Validation of altimeter data by comparison with tide gauges measurements

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

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1. Introduction - Document overview

This document is the altimeter/tide gauges comparison activities synthesis report for 2011, performed in the frame of the 2011-2015 SALP project (CNES) and supported by ESA concerning Envisat.

Calibration and validation of altimeter data is widely processed by comparison with in-situ time series since they provide external and independent information to be used as a reference (note that a synthesis report on the cross-comparison between altimeter data and Argo T/S profiles is also available). Indeed, tide gauge measurements and Argo T/S profiles constitute two complementary datasets for this activity. Although the spatial coverage is worse with tide gauges (only a few part of coastal areas are covered while the Argo network can sample the global open ocean), the temporal sampling of tide gauge measurements is really better (one measure each hour whereas one profile every ten days for Argo T/S profiles). That be, the combination of the several results obtained through this activity can be considered as reliable thanks to the use of multiple in-situ datasets. Moreover, these cross-comparisons with external independent in-situ measurements increase the quality of calibration and validation of altimeter measurements.

Whatever in-situ dataset used in the frame of this activity, tide gauge measurements as well as Argo T/S profiles, these studies are focusing on the comparison with the Sea Surface Height (SSH) derived from altimetry in order to:

1. Detect drifts and jumps in the altimeter sea level time series and give an assessment of the global and regional MSL trend

2. Estimate the potential improvement provided by new altimeter standards (orbit solution, geophysical corrections...) on the SSH consistency

3. Perform a quality control of the in-situ time series, where drifts and jumps can remain, with no physical signification (drift of sensors, anthropogenic sources ...)

This complementary approach tends to improve our knowledge of the measured physical content, where tide gauges provide high temporal resolution of SSH in coastal regions whereas T/S profiles of the Argo network provide sea level dynamic heights in the almost whole global open ocean with a 10-day sampling.

In the first place, the document describes the tide gauges database used and its computation in order to make them comparable to altimetric SSH. The tide gauge networks used and the data availability are precisely described, and new corrections used in the in-situ SSH calculation are also specified.

During 2011, the main goal was to improve the processing sequence and especially the colocation between altimetry and tide gauges to compare altimeter data and in-situ measurements. The document thus details the method developed to compare altimeter data and tide gauge measurements and results derived from the cross-comparison of both datasets.

Then the document describes the main results concerning the detection of altimeter MSL drift. It focuses on the four main altimeter missions TOPEX/Poseidon (T/P), Jason-1, Jason-2 and Envisat, as well as on DUACS DT multi-mission products.
Results concerning the comparison procedure of new altimeter standards are discussed from temporal diagnoses, especially through the monitoring of the variance differences.
The report will also present the cross-comparison indicator performed on tide gauges to highlight spurious measurements. Basically, this method is based on a multi-cross-calibration between tide gauges and multiple altimeter time series so as to detect potential jumps or abnormal drifts in tide gauges time series.
Finally some particular studies carried out during 2011 are presented to demonstrate the interest of comparing altimetry with in-situ tide gauges measurements and thus make the altimeter SSH more accurate.

2. Presentation of the tide gauges database

2.1. Overview

The tidal database consists in records of tide gauges Sea Surface Height (SSH) from independent networks. Several types of geophysical corrections such as tide, pressure and wind effects are then applied on these raw data so as to deduce filtered Sea Level Anomalies (SLA) from high frequency phenomena in order to be consistent with altimeter data. The comparison of the latter with tide gauges measurements is thus made possible thanks to this tidal database and softwares dedicated to its computation. This section details the way of manipulating tide gauges measurements.

2.2. Origin

The tidal database, which to date consists in 5 different tide gauges networks (GLOSS/CLIVAR, REFMAR, OPPE, BODC and IMEDEA), results from different collaborations. During 2011, in the frame of different projects, the CLS in-situ database has been enhanced with tide gauges from both GLOSS/CLIVAR and REFMAR networks.
Here are the details of the networks computed in the CLS database (figure 1):

- GLOSS/CLIVAR (Global Sea Level Observing System/Climate Variability and Predictability) "fast" sea level data: this network provides 280 tide gauges gathered by the University of Hawaii Sea Level Center (USHLC) and updated within a few weeks or a few months (*ilikai.soest.hawaii.edu/uhslc*). 9 tide gauges have been added in 2011.

- REFMAR (Réseaux de référence des observations marégraphiques): this network consists in 33 tide gauges which major part is set on the french shoreline (*refmar.shom.fr*).

- BODC (British Oceanographic Data Centre): 45 UK tide gauges of this network, which are held by the Permanent Service for Mean Sea Level (PSMSL), are computed in the tidal database (*www.bodc.ac.uk*)

- OPPE (Organismo Público de Puertos del Estado): 19 of these tide gauges are built in the CLS database, which are uniformly sampled along spanish coasts (*www.puertos.es*)

- IMEDEA (Mediterranean Institute for Advanced Studies): 48 tide gauges widespread in the Mediterranean Sea computed in the CLS in-situ tide gauge database (*www.imedea.uib.es*)

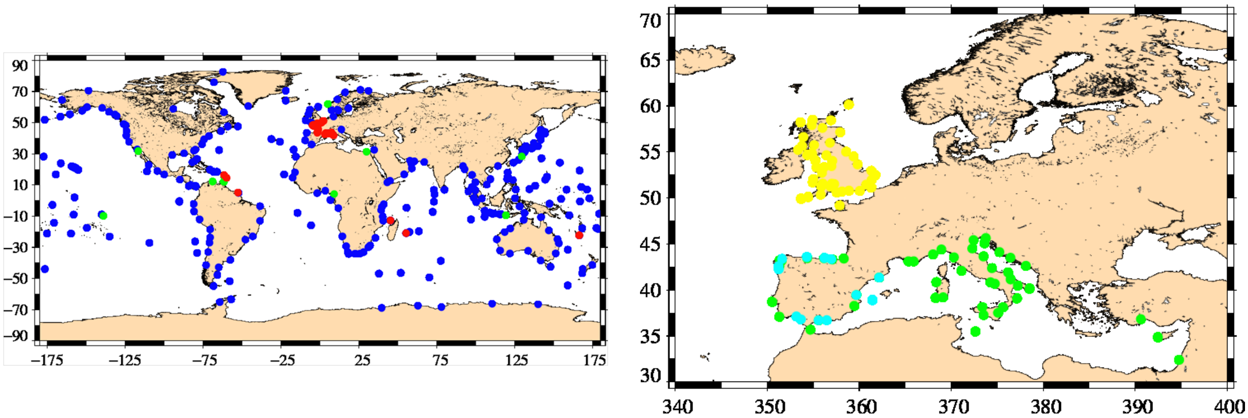


Figure 1: *Location of the tide gauges. Left: GLOSS/CLIVAR (blue) and REFMAR (red). Green dots correspond to GLOSS/CLIVAR tide gauges added in the CLS database in 2011. Right: BODC (yellow), OPPE (cyan) and IMEDEA (green).*

Concerning the Senetosa tide gauge, time series of the M3, M4, M5 and M7 sensors are about to be available on the AVISO website (*www.aviso.oceanobs.com*), where the in-situ section will be improved in 2012 (2 parts, one concerning the absolute calibration and the other dedicated to the global comparison with altimetry).

Furthermore, in the frame of the MyOcean project, new tide gauges from different providers and delivered by IFREMER are planned to be added in the CLS tide gauge database. These new data, as well as the integration of the whole PSMSL database, will be very relevant to improve the tide gauge global sampling and thus make ever reliable studies about long-term sea level variability, globally and regionally. For instance, studies performed in the Artic Sea relies upon the processing sequence developed in the frame of this activity (see part 3.3.), where a subset of monthly mean sea level data has been extracted from the PSMSL database (*www.psmsl.org*) and compared to DUACS DT multi-mission products at high latitudes. Results are discussed in part 7.4., showing that the method described in this document is reliable using tide gauge data.

2.3. Data availability

For the whole tidal networks, hourly data are computed and archived according to a linear procedure:

- 1. Weekly download of the updated data
- 2. Conversion from the original-sized data to the CLS-sized data (in-situ measurements tables) with several steps of validations
- 3. Implementation of dedicated filters for tide gauge data in order to remove the short and long tide wavelengths (diurnal, semi-diurnal and long period tides)

- 4. Record of the high resolution dynamical atmospheric correction (MOG2D model) to remove high frequency signals

By the means of "in-situ measurements tables" specific format, SSH measured by tide gauges can be filtered from high frequency phenomena quoted above.
To date, the tidal database is updated every week according to the availability of new tide gauge measurements. With both MyOcean and PSMSL new tidal networks, the acqusition processing will be updated in 2012 so as to become an operational system. Thus, the tidal database will be updated every day, in line with the availability of the MyOcean tide gauges measurements.

3. Description of the altimeter/tide gauges comparison procedure

3.1. Overview

The main goal of this activity is to compare altimeter and in-situ tide gauges sea level anomalies. To make this comparison possible, sea surface height measurements have first to be processed. The physical content of tide gauge measurements and altimeter data are not completely equivalent. Both datasets have thus to be pre-processed before comparing each other. The general operating diagram derived from the altimeter/tide gauges comparison is displayed in annex 10.1..

3.2. Pre-processing of the altimeter and in-situ tide gauge sea surface heights

3.2.1. Calculation of the altimeter sea surface height

Radar altimeters provide Sea Surface Heights (SSH), which need to be referenced and corrected from geophysical signals to provide Sea Level Anomalies (SLA) comparable with in-situ measurements. In this study, we use along-track (level 2) SSH from several satellite altimeters, where standards are updated compared with the official Geophysical Data Record (GDR) altimeter products. Details of the SSH computation and time period for each altimeter are presented in annex 10.2. and available in the MSL part of the AVISO website (*www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/processing-corrections/index.html*).

The Sea Surface Height (SSH) calculation is defined below :

$$SSH = Orbit - Altimeter\ Range - \sum_{i=1}^{n} Correction_i - Mean\ Sea\ Surface$$

where the usual corrections are:

$$\begin{aligned}
\sum_{i=1}^{n} Correction_i &= Dry\ troposphere\ correction : S1\ and\ S2\ atmospheric\ tides\ applied \\
&+ Combined\ atmospheric\ correction : high resolution MOG2D\ and\ inverse\ barometer \\
&+ radiometer wet\ troposphere\ correction \\
&+ Dual\ frequency\ ionospheric\ correction \\
&+ Non\ parametric\ sea\ state\ bias\ correction \\
&+ Geocentric\ ocean\ tide\ height,\ GOT\ 4.7 : S1\ parameter\ is\ included \\
&+ Solid\ earth\ tide\ height \\
&+ Geocentric\ pole\ tide\ height
\end{aligned}$$

Note that SLA for the whole altimeter missions are computed with a reference to the Mean Sea Surface (MSS) CLS 2001 model (Hernandez and Schaeffer, 2001 [23]). We focus our analyses on

T/P, Envisat, Jason-1 and Jason-2. Concerning the T/P mission, MGDR products have not been reprocessed since the end of life of the mission (October 2005), and more recent corrections, compatible with the standards used for the Jason missions, have therefore been used. Concerning Envisat, despite of the remaining level-1 processing heterogeneities for instance, some of the most relevant corrections like the orbit have been updated with GDR-C standards. This makes Envisat SSH homogeneous enough to be compared with Jason-1 sea level while the whole reprocessing is performed. The remaining heterogeneities, directly impacting the assessment of the MSL trend, are expected to be improved and even corrected in the reprocessing which is currently under progress on Envisat. Thus, the comparison with in-situ data is performed by computing 10-days global altimeter SLA grids with a spatial resolution of 1 degree latitude and 3 degrees longitude. Although this space resolution provide reliable results, the impact of other spatial resolutions (1°x2°, 1°x1.5°, 1°x1°) on altimeter SLA grids will be estimated in 2012.

3.2.2. Calculation of the in-situ sea surface height

The assessment of in-situ sea surface height is comparable to the altimeter one. However, since relative bias between altimeter and in-situ data are searched out, tide gauges time series are offset on the Mean Sea Surface (MSS) used in the altimeter SSH computation, which provides a common reference to the whole tide gauges dataset considered. Oceanic tidal effects are corrected by filtering high frequency diurnal and semi-diurnal tides using the Demerliac low-pass filter (Bessero, 1985 [13]). Long-time tidal waves are also corrected using a specific algorithm based on well-balanced tide tables (Cartwright and Eden, 1973 [17]). Furthermore, atmospheric are corrected by withdrawing the high frequency Dynamical Atmospheric Correction (DAC) (Dorandeu and Le Traon, 1999 [21]; Carrere and Lyard, 2003 [16]).

In 2011, one of the improvement of the in-situ dataset consisted in correcting tide gauges measurements from vertical movements. Indeed, many studies demonstrated the need for tide gauges to be adjusted from land motion when compared with altimeter data (Cazenave et al., 1999 [18]; Nerem et al., 2002 [29]). However, even if such projects as the International Global Navigation Satellite System Service (IGS) Tide Gauge Benchmark Monitoring Pilot Project (TIGA) (Schöne et al., 2009 [35]) are willing to position GPS at each tide gauge site (Bouin et al., 2010 [15]), only a few of the latter, belonging to the GLOSS/CLIVAR database considered, can be corrected from crustal drift movements. Thus, in order to take into account the full in-situ database and give the best assessment of land motion at each tide gauge location, in-situ time series are corrected from Glacial Isostatic Adjustment (GIA) using the ICE-5G model (Peltier, 2004 [32]). The impact of taking into account such correction on tide gauges time series is displayed in part 7.3.

Considering the homogeneous SSH derived from both altimeter and tide gauges, reliable long-term trend evolutions are studied. Thus, the selection of the most relevant tide gauges measurements is performed by considering tide gauges time series lasting for at least 2 years. Moreover, the potential spurious values detected through the mean of SSH differences threshold (specified at 12 cm in order to get rid of strong ocean variability or potential aberrant values in the tide gauges measurements) are filtered out without impacting the whole time series so far.

3.3. Computation of the potential relative bias

After homogenizing in-situ measurements and altimeter SLA, the method of comparison consists in colocating both types of data. Thus, the method is based on a criterion of maximal correlation between tide gauges time series and altimeter gridded products, where the most consistent state of the ocean between both data time series is considered within a 100 km distance circle around the tide gauge (figure 2). The main advantage of the method is to reduce the effect of the oceanic variability and the error on the mean sea surface considering the same altimeter point. A spatial weighting of the in-situ network has to be performed in order to take into account the non-homogeneous sampling of tide gauges in the whole ocean.

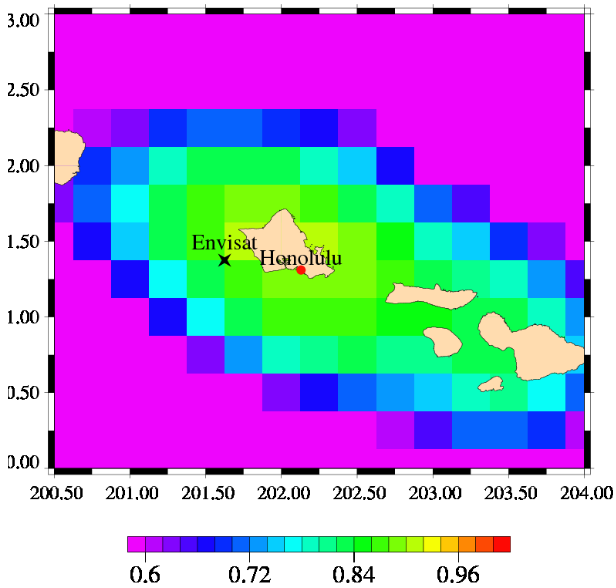


Figure 2: *Example of colocation between altimeter and tide gauge time series by computing the maximum of correlation on Envisat from gridded altimeter products*

After extracting couples of colocated altimeter and tide gauges data, some additional quality controls are performed on each altimeter and in-situ dataset in order to perform the computation of SSH differences on the most reliable time series. Colocated altimeter and tide gauges time series are kept if their correlation is higher than 0.7. This value is high compared to other studies (0.3 in Mitchum, 1998 [28]) but allows so far keeping a large number of tide gauges. Colocated altimeter and tide gauges time series are then kept if the standard deviation of the differences is lower than 10 cm. Finally, the altimeter time series should contain at least 70% of valid points (in percentage of the number of data to be computed). Indeed, when the altimeter residual time series contains less than 70% of valid points, the time series is rejected and the process considers the next altimeter time series the most correlated to the in-situ tide gauge one.

Then, from all corrections previously detailed, the altimeter drift can be calculated as presented below:

Bias = ΔAltimeter - ΔTide Gauge (+/- errors on models, corrections and measurements)

and statistics of sea level differences are computed on the whole CLS tide gauge database.

4. Analyses of potential drifts or jumps in altimeter MSL

4.1. Overview

The cycle by cycle monitoring of average SLA differences between altimeter and tide gauge data provide relevant information to detect potential drifts or jumps on mean sea level trend derived from altimetric data. New assessments of these long-term comparisons until the end of 2011 are presented in this part in agreement with the MSL calculation and using an extended in-situ network, and trends for the SLA differences statistic monitoring are 60-day filtered with annual and semi-annual signals adjusted.
Note that during 2011, both Jason-2 space mission and DUACS DT multi-mission products have been routinely added to the global altimeter/in-situ tide gauges comparison.

4.2. Analyses on T/P, Jason-1, Jason-2 and Envisat altimeter missions

Colocated altimeter and tide gauges SLA differences are first averaged globally to assess the long term MSL drift from the different altimeter time series. The number of tide gauges considered may vary from one altimeter mission to another regarding both altitude and orbit of the satellite. While the global number of in-situ time series available in the GLOSS/CLIVAR network is to date close to 300, the mean number of selected tide gauges ranges from 80 to 150, linearly evolving with the availability of new tide gauges in the whole ocean. From this subset of tide gauges, results displayed in this study are in agreement with Nerem et al. (2010 [30]) considering T/P and Jason-1&2.

Since T/P space mission delivered the longest available altimeter time series, the comparison with tide gauges has become of reference regarding studies about MSL drift. Results on the differences between T/P data and tide gauge measurements (figure 3) display a global trend of about 0.4 mm/yr over the 1993-2005 time period. The low rms differences ($<$ 3.6 cm) and the low formal adjustment error ($<$ 0.1 mm/yr) is in favor of a reliable assessment of T/P global MSL on the whole altimeter time period. However, focusing on both TOPEX-A (cycles 11 to 236) and TOPEX-B (cycles 237 to 364) time periods, the behavior of the altimeter is quite different. Over the TOPEX-A time period, a negative drift of -1.1 mm/yr appears between 1993 and 1996 whereas a positive drift of +1.8 mm/yr is detected from 1996 to 1999, equivalent to a jump close to +6 mm. Although both TOPEX-A periods are likely too short (3 years) to determine an accurate drift by comparison with tide gauges, the TOPEX-B MSL appears more stable with no drift from February 1999 onwards. The significant positive drift detected on TOPEX-A from 1996 onwards corresponds to the beginning of the TOPEX-A anomaly (cycles 130 to 236) where strong instrumental instabilities have been highlighted on significant wave height and backscatter coefficient parameters. Comparisons with tide gauges tend to demonstrate for the first time that these anomalies have also an impact on the sea-level stability during this period. On the beginning of TOPEX-A from 1993 to 1996, thorough investigations have to be performed to explain the negative drift observed. Although T/P measurements provide accurate measurements for climate studies, the long-term stability of TOPEX-A data could be improved.

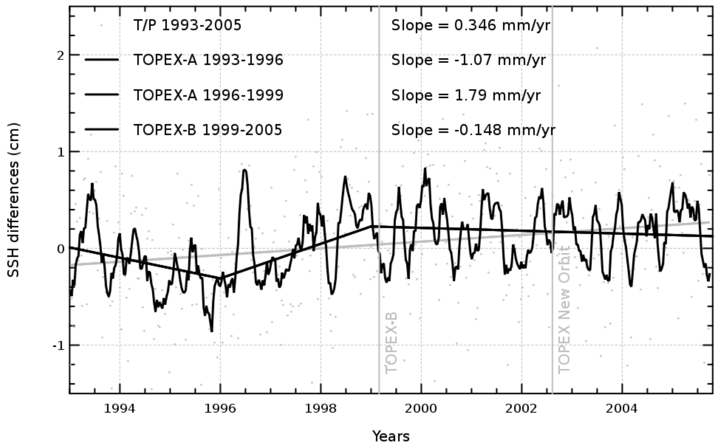
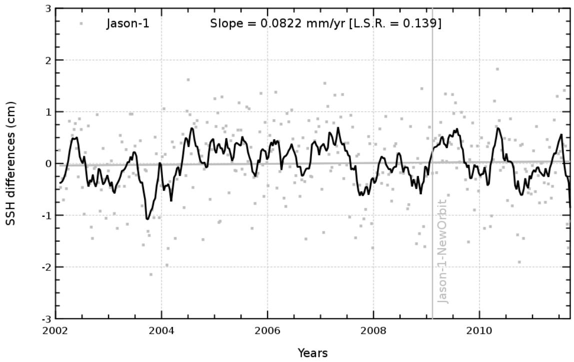


Figure 3: *Cycle by cycle monitoring of mean SLA differences between T/P and tide gauge measurements.*

Considering Jason-1, the comparison with tide gauges measurements provides consistent long-term trend differences of 0.1 mm/yr (figure 4 left), with a formal adjustment error of the same order. Again, on almost 10 years of consistent altimeter data delivery, the coherence with in-situ measurements along coastal areas is pretty good, and rms differences are lower than 3.7 cm. Although the drift is close to zero, some misunderstood signals are observed, especially in 2004 with a small jump of few millimeters. Currently, the accuracy of the method of comparison between altimetry and tide gauge is not able to determine if these signals are due to errors on Jason-1 data or intrinsic uncertainties of the method. Furthermore, looking at the Jason-2/tide gauges residual signals superimposed with Jason-1 (figure 4 right), the 2 cm amplitude and periodic signals of the global data time series differences are in very good agreement on the same time period. However, trend differences are slightly different with Jason-1's between 2008 and 2011 (-0.5 mm/yr for Jason-1 and -0.9 mm/yr for Jason-2, with a formal adjustment error of about 0.7 mm/yr) but on the same order within the intrinsic error of the method. Since Jason-2 time period is too short, it doesn't yet allow enough confidence in the altimeter drift assessment. Thus, results on the comparison with tide gauges measurements will have to wait for longer time series to be compared with the other on-flight altimeter missions like Jason-1 or Envisat for instance.



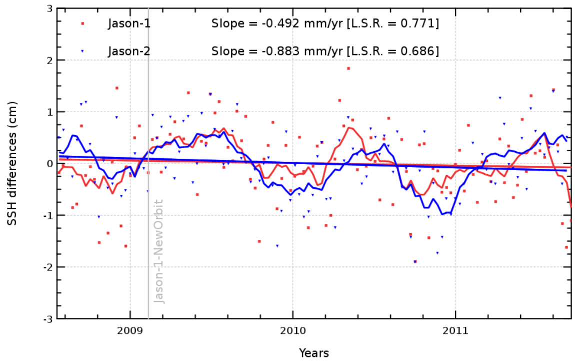


Figure 4: *Left: Cycle by cycle monitoring of mean SLA differences between Jason-1 and tide gauge measurements. Right: Cycle by cycle monitoring of mean SLA differences between Jason-1&2 and tide gauge measurements.*

As for Jason-1 and Jason-2, Envisat measurements are computed in order to provide an accurate assessment of the SSH. Global MSL studies show a particular behavior of the Envisat MSL on the whole altimeter time period, especially at the beginning of the period (AVISO, 2011, Envisat annual validation report [7]). On the 2002-2011 time period, the differences between Envisat data and tide gauges measurements display a negative drift close to -1.9 mm/yr (figure 5), strongly different from results obtained on T/P, Jason-1 and Jason-2. The formal adjustment error is slightly higher than other missions (close to 0.2 mm/yr) and amplitudes of residual signals are greater than 3 cm. The strong drift described here has already been mentioned when comparing Jason-1 and Envisat global MSL (AVISO, 2011, Envisat annual validation report [7]). Over the global ocean, a drift close to -1.2 mm/yr have been calculated over the 2004-2010 time period, in agreement with the drift obtained here between Envisat and tide gauges. On the first hand, this demonstrates both reliability and accuracy of the method to compare altimetry and tide gauges in order to detect potential drifts over the global ocean. On the second hand, this also argues in favor of the drift observed between Jason-1 and Envisat as an error on Envisat data. Thus, the use of tide gauges aims at understanding and investigating some potential drift linked to an on-board instrument on Envisat, like the Ultra Stable Oscillator (USO) clock period for instance (Martini, 2003 [27]), waiting for the use of the reprocessed altimeter data in 2012. Some other anomalies, like the Point Target Response (PTR) data processing (see part 5.5.), have been highlighted during the Envisat mission thanks to in-situ comparisons. Investigations performed on the Envisat mission argue in favor of Jason (1&2) missions to be considered as reference altimeter missions. In this way, multi-mission cross-calibration are useful to understand and then enhance the relevance of altimeter global MSL.

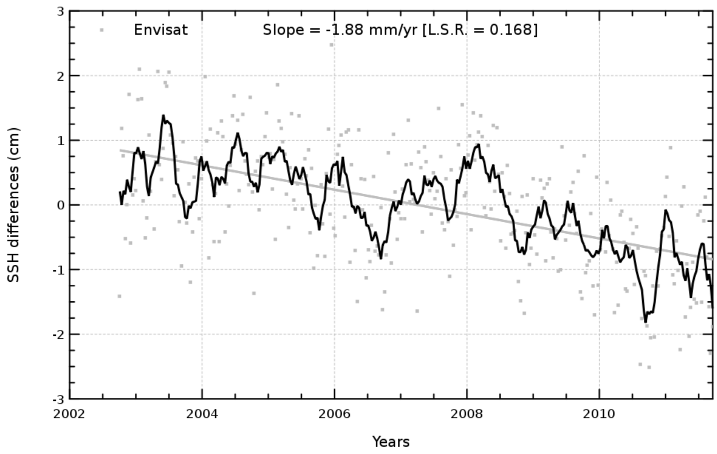


Figure 5: *Cycle by cycle monitoring of mean SLA differences between Envisat and tide gauge measurements.*

4.3. Assessment of SSH differences on the whole altimeter time period

The DUACS Delayed Time multi-mission products have been compared with tide gauges, which enables a global comparison with tide gauges on the entire altimeter time period. On the 1993-2011 time period, the MSL drift is almost -0.1 mm/yr (figure 6), within the error of the method of $\pm$ 0.5 mm/yr. Looking at the number of satellites merged during the whole time period, amplitudes of SSH differences are greater when considering 2 or 3 satellites, and reduced between the 16 of September 2002 and the 8 of October 2005, with the combination of the four missions T/P, Geosat Follow-On, Jason-1 and Envisat. However, periodic signals seem to be displayed over all the altimeter time period, which are to be thoroughly investigated.
Therefore, the use of tide gauges measurements is a way of assessing long-term drifts considering DUACS DT gridded products.

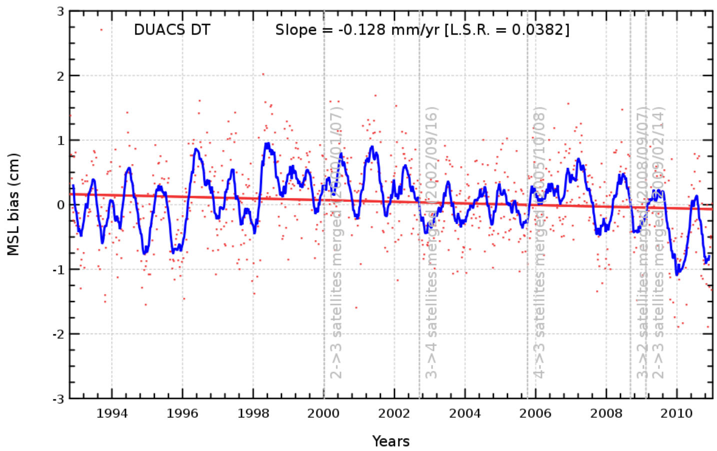


Figure 6: *Cycle by cycle monitoring of mean SLA differences between DUACS DT multi-mission products and tide gauge measurements (60-day filtered without annual and semi-annual signals adjusted).*

4.4. Standard deviation and number of tide gauges of the SSH differences

Concerning the standard deviation of the SSH differences computed from level-2 altimeter gridded products (figure 7 left), results obtained are agreement between the whole missions, with a mean value of standard deviation close to 3.5 cm. The reliability of such is demonstrated through the different time periods of the main altimeter missions. Indeed, the standard deviation of SSH differences is stable and in agreement with the smoothed grids derived from DUACS Delayed Time multi-mission products. However, the use of level-2 gridded products provides some interesting information in SSH differences. For instance, the jump in 2002 when T/P moved on its new ground track (corresponding to the TOPEX new orbit phase), may be related to the higher SLA variability explained by the less precise MSS outside T/P's nominal track but also to data losses linked to anomalous behaviors of the onboard tape recorders (AVISO, 2006, TOPEX/Poseidon annual validation report [10]).
Considering the cycle by cycle number of tide gauges considered in the processing sequence, results are again in agreement with each other (with a mean number of tide gauges of about 95), except with Jason-2 and DUACS DT products where the number of tide gauges selected is higher (close to 140). Concerning DUACS DT multi-mission products, the difference with level-2 altimeter data is obvious as the smoothing enables more tide gauges to be correlated to altimeter time series within a 500 km distance circle. Regarding Jason-2 results, this good result means that altimeter data are physically consistent with tide gauges measurements along coastal areas, maybe thanks to the use of the median tracker on Jason-2 (AVISO, 2011, Jason-2 annual validation report). However, results have to be thoroughly studied to understand such few correlations between altimeter and tide gauges data time series and more precisely on DUACS DT gridded products.

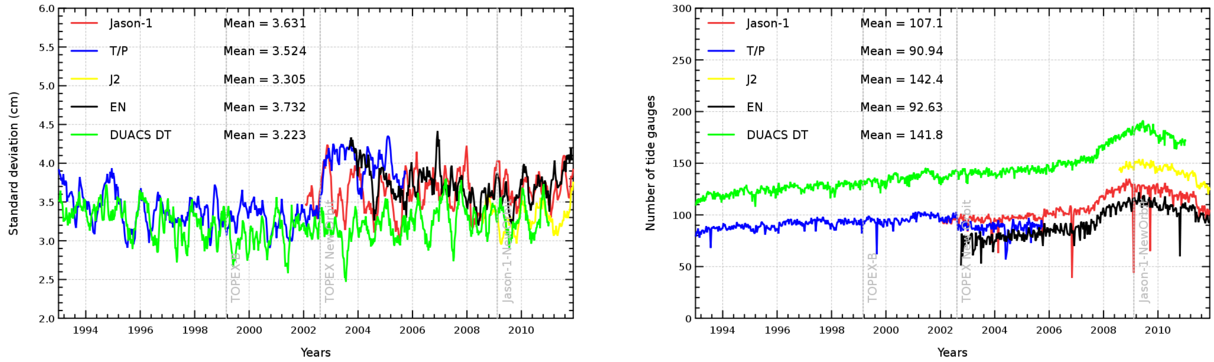


Figure 7: *Left: Cycle by cycle monitoring of the standard deviation of SLA differences between altimeter data and tide gauge measurements. Right: Cycle by cycle monitoring of the number of tide gauges considered in the processing sequence.*

5. Estimation of altimeter SSH improvements

5.1. Overview

As already mentioned, the second main goal of the Calval in-situ activity is to estimate improvements of altimetric data analyzing the SSH consistency between altimeter and in-situ measurements. This part aims at presenting the capability of the altimeter/tide gauges comparison procedure to measure the impact of new altimeter standards on the SSH consistency. Thus, new geophysical corrections (tide model correction, dynamical atmospheric correction,...), new orbits or new algorithms in ground processing are estimated by comparison with in-situ measurements using successively the old and new version of the altimeter standard in the SSH calculation. The potential improvement is assessed in terms of the evolution of the drift of the sea level differences, with the aim of computing a new release of altimeter products.

The following analyses presented in this part of the document are not exhaustive. Their main objective is to illustrate and demonstrate the interest of the method.

5.2. Impact of the GDR-C reprocessing on altimeter/in-situ SLA consistency

One of these studies concerns the impact of the new GDR-C reprocessing on Jason-1, which can be estimated at tide gauge locations by comparison with GDR-B products. Here are the main improvements released in this reprocessing (Commien et Philipps, 2008 [19] and 2009 [20]):

- the main change of the new version is the POE orbit solution, which includes a new gravity model (EIGENGL04C instead of EIGEN-CG03C), and a time-varying part (without drifts).
- the JMR (radiometer) has been recalibrated with parameters derived from cycles 1 to 227 (GDR-B) so as to provide more accurate brightness temperature and therefore wet tropospheric correction.
- altimeter instrument corrections were updated. This has an impact on several altimeter parameters: backscattering coefficient (sigma0), sea wave height, range. Through the range, the bifrequency ionospheric correction is also slightly modified.
- a new sea state bias (SSB) solution, computed on a 3-year basis of GDR version B (cycles 1 to 111), improves significantly the sea surface height (SSH) calculation.
- the dry troposphere correction still uses the ECMWF model, which has evolved to correct for spurious oscillation effects.
- the dynamical atmospheric correction (DAC), which includes inverse barometer and MOG2D model, now uses high resolution MOG2D grids.
- for FES2004 ocean tide model, S1, K2 and loading tides have been updated.
- an empirically-computed pseudo time-tag bias correction has been added in the product and taken into account in SSH calculation, and a mean dynamic topography (MDT Rio, 2005 [34]) has been added too.

- a new algorithm, based on AGC instead of sigma0, is used for rain flag estimation.
- the computation of the ice flag is also slightly changed. It no longer shows a discontinuity in the Hudson bay.

While the main benefit is to estimate the performance of the GDR-C reprocessing through in-situ independent datasets comparison, the drawback of this method is that each correction can't be individually assessed in the global reprocessing. Results displayed on figure 8 show the better temporal consistency between altimeter data and tide gauge measurements with a mean value of -0.73 cm^2. However, like previously, a residual annual signal is remaining, which periodically inverts the consistency to either GDR-C or GDR-B orbit. In agreement with Calval studies, this annual signal may be due to the new gravity model and the time-varying part used in the POE orbit solution. Moreover, at tide gauge locations, the SSH consistency is also slightly improved, maybe influenced by the sign inversion of variance differences. Thus the mean is -0.73 cm^2 and confirm the enhancement of the consistency between altimeter and in-situ data thanks to GDR-C reprocessing.

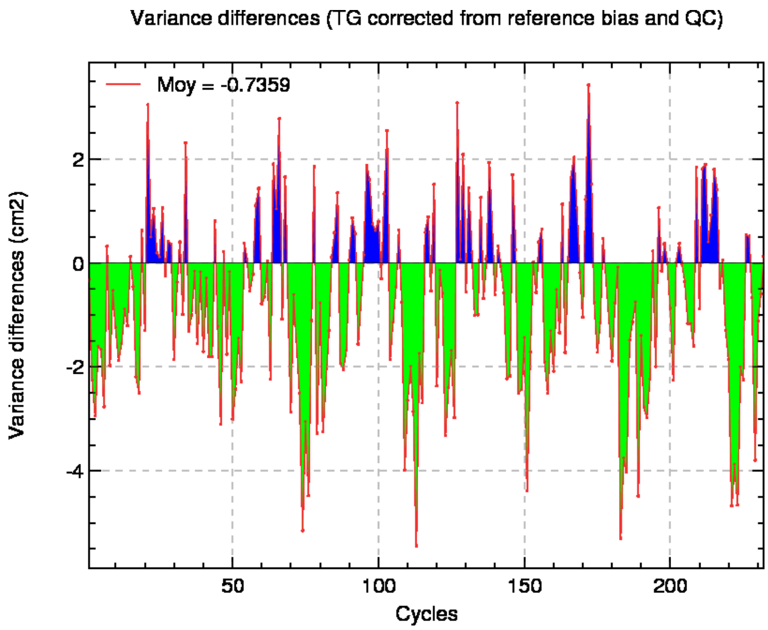
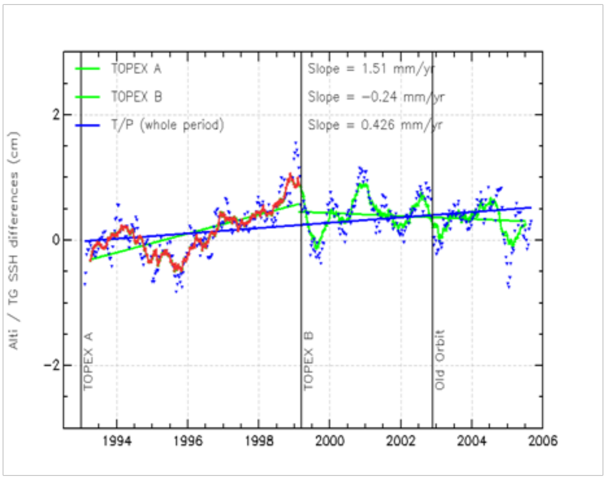


Figure 8: *Monitoring of SSH variance differences computed with GDR-C and GDR-B for Jason-1 (cm^2)*

5.3. Impact of new Sea State Bias (SSB) correction on TOPEX/Poseidon

Reprocessings of SSALTO/DUACS multimission products aim at computing the latest and most accurate altimetric corrections in the SSH calculation (GSFC orbit, GOT4.7 tide correction ...). The use of the Gourrion wind, more relevant than Chelton's one, have led to a new computation of the TOPEX/Poseidon SSH (see technical note [38]). Next to the study between the old and the new SSB corrections, the altimeter and in-situ long term differences provide results as seen on figure 9. On the left, a drift is observed on the TOPEX-A time period, corresponding to instrumental problems (OSTST, Seattle 2009 [2]). When comparing new results to in-situ tide gauge measurements, this drift is strongly decreased, which indicates the new TOPEX MSL is more reliable. The new trend on TOPEX-A is 0.8 mm/year with the new 2-parameters SSB computed with Gourrion's wind whereas it was 1.5 mm/year with Chelton's wind.



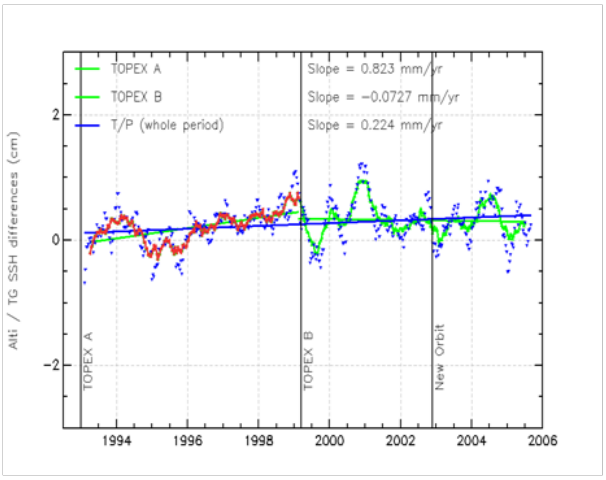


Figure 9: *Impact of the new 2-parameters Sea State Bias computed with Gourrion's wind on the monitoring of the mean altimeter/in-situ tide gauge differences. Left: Old SSB (Chelton's wind). Right: New SSB (Gourrion's wind)*

5.4. Impact of the ECMWF model wet troposphere correction

When comparing the global MSL estimated from multiple altimeter data, several kinds of corrections are thoroughly investigated to explain the potential discrepancies deduced from altimeter cross-comparisons. In this way, the use of tide gauges measurements, as an external and independent dataset, can contribute to understand these differences. The wet troposphere correction recorded by on-board radiometers is often discussed when evaluating altimeter products and thus compared to the ECMWF wet troposphere model.
Figure 10 displays the slope differences between radiometer and ECMWF model wet troposphere correction using tide gauges measurements and considering both Jason-1 (left) and Envisat (right). Such results show that differences between radiometer and model are lower and thus more homogeneous on Jason-1 (0.5 mm/yr) than on Envisat (1.1 mm/yr). This argues in favor of a radiometer wet troposphere correction weaker on Envisat than its nominal value. Note that results obtained in global Jason-1/Envisat MSL comparisons are slightly different considering the whole ocean. Further investigations will have to be performed to undertand such coastal discrepancies when comparing to tide gauges measurements.

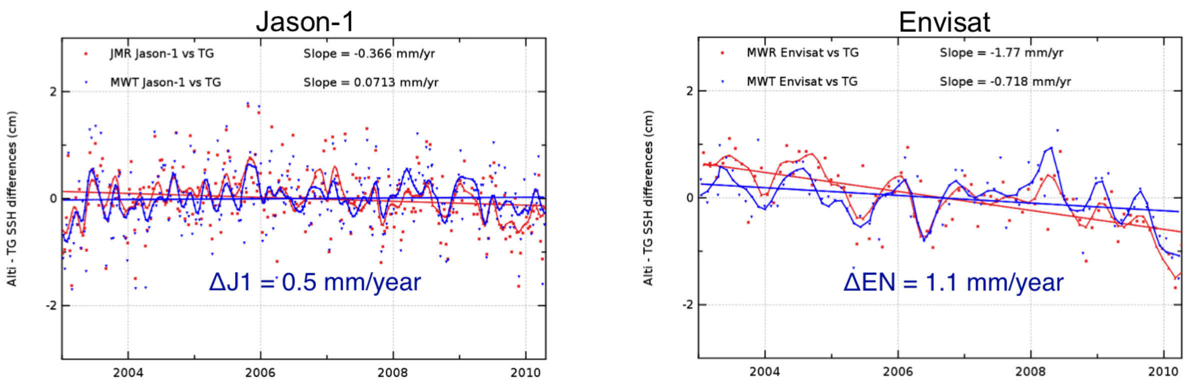


Figure 10: *Impact of the ECMWF wet troposphere correction on cycle by cycle monitoring of mean SLA differences between altimeter and tide gauge measurements. Left: Jason-1. Right: Envisat.*

5.5. Impact of the new PTR data processing on Envisat

As already discussed earlier in part 4.2. concerning Envisat, some discrepancies can come from corrections applied to the raw Sea Surface Height provided by the altimeter. Improvements of new altimeter standards can be assessed thanks to tide gauges measurements to make the SSH more accurate. An example is described here when applying a new PTR data processing (that corrects for the internal path delay and attenuation) in the SSH calculation. Note that this new PTR data processing is not included in the 2011 Envisat reprocessing (V2.1).

Since tide gauges measurements are a way of estimating new standards in altimeter products, they have been used to demonstrate the relevance of a new PTR correction in the frame of the Sea Level Climate Change Initiative (SL-CCI) project supported by ESA (*www.esa-sealevel-cci.org*). In this frame, a study has been realized to compare the Envisat SSH time series deduced from 2 different PTR corrections with tide gauges measurements. As shown on figure 11, on the 2004-2010 time period, the monitoring of Envisat data when adjusting the new PTR displays an improvement in the consistency with tide gauges compared to the previous PTR correction. The slope differences between altimetry and tide gauges becomes on the same order of Jason-1 results, with a global trend of 0.2 mm/yr and a formal adjustment error of 0.17 mm/yr, in agreement with the theory and the multi-mission cross calibration studies. Such results demonstrate the ability of tide gauges measurements to quantify the improvement of the long-term MSL drift evolution on Envisat. Therefore, using external and independent datasets such as tide gauges is relevant in the estimate of new altimeter standards and thus the computation of new altimeter products.

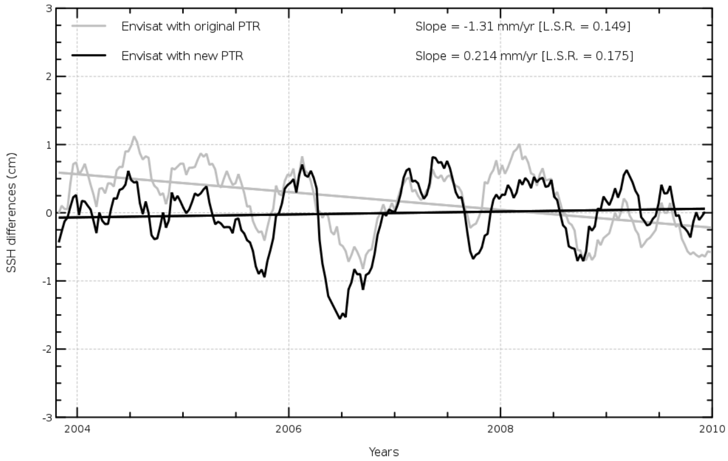


Figure 11: *Sea level differences between Envisat altimeter and tide gauges over the 2004-2010 time period (cm). Grey curve: Envisat original data. Black curve: Envisat corrected from the new PTR data processing.*

6. Quality assessment of tide gauges time series

To complete the global assessment of altimeter data where in-situ measurements are used as independent sources of comparison, tide gauge networks are compared to altimeter SLA time series. This part aims at detecting anomalies on in-situ time series from comparisons with all available altimeter data. This is mainly possible comparing SLA differences and allows us to detect jumps on in-situ time series which are not detected on altimeter ones. Moreover, maps of temporal correlation between altimeter and in-situ SLA time series are systematically produced for each tide gauge.

6.1. Presentation of the quality control performed on tide gauges measurements

The basic principle of the information cards is based on a summary of in-situ informations compared to altimeter data, which are then used to perform a quality control on each tide gauge.
Here are the main purposes of such information cards (figure 12):

- Tide Gauge identification: this part contains general informations about the tide gauge (network, coordinates, time period coverage and potential colocated GPS close to the tide gauge). The latter is important to correct the tide gauge from vertical movements. But to date, only a few tide gauge are colocated to a GPS beacon, that's why tide gauges are corrected from a global bias of -0.2 mm/year (Peltier, 2004 [32]).

- Temporal SLA comparisons with TOPEX/Poseidon, Envisat, Jason-1 and Jason-2: in this part results from the tide gauge processing data are used to compare the in-situ and altimeter SLAs and their differences on the tide gauge time period. Thanks to the multi-cross-calibration, drifts or jumps on tide gauge time series can be detected and then be used to perform the quality control.

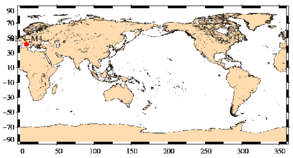
- Maps of SLA correlation with Jason-1, TOPEX/Poseidon and Envisat: to make the multi-cross-calibration reliable, another useful diagnostic concerns the correlation between altimeter and in-situ SLAs. Such maps have a double interest, first to estimate the distance between altimeter tracks and the tide gauge and second to see if both SLA are well correlated. The proximity of altimeter tracks depends on the mission itself, thus the distance between Envisat tracks and tide gauges is logically smaller than for Jason-1 (which does not mean correlations are even better). Concerning TOPEX/Poseidon, the tandem mission has a positive effect on this proximity with regard to Jason-1. Generally the correlation is good close to the coasts up to 0.9. But for some tide gauges, the value is low, maybe due to geophysical processes but also to jump or drift in in-situ data. The comparison of altimeter and in-situ SLA allows us to assess the tide gauge SLA as well as the altimeter SLA.

- Tide Gauge reliability: finally the information card gives a summary of different relevant diagnostics such as the slope of the potential tide gauge crustal drift, the SLA maximal correlation, the filtered and non-filtered SLA differences RMS, the SLA differences slope and finally the quality control applied on each tide gauge deduced from all these informations.

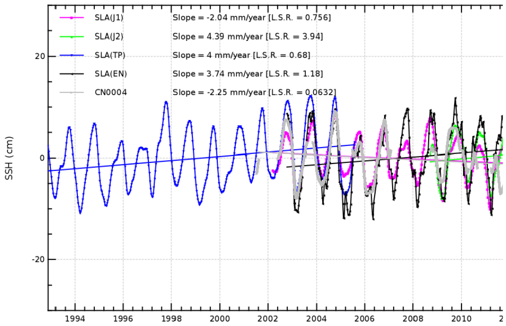
SENETOSA_M4(CN0004)

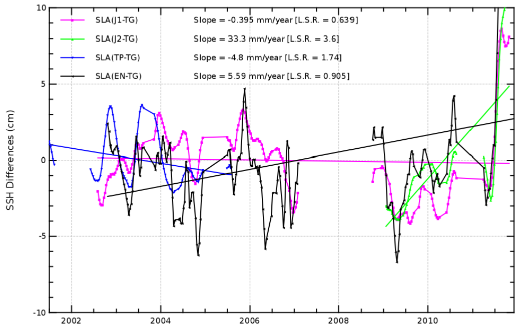
Tide Gauge identification

Tide Gauge Network	CNES
Location (Lat/Lon)	41.56 deg / 8.80 deg
Time series coverage	From 01/01/1997 to 31/03/2012
Vertical movements drift	YES (0 mm/yr)
Key Performance Indicator (1)	

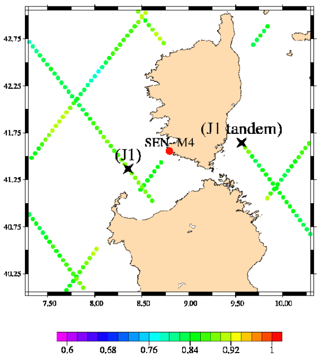


Temporal SSH comparisons with Jason-1 and Jason-2, TOPEX/Poseidon and Envisat

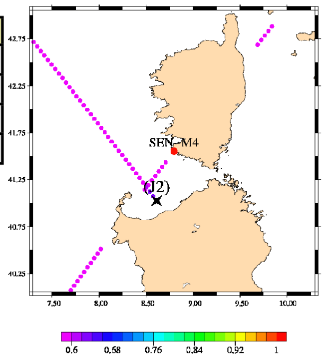


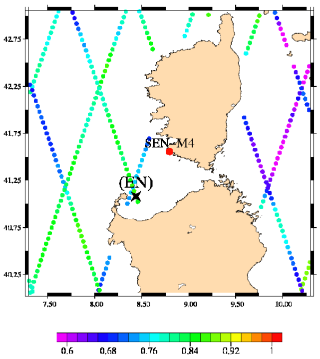


Maps of SSH correlation with Jason-1 and Jason-2, TOPEX/Poseidon and Envisat

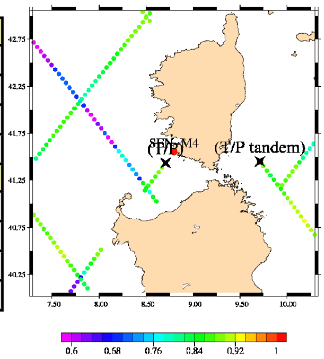


Jason-1	Jason-2
42.4 km (2)	60.9 km (2)
0.89 (3)	0.65 (3)
0.98 cm (4)	3.6 cm (4)
-1.1 mm/yr (5)	29.7 mm/yr (5)
Jason-1 (tandem)	
64.6 km (2)	
0.91 (3)	
0.79 cm (4)	
11.6 mm/yr (5)	





Envisat	T/P
60.9 km (2)	15.4 km (2)
0.87 (3)	0.90 (3)
1.6 cm (4)	- cm (4)
2.2 mm/yr (5)	16.4 mm/yr (5)
	T/P (tandem)
	77.2 km (2)
	0.89 (3)
	1 cm (4)
	1.3 mm/yr (5)



[1]Performance of the TG with regard to altimetric missions (Correlation > 0.7 and Rms differences < 10 cm)
[2]Distance between the tide gauge and the maximum of altimeter SSH correlation
[3]Maximum of SSH correlation
[4]Standard deviation of filtered SSH differences
[5]Slope of filtered SSH differences

Figure 12: *Example of an information card for the Senetosa tide gauge*

These cross-comparisons are performed by analyzing the correlation between altimeter and tide gauge SSH time series. Spurious measurements detected on tide gauge time series can then be corrected or removed to further improve the SSH comparison with altimeters. An example is given for the Balboa tide gauge located at the beginning of the Panama Canal in the Pacific Ocean (figure 13).
Looking at the SSH differences with altimeter data, a weird behavior of the sensor is highlighted thanks to the 3 main missions Jason-1, TOPEX/Poseidon and Envisat between 2002 and 2006, which trends differences are on the order of -3 mm/yr for Jason-1 and Envisat and -6 mm/yr for TOPEX/Poseidon. However, since trend differences from the different altimeter regarding tide gauges measurements are very well correlated with each other, a potential anomaly seems to be detected on the tide gauge itself. Comparing multiple altimeter data with each tide gauge measurements is a way of detecting potential drifts or jumps on in-situ time series. Thus, the combination of several altimeter data can provide a quality control for the whole tide gauge dataset.

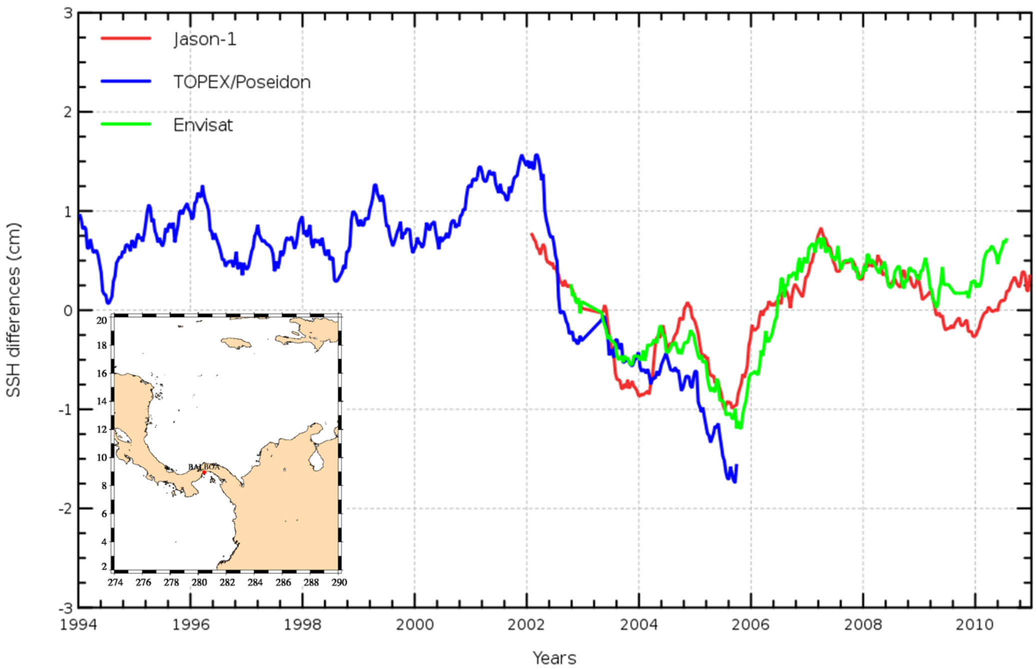


Figure 13: *SSH differences between the main altimeter data and Balboa tide gauge measurements using a 8 months Lanczos filter (and location of the Balboa tide gauge in the Panama Canal)*

From now on, this quality control of each tide gauge is displayed as a cross-comparison indicator on the AVISO website (*www.aviso.oceanobs.com/fr/calval/in-situ-global-statistics*). It is performed to select relevant tide gauges for the altimeter/in-situ comparisons. The map of cross-comparison indicators (figure 14) displays the way comparison between altimetry and tide gauges is reliable. This reliability of an altimeter mission in the assessment of the quality of the in-situ time series is defined through the two main criteria (correlation and rms) described in the method itself (see part 3.3.). If both altimetry and in-situ meet the conditions for the main missions T/P, Jason-1&2 and Envisat, the tide gauge is considered reliable enough to be compared with altimetry.

Figure 14: *Map of the Cross Comparison Indicator applied on tide gauges as displayed on the AVISO website. Credits: GoogleMap (Imagerie 2011 NASA)*

Thus, 5 colors have been chosen to represent the number of altimeter consistent with the tide gauges ones:

- Black: No satellite checking the criteria
- Red: 1 satellite checking the criteria
- Orange: 2 satellites checking the criteria
- Yellow: 3 satellites checking the criteria
- Green: at least 4 satellites checking the criteria

Consequently, while a green indicator will attest of the relevance of a tide gauge time series to perform SSH differences with altimetry, a black indicator does not indicate necessarily a bad quality of a tide gauge time series but for instance that there is none altimeter data covering the time period of the tide gauge and thus that the tide gauge will not be used in the assessment/validation of altimeter data. To date, the cross comparison indicator can attest of the reliability of tide gauges time series in the detection of altimeter MSL drifts or the assessment of new altimeter standards. Further out, it could be used to improve and even correct some anomalies detected in tide gauges time series, which is of particular interest to the altimeter/tide gauges comparisons.

6.2. Availability of tide gauge information cards

Since September 2009, information cards for both GLOSS/CLIVAR and REFMAR networks are routinely performed each week and distributed on the AVISO website (*www.aviso.oceanobs.com/fr/calval/in-situ-global-statistics*).
A googlemap mapplet has been developed and information cards can be visualized online (figure

14). As the tide gauge coordinates accuracy is on the order of the minute, the geodetic reference system of our database may slightly differ from the googlemap one, which can induce some slight differences in tide gauge locations.

In 2012, the computation of information cards and thus the cross-comparison indicators will also be performed for the new tide gauges networks such as MyOcean and PSMSL and thus displayed on the AVISO website.
Concerning the Senetosa tide gauge, figure 12 demonstrates the first guess of the information card concerning the cross-comparison indicator of the M4 tide gauge time series.
Furthermore, future actions in 2012 will improve this googlemap on the AVISO website, especially with arrows concerning the Mean Sea Level trend at the tide gauge location.

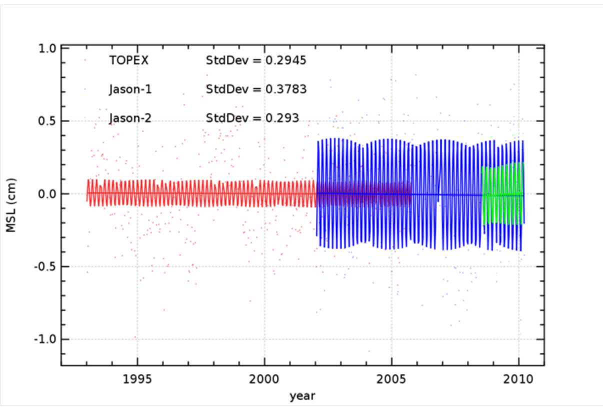
7. Particular investigations using tide gauges measurements

7.1. Overview

The new processing sequence developped during the past year reinforced the idea that using independent datasets like in-situ measurements is a reliable external way of validating altimeter data of multiple space missions. In addition to these basic diagnostics, several studies were performed in the frame of the different activities involving tide gauge measurements. In 2010 for instance, a study was dedicated to consider in-situ tide gauges measurements so as to detect the 58.74 day signal observed on the MSL derived from Jason-1/2 and TOPEX or anomalies on the Envisat altimeter data.
In 2011, several investigations have been performed too. This part will first demonstrate the impact of the Glacial Isostatic Adjustment on tide gauges time series and its relevance in the comparisons with altimeter data. Then will be presented results deduced from the processing sequence and concerning the comparison of altimeter products with tide gauges measurements to assess the sea level variability in the Arctic Ocean.

7.2. Analysis of the 58.74 day signal observed on Jason-1&2 and TOPEX data

As shown on figure 15 left, global MSL time series display a strong 58.74 day signal on Jason-1 and 2 (with amplitudes around 3-4 mm)) while it is smaller on TOPEX data (1 mm). In the same way, the map of the 58.74 day amplitude signal (figure 15 right) displays stronger amplitude patterns for Jason-1 (greater than 5 mm) in the -40°/40° latitude area.



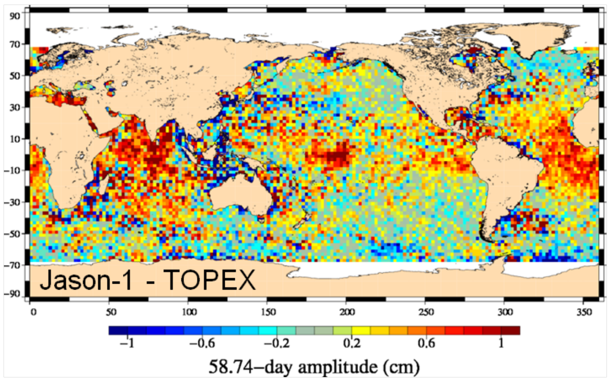
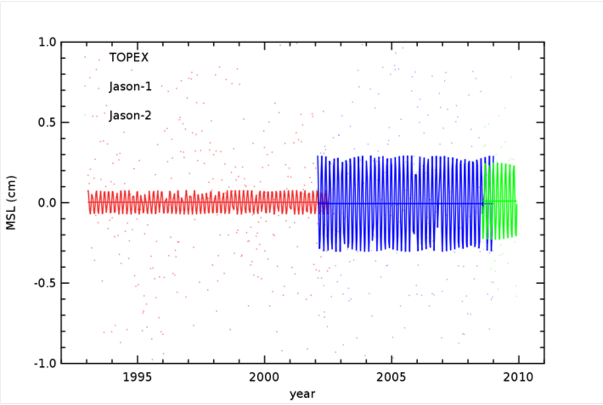


Figure 15: *Left: 58.74 day signal on global MSL after removing the global trend. Right: Map of the 58.74 day signal observed between Jason-1 and TOPEX.*

To check such results obtained between Jason-1 and TOPEX, in-situ measurements were used and computed with the new processing sequence developped in 2010. It appears that SSH differences between altimetry and tide gauges highlight a 58.74 signal of about 3-4 mm for Jason-1 and 1 mm for TOPEX too (see figure 16).
Thanks to the comparison with independent in-situ tide gauge datasets, it has been demonstrated that the 58.74 day signal was not a physical signal but an error in altimeter data.



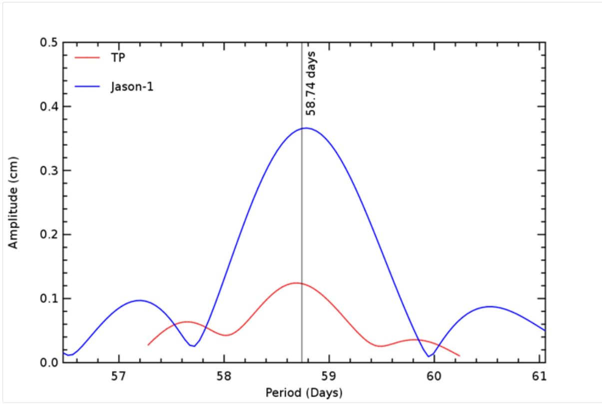


Figure 16: *Left: 58.74 day signal on altimeter/tide gauges SSH differences after removing the global trend. Right: Periodogram on altimeter/tide gauge SSH differences focused on 58.74 day signal*

Although the comparison of altimeter data with tide gauges measurements do not bring the solution of this processing anomaly, this study demonstrates how useful are these independent in-situ data to confirm such potential problems on altimeter corrections. In this study, differences observed between GOT4.7 and FES04 are likely due to differences in altimeter standards applied to assimilate altimeter measurements in the model processing.

In this case, it has been concluded that the main part of the 58.74 day signal observed on the Jason-1 MSL is due to the use of the GOT model in the SSH calculation, which may have absorbed errors contained in the altimeter measurements. Indeed, using the altimeter/tide gauges SSH differences data to estimate the spatial amplitude of the 58.74 day signal on Jason-1 (see figure 17), we can observe that residual signals are two times higher than FES04 in terms of amplitude considering the GOT4.7 tide model (8 mm with GOT4.7 whereas it is 4 mm with FES04).

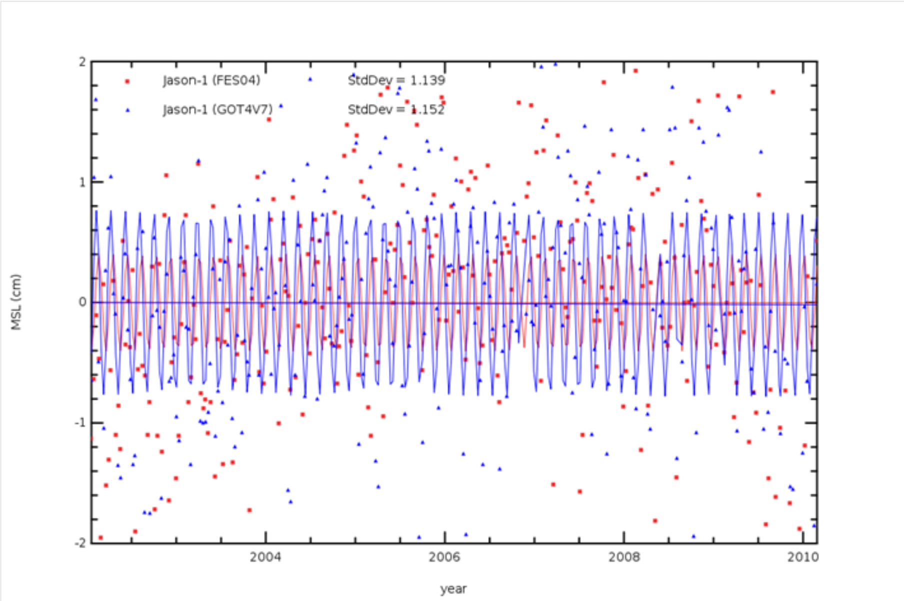


Figure 17: *Spatial amplitude of the 58.74 day signal on Jason-1/tide gauges SSH differences using GOT4.7 and FES04 tide models*

7.3. Assessment of the Glacial Isostatic Adjustment on tide gauges time series

In order to assess the rate of global sea level rise, two problems have to be taken into account when using tide gauges. The first is the fact that tide gauges measure sea level relative to a point attached to the land which can move vertically at rates comparable to the long term sea level signal. The second problem is the spatial distribution of tide gauges, in particular those with long records, which are restricted to the coastlines (Woppelmann et al., 2007 [42]). This part of the document focuses on the first point, related to the Glacial Isostatic Adjustment (GIA).

Indeed, so as to make the comparison with altimeter data more relevant, the effect of GIA on tide gauges has to be taken into account. To date, the problem of correcting tide gauges records from vertical land motion upon which they are settled has only been partially solved. At best, the analyses so far have included corrections for one of the many processes that can affect the land stability, namely the Glacial Isostatic Adjustment (GIA). In this study, ICE-5G VM2 and ICE-5G VM4 GIA models are considered (Peltier, 2004 [32]). Figure 18 displays the global trends derived from these both datasets. Since only slight differences remain between these ice models, it has been decided to correct tide gauges time series from the ICE-5G (VM4), which is the most recent and updated GIA model (it is computed with the VM4 viscosity profile in the Earth model) and thus provides the most accurate assessment of GIA trends at each tide gauge location.

Considering Jason-1 (figure 19 left), the global trend of the time series considering the ICE-5G (VM4) GIA model is reduced to 0.2 mm/year (red curve), which slightly improves the consistency between both datasets. On the Envisat monitoring (figure 19 right), the slope is -2 mm/year considering the ICE-5G (VM4) GIA model (red curve). Linked to previous results (see part 5.5.), the consistency should be improved with the new PTR correction.

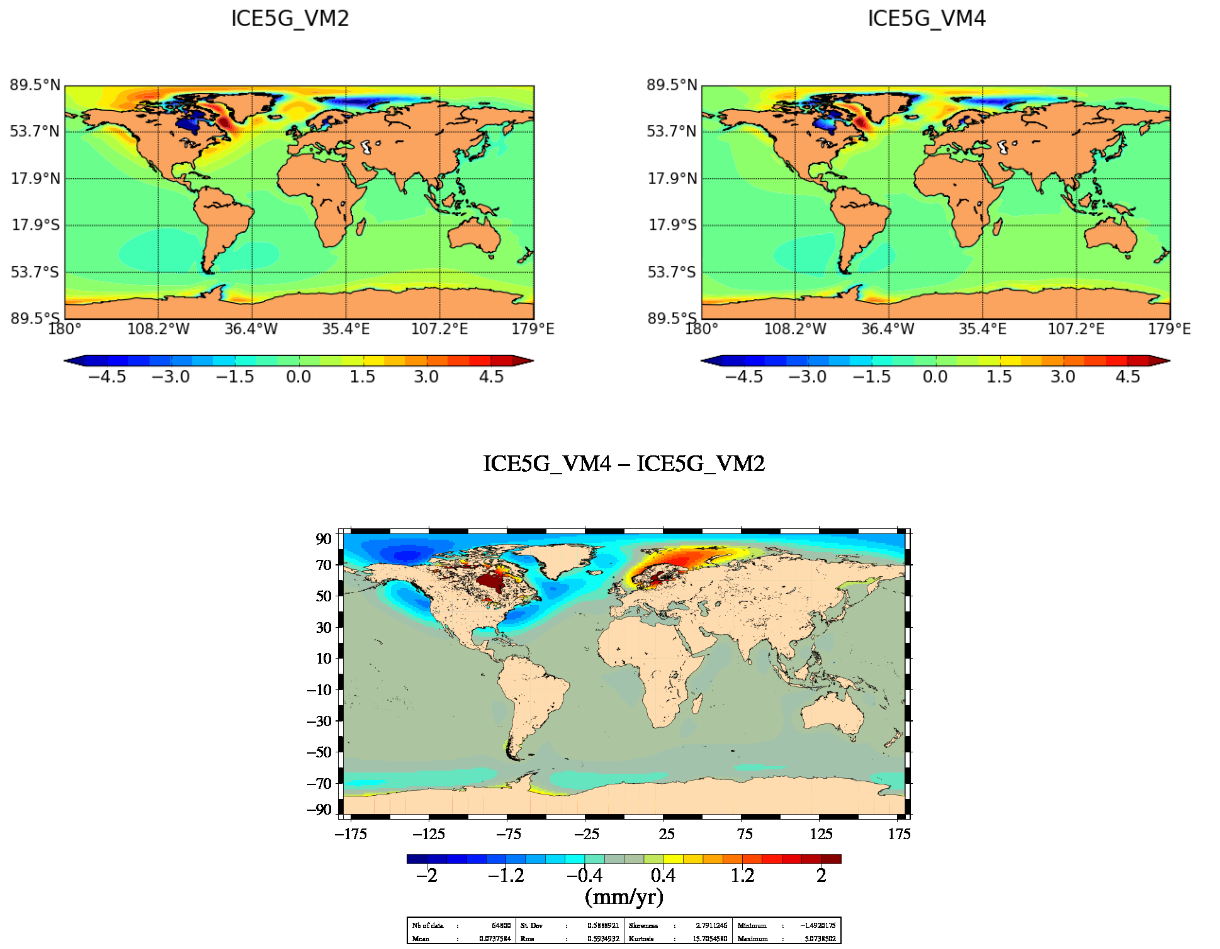


Figure 18: *Map of the trends of GIA derived from the ICE-5G model from Peltier (mm/year). Left: VM2. Right: VM4. Bottom: Differences between both VM4 and VM2 ICE-5G GIA models.*

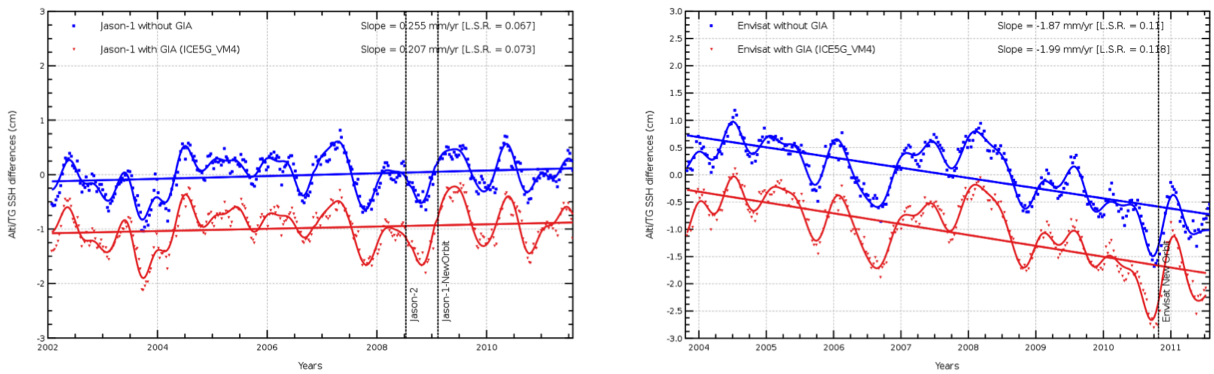


Figure 19: *Impact of the ICE-5G (VM4) ice model on the cycle by cycle monitoring of mean SLA differences between altimeter and tide gauges measurements. Left: Jason-1. Right: Envisat.*

However, GIA models don't account for the other sources of vertical land motion that can affect tide gauges. Thanks to GPS beacons, a very accurate estimate of vertical movements could be calculated at tide gauge locations. Thus, studies will have to be performed in the next years to perform a new method to compute an accurate vertical movement correction at tide gauges location using GPS data.

7.4. Sea level variability in the Arctic Ocean

This part aims at comparing monthly tide gauges time series from the Pemanent Service for Mean Sea Level (PSMSL) at high latitudes to the reprocessed Arctic gridded products derived from DUACS DT data. Results deduced from this study has underlined several problems on both in-situ and altimeter data in this area, such as discontinuities on data time series or a strong impact of the GIA. Indeed, while the map of maximum of correlation between altimetry and tide gauges (figure 20 left) displays a pretty good consistency between both datasets along the Norvegian coasts, correlations strongly decrease when evolving inside the basin. However, the comparison between altimeter data and tide gauges measurements lead to multiple interesting conclusions:

- Map of the RMS of SLA for both altimetry (background colors) and tide gauges (colored circles superimposed) as displayed on figure 20 right confirms the idea of a strong variability area in the East Siberian Sea, which is therefore not an error in the altimeter data.
- High resolution altimeter gridded products (1/8° spatial resolution) are able to render the same coastal dynamical effects as recorded with tide gauges measurements (see figure 20 bottom where the correlation suddenly decreases over the continental shelf).
- However, because of errors related to the GIA on tide gauges and large uncertainties on altimetry at these latitudes, the processing sequence cannot yet provide an accurate estimate of a potential drift on altimeter data regarding tide gauges measurements.

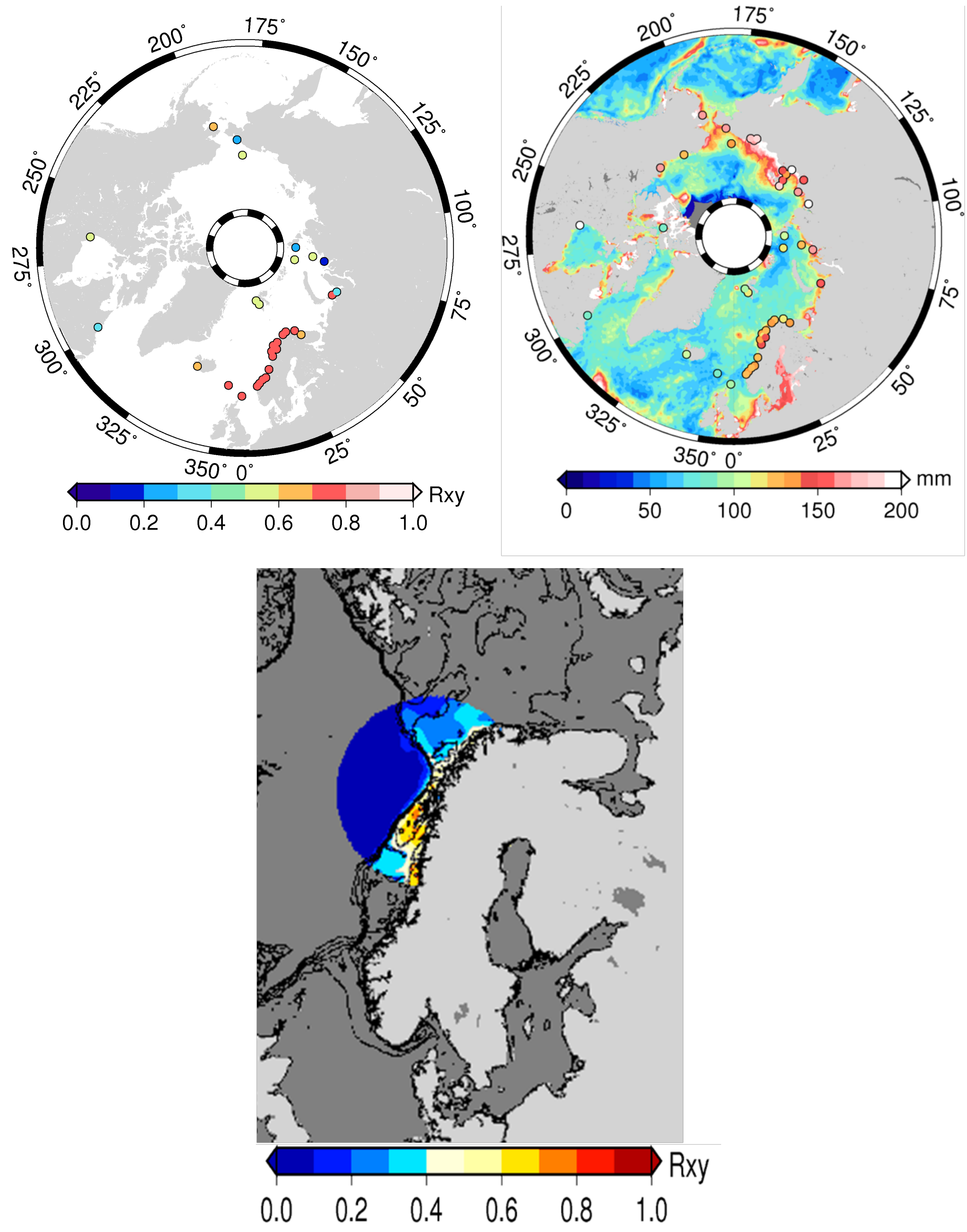


Figure 20: *Left: Maximum of correlation between reprocessed Arctic gridded products derived from DUACS DT data and tide gauges measurements in the Arctic Sea. Right: RMS of SLA for both altimetry (background colors) and tide gauges (colored circles surimposed). Bottom: Correlation coefficients between reprocessed Arctic gridded products derived from DUACS DT data and tide gauges measurements along the norvegian coast.*

8. Conclusions and futures

This report demonstrates the interest of tide gauges measurements to assess potential drifts or jumps in the altimeter measurements. Reliable results are obtained thanks to a data processing procedure performed in an operational frame (development and operational account, automatic processing, ...). This operational aspect of the data processing procedure is fundamental to quickly reprocess the whole altimeter period and take into account new altimeter standards as it was performed in 2009 for Jason-1 and in 2011 for Envisat GDR-C releases.

Concerning the accuracy of altimeter data, the reliability of Jason-1 missions has been confirmed since no MSL drift is detected when comparing to tide gauges, within the error of the method, estimated to 0.5 mm/yr over the altimeter time period (Ablain et al., 2009 [3]). In the same way, a drift of almost -2 mm/yr is highlighted on Envisat, linked to some potential errors on instrument like the USO clock period for instance (Martini, 2003 [27]). The comparison with tide gauges measurements has also underlined some errors in the sea level computation such as the TOPEX-A anomalies (whose impact on climate studies could be corrected by a T/P reprocessing) and the 58.74-day aliased signal in ocean tide models (AVISO, 2011, Jason-1 annual validation report [8]). These results are in agreement with global Calval studies, which reinforced the idea of using independent in-situ tide gauge measurements is a way of getting an assessment of the error on the global MSL trend.

Global or regional drifts detected on altimeter time series are then supposed to be corrected to improve altimeter products for end-users. Therefore, new altimeter standards are produced, and their impact in the sea level computation can be assessed thanks to in-situ measurements. The comparison with tide gauges data has confirmed that the Envisat MSL drift, calculated with the new PTR correction computed in the frame of the Sea Level Climate Change Initiative (SL-CCI), becomes more homogeneous with Jason-1 results, with a SSH slope differences of 0.2 mm/yr. Thus, considering Envisat GDR-C reprocessing, the use of the new PTR SL-CCI data processing, really improves the Envisat long-term stability.

Moreover, the method presented here can provide a quality assessment on both altimeter and in-situ datasets through SSH comparisons. Thus, cross-comparison indicators are displayed as information cards for both GLOSS/CLIVAR and REFMAR networks, which are now routinely performed each week and distributed on the AVISO website (*www.aviso.oceanobs.com/fr/calval/in-situ-global-statistics*). The goal of such quality assessment is to detect anomalies and thus qualify in-situ measurements using multiple altimeter time series. Therefore, the comparison of tide gauges measurements with altimeter data enables to point out drifts or jumps in in-situ time series, which need to be corrected to improve the coherence between both datasets. These quality controls then provide reliable datasets of in-situ measurements, which are relevant to detect potential altimeter drifts or jumps and to estimate the quality of new altimeter standards.

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. Other kinds of in-situ instruments such as gliders (Bouffard et al., 2010 [14]) can be considered to perform comparison with altimeter sea level provided that physical contents are corresponding. The duality of these both types of data will constitute an asset for the calibration of future space missions as the Sentinel3 mission (*sentinelle3.com*) or the Surface Water Ocean Topography (SWOT) mission (*swot.jpl.nasa.gov*). It will also be of great interest to assess improvements of reprocessed altimeter data such as time series of ERS-1&2 (ESA REAPER project). 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.

Finally, while the method described in this study provide reliable results on the comparison between independent altimeter and tide gauges datasets, some improvements on both method and datasets still remain. For instance, vertical movements on tide gauges are currently taken into account in the SSH computation when considering Glacial Isostatic Adjustment models (Peltier, 2004 [32]). The use of GPS (Global Positioning System) measurements at tide gauges locations (Bouin et al., 2010 [15]) are of great interest and would probably improve results. Moreover, although the new processing sequence is fully operational and routinely used in the different studies involving in-situ data, several improvements are planned for the next years in order to better benefit from tide gauge measurements and thus improve the relevance of analyses. In 2012, several points will be developed to give better results:

1. Considering the tide gauges datasets:

   - Both MyOcean and PSMSL tide gauges datasets will be routinely computed in the CLS database.
   - Concerning vertical movements, several tests on regional areas or specific basins will be performed to quantify the impact of this correction with a better GPS space sampling at tide gauges locations.
   - The impact of non-equilibrium long period tides will be further studied since it is considered as a potential explanation for the remaining annual and semi-annual signals in altimeter and tide gauges SSH differences.
   - New algorithms or filters are expected to be tested to remove high frequency signals from tide gauges measurements.

2. Considering the processing sequence:

   - A new processing sequence based on the computation of the minimal Taylor distance (combining both correlation and RMS of the altimter/tide gauges SSH differences) will be developed.
   - The impact of computing altimeter gridded products with different spatial resolutions will be studied.
   - The new 2011 Mean Sea Surface has to be computed in the processing sequence.

3. Considering the AVISO website:

   - The Senetosa tide gauges data time series will be distributed.

- A feedback to the suppliers of tide gauges measurements will take place to perform a routinely operational quality control of the in-situ data distributed.
- The tide gauge googlemap will be improved, especially with arrows concerning the Mean Sea Level trend at tide gauges locations.

Note that this activity has been presented this year at both Envisat Quality Working Group (QWG) in Corsica and Italy, at the OSTST in San Diego [39], and to the CNES in CLS office. Furthermore, a training period, aiming to develop a worldwide access to CLS in-situ databases, was performed in 2011 and a paper has been submitted for the 3rd issue of Marine Geodesy OSTM science results (Valladeau et al., submitted [40]).

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10. Annexes

10.1. Annex: General operating diagram

The following diagram sums up the main steps of the altimeter/tide gauges comparison procedure:

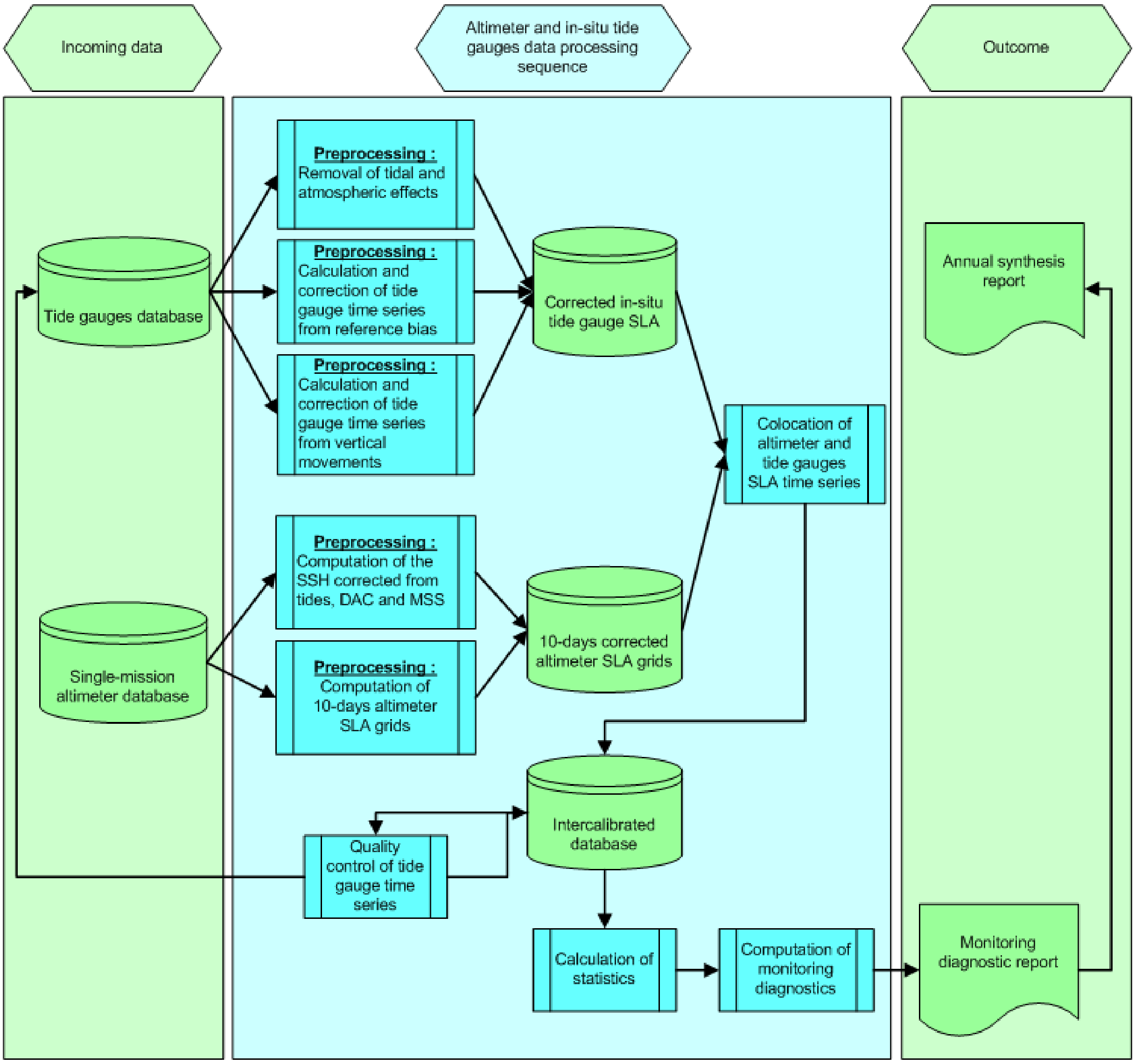

Figure 21: *General operating diagram of the tide gauge data processing sequence*

The main point is to underline the matter of the whole components of the Calval activity and their flexibility in performing this data processing sequence. In addition, the method presented here is scalable and thus reliable, which makes the altimeter/tide gauges comparison procedure a perennial validation activity for space missions in the Space Oceanography Division at CLS.

10.2. Annex: Corrections applied for altimeter SSH calculation

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

Sea Surface Height field name	Altimeter standards			
	Jason-1 (GDR-C)	Jason-2 (GDR-T)	TOPEX/Poseidon (MGDR)	Envisat (GDR-V2.1)
Orbit	CNES POE (GDR-C standards)		GSFC POE (09/2008), ITRF2005+Grace	Cycle 15 onwards: CNES POE (GDR-C standards)
Mean Sea Surface (MSS)	MSS CLS01 (v1)			
Dry troposphere	ECMWF model computed			
Wet troposphere	Jason-1 radiometer (JMR)	Jason-2 radiometer (AMR)	TMR with drift correction and empirical correction of yaw maneuvers	MWR (corrected from side lobes from cycle 41)
Ionosphere	Filtered dual-frequency altimeter range measurements		Filtered dual-frequency altimeter range measurements (for TOPEX) and Doris (for Poseidon)	Dual-Frequency Updated with S-Band SSB (< cycle 65) GIM model + global bias of 8 mm (>= cycle 65)
Sea State Bias	Non parametric SSB (GDR product)		Non parametric SSB (for TOPEX), BM4 formula (for Poseidon)	Updated homogeneous to GDR-C
Ocean tide and loading tide	GOT4.7 (S1 parameter is included)			
Solid Earth tide	Elastic response to tidal potential [Cartwright and Taylor, 1971], [Cartwright and Eden, 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	Jason-2 / T/P global MSL bias	Doris/Altimeter ionospheric bias, TOPEX-A/TOPEX-B bias and TOPEX/Poseidon bias	USO correction from auxiliary files + bias for side-B

Figure 22: *Altimeter standards applied to TOPEX/Poseidon, Jason-1&2 and Envisat*