Benefit of a second calibration phase to estimate the relative global and regional mean sea level drifts between Jason-3 and Sentinel-6a

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Abstract

The originality of this study is to propose a new calibration method based on two calibration phases between Jason-3 and Sentinel-6A (S6A) to better estimate the relative global and regional mean sea level drifts between the two missions. To date, a first calibration phase of approximately 11 months is planned from January 15, 2021, to December 31, 2021, when both satellites will be on the same orbit spaced out by approximately 1 minute. This calibration will allow for a very accurate assessment of the GMSL bias between Jason-3 and S6A (less than 0.5 mm, see Zawadzki and Ablain, 2016). A second calibration phase after a few years would reduce the uncertainty levels of the GMSL (global mean seal level) drift estimate. The uncertainty would be low enough to detect any drift detrimental to the stability of the current GMSL record. It would indeed be possible to evaluate the stability between the two satellites with an accuracy at least 3 times better at the global scale than with the most accurate method to date. At regional scales, the second calibration phases would provide regional MSL drift estimates with very good precision. This study also shows that the time spent between the two calibration phases is significantly more sensitive than the length of the second calibration phase for the reduction in uncertainties. Finally, a possible scenario proposed by this study would consist of carrying out the beginning of the second calibration phase approximately 1.5-2 years after the first and for a duration of 3-4 months. This calibration would allow the detection of a relative GMSL drift of approximately 0.15 mm/yr and 0.4-0.5 mm/yr at oceanic basin scales (2000-4000 km).

Keywords: altimetry, mean sea level, trend uncertainties

Introduction

The current GMSL (global mean sea level) has been calculated on a continual basis since January 1993 with the altimetric measurements from 4 successive reference missions: TOPEX/Poseidon (TP), Jason-1, Jason-2 and Jason-3. Calibration phases, during which the satellites follow each other in close succession (TP/Jason-1, Jason-1/Jason-2, then Jason-3/Jason-2), help to link these different missions by precisely determining any bias between them (Zawadzki and Ablain, 2016).

To extend the current GMSL data time series, the Sentinel-6 mission (also named Jason-CS for the Jason Continuity of Service) is scheduled to launch its first satellite by the end of

2020 (S6A) and the follow-up satellite in 2026 (S6B). The Sentinel-6 altimeters will operate in SAR mode (synthetic aperture radar mode) already used on Sentinel-3 missions and LRM (low resolution mode), which is the standard radar mode used by Jason/TP missions.

Recent studies (Ablain, 2019; Raynal, 2019; etc.) have highlighted a strong 1.3-1.4 mm/yr relative GMSL drift between Sentinel-3 missions (S3A and S3B) and other altimeter missions (Jason-3, Saral-Altika, Jason-2) in SAR mode even after homogenisation of the geophysical corrections between all missions (e.g., use of wet tropospheric correction from a model). The origin of the S3A/S3B drift has not yet been fully explained and is under investigation by altimeter experts.

Processing S3A/S3B data using the PLRM mode (Pseudo-LRM, derived from the SAR mode) yields a low GMSL drift, which was estimated by Poisson, 2019 to be approximately 0.3-0.4 mm/yr and due to the PTR (point target response) drifts. This small drift is not statistically detectable over a 3-year period with classical calibration methods (e.g., GMSL differences, comparison with tide gauges).

As the S3A and S3B missions are not directly used to build GMSL data records (they are not the reference missions), there is no impact on the accuracy of the GMSL time series. However, in the event of similar drift on S6A/S6B, which uses similar technology to S3A/S3B, the reliability of the GMSL evolution would be adversely affected. It is then essential to be able to detect such drifts on S6A/S6B missions as soon as possible after their launch to correct them and ensure the accuracy of the long-term evolution of the GMSL time series. Thus, the main question raised is how accurately a GMSL drift can be detected after the launch of S6A for short periods of up to a few years.

The objective of this note is to answer this question through the comparison of three GMSL calibration methods and the evaluation of their accuracy. Two of these calibration methods are known methods based on altimetry and tide gauge data comparisons (Alti/TG hereafter) and direct GMSL comparisons between 2 missions (ΔGMSL). The uncertainties of such approaches have already been thoroughly described (Ablain, 2018, 2019). However, as presented below, these calibration methods are not able to detect GMSL drifts of less than 0.6 mm/yr (at 1-sigma) over a 3-year period. Such a level of uncertainty would not be sufficient to, for instance, detect a potential GMSL S6A drift of 0.3-0.4 mm/yr due to PTR drift (as for S3A/S3B).

The originality of this study is to propose a new calibration method based on two calibration phases between Jason-3 and S6A. To date, a first calibration phase of approximately 11 months is planned from January 15, 2021, to December 31, 2021, where both satellites will be on the same orbit spaced out by approximately 1 minute. On the calibration phase, the ocean variability between the two missions can be neglected, and the GMSL differences between the Jason-3 and S6A measurements can therefore be evaluated very accurately. Notably, this first calibration phase will allow for a very accurate assessment of the GMSL bias between Jason-3 and S6A (less than 0.5 mm, see Zawadzki and Ablain, 2016).

The proposal of a second calibration phase between Jason-3 and S6A after a few years would make it possible to obtain new high accuracy evaluations of the GMSL differences between the 2 missions. The GMSL drift could then be determined with good accuracy, which depends on the duration of this second calibration phase and the time elapsed between the two phases. To be able to recommend a scenario to space agencies, it is important to determine the smallest values for two parameters that meet the necessary precision requirements to ensure a continued accurate GMSL record.

Although this study mainly focuses on the global scale, the impact of using two calibration phases between Jason-3 and S6A has also been analysed at regional scales and is described briefly in this note.

Method

The estimation of the GMSL drift uncertainty is based on the method described in detail by Ablain et al., 2019. Briefly, the method first consists of describing the uncorrelated and correlated errors of a time series (e.g., differences in GMSL time series, altimetry and tide gauge comparison). From this error budget, the variance-covariance matrix of the error (Σ) is calculated. Then, the uncertainty of the trend is computed from a general formalism of the distribution of the ordinary least squares (OLS) estimator (β):

$$\widehat{\beta} = N\left(\beta, \left(X^tX\right)^{-1}\left(X^t\Sigma X\right)\left(X^tX\right)^{-1}\right)$$

The main difficulty of the method is to provide the error budget. For the two existing GMSL calibration methods (Alti/TG and ΔGMSL), both error budgets have already been provided within the framework of recent studies.

For the Alti/TG method, which consists of comparing tide gauge sea level time series with altimeter measurements collocated at the tide gauge location (Valladeau et al., 2012; Watson et al., 2015), the error budget is based on high-frequency errors, including tide gauges and altimetry errors, and large-scale errors associated with the tide gauge network and the method used to compare the two types of measurements (see Fig. 7 in the additional materials section for more details).

For the ΔGMSL method, which consists of comparing the GMSL time series of two missions on different orbits (e.g., Jason-3 and S3A), the error budget was derived from the GMSL error budgets from both satellites. The error budget and its different error sources have been updated considering the correlated and uncorrelated errors between the two GMSL time series (see Fig. 8 in the additional materials section). Furthermore, the contribution of the wet tropospheric correction to the relative GMSL drift has been removed by applying the model correction for both satellites. However, the long-term errors due to orbit calculations (e.g., gravity field, ITRF) are assumed to be uncorrelated. This is a conservative point of view without more information on the subject at the moment. Therefore, the variance associated with these errors has been multiplied by a factor of 2.

For the new calibration method proposed in this study based on 2 calibration phases between Jason-3 and S6A, the relative GMSL drift is calculated from the differences in GMSL measurements during the two phases, as basically represented in Fig. 1.

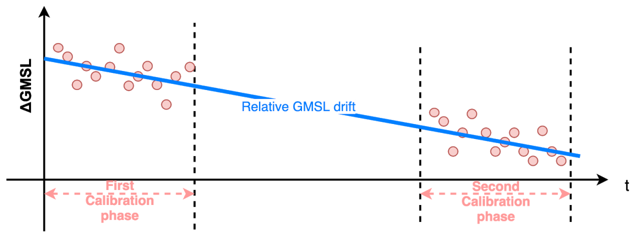


Figure 1: Basic principle of the “2-phase calibration” method

The error budget is then deduced from that of the ΔGMSL calibration method (Fig. 2). In this case, the errors due to large frequency errors and long-term drift errors are assumed to be fully correlated during the calibration phase, and their associated variance is therefore zero. As no S6A data are available, the variance in the high-frequency errors (lower than 2 months and between 2 and 6 months) has been derived from the analysis of the GMSL time series differences from the Jason-1/Jason-2 and Jason-2/Jason-3 calibration phases. The level of variance is divided by approximately 2 in comparison with the ΔGMSL calibration method because geophysical errors are fully correlated during the calibration phase. Only uncorrelated errors due to altimeter noise or random orbit errors have an impact. High-frequency errors are slightly higher during the Jason-1/Jason-2 calibration phase than those during the Jason-2/Jason-3 calibration phase, most likely due to additional errors in the Jason-1 orbit calculation. For the Jason-3/S6A calibration phase, a similar error budget can be applied, as the errors should probably be very similar. Nevertheless, additional errors could be introduced to take into account the difference in platforms between the two satellites, which could introduce uncorrelated orbit errors. Those error sources were not estimated in this study. However, the Jason-1/Jason-2 and Jason-2/Jason-3 error budgets can be respectively considered pessimistic and optimistic error budgets for Jason-3/S3A.

Source of errors	Error category	GMSL differences without calibration phases uncertainty level (at 1 σ)	GMSL differences with calibration phase Uncertainty level (at 1 σ)
High frequency errors: altimeter noise, geophysical corrections, orbits ...	Correlated errors (λ = 2 months)	σ between 0.6 and 0.8 mm (depending on altimeter missions)	σ = 0.3-0.4 mm
Medium frequency errors: geophysical corrections, orbits ..	Correlated errors (λ = 1 year)	σ between 0.5 and 0.7 mm (depending on altimeter missions)	σ = 0.2-0.3 mm (λ = 6 months)
Large frequency errors: wet tropospheric correction (WTC)	Correlated errors (λ = 5 years)	σ = 0 (model WTC error are cancelled between 2 missions)	σ = 0 (model WTC error are cancelled between 2 missions)
Large frequency errors: orbits (Gravity fields)	Correlated errors (λ = 10 years)	σ = 0.5 mm * sqrt(2)	σ = 0 (error orbit assumed correlated at long scales)
Long-term drift errors: orbit (ITRF) and GIA	Drift error	δ = 0.1 * sqrt(2) (GIA error is removed between 2 missions)	σ = 0 (error orbit assumed correlated at very long scales)

Figure 2: Error budget of the GMSL differences without a calibration phase (on the left) and with a calibration phase (on the right)

Sensitivity of the “2-phase calibration” method

Before comparing the different calibration methods, the sensitivity of the “2-phase calibration” approach to the length of the second calibration phase was analysed. To perform this analysis, the error budget from Jason-2/Jason-3 has been applied (corresponds to the minimal values of Fig. 2), and the length of the first calibration phase between Jason-3 and S6A has been fixed to 10 months (in theory, it will last approximately 11 months, but in practice, some cycles may not be usable for various reasons).

The uncertainty evolution of the relative GMSL drift between Jason-3 and S6A has been plotted in Fig. 3 versus the time spent between the 2 calibration phases (between 6 months and 4 years) for 4 different time spans of the second calibration phase (from 1 month to 6 months). For a 6-month time span between the 2 calibration phases, the uncertainties range from 0.27 mm/yr for a 6-month second phase duration to 0.36 mm/yr for a 1-month second phase duration. These values are reduced to approximately 0.10-0.13 mm/yr after 3 years between the 2 calibration phases. These results show that the uncertainty of GMSL drift is weakly sensitive to the duration of the second calibration phase. Thus, there is a very low interest in recommending a second calibration phase longer than 4 months.

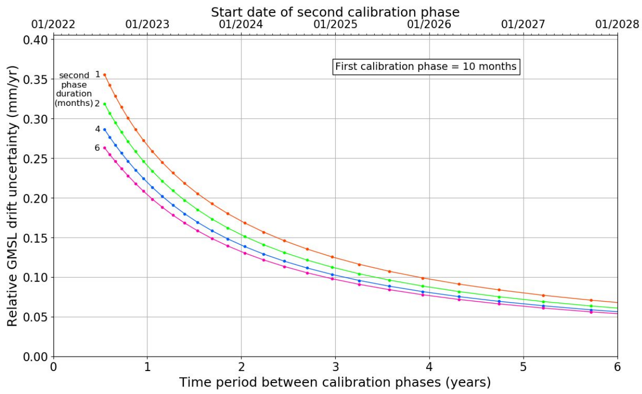


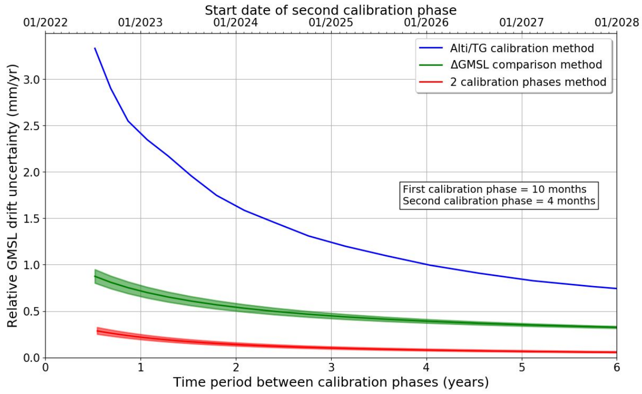
Figure 3: Evolution of the relative GMSL drift uncertainties with the time spent between the two calibration phases between Jason-3 and S6A for several different durations of the second calibration phase from 1 month to 6 months.

Comparison of the GMSL drift uncertainties between the different methods

The “2-phase calibration” method is compared to the Alti/TG and ΔGMSL calibration methods in Fig. 3. The uncertainties of the GMSL drift have been plotted versus the time spent between the 2 calibration phases of Jason-3 and S6A. The duration of the second calibration phase was arbitrarily set at 4 months since it was just demonstrated that the sensitivity of this parameter is low (see above). Furthermore, for the "2-phase calibration" and ΔGMSL calibration methods, an error envelope was superimposed on the GMSL drift uncertainty to take into account the sensitivity of the results to the error budget. For instance, for the "2-phase calibration" method, the error budgets of the Jason-2/Jason-3 and Jason-1/Jason-2 calibration phases have been taken into account to calculate the minimum and maximum values of the envelope error. Moreover, the total length of the time series used to calculate the uncertainties for all the calibration methods includes the duration of both calibration phases. This means that for 1 year spent between the two calibrations phases, the total length of the time series is 2 years and 2 months (1 year + 10 months + 4 months).

The analysis in Fig. 3 clearly shows that the new "2-phase calibration" method significantly reduces the GMSL drift uncertainties. By repeating a second calibration phase 1 year after the first one, the GMSL drift uncertainty is 2.4 mm/yr with the Alti/TG method. This value is reduced to 0.7-0.8 mm/yr with the ΔGMSL calibration method, whereas with the new "2-phase calibration" method, the uncertainty decreases to 0.25-0.30 mm/yr. Increasing the time spent between the two Jason-3/S6A calibration phases to 2 years leads to lower uncertainties for each method with 1.7 mm/yr, 0.5-0.6 mm/yr and 0.14-0.16 mm/yr, respectively. After 3 years, the GMSL drift uncertainty falls below 0.1 mm/yr with the new method, whereas it remains close to 0.5 mm/yr with the ΔGMSL method.

In other words, such a level of uncertainty with the new "2-phase calibration" method makes it possible to detect a relative drift between Jason-3 and S6A lower than 0.3 mm/yr within a confidence level of 68% for a period of 1 year between the two calibration phases, 95% for 2 years and 99.7% for 3 years.



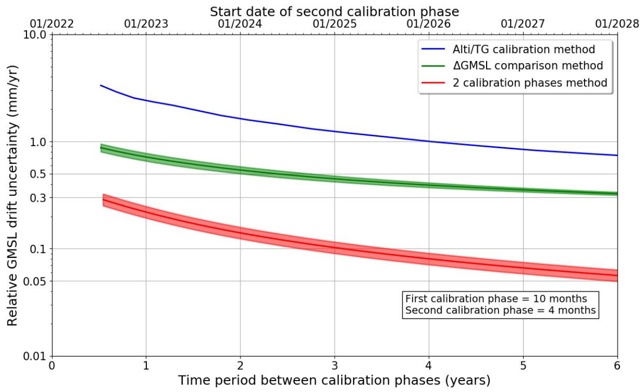


Figure 4: Evolution of the relative GMSL drift uncertainties with the time period between the two calibration phases between Jason-3 and S6A for the different calibration methods (normal y-axis scale on the top and a logarithm y-axis scale on the bottom).

Uncertainties at regional scales with the "2-phase calibration" method

The potential drifts of MSL (mean sea level) at regional scales are also an important issue for understanding ocean processes at climate scales (Meyssignac et al., 2017). At ocean basin scales (several hundred kilometres), orbit solutions are one of the main sources of error close to 1 mm/yr over a 10-year period (Couhert et al., 2015). Other sources of errors also impact regional MSL trends (Prandi et al., in prep.); however, these sources are generally small, on the order of a few tenths of mm/yr (e.g., wet tropospheric correction). It is therefore very relevant to be able to detect relative regional MSL drifts between two missions with an order of magnitude lower than 0.5 mm/yr to be able to detect at least the errors in the orbit solutions.

However, the methods used at the global scale are not accurate enough to be used at regional scales. For instance, the Alti/TG method is dominated by TG drift errors at local scales that are not averaged over small areas (even at ocean basin scales). Furthermore, the direct comparison of regional MSL trends between two missions is dominated by the effect of ocean variability (e.g., mesoscale, inter-annual signals) that prevents the detection of regional MSL drifts lower than a few mm/yr over large periods (greater than 5 years). For the sake of illustration, the regional MSL trend differences between Jason-3 and S3A plotted over a 3-year period (see Fig. 10 in the additional materials section) clearly highlight ocean variability patterns with trends of approximately 10 mm/yr preventing any identification of regional MSL drifts between the two missions.

The potential gain of the “2 calibrations phases” method has thus been analysed at regional scales with the same statistical model. The error budget used as input has been revisited and adapted to regional scales to estimate the high-frequency variance in the regional data time series (see Fig. 9 in the additional material section). As the long-term errors of orbit calculation are the main sources of errors at regional scales, they are not taken into account in the error budget table: these are the errors to be found. Different spatial scales have been analysed with box sizes from 3x3 degrees (~330 km) to 36x36 degrees (~4000 km corresponding to oceanic basin scales). Fig. 5 shows the evolution of the average regional MSL drift uncertainties for these different configurations versus the time spent between the two Jason-3/S6A calibration phases. The detection of a relative regional MSL drift lower than 0.5 mm/yr is possible at large basin scales (several thousands of kilometres) as early as 2 years between the two Jason-3/S6A calibration phases. After 3 years, the uncertainties become less than 0.5 mm/yr for spatial scales up to approximately 1000 km.

Although this average representation of regional MSL drift uncertainties conceals regional variations (a few tenths of mm/yr mainly depending on altimeter noise), such a level of uncertainty would allow the detection of large-scale errors of approximately 0.5-1.0 mm/yr with a good confidence interval (at least 90%). This situation would also allow the detection of long-term orbit errors between Jason-3 and S6A and would provide a way to measure the improvement of orbit solutions in the future.

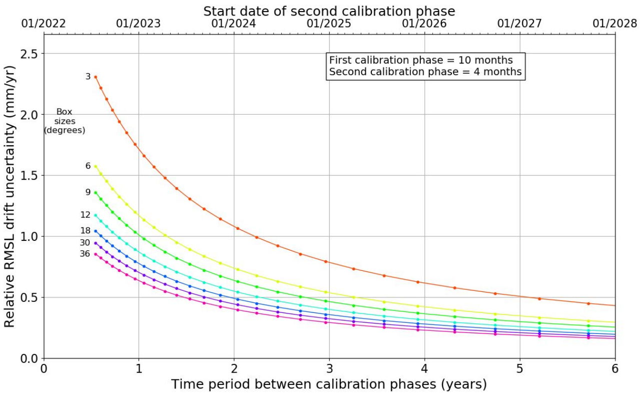


Figure 5: Evolution of the relative averaged regional MSL drift uncertainties with the time period between the two calibration phases between Jason-3 and S6A for different box sizes from 3x3 degrees (corresponding to ~330 km spatial scale) to 36x36 degrees (corresponding to ~4000 km spatial scales).

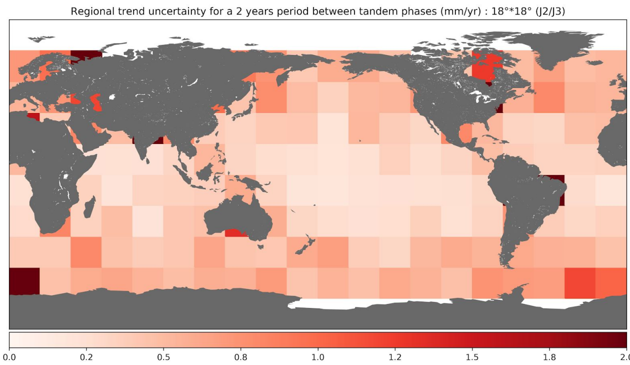


Figure 6: Map of relative MSL drift uncertainties derived from the "2 calibration phases" method for a box size of 18x18 degrees and for a 2-year time spent between the two J3/S6A calibration phases.

Conclusion

The benefits of a second calibration phase between Jason-3 and S6A for climate studies are clearly demonstrated in this study. The uncertainty levels on the GMSL drift estimate would be low enough to detect any drift detrimental to the stability of the current GMSL record. It would indeed be possible to check the stability between two satellites with an accuracy at least 3 times better at the global scale than with the most accurate method to date (ΔGMSL calibration method) for any period of time. The same is true for the regional scale for which the ΔGMSL calibration method and Alti-TG calibration method are far from accurate enough to provide statistically significant results on regional MSL drift and where the “2-phase calibration” method would provide RMSL drift estimates with very good precision. For instance, the “2-phase calibration” method is more accurate on 6x6 degrees RMSL drift estimates than the ΔGMSL calibration method on the global scale GMSL drift estimate.

This study also shows that the time spent between the two calibration phases is significantly more sensitive than the length of the second calibration phase for the reduction in uncertainties. In other words, a second short calibration phase (a few months) will have no significant impact on the uncertainty level and will therefore allow Jason-3 to return quickly to an orbit that will allow it to contribute again to independent observations. Therefore, assuming that it would be technically feasible to move Jason-3 to its initial orbit in a few years, an optimal scenario can be recommended. This scenario would consist of carrying out the second calibration phase approximately 1.5-2 years after the first and for a duration of 3-4 months. This situation would allow the detection of a relative GMSL drift with an accuracy of approximately 0.15 mm/yr and 0.4-0.5 mm/yr at oceanic basin scales (2000-4000 km). With such a scenario, the currently unobservable 0.3-0.4 mm/yr instrumental GMSL drift present on S3A and S3B due to the PTR evolution would be detectable on S6A (if it is present) within a confidence level of 95%.

Pushing forward the limits of the method, we can imagine a third calibration phase between Jason-3 and S6A in the ideal case Jason-3 is still operational,. Assuming such a scenario is feasible 1 year after the end of the second calibration phase, the relative GMSL drift uncertainties would be lower than 0.1 mm/yr. This level of stability has never been reached before. With such a stability a whole series of new unprecedented scientific perspectives could be tackled with the sea level data. These perspectives range from the detection of the deep ocean contribution and the permafrost contribution to GMSL rise (see for e.g. WCRP Global Sea Level Budget Group, 2018), the closure of the regional sea level rise (see for e.g. Rietbroek et al., 2016, Bamber et al., 2019) the detection and attribution of regional sea level changes in response to anthropogenic emissions (see for e.g. Fasullo and Nerem, 2018; Palanisamy et al., 2015; Bilbao et al., 2015) or the monitoring of the Earth energy imbalance in response to climate natural variability (such as the Hiatus, El Niño Southern oscillations, volcanic eruptions etc, see for e.g. Meyssignac et al., 2019). We argue that the scientific added value would be such that the option of a multiple calibration phases (with 2 or 3 phases) between Jason 3 and S6A should be considered. Of course, the results presented in this study are sensitive to the error budget considered at the input of the statistical model used. Some approximations have been made to account for uncorrelated errors between Jason-3 and S6A (for example, orbit errors due to the different platforms). Sensitivity tests have been performed, showing that the impact of these approximations is low (see for e.g. the envelope error in Fig. 4). Further work needs to be done to better model these unknown errors and provide further more accurate results.

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Additional materials

Source of error	Temporal correlation	Uncertainty at 1σ		
		T/P	J1	J2+J3
High frequency errors due to tide gauge and altimeter measurement errors, but also due to the collocation of both datasets.	λ= 6 months	σ = 4.0 mm	σ = 3.5 mm	σ = 2.3 mm
	λ = 1 year	σ = 1.0 mm	σ = 0.7 mm	σ = 0.5 mm
Large correlated errors due to the tide-gauge networks (e.g. averaging method to take into spatial distribution), long-term stability of tide gauge time series.	λ = 3 years	σ = 1.0 mm		
	λ = 10 years	σ = 1.0 mm		
Linear error (drift) over all the altimetry period due to the VLM errors of tide-gauge network.	Drift error	σ = 0.2 mm/yr		

Figure 7: Error budget of the GMSL altimeter and tide gauge comparisons for the GLOSS/CLIVAR network.

Source of errors	Error category	Jason-2/3 GMSL uncertainty level (at 1 σ)
High frequency errors: altimeter noise, geophysical corrections, orbits ...	Correlated errors (λ = 2 months)	σ = 1.2 mm
Medium frequency errors: geophysical corrections, orbits ..	Correlated errors (λ = 1 year)	σ = 1 mm
Large frequency errors: wet tropospheric correction (WTC)	Correlated errors (λ = 5 years)	σ = 1.1 mm (⇔ to 0.2 mm/yr for 5 years)
Large frequency errors: orbits (Gravity fields)	Correlated errors (λ = 10 years)	σ = 0.5 mm (⇔ to 0.05 mm/yr for 10 years)
Long-term drift errors: orbit (ITRF) and GIA	Drift error	δ = 0.12 mm/yr

GMSL differences Uncertainty level (at 1 σ)
σ between 0.6 and 0.8 mm (depending on altimeter missions)
σ between 0.5 and 0.7 mm (depending on altimeter missions)
σ = 0 (model WTC error are cancelled between 2 missions)
σ = 0.5 mm * sqrt(2)
δ = 0.1 * sqrt(2) (GIA error is removed between 2 missions)

Figure 8: Error budget of Jason-2/Jason-3 (on the left) and the derived error budget for the ΔGMSL calibration method (on the right).

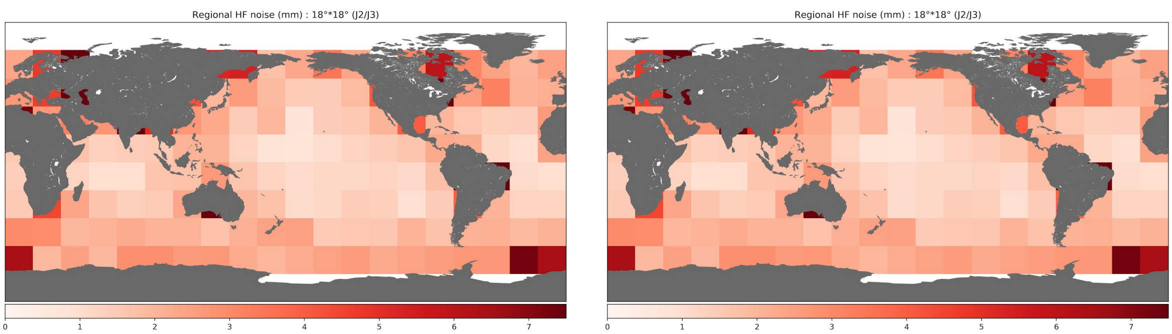

Figure 9: Regional standard deviation (mm) of the errors between Jason-2 and Jason-3 during the calibration phase for high-frequency errors lower than 2 months (on the left) and for errors between 2 and 6 months (on the right) for 18x18 degree boxes

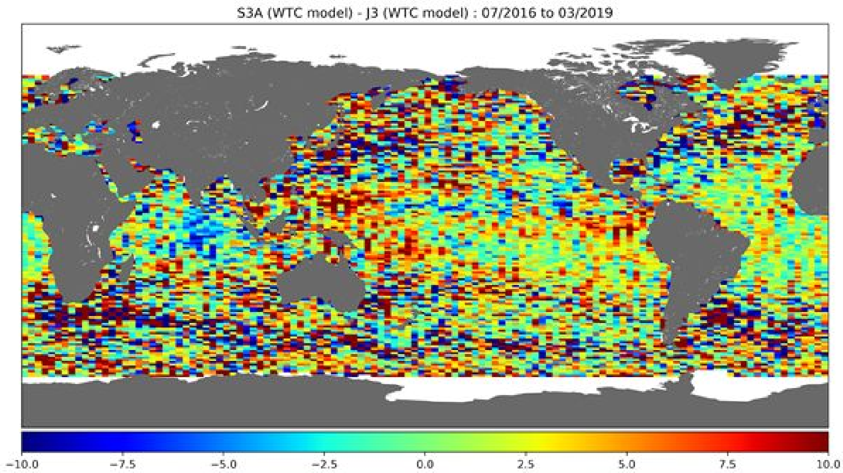

Figure 10: Map of regional MSL trend differences between S3A and Jason-3 over a 3-year period (mm/an)