CalVal In-Situ altimetry/tide gauges

Validation of altimeter data by comparison with tide gauge measurements: yearly report 2014

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

Contract No 104685/00 - lot1.2A

Reference : CLS-DOS-NT-15-020

Nomenclature : SALP-RP-MA-EA-22419-CLS

Issue : 1rev 0

Date : January 23, 2015

CLS - 11 Rue Hermès - Parc Technologique du Canal - 31520 Ramonville St-Agne - FRANCE
Telephone 33 5 61 39 47 00 / Fax 33 5 61 75 10 14

Chronology Issues:		
Issue:	Date:	Reason for change:
1.0	Dec, 1st, 2014	Creation

People involved in this issue:		
Written by:	P. Prandi G. Valladeau	CLS CLS
Checked by:	S. d'Alessio	CLS
Approved by:	J.P. Dumont M. Ablain	CLS
Application authorized by:		

Index Sheet:	
Context:	
Keywords:	
Hyperlink:	

Distribution:		
Company	Means of distribution	Names
CLS/DOS	1 electronic copy	G.DIBARBOURE
	1 electronic copy	M.ABLAIN
DOC/CLS	1 electronic copy	DOCUMENTATION
CNES	1 electronic copy	thierry.guinle@cnes.fr
CNES	1 electronic copy	aqgp_rs@cnes.fr
CNES	1 electronic copy	dominique.chermain@cnes.fr
CNES	1 electronic copy	delphine.vergnoux@cnes.fr
ESA	1 electronic copy	P.FEMENIAS

List of tables and figures

List of Tables

List of Figures

List of items to be defined or to be confirmed

Applicable documents / reference documents

Contents

1. Introduction - Document overview

This document is the altimeter/tide gauges comparison activities synthesis report for the year 2014. It sums up the activities performed in the frame of the 2011-2015 SALP project funded by CNES. This year, these activities are no longer supported by ESA.

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 cross-compare two or more altimeter missions to check for any drfit or biases,
- comparisons with in-situ data which provide an independent reference.

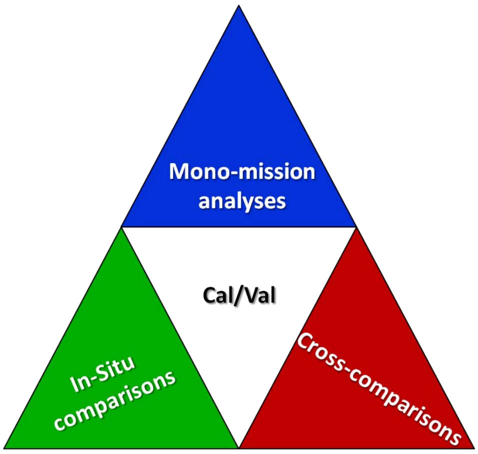


Figure 1: The triforce of Cal/Val activities for satellite altimetry missions

In the present report we focus on the latter category of activities, and more specifically on comparisons with tide gauges. Both tide gauges and Argo T/S profiles constitute two complementary datasets for assessing satellite altimetry performance, each with its interests and limitations. The spatial coverage for example is strongly limited with tide gauges, as stations must be installed at the coast while the Argo network can sample the open ocean. On the other hand the temporal sampling of tide gauge measurements is better than the Argo one: a typical gauge delivers hourly measurements while an Argo float measures one vertical profile every 10 days. Tide gauges also provide historical sea level measurements over the whole altimeter period while the coverage of the Argo network has been global since 2004 only.
The two techniques complement each other, and comparing the results obtained with different in-situ datasets increases the reliability of the anlysis. These cross-comparisons with external independent in-situ measurements are an important part of the calibration and validation activities, as they help evaluate and increase the quality of altimeter measurements.
The mothodology for comparing tide gauge measurements to satellite altimetry data relies on the comparison of in-situ and satellite altimetry derived sea surface heights (SSH) and has three goals:

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

2. Estimate the improvements 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 ...)

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. This year we made several improvements to this database, which are described. The second one concerns the comparison methodology used. It includes a precise description of how the comparisons are drawn from local SSH at taide gauge stations to global averages. The third part of this report sums up 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

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

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 in order to deduce filtered Sea Level Anomalies (SLA) from tide gauges SSH in order to be consistent with altimeter data. The comparison of the latter with tide gauge measurements is thus 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 presented two years ago, and was 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 database are now available:

- a *raw* database which results of the direct download and the storage of the raw data in CLS format, 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 (easy download of the data from ftp, http adresses or even process local data), the post-processing is specific for each one.

2.2. Acquisition and post-processing steps

For all tidal networks,tide gauge measurements are computed and archived following a sequential procedure:

1. data download from the servers of data distributors (weekly update),
2. conversion from the original data format to the CLS data format (in-situ measurements tables) with several steps of validation,
3. filtering of tide gauge data in order to remove the short and long tidal wavelengths (diurnal, semi-diurnal and long period tides),
4. record of the high resolution dynamical atmospheric correction (MOG2D model) to remove high frequency wind driven signals.

As said previously, two different databases have been processed in 2013 and consist of two parts. First the acquisition procedure, supplied with the raw sea surface height and the several static information (name, network, coordinates, ...). Then, the post-processing of the raw data and the dedicated corrections used to calculate an altimeter-consistent SSH.

The global procedure of the database for the acquisition process is presented in figure 2. 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 considered as an operational system and updated every week according to the availability of new tide gauge measurements.

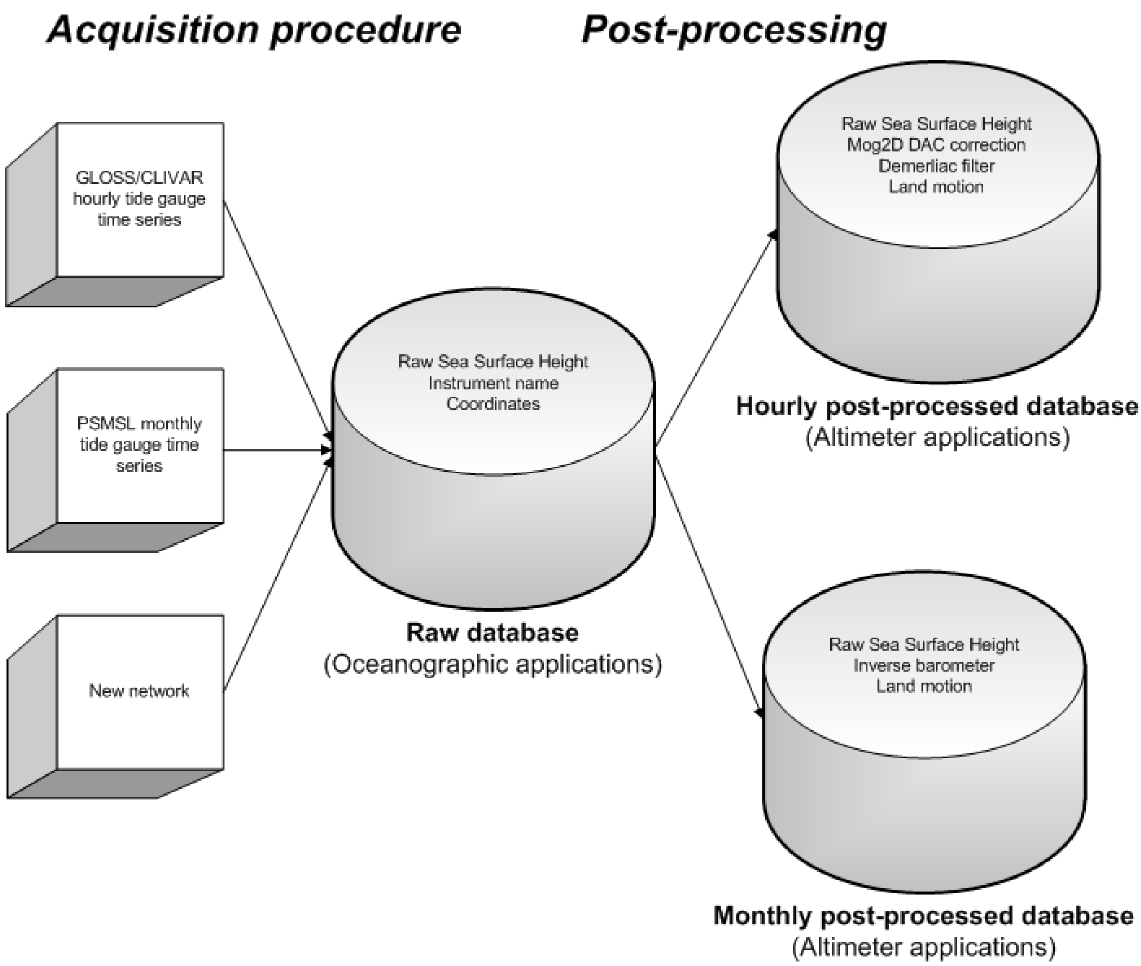


Figure 2: Acquisition procedure of tide gauge data and conversion to "in-situ measurements tables" specific format.

2.3. 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 many kind of scientific studies. With the same goal, the new database is now routinely supplied with two global tidal networks, weekly updated and post-processed. Other networks are also acquired, and are presented here.

2.3.1. 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 ensure that the delay between sensing time and delivery time is short. Data are retrieved through the University of Hawai'i 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.

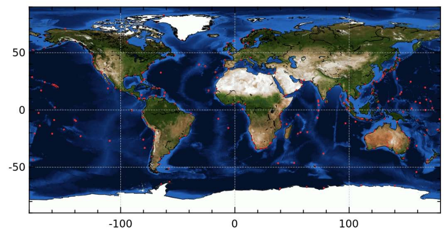


Figure 3: Geographical distribution of GLOSS/CLIVAR tide gauges stations

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

- a service interruption over early summer, without any access to data possible, with no information from UHSLC to users,
- an inconsistency is now observed between the ftp and http servers at UHSLC, with the ftp files being incomplete (no data after the end of August).

Despite an efficent feesback from UHSLC team members, data acquisition on our side may be impacted such events.

2.3.2. 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 eb noted that all the stations are not suitable for global comparisons to altimeter data.

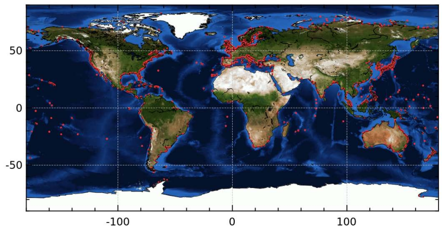


Figure 4: Geographical distribution of PSMSL tide gauges stations

2.3.3. REFMAR database

This year we performed the acquisition of the REFMAR database. This is 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

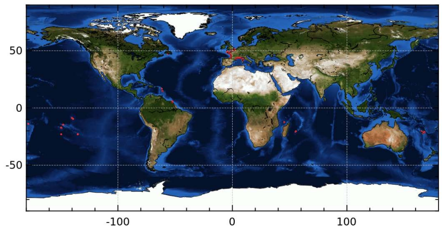


Figure 5: Geographical distribution of REFMAR tide gauges stations

2.3.4. Other data sources

Other data sources were acquired in our database system this year, but that we do not use routinely in our global comparisons. Last year, the Senetosa tide gauge time series of the M3, M4, M5 and M7 sensors were 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. This year, as a DUACS team request, we acquired the GLOSS research quality dataset, which is a subset of the GLOSS/CLIVAR network descibed above. This is a one-shot work and no routine update of the data is performed.

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 6 displays a schematic overview of the processing:

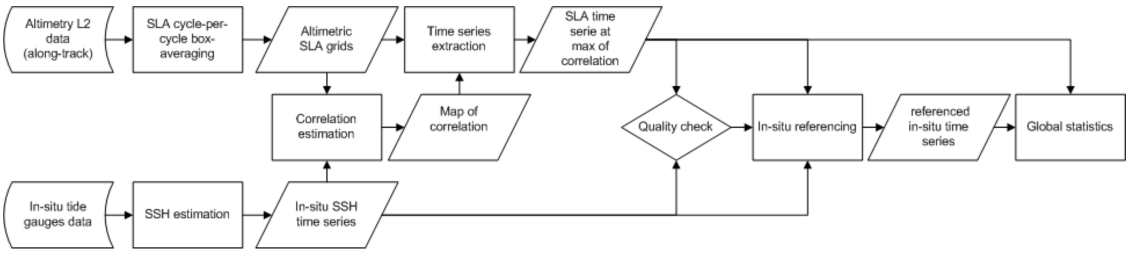


Figure 6: General workflow of the altimetry versus tide gauges comparison process

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. When comparing to in-situ measurements from tide gauges, we use along-track (level 2) SSH from several satellite altimeters, 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 [?]. In practice, the geophysical corrections usde follow the one used to estimate the global mean sea level. 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 2° by 2° grid, with a temporal sampling corresponding to each mission's repetitivity. This represents a change regarding last year's processing where 1° latitude by 3 ° longitude boxes were used for the averaging af satellite altimetry data.

The pre-processing applied to level 2 satellite altimetry data is summarized on figure 7.

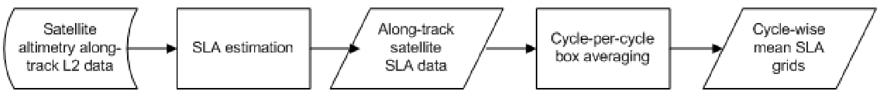


Figure 7: Schematic representation of the pre-processing of satellite altimetry data

3.2.2. Tide gauge data

The goal of this pre-processing is to extract a corrected sea surface height time serie at each tide gauge station, with a physical content comparable to the satellite altimetry one. The relative sea surface height measured by tide gauges is different from the one from satellite altimeters, therefore the pre-processing to be 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 8.

Figure 8: Schematic representation of the pre-processing of in-situ data

3.2.2.1. High frequency signals

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 [11]; Carrere and Lyard, 2003 [9]). Note that the correction applied also contains the inverse barometer effect.

Note that concerning PSMSL monthly data, the computation is slightly different: we do not correct the data for tidal and atmospheric high frequency effects. We consider these high frequency variations are filtered out when monthly averages of the data are computed (at PSMSL level). Therefore, we only apply on these data an ERA-interim derived inverse barometer correction.

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 few stations are associated with such monitoring devices. As a consequence, we are not able to correct 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 [14, (Peltier, 2004)] to correct tide gauges time series for vertical land motion due to GIA.

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

At this point of the processing workflow, both altimeter and tide gauge data show comparable SSH physical contents. The next step of the comparison process is to extract one satellite altimetry time serie at each tide gauge site. The process used to extract the altimetry time serie and to generate collocated time series at each tide gauge station is schematically described on figure 9. This processing is applied for each tide gauge station in the database. The different steps are described in the present section.

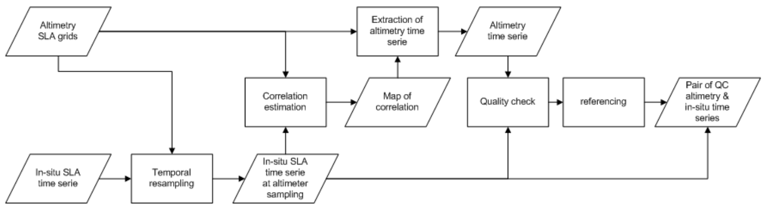


Figure 9: Schematic representation of the process used to generate collocated satellite altimetry and in-situ time series

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. 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 an average 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 coefficients between the altimetry grids and the in-situ record is computed. Note that the tide gauge time serie 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 serie 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.

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 serie.

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 serie 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 by 3° 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 10.

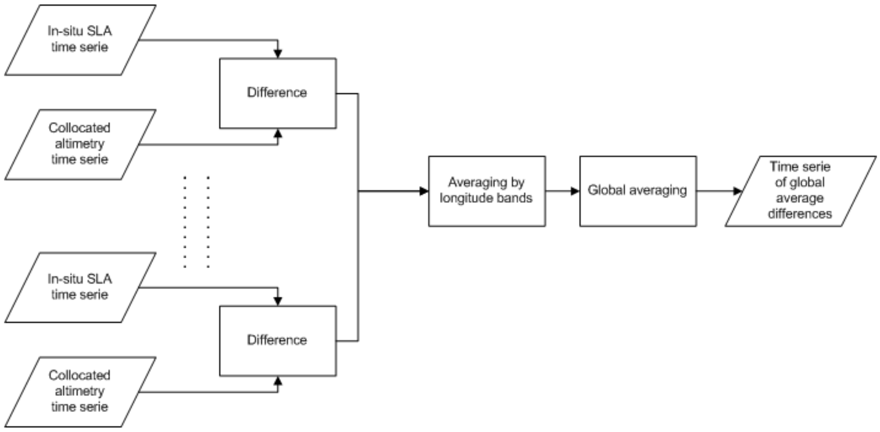


Figure 10: Representation of the global averaging methodology

3.5. Summary

In the present section, we described the processing used to compare satellite altimetry data to in-situ sea surface height measurements from tide gauges. The result of this complex processing is to to detect drifts or regime changes in satellite altimetry records by averaging the differences with in-situ time series.

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 11. 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 presented at the 2014 OST/ST meeting as a poster. This poster is reproduced in this report as annex 9.1..

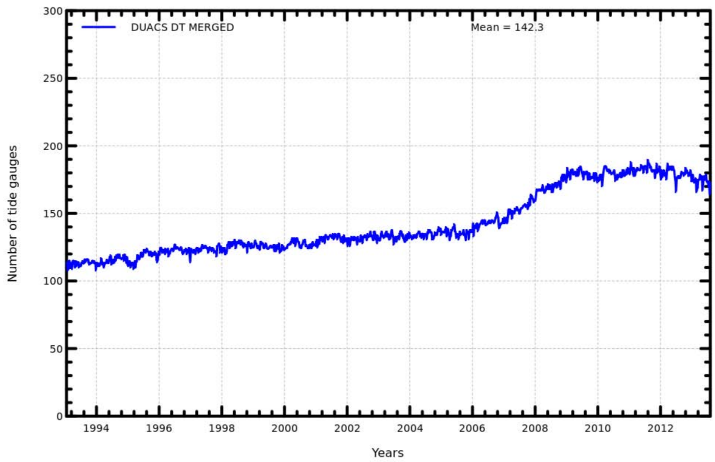
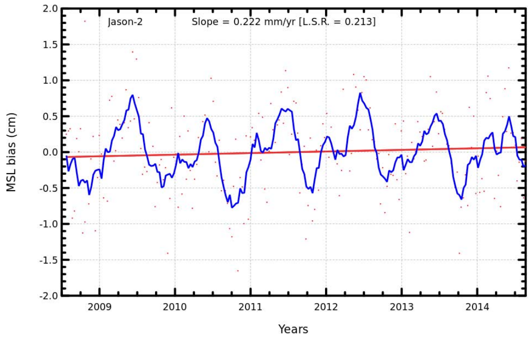


Figure 11: Monitoring of the number of tide gauges considered in the comparison between in-situ data and DUACS DT altimeter products

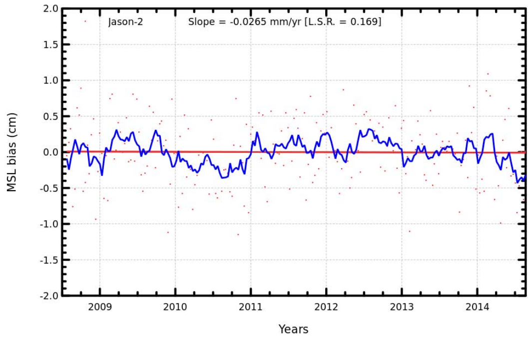
Moreover, note that all the time series presented in this section have been corrected for GIA effects on satellite altimetry data using a uniform $-0.3\,mm.yr^{-1}$ trend correction. The details of this GIA correction can be found in the 2013 annual report for the altimetry/tide gauges global comparisons [18].

4.1. Analysis on Jason-2 mission

Figure 12 displays the time series of global average differences between Jason-2 and tide gauges, either keeping (12a) or removing (12b) the seasonnal cycle. Considering both curves, the comparison with tide gauges measurements shows no long-term trend differences (0.2 mm/year with the seasonnal cycle, 0.02 mm/yr without). The formal adjustment error is low, close to 0.1 mm/yr, but we estimate that the total error of the method is larger, around 0.7 mm.yr.



(a) with seasonnal signal



(b) seasonnal signal removed

Figure 12: Time series of global average differences between Jason-2 and tide gauges, with (12a) and without the annual cycle (12b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

Figure 12 confirms the excellent stability of the Jason-2 mission with respect to tide gauges.

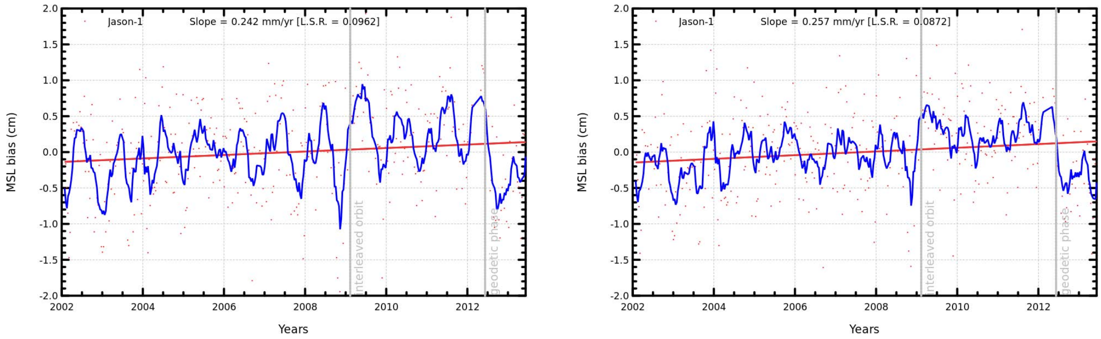
4.2. Analysis on Jason-1 mission

Figure 13 displays the time series of global average differences between Jason-1 and tide gauges, either keeping (13a) or removing (13b) the seasonnal cycle. Considering both curves, the comparison with tide gauges measurements shows no statistically significant long-term trend differences (0.2 mm/year, which is below the estimated error of the method).
However two biases can be noticed in the time series of global averages of SSH differences. The second one is the most obvious and corresponds to the beginning of the geodetic phase. A bias is also observable on the monitoring of the global Jason-1 MSL.

Here me might observe the combination of two effects:

- a true bias between the interleaved and geodetic phases of Jason-1 mission,
- the impact of ground track change on the altimetry/in-situ comparisons.

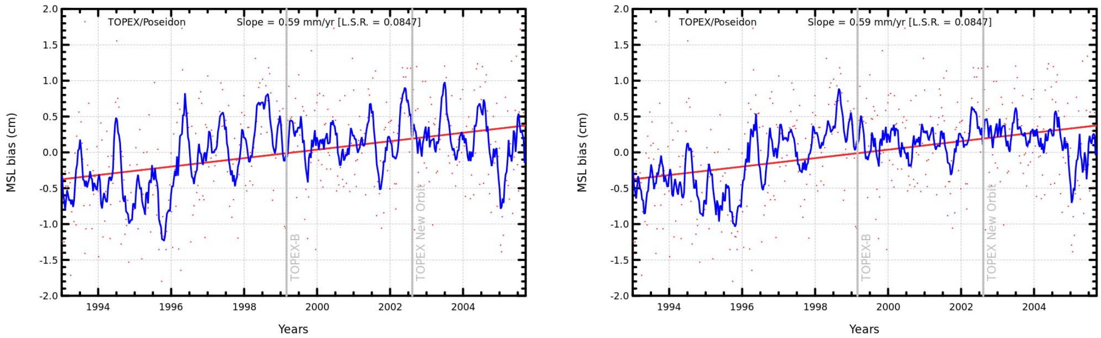
Another smaller bias is also noticeable at the change between the nominal and interleaved orbits.



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

Figure 13: time series of global average differences between Jason-1 and tide gauges, with (13a) and without the annual cycle (13b). The red points represent the raw data while the blue curve is obtained after applying a two months running mean filter

4.3. Analysis on TOPEX/Poseidon



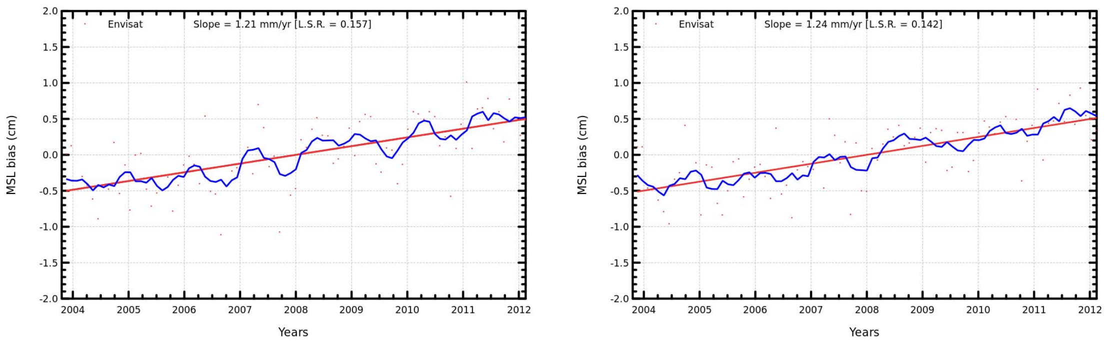
(a) with seasonnal signal *(b) seasonnal signal removed*

Figure 14: Time series of global average differences between TOPEX/Poseidon and tide gauges, with (14a) and without the annual cycle (14b). 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 gauge measurements (figure 14) display a global trend of about 0.6 mm/yr over the 1993-2005 time period. Differences with previous results have been explained last year with the change of the spatial resolution of the gridded altimeter SSH computed, especially on the TOPEX new orbit time period (2002-2005). Indeed the 1°x3° spatial sampling had an impact on the computation of the maximum of correlation on the whole time series. Applying the new 1°x1° altimeter gridded SSH solved this artefact. 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. Next to the improvements on the method, a better reliability on the consistency between altimeter data and tide gauge measurements is expected although the global trend slightly increased (around 0.6 mm/yr). However, some remaining drifts and high amplitude residual signals are still to be understood, especially over the TOPEX-A time period where a negative slope was highlighted between 1993 and 1996 and a positive one from 1996 to 1999. 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 (Ablain et al., 2012 [1]). Comparisons with tide gauges tend to demonstrate 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 provides accurate measurements for climate studies, the long-term stability of TOPEX-A data could be improved.

4.4. Analysis on ENVISAT

Figure 15 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 $1.2 mm/yr$. 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 fot the global MSL.

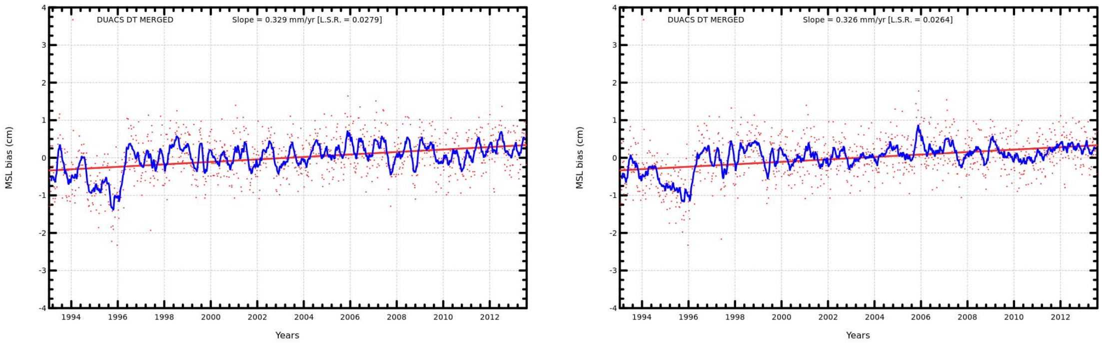


(a) with seasonnal signal *(b) seasonnal signal removed*

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

4.5. Analysis on 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 16 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 16: 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

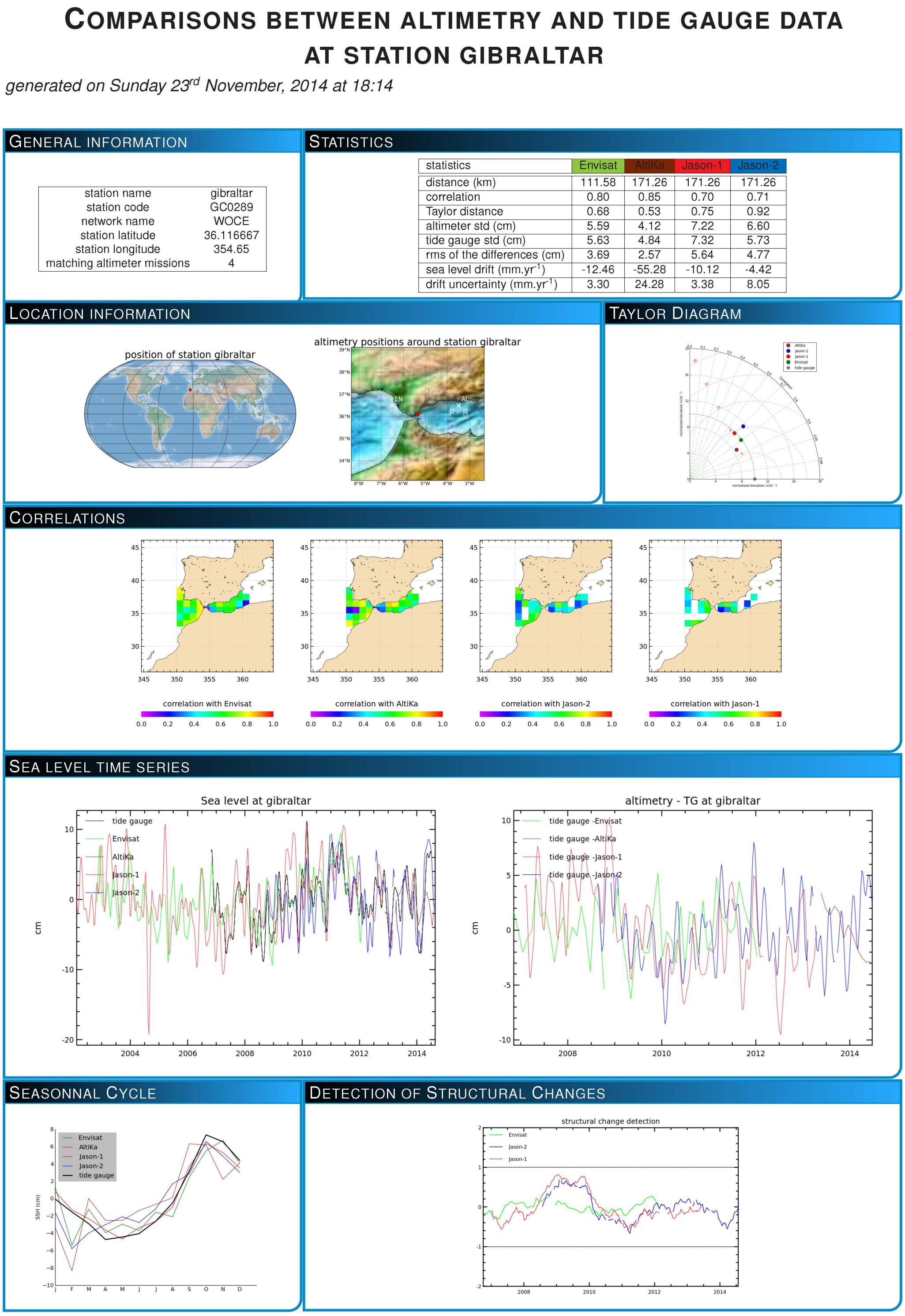
5. Quality assessment of tide gauge time series

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 highlighting potential anomalies on in-situ time series:

- from the detection of structural changes in in-situ time series
- from comparisons with all available altimeter data

The classical way to assess the quality of sea level time series recorded by tide gauges is to perform a comparison to satellite altimetry missions. Performing sytematically such comparisons for each station in the network allows us to detect drifts and jumps in in-situ time series. For each station, the results of this quality assessment process are summarized on an in-situ information card. The aim of this card is to quickly represent the performance of the in-situ sensor with respect to satellite altimetry. An example of the new design of in-situ information cards is given in Figure 17. The card is composed of several boxes whose content is described below:

- **General Information**: contains general information about the tide gauge station, its name and position, the station code, the station network and the number of satellite altimetry missions matching this station.
- **Statistics**: this section of the information card summarizes statistics estimated on the time series of the differences between altimetry and tide gauge data. The statistics considered here are the correlation, the Taylor distance, the altimetry and tide gauge SSH standard deviation, the RMS of the differences, the trend of the differences and the uncertainty on this trend based on a Monte-Carlo simulation. The distance between the tide gauge position and the position where the satellite altimetry time series was extracted is also displayed.
- **Location Information**: this box contains two maps, a global one representing the position of the tide gauge station and a zoom centered around the tide gauge position where the positions of the satellite altimetry time series are extracted.
- **Taylor diagram**: the taylor diagram in this box uses the in-situ data as a reference, the color points therefore refer to the different altimetry missions considered.
- **Correlations**: this box displays the maps of the correlation coefficient between tide gauge and altimeter SSH, for each matching satellite altimetry mission.
- **Time Series**: this box contains two plots, one for the SSH from in-situ data and from matching satellite altimetry data, and one for the time series of the SSH differences between altimetry and in-situ data.
- **Seasonnal Cycle**: the seasonnal cycle is very often a dominant feature of sea level variability and it is useful to have a visual display of its shape.
- **Structural changes**: this monitoring intends to emphasize quickly potential structural changes in time series of SSH differences.



station name	gibraltar
station code	GC0289
network name	WOCE
station latitude	36.116667
station longitude	354.65
matching altimeter missions	4

statistics	Envisat	AltiKa	Jason-1	Jason-2
distance (km)	111.58	171.26	171.26	171.26
correlation	0.80	0.85	0.70	0.71
Taylor distance	0.68	0.53	0.75	0.92
altimeter std (cm)	5.59	4.12	7.22	6.60
tide gauge std (cm)	5.63	4.84	7.32	5.73
rms of the differences (cm)	3.69	2.57	5.64	4.77
sea level drift (mm.yr^{-1})	-12.46	-55.28	-10.12	-4.42
drift uncertainty (mm.yr^{-1})	3.30	24.28	3.38	8.05

Figure 17: Comparison between altimetry ad tide gauge data at Gibraltar

These new information cards will be available in the coming weeks through the AVISO website for the GLOSS/CLIVAR, PSMSL and REFMAR tide gauge networks. A reading guide for these new tide gauges information cards will be also be available (see Appendix 9.2.).
In addition, a simplified information card will be distributed along with the complete version (see figure 18). Therefore, both versions of the in-situ information cards could be simultaneously available for end-users to provide these two levels of information. Finally, these new information cards will be routinely generated and distributed through the AVISO website on a weekly basis, allowing for a quick overview of the tide gauge performance for the comparison with altimetry.

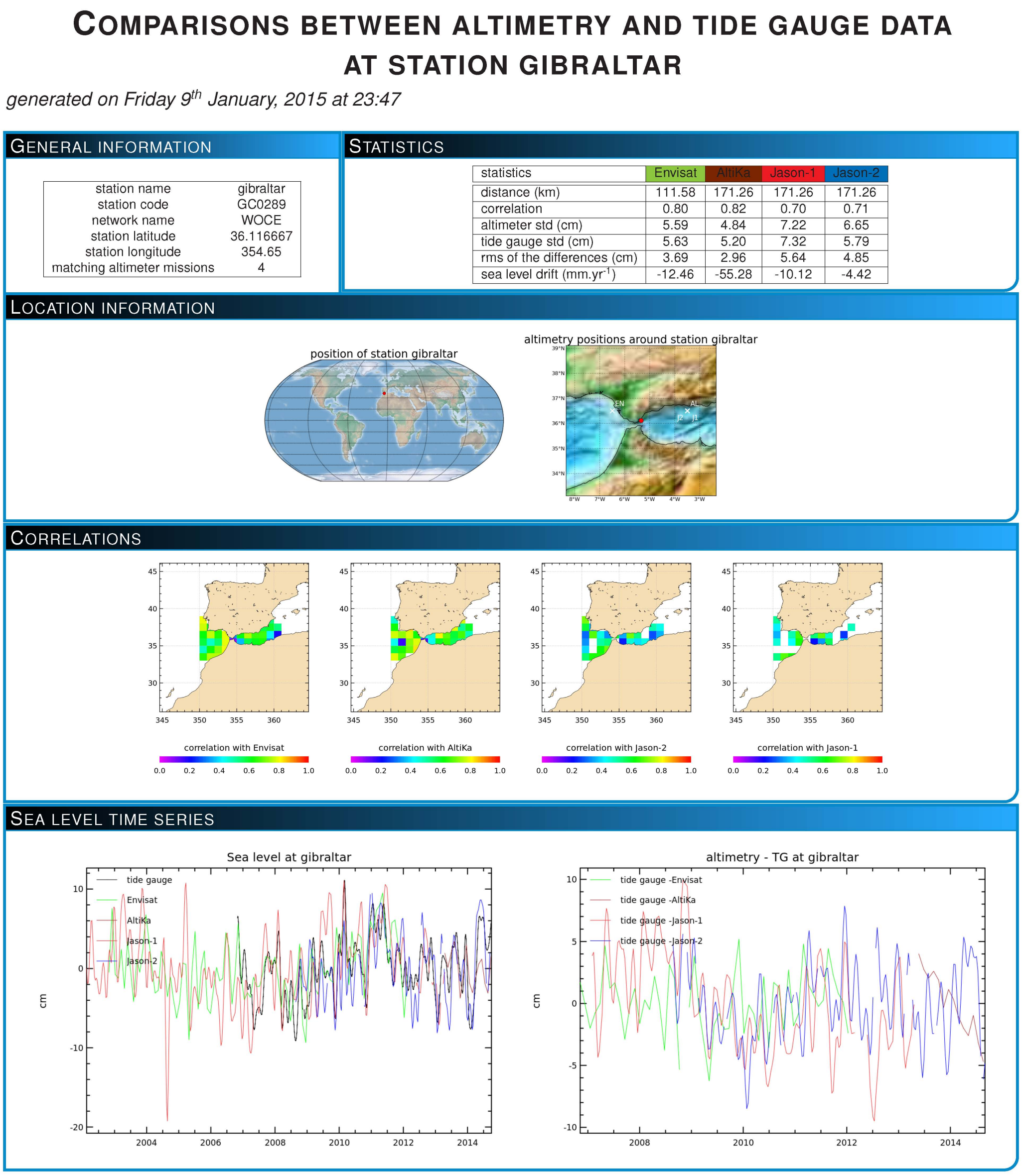


Figure 18: Comparison between altimetry ad tide gauge data at Gibraltar

6. 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.

We initiated this work with our CSIRO colleague C. Watson, unfortunately to no quantitative result at the moment. However, we kept working on the sensitivity of our comparison method. Last year, impacts of different strategies to correct for GIA effects were discussed. This year we focused on two sensitivity studies: the first one adresses the impact of correcting or not for the annual signal in altimetry and in-situ time series when estimating the correlations, the second one is dedicated to 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.

6.1. Sensitivity to the removal of annual signals

In this section we explore the behavior of our methodology to the removal of the annual signal from both altimetry and in-situ records before estimating the correlations between them.

6.1.1. Position of the problem

The methodolgy we use for comparing, at a global scale, altimetry data to in-situ records is precisely described in section . One key point of sthis method is the colocation step, which is described in section 3.3.. This colocation relies on the estimation of a map of correlation values between altimetry and in-situ for each in-situ station. For the large number of stations, the signal (for both in-situ and altimetry) is strongly dominated by the annual cycle of the SLA and so is our estimation of the correlation. For instance, figure 19 shows the time series for in-situ and altimetry (Jason-1 here) for a given station, as estimated by the standard processing.

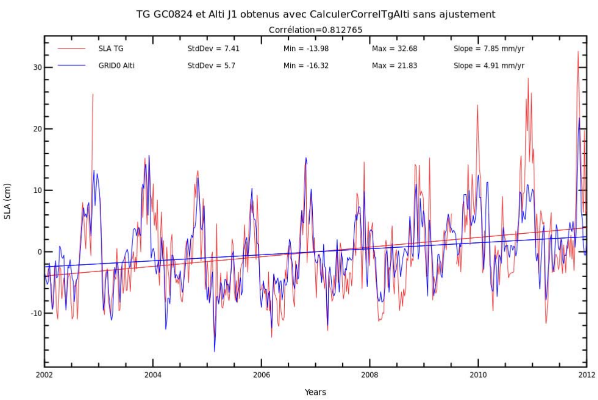


Figure 19: Example of the time series for the tide gauge and the altimetry at one station

A strong annual signal is observed on both time series, which results in an excellent correlation coefficient between in-situ and altimetry ($\rho > 0.8$). But the correlation coefficent gives little information about the common behavior of the two measurements systems regarding inter-annual variability for example, which is clearly important to detect altimeter drifts.
The question that arises is therefore: what happens to the global altimetry drift results if we remove the annual signal from the time series before estimating correlations ? and how are the results sensitive to this processing choice ?
In order to answer these questions, we tried to remove the annual cycle from the time series before estimating the correlation maps, and evaluated the different impacts.

6.1.2. Removing the annual signal

The first step of this experiment is therefore to remove the annual signal from the time series. As easy as it may seem, deciding how to perform this removal is not straightforward and several options are available. Two questions must be answered:

1. should the signal removed be the same on the tide gauge and the altimeter time series, or, in other words, should the tide gauge and altimeter see the same annual signal ?

2. how to estimate this annual signal, can it be described as a sum of sines ? or should we use another technique ?

The global altimeter drifts estimated with respect to tide gauges for all missions show a residual annual signal (see section). There are multiple reasons that could explain the fact that altimetry and tide gauges do not measure the same annual cycle, and this is observed at the individual station level. Figure 20 shows the annual cycle estimated from altimetry and from the tide gauge measurement.

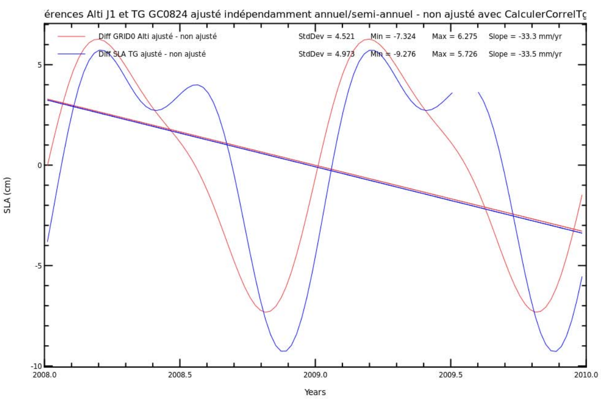


Figure 20: Annual cycles fitted on the altimetry and on the tide gauges time series displayed on figure 19

Looking at figure 20 clearly shows that the two sensors observe different annual cycles. We can make several hypothesis to explain such a difference in annual cycles: a true difference between the in SL between onshore and offshore, effects of an annual loading on the tide gauge benchmark, coastal errors of the models (tides and DAC) that result in an annual signal... In order to prevent any residual signal from the time series of the differences (and therefore from the global drifts estimates), we chose to remove the annual cycle on each time series independently.
Another issue is how to correct for the annual signal, two techniques were available (codes already existing) at CLS:

- fitting a sine wave in a least squares sense,
- estimating monthly climatologies to derive the seasonnal cycle.

After different tests, we chose to fit a the sum of two sine waves: $Asin(\omega t + \phi) + Bsin((\omega/2)t + \psi)$. An example of the results of this adjustement on a practical case is displayed on figure 20.

6.1.3. Effects of the annual signal removal on global estimates

In this section we explore the impacts on the global results of the removal of the annual cycle on different outputs of the methodology. Several effects are expected and discussed here.

6.1.3.1. Correlations

An impact on correlations is expected from the removal of the annual signals. For example, considering the time series of figure 19, removing the annual signal from the altimeter and in-situ time series leads to a slight correlation drop from 0.8 to 0.7. If we consider all in-situ stations, the impact on the average correlation is low with a small correlation drop of 0.06, but with an uneven geographical distribution which is displayed on figure 21.

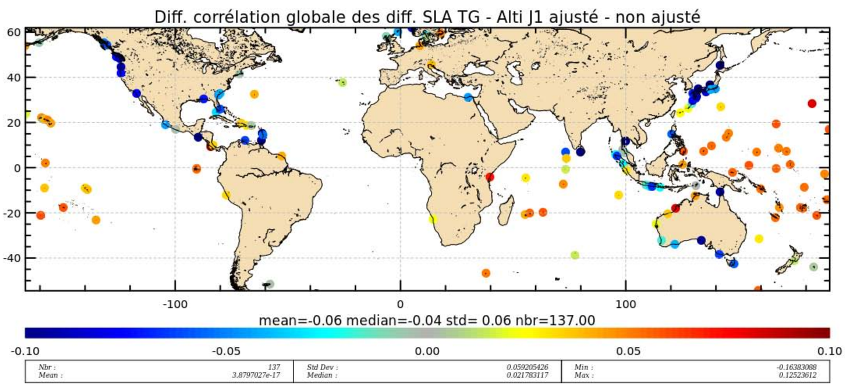
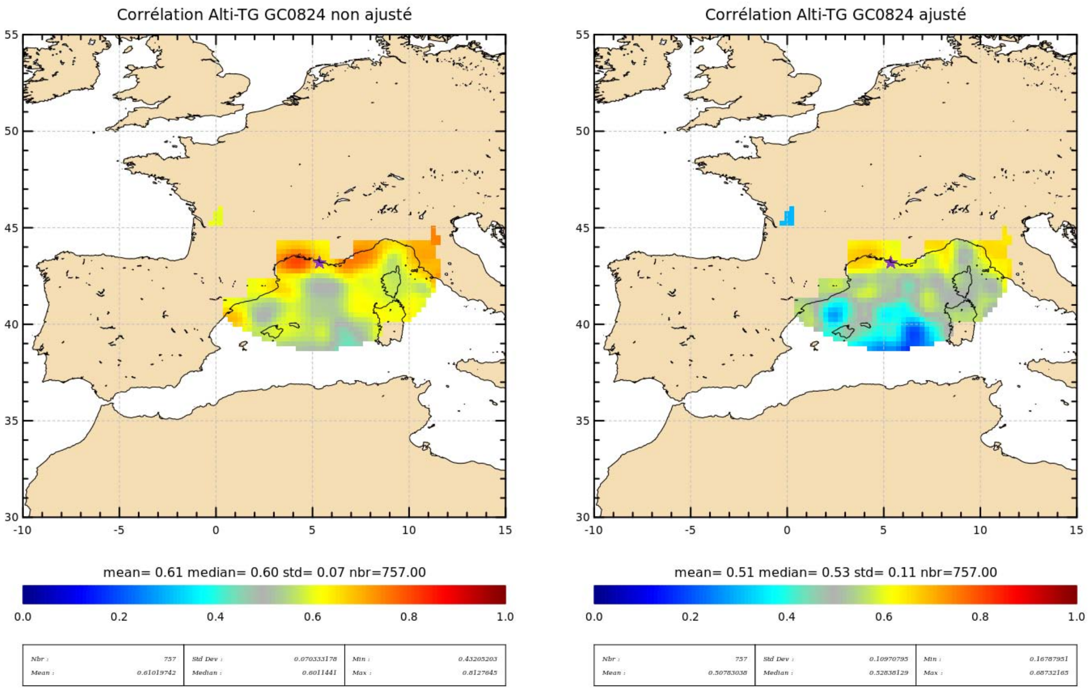


Figure 21: Impact of fitting the annual cycles on correlations between altimetry and in-situ

Correlation changes range from −0.16 to 0.13 with a strange geographical pattern: at island stations, correlations seem to increase while at continental stations, the correlations tend to decrease. Another explanation might be the tropical/extra tropical distribution of stations.

6.1.3.2. Average distance

Linked to the impacts on correlation, we expect effects on the average distance between in-situ stations and the position of selected altimeter grid points. When removing the annual signal, the map of correlations between altimetry and in-situ that we estimate at each station changes. An example of this efect at the Marseille station is given on figure 22 and illustrates how the local correlation distribution may vary when the annual signal is removed.



(a) with the annual cycle *(b) annual cycle removed*

Figure 22: Impact of the removing the annual cycle on the map of altimetry/in-situ correlations at the Marseille tide gauge

As a result both the value of the correlation maximum and its position may change, and therefore the altimeter selection routine may extract the altimetry time series from a different grid point whrn the annual signal is removed before correlations are estimated. Consequently the distance between the extraction point of the altimeter time series and the position of the in-situ stations might vary. The global map of this distance change is displayed on figure 23. On average, removing the annual signal leads to a small 2 km distance increase, with large differences between the stations (the differences can reach 80 km).

6.1.3.3. RMS of the differences

The last impact is on the RMS of the SSH differences between altimetry and in-situ records. Here we are interested in the temporal RMS of these SSH differences at each station (we also estimate an ensemble RMS at each time step, but which is adressed in the next section).
The impact of the removal of the annual signal on the standard deviation of SSH differences is displayed on figure 24. At a majority of stations, the RMS of the SSH differences is reduced, however the global average reduction is small. At a few stations, an increase is observed.

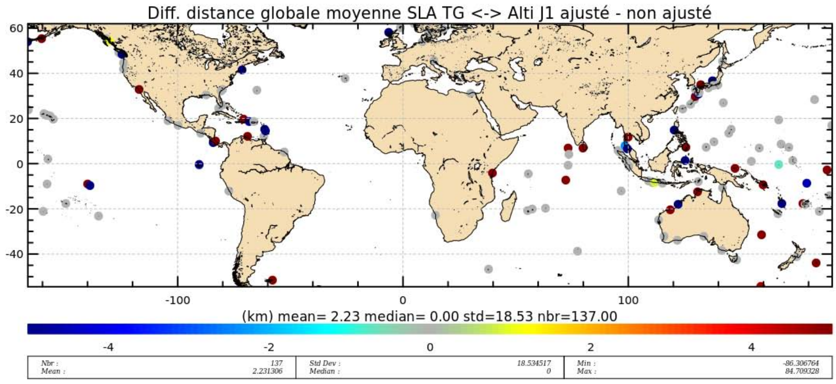


Figure 23: Impact of fitting the annual cycles on distances between altimetry and in-situ

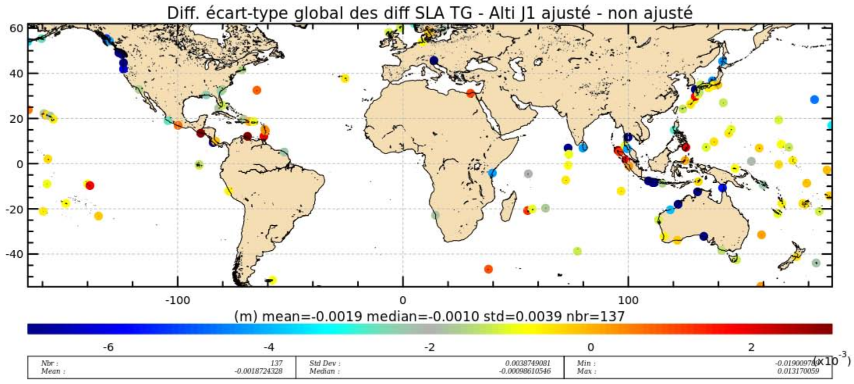


Figure 24: Impact of fitting the annual cycles on the standard deviaition of SSH differences between altimetry and in-situ

6.1.3.4. Global ensemble averages

The most important metrics derived from the in-situ comparisons are drifts estimates of the altimeter missions. These drifts estimates are computed from an ensemble average of all SSH differences available at each time step.

Figure 25 displays the effect of the annual signal removal on the global Jason-1 drift estimated with respect to tide gauges. The impact is very low on the the trend ($< 0.1 mm/yr$), and thus brings confidence on our estimates. An annual signal is visible on figure 25, and differences can reach 1 cm.

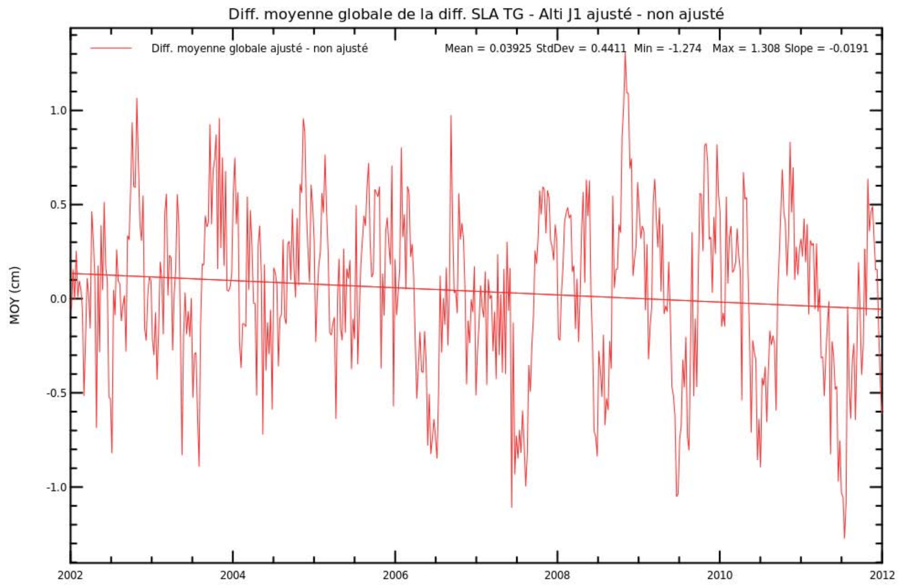
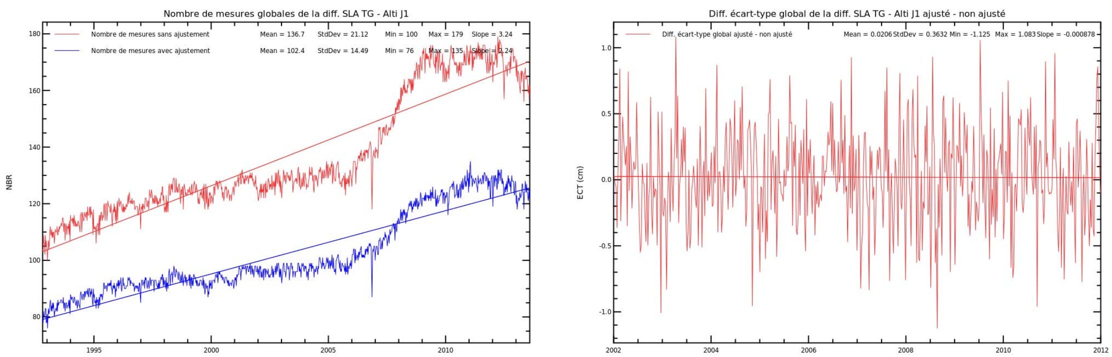


Figure 25: Impact of fitting the annual cycles on the global altimeter drift estimation

Another impact is that with the general drop in correlations, several in-situ stations that are used in the reference processing (when no annual signal is removed) do not meet the correlation criterion when the annual cycle is removed and are rejected at the station selection level.

Figure 26a displays the number of tide gauges used in the comparison process. The blue curve is obtained when the annual signal is removed, on average over the whole period about 20% of the stations are edited. Further investigation remains needed to see if we can relax the correlation threshold used in order to re-integrate the edited stations in the process and at what cost. A very small increase of the standard deviation of the differences is observed, likely related to the drop in the number of stations used (this is an ensemble standard deviaition, and is therefore not the same metric as the standard deviaitions displayed on figure 24).



(a) number of tide gauges

(b) standard deviation of the differences

Figure 26: Impact of the removing the annual cycle on the number of tide gauges considered in the comparison (26a) and on the standard deviaition of the differences (26b)

6.2. Sensitivity to short in-situ time series

In this section, we present the results of the investigation we performed this year focusing on the impact of including short time series in our analysis rather than selecting only long in-situ time series that cover the whole altimetry time span.

6.2.1. Introduction

Tide gauges time series are reference in local height systems (generally national) and these height systems are not linked one to another. Therefore we can not express all in-situ SSH time series in a common reference frame. This is clearly illustrated on figure 27 where in-situ SSH time series are expressed in their local reference frame. Note the very large dispersion of the mean values spreading over nearly 10 meters due to inconsistent local reference levels.

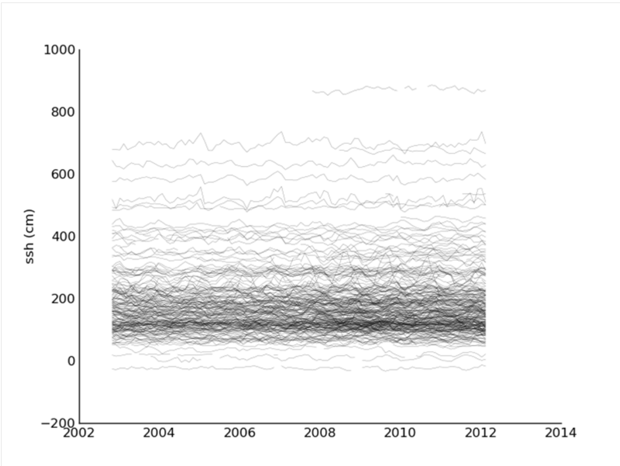
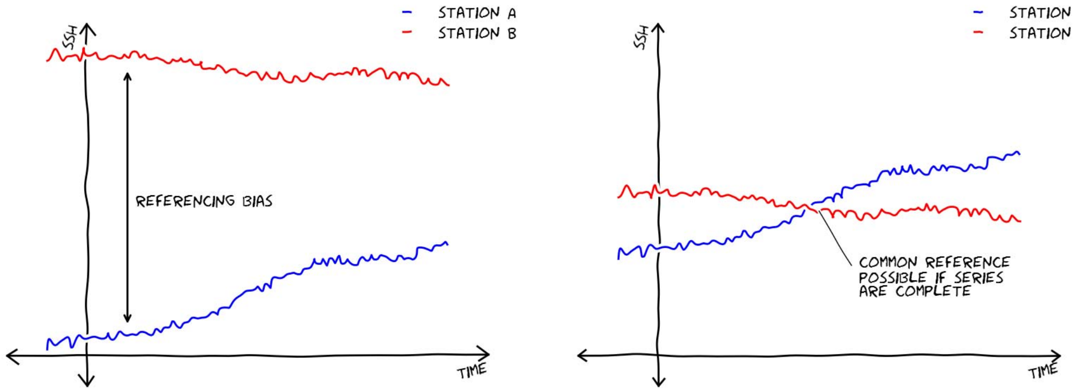


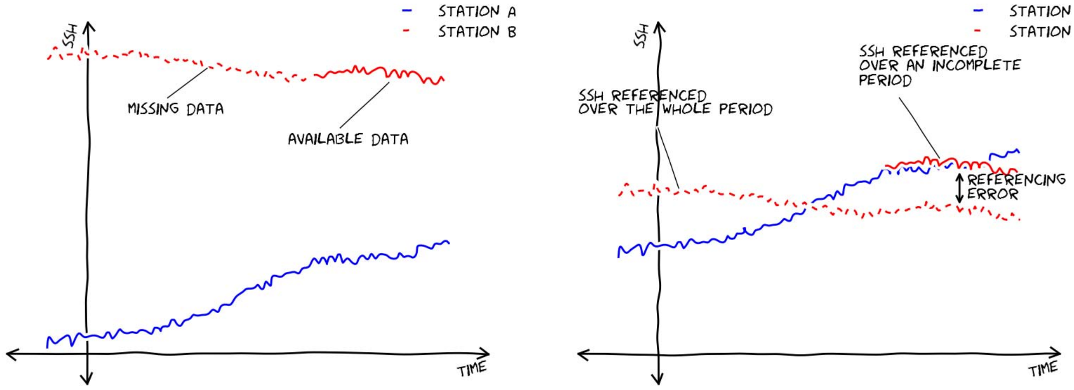
Figure 27: In-situ SSH time series as expressed in their local reference frame

In order to be compared to satellite altimetry, in-situ time series must be commonly referenced. This not an issue when only complete in-situ time series are considered (which cover the whole studied time span), as the time series can be easily centered and thus referenced to a common (but unknown) surface. Figure 28 illustrates this case. The choice of the mean surface translates into a constant bias on the final result, but has no impacts on drifts of bumps in time series.
Concerns arise when time series that do not cover the same time span are used. This is the case in our methodology as we try to include as many stations as possible in our analysis, even if they do not cover the entire altimeter time span. Such case is illustrated on figure 29, where we do not know the first part of the red time series: we commit an error on the referencing of the time series. In practice, we use local altimeter data as a reference for in-situ time series (the blue line on figures 28 and 29 would be altimetry time series).
There is therefore a concern that including time series shorter than the altimeter period in the analysis might introduce an error in global averages and bias our drifts estimates low. The analysis presented here aims at estimating the sensitivity of the results to this effect. Several alternative processing solutions are used.



(a) before referencing *(b) after referencing*

Figure 28: Impact of the referencing on complete time series



(a) before referencing *(b) after referencing*

Figure 29: Impact of the referencing on incomplete time series

6.2.2. Description of the experiment

To evaluate the sensitivity of the global averages, we compare four processing choices:

1. standard procedure, which is routinely used, and relies on local altimeter time series to provide a reference for in-situ time series, in practice, this si simply centering the time series of altimeter minus in-situ SSH differences,

2. using only complete time series, this is the approach adopted by other groups for performing global altimetry/in-situ comparisons, then we are in the case described on figure 28, and the in-situ time series are simply centered,

3. a methodology where we use an inverse method to estimate a bias between in-situ time series. This relies on an *a priori* model of the error covariance (we prescribed drifts errors at the mm/yr level), but is not dependent on any altimeter data,

4. a method using DUACS mono-mission (Topex/Poseidon, Jason-1 and Jason-2 only) time series to estimate the referencing bias of in-situ time series and then use these biases to

estimate the drfit of another mission (here ENVISAT).

The results of this analysis are presented here based on the evaluation of the global differences between the ENVISAT mission and tide gauges between 2004 and 2012.

6.2.3. Results

The present experiment focuses on the estimation of global altimeter drifts, and we are mainly interested on long term drifts. Other characteristics of the signal are not thoroughly evaluated here. Figure 30 presents the global ENVISAT bias estimates using the four processings described above.

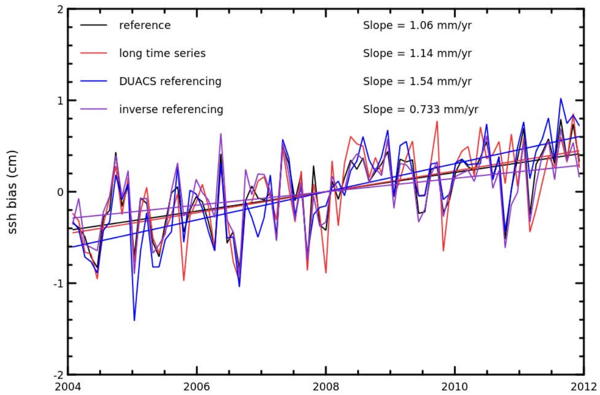


Figure 30: Global ENVISAT biases evaluated with respect to tide gauges using four different processings

Over the period considered here, the long term drfits estimates range from 0.7 to 1.5 mm/yr, which is in line with the estimated uncertainty of the method (about 0.7 mm/yr). Interestingly the black line which corresponds to our standard processing is very close to the red one wich corresponds to the estimate using only complete time series, and which is the one where we believe the smallest long-term error is committed. The temporal variability of the drfit is comparable in all cases with a slightly larger variability for the solution using only long time series (which leads to using less stations in the analyis).
This small experiment shows that our current processing has no important long-term drift. Our estimates are therefore reliable and the method provides consistent estimates, with the advantage of including a large sample of in-situ stations, thus reducing the standard devaition of the differences.

7. Conclusions

This report presents the operating result of the altimeter/tide gauges comparison processing. As an operational component of the altimeter calibration/validation activity (development and operational account, automatic processing, ...), reliable results from the comparison to tide gauge measurements are compiled thanks to an homogeneous tidal database and a robust methodology to assess potential drifts or jumps in the altimeter measurements. Therefore, the processing sequence is routinely performed in the whole studies involving altimeter data in order to better benefit from the external and independent comparison with tide gauge measurements and improve the relevance of analyses.

In 2014, little changes were made to the database part of the processing. We still routinely acquire PSMSL monthly data as well as GLOSS/CLIVAR fast delivery dataset from the University of Hawai'i. In addition to this we now downlaod and process hourly data downloaded from the french REFMAR network. This improves the data coverage along the french coasts. However this network is not in use in the routine comparisons between altimetry and tide gauges.

The first objective of the altimetry in-situ comparisons is to detect any drifts or jumps in satellite altimetry time series:

- 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 drfit either, yet to jumps are observed on the time series of SSH differences, corresponding to the orbit changes of the mission.
- In the TOPEX/Poseidon, two phases can be identified, separated by sudden increase in the SSH differences in 1996. The origin of this increase is still unknown.
- 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.

A second objective of the activity is to provide an evaluation of new altimeter standards. For example, in 2013, the GPd wet tropospheric correction was assessed. This year the tide gauges database and comparison chain were used to validate the new version of DUACS multi-mission gridded products (see section 6.4.3 of [16]).

In addition, several investigations have been performed in 2013 to evaluate the sensitivity of the comparison methodology to several processing choices. This kind of sensitivity tests will be a part of next year's work with a double intent: contribute to a better estimation of the uncertainties of the method and prepare the cross-comparison between groups. Moreover, the last two OSTST meetings emphasized the importance of having all groups performing altimetry/tide gauges comparisons working together to understand the differences in their processings and results. This work has been initiated this year, unfortunately to no quantitative results, but will be a priority of next year's activity.

8. References

References

[1] Ablain, M., S. Philipps, M. Urvoy, N. Tran, and N. Picot, 2012: Detection of long-term instabilities on altimeter backscatter coefficient thanks to wind speed data comparisons from altimeters and models. Marine Geodesy 2012, DOI: 10.1080/01490419.2012.718675.

[2] Ablain, M., A. Cazenave, G. Valladeau, and S. Guinehut, 2009: A new assessment of global mean sea level from altimeters highlights a reduction of global trend from 2005 to 2008. Ocean Sci. Disc., 6, 31-56.

[3] AVISO, 2013: Envisat RA2/MWR ocean data validation and cross-calibration activities. 2013 annual validation report. SALP-RP-MA-EA-XXXXX-CLS ed. 1.0, 129 pp.

[4] AVISO, 2013: Jason-2 validation and cross calibration activities. 2013 annual validation report. SALP-RP-MA-EA-22270-CLS ed. 1.0.

[5] Bessero, G., 1985: Marées, Service Hydrographique et Océanographique de la Marine, Brest.

[6] ESA Sea Level CCI Validation Report, WP2700 Coastal areas, 2011 http://www.esa-sealevel-cci.org/webfm_send/186.

[7] Legeais, J.F., and P. Prandi, 2013: Validation of altimeter data by comparison with in-situ Argo T/S profiles. SALP-RP-MA-EA-22281-CLS ed. 1.0.

[8] Bouffard, J., A. Pascual, S. Ruiz, Y. Faugère, and J. Tintoré, 2010: Coastal and mesoscale dynamics characterization using altimetry and gliders: A case study in the Balearic Sea. J. Geophys. Res., 115, C10029, doi:10.1029/2009JC006087.

[9] Carrère, L. and F. Lyard, 2003: Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations. Geophys. Res. Lett., Vol. 30, 1275, 4 pp. doi:10.1029/2002GL016473.

[10] Cartwright, D.E., and A.C. Eden, 1973: Corrected Tables of Tidal Harmonic, Geophys. J. R. Astr. Soc., 17 (5), 619-622.

[11] Dorandeu, J., and P.-Y. Le Traon, 1999: Effects of global mean atmospheric pressure variations on mean sea level changes from Topex/Poseidon, J. Atmos. Oceanic Technol., 16, 1279-1283.

[12] Labroue, S., 2007 : RA2 ocean and MWR measurement long term monitoring, 2007 report for WP3, Task 2 - SSB estimation for RA2 altimeter. Contract 17293/03/I-OL. CLS-DOS-NT-07-198, 53pp. CLS Ramonville St. Agne

[13] Prandi, P., G. Valladeau, J.F. Legeais, M. Ablain, and N. Picot, 2013: Analyses of altimetry errors using in-situ measurements: tide gauges and Argo profiles. OSTST, Boulder.

[14] Peltier, W. R., 2004: Global Glacial Isostasy and the surface of the ice-age earth: the ICE-5G (VM2) Model and Grace. Annu. Rev. Earth Planet. Sci., 32 (2004), pp. 111-149.

[15] Ruiz Etcheverry, L. A., M. Saraceno, A. R. Piola, G. Valladeau, and O. O. Möller: Annual cycle in coastal sea level from gridded satellite altimetry and tide gauges. Continental Shelf Research, in press.

[16] Specific Works and Studies done during year 2014 within DUACS/GIM Expertise and Quality Activities, 2015, ref: CLS-DOS-NT-14-264/SALP-RP-MA-EA-22401-CLS

[17] Tamisiea, M.E., and J.X. Mitrovica, 2011: The moving boundaries of sea level change: Understanding the origins of geographic variability. Oceanography 24(2):24–39.

[18] Validation of altimeter data by comparison with tide gauge measurements: yearly report 2013, ref: CLS-DOS-NT-13-285/SALP-RP-ME-EA-22294-CLS

[19] Valladeau, G., J.F. Legeais, M. Ablain, P. Prandi, N. Picot, P. Femenias, and J. Benveniste, 2013: Analyses of altimetry errors using in-situ measurements: tide gauges and Argo profiles. ESA Living Planet Symposium, Edimbourg.

[20] Valladeau, G., J.F. Legeais, M. Ablain, S. Guinehut, and N. Picot, 2012: Comparing altimetry with tide gauges and Argo profiling floats for data quality assessment and Mean Sea Level studies. Marine Geodesy 2012, DOI: 10.1080/01490419.2012.718226.

[21] Valladeau, G., L. Soudarin, M. Gravelle, G. Wöppelmann, and N. Picot, 2013: Quality assessment of altimeter and tide gauge data for Mean Sea Level and climate studies.

[22] Zeilis, A., C. Kleiber, W. Krämer, and K. Hornik, 2003: Testing and dating of structural changes in practice. Computational Statistics & Data Analysis 44 (2003) 109 – 123.

[23] Zeilis, A., A. Shah and I. Patanaik, 2010: Testing, monitoring and dating structural changes in exchange rate regimes. Computational Statistics & Data Analysis 54 (2010) 1696 – 1706.

9. Appendix

9.1. Poster presented at OSTST 2014

Quality assessment of altimeter data through tide gauge comparisons

P. Prandi[1], G. Valladeau[1], M. Ablain[1], N. Picot[2], J-D. Desjonqueres[2] and E. Bronner[2]

[1]CLS
[2]CNES

Alti/Tide gauges primer

Tide gauges provide an independent SSH measurement and are used to provide absolute calibration of altimetry missions.

Here we use a network of tide gauges as large as possible to estimate altimetry minus in-situ differences with three goals:

- detect drift and biases in altimetry time series,
- evaluate the impact of new altimetry standards,
- provide in-situ data quality assessment.

These metrics are used in conjunction with classical Cal/Val metrics (internal consistency and cross-comparisons) and with comparisons to Argo floats

Comparison method

- Tide gauges time series are corrected for tidal signals, DAC effects and vertical uplift resulting from GIA process.
- At each tide gauge station, we estimate a correlation map (Figure 1) between the tide gauge time serie and altimetry with a given distance of the station.
- An iterative scheme selects the altimeter point where the correlation is maximum and where the RMS of the differences is below a given threshold. Time series with too many gaps are rejected.
- Tide gauges time series are referenced to altimetry (mean difference is set to 0).

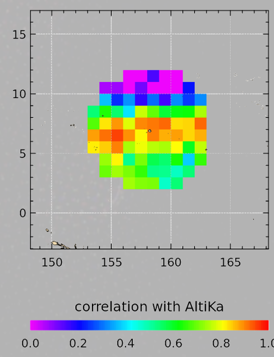


Figure 1: Map of the correlation between one in-situ station and SARAL/AltiKa

Global altimetry drifts

METHODOLOGY

- For each altimeter mission, all stations where a significant correlation was found are used,
- At each time step, the global bias is estimated from the ensemble mean at all available stations. Weights are applied to account for the uneven station distribution.
- We apply a -0.3 mm/yr correction on altimeter time series to account for GIA effects.

RESULTS

- No statistically significant drift of the Jason-2 mission is observed : -0.2 mm/yr with a Monte-Carlo uncertainty of 0.7 mm/yr (95%), see Figure 2.
- Biases between the different phases (interleaved orbit, geodetic phase) of Jason-1 mission are detected when comparing to tide gauges (Figure 3).
- Envisat mission still displays a larger drift with respect to tide gauges than other missions (1.2 mm/yr +/- 0.5 mm/yr, Figure 4) in agreement with cross-comparisons and comparisons to Argo floats
- Comparison with TOPEX/Poseidon (Figure 5) suggests a higher uncertainty level on TOPEX-A with a jump in 1996
- Comparisons with SARAL/AltiKa are performed, but the time series is still too short to draw any significant drift result

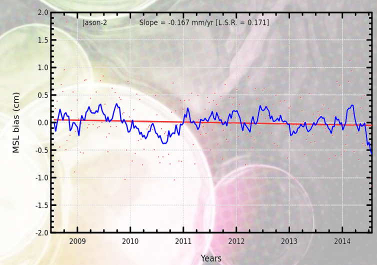


Figure 2: Global bias between Jason-2 and tide gauges

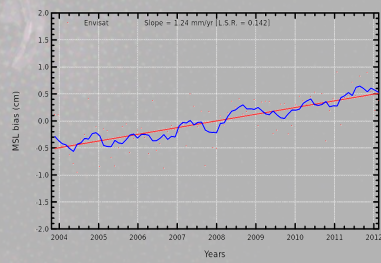


Figure 4: Global bias between Envisat and tide gauges

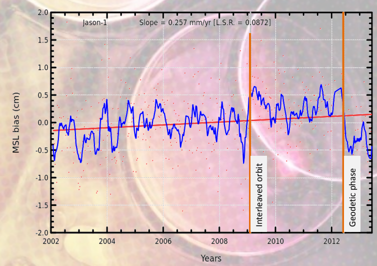


Figure 3: Global bias between Jason-1 and tide gauges

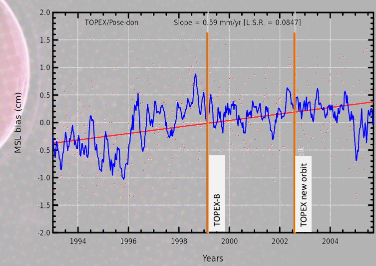


Figure 5: Global bias between TOPEX/Poseidon and tide gauges

Detecting structural changes in tide gauges time series

Can we automatically detect regime changes (trend changes, biases, variance changes) in tide gauges and/or altimetry time series ?

METHODOLOGY

- We use the statistical tools proposed by Zeileis et al (2003)[1]
- Relies on the assumption that, if there are no regime changes, then the quantity:

$$F_p \propto \frac{1}{\sigma\sqrt{n}} \sum_{i=1}^{\lfloor nt \rfloor} \varepsilon_i$$

where ε is the residual from a linear fit

should not change much.

RESULTS

This provides a quantitative assessment of regime changes, with significance level.

As an example, we apply this test to the time series of altimetry minus tide gauges SSH differences at station Majuro (Figure 6). Figure 7 displays the results of the test, and detect a structural change in 2007-2009, corresponding to a bias in the SSH differences.

This is seen for both Envisat and Jason-1 and points to an issue in the tide gauge time serie.

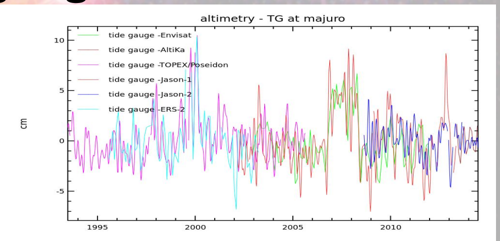


Figure 6: SSH differences at station Majuro

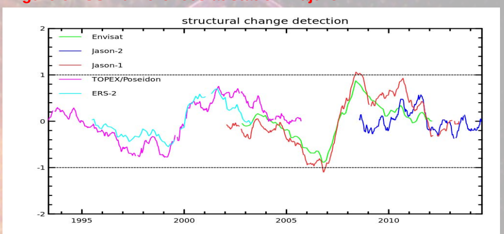


Figure 7: Results of the structural change test

Following OSTST 2013 recommandations work has been initiated to perform method intercomparison between groups

[1]*Testing and dating of structural changes in practice*, A Zeileis, C Kleiber, W Krämer, K Hornik - Computational Statistics & Data Analysis, 2003

CLS cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

Ocean Surface Topography Science Team Meeting - October 2014

9.2. A reading guide for tide gauges information cards

A new version of in-situ information cards was introduced last year, this new version included new statistical tests such as Taylor diagrams. In order to explain how these statistical information is produced, we writed a reading guide for thes information cards. This *vademecum* is reproduced here.

Note on in-situ information cards

Pierre Prandi

January 21, 2015

The present document intends to give the reader useful information about how to understand the in-situ information cards available on the AVISO website [1]. We provide here a short introduction on the information displayed by the different tables and plots as well as useful references for readers who might be interested in digging deeper into the methodologies.

Please adress any remarks or enquiries to *pprandi@cls.fr*.

[1] available at `http://www.aviso.altimetry.fr/en/data/calval/in-situ-calibration-and-validation/in-situ-global-statistics.html`

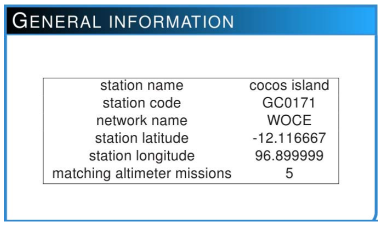
Introduction

We will present the different information boxes that appear on the in-situ information cards. In the current version of the processing, two information cards are generated for each tide gauge station in the database. The standard version presents the key metrics while the expert version is enriched with specific tests and results and provide more information on the agreement between altimetry and in-situ records.

This document is illustrated with plots and figures taken from actual in-situ information cards [2]. The presenting order used here follows the content of the expert mode information cards.

[2] I've used the Cocos Island station for this pupose

General information



GENERAL INFORMATION

station name	cocos island
station code	GC0171
network name	WOCE
station latitude	-12.116667
station longitude	96.899999
matching altimeter missions	5

Figure 1: General information box for station Cocos Island

This box is present in both standard and expert versions of the information card and provides general information about the station:

- the station's name and code,
- its network,
- its position, as provided by the data delivery service,
- and the number of matching altimetry missions.

This last figure is the first quality indicator for the in-situ record, the higher this number the better the agreement between in-situ and altimetry. We currently proceed to comparisons to 6 altimeter missions: ERS-2, TOPEX/Poseidon, Jason-1, Envisat, Jason-2 and SARAL/AltiKa. A complete description of the methodology used to compare satellite altimetry to tide gauge records can be found in the 2013 annual report of this activity [3], the important point here is that a positive match is set if the two time series fall within correlation and RMSd thresholds.

[3] also available through AVISO website at `http://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/annual_report_insitu_TG_2013.pdf`

Statistics

This box is present in both the standard and expert versions of the information card but some extra statistics are added in the expert version. Each satellite altimetry mission is associated with a color

STATISTICS

statistics	Envisat	AltiKa	TOPEX/Poseidon	Jason-1	Jason-2
distance (km)	158.05	81.27	94.75	94.75	94.75
correlation	0.94	0.97	0.93	0.92	0.94
Taylor distance	0.35	0.28	0.38	0.40	0.36
altimeter std (cm)	9.94	10.47	12.36	11.43	13.00
tide gauge std (cm)	10.27	9.96	12.19	11.85	12.93
rms of the differences (cm)	3.55	2.54	4.67	4.65	4.61
sea level drift ($mm.yr^{-1}$)	-4.22	-33.05	-1.38	-2.96	-3.99
drift uncertainty ($mm.yr^{-1}$)	4.62	32.52	3.22	2.90	7.58

Figure 2: Statistics box for station Cocos Island

with is consistently used throughout the whole information card. For each matching satellite altimetry mission, different metrics are estimated:

- the distance between the tide gauge station and the point (grid cell) where the satellite altimetry time series was extracted,
- the correlation between in-situ and altimeter time series,
- the Taylor distance between the two time series[4],
- the standard deviation of altimetry SSH,
- the standard deviation of in-situ SSH[5],
- the RMS of the SSH differences between altimetry and in-situ time series,
- the SSH drift or the trend of the SSH differences,
- the uncertainty associated with this trend, estimated using a Monte-Carlo method using and AR(1) process to model the residuals.

[4] this metric is presented in section dedicated to Taylor diagrams

[5] this is not a constant because the estimation is performed over each altimeter's period and therefore vary

Location Information

The location box is present on the standard and expert versions of the information cards and provides information about the position of the tide gauge station and the position where satellite altimetry time series were extracted. Two plots are shown, the first one is a global map displying the position of the tide gauge station. The

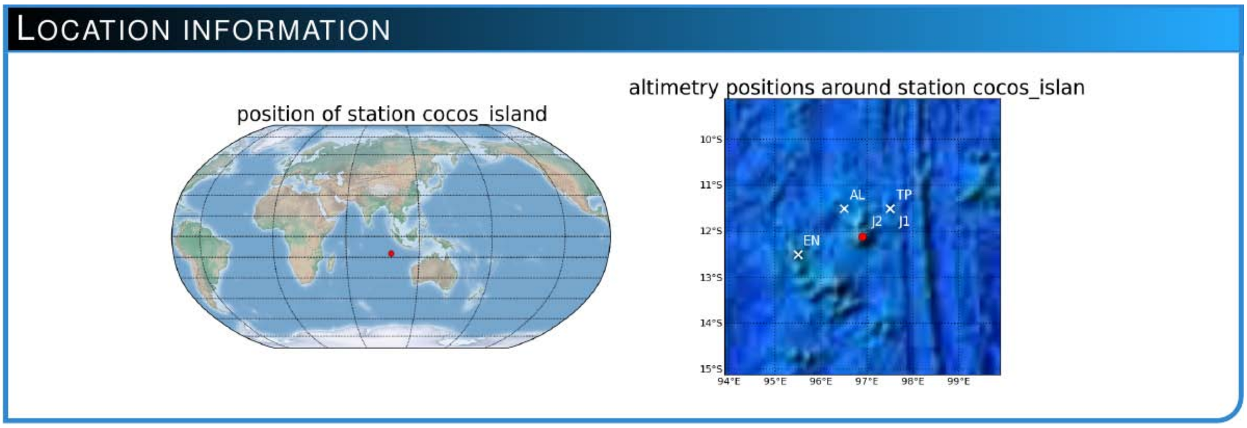


Figure 3: Location box for station Cocos Island

second one is a zoom centered on the tide gauge station (red dot) where the white crosses indicate the positions from which satellite altimetry time series (in the process, satellite altimetry along-track data are averaged onto 1 degree grids) were extracted. All these information are plotted over the ETOPO bathymetry[6].

[6] Amante, C. and B.W. Eakins, 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M

Taylor diagram

Taylor diagrams allow for an easy graphical representation of how close two time series are. This diagram is only available on the expert version of the information cards [7].

[7] I'll only give here a few clues on how to understand the present diagram, for an excellent introduction to Taylor diagrams, please refere to `http://www-pcmdi.llnl.gov/about/staff/Taylor/CV/Taylor_diagram_primer.pdf`

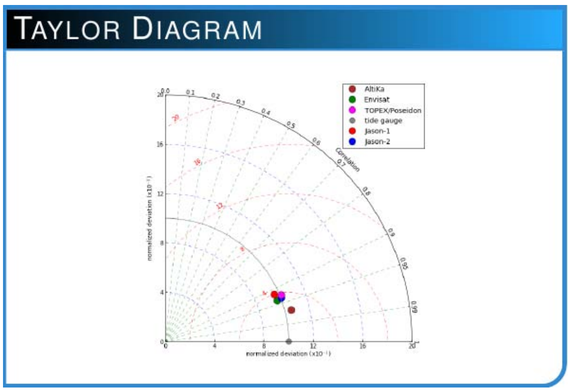


Figure 4: Location box for station Cocos Island

How to read such a diagram ? The horizontal axis displays the standard deviation of the reference time series (in this case the in-situ SSH time series). In order to display multiple points on one diagram, all standard devation are normalized, hence the reference is the unique grey dot corresponding to $\sigma = 1$. The vertical axis refers to the standard deviation of the observation (here altimeter SSH time series for the different missions considered) and is supplemented by the blue lines while the quarter of a circle axis displays the correlation between the observed and reference time series (supplemented by green lines). The red lines show contours of RMSd between time series. As a result the Taylor Diagram displays how close the reference (in-situ) and observed (each altimetry missions, represented by a colored dot) time series are in terms of correlation and ratio of standard deviations. It also provides a unique measure, the Taylor distance, for this level of agreement which is simply the distance of the observation point to the reference in the Taylor diagram space.

Correlations

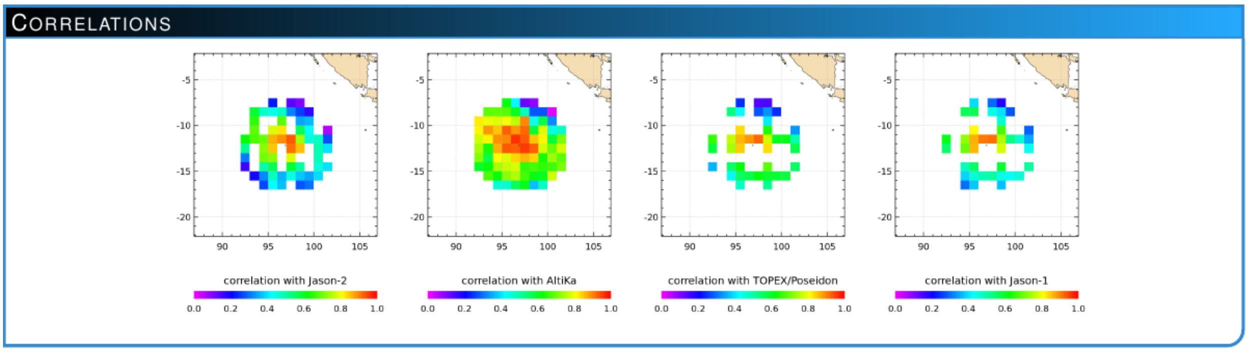


Figure 5: Correlations box for station Cocos Island

This part of the information card shows the correlations obtained when comparing in-situ to altimetry SSH time series. The comparison process involves the estimation of a correlation map for each altimeter mission, which is shown here. These maps show us the spatial distribution of correlations between the tide gauge SSH and the different altimtry missions. At some stations, a very peaky pattern is observed with the correlation decreasing very quickly with the distance, at other stations high correlations are more widely distributed. Sometimes a relation with the bathymetry can be observed.

Sea level time series

This section of the information cards displays two time series graphs. These plots are availbale on both the standard and expert version of the informations cards. The left one represents the SSH time series for the tide gauge (black line) and altimetry missions (colored lines). The right one is the time series of altimetry minus tide gauge SSH differences. For both graphs, all time series are centered before

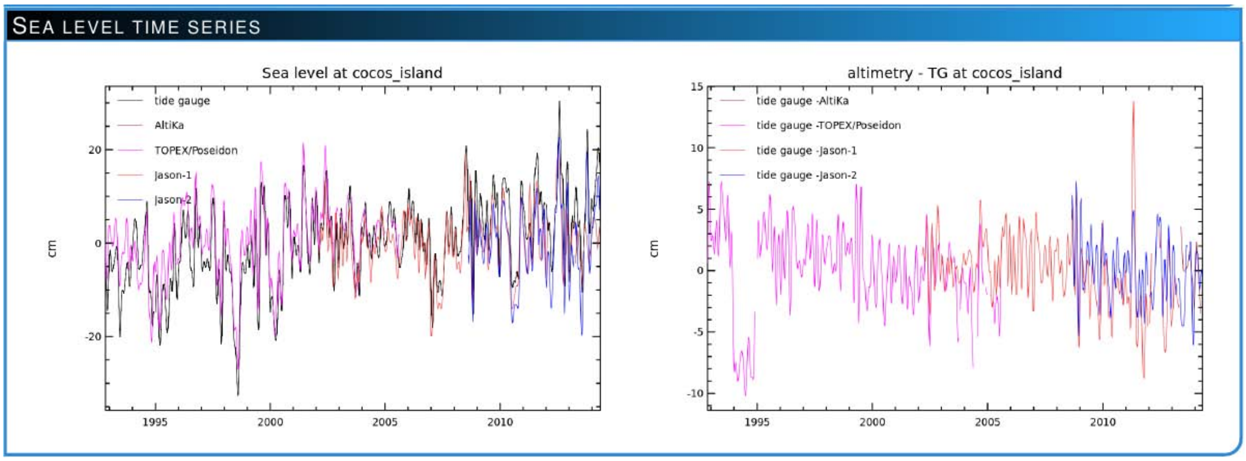


Figure 6: Time series box for station Cocos Island

plotting them.

Seasonnal cycle

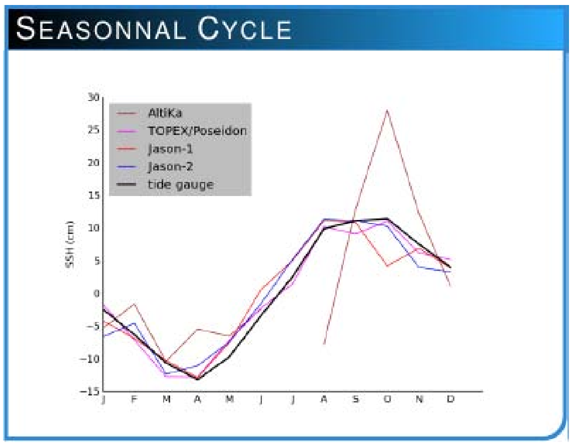


Figure 7: Seasonnal cycle box for station Cocos Island

The seasonnal cycle section presents an estimation of the seasonnal cycle for the in-situ SSH and for the different altimeter missions selected. The purpose is to give the reader an indication about how the seasonnal cycles of altimetry and tide gauges match or differ. The seasonnal cycle is estimated by computing monthly climatologies from all available data, and is therefore not constrained by any model[8].

[8] like a $cos(\omega t) + sin(\omega t)$ model for example

Structural change detection

This section of the information cards is only available in the expert version. The aim of test performed here is to detect any structural change in the time series of altimetry minus in-situ SSH differences, like jumps, drifts changes or sudden variance changes. The test proposed here is based on the work of Zeilis et al., 2003[9]. We only provide here the general idea behind the test, the interested reader may read the original paper. The test is based on estimating a simple linear model $\hat{y} = \alpha \times t + \beta$ linking the SSH differences to time, of course this does not describe the full variability of SSH differences and we study the residuals $r = y - \hat{y}$ to this model. The assumption behind the test is that a structural change in the time series will translate as a modification of the distribution of the residuals. A metric for the distribution of residuals is built over the full period and compared to the same metric estimated over segments of the initial time series. On the plot displayed on figure 8, the two black dotted horizontal lines show the 95% uncertainty level. If, for a given mission, the metric goes beyond these lines (either above or below), there is a statistically significant structural change in the SSH differences time series at the 95% confidence level. If this gives no clue about which change is occuring (it could be a jump or a drift change for example), it does provide a dating of this change and one can refer to the SSH differences plot (see section on time series) around the same time to try to detect the change. On this example, the jump at the beginning of the TOPEX/Poseidon time series is clearly visible.

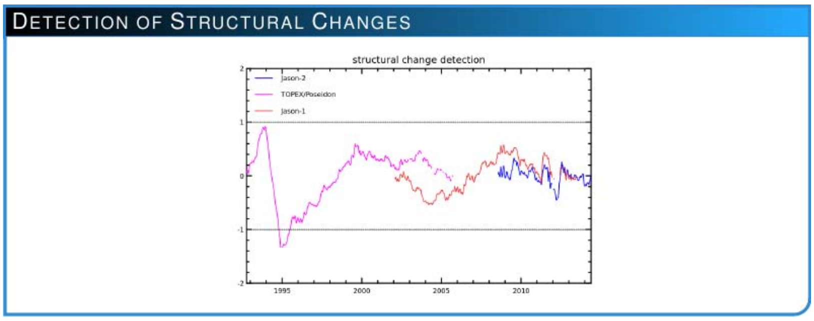


Figure 8: Structural change detection box for station Cocos Island

[9] Achim Zeileis, Christian Kleiber, Walter Krämer, Kurt Hornik, Testing and dating of structural changes in practice, Computational Statistics & Data Analysis, Volume 44, Issues 1–2, 28 October 2003, Pages 109-123, ISSN 0167-9473. available at `http://www.sciencedirect.com/science/article/pii/S0167947303000306`