Validation of altimeter data by comparison with tide gauges measurements: yearly report 2015

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

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1. Introduction - Document overview

This document is the altimeter/tide gauges comparison activities synthesis report for the year 2015. It sums up the activities performed in the frame of the 2011-2015 SALP project funded by CNES. Note that these activities were also supported by ESA concerning the ENVISAT mission.

Methods used for the calibration and validation of satellite altimetry data can be separated in three broad categories, which are graphically summarized as the *CalVal triforce* on figure 1. These three categories are:

- mono-mission analysis where the internal consistency of one mission is assessed,
- multi-mission analysis which cross-compare two or more altimeter missions to check for any drifts or biases,
- comparisons with in-situ data which provide an external, independent reference.

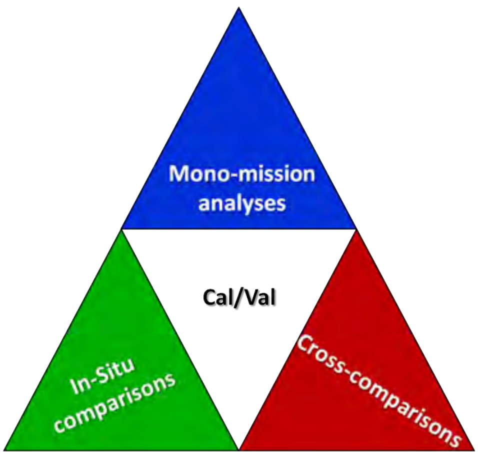


Figure 1: The triforce of Cal/Val activities for satellite altimetry missions

In the present report we focus on the latter category of activities, and more specifically on comparisons with tide gauges. Comparisons between satellite altimeter data and tide gauges are performed by several groups, and the methods used can be divided into two categories:

- comparisons at dedicated calibration sites where one (or a few) carefully monitored in-situ sensor is used, with the aim of detecting offsets and long-term drifts of altimeter missions. Such sites are rare (Harvest, Senetosa and Bass Strait) and generally dedicated to the validation of one mission (orbit dependent),
- global comparisons using a wide network of tide gauges (generally around 100 sites) distributed over the entire ocean. From this ensemble of local altimetry/in-situ comparisons, global averages are estimated.

At CLS, we use a global altimetry/tide gauges comparison method which falls in the second category of these techniques: a global difference is estimated at each time step from a network of in-situ stations. This way of processing data is replicated for all altimetry cycles to build global average time series. These time series, along with other statistics, are used for three main goals:

1. Detect drifts and shifts in the altimeter sea level time series

2. Estimate the improvements provided by new altimeter standards (orbit solution, geophysical corrections...) on the SSH consistency between altimetry and tide gauges

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 ...)

In 2015, and following the work initiated in 2014 as an answer to OST/ST 2013, we have emphasized our work on estimating the sensitivity of the method. A large part of this report is thus dedicated to this topic. The present report is organised in four main chapters:

- the first one is dedicated to the description of the tide gauges database used at CLS, with a focus on the work performed to ensure a better robustness of how we acquire in-situ data,
- the second one is dedicated to the comparison methodology used. It includes a precise description of how the comparisons are drawn from local SSH at tide gauge stations to global averages,
- the third part of this report presents the latest results of the routine monitoring we perform on satellite altimetry missions to detect any biases or drifts on satellite records,
- the fourth and last section of the report presents the different investigations performed this year, which are mainly dedicated to the assessment of the sensitivity of the method.

2. Database: a review of tide gauges datasets in use

2.1. Overview

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

A new way to acquire tide gauge data was introduced three years ago, and was gradually made robust and fully operational since then. This year, the work on acquisition routines has been carried on in order to provide an operationnal solution to tide gauge end users.
Two different databases are now available:

- a *raw* database which results of the direct download and the storage of the raw data, with the whole information about each tide gauge (name, network, coordinates, quality and other miscellaneous information), as provided by the data delivery services,
- a *validated* database dedicated to the comparison with altimetry, where different standards are updates (oceanic tide, land motion, wind stress effects, ...) in order to get fully post-processed tide gauge measurements.

Multiple post-processed databases can be set up, depending on the temporal resolution of the tide gauge time series. Note that although the first step of this acquisition is the same for all networks (retrieval of the data from ftp, http adresses or even process local data), the post-processing is specific for each one, depending on the characteristics of the in-situ time series acquired.

2.2. Acquisition

For the different tidal networks used at CLS (see section 2.4 “Tidal networks”), we routinely check the data provider servers for data updates. If so the new data are downloaded and converted into CLS internal format to create our raw database. At this step, the raw sea surface height and several static informations are acquired (network, sensor code, sensor coordinates). In 2015, we had to face several events regarding data retrieval from external servers leading to acquisition errors on CLS side, and a delay on the update of our databases. In order to prevent future impacts on the update of the in-situ database, acquisition software has been made more robust to errors on the data providers side.

2.3. Post-processing

After downloading and converting in-situ SSH measurements into our internal raw database, the measurements are used to populate the validated database where several post-processing steps are applied to the data to enrich the raw in-situ SSH values and make them comparable with satellite altimetry data:

1. filtering of tide gauge data in order to remove the short and long tidal wavelengths (diurnal, semi-diurnal and long period tides),
2. interpolation of the high resolution dynamical atmospheric correction (MOG2D model) at the time and position of the measurement to remove high frequency wind driven signals,
3. interpolation of a model for local vertical land motion,

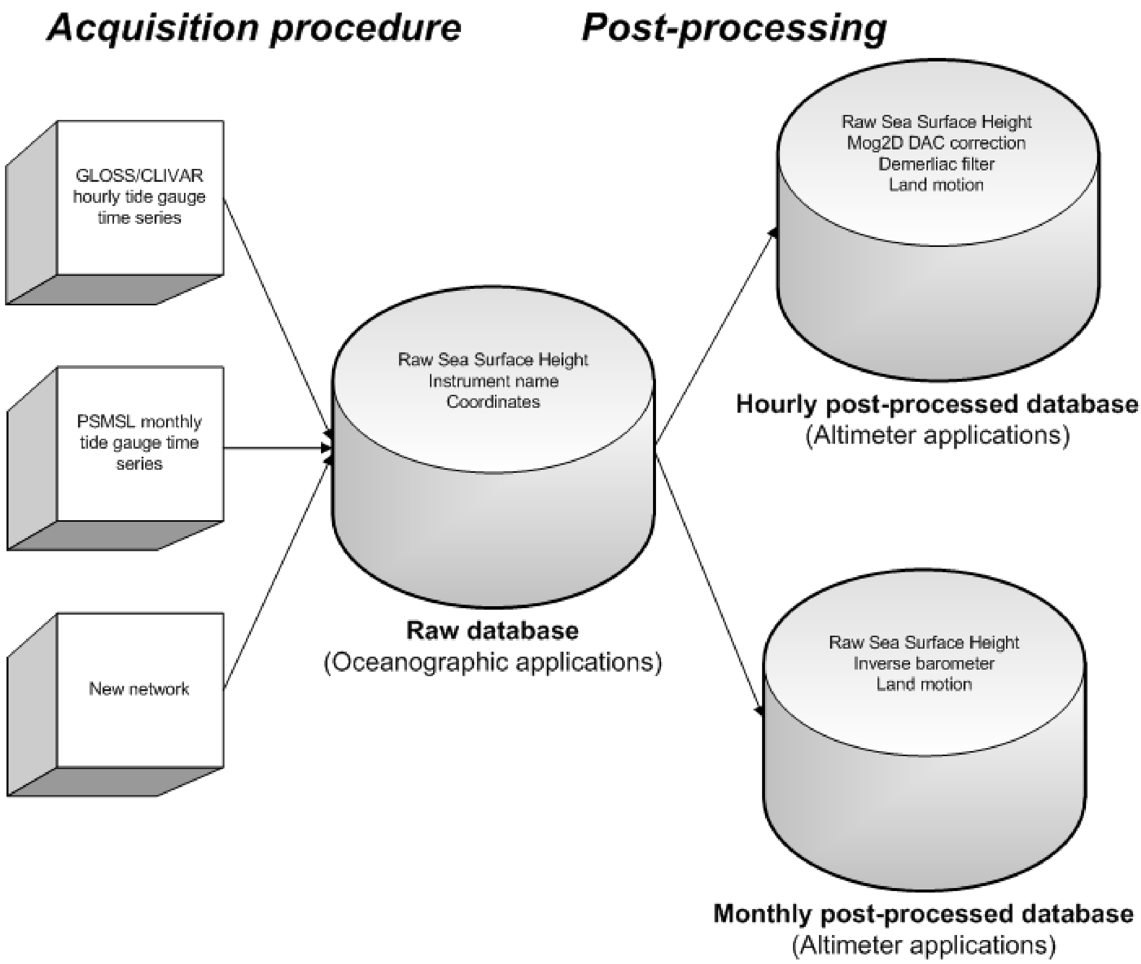


Figure 2: Acquisition procedure of tide gauge data and conversion to "in-situ measurements tables" specific format.

To date, the tidal database is considered as an operational system and updated every week according to the availability of new tide gauge measurements.

2.4. Tidal networks

This section presents the tidal networks currently available at CLS. The historical tidal database consisted in different tide gauges networks resulting from different collaborations. The data covered several time periods and were used for various kind of scientific studies. With the same goal, the current database is now routinely updated with two global tidal networks (GLOSS/CLIVAR and

PSMSL). Other networks are also acquired, but they are often less complete than the two previous ones. The whole tide gauges networks available in our database are presented here.

2.4.1. GLOSS/CLIVAR network

The GLOSS/CLIVAR (Global Sea Level Observing System/Climate Variability and Predictability) network is the most important network currently in use. It provides time series at about 250 tide gauges stations, with an hourly temporal sampling. These measurements are used for tide prediction as well as altimetry validation. We use the fast delivery dataset to benefit from the short delay between sensing time and delivery time. Data are retrieved through the University of Hawaii' Sea Level Center (UHSLC) ftp server at ftp.soest.hawaii.edu/uhslc/woce/. The current geographical distribution of the GLOSS/CLIVAR data is displayed on figure 3.

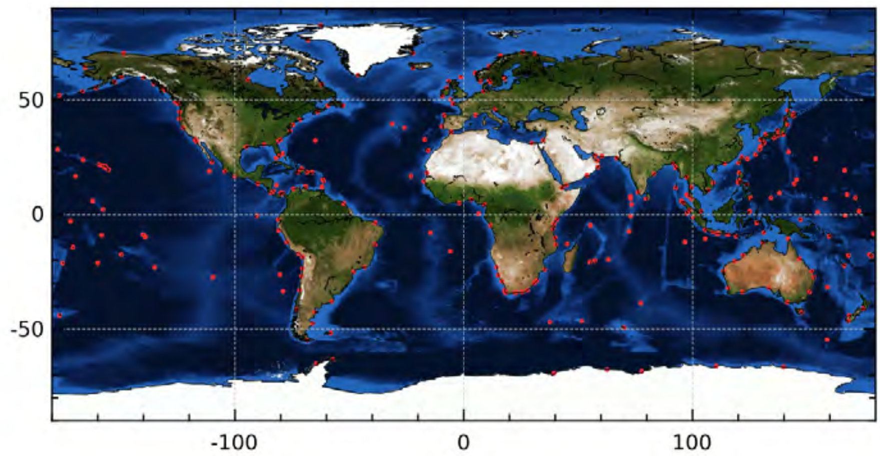


Figure 3: Geographical distribution of GLOSS/CLIVAR tide gauges stations

It should be noted that we are therefore heavily relying on the UHSLC to retrieve data. One event occured this year that prevented us from getting data:

- a change in access rights on the UHSLC ftp server for one file, which caused an error of our software (no data acquired at all).

Despite an efficent feedback from UHSLC team members and a continuous effort to make our software more robust, data acquisition on our side may be impacted by such events in the future.

2.4.2. PSMSL database

The Permanent Service for Mean Sea Level (PSMSL) maintains a large historical database which contains more than 1350 tide gauges. Monthly estimates of SSH are provided, higher frequency data is not available. Data are retrieved through the PSMSL website at http://www.psmsl.org, on a weekly basis, but the delivery delay is generally much longer than for the GLOSS network. The geographical coverage of this network is displayed on figure 4, but it should be noted that all the stations are not suitable for global comparisons to altimeter data.

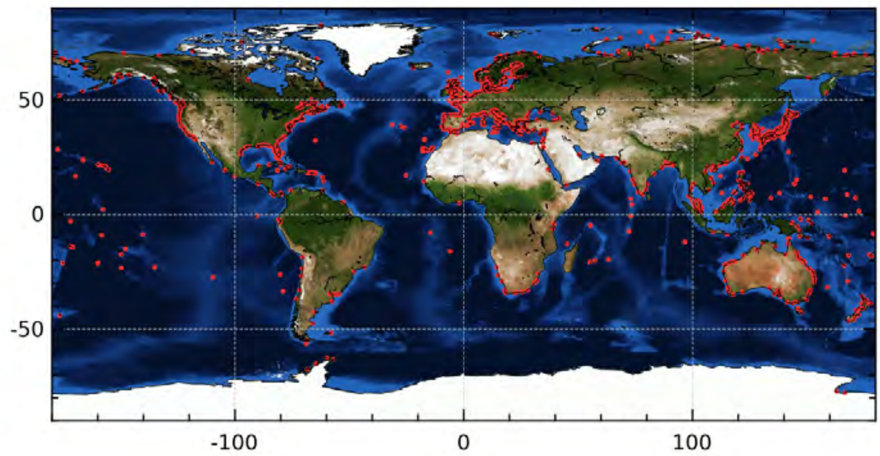


Figure 4: Geographical distribution of PSMSL tide gauges stations

2.4.3. REFMAR database

Last year we begun the acquisition of the REFMAR database, which was continued over year 2015. This is a French database operated by SHOM (http://refmar.shom.fr). We are currently downloading weekly the data from the SHOM servers. The geographical coverage of this network is displayed on figure 5.

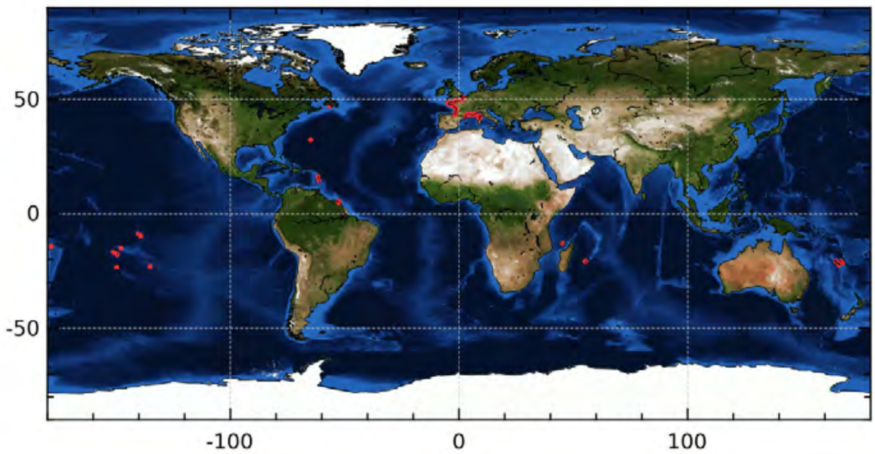


Figure 5: Geographical distribution of REFMAR tide gauges stations

2.4.4. Copernicus dataset

Tide gauges time series are delivered daily by IFREMER in the framework of the Copernicus project. For data validation purposes, we perform daily acquisitions of this data but do not use these data for Cal/Val activities. For information purposes, the distribution of the Copernicus network is displayed on figure 6.

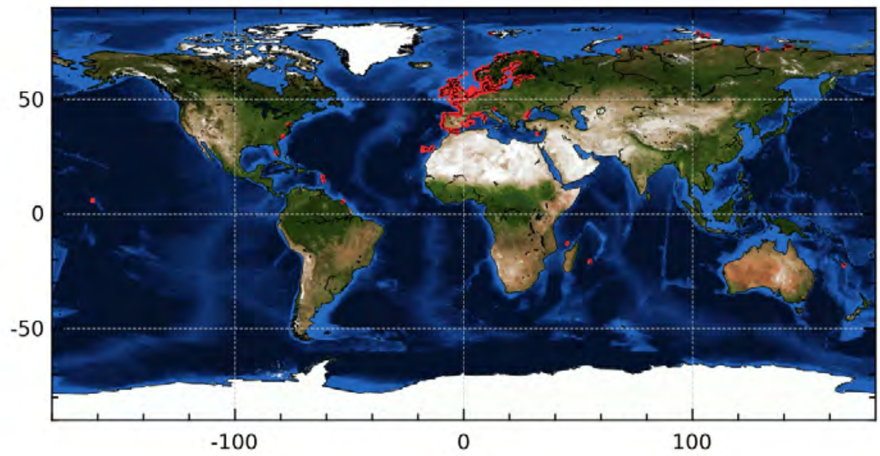


Figure 6: Geographical distribution of Copernicus tide gauges stations

2.4.5. Other data sources

Note that the Senetosa tide gauge time series of the M3, M4, M5 and M7 sensors are made available through the AVISO website (*www.aviso.oceanobs.com*), where the in-situ section is divided into 2 parts, one concerning the absolute calibration and the other dedicated to the global comparison with altimetry. All these sensors are located in Corsica, as shown on the map fo figure 7.

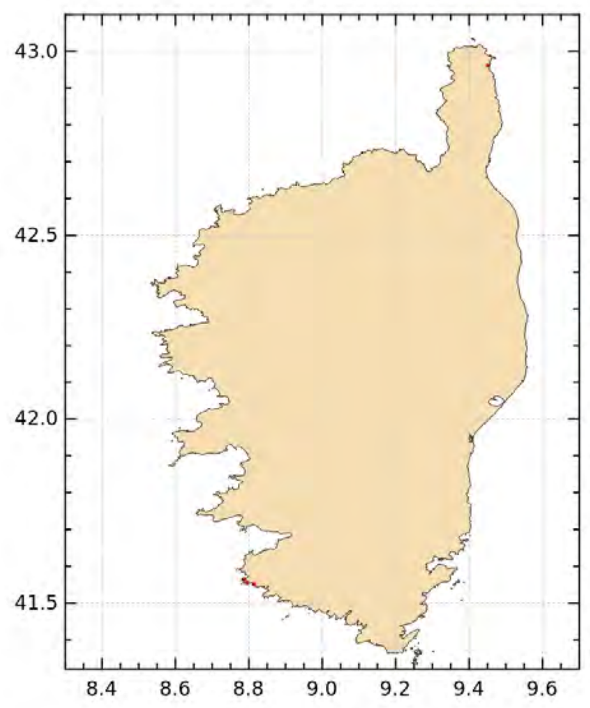


Figure 7: Geographical distribution of Senetosa tide gauges

3. Methodology: a careful description of the altimeter/tide gauges comparison procedure

3.1. Overview

In the present section of this report, we provide a careful description of the processing used at CLS to compare altimetry data to in-situ measurements from tide gauges. Please note that no changes were made to the processing this year, this section is therefore the same as in last year's report. However we believe it remains a useful reminder.
Different schematic representations of the processing are used to ease the description. We used a consistent representation rule to display the different elements of the processing:

- processing steps that imply a transformation of the input data are displayed as rectangles,
- processing steps that do not transform the imput data are displayed as diamonds,
- the original databases are displayed as tube sections (rectangles with curved vertical sides),
- intermediate datasets are displayed as parallelograms.

Figure 8 displays a schematic overview of the processing:

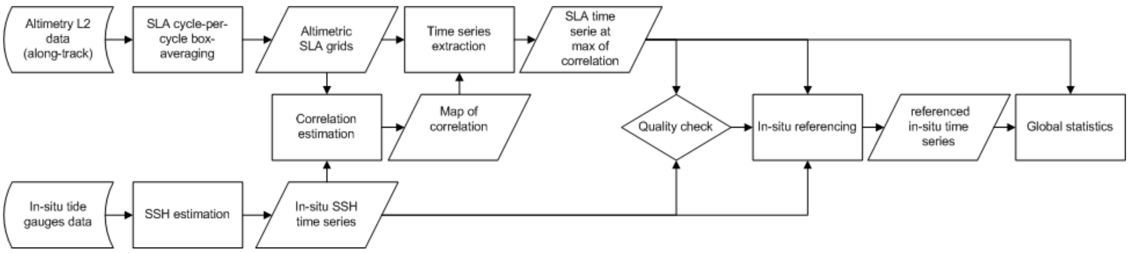


Figure 8: General workflow of the altimetry versus tide gauges comparison process

The major steps of this processing are:

- the pre-processing of altimetry and tide gauge data to derive sea level anomalies,
- the estimation of correlation maps between altimetry and tide gauge,
- the extraction of a satellite altimetry time serie for each tide gauge station,
- the referencing of the tide gauges time series with respect to altimetry data,
- the estimation of global statistics.

The five steps of the processing listed above are described with more details in the sections of the present chapter.

3.2. Pre-processing of altimetry and in-situ data

3.2.1. Satellite altimetry data

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. Concerning altimeter data, along-track (level 2) SSH from several satellite altimeters are considered, where standards can be updated compared with the Geophysical Data Record (GDR) altimeter products. The Sea Level Anomalies (SLA) are computed from the along-track data according to equation 1:

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

where the corrections applied are:

$$\begin{aligned}\sum_{i=1}^{n} Correction_i &= Dry\ troposphere\ correction \\ &+ Dynamic\ atmospheric\ correction \\ &+ Wet\ troposphere\ correction \\ &+ Ionospheric\ correction \\ &+ Sea\ state\ bias\ correction \\ &+ Ocean\ tide \\ &+ Solid\ earth\ tide \\ &+ Geocentric\ pole\ tide\end{aligned}$$

More details about the actual corrections used in SLA estimation (for example the model used to estimate the ocean tide) for each altimeter are can be found in annex [21]. In practice, the geophysical corrections used follow the one used to estimate the global Mean Sea Level (MSL). We use valid-only satellite altimetry measurements, and rely on a Cal/Val flag to perform this selection. Along-track SLA are then averaged on a regular 1° by 1° grid, with a temporal sampling corresponding to each mission's repetitivity.

The pre-processing applied to level 2 satellite altimetry data is summarized on figure 9.

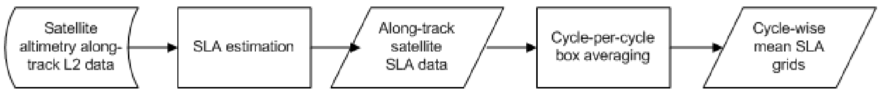


Figure 9: Schematic representation of the pre-processing of satellite altimetry data

3.2.2. Tide gauge data

The goal of this pre-processing is to extract a corrected sea surface height time series at each tide gauge station, with a physical content comparable to the satellite altimetry one, although relative sea surface heights measured by tide gauges are different from absolute sea surface heights from satellite altimeters. Therefore the pre-processing applied to in-situ measurements differs from the satellite altimetry one.

The first difference is that tide gauges were designed to estimate tides and, as a consequence, generally have a much higher sampling rate than satellite altimetry records. Typically, tide gauges would sample the ocean every hour while, at a given point, the satellite altimetry sampling is higher than ten days. The second difference results from the fact that tide gauges measure the sea surface height relative to an on-ground benchmark. Every movement of this local datum has a direct effect on sea level measurements.

The pre-processing applied to in-situ measurements from tide gauges is summarized on figure 10.

Figure 10: Schematic representation of the pre-processing of in-situ data

3.2.2.1. High frequency signals

Concerning GLOSS/CLIVAR in-situ measurements, high frequency tidal effects on tide gauges data are corrected using the Dermerliac low-pass filter ([5, Bessero, 1985]). Long period tidal waves are also corrected using a specific algorithm based on well-balanced tide tables ([10, Cartwright and Eden, 1973]). High frequency atmospheric effects are corrected by withdrawing the Mog2d Dynamical Atmospheric Correction (DAC) (Dorandeu and Le Traon, 1999 [12]; Carrere and Lyard, 2003 [9]). Note that the correction applied also contains the inverse barometer effect.

3.2.2.2. Vertical motion of the tide gauge benchmark

One large uncertainty concerning tide gauge data is the vertical stability of the tide gauge benchmark over time. Vertical motions of tide gauges benchmarks can be monitored accurately using geodetic techniques such as DORIS or GPS levelling. In fact, only a few stations are associated with such monitoring devices. As a consequence, we are not able to correct all tide gauges for vertical motions of the benchmark derived from GPS or DORIS data.

One part of crustal motions is the response of the Earth's crust to the last deglaciation (known as GIA), which can induce large vertical motions. Models are available to estimate this effect, and predict vertical land motion rates over the globe. We use the ICE-5G/VM4 model [15, (Peltier, 2004)] to correct tide gauges time series for vertical land motion due to GIA. A new GIA model by [16, Peltier (2015)] named ICE-6G(VM5a) is now available and will be tested.

3.3. Station-wise comparison between altimetry and tide gauge data

At this point of the processing workflow, both altimeter and tide gauges data show comparable SSH physical contents. The next step of the comparison process is to extract one satellite altimetry time series at each tide gauge site. The process used to extract the altimeter time series and to generate collocated time series at each tide gauge station is schematically described on figure 11. This processing is applied for each tide gauge station in the database, and the different steps involved are described in the present section.

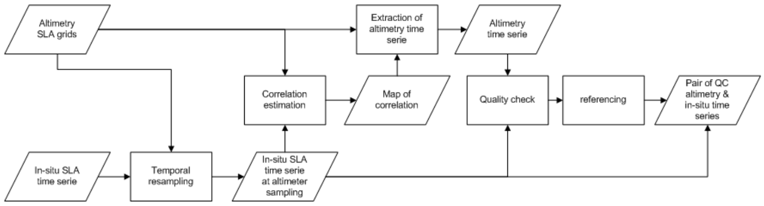


Figure 11: Schematic representation of the process used to generate collocated satellite altimetry and in-situ time series

3.3.1. Temporal resampling

The temporal sampling of satellite altimetry corresponds to the repetitivity of the mission, while tide gauge measurements generally have a much higher temporal sampling frequency (at least for the GLOSS/CLIVAR network which is the main network in use). Before performing any comparison between the two measurements, the high frequency tide gauge data are resampled at the low frequency of the altimetry data by performing averages over one altimeter cycle windows.

3.3.2. Correlation estimation, quality check and extraction

After resampling the tide gauge time series, a map of the correlation coefficient between the altimetry grids and the in-situ record is computed. Note that the tide gauge time series has to contain at least 2 years of measurements to be taken into account.
The satellite altimetry time series is then extracted where the maximum of correlation is found, given that this maximum is found within a 150 km radius distance of the tide gauge, and that the satellite altimetry time serie matches a number of quality criteria. A satellite altimeter time serie is extracted if:

- the correlation between altimetry and tide gauge time series is higher than 0.7,
- the length of the satellite altimetry time serie is at least 80% of the corresponding tide gauge time serie over the common time span (too gappy altimeter records are rejected),
- the standard deviation of the differences between altimetry and tide gauge data does not exceed 10cm,
- the difference between altimetry and tide gauge data does not exceed 12cm (estimated after both time series are centered).

If one criteria is not fulfilled, the satellite altimeter time series extracted at the next lower correlation value is tested, and so on iteratively. At the end of this step, for each tide gauge station, we have a matching satellite altimetry time serie, at the same temporal sampling and with similar physical contents.

We have now developped a way to remove seasonnal signals from altimetry and in-situ time series before performing the correlation estimation. The impacts of this processing choice are currently under evaluation, and this new methodology will be added to our routine processing, as an addition to the standard methodology.

3.3.3. Referencing of tide gauges time series

An important step of the processing is to reference tide gauge time series onto altimetry ones. Tide gauge measurements are referenced with respect to a local benchmark, whose position is generally given within the frame of a national datum system. In this processing, satellite altimetry is considered as a model for in-situ data to be referenced into a common frame. Therefore, the mean of the altimetry-TG SSH differences is computed and substracted from each tide gauge time series.

Using satellite altimetry to reference tide gauge time series implies an important limitation af all further analysis: this technique will prevent tide gauge measurements from detecting regional biases in altimeter records. This remains an important issue with our current comparison method. Investigating new referencing procedures and evaluating the sensitivity of the results should be a priority for next year's work.

3.4. Computation of global statistics

One of the main goals of the comparison procedure is to generate global statistics between altimetry and in-situ measurements, indicating the global drift of the level-2 satellite altimeter data.
At this moment, a set of pairs of collocated altimetry and in-situ time series that all meet the different quality criteria has been produced. The aim of this last step of the processing is to generate one global time series of the differences between altimetry and in-situ from the larger set of collocated time series. This is performed by averaging all records together.

Tide gauges stations are unevenly distributed along the global coastline, and some regions (like the European Atlantic coasts) are oversampled while other areas (such as the Southern Ocean) are almost not observed. In order to mitigate the effects of this uneven sampling, the global mean average is estimated through a two step process:

- data are averaged first on 6° wide longitude bands,
- longitude bands are then averaged into the global mean.

The averaging method used to compute global mean averages from a set of collocated altimetry and tide gauges time series is schematically displayed on figure 12.

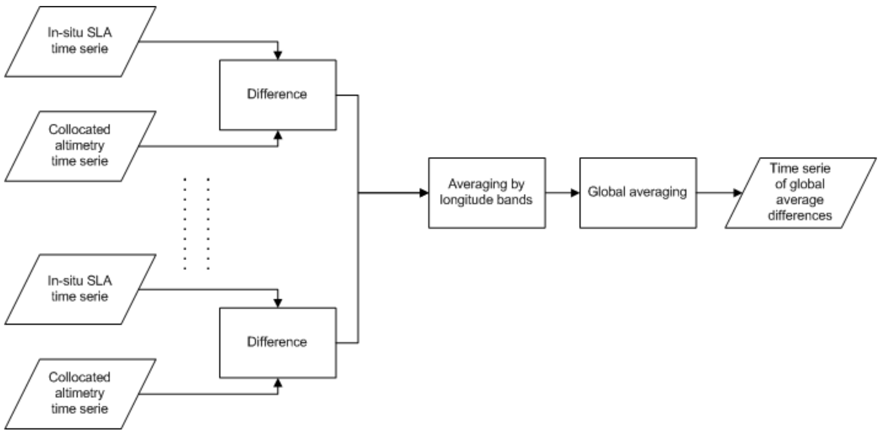


Figure 12: Representation of the global averaging methodology

4. Detection of drifts and jumps on global altimeter records

The cycle by cycle monitoring of global average differences between altimetry and in-situ sea surface height measurements provides a way to assess the satellite data quality and to detect jumps an drifts affecting sea level records.

In the present study, tide gauges from the GLOSS/CLIVAR database are compared to level-2 altimeter records. However due to the quality criteria that are applied, the average number of stations retained in each point of comparison may vary. The number of tide gauges considered differs from one altimetry mission to another, and over time for a given mission, depending on the availability/unavailability of the in-situ sensors. A typical evolution of the number of tide gauges used in the global average estimation is represented on figure 13. While an almost linear growth of the number of tide gauges, corresponding to the availability of new stations in the dataset, is displayed for the most part of the time period, a slight decrease can be observed at the end due to the time lag of the update of tide gauge measurements in the database.
The results summarized here were briefly presented at the 2015 OST/ST meeting as a part of an oral presentation.

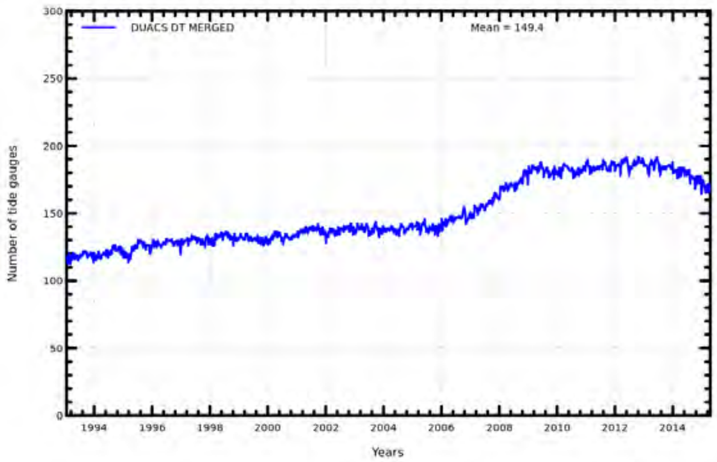
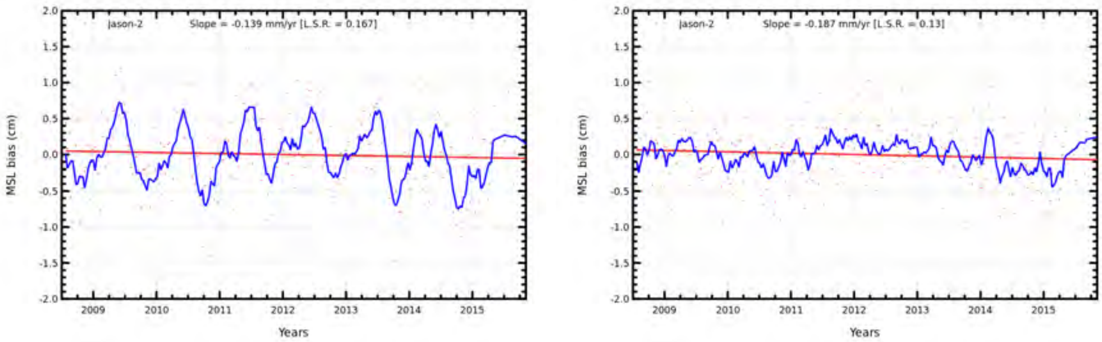


Figure 13: Monitoring of the number of tide gauges considered in the comparison between in-situ data and DUACS DT altimeter products

Note that all the global mean differences time series presented in this section have been corrected for GIA effects on satellite altimetry data using a uniform $-0.3\,mm.yr^{-1}$ trend correction. The details of this GIA correction can be found in the 2013 annual report for the altimetry/tide gauges global comparisons [20].

4.1. Jason-2

Figure 14 displays the time series of global average differences between Jason-2 and tide gauges, either keeping (14a) or removing (14b) the seasonnal cycle. Considering both curves, the comparison with tide gauges measurements shows no long-term trend differences, around −0.2 mm/year. The formal adjustment error is low, close to 0.1/0.2 mm/yr, but we estimate that the total error of the method is larger, around 0.7 mm.yr [23, (Valladeau et al., 2012)].



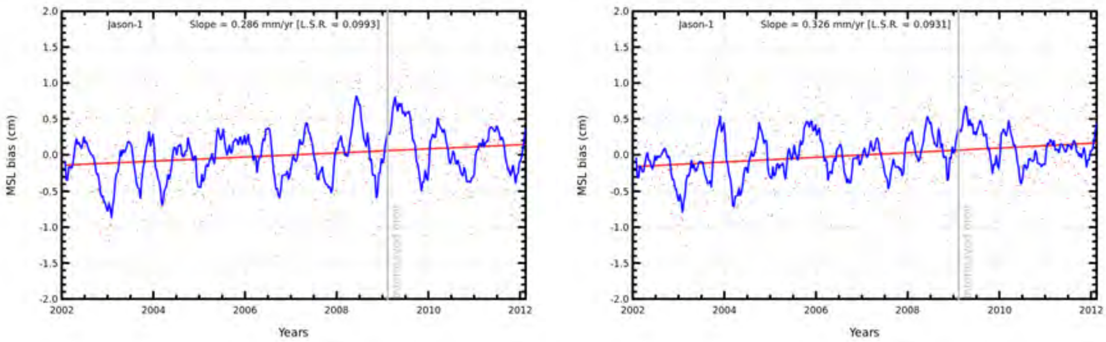
(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 14: Time series of global average differences between Jason-2 and tide gauges, with (14a) and without the seasonnal cycle (14b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

Figure 14 confirms the excellent stability of the Jason-2 mission with respect to tide gauges.

4.2. Jason-1

Figure 15 displays the time series of global average differences between Jason-1 and tide gauges, either keeping (15a) or removing (15b) the seasonnal cycle. Considering both curves, the comparison with tide gauges measurements shows no statistically significant long-term trend differences (0.3 mm/year, which is below the estimated error of the method).

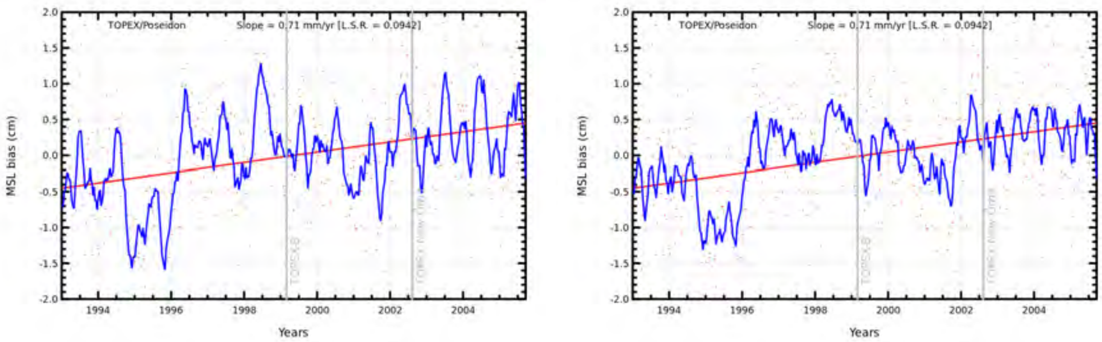


(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 15: time series of global average differences between Jason-1 and tide gauges, with (15a) and without the seasonnal cycle (15b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

Due to the changing point of closest approach and therefore altimetry/in-situ colocation during Jason-1 geodetic phase, we removed this phase (from May 2012 onward) from our routine analysis. Still a small bias is noticeable at the change between the nominal and interleaved orbits. This bias might result from two effects: either there is a true bias between the two phases of the mission or the different ground tracks imply a bias in our colocation method.

4.3. TOPEX/Poseidon



(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 16: Time series of global average differences between TOPEX/Poseidon and tide gauges, with (16a) and without the seasonnal cycle (16b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

Since T/P space mission delivered one of 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 gauges measurements (figure 16) display a global positive trend of about 0.7 mm/yr over the 1993-2005 time period. Furthermore, the low rms differences 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. 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, range and backscatter coefficient parameters (Ablain et al., 2012 [1]). The TOPEX-B MSL appears more stable with no drift from February 1999 onwards. Although T/P seems to provide accurate measurements for climate studies, the long-term stability of TOPEX-A data could be improved. A reprocessed dataset for TOPEX/Poseidon was presented at OSTST ([29]) and will be compared to tide gauges when available.

4.4. TOPEX historical ground track

In the sections above, we considered separetely, and over their longest period the three missions used to construct the GMSL record. But one important concern when comparing altimetry to tide gauges is whether the 20+ years long GMSL record from TOPEX/Poseidon, Jason-1 and Jason-2 is stable over time. Figure 17 displays the global mean alti minus tide gauges differences for these three missions limited to the period they are used as reference mission for the GMSL record.

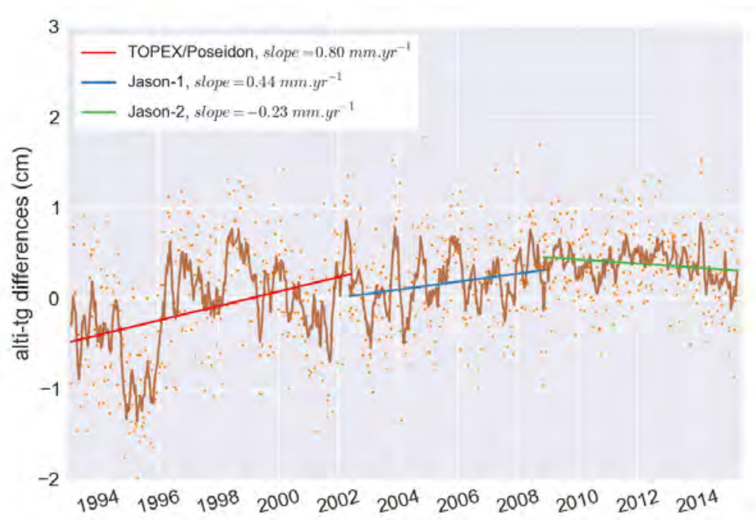
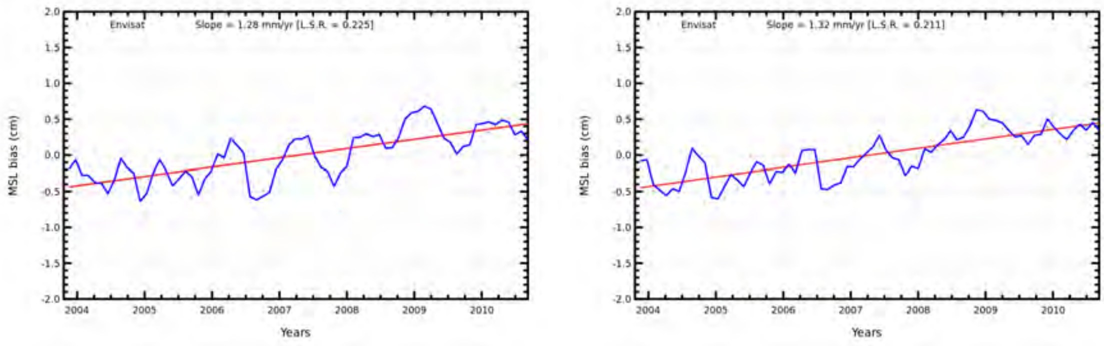


Figure 17: Global mean differences for TOPEX/Poseidon, Jason-1 and Jason-2, each mission limited to the period it is used as the GMSL reference

The positive drift observed on TOPEX/Poseidon global differences with in-situ (0.8 mm/yr) suggests that over the TOPEX/Poseidon period, the altimetry record might be over estimating the GMSL rise. This is consistent with findings by other groups ([27]). Concerning Jason-1 and Jason-2, drifts with respect to tide gauges are smaller (respectively 0.4 mm/yr and -0.2 mm/yr).

4.5. ENVISAT

Figure 18 displays the results of the global bias estimation with respect to tide gauges for the ENVISAT mission. Compared to Jason-1, Jason-2 and TOPEX/Poseidon missions, ENVISAT shows larger SSH differences drift at $1.2mm/yr$. This value is larger than the uncertainty of the method and therefore statistically significant. Such a drift is also consistent with comparisons between Jason-1 and ENVISAT for the global MSL.

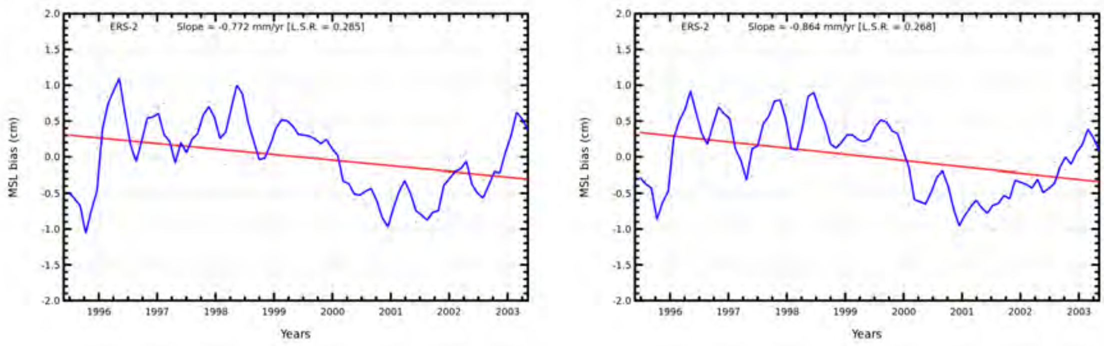


(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 18: Time series of global average differences between ENVISAT and tide gauges, with (18a) and without the seasonnal cycle (18b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

4.6. ERS-2

Figure 19 displays the results of the global bias estimation with respect to tide gauges for the ERS-2 mission. Compared to Jason-1, Jason-2 and TOPEX/Poseidon missions, ERS-2 shows larger negative SSH differences drift at $-0.7/-0.8mm/yr$. Such a drift is also consistent with comparisons between TOPEX/Poseidon and ERS-2 for the global MSL.

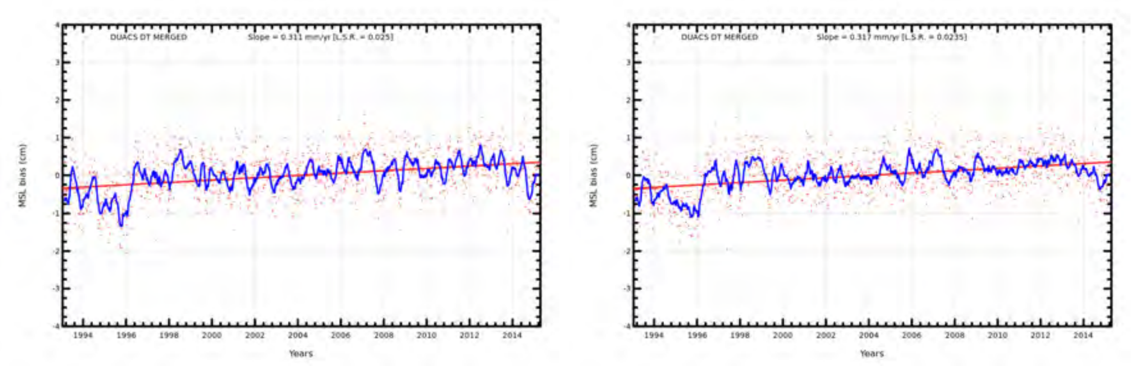


(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 19: Time series of global average differences between ERS-2 and tide gauges, with (19a) and without the seasonnal cycle (19b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

4.7. SSALTO/DUACS maps of Sea Level Anomaly

Analysing multi-mission datasets provides a way to study long, homogeneous time series. In this section we present the activities performed over the last year regarding the comparison of the so-called "value added" products to in-situ SSH measurements from tide gauges. Figure 20 displays the time series of the global biases between DUACS multi-mission product and tide gauges. The time series does not show any statistically significant drift. The variability of the bias is higher at the beginning of the period, and consistent with the comparison between TOPEX and tide gauges, as TOPEX/Poseidon is the reference mission at the beginning of the record.



(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 20: Time series of global average differences between SSALTO/DUACS maps of SLA and tide gauges keeping (left) or removing (right) the seasonnal cycle. The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

5. Particular investigations

In October 2013, the OSTST community recommended that the different groups should intercompare their methodologies with two goals:

- understand the origin of the differences observed on the global results,
- come to a better knowledge of the sensitivity and uncertainty of the method.

This type of sensitivity testing had begun on CLS side in 2013 when we adressed GIA corrections and was continued in 2014 focusing on two axes:

- the impact of correcting or not for the annual signal in altimetry and in-situ time series when estimating the correlations,
- the effects of including incomplete time series in our analysis rather than rejecting all stations that do not cover the whole period of the study.

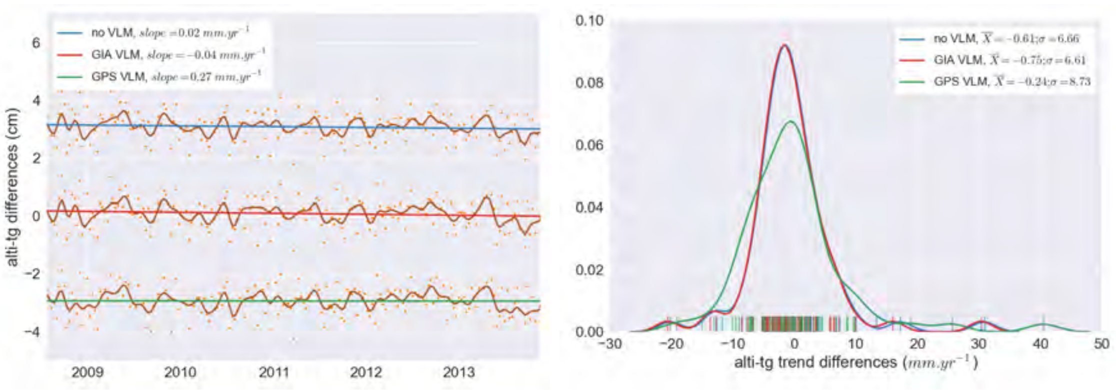
The results can be found in the previous yealry reports for the activity [20] and [21]. In 2015, a session at the OSTST meeting was mainly dedicated to altimetry/in-situ comparisons and discrepancies, and we performed several investigations regarding the sensitivity of our comparison method and its uncertainty. The results of this sensitivity testing were presented at OSTST in Reston, and the present section of the yearly report derives from this oral presentation.

5.1. Vertical Land Motion

Correcting accurately for vertical land motions of tide gauges is crucial to estimate reliable altimeter drifts from comparisons with tide gauges, both at dedicated calibration sites and for global averages methods. This remains to date a large uncertainty source on global comparisons. This year, we performed a simple experiment to evaluate the error commited when not correction in-situ stations for vertical land motions.

Our standard processing uses a GIA model to correct tide gauges stations but this does not account for all vertical land motion. Here we compare the estimated Jason-2 drift using a sub network of tide gauges and three vertical land motion corrections: no correction, GIA model and GPS vertical velocities ([11]). Results regarding the global drift are displayed on figure 21a and show a small impact of using the GIA versus no correction at all, and a larger (about 0.25 mm/yr) impact of using GPS derived vertical velocities of stations.

Of course the next question is whether the GPS solution provides a better estimate of the altimetry drift ? As a rule of thumb, one would expect that if GPS velocities do correct an error, then consistency between altimetry and tide gauges should improve when using them. The right panel (21b) shows the distribution of altimetry minus tide gauges trends (station-wise): there is no reduction of the spread of the distribution when using GPS velocities. We are therefore not able to demonstrate that the use of GPS velocities improves our drift estimate on this case. We can make several hypothesis regarding this unexpected result: maybe the period used here is too short, and a similar experiment performed on 20 years of data processed for instance within the SSALTO/DUACS multi-mission products would be better; maybe the linear motion assumption made when using GPS velocities is wrong and does not provide improvement over GIA (just a different solution); All these hypothesis should be tested in the future.



(a) global mean bias *(b) with ensemble spread overlaid*

Figure 21: Time series of global average differences between Jason-2 and tide gauges using three VLM corrections, and the corresponding histogram of altimetry-tide gauges trends

5.2. Ensemble Mean Estimation

At a certain point in the processing, one needs to estimate, at each time step the global mean, $\overline{\delta}_t$, from a set of altimetry minus tide gauges differences $\{\delta_i\}_t$ unenvenly distributed over the global ocean. We also want this ensemble mean to represent the true bias between altimetry and tide gauges at time t so that its temporal evolution can be reliable. The way to estimate $\overline{\delta}_t$ is a processing choice, and different groups use different averaging schemes. For example Watson [27] uses an uncertainty-based weighing scheme (more consistent tide gauges are favored), while Jevrejeva [28] uses regional averages through an iterative virtual station method. At CLS, we use a different geographical weighing that accounts for the asymetric North/South distribution of tide gauges stations: we first estimate the averages in longitude bands and then average the values across longitudes.

This processing was designed so that the few stations in the southern hemisphere are not outnumbered by northern hemisphere stations. In order to check the impact of this weighing scheme we compare it, for the same in-situ network, to a very simple average where all stations are given the same weight. This simple check was performed using the SSALTO/DUACS grids of sea level anomaly to get the longest continuous record available. Results of the experiment are presented on figure 22. There is a 0.15 mm/yr trend difference between the two curves, and slightly different interannual variabilities are observed.

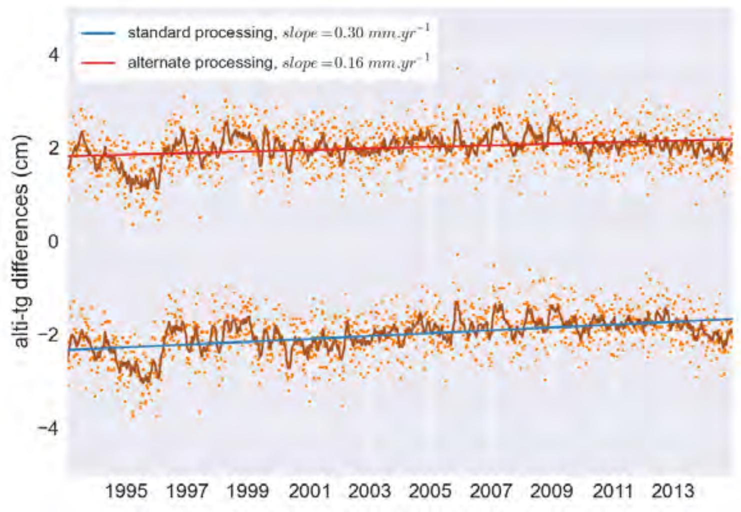
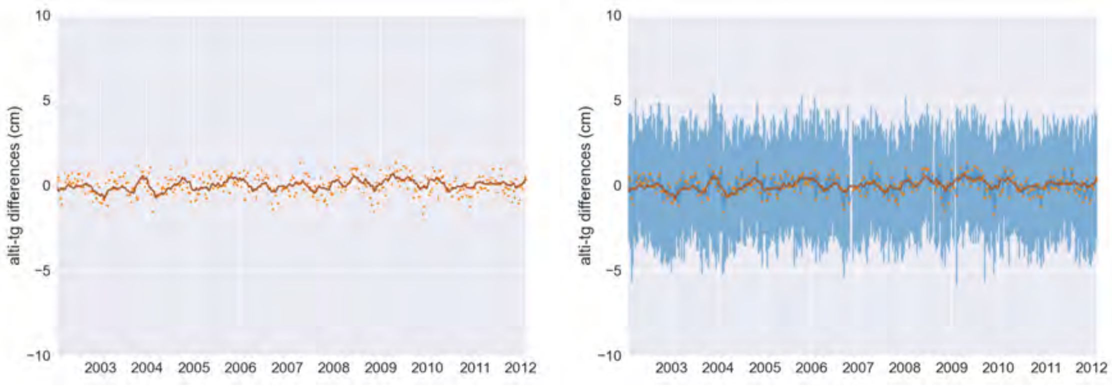


Figure 22: Global mean differences between SSALTO/DUACS grids and tide gauges using two different averaging schemes

This a first result and other averaging methods should be added to the analysis, yet it already reveals that how the ensemble mean is estimated can make a difference in the observed drift between altimetry and tide gauges.

5.3. Global mean drift estimation

Another important aspect of the ensemble mean issue is how we deal with uncertainties when estimating the global drift between altimetry and in-situ (*i.e.* the trend on the global mean differences time series). The usual way we represent data is shown on figure 23a, with the dots representing the ensemble mean at each time step and the dark brown line the results of a low-pass filter applied to the data to remove high-frequency (generally 2 months period) noise. To derive the trend, we would typicallly apply a least squares fit to the light brown. Figure 23b displays the spread (1σ) of the ensemble used a at each time step to estimate the mean bias. If we include this information into a weighed least squares estimate of the trend uncertainty, the confidence interval goes slightly up (because of error heteroscedasticity) to 0.2 mm/yr. We believe this is a more realistic estimate of uncertainty coming only from the trend fit.



(a) global mean bias *(b) with ensemble spread overlaid*

Figure 23: Time series of global average differences between Jason-1 and tide gauges, with (23a) and without (23b) the ensemble spread

5.4. In-situ network

Clearly the comparisons between altimetry and tide gauges depend on the in-situ network used. Previous tests and analysis showed that using a large ensemble of tide gauges resulted in a lower standard deviation of bias estimates, with little impact on interannual signals and long-term trends, and we thus use the widest network available, given that quality checks are passed. However we have no way to measure how sensitive to the network the global results are. Here we propose a small statistical experiment to evaluate the sensitivity of the global comparison method to changes in the in-situ network used.

Starting from the results of our routine comparisons using the largest available ensemble of in-situ stations, we remove random combinations of in-situ sensors so that the number of in-situ stations used in the analysis is reduced (for example removing randomly 5% of the stations). We perform 100 iterations using 100 unique and randomly generated combinations of stations to be removed. By doing this we ensure that we have no systematic geographical bias when subsampling the results (as it would be if we chose to remove top weighed stations for example). The results of this experiment are displayed on figure 24. We removed 5, 10 and 20% of the in-situ network respectively. For each subsampled network, we estimated the global mean difference (in black). The global mean from the whole network is displayed in red. The right panel shows the distribution of the members' trends.

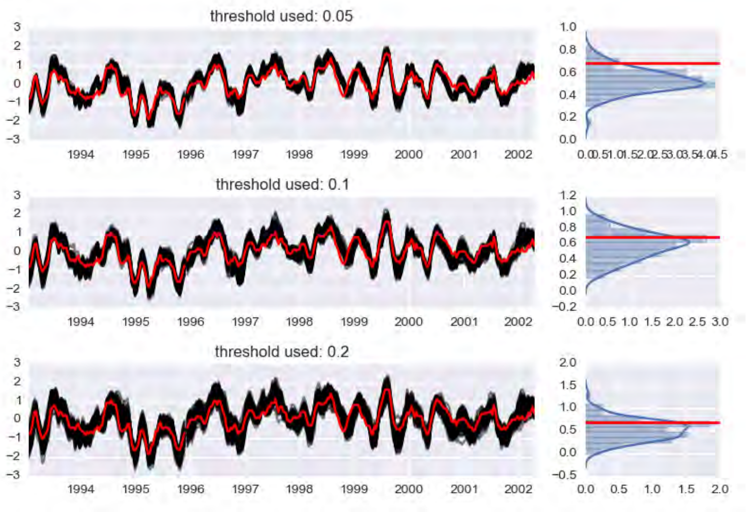


Figure 24: Global mean differences between TOPEX/Poseidon and randomly sub sampled tide gauges networks

The results of this analysis show that by changing randomly the network by only 5%, the estimated global drift can vary by $\pm 0.3\ mm/yr$. When removing 10% of the network, this effect grows to $\pm 0.5\ mm/yr$. The experiment conducted here was based on an initial network of 100 stations, and removing 5 or 10 stations out of 100 could easily happen due to quality checks applied on stations.

6. Conclusions

This report presents the status of the global comparison between altimetry and tide gauges, as well as the work and investigations performed in 2015. These activities can be roughly separated in three: in-situ data acquisition and processing, altimetry validation and investigations. These are briefly summarized in this conclusion.

No major change to our acquisition processing happened in 2015, but several improvements were made:

- software changes to be less impacted by issues on data provider side,
- versioning of all software and parametrization files,
- use of a dedicated computer for acquisition purposes (not depending on personal work stations),
- monitoring of acquisition status via email.

We still routinely acquire several networks into CLS tide gauges database:

- the GLOSS/CLIVAR fast delivery dataset,
- the PSMSL dataset,
- the REFMAR french dataset,
- the CNES Senetosa sites,
- the Copernicus european dataset.

The main objective of the altimetry in-situ comparisons is to detect any drifts or jumps in satellite altimetry time series, main results are listed below:

- Jason-2 is the current reference mission for climate studies, the comparison to tide gauges shows no statistically significant drift, and demonstrates the excellent stability of the mission. the dispersion around the linear fit is also very small for this mission.
- Jason-1 doesn't show any drift either, yet two jumps are observed on the time series of SSH differences, corresponding to the orbit changes of the mission.
- In the TOPEX/Poseidon records, two phases can be identified, separated by sudden increase in the SSH differences in 1996. The origin of this increase is still unknown. TOPEX/Poseidon shows a small negative drift with respect to tide gauges
- The comparison to the DUACS series of sea level anomaly maps shows no significant drift. The gradual reduction of the standard deviation of the SSH difference is observable as a result of the increased quality of DUACS products over time and the increase of the comparison sample size with the inclusion of new stations in the network.
- A significant positive trend is still observed on the ENVISAT mission ($1.2mm/yr$). This positive trend is consistent with global MSL analysis and comparisons to Argo floats.

As a logical follow-on to the analysis performed on 2013 and 2014, 2015 investigations have mainly been devoted to the estimation of the sensitivity of the method. The analysis presented in this report have been focusing on:

- correction of in-situ vertical land motion,
- impacts of the in-situ network used,
- effects of the averaging process and how to propagate errors to the final drift estimate.

Results have been presented at the OSTST2015 meeting, and we believe there is still a need for an exhaustive review of errors and uncertainties affecting global altimetry/tide gauges comparisons. Such investigations will continue in 2016.

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