Consortium Members

ESA Sea Level CCI

Error Characterization Report: Altimetry Measurements Errors at Climate Scales

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List of tables and figures

List of tables:

List of figures:

Applicable documents

AD 1 Sea level CCI project Management Plan
CLS-DOS-NT-10-013

Reference documents

RD 1 Manuel du processus Documentation
CLS-DOC

RD 2 SLCCI-Sensitivity_MSL_S3-WP2520-1-0. Task 2520: Sensitivity of the MSL calculation changing the orbit of the reference mission: Sentinel-3 instead of Jason missions. SLCCI-WP2520, CLS-DOS-NT-15-016. V1.0.

Acronyms List

CLS	Collecte Localisation Satellite
CNES	Centre National d'Etudes Spatiales
DAC	Dynamical Atmospherical Correction
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DTU	Denmark Technical University
DUACS	Data Unification and Altimeter Combination System
ECMWF	European Centre for Medium-range Weather Forecasts
ERA	ECMWF ReAnalysis
ESA	European Space Agency
FES	Finite Element Solution
GCOS	Global Climate Observing System
GDR	Geophysical Data Record
GIA	Glacial Isostatic Adjustment
GMSL	Global Mean Sea Level
GMWS	Global Mean Wind Speed
GOT	Goddard Ocean Tide
GPS	Global Positionning System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
ITRF	International Terrestrial Reference Frame
JMR	Jason-1 Microwave Radiometer
LSR	Least Square Regression
MGDR	Merged Geophysical Data Record
MSL	Mean Sea Level
MSS	Mean Sea Surface
MWR	Micro-Wave radiometer
OSTST	Ocean Surface Topography Science Team
POD	Precise Orbit Determination
RBU	Relative Bias Uncertainty
RMSL	Regional Mean Sea Level

SALP	Satellite Altimetry Localisation Précise (CNES project)
SLA	Sea level Anomalies
SLCCI	Sea Level - Climate Change Initiative
SLR	Satellite Laser Ranging
SSB	Sea State Bias
STD09	Standard-09
SWH	Significant Wave Height
T/P	TOPEX/Poséidon
TMR	Topex Radiowave Radiometer

List of Contents

1. Objectives

Thanks to studies performed in the framework of the Satellite Altimetry Localisation Précise (SALP) project (supported by CNES) since the TOPEX era, and more recently in the framework of the Sea-Level Climate Change Initiative (SLCCI) project (supported by ESA), strong improvements have been achieved on the estimation of the Global and regional mean sea level over the whole altimeter period for all altimetric missions. Thanks to these efforts, a better characterization of altimeter measurements errors at climate scales has been performed and is presented hereafter. These errors have been compared to user requirements in order to assess if scientific goals are reached by altimeter missions. This study also underlines the importance to enhance the link between altimetry and climate communities to improve or refine user requirements, and to better specify future altimeter systems for climate applications but also to reprocess older missions data beyond their original specifications.

2. Overview

Thanks to satellite altimetric missions, the Global Mean Sea Level (GMSL) has been computed on a continual basis since January 1993. 'Verification' phases, during which the satellites follow each other in close succession (TOPEX/Poseidon--Jason-1, then Jason-1--Jason-2), help to link up these different missions by precisely determining any relative bias between them. Envisat, ERS-1 and ERS-2 are also used, after having being adjusted on these reference missions, in order to compute the Mean Sea Level at higher latitudes (Topex and Jason missions operate between +/-66°), and also to improve the spatial resolution by combining all these missions together.

The GMSL deduced from TOPEX/Poseidon, Jason-1 and Jason-2 indicates a global rate of **3.2** mm/yr from 1993 to 2012 applying the post glacial rebound (MSL AVISO website). The correction of post glacial rebound allows to take into account the rise of land masses that were depressed by the weight of ice sheets during the last glacial period [Peltier, 1999]. Besides, the regional MSL trends bring out an inhomogeneous repartition of the ocean elevation with local MSL slopes ranging from ± 8 mm/yr.

Thanks to studies performed since the TOPEX era in the framework of the SALP project (supported by CNES) and more recently in the framework of the Sea-Level Climate Change Initiative (SLCCI) project (supported by ESA), strong improvements have been achieved in the estimation of the global and regional MSL over the whole altimetry period for all the altimetric missions. This resulted in a better characterization of errors impacting the evolution of the Global and the regional MSL. These errors concern different time scales but the long-term evolution (> 10 years) is likely the most important scale for climate studies. Studies have shown that the Global MSL trend error was 0.6 mm/yr with a 90% confidence interval over the 1993-2008 period [Ablain et al, 2009]. However, other time scales, such as the inter-annual signal and other periodic signals (annual and semi-annual periods), are also of great interest for climate studies. Errors could reduce the accuracy of observations of Global MSL variations at these scales leading to a difficult interpretation of geophysical mechanisms at the origin of these inter-annual signals.

In this report, we propose to describe and quantify these errors as precisely as possible and to discuss on their potential origins. We focus our study on TOPEX, Jason-1 and Jason-2 data using level-2 products (MGDR, GDR) updated with the latest altimeter standards available in the frame of SALP (CNES) and Sea-Level CCI (ESA) projects. The errors are also described in regards to the Climate User Requirements defined in the frame of the SLCCI project.

In the version 2.0 of this report, we have also provided an estimation of the envelop error of the global MSL times series for Jason-1 and Jason-2 missions. This approach allows us to accurately determine the temporal evolution of errors by estimating for each GMSL value the uncertainties in altimetry standards, data selection, inter-mission relative biases and computational methodology. At the moment, this work is on-going: it will be extended in 2017 to TOPEX and others altimeter missions.

3. Sources of altimetry errors

Several sources of errors at climate scales have been identified. The largest ones concern the orbit computation, the wet troposphere corrections and the altimeter instrumental parameters. Others corrections used in the MSL computation are, however, not negligible to establish the altimetric budget error. All these errors are described in this section.

3.1. Orbit solutions

Orbits solutions have been dramatically improved in the last years, reducing errors especially for regional MSL. Errors in the International Terrestrial Reference Frame (ITRF) and in gravity field models are the main causes of error in the orbit computation.

ITRF solutions reduce the heterogeneity between hemispheric MSL trends especially concerning long-term trends. In SLCCI products, the latest orbit solutions based on ITRF2008 (CNES GDR-D) have been applied on Jason-1 and 2 data. For TOPEX, the GSFC orbit solution is used (std09). It is based on ITRF2005. Compared to former orbits solutions based on ITRF2000, the improvements in Jason and T/P MSL records are significant: the MSL trend differences between North and South hemispheres from 1993 to 2012 have been reduced from 1 mm/yr to 0.5 mm/yr (Fig. 1). As expected, the MSL evolution between hemispheres is similar over the long period, therefore these differences provide a maximal threshold of the long-term error at hemispheric scales. However, the average error estimated in hemispheres is not homogenous: errors are higher at high latitudes and almost null at the equator. Therefore, at local scales (~100km), the current long-term errors due to the ITRF solution have been estimate lower or equal to 1 mm/yr.

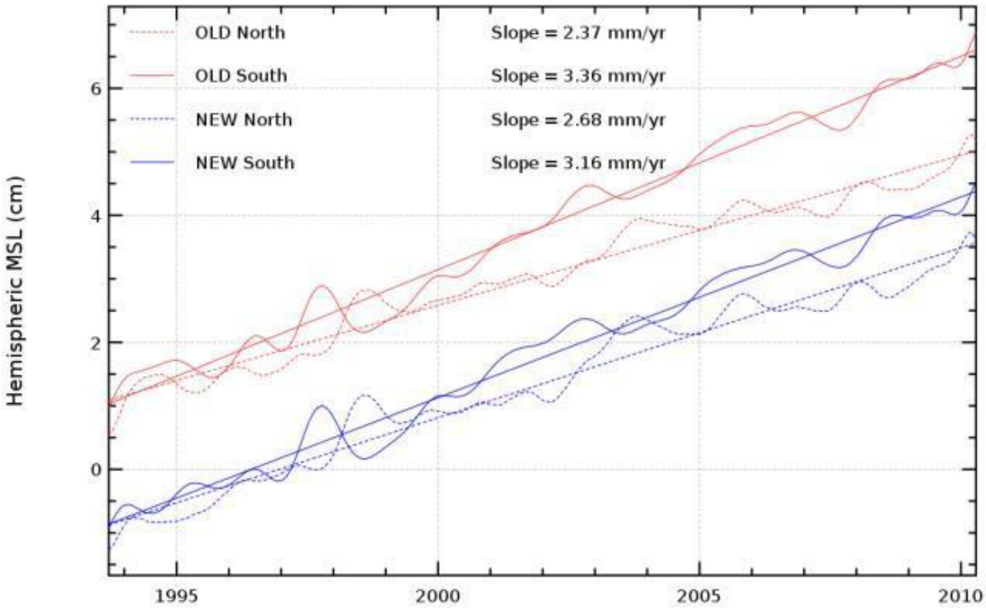

Fig. 1: Hemispheric MSL evolution using the latest altimeter orbit solution (ITRF2008 & ITRF2005, 'NEW') and the former one (ITRF2000, 'OLD'). The corresponding linear regressions are displayed as well. MSL trend differences between hemispheres are now reduced to 0.5 mm/yr with the latest orbit solution (for 1.0mm /yr with the former solution).

Latest gravity field models also improved significantly regional MSL trends at basin scales. For instance, regional MSL trend differences between Envisat and Jason-1 have been significantly reduced using CNES/GDR-D orbit solutions instead of CNES/GDR-C ones [Ollivier et al., 2012]. On Jason-1, the impact is close to ± 1.5 mm/yr at basin scales (Fig. 2). However, errors in gravity field modelling are still observed and impact on orbit computation at climate scales. For instance, for the first decade of altimetry (TOPEX-era, from 1992 to 2002), GRACE data is not available. Therefore, the level of error is very likely higher than for the second altimetry decade (from 2002 to 2012). Consequently, it is difficult to estimate accurately the orbit error at climate scale due to gravity fields. However, by comparing several orbit solutions using different approaches to model gravity fields, we estimated an upper bound of the error for regional MSL trends close to 1 mm/yr [Ollivier et al., 2012. We have also observed differences in the annual cycle close to 1 mm of amplitude for global MSL and to 5 mm for regional MSL [Ollivier et al., 2012].

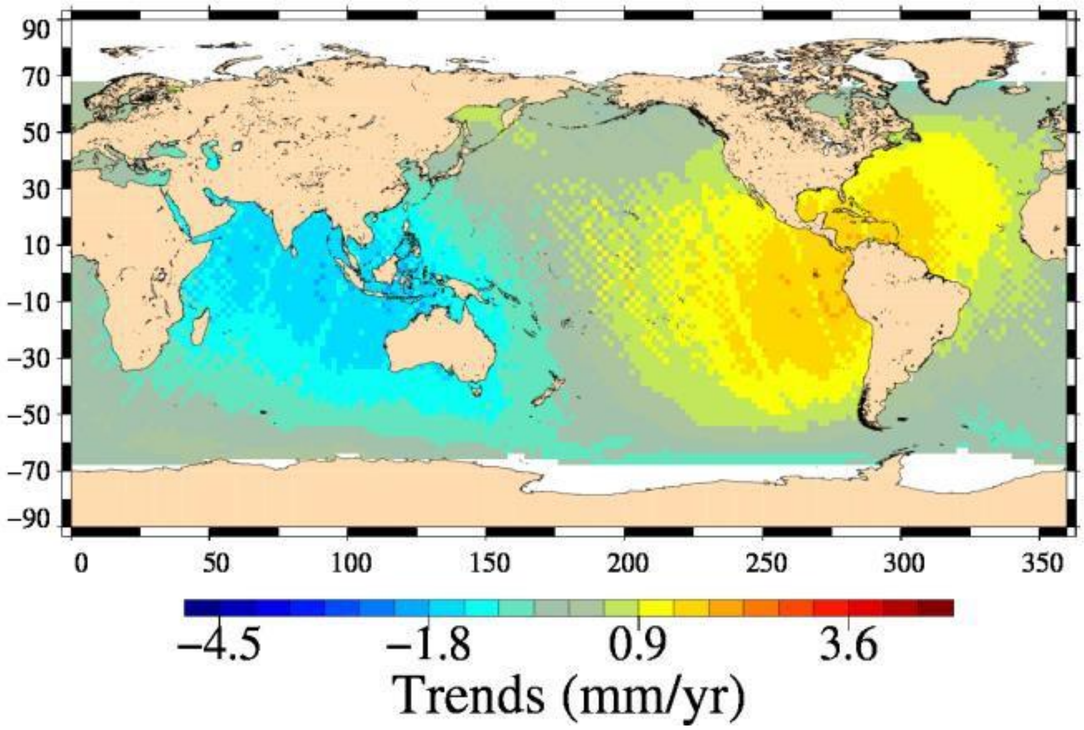

Fig. 2: Regional MSL trends differences between CNES GDR-C (Eigen-GLO4S) and GDR-D (Eigen GRGS) orbit solutions for Jason-1.

Other sources of error can also impact orbit solutions. For instance on Jason-1 mission, GPS data are unavailable from 2008 onwards, which decreases the quality of the orbit computation. The impact can be tested on Jason-2 data simulating orbit solutions with several techniques: GPS, Laser and Doris data. For instance, annual signal differences are observed by comparing orbit solutions obtained with GPS data to those obtained with DORIS+SLR data (Fig. 3).

Thanks to these analyses, the error budget of orbit solutions at climate scales has been established in the current study (Tab. 1).

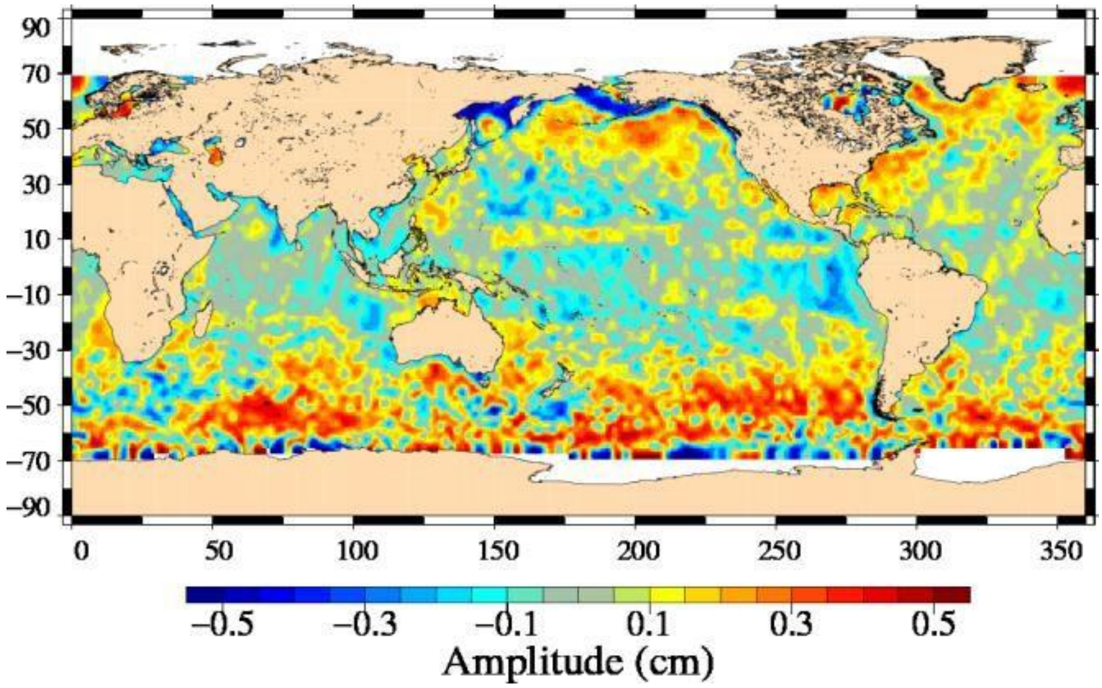

Fig. 3: Impact of Jason-2 orbit solutions (GPS-based vs. DORIS+SLR based) on annual amplitude signal.

Spatial Scales	Temporal Scales	Orbit solutions errors
GMSL	Long-term evolution	< 0.1 mm/yr
	Inter annual signals	< 1mm
	Periodic signals	< 0.5 mm for annual signal
RMSL	Long-term evolution	< 2 mm/yr
	Periodic signals	< 5 mm for annual signal

Tab. 1 : Error budget of orbit solutions at climate scales [Results obtained in present study]

3.2. Wet troposphere corrections

One major source of error affecting the MSL estimates is the wet troposphere correction derived from microwave radiometers on-board altimetric satellites. Indeed, this correction is potentially contaminated by long-term instrumental drifts. Such drifts may result from internal temperature changes induced by yaw maneuvers or happen when the instrument is turned off. Calibrations with external measurements are periodically performed to detect drifts in T/P (TMR) and Jason-1 (JMR) radiometers and also on Jason-2. Though meteorological models do not represent necessarily the truth in term of stability, they provide a good estimate of the radiometer drift error through the cross-calibration of altimetry missions and models.

Inconsistencies between corrections derived from models and radiometers have been highlighted at several spatial and temporal scales*:*

- Global MSL trend differences between radiometers and models lead to an uncertainty close to ±0.3 mm/yr over all the altimetry period [Ablain et al., 2009].
- Inter-annual differences between Jason-1 (JMR) & Envisat (MWR) radiometers and models have been observed (*Fig. 4*).
- Regional MSL evolution is also impacted especially for long-term signals. Trend differences between radiometers and models displayed discrepancies between 1 and 2 mm/yr in the tropical band (*Fig. 5*, [Legeais et al., 2014]).

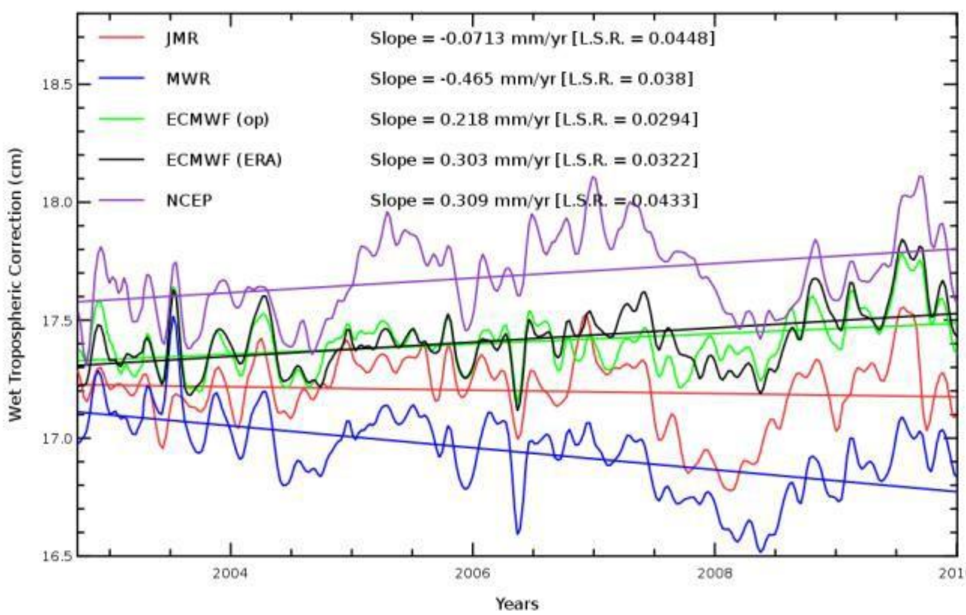

Fig. 4: Evolution of the wet troposphere content derived from Jason-1 (JMR) and Envisat (MWR) radiometers and 3 models (ECMWF operational, ECMWF Re-Analysis ERA-Interim, NCEP) from 2002 onwards.

These analyses lead to the following error budget (Tab. 2) for the wet troposphere correction derived from TOPEX, Jason-1 and Jason-2 radiometers.

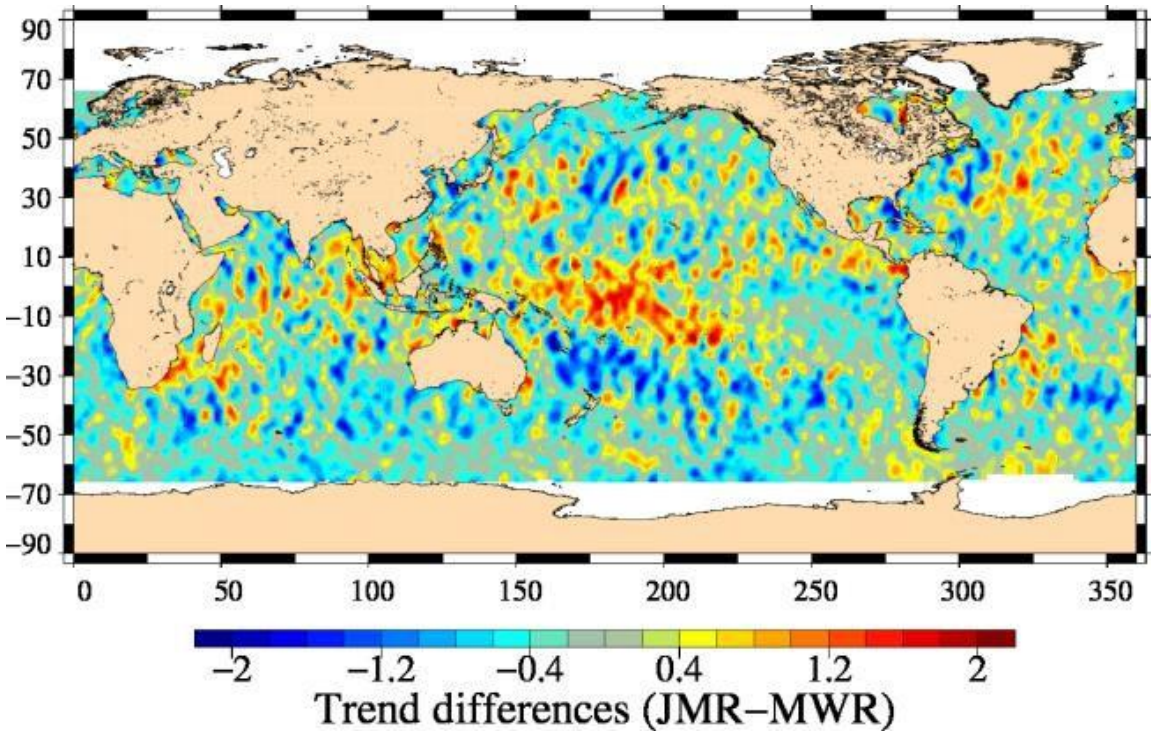

Fig. 5: Regional MSL trend differences between JMR and MWR radiometers from 2003 to 2012 (mm/yr)

Spatial Scales	Temporal Scales	Wet tropo. errors
GMSL	Long-term evolution	≤ 0.3 mm/yr
	Inter annual signals	≤ 2 mm
	Periodic signals	≤ 3 mm for 60-day signal
RMSL	Long-term evolution	≤ 2 mm/yr
	Periodic signals	Not evaluated

Tab. 2 : Error budget of wet troposphere correction at climate scales[Results obtained in present study]

3.3. Altimeter instrumental parameters

Other sources of error are due to the instrumental ageing or to errors in the ground processing. Altimeter parameters are precisely monitored over all the mission life-time to detect, monitor and correct instrumental anomalies. However, instrumental instabilities are still observed especially on the first altimetry decade on TOPEX data.

In recent studies [Ablain et al, 2012], the presence of long-term instabilities on altimeter backscattering coefficients has been highlighted. Thanks to a thorough cross-comparison between the Global Mean Wind Speed (GMWS) derived from altimetry and the atmospheric reanalysis, drifts or abnormal variations have been detected and accurately characterized. The major interest of estimating these instrumental errors is related to their impact on the GMSL evolution. As far as the GMSL is concerned, the impact of small drifts (-0.03 dB from mid-2004 to 2005 for Jason-1 and -0.1 dB from 1993 to 2002 for TOPEX) is low, but not negligible, leading to overestimate the GMSL trend by about 0.1 mm/yr over the 1993 to 2011 period. On the other hand, the abnormal behaviours detected at annual or inter-annual time scales, especially in TOPEX time-series, have a significant impact on the GMSL evolution leading to errors close to 2 mm (in 1997-1999 and in 2000-2002). Such an error level is higher than the 0.5 mm requirement for the inter-annual time scale (see ***Fig. 6***) and could impact the interpretation of geophysical processes at the origin of these inter-annual signals.

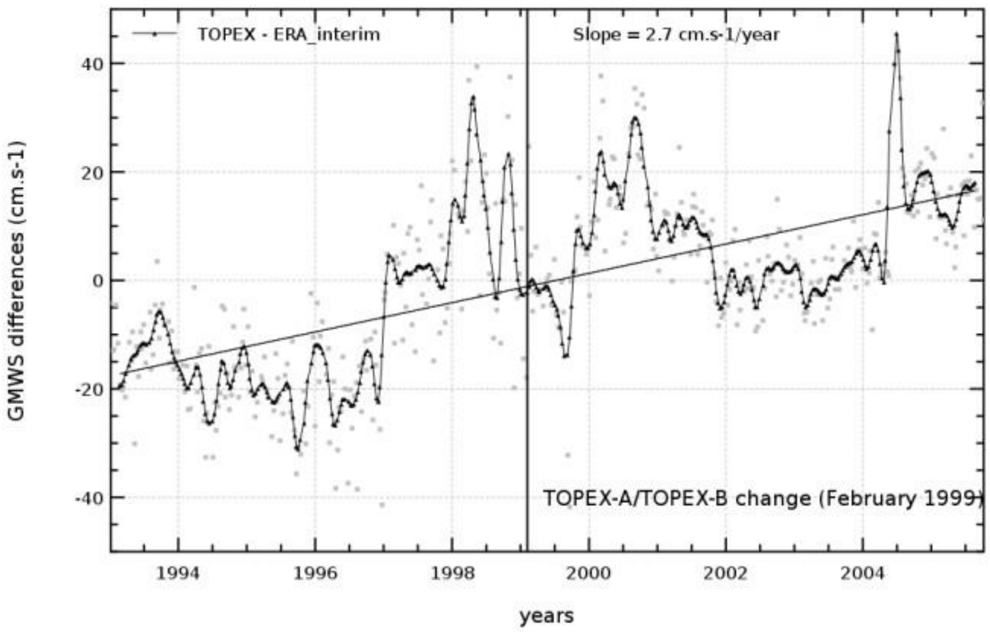

Fig. 6: Evolution of Global Mean Wind Speed (GMWS) differences between TOPEX and ERA-interim before (dots) and after (solid line) filtering out signals lower than 2 months and removing residual annual and semi-annual signals.

A 59-day erroneous signal has been also detected in the TOPEX retrievals [Zawadzki et al., 2016]. It has been subsequently detected in Jason-1 and later in Jason-2 MSLs. This signal resulted from the aliasing of a higher frequency error inherited from the tide model correction:

the semi-diurnal wave S2. This error has an indirect impact on the Jason-1&2 MSLs through oceanic tidal models which assimilate altimetry data (as stochastic solutions) and on TOPEX semi-diurnal errors not differentiable with the S2 tidal wave. Because of the aliasing effect, semi-diurnal signals were observed at 58.77 days with GOT4.7 ocean tide model (*Fig. 7*).

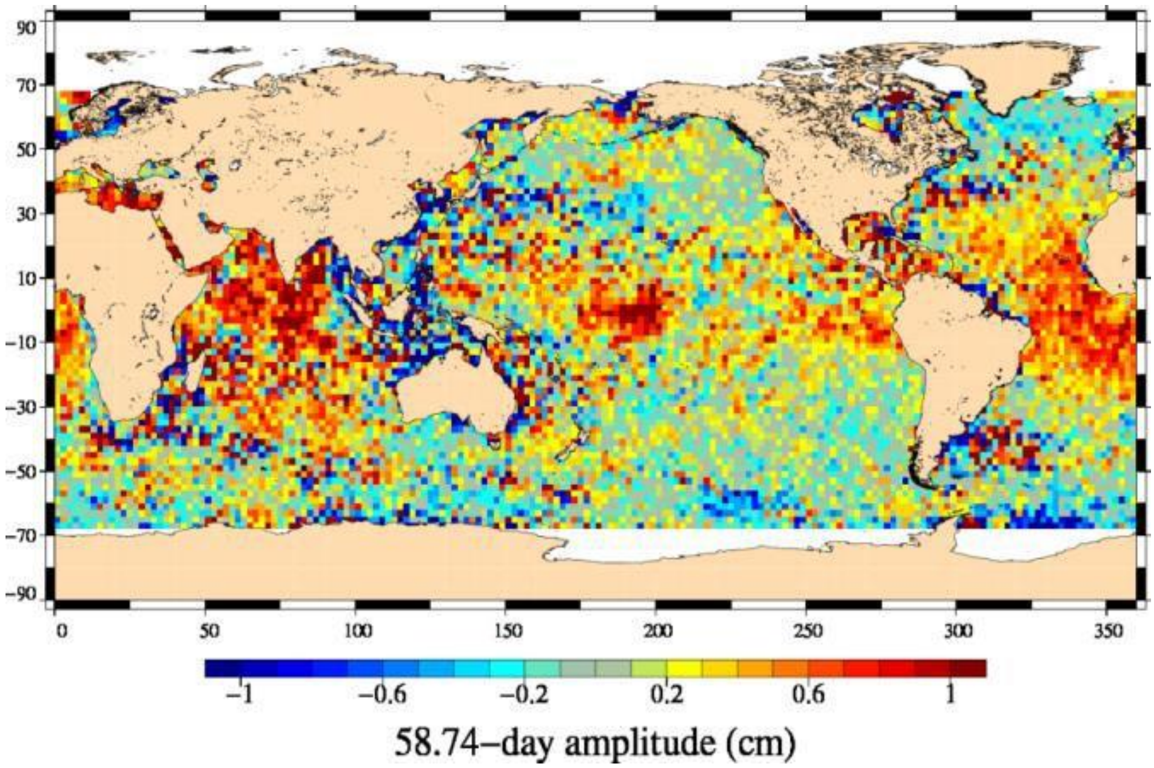

Fig. 7: Map of 58.77–day signal amplitude between TOPEX and Jason-1 MSL using GOT ocean model (Ablain et al., OSTST 2010).

However, since 2010, considerable efforts have been undertaken within the ocean tide community to correct the error in ocean tide S2-waves, particularly in the Global Ocean Tide (GOT, computed by Goddard/NASA) and in the Finite Element Solution (FES, computed by LEGOS/NOVELTIS/CLS) latest versions: GOT4.8 and GOT4.10 (Ray 2013), FES2012 and FES2014 (Fig. 8, and Fig. 9).

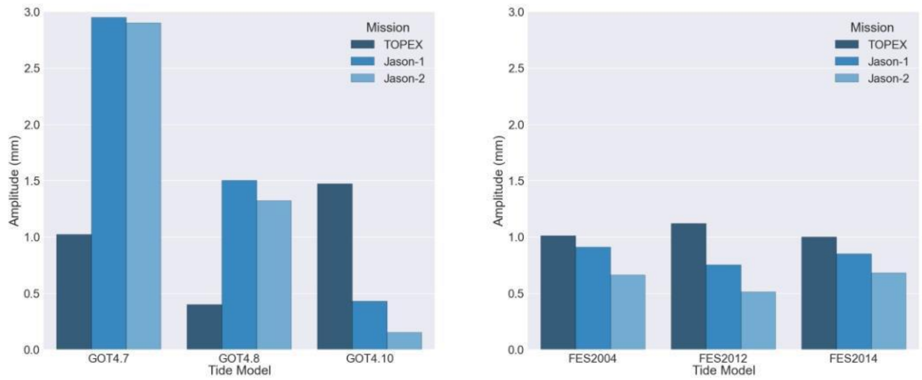

Fig. 8: Amplitude of 58.77-day error in Global MSL for TOPEX, Jason-1 and Jason-2 with the latest GOT (left panel) and FES (right panel) releases. [Zawadzki et al., 2016]

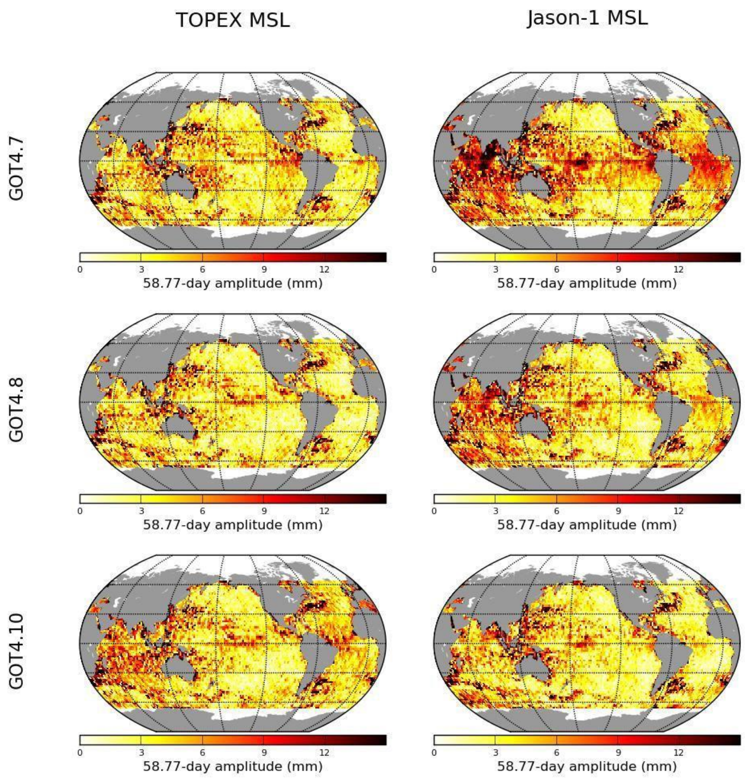

Fig. 9: Amplitudes of 58.77-day error in TOPEX, Jason-1 and Jason-2 MSL in 2°x2° boxes with the latest GOT releases [Zawadzki et al., 2016]

These errors lead to altimeter parameter error budget defined in Tab. 3. Errors are lower in the second altimetry decade (Jason-1 & 2, from 2002 to 2012).

Spatial Scales	Temporal Scales	Altimeter parameter errors
GMSL	*Long-term evolution*	< 0.1 mm/yr
	Inter annual signals	< 2 mm
	Periodic Signals	< 2 mm for 60-day signal
RMSL	*Long-term evolution*	< 1 mm/yr
	Periodic Signals	< 1cm for 60-day signal

Tab. 3: Error budget of altimeter parameter at climate scales

3.4. MSL bias to link altimeter mission together

The global biases between altimetric missions have been accurately calculated [Ablain et al, 2009]. The MSL bias strongly depends on the altimeter standards used to calculate the MSL. Global Biases between TOPEX-B and Jason-1 and between Jason-1 and Jason-2 can be calculated thanks to the Jason-1 and Jason-2 verification phases (at the beginning of each mission) where both satellites were on the same ground track as T/P and were spaced out by 72 seconds and 54 seconds, respectively. The global relative biases and associated uncertainties estimated in the current study are for:

- TOPEX-B/Jason-1 (April 2003) : 84.5 mm ± 1 mm
- Jason-1/Jason-2 (October 2008) : 74.6 mm ± 0.5 mm

The Relative Bias Uncertainty (RBU) between Jason-1 and Jason-2 (±0.5 mm) is lower than the one between TOPEX-B and Jason-1 (±1 mm) because the ground processing between Jason-1 and Jason-2 is more homogeneous. The same is valid for the orbit computation and for instrumental parameters (range, SWH, Sigma-0,…).

For TOPEX-A and TOPEX-B, no datasets overlapping is available to accurately estimate the relative bias. Furthermore, a strong decrease of the MSL evolution during the year 1999 is observed in relationship with "La Niña" preventing an accurate SSH bias computation between TOPEX-A and TOPEX-B. Therefore, the global relative bias has been estimated with a higher RBU:

- TOPEX-A/TOPEX-B (April 2003) : 11.7 mm ± 2 mm

The RBU associated with each bias is large enough to significantly affect the global MSL trend. By considering extreme bias errors, the global MSL trend is ranging from 2.8 to 3.3 mm/yr [Ablain et al, 2009]. Therefore, a realistic error of ±0.25 mm/yr on the global MSL trend has been deduced.

For the regional MSL, regional biases corrections have been also developed in the frame of the SLCCI project. They allow to take into account geographical biases between TOPEX and Jason-1 and between Jason-1 and Jason-2. These new corrections significantly improve the estimation of regional MSL trends (*Fig. 10*) reducing the errors by 0.3 mm/yr [SL_cci Validation Report WP2500]. The remaining error at regional scale is higher than for the global MSL since the TOPEX- A/TOPEX-B regional bias has not been estimated and therefore corrected. The error on regional MSL trends due to regional MSL bias uncertainties has been estimated lower than 1.5 mm/yr over all the altimeter period [SL_cci Validation Report WP2500].

Missions	*Global MSL bias errors [RBU]*
TOPEX-A/TOPEX-B	*±2 mm*
TOPEX-B/Jason-1	*±1 mm*
Jason-1/Jason-2	*±0.5 mm*

Tab. 4 : Summary of Relative Bias Uncertainties due to MSL bias.

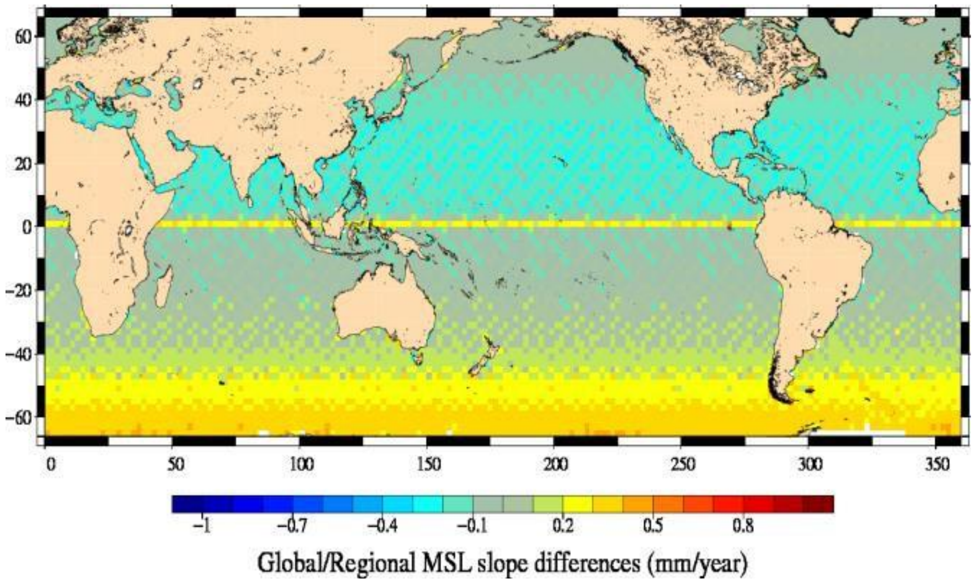

Fig. 10: MSL trend differences from 1993 to 2010 between MSL time series with and without including regional bias corrections on TOPEX/Jason-1 and Jason-1/Jason-2. The line at the equator is due to an error in TOPEX measurements which is corrected with the regional bias.

3.5 Estimation of the uncertainty on the relative bias between two missions

The estimation of relative biases between Jason-1/Jason-2 (see 3.4) has also been estimated with a complementary approach in the framework of the SL-CCI task 2520 (Sensitivity of the MSL calculation changing the orbit of the reference mission: Sentinel-3 instead of Jason missions, see RD 2). The Relative Bias Uncertainty (RBU) estimation has been extended to the linking of Jason-2/Jason-3 missions and Jason-2/Sentinel-3a missions.

Sentinel-3 mission was launched in February 2015. One of the main objectives is to measure the sea surface topography for environmental and climate monitoring. Until now, the Global Mean Sea Level (GMSL) indicator has been computed using the TOPEX/Jason « reference missions » only. These missions have the same ground-track, and the accurate continuity of the GMSL record is ensured by "calibration phases". As mentioned, Sentinel-3 altimeter and platform are designed to provide accurate estimations of MSL evolutions. Therefore, it would be desirable to change the reference orbit in the future to continue computing the MSL evolution: could Sentinel-3 replace Jason-2 or Jason-3 missions? The problem is as follows: Jason missions have similar ground-tracks, platforms, altimeters and a calibration phase enabling an accurate computation of the inter-missions relative bias. However, this will not be the case between Sentinel-3 and any of Jason missions. Consequently, what is the impact of linking MSL data measured by two missions that do not share a calibration phase? What is the impact of Sentinel-3 and Jason different space-time samplings on the Mean Sea Level evolution?

In order to provide an answer, the Relative Bias Uncertainty (RBU) is firstly estimated in the most accurate case, i.e with the calibration phase. This scenario corresponds to the linking of Jason-1/Jason-2 missions (or Jason- 2/Jason-3 in the future). This gives the minimal uncertainty that may be achieved when linking two missions. Then, the RBU is estimated in the working configuration, i.e. without any calibration phase. This scenario may be found with Jason-2/Sentinel-3 or Jason- 3/Sentinel-3.

One of the main results is that, in the absence of a calibration phase, the 88% of the uncertainty on the MSL linking is due to the decorrelation of measurement errors between the two missions, while the remaining 12% is due to oceanic variability. This result stresses that the correlation of measurement errors, induced by calibration phases, is crucial for the accuracy of MSL relative bias. Therefore, even if Sentinel-3 data will provide more accurate Mean Sea Level measurements than Jason-3 data, the uncertainty generated by linking this mission to a Jason MSL time series would not meet user requirements.

3.5. Other sources of errors

Other sources of errors have been identified with less significant but not negligible impact at climate scales.

Among these errors, high frequencies errors (< 20 days) on Dynamical Atmospheric Corrections (DAC) and dry troposphere corrections have also an impact at all MSL climate scales. For instance, by re-computing the DAC correction using pressure fields derived from ERA-interim (ECMWF), the impact on regional MSL trends (*Fig. 11*) is close to ± 1 mm/yr at high latitudes [Carrere et al., 2016].

Concerning tidal models, errors associated with temporal signals lower than 20 days can be highlighted. Because of aliasing, these errors have a periodic signature at higher scales. As already mentioned, we have detected errors at 58.77 days (*Fig. 7*) [Zawadzki et al., 2016].

The Sea State Bias (SSB) correction could also modify the estimation of inter-annual signals versus the model used, especially in the case of TOPEX. Indeed, TOPES altimeter contains a drift in wind and wave observations. These have an impact on the SSB estimation. Depending on the SSB solution, the MSL interannual evolutions may be modified [Ablain et al., 2012].

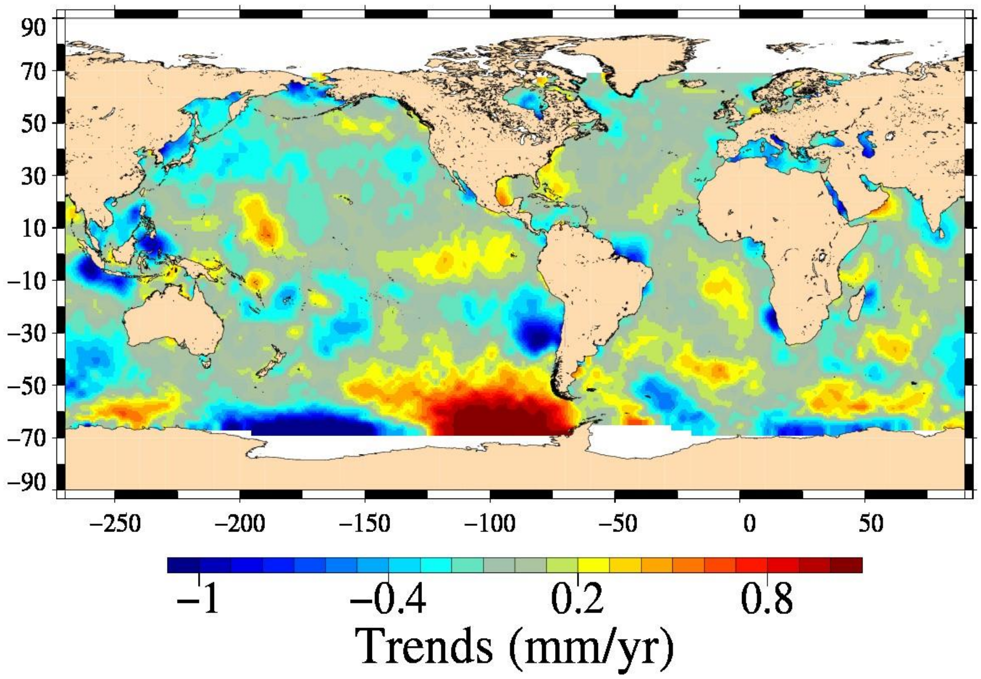

Fig. 11: RMSL trend differences between DAC derived from ERA-interim and ECMWF operational pressure fields on TOPEX: RMSL trends reach 1 mm/yr at high latitudes

4. Altimetry error budget & User requirements

Thanks to the accurate analysis of each source of error in the sea-level computation, we are able to determine the sea level error budget at climate scales as defined in Tab 5. Errors have been defined by an upper bound limit taking into account all sources of error previously defined for all climate scales.

The quadratic sum of each error could lead to this upper bound limit. However, such a basic method does not take into account the potential correlation between each error and the no-linear MSL evolution. In addition, the confidence interval of the total error is unknown. Then, an inverse method [Bretherton et al., 1976] has been applied to estimate a more realistic error from a statistical approach. This method is detailed for the global MSL trend error in [Ablain et al., 2009].

Spatial Scales	Temporal Scales	Altimetry Errors	User requirements
Global Mean Sea Level (10-day averaging)	Long-term evolution (> 10 years)	< 0.5 mm/yr	0.3 mm/yr
	Inter Annual signals (< 5 years)	< 2 mm over 1 year	0.5 mm over 1 year
	Periodic signals (Annual, 60-day,...)	Annual < 1 mm 60-day < 2 mm	Not defined
Regional Mean Sea Level (2x2 deg boxes and 10-day averaging)	Long-term evolution (> 10 years)	< 3 mm/yr	1 mm/yr
	Inter Annual signals (> 1 year)	Not evaluated	Not defined
	Periodic signals (Annual, 60-day,...)	Annual < 1 mm 60-day < 1 cm	Not defined

Tab. 5: Total error budget of altimeter measurements derived from TOPEX, Jason-1 and Jason-2 at all climate scales

5. Other Altimetry Error Monitoring Methods

5.1. In situ measurements

Another way to check these errors is by using in-situ measurements such as Argo profiles (temperature and salinity) and tide gauges. For instance, global MSL differences between altimetry and tide gauges (*Fig. 12*) highlight a drift almost null within the error of the method of ±0.5 mm/yr [Valladeau et al., 2012]. Few millimetres variations at inter-annual scales are also observed. This figure is in agreement with errors defined in Tab 5.

Besides, user requirements have been defined in Sea-level CCI project and in the last Global Observing System for Climate (GCOS) report. Comparing these scientific goals with altimetry errors allows us to give a reference on the level of altimetry errors. Most of the time altimetry errors are higher than scientific goals. For instance, the global MSL trend error is 0.5 mm/yr, whereas the user requirement is 0.3 mm/yr. Moreover, for some climate scales, scientific goals have not been clearly defined in GCOS reports (e.g. for periodic signals).

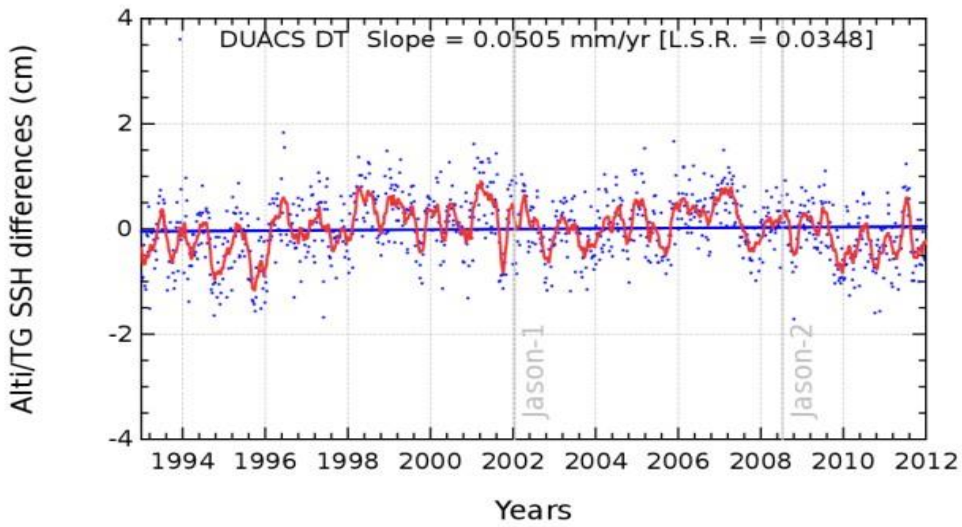

Fig. 12: GMSL comparison between altimetry (TOPEX, Jason-1 & Jason-2) and tide gauges from 1993 onwards: drift is close to 0 with an error of ± 0.5 mm/yr. Few millimetres variations at inter-annual scales can be observed. Interannual differences are small and within the accuracy of the method. The long-term difference (slope) is not significant: 0.05 mm/yr with a Least Square Regression (LSR) uncertainty of ± 0.035 mm/yr and a method accuracy estimated to 0.5 mm/yr [Valladeau et al., 2012].

5.2. Global MSL confidence envelop

The MSL error budget method described in this paper allows the separation of the different temporal scales. This approach is very useful to estimate the general uncertainty of Global Mean Sea level records. However, it does not provide the uncertainty in a given moment. In this section, we propose a complementary approach to estimate the GMSL uncertainty. It is designed to provide a confidence envelop of GMSL continuous records.

The idea of this approach is similar to the error budget, as it is based on the comparison between standards of equivalent qualities. A set of GMSL time-series which a priori have equivalent qualities is generated by tuning four identified parameters: standards, data selection, average meshgrids, and inter-mission relative biases. Of course, the tuning of these parameters require exhaustive preliminary studies to assess the equivalence of qualities. The dispersion of the set will draw a confidence envelop which will require specific adaptations according to the specific objectives of each analysis .

The description of the four tuning parameters is summarized in Tab. 6. This leads to the generation of a set of more than 18000 GMSL records, allowing a significant statistical estimation of the uncertainty.

Parameter	Description
Standards	Errors in standards are the main source of uncertainty in the GMSL computation. Several combinations of standards with equivalent qualities are therefore generated for the set: MSS (CNES/CLS, DTU), tidal model (GOT, FES), etc.
Data Selection	The selection of near-coast measurements is a large source of uncertainty. Three different thresholds are therefore used for the bathymetry in the set: bathymetry > 0,100,200m)
Average Meshgrid	The GMSL is computed by averaging measurements in grids at each mission cycle before averaging the grids themselves. However, there is *a priori* no ideal meshgrid. Several meshgrids are therefore used in the set: 1°x3°, 1.5°x3°, 2°x3°, …etc.
Relative Bias	GMSL records of each mission are linked in order to generate a large continuous GMSL record. The relative bias between missions is estimated over the calibration phases with an average window. However the choice of the central cycle and the window width are subjective. These two parameters take several values in the set.

Tab. 6: Description of confidence envelop tuning parameters

With this method, we were able to:

- Separate the uncertainty due to each tuning parameter (see Fig. 13), all time scales are combined.
- Estimate the uncertainty on the Jason-1/Jason-2 GMSL long-term evolution: ± 0.32mm/yr
- Estimate a confidence envelop of the Jason-1/Jason-2 GMSL continuous record, see Fig. 14.

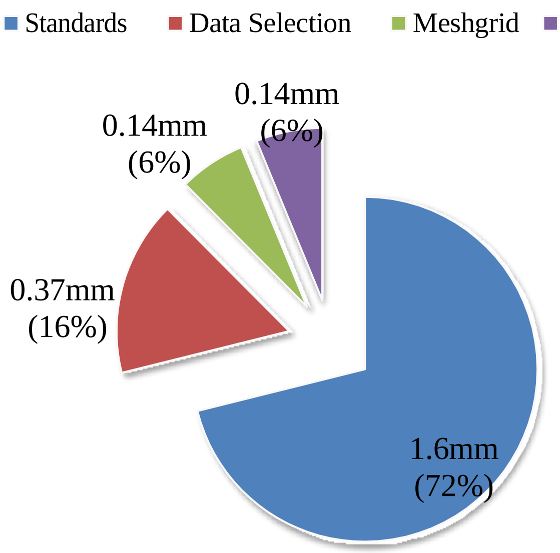

Fig. 13: GMSL uncertainty due to each tuning parameter for Jason-1/Jason-2 confidence

envelop

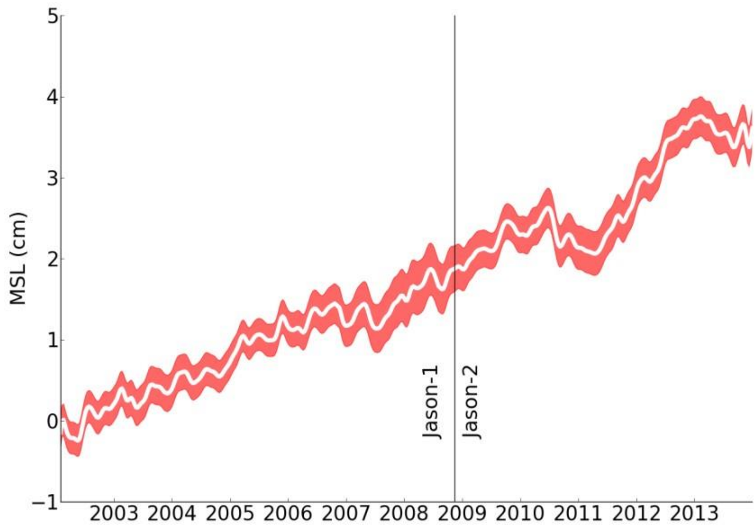

Fig. 14: GMSL confidence envelop over Jason-1 and Jason-2 missions. Annual, semi-annual signals have been removed, glacial isostatic adjustment (GIA) is applied.

Results in Fig. 13 are consistent with the error budget, see Tab. 5, considering that the period of study is limited to Jason-1/Jason-2 and that all time scales are combined. The total average uncertainty is 2.21mm for both periodic and interannual signals. The long-term evolution uncertainty, 0.32mm/yr over 10 years, is also consistent with Tab. 5 (<0.5mm/yr) [Ablain et al., 2015].

The confidence envelop provided by this complementary approach shows the uncertainty on the inter-annual signal is consistent with Tab. 5 (<2mm). It shows the evolution in time of the GMSL record uncertainty.

This envelop has been requested by users involved in MSL closer budget studies (combining mass and steric components). It could be refined by taking into account altimeter instrumental instabilities (neglected here), and extended to other missions (T/P, Envisat, ERS, ….).

Currently this work is on-going. It has been already presented at the last OSTST (Konstanz, 2014), see poster in annex A (section 8). In 2017, we planned to extend these analyses to TOPEX in order to cover all altimeter time series. Such an approach could be applied to others missions (ERS, Envisat) although they are not used as a reference to calculate the long-term evolution of the mean sea level.

5.3. Estimation of the uncertainty on the regional MSL trend

The altimetry error budget for each temporal described in Section 4, as well as the Relative Bias Uncertainties (RBU) estimated in Section 3.4, allow to model errors affecting Sea Level Anomaly time series. The variance-covariance matrix may be designed using these inputs [Ablain et al., 2009] :

- Periodic signals uncertainties are represented with a Gaussian centred on the matrix' diagonal

- RBU are represented with constants for each mission
- Long-term uncertainties are represented with a decrease of the covariance

This model is used in [Ablain et al., 2009] to estimate the uncertainty on the Global Mean Sea Level trend based on a Generalized Least Square approach. A recent update of this paper, [Ablain et al., 2015] estimated a trend uncertainty of 0.5mm/yr over the time period 1993-2010 at global scale .

A more recent study (Prandi et al., in preparation) uses the same approach to derive a map of regional MSL trend uncertainties, see Fig. 15.

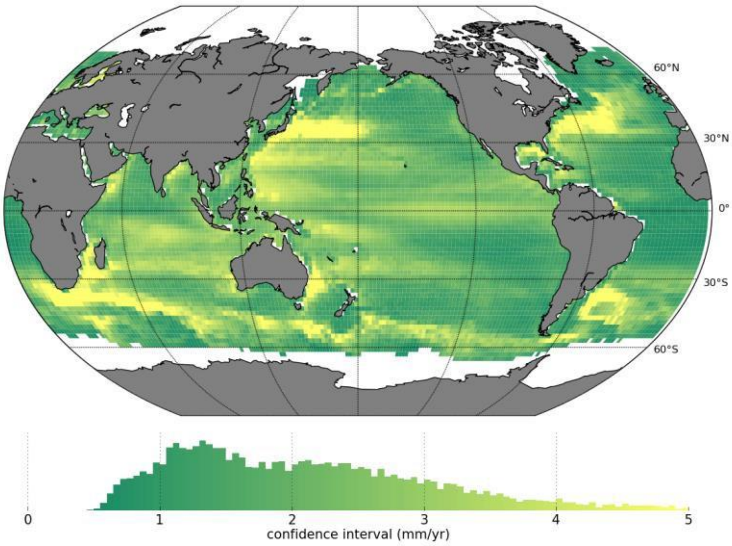

Fig. 15: Trend uncertainties (in mm/yr) on local sea level trends at confidence level 95%

5.4. Improvement of the SLA estimation in the Arctic ocean

The Arctic is an area undergoing rapid climatic changes, among which the dramatic reduction of sea ice extent. Models predicted that the Arctic Ocean will be experiencing significant changes in the future and altimetry data could be very useful to evaluate past, present and future changes. To date, the Arctic Ocean remains poorly observed by satellite altimetry, mainly because the sea-ice cover prevents measurements. Moreover, the uncertainty on SLA estimations is relatively higher than at lower latitudes.

Within the phase II of the SL_cci project, a significant work has been made improving the quality of the sea level estimation in the Arctic Ocean (see OSTST 2015 poster in annex 8.2). Arctic Sea level products have been delivered and their evaluation is currently in progress

This work contributes to reduce the uncertainty of the sea level estimation and thus to improve the accuracy of mean sea level climate studies.

6. Summary and Conclusions

For climate studies, altimetry errors have been only defined for the long-term evolution of the MSL. This study precisely described altimeter measurement errors at several climate scales. The comparison of these errors with user requirements defined by the climate community is a way of defining a reference on the level of altimetry errors.

This work is currently on-going and should be complemented in 2015 providing the envelop error for both TOPEX and others missions and also separating the error between the two altimeter decades (before and after 2002).

Although altimetry errors are in agreement with mission specifications, a main conclusion of this study is that altimetry errors are higher than user requirements at all climate scales. In order to reduce these errors, there are several possibilities to improve existing data, e.g.:

- TOPEX data reprocessing is needed to improve the stability of altimeter instrumental parameters.
- Future orbit solutions should continue to improve regional MSL.
- Wet troposphere corrections remain the main source of errors and should be improved.

A second main conclusion of this study concerns the link between altimeter and climate communities which should be enhanced:

- To improve or refine user requirements
- To better specify future altimeter systems for climate applications
- To reprocess older missions beyond their original mission specifications

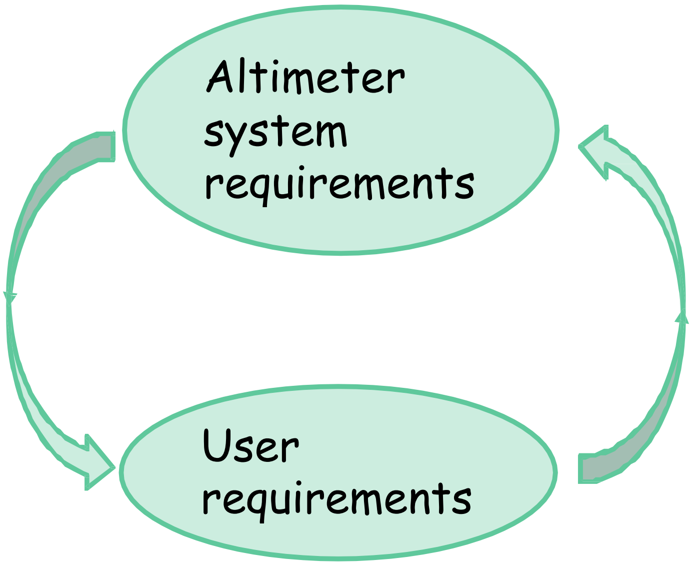

Fig. 16: Improving the link between altimetry and climate communities will allow us to better specify requirements of future and current altimeter missions and to refine user requirements at climate scale.

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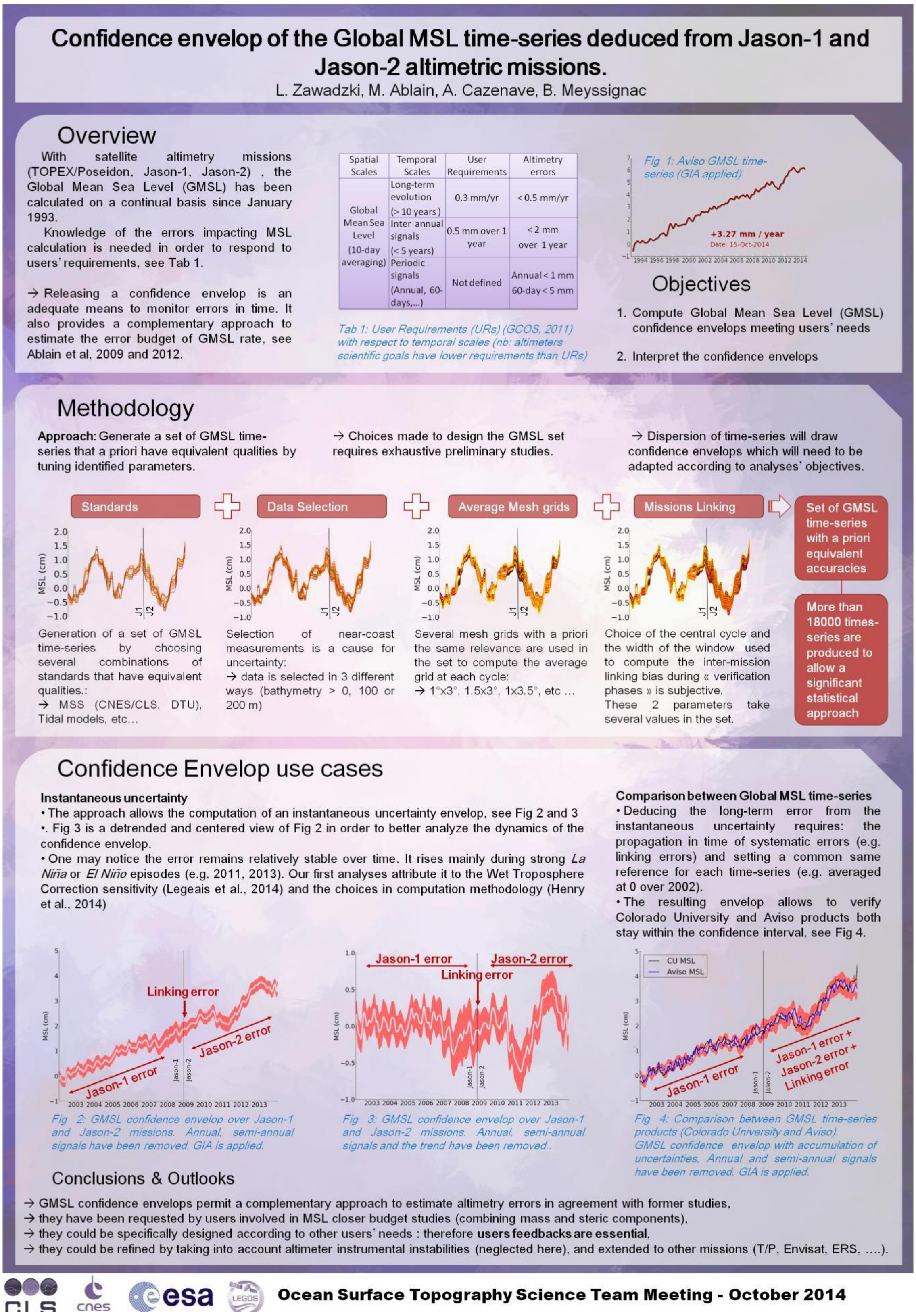
8. Appendix

8.1. OSTST Poster, Konstanz 2014



Confidence envelop of the Global MSL time-series deduced from Jason-1 and Jason-2 altimetric missions.

L. Zawadzki, M. Ablain, A. Cazenave, B. Meyssignac

Overview

With satellite altimetry missions (TOPEX/Poseidon, Jason-1, Jason-2) , the Global Mean Sea Level (GMSL) has been calculated on a continual basis since January 1993.

Knowledge of the errors impacting MSL calculation is needed in order to respond to users' requirements, see Tab 1.

→ Releasing a confidence envelop is an adequate means to monitor errors in time. It also provides a complementary approach to estimate the error budget of GMSL rate, see Ablain et al, 2009 and 2012.

Spatial Scales	Temporal Scales	User Requirements	Altimetry errors
Global Mean Sea Level (10-day averaging)	Long-term evolution (> 10 years)	0.3 mm/yr	< 0.5 mm/yr
	Inter annual signals (< 5 years)	0.5 mm over 1 year	< 2 mm over 1 year
	Periodic signals (Annual, 60-days,...)	Not defined	Annual < 1 mm 60-day < 5 mm

Tab 1: User Requirements (URs) (GCOS, 2011) with respect to temporal scales (nb: altimeters scientific goals have lower requirements than URs)

Fig 1: Aviso GMSL time-series (GIA applied)

Objectives

1. Compute Global Mean Sea Level (GMSL) confidence envelops meeting users' needs
2. Interpret the confidence envelops

Methodology

Approach: Generate a set of GMSL time-series that a priori have equivalent qualities by tuning identified parameters.

→ Choices made to design the GMSL set requires exhaustive preliminary studies.

→ Dispersion of time-series will draw confidence envelops which will need to be adapted according to analyses' objectives.

Standards + Data Selection + Average Mesh grids + Missions Linking ⇒ Set of GMSL time-series with a priori equivalent accuracies

Standards: Generation of a set of GMSL time-series by choosing several combinations of standards that have equivalent qualities.: → MSS (CNES/CLS, DTU), Tidal models, etc…

Data Selection: Selection of near-coast measurements is a cause for uncertainty: → data is selected in 3 different ways (bathymetry > 0, 100 or 200 m)

Average Mesh grids: Several mesh grids with a priori the same relevance are used in the set to compute the average grid at each cycle: → 1°x3°, 1.5x3°, 1x3.5°, etc …

Missions Linking: Choice of the central cycle and the width of the window used to compute the inter-mission linking bias during « verification phases » is subjective. These 2 parameters take several values in the set.

More than 18000 times-series are produced to allow a significant statistical approach

Confidence Envelop use cases

Instantaneous uncertainty

- The approach allows the computation of an instantaneous uncertainty envelop, see Fig 2 and 3
- . Fig 3 is a detrended and centered view of Fig 2 in order to better analyze the dynamics of the confidence envelop.
- One may notice the error remains relatively stable over time. It rises mainly during strong *La Niña* or *El Niño* episodes (e.g. 2011, 2013). Our first analyses attribute it to the Wet Troposphere Correction sensitivity (Legeais et al., 2014) and the choices in computation methodology (Henry et al., 2014)

Comparison between Global MSL time-series

- Deducing the long-term error from the instantaneous uncertainty requires: the propagation in time of systematic errors (e.g. linking errors) and setting a common same reference for each time-series (e.g. averaged at 0 over 2002).
- The resulting envelop allows to verify Colorado University and Aviso products both stay within the confidence interval, see Fig 4.

Fig 2: GMSL confidence envelop over Jason-1 and Jason-2 missions. Annual, semi-annual signals have been removed, GIA is applied.

Fig 3: GMSL confidence envelop over Jason-1 and Jason-2 missions. Annual, semi-annual signals and the trend have been removed..

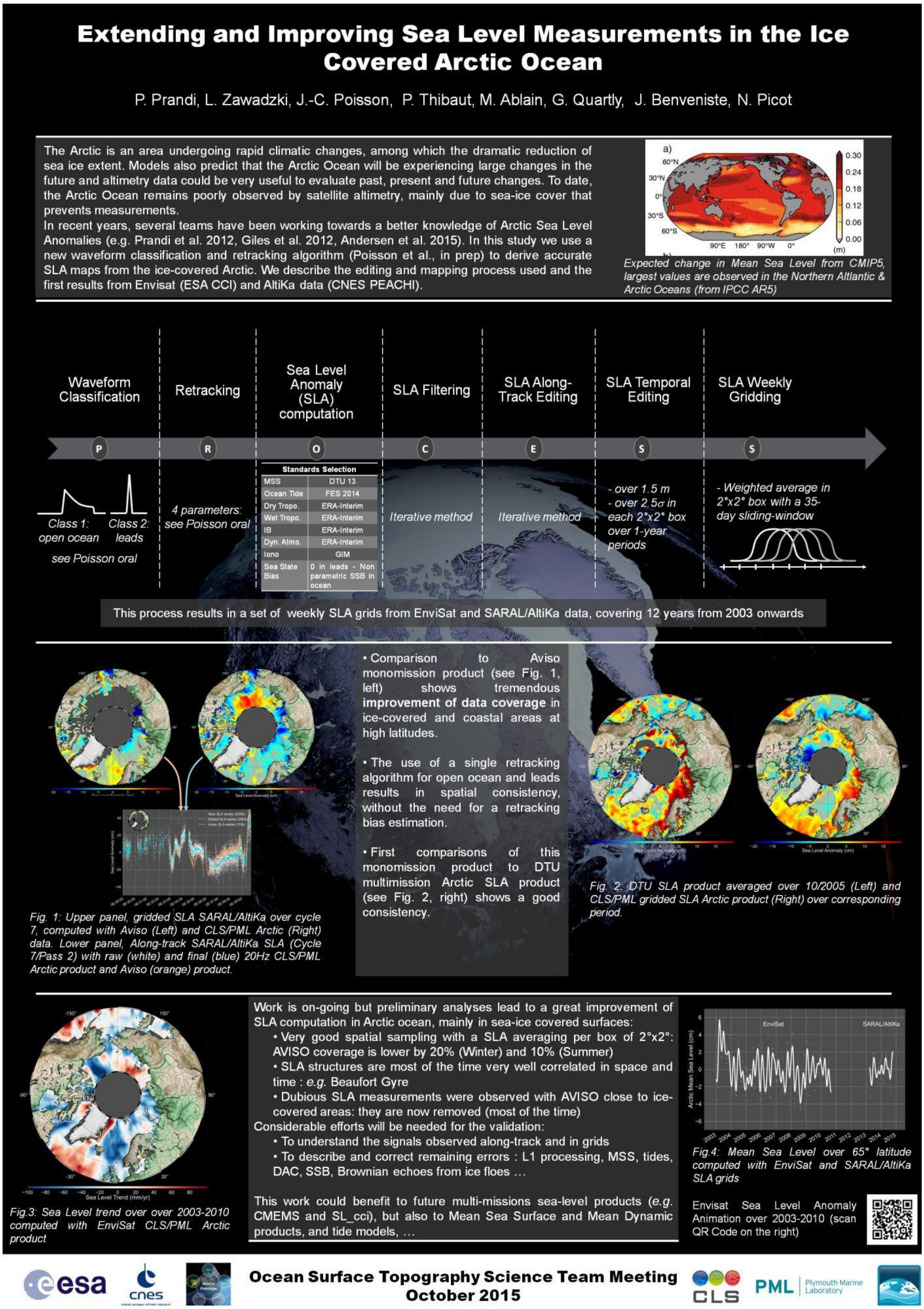
Fig 4: Comparison between GMSL time-series products (Colorado University and Aviso). GMSL confidence envelop with accumulation of uncertainties. Annual and semi-annual signals have been removed, GIA is applied.

Conclusions & Outlooks

→ GMSL confidence envelops permit a complementary approach to estimate altimetry errors in agreement with former studies,
→ they have been requested by users involved in MSL closer budget studies (combining mass and steric components),
→ they could be specifically designed according to other users' needs : therefore **users feedbacks are essential**,
→ they could be refined by taking into account altimeter instrumental instabilities (neglected here), and extended to other missions (T/P, Envisat, ERS, ….).

Ocean Surface Topography Science Team Meeting - October 2014

8.2. OSTST Poster, Reston 2015



8.3. EGU Poster, Vienna 2015

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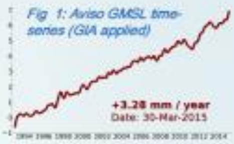

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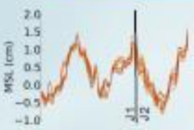

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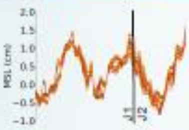

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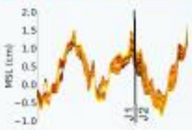

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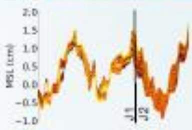

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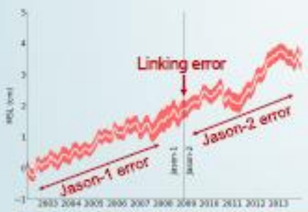

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