envisat**	**J1 - EN**
Global Cal/Val	2.2	0.7	1.5
SLA - tide gauges	-0.8	-2.3	1.5
SLA - DHA - Mass	0.2	-0.3	0.5

Table 3: *Altimeter (Jason-1 and Envisat) MSL trend (1^{st} line) and drifts compared with tide gauges (2^{nd} line) and Argo+Grace (3^{rd} line). The slope differences is also indicated. Annual and semi-annual signals are removed and data are 2-months filtered.*

amplitude with Jason-1 and Envisat data respectively (with the new method using the mass signal). As discussed later (figure 14), this decrease is not as strong with Jason-2 data. This could be partly derived from GRACE data since this dataset results from an inverse method and the quality of data at the end of the period could be deteriorated. This anomaly should be analyzed in details to be better understood.

The use of the mass contribution added with Argo data is thus prefered compared with the use of the extrapolated DHA in order to better estimate the altimeter MSL drift and also to detect the impact of a new version of altimeter standard. Nevertheless, the use of the mass contribution does not allow to analyze recent altimeter measurements since the monthly grids are limited to May 2011 and the frequency of update of the timeseries is not known. In addition, the reduced spatial distribution of the mass signal (as shown on figure 11, right) also excludes some regions of the ocean (¡300km from the coasts). But the impact on the quality of the results is considered to be reduced compared with the former method since Argo profiles reach 2 000m and are thus far from the coasts. At last, Quinn and Ponte (2010, [21]) point out that the GRACE-derived mass contribution to the sea level and the associated ocean mass trend are potentially strongly affected depending on which GRACE product is used, which adjustments are applied and how the data are processed. This should be kept in mind when analyzing the results.

4. Analyses of the altimeter sea level differences with external and independent data

We describe here the analyses of the altimeter SLA residuals compared with Argo steric DHA and the mass contribution from GRACE reconstructed as detailed in previous section. The mean residuals from various altimeter missions are first compared and the associated variance is also discussed. The detection of relative regional altimeter MSL drift between Jason-1 and Envisat is then analyzed.

4.1. Mean SLA residuals compared with steric and mass signals

4.1.1. Temporal analyses of the mean differences

The SLA residuals compared with DHA from Argo and the mass signal from GRACE reconstructed has already been shown in figure 13 for Jason-1 and Envisat with trend of 0.2 mm/yr and -0.3 mm/yr respectively over July 2004 - May 2011. The new method leads to an improved homogeneity between both missions but as discussed later, regional discrepancies are detected between the MSL trends computed with both missions and these biases contribute to the observed difference between both trends. It will be modified according to further evolutions in the Envisat SLA computation (use of reprocessed V2.1 timeseries, orbit update and evolution of the PTR instrumental corrections).

The comparison of Jason-1 and Jason-2 altimeter residuals (figure 14, left) reveals relatively similar behaviour of both altimeter residuals. The focus on Jason-2 time period (right panel) shows a difference of behaviour after October 2010 with a decrease of Jason-1 residuals of 6 mm (already described in previous section). The origin of this anomaly which is not seen by all altimeter missions should be understood. This leads to a trend difference of 1.1 mm/yr between both missions over the almost 3 years of Jason-2 period (-1.5 mm/yr for Jason-1 and -0.4 mm/yr for Jason-2).

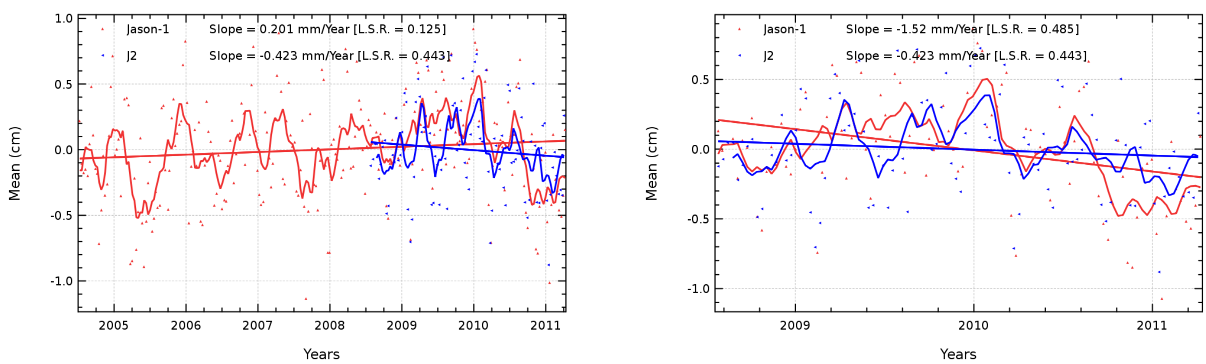

Figure 14: *Altimeter residuals for Jason-1 (red) and Jason-2 (blue) over Jason-1 period (left) and Jason-2 period (right). Annual and semi-annual signals are removed and data are 2-month filtered.*

4.1.2. Spatial analyses of the mean differences

Regional SSH biases have already been detected in altimeter space missions thanks to inter mission comparisons, but the detection of potential systematic altimeter errors is made possible thanks to the comparison with independent measurements. Map of the mean altimeter SLA residuals is shown on figure 15 for Jason-1 and Envisat. Similar distributions are observed for both missions with remaining biases observed in particular in the Pacific ocean. Note the the observed negative residuals obtained with the new method in the north-west and south-west Pacific ocean appears to be strongly correlated with the GRACE data since similar patterns are observed on the trend of the ocean mass signal (see figure 9).

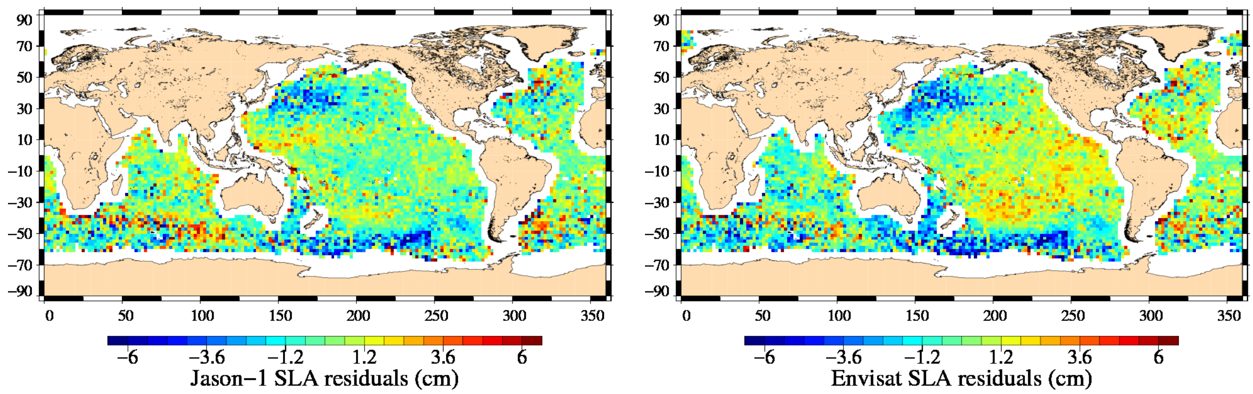

Figure 15: *Map of the altimeter residuals for Jason-1 (left) and Envisat (right).*

The difference between both altimeter residuals from Jason-1 and Envisat is shown on figure 16 and is actually equivalent to the results obtained with the Cal/Val cross calibration between both missions colocated to in-situ T/S profiles. The east / west observed bias is associated with the orbit computation and will be thoroughly discussed in the following section.

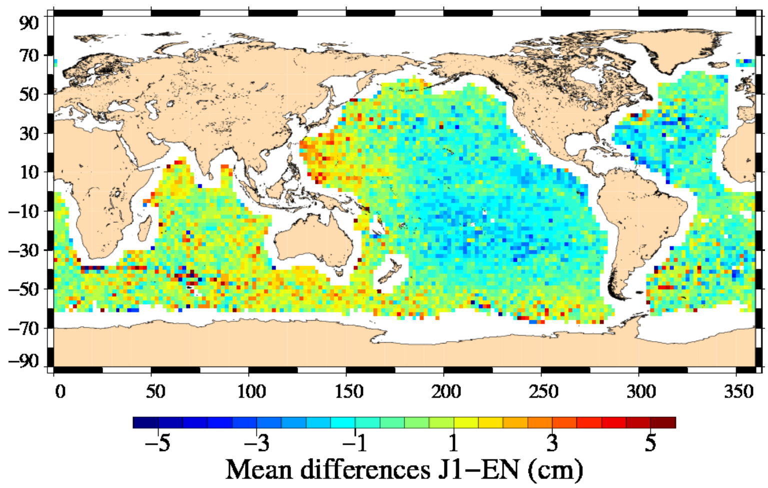

Figure 16: *Altimeter residuals difference between Jason-1 - Envisat.*

4.2. Variance of SLA residuals compared with steric and mass signals

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The evolution of the coherence of altimeter data with combined Argo and GRACE external data is provided by the variance of the SLA residuals over the studied period (figure 17). As presented in the former section when comparing both methods, the mean variability is 2 cm lower with the new method using the mass signal, which confirms that the compared data are now more consistent. Mean values associated with Jason-1 & 2 and Envisat are identical (5.4 cm).

Standard deviations of Jason-1 and Envisat residuals regularly decrease until 2008 due to the regular increase of the spatial and temporal distribution of in-situ Argo profiles over this period. But the variability increases from 2009 for the three available missions by more than 6 mm. The fact that this evolution was also detected with the previous method using regression coefficients suggests that this evolution is related with the data themself. The annual maps of the Jason-1 residuals standard deviation is shown on figure 18 from 2004 until 2010 in order to detect potential impact of the data sampling. A clear increase of the spatial density of the Argo measurements is observed from 2004 to 2008 whereas no major increase is observe afterwards. However, the sampling of high ocean variability regions has been slightly improved for the last three years and particularly the southern ocean, which directly impacts the global level of variance as observed on figure 17. The comparison of the residuals variance in the global ocean and without these regions of high ocean variability indicates that the recent observed evolution is reduced when these regions are excluded (not shown). The variance evolution is also reduced when the analysis is restricted to the northern hemisphere (not shown).

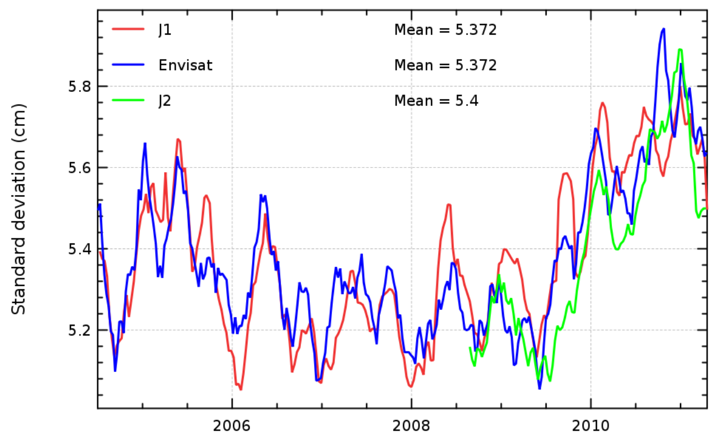

Figure 17: *Standard deviation of the altimeter residuals for Jason-1, Envisat and Jason-2.*

However, some other reason may explain the observed evolution and the 2003-2009 time reference period of altimeter SLA and Argo DHA may also contributes to the recent evolution since latest data are likely to be out of this mean and thus could contribute to the standard deviation increase. An homogeneization of the reference period used for the mass signal from GRACE data (currently 2003-2010) could also improve the evolution.

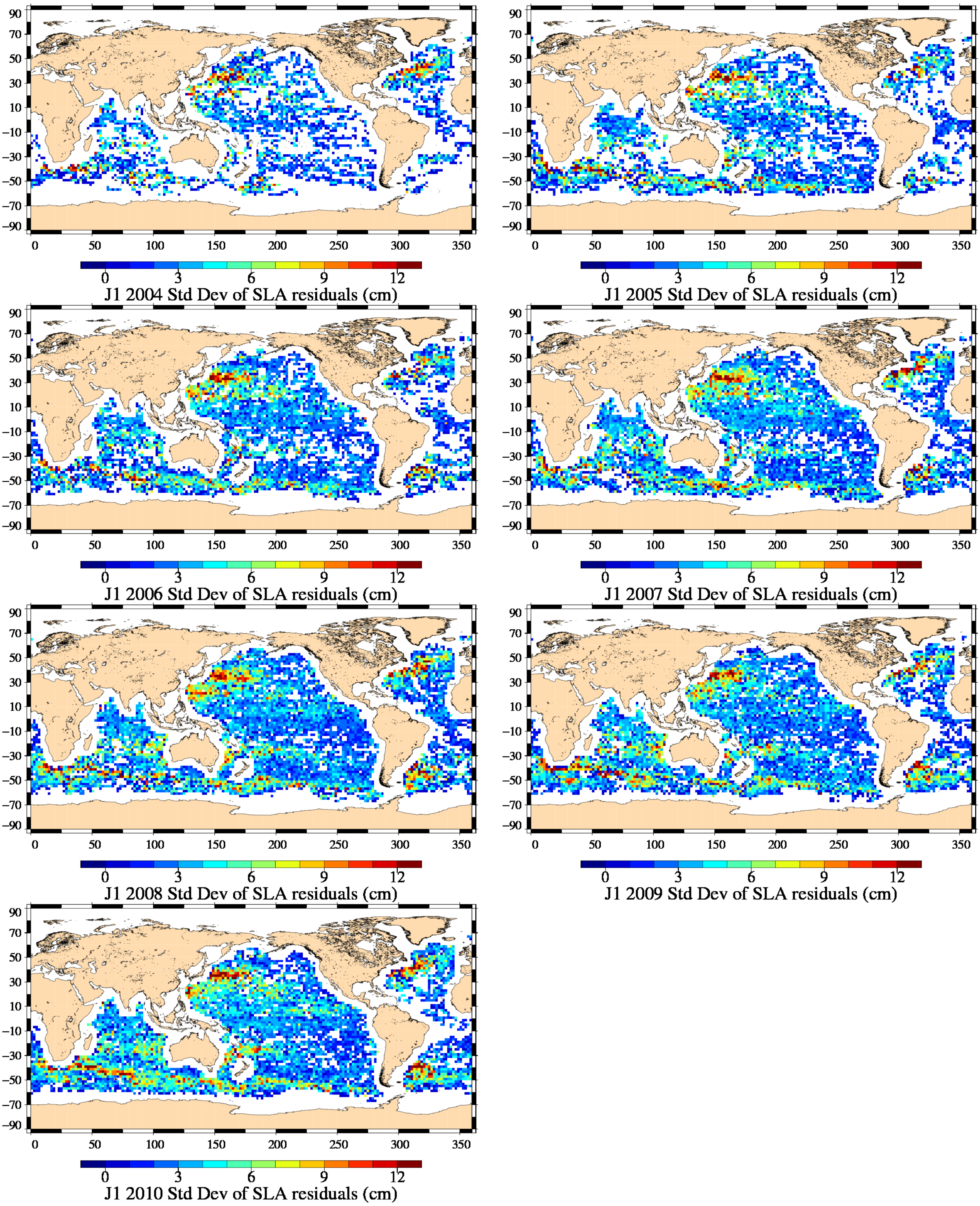

Figure 18: *Annual maps of the standard deviation of the altimeter residuals for Jason-1 from 2004 to 2010.*

4.3. Detection of regional altimeter MSL drift

We discuss here the interest of comparing altimetry with external and independent data to study the regional altimeter MSL trend discrepancies observed between Jason-1 and Envisat data. In 2011, this study has been carried out by comparison with Argo steric DHA only. This makes possible the analysis of relative differences between two different altimeters.

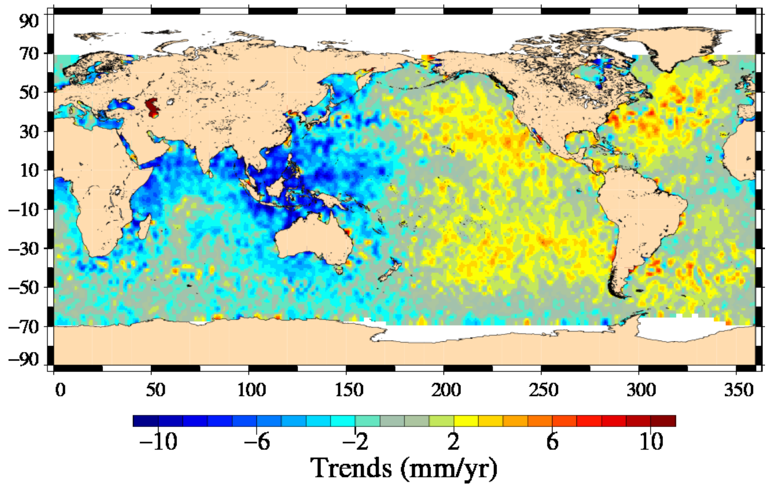

Figure 19: *MSL trend differences (mm/yr) between Envisat and Jason-1 missions computed with GDR-C orbit (Envisat cycles 10-93 and Jason-1 cycles 28-323)*

The map of the MSL trend differences between Jason-1 and Envisat missions underlines a large longitudinal discrepancies of ± 3 mm/yr between the eastern (0°, 180°) and the western (180°, 360°) part of the global ocean (figure 19). But the mission at the origin of this regional bias can not be detected with this cross-calibration. Therefore, the Argo in-situ profiles are used as an external and independent reference to compare both altimeter missions. Time series of sea surface heights differences between altimetry and in-situ data are computed for both Jason-1 and Envisat missions. Then, the drifts of these differences are estimated separating east (0°/180°) and west (180°/360°) parts in order to detect which mission is closest to the in-situ reference. The analysis with Jason-1 data (figure 20, left) indicates that the MSL trends difference between west and east hemispheres is of -0,9 mm/yr whereas the same approach with Envisat data reveals a trends difference of up to 3,8 mm/yr (figure 20, right). Considering the associated precision (about ± 0.5 mm/yr), it indicates that both Envisat and Jason-1 altimeter SSH are affected by the regional difference but it affects more Envisat measurements. Further analysis has shown that this anomaly is in relationship with the calculation of the orbit in Envisat GDR-C products (Ollivier et al., submitted, [17]). This has been solved with the preliminary version of the GDR-D orbit and its impact will be described in the next section.

The comparison with the global network of Argo profiles is preferred for such analysis compared with the use of tide gauges since, (i) the global ocean coverage of these instruments is reduced and the sampling is even more reduced when considering each of the East and West hemispheres and, (ii) coastal altimeter measurements are affected by enhanced errors (wet troposphere and tide corrections) compared with the open ocean. The errors of the altimeter regional (East/West) MSL drifts compared with tide gauges may thus become higher than the searched anomaly. These results demonstrate that the use of Argo in-situ data to compute relative estimations of the altimeter MSL trend makes possible the detection of regional relative drifts in altimeter measurements. In addition, such differences observed between two hemispheres indicate that the errors associated with the regional altimeter MSL trend currently strongly affect climate studies at the spatial scale of a single ocean basin. This result has been submitted for publication in Marine Geodesy 2012 ([27]).

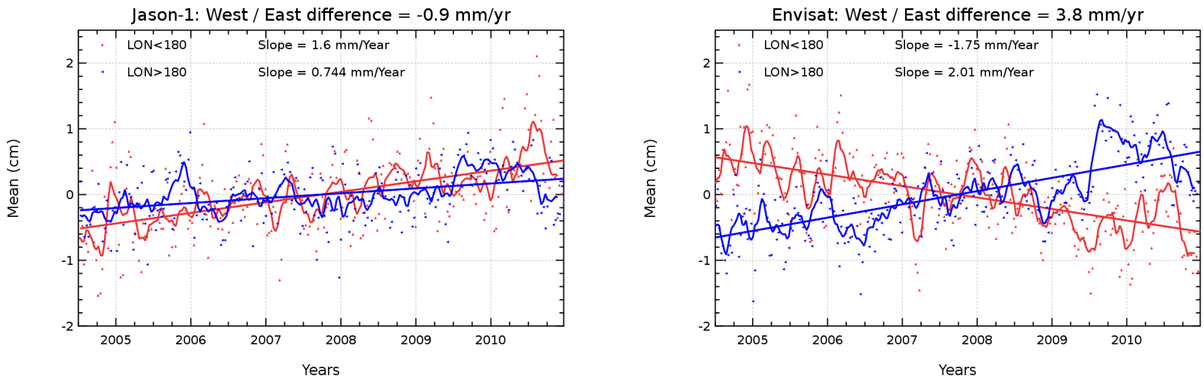

Figure 20: *SSH difference (cm) between altimeter data and Argo in-situ measurements for Jason-1 (left) and Envisat (right) computed with GDR-C orbit, separating east (<180°) and west (>180°) longitudes. Corresponding annual and semi-annual signals are removed. Trends of raw data are indicated and the 2-month filtered signal is added.*

5. Evaluation of new altimeter standards

5.1. 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 in the sea level calculation. Argo measurements have already been used to compare Jason-1 orbits (GDR-C vs GDR-B, see 2008 annual report [23]) or to estimate the impact of comparing Duacs delayed time merged products with Argo data rather than measurements from a single mission (see 2009 annual report [12]). In 2010, this method has been used to evaluate the new version of Duacs delayed time merged products and to compare the impact of computing altimeter SLA with modelled or radiometric wet tropospheric correction. All these analyses have been performed with a criterion of improvement based on the variance differences between old and new versions of the studied field in order to quantify their consistency with in-situ data. However, this approach has not provided major conclusions since the impact of the studied evolutions are weaker and weaker and the searched impact are usually smaller than the uncertainty of the method using extrapolated Argo DHA with regression coefficients (estimated to be at least 1 cm^2).

To improve the estimation of weak evolutions, complemented diagnoses should be used such as the evolution of the correlation between both datasets with the old and new altimeter standards. This diagnosis together with the evolution of the coherence (reduction of variance) of the datasets should be both used and synthetized with a Taylor diagram (analysis of both the correlation and the rms differences). An improved correlation between datasets will provide a reduced formal error of the altimeter MSL drift and thus an improved confidence in this drift. In addition, the use of the new method (introduction of the mass contribution with steric Argo DHA) makes the compared datasets more homogeneous (see section "Method") and the detection of the impact of a new altimeter standard should be improved.

Moreover, as the searched evolution is of much less magnitude (1 to 5 cm^2) than the global variance of the altimeter residuals (about 30 cm^2), data should be first filtered out in the frequency band where the impact of the new standard is expected to be maximal.

Whatever the method of comparison used, the impact of an updated altimeter standard can also be estimated in terms of the evolution of the MSL trend: a reduced slope of the differences will be associated with a better altimeter standard. In 2011, regarding the regional MSL trend discrepancies observed between Jason-1 and Envisat, the impact of a new orbit solution has been estimated and preliminary results from the Envisat V2 reprocessed data are discussed below. In these analyses, the mass contribution has not been taken into account since the new approach has been performed later.

5.2. Impact of a new orbit solution

The regional MSL drift difference previously discussed between Jason-1 and Envisat has been attributed to the orbit computation of the latter mission. A new preliminary CNES GDR-D orbit solution has been developed (Cerri et al., 2011: [3]) where the long term evolution of the

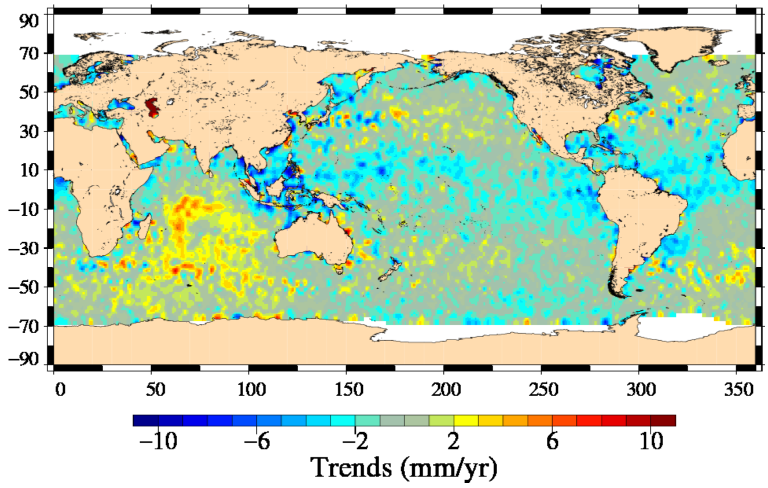

Figure 21: *MSL trend differences (mm/yr) between Envisat and Jason-1 missions computed with CNES preliminary GDR-D orbit (Envisat cycles 10-93 and Jason-1 cycles 28-323)*

gravity field has been improved. Its use in the SSH calculation reduces the observed regional discrepancy since the previous longitudinal structures using GDR-C orbit solution (figure 19) are now removed (figure 21). Altimeter data with the new orbit solution are compared with Argo in-situ measurements in order to detect potential remaining errors. Indeed errors with similar impact on both missions would not be detected without a comparison with external data as in-situ Argo profiles. It has a strong impact on the East / West difference observed with Envisat: initially +3.8 mm/yr (figure 20, right), the difference is now reduced to +1.0 mm/yr (figure 22, right).

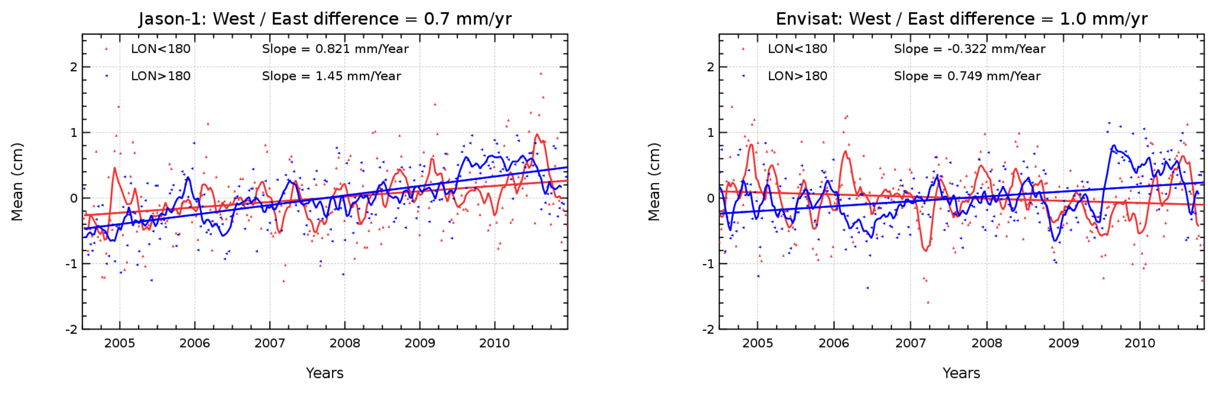

Figure 22: *SSH difference (cm) between altimeter data and Argo in-situ measurements for Jason-1 (left) and Envisat (right) computed with CNES preliminary GDR-D orbit, separating east (≤180°) and west (≥180°) longitudes. Corresponding annual and semi-annual signals are removed. Trends of raw data are indicated and the 2-month filtered signal is added.*

In addition, the new orbit solution makes both missions more homogeneous since the East / West difference observed with Jason-1 is increased from -0.9 mm/yr (figure 20, left) to +0.7 mm/yr (figure 22, left), which is similar to the Envisat result. Note that the East/West MSL trend differences are enhanced with Envisat mission because the satellite is closer to the Earth and thus more affected by the gravity field than Jason-1 (Cerri et al., 2011: [3]). Thus the comparison of altimeter measurements with Argo profiles makes possible the estimation of the impact of a new altimeter standard in the SSH calculation. This result has been submitted for publication in Marine Geodesy 2012 ([27]).

In order to assess the impact of the GDR-D orbit compared with GDR-C version, the correlation and the standard deviation of the differences between Jason-1 SLA and steric DHA and mass signal are computed with GDR-C and GDR-D orbits to assess the impact of the new standard. The standard deviation of the differences is not changed (5.5 cm) and the correlation is slithly reduced from 0.73 to 0.72. This confirms that some new standard may only affect particular scales of the altimeter signal and are thus only detected by some diagnoses (changes in altimeter regional trends in the case of the impact the long term evolution of the gravity field in the new orbit). The impact of this new orbit should be assessed with the new method using the mass contribution in terms of regional but also global altimeter MSL trend for Envisat and Jason-1 missions.

5.3. Impact of the Point Target Response data processing on Envisat SLA

The impact of new altimeter standards is estimated in terms of the relative evolution of the altimeter MSL drift compared with Argo profiles extrapolated to the total water column with regression coefficients. The impact of the new reprocessed Envisat V2 timeseries is analyzed (with available measurements until May 2009). Figure 23 indicates that the MSL drift compared with Argo profiles decreases from -0.3 mm/yr with Envisat raw data (red curve) to -1.0 mm/yr with reprocessed measurements (blue curve). This evolution of the altimeter drift compared with external data was not expected and further investigation has suggested that it is related with the Point Target Response (PTR) data processing (that corrects for the internal path delay and attenuation) in the Envisat SSH calculation (Ollivier et al., submitted, [17]). The detection of this data processing anomaly has already been described by comparison with Argo in-situ data (2010 annual report [13]). A new PTR data processing has been computed in the frame of the Climate Change Initiative (CCI) project supported by ESA (which is not included in the V2 Envisat mesurements) and its impact on the Envisat sea level calculation is also analyzed. The obtained drift with this new correction and the V2 products is now increased to 1.2 mm/yr (figure 23, in green). These relative evolutions of the Envisat sea level drift are in total agreement with the relative evolution of the MSL trend obtained with global internal analysis of the Envisat measurements (Ollivier et al., submitted, [17]). Such analysis should be performed with the new method of comparison using the mass contribution in order to confirm these results and to discuss the absolute MSL drifts and no more with the regression coefficients which introduce a high level of uncertainty. This demonstrates the ability of Argo in-situ data to estimate the impact of new altimeter standard and quantify the improvement of the Envisat MSL drift.

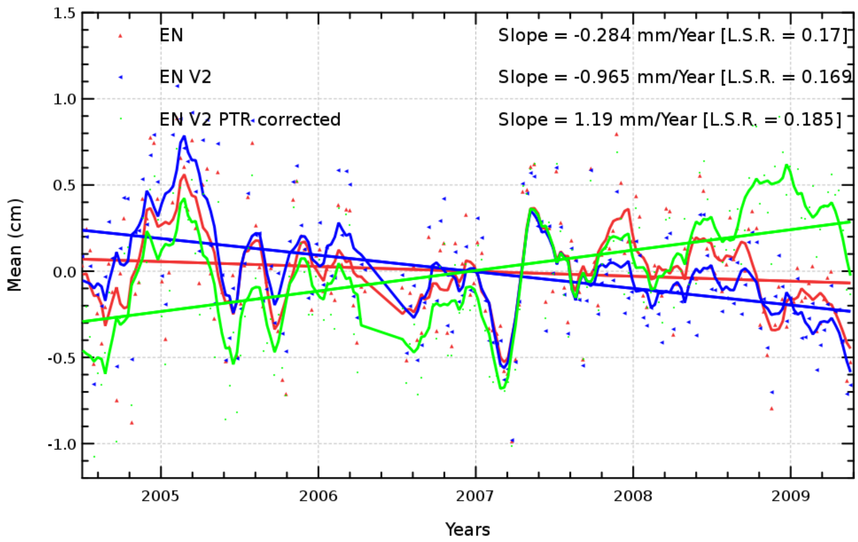

Figure 23: *Sea level differences between Envisat altimeter and extrapolated Argo DHA with regression coefficients over the current reprocessed time period (2004.5-2009.4) (cm). Red curve: Envisat original data. Blue curve: Envisat reprocessed data. Green curve: Envisat reprocessed data corrected from the new PTR data processing*

6. Conclusions and futures

A key issue on altimetry and in-situ comparisons is the close link between the objectives introduced in this work. In-situ steric DHA from Argo profiles have been used as a reference to detect regional altimeter MSL drifts discrepancies by relative comparison between Jason-1 and Envisat measurements. Secondly, altimeter anomalies are supposed to be corrected to improve altimeter products for end-users. The detection of the impact of new altimeter standards is now not only assessed by the evolution of the coherence between both types of data (variance differences, as previously performed), but also in terms of correlation and of altimeter drift evolution. For instance, the new preliminary CNES GDR-D orbit solution has been produced to correct the observed regional differences between Jason-1 and Envisat. This orbit solution has been validated by Argo steric DHA as the remaining error on the trend of both missions is greatly reduced compared with the former solution. In addition, the new PTR Envisat data processing has also been validated thanks to in-situ data since its use in the altimeter sea level computation makes the relative evolution of the Envisat MSL drift consistent with internal analyses of the mission. The obtained results demonstrate the ability of Argo in-situ T/S profiles to detect altimeter regional MSL drift and to estimate the impact of new altimeter standard on the sea level computation. The third goal is to detect anomalies in in-situ measurements and thus qualify these data, which is not performed in the context of this study (Guinehut et al., 2009 [9]). But our results are strongly dependent of this validation phase since it provides reliable datasets of in-situ measurements.

A large part of the activity in 2011 has consisted in improving the method of comparison of altimetry with in-situ data. Several evolutions have been performed but the main limitation derives from the use of regression coefficients to extrapolate in-situ DHA and compare similar physical content with altimetry. The associated uncertainty (more than 1 mm/yr drift and 1 cm^2 in variance difference) prevents us from estimating the absolute altimeter MSL drift and detecting evolution associated with a new standard. Thus a new method has been developed by comparing altimeter SLA with the sum of in-situ Argo steric DHA and the mass contribution to the sea level from GRACE data. The results from this new method have been compared in details with the former method and this new approach is prefered compared with the use of the extrapolated DHA in order to better estimate the altimeter MSL drift and also to detect the impact of a new altimeter standard. However, this new dataset has a reduced temporal and spatial distribution compared with Argo data and the comparison with others results (CalVal internal analyses and comparison with tide gauges) suggest that the uncertainty on the absolute altimeter MSL drift remains high (maybe up to 1 mm/yr) but the method could benefit from some improvements which could reduce this error (temporal reference period).

This work has been presented this year at the OSTST meeting in San Diego ([26]), at the Envisat Quality Working Group (QWG) meetings (May and November 2011) and at informal discussions with CNES (November 2011). A training period, aiming to develop a worldwide access to CLS in-situ databases, has been performed in 2011. In addition, results concerning the regional MSL trend discrepancies between Jason-1 and Envisat missions have been submitted for publication in Marine Geodesy [27].

The improvements of the in-situ database and of the processing chain have provided analyses of better quality. This is performed in an operationnal framework which is essential to operate systematic analyses and thus make this activity durable. In 2012, various results obtained with the new method using GRACE data will have to be validated compared with the previous approach and the method remains to be implemented in the processing chain. It will be adapted to assess the quality evolution of the V2 Envisat data over the entire reprocessed period. In addition, it will provides estimation of the quality improvement of the ERS reprocessed data (Reaper project) as well as the planned reprocessing of the Duacs delayed time merged products over the altimeter era.

In addition to the complementarity between the three main goals described in this study, it is important to underline the synergy of both in-situ datasets to assess the quality of altimeter data. Indeed, while tide gauge measurements provide long time series but a limited spatial sampling, Argo T/S profiles cover the global ocean on a shorter time period. Thanks to the cross-comparisons between results provided by the different approaches, the assessment of the MSL drift is more and more reliable and accurate, globally as well as regionally.

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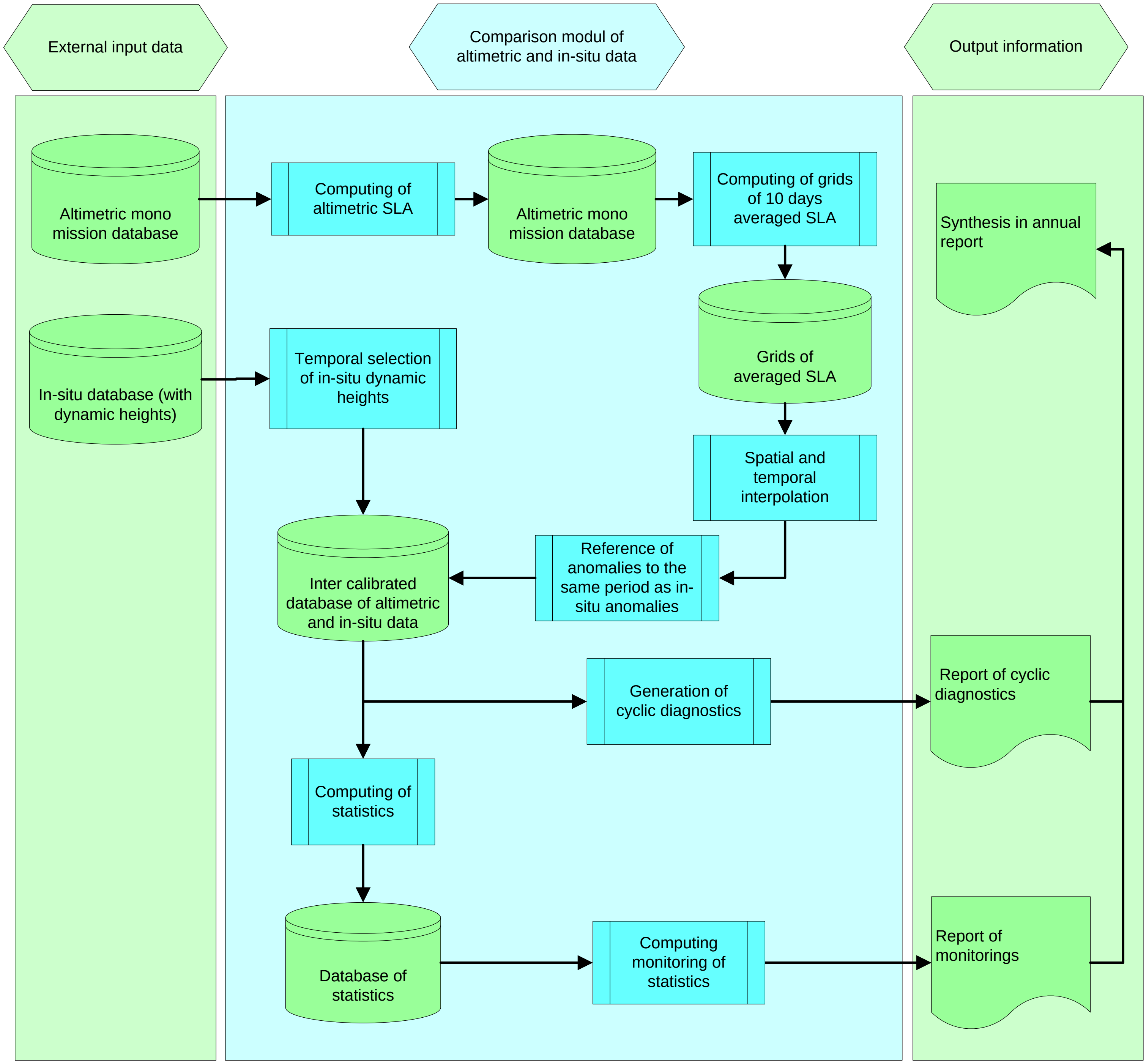
8. Annexes

8.1. Annex: Schematic view of the CalVal in-situ Argo processing chain


External input data
Comparison modul of altimetric and in-situ data
Output information
Altimetric mono mission database
Computing of altimetric SLA
Altimetric mono mission database
Computing of grids of 10 days averaged SLA
Synthesis in annual report
Grids of averaged SLA
In-situ database (with dynamic heights)
Temporal selection of in-situ dynamic heights
Spatial and temporal interpolation
Reference of anomalies to the same period as in-situ anomalies
Inter calibrated database of altimetric and in-situ data
Generation of cyclic diagnostics
Report of cyclic diagnostics
Computing of statistics
Database of statistics
Computing monitoring of statistics
Report of monitorings

8.2. Annex: Corrections applied for altimeter SSH computation

All the corrections applied on SSH for TOPEX/Poseidon, Jason-1, Jason-2 and Envisat altimeter 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)	CNES POE (GDR-C standards)	Cycle 15 onwards: CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CLS01 (v1)	MSS CLS01 (v1)	MSS CLS01 (v1)	MSS CLS01 (v1)
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 from cycle 41)
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
Ocean and loading tides	GOT4.7 (S1 parameter is included)	GOT4.7 (S1 parameter is included)	GOT4.7 (S1 parameter is included)	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]
Pole tide	[Wahr,1985]	[Wahr,1985]	[Wahr,1985]	[Wahr,1985]
				.../...

Orbits and corrections	TOPEX/Poseidon	Jason-1	Jason-2	Envisat
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 from auxiliary files + bias for side-B

Table 4: *Corrections applied for altimetric SSH calculation*