CalVal In-Situ altimetry / TS profiles

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

for TOPEX/Poseidon, Jason-1, Envisat and Jason-2

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1. Introduction

This document is the synthesis report for 2010 concerning altimetric and in-situ validation activities which aims at comparing altimetric 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 (package 2-C) for all altimetric missions. 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 altimetric measurements of the sea level which can not be detected by comparison with other altimetric missions.
- To evaluate the quality of altimetric measurements and their corrections through the analysis of the coherence between the two type of data. It is indeed an external and independant way of estimating the improvement brought by new altimetric 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.

Studies carried out in 2010 were made with these objectives kept in mind in the context of an automatic processing of the data in order to make the activity durable and reliable.

What is more, 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, [7] and OSTST presentation, [8]).

Argo T/S profiles constitutes a complementary dataset to tide gauges measurements. Indeed, although the temporal sampling is worse (one profile every ten days for one float and one hourly measure for tide gauges), the spatial coverage of the Argo network is much larger since the global open ocean is almost completely sampled. Anyway, it is important to keep in mind that several results obtained through this activity are made robust thanks to the use of multiple types of in-situ data (T/S profiles and tide gauges). These cross comparisons with several types of in-situ datasets increase the quality of calibration and validation of altimetric measurements.

Contrary to tide gauges measurements which are (almost) directly comparable with altimetry, T/S profiles only provide steric height above a reference level (chosen as 900 meters) which is called the Dynamic Height Anomaly (DHA). As altimetry provides the height of the total water column, we use a specific method (detailed in this report) to discuss the same physical content and compare the two types of data.

We describe in this report the analyses performed in 2010. A major evolution has been performed: using a common temporal reference for the computation of height anomalies. It impacts the drift and the regional distribution of the bias between altimetry and in-situ data compared with previous results. Investigations were also carried out concerning the regression coefficient used to compare both types of data. Then the coherence between each altimetric mission and T/S profiles is analyzed. Comparisons of altimetry with in-situ measurements was used in the frame of various studies performed this year. These analyses were made on the principle that even if a non negligeable uncertainty remains concerning the estimate of the absolute drift between altimetry and T/S profiles, a major interest of this dataset is the possibility of discussing relative drifts (between different altimeters, different regions or hemispheres,...). As described in this report, this approach of quality assessment relative to a chosen reference is a way to detect instrumental anomalies and anormal behaviour of the regional evolution of the MSL. At last, we discuss the improvement brought by the new version of the DUACS delayed time products by analyzing the coherence with in-situ data and also the impact of using the radiometric or modelled wet troposheric correction in the altimetric sea level computation.

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2. Presentation of Argo T/S profiles database

2.1. Overview

An important way of calibration and validation of the altimetric sea level estimation consists in the comparison with in-situ data. These are temperature and salinity profiles measured by lagrangian profiling floats of the Argo network between the surface and around 2 000 dbar for most of them. Today more than 3 000 of these floats provide operationally within a few hours dynamic height anomalies (DHA, computed from T/S profiles referenced to 900 dbar in this study) over almost the global open ocean (see figure 1). We use T/S profiles from the Coriolis Data Assembly Center (http://www.coriolis.eu.org) to generate an in-situ database at CLS with the corresponding dynamic height anomalies over the period Juanuary 2002 - May 2010 (but the period considered in our study is slightly shorter, as discussed below).

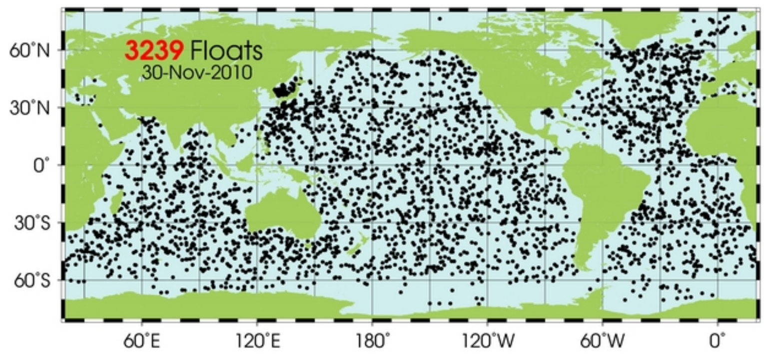


Figure 1: *Spatial distribution of Argo floats on November 30th 2010*

2.2. Spatial and temporal sampling

Unlike tide gauges, T/S Argo profiles are almost available over the global open ocean. They are operationnally collected by Coriolis data assembly center and made available in real time (24 hours) or delayed time (5 months delay). This delay is mainly due to the calibration and quality control of the profiles in the frame of MSL Argo studies. Only delayed time data are used in our study. Figure 2 shows spatial and temporal distribution of Argo measurements over the period 2002 - May 2010, (last update of the in-situ database).

The vast amount of T/S profiles (more than 300 000 over the period) are available over the global open ocean (figure 2, left). Best sampled areas (Kurushio current, bay of Biscay) have up to 200 profiles per box of 1°x3°. 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 100 000 in 2009 (in 2010, data are used until May). This consitues a great asset for latest altimetric missions (Jason-1, Envisat et Jason-2).

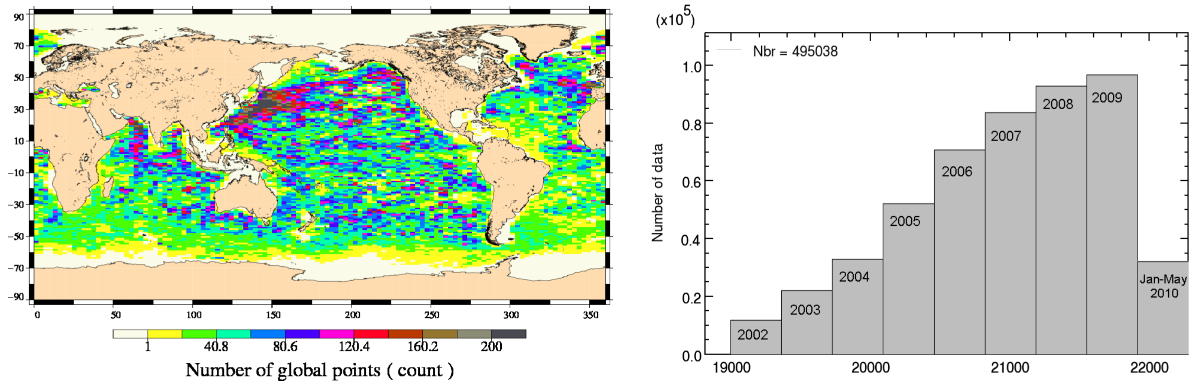


Figure 2: *Spatial (left) and temporal (right) distribution of temperature and salinity Argo profiles over 2002/2010.*

Nevertheless, spatial distribution has not always been high enough in some areas to produce statistically valid analyses (especially because of a lack of salinity data before 2003, since only temperature profiles were available). Considering a threshold of 80% of the global ocean surface covered by Argo floats, figure 3 indicates that analyses should be performed with in-situ data from mid 2004 and later. This is what is done in this report.

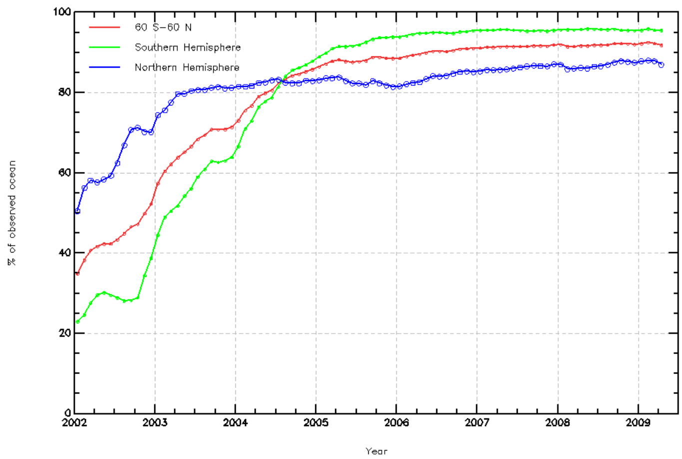


Figure 3: *Monitoring of the percentage of the ocean covered by Argo profiling floats for the global ocean and both hemispheres.*

The vast amount of available T/S profiles constitutes an independant dataset well adapted for comparison with altimetric 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 altimetric missions.

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

3.1. Description of the processing sequence

3.1.1. Overview

We present in this section the method of comparison of altimetric measurements with in-situ dynamic height anomalies (DHA). In-situ DHA are representative of the sea level integrated between a reference level (900dbar in our study) and the surface. Annex 8.1. provides a schematic view describing how the processing sequence works. Main steps are described hereafter:

1. Assessment of in-situ dynamic height anomalies: 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 with altimetric measurements
2. Colocation of in-situ and altimetric data: altimetric measurements are averaged over 10 days providing grids of data with sufficient spatial coverage. These data are then spatially and temporally interpolated in space and time of in-situ measurements
3. Validation of colocated in-situ and altimetric measurements in order to exclude bad data
4. Estimate of global statistics: mean differences of sea surface height biases and consistency of measurements (variance differences)

3.1.2. Total and steric dynamic heights

Altimetric 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; [5]). 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 altimetric 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 altimetric SLA

Coefficients are estimated on a 2° resolution grid using available observations in a 2° latitude by 10° longitude box. Figure 4 indicates 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.

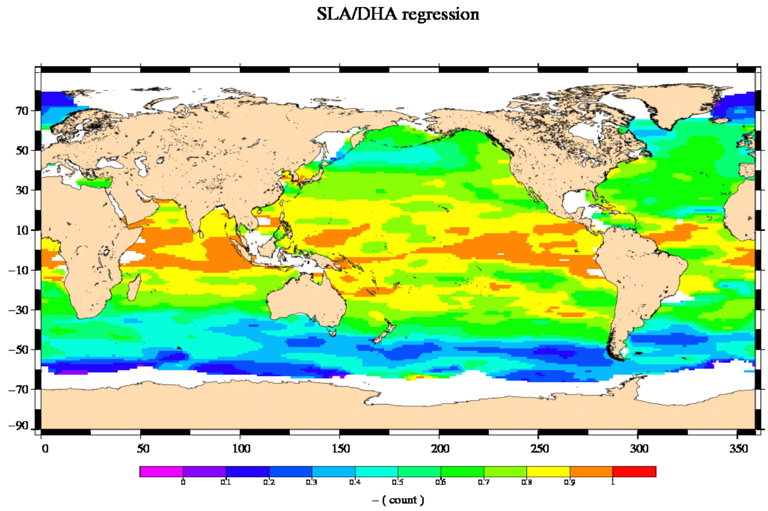


Figure 4: *Cartography of the regression coefficients between altimetry and in-situ T/S profiles between the surface and 900 dbar (about 900m)*

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. But it has been demonstrated that the use of seasonnal maps of this coefficient has a negligeable impact on the long-term drift of the altimetry - in-situ differences ([4]). In addition the computation of new regression coefficients with the same altimetric standards than the one used for the analyses should improve the accuracy of the results. Moreover the use of annual grids could help to improve mean sea level monitoring. Indeed temporal evolution of mean sea level associated with mass and steric contributions (sum gives total MSL) are estimated to be linear in our case wheras it might not be true over the studied period. Nevertheless, the estimated impact of these evolutions is rather weak.

3.1.3. Colocation of in-situ and altimetric data

Spatial coverage of altimetric measurements over one cycle is better than the in-situ coverage. Altimetric SLA is thus averaged over 10 days (grids) in order to have a sufficient spatial coverage. Then colocation of both types of data is made via the interpolation of these grids of altimetric data (bilinear in space and linear in time) at the location and time of in-situ measurements.

3.1.4. Validation of compared altimetric and in-situ measurements

In order to exclude bad data and improve statistic analyses, a two steps selection is made in the processing chain over altimetric and in-situ SLA:

- Selection over the difference between altimetric 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. This selection may be written as: $|SLA_{alti} - SLA_{HydroTotal}| \leq 0.30m$.

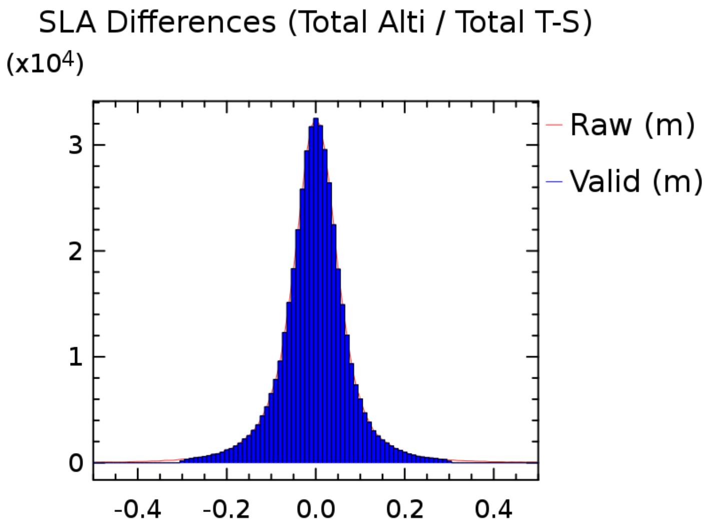


Figure 5: *Histogram of raw and validated Jason-1 SLA - in-situ DHA differences*

- Selection over a maximal dynamic height anomaly 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: $|SLA_{hydro}| \leq 1.5m$

3.1.5. Computation of global statistics

The processing sequence uses the altimetry / in-situ database to generate cycle by cycle statistics for each altimetric mission. Then, various diagnostics are produced from these statistics in order to validate altimetric data as the monitoring of elementary statistics (mean, standard deviation, number of data, minimum, maximum), the impact of the selection over ocean variability, the global mean or mean per box and histogramms of SLA differences between altimetry and in-situ data.

3.2. Evolution of the processing sequence in 2010

According to the objectives described in previous annual report (see [9]) some improvements have been performed in 2010 concerning both types of data but also within the method itself. Evolutions are described below and global results of 2010 are presented in the following section.

3.2.1. Altimetric database

No major update has been performed since last year concerning altimetric measurements: GDR-C standards are used for Jason-1 and Envisat orbit is version 2 (GDR-C). Please note that Envisat data are sampled over 10 days sub cycles (usual cycles last 35 days) in order to be consistent with results from Jason-1. Main evolution concerns all missions (Jason-1, Jason-2 and EnviSat) since we now use GOT V4.7 tide correction (instead of GOT00V2 before) and a composite wet tropospheric correction (radiometer in the open ocean and ECMWF model in coastal areas). But this latter evolution has no impact since Argo profiles are only available in the open ocean.

3.2.2. In-situ T/S database

In-situ profiles from Argo floats are transmitted to the Global Data Assembly Center (in the U.S. and France). Data from the latter (Coriolis center, Ifremer) are stored as netcdf files in our internal database. Thus these data are available at CLS for different projects (CalVal, ARMOR, PISTACH...). In our study, we mirror the database at a given date in order to avoid being impacted by potential evolutions of the database. Results presented in the following section have been computed until May 2010. Even if data are automatically downloaded from the Coriolis center, the storage in the database requires another quality control (in the framework of a feedback to the Coriolis center). This control (method decribed in [6]) is also made in the framework of ARMOR project and has been performed every 3 months since 2008. It is based on the analysis of the correlation between altimetric SLA and DHA from Argo T/S profiles and the analysis of the mean difference between the two types of data. Altimetric measurements enable us to detect potential errors in the Argo profiles time series. About 4% of the floats have been removed from the processing sequence thanks to this additional control.

3.2.3. Evaluation of new altimetric standards

The opportunity to estimate the improvement brought by a new altimetric standard (geophysical correction of SSH, orbit...) in the computation of altimetric SLA has been previously developped for the comparison of Jason-1 orbits (GDR-C vs GDR-B, see 2008 annual report [15]) or for the comparison of Duacs delayed time merged products with measurements from a single mission (see 2009 annual report [9]). One quality diagnostic is based on the assessment of variance differences between old and new versions of the studied field in order to quantify their consistency with in-situ data, which are considered as an independent reference.

This method has been used in 2010 in the framework of different projects to evaluate the new version of Duacs delayed time merged products and to compare the impact of computing altimetric SLA with modelled or radiometric wet tropospheric correction. The results of these two investigations are discussed later in this report.

3.2.4. Homogeneizing temporal reference for the computation of altimetric and in-situ anomalies

In-situ dynamic height anomalies are referenced to a mean dynamic height anomaly (DHA) which is estimated from Argo profiles over the period 2003-2008. We compare in-situ DHA with altimetric sea level anomalies (SLA) which are computed as the difference between sea surface heights and a mean sea surface ($SLA = SSH - MSS$). This MSS (CLS01V1, to be consistent with altimetic Aviso products) is computed over the 1993-1999 time period. Results obtained until last year were computed with different temporal references for the two types of data. The monitoring and the regional distribution of the SLA - DHA differences are shown on left part of figures 6 and 7. It introduces a strong regional bias at basin scales between altimetry and Argo data (both for Envisat and Jason-1).

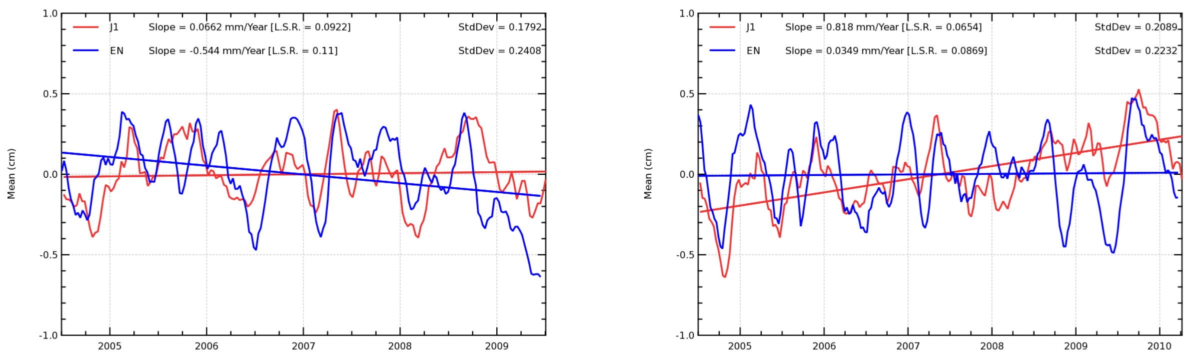


Figure 6: *Monitoring of the mean differences altimetry vs Argo for Jason-1 and Envisat without (left) and with (right) common temporal reference (2003-2008) for the estimation of both types of anomalies (SLA and DHA)*

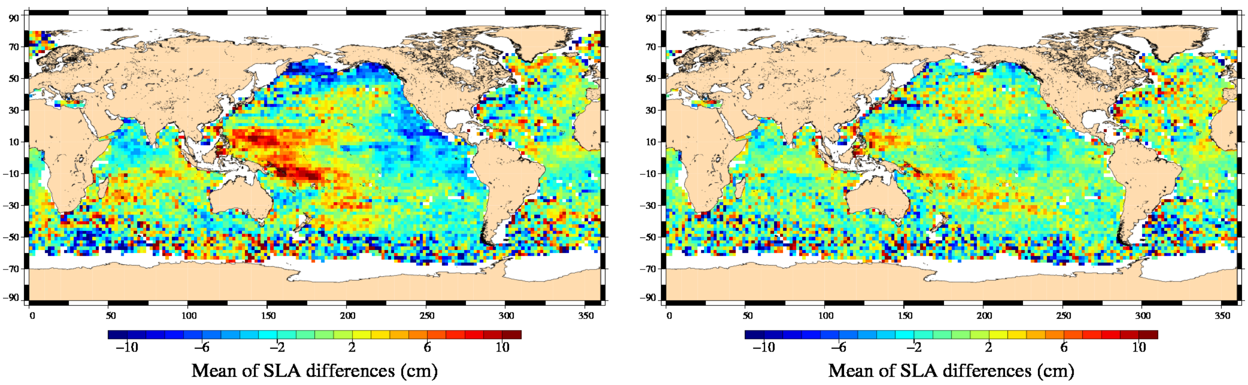


Figure 7: *Map of the mean altimetry vs Argo differences for Envisat without (left) and with (right) common temporal reference (2003-2008) for the estimation of anomalies (SLA and DHA)*

In order to use a common temporal reference for both types of data, we now compute altimetric SLA with the temporal reference of in-situ data by removing the mean of altimetric SLA over

2003-2008. The use of a common temporal reference has a significative impact on the slope of sea level differences (figure 6, right): +0.7 mm/y for Jason-1 and +0.5 mm/y for Envisat. Nevertheless, as we will see in the following sections, we are mainly interested in relative differences of slopes (between different missions, hemispheres...) and not absolute differences. We will keep the result that the difference between the two missions remains similar. Moreover formal errors of the slope estimations are now smaller (0.09mm/y before and 0.07mm/y after for Jason-1 and 0.11mm/y before and 0.03mm/y after for Envisat). But the main impact of this evolution is that it considerably reduces the amplitude of regional biases (figure 7), which means that the coherence of altimetry and in-situ measurements is improved.

3.2.5. Improving altimetric and Argo profiles comparison

The map of the regression coefficients between altimetry and in-situ data (figure 4) reveals regions of barotropic ocean dynamic at high latitudes (coefficients close to zero) where strong differences are found between the total and steric parts of the water column due to the mass field signal. Are global results affected by these areas? Is global annual signal modified by these data? Moreover, figure 2 indicate that the number of Argo profiles is lower in these regions (20 to 30 profiles available in the south of the southern ocean). So would we rather exclude these regions in our diagnostics?

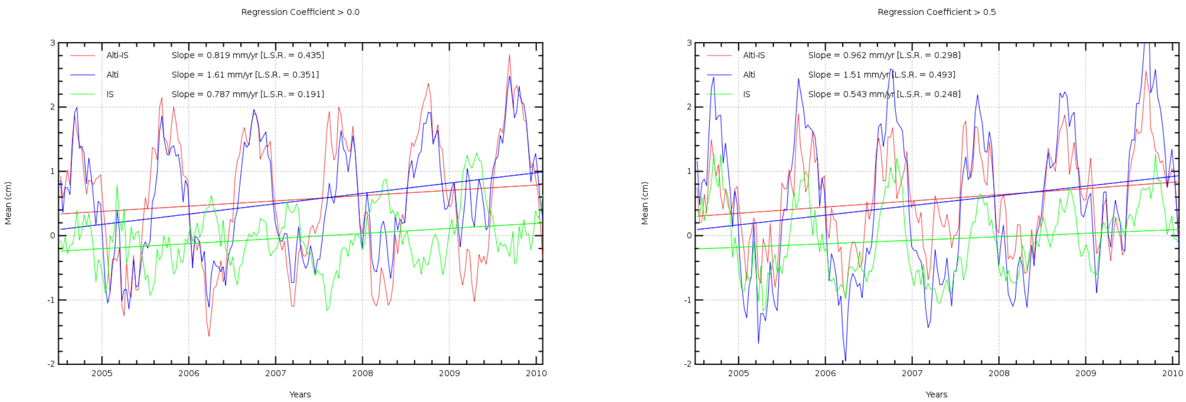


Figure 8: *Monitoring of the altimetric SLA, in-situ DHA and the SLA-DHA difference over the whole water column for Jason-1 over the global ocean (left) and restricted to values of regression coefficients >* 0.5 *(cf figure 4) (right).*

Figure 8 shows the evolution of altimetric SLA (Jason-1), in-situ DHA and their difference. The amplitude of the annual signal is smaller with in-situ data rather than with altimetry. Moreover there is a phase difference (almost quadratic) between both curves. This is associated with the mass field (not sampled by Argo floats) which is not in phase with steric signal (Chen et al., [3]). This is a characteristic of the global mean. Indeed this phase difference is not observed when restricting to some regions of the ocean (low latitudes or north Atlantic) since the mass field equilibrium varies spatially. The amplitude of the global difference between both signals (red curve on figure 8, left) is thus slightly higher than the one of altimetry or in-situ themselves.

The limitation to higher values of regression coefficients (low latitudes with baroclinic circulation, cf figure 4) will provide results in regions where altimetry and in-situ data measure similar signals and there will be no phase difference any more between both signals, as seen on figure 8 (right, blue and green curves).

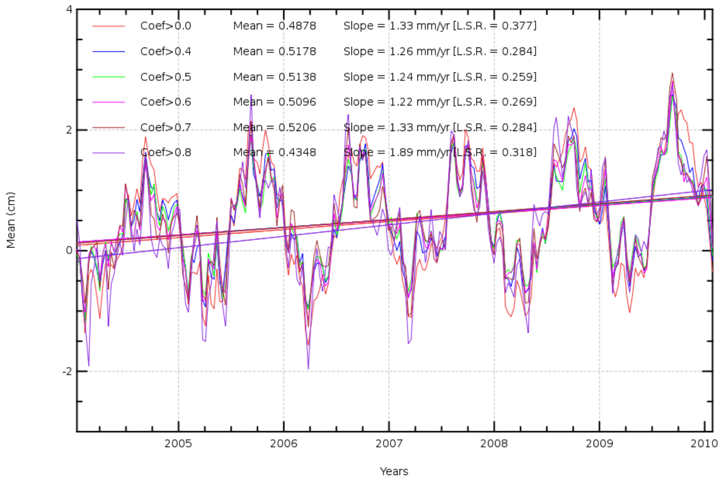


Figure 9: *Monitoring of the SLA-DHA differences over the whole water column for Jason-1 for different values of regression coefficients (0.0, and 0.4 to 0.8 by step of 0.1).*

The geographical limitation (via the coefficients) impacts the phase difference between signals from altimetry and in-situ data but in order to detect potential influence on the difference between them, we show on figure 9 the monitoring of SLA-DHA differences for various values of the coefficient. It reveals that it has no impact on the phase of the annual signal of the differences. The amplitude of this signal is also not modified and there are minor modifications of trends.

What is more, standard deviation of these signals are indicated on figure 10 and indicates that it decreases with limitation on higher values of the coefficient. This is due to the fact that as it gets higher, we select regions where altimetry and in-situ data measure more and more similar signals and both measurements are more and more coherent.

These results confirm the robustness of our method of comparison and indicate that even if less in-situ profiles are available in these regions, we can keep the data associated with low values of regression coefficients without affecting global results of our analyses, in terms of amplitude, phase or drift of the signal.

In 2010 as well as in 2009, one part of the work has consisted in routinely presenting the most important results for each mission. A global powerpoint document, gathering the main results concerning altimeter and in-situ comparisons (tide gauges as well as T/S profiles) has been initialized in order to display a global view of the whole studies concerning each in-situ activity (see annex 8.2.).

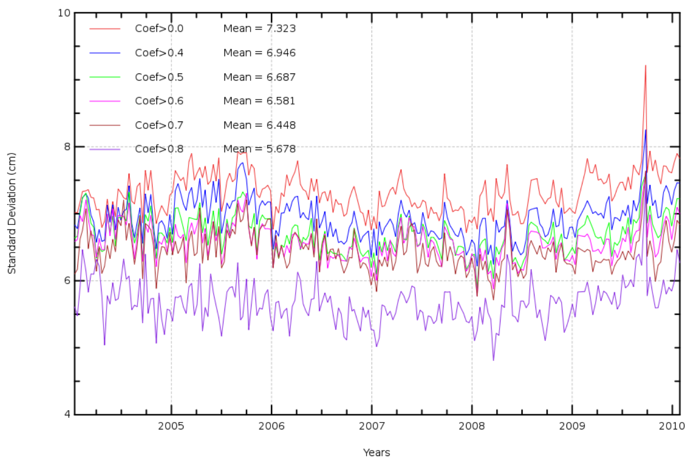


Figure 10: *Monitoring of the standard deviation of the SLA-DHA differences over the whole water column for Jason-1 for different values of regression coefficients (0.0, and 0.4 to 0.8 by step of 0.1).*

4. Analysis of altimetric and in-situ differences

We describe here the analyses of the differences between altimetry (SLA) and Argo profiles (DHA). On the one hand, the mean differences are used to detect drifts, jumps and potential systematic regional biases of altimetric measurements. On the other hand temporal and spatial coherence of altimetry with in-situ data is analyzed with variance differences. Moreover we describe the detection of altimetric anomalies by the comparison with in-situ data.

4.1. Mean differences between altimetry and Argo data

4.1.1. Monitoring of the mean differences

The monitoring of the SLA-DHA differences over the whole water column and with the same temporal reference (see previous section for details) are shown on figure 11 for TOPEX-Poseidon, Jason-1 and Jason-2 (left) and Envisat [1] (right). Raw and 2 months filtered data are plotted after removing semi-annual and annual signals from Jason-1 time series [2]. Jason-1 SLA is computed with GDR-C standards to process homogeneous data over the whole period. Envisat SLA is not homogeneous over the period (GDR-A and C) and it remains some inhomogeneities (level 1 processing...) which impact the MSL stability. However the orbit has been updated with GDR-C standards.

TOPEX-Poseidon (1.3 year) and Jason-2 (1.8 year) time series are too short for trends to be statistically significant and only slopes for Jason-1 and Envisat time series are shown. Associated formal errors (both of 0.13 mm/y) are mathematical errors corresponding to the distribution of measures around the slope, which is estimated without *a priori* knowledge of associated *physical* errors of the signal, which means without knowledge of the temporal auto correlation of the signal.

Time series have similar standard deviations (0.35 cm for Jason-1 and 0.34 cm for Envisat) and TOPEX-Poseidon and Jason-2 measurements are very close to the estimations from Jason-1, which is in agreement with Cal/Val intercomparison of these missions.

Slopes of the mean differences are significantly different for Jason-1 and Envisat. Whereas a 0.8 mm/y drift is observed for the Jason-1 / in-situ difference, no drift is detected with Envisat (0.0 mm/y) [3], which reveals a very good consistency with in-situ measurements. As mentionned above, standards used for the computation of altimetric SLA are not the same for Jason-1 and Envisat over the whole period. The use of Envisat reprocessed data (version 2) over the total period of the mission (reprocessing planned to last until the beginning of 2012) should alters these results and the drift in particular. Moreover as we describe in the following section, regional discrepancies are detected between the MSL trends computed with the two missions and these biases contribute to the observed difference between the two slopes. These investigations are confirmed with Cal/Val studies and investigations are being performed to estimate if the introduction of regional biases in the altimetric SLA computation has an impact on the global trend of the MSL (see 2010 Envisat annual report, [12]). These results confirm that comparison of altimetry with external independant in-situ measurements is useful in the detection of anomalies.

[1] Envisat subsampled at 10 days cycles in order to have similar statistics
[2] similar results are obtained while removing semi-annual and annual signals estimated from several missions
[3] a similar drift is obtained with original Envisat mission with 35 days cycles

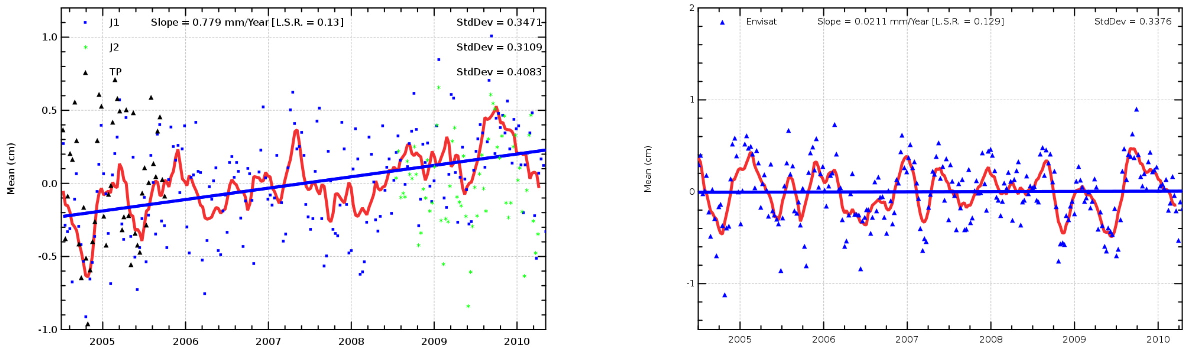


Figure 11: *Altimetric SLA - in-situ DHA over the whole water column for Jason-1, Topex-Poséidon, and Jason-2 missions after removing semi-annual and annual signals from Jason-1 timeserie. Associated 2 months filtered is shown for Jason-1 (left) and Envisat (right).*

4.1.2. Spatial analyses of the mean differences

Regional SSH biases have already been detected in altimetric space missions thanks to inter mission comparisons, in particular during the verification phase of Jason-1 in 2002 and Jason-2 in 2008. The improvement of altimetric standards has also contributed to the homogeneities of missions between each other. But systematic SSH biases could remain in the data of all missions which means that the same error may be observed with several missions, especially if it is due to the orbit determination. Comparison with in-situ independent measurements is thus an adapted method to detect such biases.

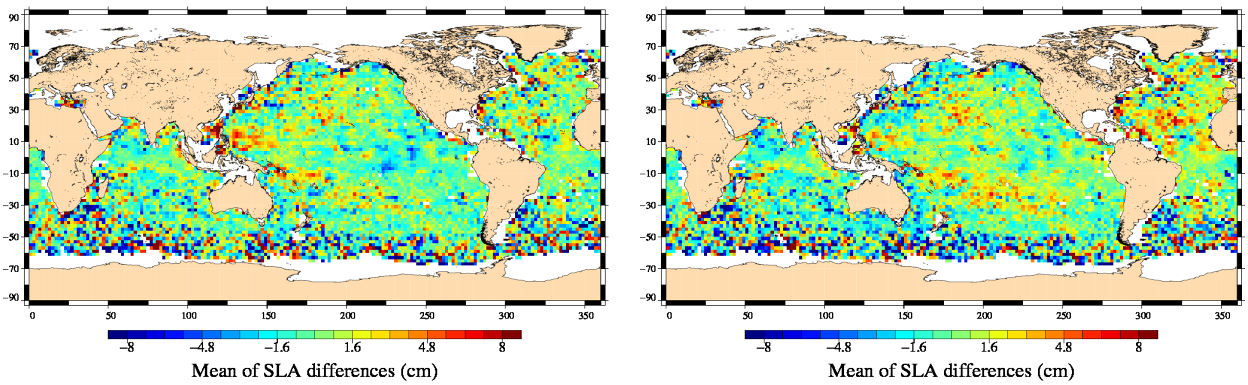


Figure 12: *Map of the centered mean difference of altimetric SLA - in-situ DHA over the whole water column for Jason-1 (left) and Envisat (right).*

Map of the mean difference between altimetric SLA and in-situ DHA over the whole water column is shown on figure 12 for Jason-1 and Envisat. Similar distributions are observed for both missions. The use of the same temporal reference for the computation of both types of height anomalies has strongly reduced the previously observed regional biases (see previous section and 2009 annual report, [9]). Nevertheless residual biases are still observed in the Atlantic, Pacific and Indian ocean basins and especially between east and west Pacific ocean. Several explanations may be found:

- There may be a real residual systematic error associated with altimeters. Nevertheless, given the observed spatial distribution of the biases, signals have probably a geophysical origin (especially in the Pacific equatorial ocean) meaning that systematic residual error is not the major origin. This could be associated with the common temporal reference used for the SLA and DHA computation which could be improved by using a multi missions reference for instance.
- The grid of regression coefficients which gives the relationship between steric and total part of the water column could absorb part of these regional biases. Indeed erroneous coefficients may be found in some regions and / or the linear relationship between steric and total SLA may not be sufficient in some cases. The coefficients should be improved if estimated with the same altimetric standards and over the same period than the one used for the maps computation.

Moreover, altimetric standards used for the Jason-1 SLA estimation are homogeneous (GDR-C) which is not the case for Envisat, which may alters the accuracy of this type of study. The reprocessed version of Envisat products (V2) over the whole period of the mission will provide homogeneous timeseries of data which may improve this spatial analysis.

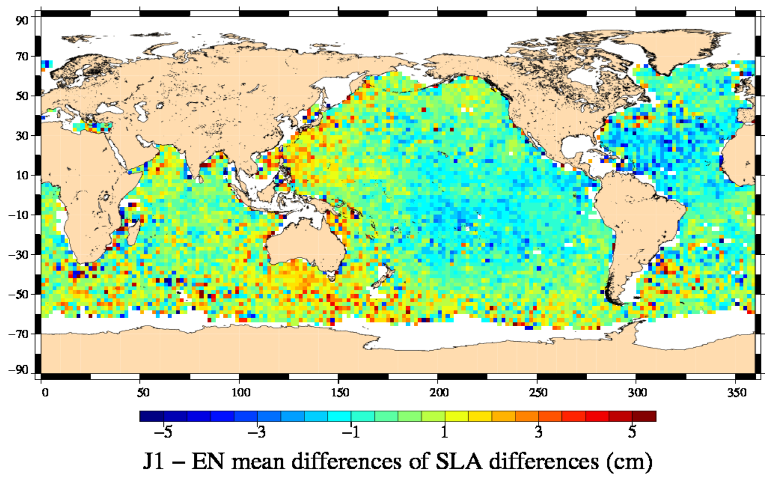


Figure 13: *Jason-1-Envisat difference of the mean SLA-DHA difference over the whole water column and with a common temporal reference.*

The difference between both maps (from figure 12) is shown on figure 13 and is actually associated with the SLA bias between Jason-1 and Envisat missions colocated to in-situ T/S in-situ profiles. It is equivalent to the results obtained with the Cal/Val cross calibration between both missions colocated to in-situ data. An already detected east / west bias is found in the Pacific ocean of $\pm$ 2 cm whereas a -2 cm bias is observed in the subtropical north Altantic. These biases are partly explained by the difference of standards of both missions and especially by the fact that Envisat GDR data are not homogeneous over its period. The regional comparison between Jason-1 and Envisat will be thoroughly discussed in the following section.

4.2. Variances differences between altimetry and Argo data

4.2.1. Temporal analyses

The analysis of the monitoring of the difference of variance between altimetry and Argo data gives an estimation of the coherence of altimetry with in-situ measurements. Figure 14 shows the monitoring of the standard deviation for Jason-1, TOPEX-Poseidon and Jason-2 missions (top left) over the total water column. The same is shown for Envisat (top right) and the 2 months filtered signals for Jason-1 and Envisat are shown at the bottom of the figure.

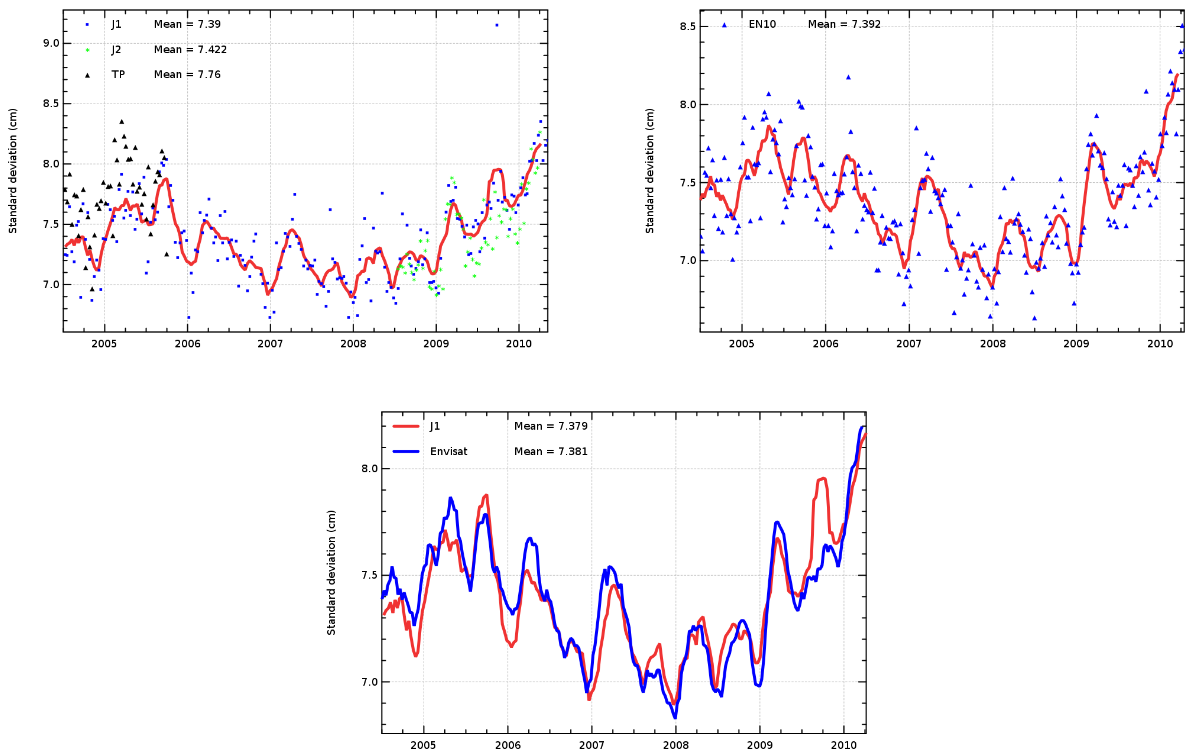


Figure 14: *Standard deviation of the altimetric SLA - in-situ DHA differences over the total water column with common temporal reference for Jason-1, TOPEX-Poseidon and Jason-2 (top left), Envisat (top right). Two months filtered signals are shown for Jason-1 and Envisat and superimposed on the bottom.*

Standard deviation values associated with TOPEX-Poseidon and Jason-2 missions are homogeneous with Jason-1 values which is in agreement with Cal/Val cross calibration studies (see Jason-1 activities annual report, [17]). Mean values over the period are identical for Jason-1 and Envisat missions (7.4 cm). Standard deviations of both missions regularly decrease until 2008 due to the regular increase of the spatial and temporal distribution of in-situ Argo profiles over this period. But standard deviation of the difference increase from 2009 for both missions. Standard deviations of both altimetric SLA are relatively stable over the end of the period whereas a clear increase of the standard deviation of in-situ DHA is detected (∼1 cm from 2008) (not shown). Thus the observed rise of the standard deviation of the SLA-DHA differences from 2008 (figure 14, bottom) would be associated with an increase of the in-situ Argo data variability, which is not explained. An evolution in the data processing could be an explanation and should be checked. Another possibility is that Dynamic Height Anomalies are computed with a reference over 2003-2008 (cf previous section). Latest data are likely to be out of this mean and thus could make the standard deviation increase as observed. An adaptation of the reference period used for DHA computation could validate this hypothesis. The use of a longer reference period is planned in 2011.

Moreover, regression coefficients providing the relationship between steric and total part of the water column were determined with altimetric measurements over a period while these data had a given and known bias compared with a Mean Sea Surface (MSS). And we use these coefficients over a different period (mid 2004 / 2010) while altimetric data have a different bias compared with the MSS (because the period is different). This discrepancy between the period while the coefficients were computed and the one while they are used may thus impact the variance of SLA-DHA differences. Nevertheless this impact is estimated to be weak and it would not be the only responsible of the observed increase on figure 14 (bottom).

What is more Jason-1 has changed of orbit since cycle 260 (Feb. 2009) and has moved to its inter-track. The MSS used for the computation of the SLA is thus of less quality on these new tracks (since less data were available for its determination). It could generate an increase of the standard deviation of the SLA-DHA differences at this time but it is not observed (not shown). It must be associated with the fact that before colocation to in-situ data, altimetry measurements are averaged over 1°x3° boxes and the change of orbit is thus filtered. This expected jump is detected while comparing Jason-1 with tide gauges measurements (see annual report of the activity, [16]) since altimetry is colocated to the instruments without any filtering.

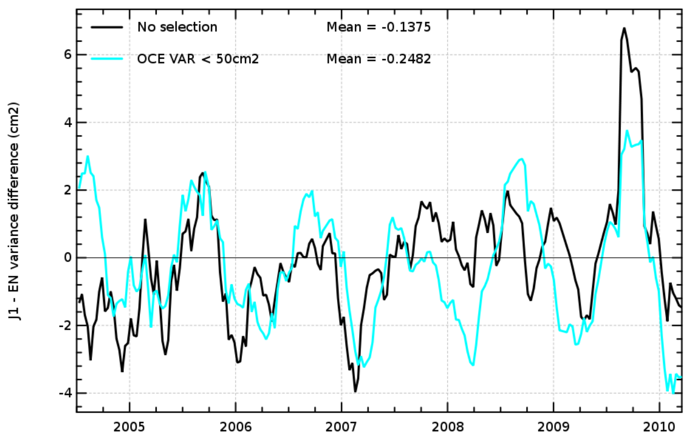


Figure 15: *Difference between Jason-1 and Envisat of the 2 months filtered variance of SLA-DHA differences over the global ocean (black curve) and with restriction to low ocean variability areas (EKE < 50cm2) (blue curve).*

In order to assess which mission is more coherent with in-situ data over the period we show on figure 15 the $J1-EN$ difference of the variance differences $(VAR(SLA_{J1}-DHA)-VAR(SLA_{EN}-DHA))$ (black curve). The mean of -0.1 cm^2 over the period of almost 6 years is not significative enough to asses which mission is more coherent with Argo data. But our method (colocation of both types of data) is less accurate in areas of strong ocean variability (in this case, we compare data which may have been acquired with several days interval and thus be significantly different in these areas) and in order to exclude these areas diagnostics over low ocean variability areas are performed (figure 15, blue curve). The slight decrease of the mean value (-0.2 cm^2) is in favour of a higher coherence of Jason-1 data with in-situ data over the period but it still remains very little significative compared with the uncertainty of the method.

We have investigated whether a regional selection (with thresholds on the regression coefficients) affect the annual signal observed. Indeed weak coefficients (close to 0.0) are associated with areas where the total and steric parts of the water column are different and the complementary part is associated with the mass field signal (which is not seen by Argo floats). Figure 16 shows the monitoring of the variance differences between Jason-1 and Envisat with selection on different values of the regression coefficients [4]. It indicates that the phase of the signal is not changed while the coefficient gets higher, which means that the observed annual signal is not due to this mass field. The use of homogeneized altimetric standards for the computation of Envisat SLA in the future should help to better understand this signal.

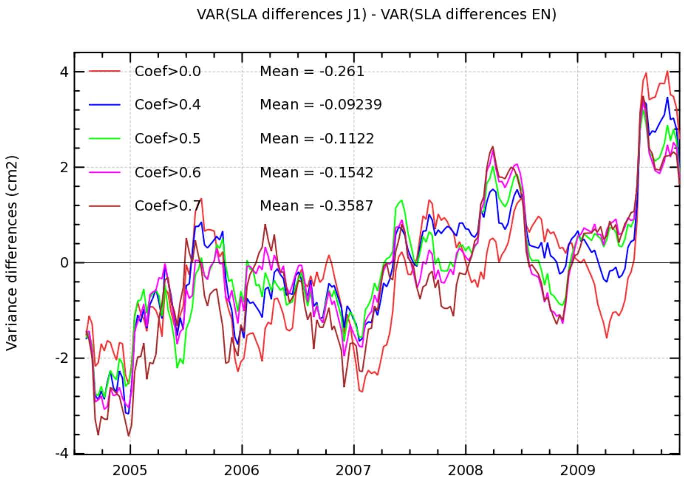


Figure 16: *Difference between Jason-1 and Envisat of the 4 months filtered variance of SLA-DHA differences with selection on different values of the regression coefficients.*

4.2.2. Spatial analyses

Maps of the variance of the SLA-DHA differences for Jason-1 and Envisat missions with the same temporal references over the 2004-2010 period. Spatial distributions are very similar for both missions and high values ($> 80\ cm^2$) are observed in regions of strong ocean variability (Gulf stream, Kurushio, Agulhas current and Antarctic circumpolar current). It is directly associated with the uncertainty of the method since the colocation of both types of data is less accurate in these regions

[4] note that the red curve (no selection) is not strictly the same as the black one on figure 15 because of a different filtering

of high oceanic variability.

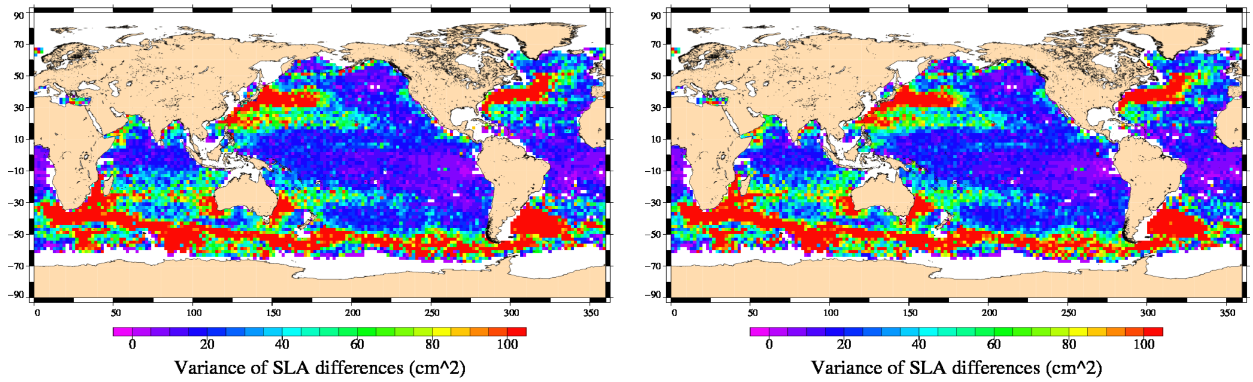


Figure 17: *Map of the variance of the SLA-DHA differences over the total water column with the same temporal reference over the period 2004-2010 for Jason-1 (left) and Envisat (right).*

In order to assess which mission is spatially more coherent with in-situ data, we show on figure 18 (left) the variance difference of SLA-DHA differences between Jason-1 and Envisat, which is:

$$\Delta VAR(SLA)_{Alti} = VAR(SLA_{J1} - DHA) - VAR(SLA_{EN} - DHA)$$

Negative values indicate that Jason-1 measurements are more consistent with in-situ Argo profiles than Envisat mission. It is associated to the mean of the variance timeseries in each box of the map [5]. A strong random signal dominates in regions of strong ocean variability. In order to exclude colocation errors of the method in these regions, the same diagnostic with restriction over areas of low variability is shown on the right of the figure with a reduced dynamic of the colorbar. Values are slightly more negative but no region of major improvement is clearly observed. Note that errors associated with the colocation of data of each mission are added in this computation which explains the relative improvement. The difference of spatial and temporal sampling of both missions generate slight differences between these errors of colocation which increase the difference of variance and limits the detection of an improvement of the coherence for one of the two missions. Note that with the same diagnostic for a single mission but with different altimetric standards, the error of colocation is cancelled which gives more confidence in the analyzed variance differences.

4.3. Use of in-situ data to detect altimetric anomalies

We discuss here the interest of comparing altimetry with in-situ Argo profiles to detect anomalies on altimetric measurements.

4.3.1. Regional discrepancies of Envisat and Jason-1 MSL

The map of the MSL trend differences between Jason-1 and Envisat missions underline a strong east/west discrepancy (figure 19, left) with a regional amplitude of +3 mm/y over the on eastern

[5] which is different than the monitoring of figure 15 which is the monitoring of the spatial variance averaged over 10 days cycles

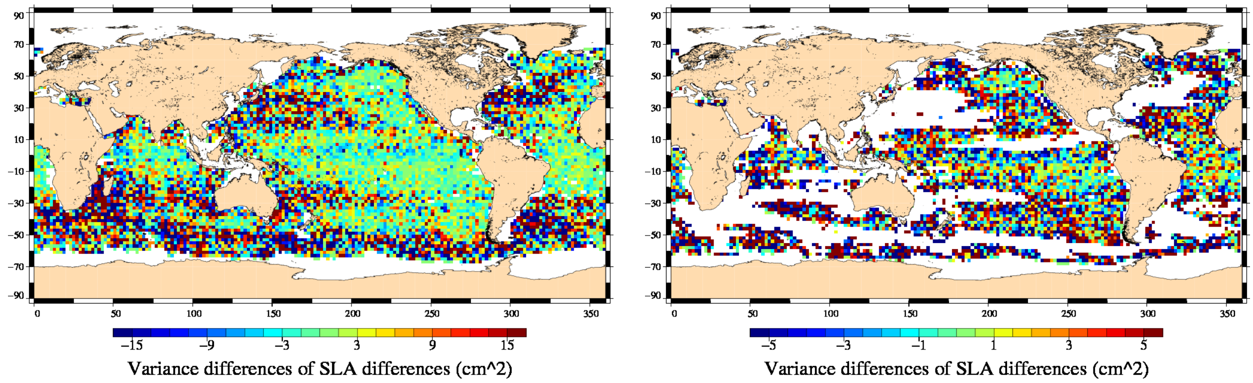


Figure 18: *Map of the variance differences of SLA-DHA differences between Jason-1 and Envisat over the global ocean (left) and with restriction to low ocean variability areas (EKE < 50cm2) (right).*

part of the global ocean (0°, 180°) and -3mm/yr over the western part (180°, 360°). This strong longitude dependence displays a sinusoidal shape (figure 19, right).

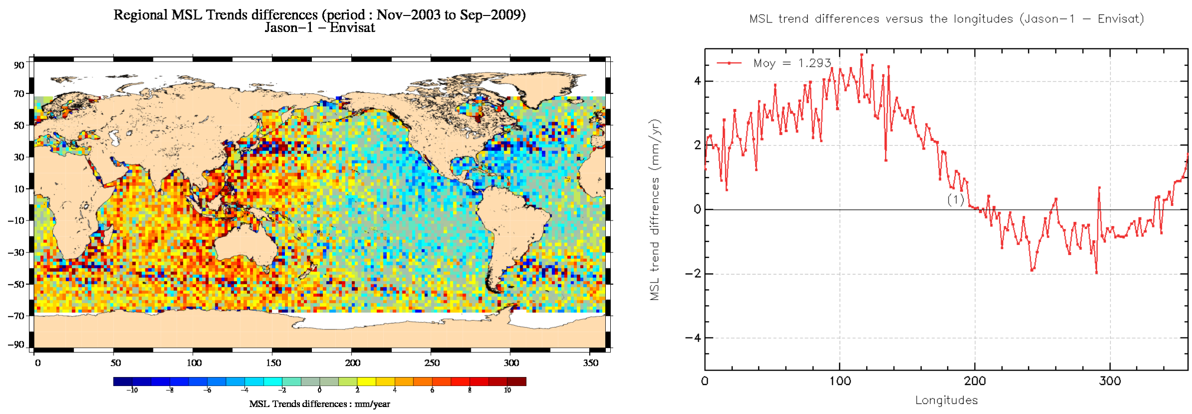


Figure 19: *Map of the MSL trends differences between Jason-1 and Envisat over the period Nov. 2003 - Sep. 2009 (left, range varies from +/-10mm/y) and associated mean per longitude (right).*

In order de determine whether Envisat or Jason-1 MSL trend is closer to the real evolution, we compare these trends with the one obtained with in-situ measurements of the Argo network of profiling floats since it provides independant measurements over the global open ocean. We compute altimetric SLA - in-situ DHA differences with Envisat and Jason-1 separating eastern (0° / 180°) and western (180° / 360°) part of the ocean (figure 20). We observe that the eastern / western drifts are more homogenous comparing Jason-1 and Argo T/S profiles than comparing Envisat and Argo T/S profiles: 1.9 mm/y difference for Jason-1 and 5.7 mm/y difference for Envisat. This probably demonstrates that the eastern / western regional differences observed between Jason-1 and Envisat is mainly due to the Envisat MSL. It could be in relationship with the orbit determination and espacially the time varying gravity fields which may affect Envisat MSL trend and this is under investigation. Note that this analysis is a good example that the in-situ Argo network is well adapted for such study since it constitues an independant dataset and the possibility to discuss relative drifts (here between different altimeters and different geographical areas) enables us to detect anomalies and to assess where does it come from.

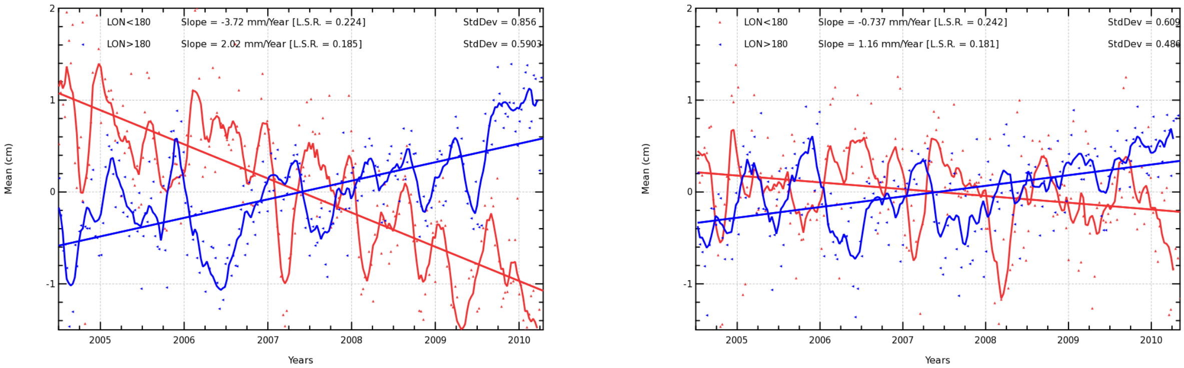


Figure 20: *Mean differences of the SLA - DHA differences over east (0°/180°) and west (180°/360°) for Envisat (left) and Jason-1 (right) missions. The slope differences between both hemispheres is of 5.7 mm/y for Envisat and 1.9 mm/y for Jason-1.*

4.3.2. Detection of instrumental anomaly

An abnormal jump has been detected in the MSL differences between Envisat and Jason-1 missions in September 2008 (see the blue curve of figure 21). In order to determine whether this anomaly comes from Jason-1 or Envisat mission, we compare altimetric SLA with in-situ DHA and it enables us to observe and quantify the impact of this anomaly on the Envisat MSL (red curve of figure 21) which is about 5 mm. The monitoring of instrumental corrections of Envisat (green curve) reveals the anomaly. It has been observed similarly while comparing altimetry with tide gauges measurements. This analysis demonstrates the ability of these comparison methods to reveal small jumps on the altimetric MSL.

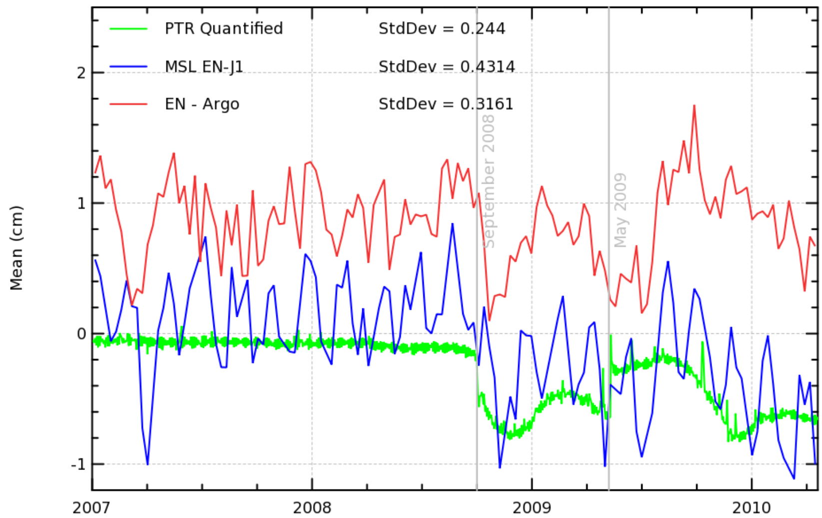


Figure 21: *Monitoring of the Envisat quantified PTR compared with the Envisat - Jason-1 MSL difference and the Envisat SLA - DHA difference*

5. Evaluation of new altimetric standards and versions

5.1. Overview

One of the objective of the method of comparison of altimetry with Argo in-situ measurements consists in the evaluation of the potential improvements in the altimeter standards. For this we estimate the evolution of the coherence of altimetry with in-situ data brought by new altimetric standards such as new geophysical correction, new orbit or new algorithm or version of products. The evaluation of the consistency with in-situ data is estimated by using successively new and old standards with the following computation:

$$\Delta VAR(SLA) = VAR(SLA_{NewStandards} - DHA) - VAR(SLA_{OldStandards} - DHA)$$

Negative values of $\Delta VAR(SLA)$ indicates that the new standards improve SSH computation. We analyse monitoring of this statistic in order to detect evolutions brought by these new standards. Others diagnostics contribute to the evaluation of the improvement such as the map and histogram by floats of $\Delta VAR(SLA)$ and periodogram of the SLA-DHA differences.

According to this method, GDR-C orbit has been compared with GDR-B orbit for Jason-1 and Envisat missions (see 2009 annual report [9]). In 2010, we have used this approach to qualify the new version of the DUACS delayed time products generated this year and also to assess the impact of using the radiometric or modelled wet tropospheric correction in the altimetric sea level computation.

5.2. Evaluation of 2010 version of Duacs DT products

We have shown in previous annual report (see [9]) that the coherence with in-situ Argo profiles is much higher with Duacs merged delayed time products rather than with mono mission data. Indeed the use of merged data from several missions with higher sampling significantly reduces the error of colocation between the two types of data.
Here we compare the new version of the Duacs delayed time (DDT) products generated in 2010 (see Duacs annual report [14] and OSTST10 poster [13]) with previous version. First of all, we compare the monitoring of the altimetric SLA - in-situ DHA difference with both versions of DDT products with Jason-1 and Envisat missions over the mid 2004 - mid 2009 period (figure 22). Jason-1 is the reference mission in Duacs over the studied period. Standard deviation of all series are similar (0.3 cm) and slightly lower with merged products. Slopes associated to both versions of DDT products are similar (0.8 mm/y and 0.9 mm/y) and are almost identical to the one of Jason-1 (0.7 mm/y). Using Envisat data, the slope is slightly reduced (-0.2 mm/y) but we considered that the differences between all these values are not significative. It suggests that 2010 version of DDT products should remain very close to previous version with reference to open ocean data of Argo in-situ profiles.

The monitoring of the SLA - DHA difference with both versions over the 2004 - mid 2009 period (figure 23, left) confirms the similar behaviour observed over the period with both versions of DDT

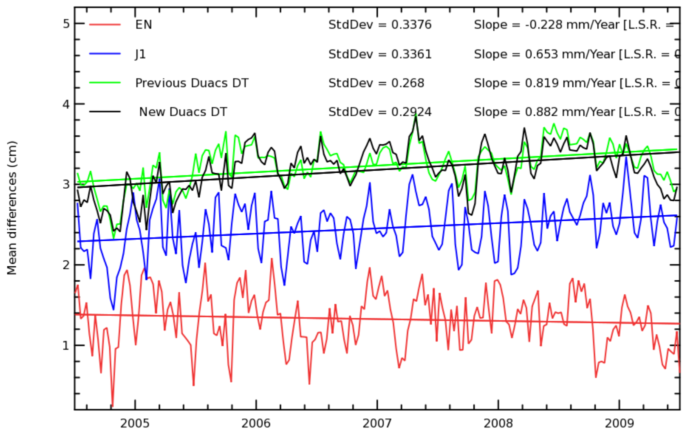


Figure 22: *Altimetric SLA - in-situ DHA for version 2010 of Duacs DT products, previous version, and for Jason-1 and Envisat missions over the period mid 2004 - mid 2009. Semi annual and annual signals from Jason-1 timeseries are removed and data are not centered.*

compared with in-situ data. The same evolution is observed and the slope difference is not significative. The monitoring of standard deviation of the differences (figure 23, right) also indicates very similar evolution between both versions with the same mean values over the period (5.6 cm). Decreasing values are observed until 2008 and standard deviation increases since then. Note that the same evolution is detected while comparing a single mission with in-situ data (cf figure 14). The use of a longer period of reference to compute heights anomalies is planned for 2011 and should help to better understand the results.

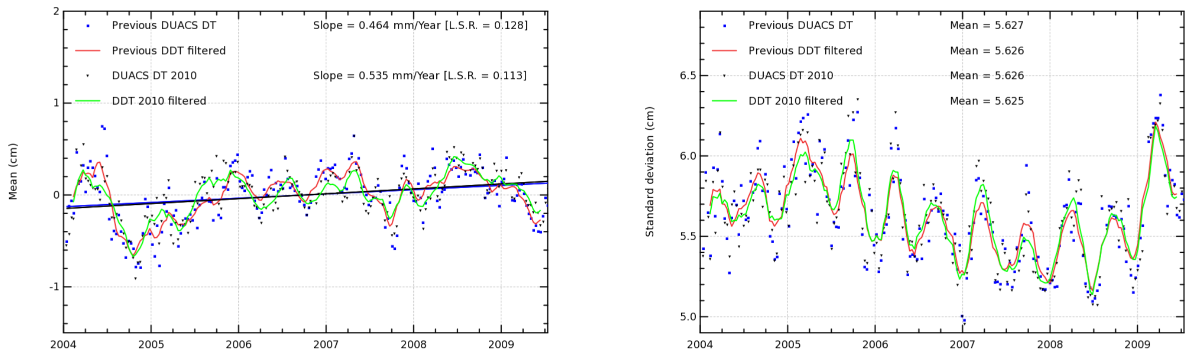
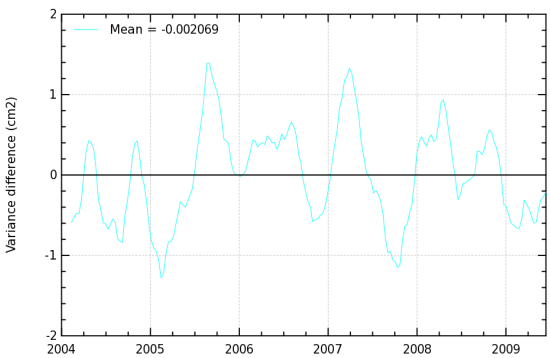


Figure 23: *Mean (left, same as figure 22) and standard deviation (right) of the SLA - DHA differences for version 2010 and previous version of Duacs delayed time products over the period 2004 - mid 2009. Semi annual and annual signals from Jason-1 timeseries are removed and the slope is indicated for the mean difference. Two months filtered signals are shown.*

In order to assess which version of DDT products is better, we analyse the temporal ans spatial evolution of the coherence with Argo in-situ profiles, which are used as an independant reference over the open ocean. This coherence is estimated according to:

$$\Delta VAR(SLA)_{Alti} = VAR(SLA_{DDTNew} - DHA) - VAR(SLA_{DDTOld} - DHA)$$

Negative values are associated with an improvement of the coherence with new version and positive values with a degradation. Temporal evolution of this quantity is shown on figure 24 (left). It reveals alternatively negative and positive values with a null global mean over the period and the signal varies between $\pm 1\ cm^2$ which is not significative. As the error of the method is increased in high ocean variability areas ($> 50\ cm^2$), we removed these values as shown on figure 24 (right). Nevertheless no major change is observed and this timeseries does not reveal any significant evolution obtained with the new version. The amplitude of the signal ($\pm 1\ cm^2$) is within the noise level of the method which explains why no evolution is detected even when high variability areas are removed. Moreover the improvement of the new version may be locally significative but the global average reduces the possibility of observing such regional evolution.



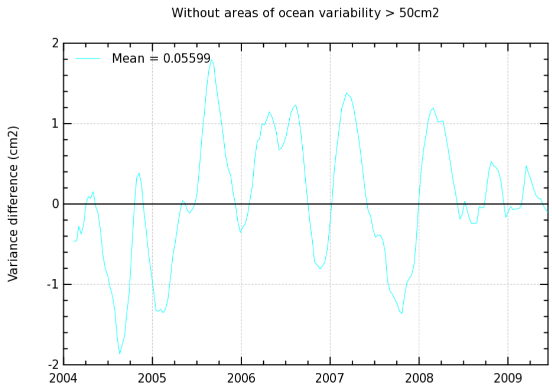


Figure 24: *Variance differences of the SLA - DHA differences between version 2010 and previous version of Duacs DT products over the global ocean (left) and restricted to low ocean variability areas ($< 50cm^2$) (right).*

In order to detect potential regional improvement with the new DDT products, we show on figure 25 the spatial distribution of the quantity $\Delta VAR(SLA)_{Alti}$ over the global open ocean (left). Relatively strong random values are observed in regions of high ocean variability and without these areas (right) and with a zoom of the colorbar, different regions are distinguished. No evolution (or even light degradation) is observed in the north subpolar Atlantic and in the south west Pacific. On the contrary a slight improvement of the coherence with in-situ data is detected with the new Duacs version in the equatorial and subtropical south Atlantic, in the south east Pacific and espacially in the north Indian ocean where the variance is reduced by more than 2 cm^2. The map of the number of available Argo profiles over the period (see figure 2) shows a significative number of measurements in this latter region which increases our confidence in these results. Moreover these results will be compared with the evolutions performed in 2010 Duacs DT products which may not be homogeneous in all ocean basins.

At last, we investigate the impact of the new Duacs version on a frequency basis with periodograms which can help to detect the impact of a new altimetric standard at a given periodic signal such

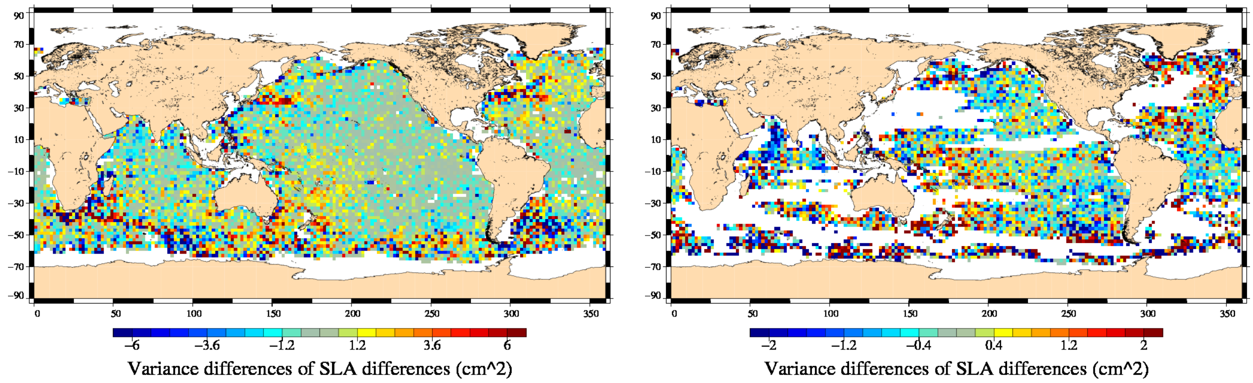


Figure 25: *Difference of variance maps of the SLA - DHA differences between version 2010 and previous version of Duacs DT products over the global ocean (left) and restricted to low ocean variability areas ($< 50cm^2$) (right).*

as annual signal. Periodograms of the altimetric - in-situ DHA are computed with new and old versions of DDT products and figure 26 shows the difference between the two periodograms. Main differences between the two versions concern semi annual (180 days) and annual (365 days) signals (which are the strongest signals observed by altimetry) but amplitude of these differences remains extremely small (0.5 mm) which is not significative and confirms that the 2010 version of DDT products brings little evolution compared with in-situ Argo data.

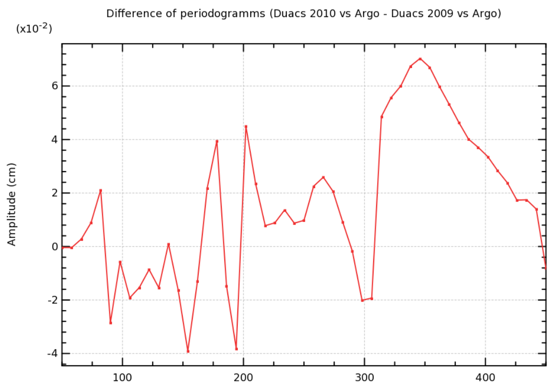


Figure 26: *Periodograms difference of the SLA - DHA differences between version 2010 and previous version of Duacs DT products.*

Conclusion of the study:
The comparison of previous and 2010 versions of Duacs delayed time products with Argo in-situ measurements has shown that no jump or bias has been introduced in the new version. It indicates that despite the high number of available in-situ data over the studied period, the improvement of the coherence with Argo measurements remains relatively weak. Whereas no evolution is temporally observed over 2004-2009, significative improvement (up to 2 cm^2) is detected in some regions such as the north Indian ocean. We associate these results to the fact that the impact of the evolutions performed in 2010 version of Duacs DT products is relatively weak in the open ocean as seen by Argo floats (see OSTST10 poster [13]) and drifts differences in these areas between

both versions and in-situ data are thus not significative. And potential regional evolutions in the products are smoothed while analyzing global timeseries and are thus not detected. Moreover the resolution of Duacs DT products (1/3° / 7 days) is higher than the one of in-situ data (one profile / 10 days for the 3 000 discrete floats) which makes difficult to detect small scales evolutions.

5.3. Impact of the use of radiometric or modelled wet tropospheric correction on the SLA computation

A study has been performed in 2010 aiming at qualifying the atmospheric water vapor products used for the mean sea level estimation (see OSTST 10 presentation [11]). Indeed water vapor is a climate variable itself and has a direct impact on the MSL. The impact of estimating water vapor content from JMR, MWR radiometers or from ECMWF model has been analyzed (figure 27) and in the context of this study, we have compared altimetric SLA and in-situ DHA with the use of radiometric or modelled wet tropospheric correction.

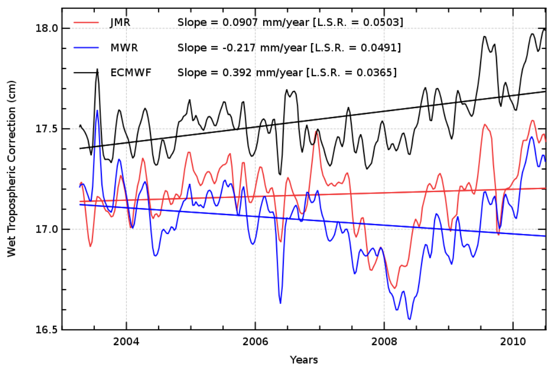


Figure 27: *Monitoring of the filtered wet tropospheric correction (absolute value) from JMR, MWR and ECMWF model (sampled by Envisat) with adjustment of the semi annual and annual signals from J1 and EN with restriction on J1 spatial coverage. Arbitrary bias is used to compare datasets.*

There is a major difficulty to obtain accurate time series of atmospheric vapor content and the associated uncertainty impacts directly the estimation of the global MSL trend since it is the main source of error in the MSL computation. Monitoring of the wet tropospheric correction (figure 27) indicates that drift and jumps are detected on radiometer corrections. Moreover models (renalyses included) do not well represent the inter-annual variability (see the dryness event in 2008).

Figure 28 shows the SLA - DHA differences with radiometric or modelled wet tropospheric correction for Jason-1 (top left) and Envisat (bottom left). Both curves show similar behaviours in the case of Jason-1 which would suggest that radiometer and model are coherent as seen at in-situ data location. Drifts between altimetry and in-situ data are computed over almost 6 years and the slope differences with the use of radiometer or model are of +0.5 mm/y for Jason-1 and +0.4 mm/y for Envisat. The drift itself between altimetry and in-situ data is smaller with the radiometer for Jason-1 but it is smaller with the model for Envisat. No major jump is detected between altimetry and in-situ measurements.

Regional analyses (not shown) indicate that difference of behaviours between radiometers and

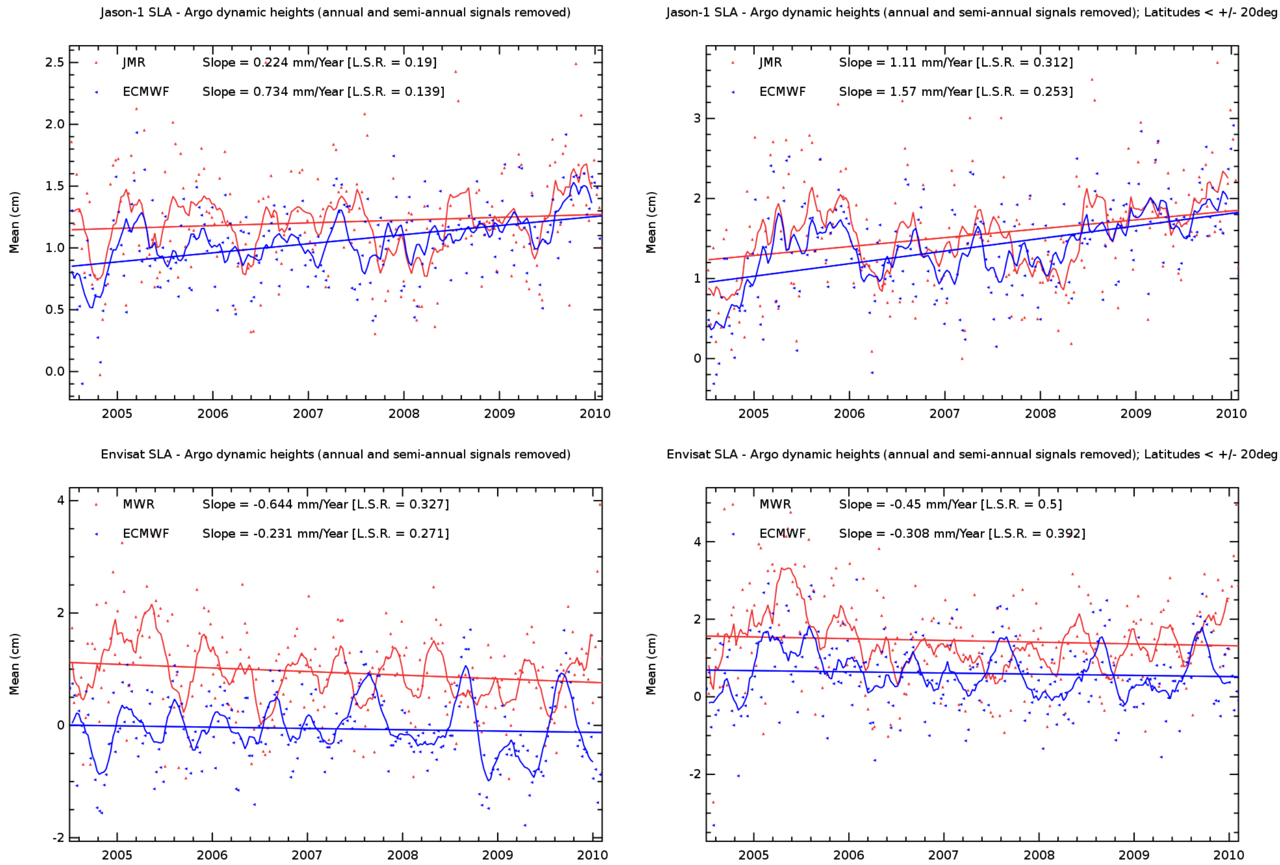


Figure 28: *Altimetric SLA - in-situ DHA difference with the use of radiometric and modelled (ECMWF) wet tropospheric correction over the global ocean (left) and restricted to low latitudes ($< 20°$) for Jason~1 (top) and Envisat (bottom). Semi-annual and annual signals (combined from both radiometer and model) are removed and 3 months filtered signals are indicated.*

ECMWF model are mainly located at low latitudes. We thus perform the same analysis with restriction on latitudes ($< \pm 20°$, see figure 28, top and bottom right). The slope difference with the use of radiometer or model remains at +0.5 mm/y for Jason-1 and decreases at +0.2 mm/y for Envisat. Selection of low latitudes has almost no impact on drifts values concerning Envisat whereas they are increased for Jason-1 with both types of correction. As far as the dryness event of 2008 is concerned, a difference is observed globally with Envisat between the use of model or radiometer, which confirms that the former doesn't see the same inter annual variability as the latter, colocated to in-situ data. Nevertheless, this event generates variation of wet tropospheric correction of about 0.4 cm (see figure 27) which is smaller than the amplitude of observed signals when restricted to low latitudes (about 1.5 cm) which makes difficult to detect such event by comparison with in-situ data.

Moreover, comparison with Argo data (in the open ocean) shows linear trend a bit higher than when comparing with tide gauges measurements (which are provided in coastal areas). This would suggest that the evolution of the wet troposphere varies spatially. Comparison of altimetry with Argo data confirms that the use of radiometric or modelled wet tropospheric correction has an impact on the MSL drift and in terms of inter annual variability. Depper analysis should be performed in order to assess which correction improves the coherence with Argo in-situ data.

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6. Conclusions

We have described in this report the validation of altimetric data by comparison with in-situ profiles of the Argo network. Improvements of the past years of the in-situ database and of the processing chain have provided analyses of better quality in an operationnal framework as classical calibration and validation processing chains of altimetric missions. This operationnal aspect of the activity is essential in order to operate systematic analyses of reprocessed altimetric data and thus make this activity durable.

The method of comparison of both data has been improved in 2010 with the use of a common temporal reference to compute altimetric sea level anomalies and in-situ dynamic heights anomalies. It significantly reduces regional biases observed on maps of the mean differences. It also impacts slopes of these mean differences which are increased compared with previous results.

As far as drifts between altimetry and in-situ data are concerned, we have mentionned that the relatively short period of study (6 years) generates a significative uncertainty (0.5 mm/y) on the slope of the in-situ DHA monitoring. If uncertainty on the slope of altimetric SLA is considered negligeable, uncertainty on the slope of the mean differences is of the same order. A longer period will reduce this uncertainty in the future and will provide more accurate results. Moreover the method could be improved with the use of adapted regression coefficients which give the relationship between the total and steric part of the water column (between altimetry and in-situ data). They should be estimated with altimetric standards and over a period in adequation with the period of study. Nevertheless, our method becomes of great use when discussing of relative drifts. Indeed we managed to detect regional heterogeneities with a strong east/west discrepancy between Envisat and Jason-1 MSL trends and the comparison of both missions with in-situ data in each hemisphere allowed us to assess that the anomaly comes from Envisat mission and is probably associated with orbit determination. Moreover our method has also provided evidence of a jump on the altimetric MSL associated with an instrumental anomaly (PTR) on Envisat mission. This demonstrates the ability of our method to detect drift and jump in altimetric measurements.

Comparison of in-situ DHA with altimetric SLA with Topex-Poseidon, Jason-2, Jason-1 and Envisat data over the period 2004-2010 has shown a good coherence between these altimetric missions, which confirms global calibration and validation of each mission. The use of independent in-situ Argo T/S profiles enables us to analyse the quality of new version of altimetric products or new standards by estimating the evolution of the coherence with in-situ profiles. We have compared new version of DUACS delayed time products of 2010 with the previous one and shown that there is no significant impact in terms of drifts but regional improvements are observed with the new version in some areas as the north Indian ocean. The method has also been used to discuss the impact of using radiometric or modelled wet tropospheric correction in the altimetric SLA computation and deeper analyses should be performed in this subject. This approach should be adapted in the future to assess the quality evolution of the entirely reprocessed Envisat data in version 2 which has started at the end of 2010.

The activity of comparison of altimetry with in-situ Argo measurements is now operational and has been used in the framework of various studies. Nevertheless the method still needs to be improved and the evolution of the database with more data will contribute to produce more and more accurate results and to better qualify altimetric missions. In 2011 several evolutions and developements of the method are planned concerning the empirical regression coefficient grid, the geographical selection, the developement of new comparison diagnostics such as periodograms in order to estimate an impact in frequency terms, the improvement of the interpolation method and investigation on the use of the ocean mass component. Moreover the reference period to compute height anomalies has been limited to 2003-2008 and a longer period will be implemented. What is more the method will be used in the frame of various activities in 2011 (CCI...) which will constitute opportunities of improvements.

Finally, this work has been presented this year at the ESA Living Planet Symposium in Bergen ([2]) and at the OSTST in Lisbon ([1]).

7. Références

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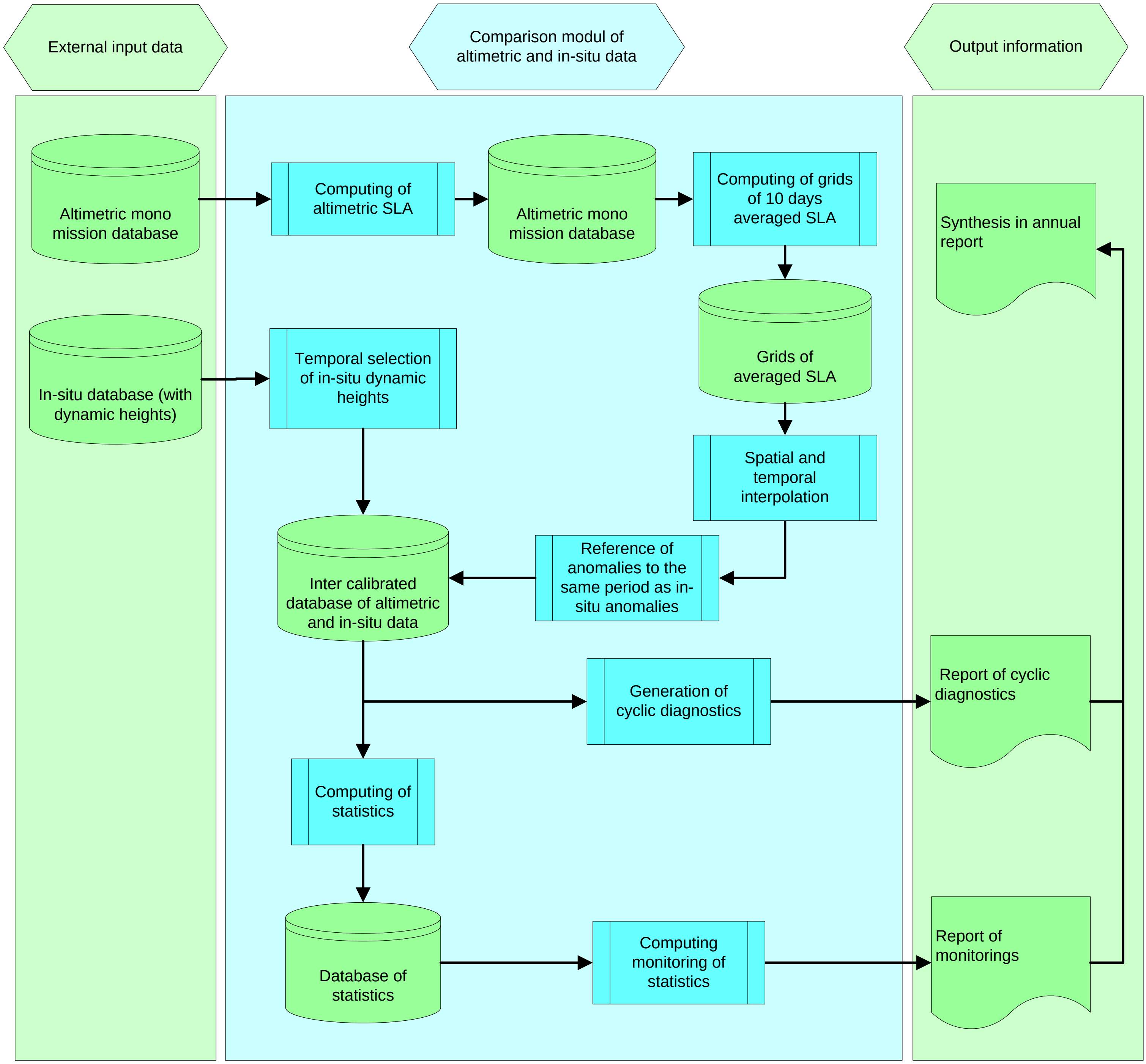
8. Annexes

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: Synthesis of in-situ and altimetric measurements comparison activity

Cross-comparisons of Sea Surface Height derived from In-Situ and Altimeter measurements

M. Ablain, G. Valladeau, J.F. Legeais

Overview

- This study is supported by ESA for Envisat and CNES for TOPEX/Poseidon, Jason-1&2 altimeter in the frame of the SALP project.

- The objective of this study is to compare the Sea Surface Height (SSH) derived from altimetry and In-Situ measurements in order to :
  - Monitor the SSH bias between altimeter and external independent in-situ measurements in order to detect potential drift or jumps in altimeter MSL
  - Estimate improvements of new altimeter standards in the SSH calculation
  - Detect potential anomalies in in-situ datasets

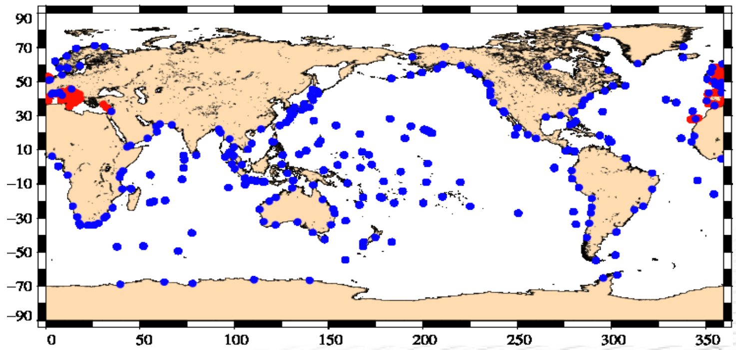
- In-situ data used are:
  - Tide gauges from global network (GLOSS/CLIVAR) and regional network (SONEL)
  - Temperature and Salinity profiles from ARGO data

- Here, we are focusing on main results concerning the altimetric and in-situ SSH comparisons.

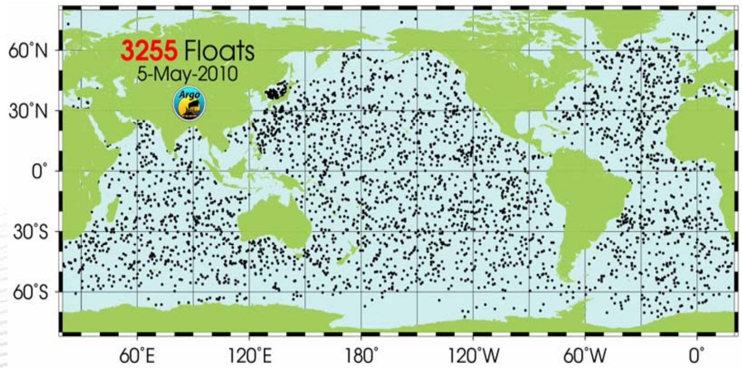
In-situ datasets and methodology

Description of in-situ datasets

- The main tide gauge network used is GLOSS/CLIVAR with a global coverage over all the altimeter period from 1992 onwards and with more than 300 tide-gauges. Regional networks as SONEL is also used
- Concerning T/S profiles, ARGO data are available from 2002 onwards with more than 3000 profiles available since November 2007.
- Both data are complementary since tide gauges provide a very good temporal sampling (hourly) but a poor spatial sampling with data only close to the coasts, whereas ARGO data are very well spread out over the open ocean but with only a 10-day sampling.



- GLOSS/CLIVAR (blue dots) and SONEL networks (red dots): about 400 tide gauges



- Global comparison from mid 2004 with more than 3000 profiles and 80% of ocean surface covered

Methodology to compare tide gauge and altimetry SSH

- The comparison method is composed of the following steps :

⇒ Calculation of the altimeter and tide gauge SSH applying DAC and tidal corrections, MSS

⇒ Colocation of altimeter and in-situ data selecting the altimeter the best correlated time data series with tide gauge one (within a maximal distance)

⇒ Calculation of SSH differences at each tide gauges after removing colocated time data series which are not well correlated enough (due geophysical processes, jump in tide gauges) and too short tide gauge time data series

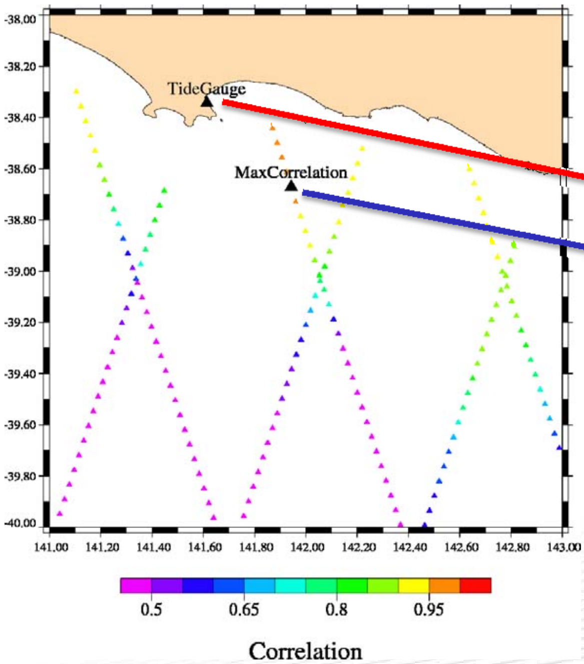
⇒ Computation of the altimeter SSH drift from all the remaining time data series (after editing)

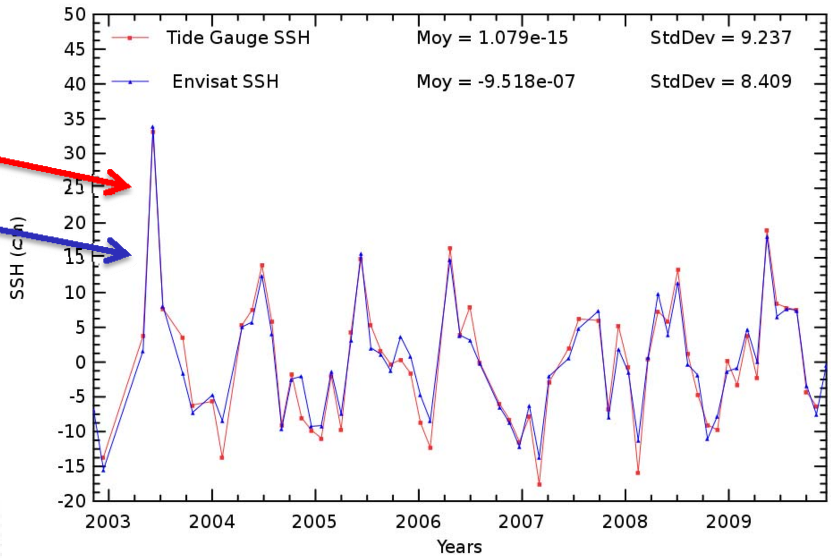
- More information are available on AVISO website :

http://www.aviso.oceanobs.com/fileadmin/documents/calval/validation_report/insitu/annual_report_insitu_2009.pdf

CLS

Methodology to compare tide gauge and altimetry SSH





Methodology to compare T/S profiles and altimetry SSH

- Altimeters measure the total height of the water column (mass and steric parts) whereas T/S in-situ profiles only measure the steric part

  ⇒ need to use of regression coefficients to extrapolate the steric content of T/S profiles to the total water column

  ⇒ Spatial / temporal interpolation between in-situ profiles and 10-days mean gridded altimeter data (to provide sufficient spatial density of data)

  ⇒ Global statistics and coherence analyses between two types of data

- More information are available on AVISO website :

http://www.aviso.oceanobs.com/fileadmin/documents/calval/validation_report/insitu/annual_report_insitu_TS_2009.pdf

Estimation of the global MSL drift

Jason-1 SSH calculation : altimetry standards applied

- Jason-1 GDR products have been used and last and homogenous altimetry standards have been applied in order to improve the Jason-1 SSH calculation.

SSH Field Name	Altimetry Standards
Orbit	CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CLS01 (v1)
Dry troposphere	ECMWF model computed
Wet troposphere	Jason-1 radiometer (JMR)
Ionosphere	Filtered dual-frequency altimeter range measurements
Sea State Bias	Non parametric SSB (GDR product)
Ocean tide and loading tide	GOT4.7 (S1 parameter is included)
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]
Pole tide	[Wahr, 1985]
Combined atmospheric correction	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)
Specific corrections	Jason-1 / T/P global MSL bias

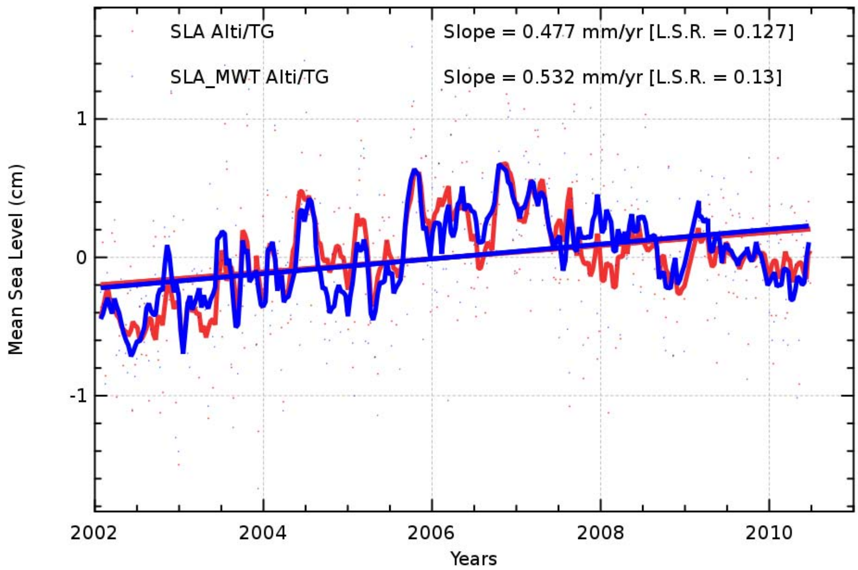
Global SSH drift between Jason-1 and tide gauges

- The global SSH drift between Jason-1 and tide gauges is 0.48 mm/yr from 2002 using the JMR wet tropospheric correction, with a formal adjustment error of 0.13 mm
- Using the ECMWF model wet tropospheric correction the global SSH drift is similar: 0.53 mm/year

- Although this method is reliable to estimate the SSH altimeter drift, the error of the method has to be taken into account: it is close to 0.5 mm/yr :

⇒ Crustal corrections not applied on TG

⇒ Colocation error between altimeter and TG data



Jason-2 SSH calculation : altimetry standards applied

- Jason-2 GDR products have been used and last and homogenous altimetry standards have been applied in order to improve the Jason-2 SSH calculation.

SSH Field Name	Altimetry Standards
Orbit	CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CLS01 (v1)
Dry troposphere	ECMWF model computed
Wet troposphere	Jason-2 radiometer (AMR)
Ionosphere	Filtered dual-frequency altimeter range measurements
Sea State Bias	Non parametric SSB (GDR product)
Ocean tide and loading tide	GOT4.7 (S1 parameter is included)
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]
Pole tide	[Wahr, 1985]
Combined atmospheric correction	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)
Specific corrections	Jason-2 / T/P global MSL bias

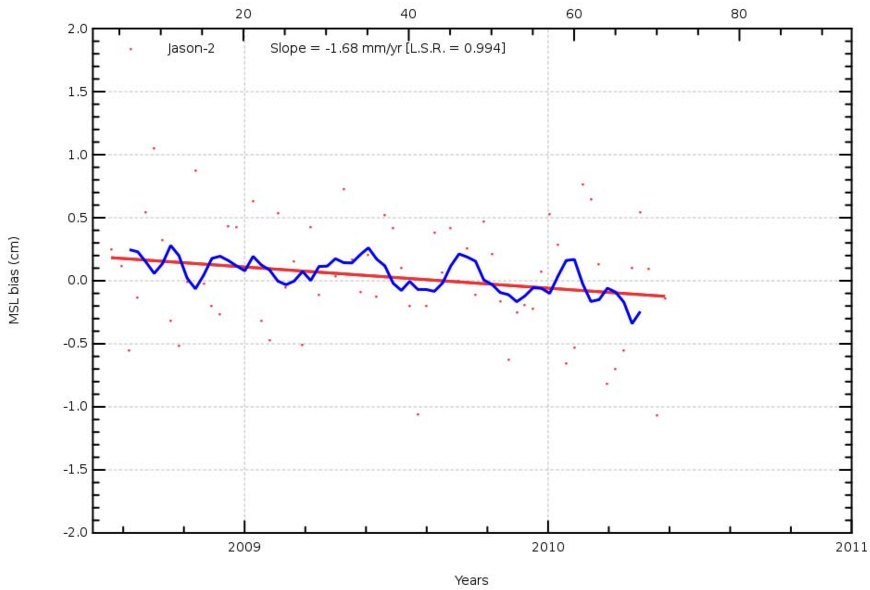
Global SSH drift between Jason-2 and tide gauges

- The global SSH drift between Jason-2 and tide gauges is -1.68 mm/yr from mid-2008, with a formal adjustment error of 1 mm
- The short time period considered implies a strong error on the global slope. However, these result has to be further studied to better understand the negative slope deduced from such analyses

- Although this method is reliable to estimate the SSH altimeter drift, the error of the method has to be taken into account: it is close to 0.5 mm/yr :

⇒ Crustal corrections not applied on TG

⇒ Colocation error between altimeter and TG data



CLS

Envisat SSH calculation : altimetry standards applied

- Envisat GDR products have been used and last and homogenous altimetry standards have been applied in order to improve the Envisat SSH calculation.

SSH Field Name	Altimetry Standards
Orbit	Cycle 15 onwards: CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CLS01 (v1)
Dry troposphere	ECMWF model computed
Wet troposphere	MWR (corrected from side lobes from cycle 41)
Ionosphere	Dual-Frequency Updated with S-Band SSB (< cycle 65) GIM model + global bias of 8 mm (>= cycle 65)
Sea State Bias	Updated homogeneous to GDR-B
Ocean tide and loading tide	GOT4.7 (S1 parameter is included)
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]
Pole tide	[Wahr, 1985]
Combined atmospheric correction	High Resolution Mog2D Model [Carrère and Lyard, 2003] + inverse barometer computed from ECMWF model (rectangular grids)
Specific corrections	USO correction from auxiliary files + bias for side-B

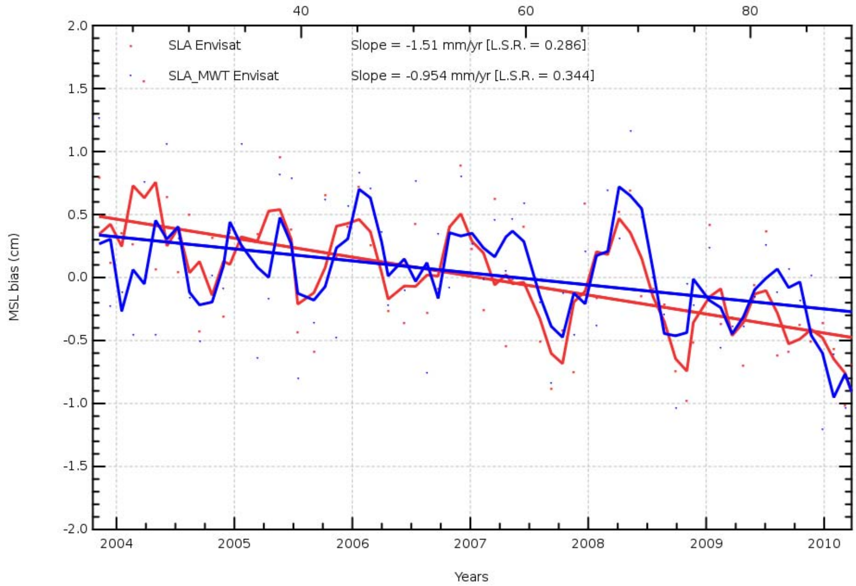
Global SSH drift between Envisat and tide gauges

- The global SSH drift between Envisat and tide gauges is -1.5 mm/yr from 2004, using the radiometer wet troposphere correction.
- Using the ECMWF one, the drift becomes -1 mm/year, with a slightly greater formal adjustment error (0.34 mm vs 0.29 previously).

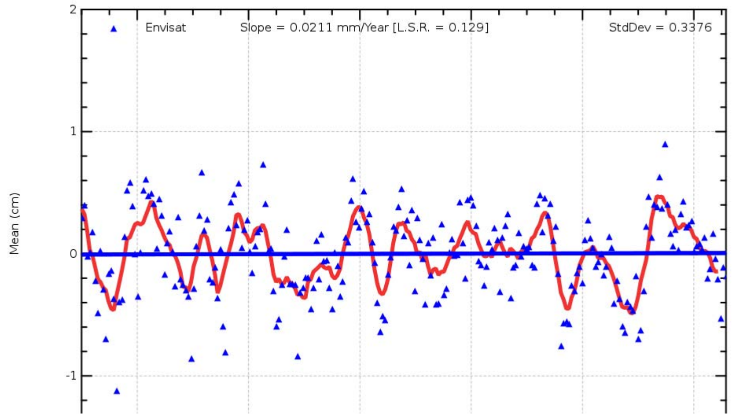
- Although this method is reliable to estimate the SSH altimeter drift, the error of the method has to be taken into account: it is close to 0.5 mm/yr :

⇒ Crustal corrections not applied on TG

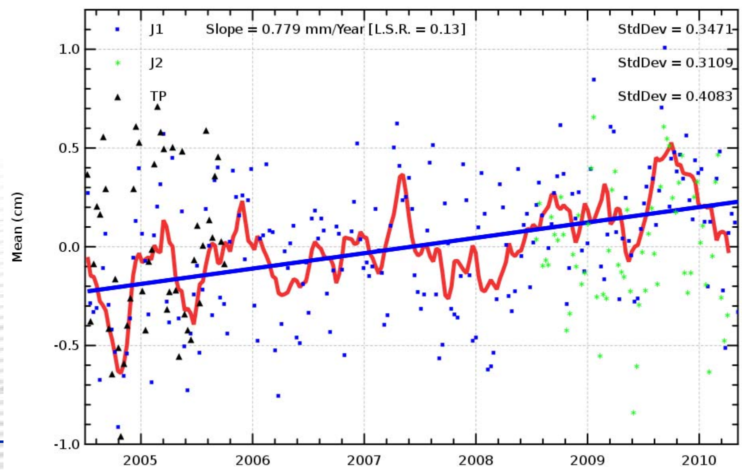
⇒ Colocation error between altimetry and TG data



Global SSH drift between Altimetry and T/S profiles



- The global SSH drift between altimeter data and T/S profiles has been estimate from mid-2004 with common temporal reference:
  - ⇒ For Envisat/TS : 0.0 mm/yr
  - ⇒ For Jason-1/TS: +0.8 mm/yr



- To date, the error of the method is likely higher than using TG: 0.7 mm/yr

⇒ Due to different physical content

- However, the drift obtained are in agreement with Altimeter/TG comparisons, with the same drift differences between Jason-1 and Envisat.

TOPEX/Poseidon SSH calculation : altimetry standards applied

- T/P homogeneous products have been used for the SSH calculation, especially with the new SSB correction from the 2-parameter Gourrion's method (SWH and Sigma-0)

SSH Field Name	Altimetry Standards
Orbit	GSFC POE (09/2008), ITRF2005+Grace
Mean Sea Surface (MSS)	MSS CLS01 (v1)
Dry troposphere	ECMWF model computed
Wet troposphere	TMR with drift correction [Scharoo et al. 2004] and empirical correction of yaw maneuvers [2005 annual validation report]
Ionosphere	Filtered dual-frequency altimeter range measurements (for TOPEX) and Doris (for Poseidon)
Sea State Bias	Non parametric SSB (for TOPEX), BM4 formula (for Poseidon)
Ocean tide and loading tide	GOT4.7 (S1 parameter is included)
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]
Pole tide	[Wahr, 1985]
Combined atmospheric correction	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

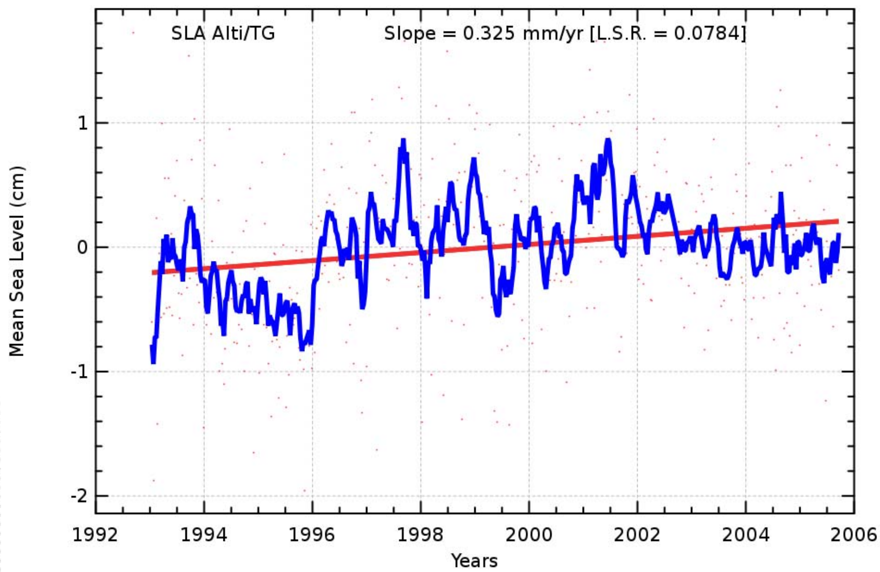
Global SSH drift between TOPEX/Poseidon and tide gauges

- The global SSH drift between T/P and tide gauges is 0.32 mm/yr with a formal adjustment error of 0.08 mm
- A strong negative drift appears on the TOPEX-A time period between 1994 and 1996 since the new SSB correction. This result will have to be investigated.

- Although this method is reliable to estimate the SSH altimeter drift, the error of the method has to be taken into account: it is close to 0.5 mm/yr :

⇒ Crustal corrections not applied on TG

⇒ Colocation error between altimeter and TG data



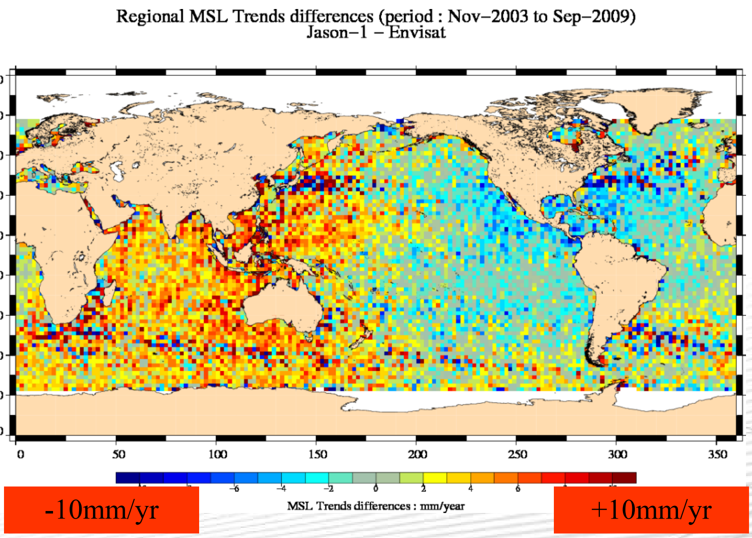
2010 investigations

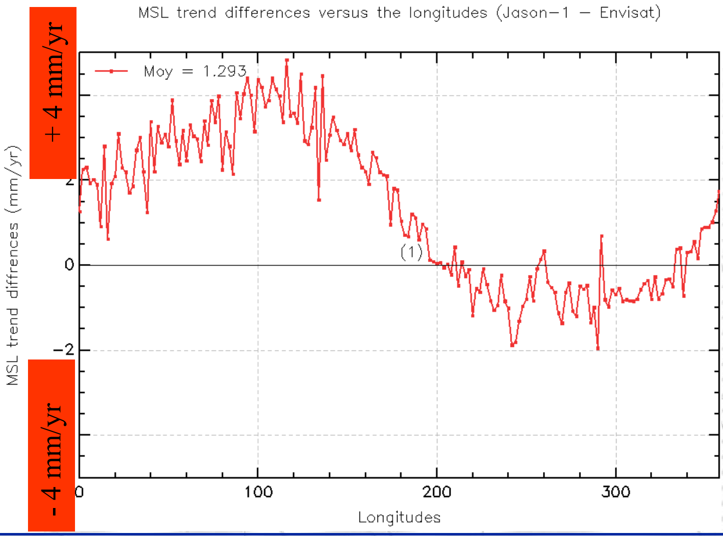
Envisat/Jason-1 regional MSL discrepancies

- Regional MSL trend differences between Jason-1 and Envisat underline East/West discrepancies :

⇒ +/- 3 mm/yr

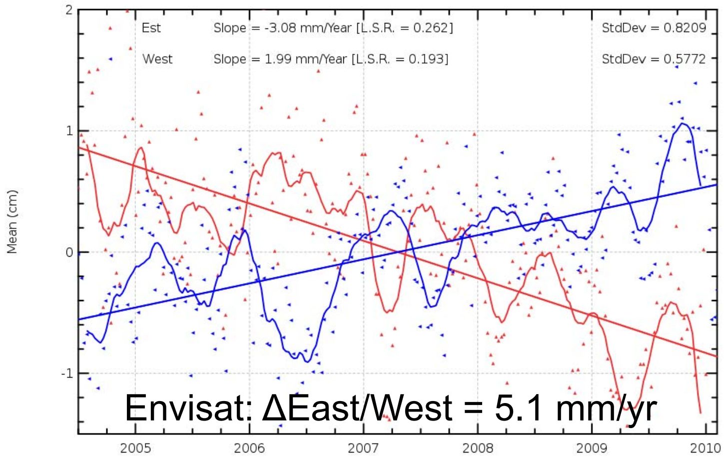
⇒ with a strong dependence versus the longitudes : sinusoidal shape

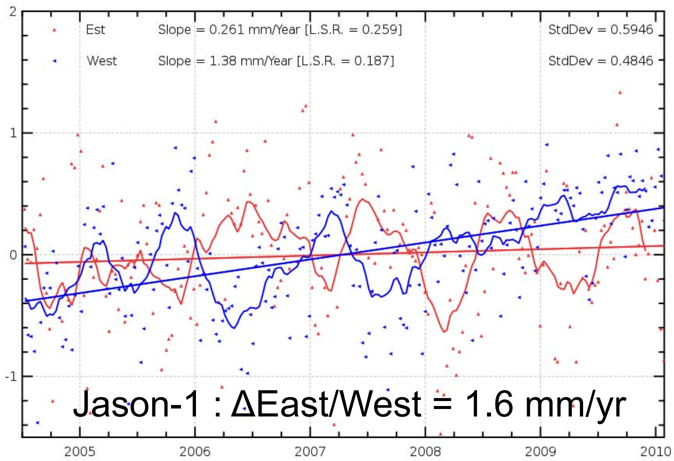




Envisat/Jason-1 regional MSL discrepancies

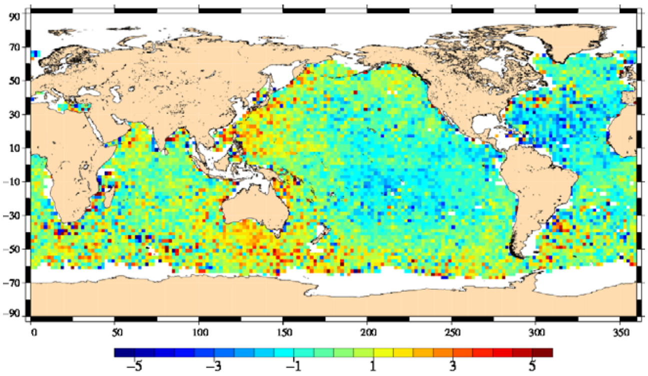
- We compute Envisat and Jason-1 SSH drift with in-situ data separating East (0°/180°) and West (180°/360°) part
- We observe that the East/West drift is more homogenous comparing Jason-1 and T/S profile than comparing Envisat and T/S profiles
- This probably demonstrates that the East/West regional differences observed between Jason-1 and Envisat is mainly due the Envisat MSL.
- It could be in relationship with the orbit calculation (under investigations).





Envisat/Jason-1 MSL discrepancies vs T/S profiles

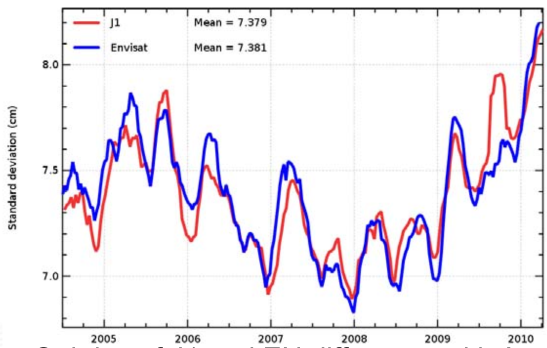
=> Which mission is more coherent with Argo data?



J1 – EN mean differences of SLA differences (cm)

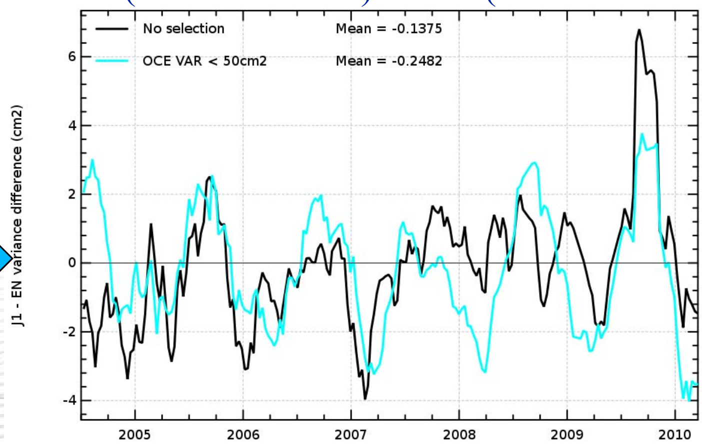
Difference J1 – EN of mean differences between altimetry and T/S profiles

=> Reduction of geographical bias due to the use of same temporal reference



Std dev of J1 and EN difference with Argo

$$VAR(SLA_{J1} - DHA_{TS}) - VAR(SLA_{EN} - DHA_{TS})$$

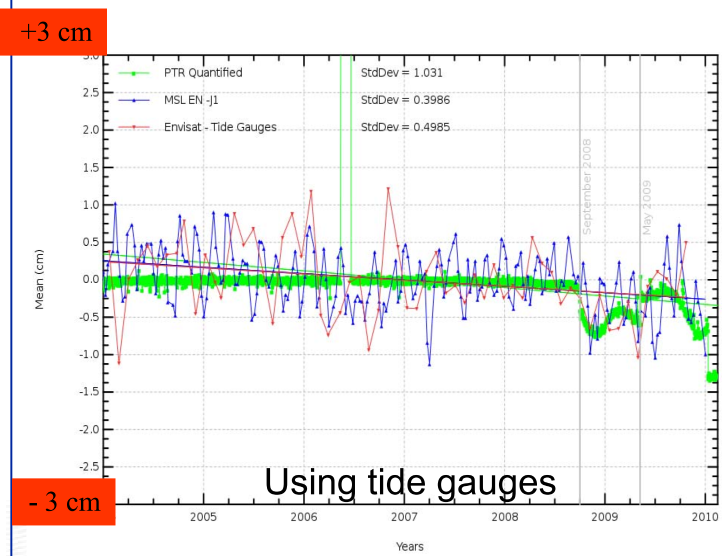


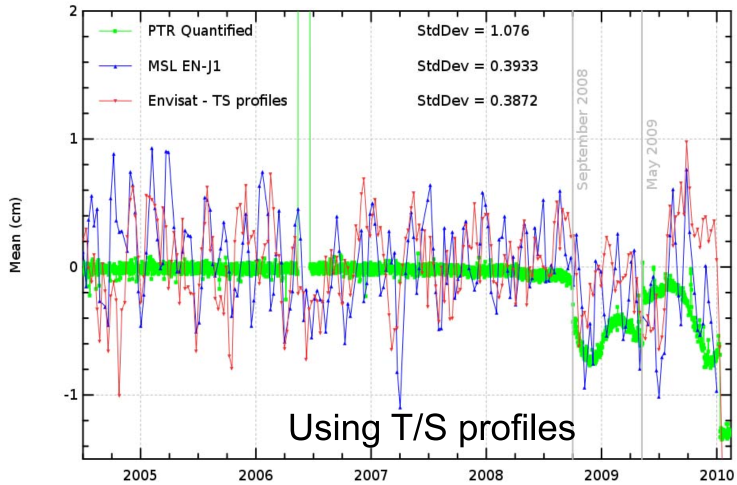
=> Why such annual signal in variance differences?

Detection of instrumental anomalies

- A PTR anomaly occurred between September 2008 and May 2009 (Faugere's talk)
- Thanks to comparisons in-situ data, we have observed and quantified the impact of this anomaly on the Envisat MSL
- This anomaly has been observed similarly using tide gauge or T/S profiles

⇒ This demonstrates the accuracy of these comparison methods to detect jumps on the altimeter MSL





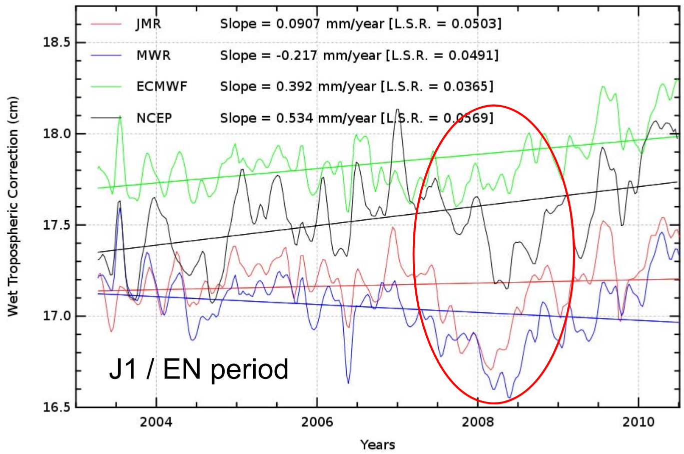
MSL computation: on the stability of the wet tropospheric correction

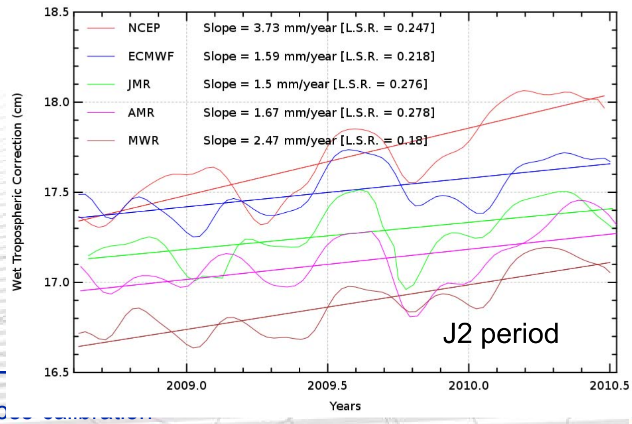
- Monitoring of radiometric and modeled wet tropospheric correction show differences of trends

⇒ +0.5 mm/yr (NCEP)

⇒ -0.2 mm/y (MWR)

- A dryness event appears in 2008: why ECMWF model wouldn't have taken it into account?



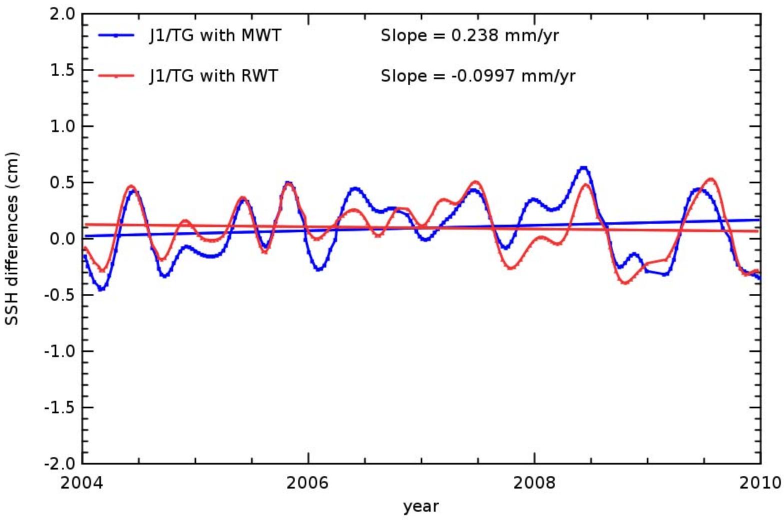


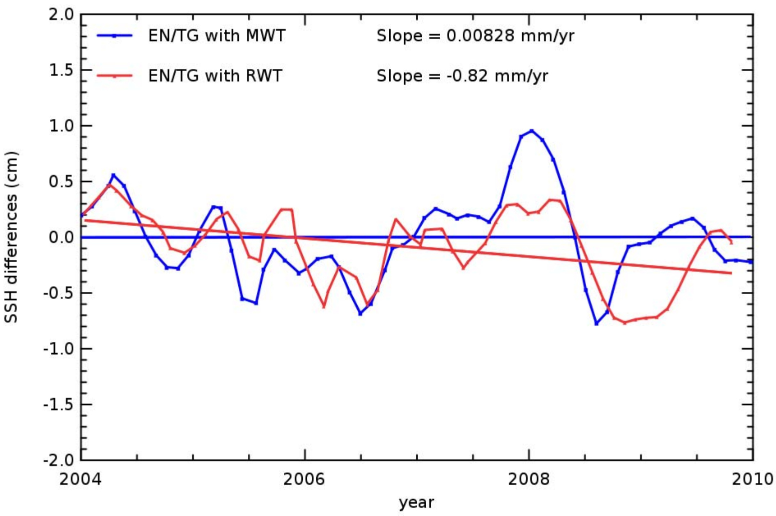
MSL computation: on the stability of the wet tropospheric correction

- Comparing altimetry with TG, with radiometric and modeled correction:
- J1 vs TG suggests good confidence with model at TG locations

⇒ Hence, EN vs TG indicates that we have less confidence in MWR measurements at TG locations

⇒ We can't say whether the radiometer or the model leads to more coherence with in-situ data

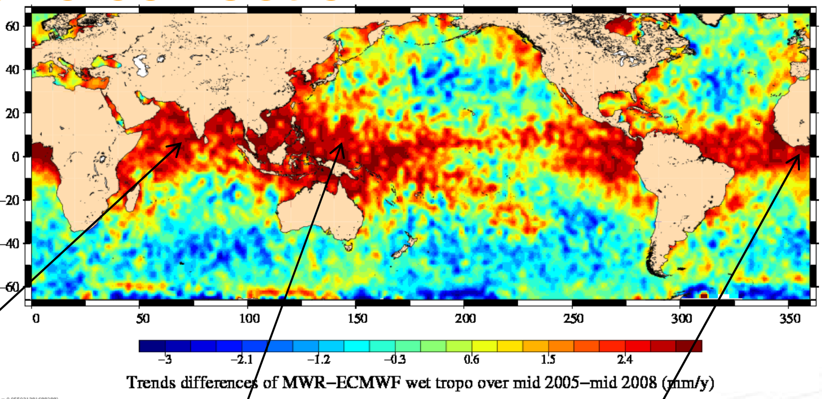


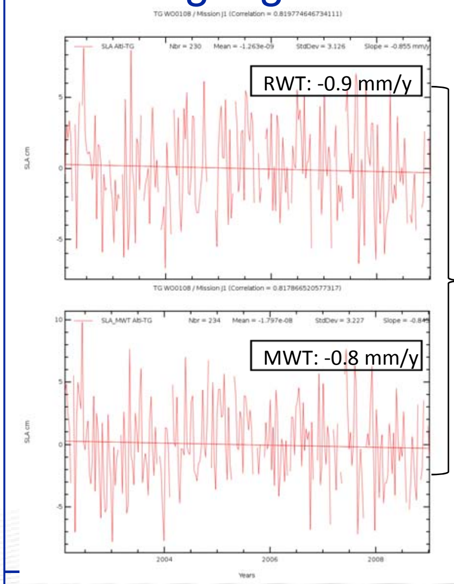


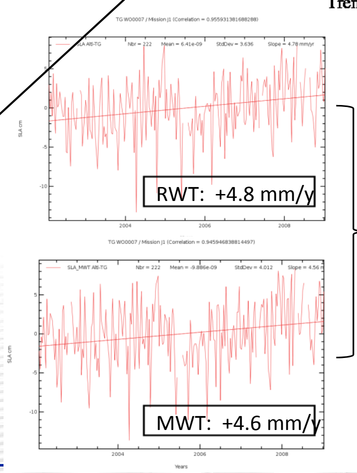
CLS

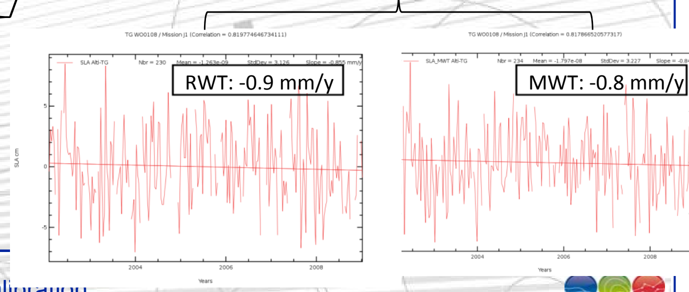
MSL computation: on the stability of the wet tropospheric correction

- ECMWF / radiometer trends differences appear mostly at low latitudes
- Local comparison with tide gauges:









MSL computation: on the stability of the wet tropospheric correction

- Comparison with Argo T/S profiles:
- Altimetric SLA with radiometric and modeled wet tropo correction:
- Restriction at low latitudes doesn't show any signature of the dry event of 2008:

⇒ Because the amplitude of the signal we're looking for is smaller (0.4mm) than the one observed here.

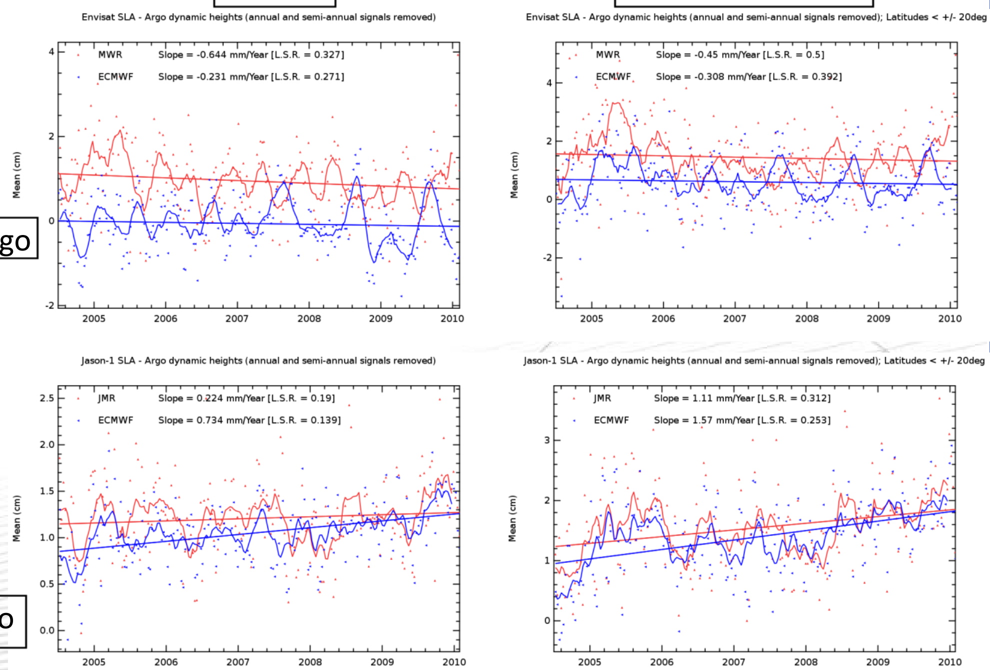
⇒ We can't say whether the radiometer or the model leads to more coherence with in-situ data

Global

Latitudes < +/- 20°

Envisat / Argo

Jason-1 / Argo



Conclusions and Prospects (Tide Gauges)

- Developments and investigations performed recently allow us to refine the Envisat MSL drift estimation :
  - ⇒ The MSL drift detected on Envisat with TG is about -1 mm/yr from 2004 to 2010
  - ⇒ The accuracy of this drift estimation has been improved and is close to 0.5 mm/yr
  - ⇒ The East/West MSL trend differences observed between Jason-1 and Envisat are likely due to the Envisat SSH (same conclusion with T/S profiles => see next slides)
  - ⇒ This Envisat East/West MSL drift limits the accuracy of the global MSL drift estimate with TG due to the poor TG spatial coverage

- In the following months is planned:
  - ⇒ To extend the global tide gauge network with GLOUP (bottom pressure tide gauges)
  - ⇒ To improve the vertical movement correction thanks to new GPS-colocated beacons
  - ⇒ To go on refining the method to even better colocate TG and altimetry
  - ⇒ To try to correct the spurious TG time series when it's possible (jumps for instance)
  - ⇒ …

Conclusions and Prospects (Argo T/S profiles)

- Investigations performed recently allow us to better estimate MSL drift from altimetry:
  - ⇒ The MSL drift *vs* T/S on 2004-2010 is 0.0 mm/y with Envisat and +0.8mm/y with J1
  - ⇒ The associated uncertainty remains high due to the short period, however these results are in agreement with the MSL drift detected with TG
  - ⇒ The East/West MSL trend differences observed between Jason-1 and Envisat are likely due to the Envisat SSH (same conclusion as TG)
  - ⇒ This method is also able to detect the recent jump in the Envisat MSL due to the PTR correction

- In the future:
  - ⇒ The method will be adapted to quantify the improvement brought by reprocessed Envisat GDR published soon
  - ⇒ Extension of the in-situ time series will allow to reduce uncertainties on slopes
  - ⇒ Implementation of recent diagnostics in the automatic data processing will provide better results

Summarize on both in-situ comparison methods

- It's important to underline the synergy of these both methods to estimate the altimetry MSL drift:
  - ⇒ While tide gauge measurements provide long time series but limited spatial sampling, T/S profiles provide global coverage but are available on a shorter time period
- The East/West Envisat MSL drift and the PTR correction anomaly are detected by both methods:
  - ⇒ This homogeneous result provide a good confidence in the MSL drift estimation
  - ⇒ Both methods are necessary to compensate the not negligible uncertainty associated on each of them
- Finally, thanks to the cross-comparisons between results provided by different approaches (global comparison between altimetry missions, Alti/TG and Alti/TS comparisons), the estimate of the MSL drift from altimetry is more and more reliable and accurate (globally and regionally)