SLCCI-WP2520

Task 2520: Sensitivity of the MSL calculation changing the orbit of the reference mission: Sentinel-3 instead of Jason missions

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Summary

1. Introduction

The Sentinel-3 mission is expected to be launched in 2015. One of the main objectives is to measure sea surface topography for environmental and climate monitoring. The satellite will be on a new orbit with a 27-days cycle and a 4-days sub-cycle. Thus, it is expected to provide accurate estimations of the MSL evolution.

Until now, the global Mean Sea Level (MSL) indicator has been computed using the TOPEX/Jason « reference missions » only. These have the same ground-track (TOPEX ground-track with a 9.91-days cycle). The first advantage of these continuous time series is the identical sampling of the oceanic variability. The second comes from the « calibration phases » between TOPEX and Jason-1 (6 months in 2002), and between Jason-1 and Jason-2 (6 months in 2008). During this period, both satellites measure the same sea level - spaced out by a few seconds – on the same ground-track. It has been demonstrated that this period is necessary to an accurate computation of the sea level bias between each mission in order to link MSL time series. At regional scales, strong regional variations of the MSL bias have been detected during the calibration phase, especially between TOPEX and Jason-1, but also between Jason-1 and Jason-2. These differences between 2 missions have been corrected in SL CCI phase 1 in order to improve the regional MSL trends.

As mentioned, Sentinel-3 altimeter and platform are designed to provide accurate estimations of MSL evolutions. Therefore, it should be possible to change the orbit of reference in the future to compute the MSL evolution: Sentinel-3 could replace Jason-2 or Jason-3 missions. But what would be the impact of the oceanic variability sampling between the Sentinel-3 and the historical TOPEX ground-tracks? Without a calibration phase between Jason and Sentinel-3, what would be the accuracy of global and regional MSL biases to link both missions? And what would be the impact on the MSL trends? This study aims at responding to all these questions before the Sentinel-3 launch.

Global and regional requirements on the MSL trend are different as –because of oceanic variability- the regional MSL may fluctuate rapidly, increasing the uncertainty on the local trend. For the same reasons, the ground-track of the platform is essential for the accurate measurement of oceanic variability: two missions on different orbits will see and measure a different local ocean state. These local effects are however averaged in the Global MSL computation and their impact is significantly reduced. Therefore, the focus is first on the Global MSL (GMSL): the uncertainty on the linking between a Jason mission and Sentinel-3 as well as the impact of both missions' ground-tracks on the GMSL long-term evolutions are estimated. Then, secondly, the regional scales are studied using a similar methodology.

2. Impact on Global Mean Sea Level

2.1. Overview

Replacing the Jason-2 (or Jason-3) sea level measurements by Sentinel-3 data in the Global MSL continuous record deduced from TOPEX, Jason-1 and Jason-2 will only be possible if Sentinel-3 error budget is similar to, or better than, Jason-2's. In this study, we assume it will be the case. What matters is the impact of the new Sentinel-3 ground track (different from the historical TOPEX/Jason ones) on the Global MSL record in terms of long-term scales (i.e. long-term trends, inter-annual signals).

To answer this question, two potential impacts were a priori identified:

- Relative Bias Uncertainties between Sentinel-3 and Jason-2 GMSL while no calibration phase[1] will exist between both satellites

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[1] Calibration phases exist between Jason-1 and Jason-2 (2008), and between TOPEX and Jason-1 (2002) where -during about 6 months- both satellites were spaced out by about 1 minute, measuring exactly the same sea-level height.

- Uncertainties on the space-time sampling differences between Jason-2 and Sentinel-3A ground tracks.

These two components will be estimated separately in the following sections.

2.2. Impact on the MSL Relative Bias Uncertainty

In order to quantify the impact of linking Sentinel-3 with the reference GMSL record[2] on GMSL accuracy, it is first necessary to estimate the minimum Relative Bias Uncertainty (RBU) that can be achieved. For this, we will place ourselves in the Jason-1/Jason-2 scenario (equivalent to Jason-2/Jason3, hereafter reference scenario), where the two missions have the same orbits over a calibration phase and are equipped with similar altimeters and platforms. Thus, the RBU is minimal since satellites observe the same ocean during a 9-month periods. Therefore:

- oceanic variability issues are non-existent,
- measurement errors are positively correlated: if orbits are identical, errors due to high frequency corrections such as ocean tide, ionosphere, inverse barometers,… are correlated.

Real data is not fitted for the estimation of the reference RBU. Indeed, a significant RBU estimator requires a large set of decorrelated estimations of the relative bias. However, the Jason-1/Jason-2 calibration phase lasts 20 cycles[3] and at least 9 cycles are required to compute the relative bias accurately. This means 12 estimations, at best, may be computed if the 9-cycle window is shifted with a 1-cycle step. The estimations will necessarily be correlated and not significant. However, this rough RBU estimation, based on real data, will be used for validation purposes.

Then, synthetic altimetric data were generated on Jason-1 and Jason-2 ground tracks (which are identical over the calibration phase) to compute two synthetic GMSL time series corresponding to the working scenario (hereafter working scenario: Jason/Sentinel-3). This way, we were able to compute a large set of relative biases and estimate more accurately the reference (or minimal) RBU.

Once this reference RBU has been quantified, the same methods were applied in the Jason/Sentinel-3 configuration. This time, no calibration phase is available and ground-tracks are very different. This implies:

- oceanic variability issues –as satellites do not observe the same ocean,
- the errors of each dataset are uncorrelated: if orbits are different, errors due to high frequency corrections are uncorrelated

This scenario also applies to many pairs of satellites such as Jason-1/Envisat or Jason-2/Cryosat-2…. Large real GMSL records are therefore available for the RBU estimation. Moreover, as we are not limited to a small calibration period, a large (thus statistically significant) set of biases was computed with real data, providing an accurate estimation of the RBU. Synthetic data is however very useful in this context too, as it gives us the opportunity to decompose the uncertainty into its component due to oceanic variability and the complementary component which is mainly due to uncorrelated measurement errors.

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[2] The reference Global MSL time series merges the GMSL from TOPEX, Jason-1 and Jason-2 altimetric missions

[3] A Jason cycle lasts 9.91 days so 20 cycles represent a 6 months period

2.2.1. Reference scenario: calibration phase

This scenario corresponds to the linking of two missions such as Jason-1/Jason-2 or Jason-2/Jason-3. The MSL Relative Bias Uncertainty (RBU)-in this context- provides the minimum uncertainty that can currently be reached. An accurate estimation is required as it will be our reference value for the rest of the study.

The real data we considered for this scenario comes from the Jason-1/Jason-2 calibration phase. Indeed, it is the only pair of satellites currently available for this configuration. However, it covers a 20-cycle period which is not large enough to be statistically significant. Our estimation based on this data is therefore a rough approximation. The use of synthetic data enables to re-create this scenario a statistically significant number of times and compute a more accurate estimation.

2.2.1.1. Real data

Jason-1 and Jason-2 MSL time series were interpolated on a common time vector over the calibration phase[4]. Then biases were estimated using a 9-cycles window, recursively shifted from 1 cycle (bias values are thus correlated). The 2-sigma value (95% confidence interval) was estimated to 0.59mm, see **Figure 1: Biases between Jason-1 and Jason-2 Global** MSL over the **calibration phase (20 cycles).**

Although this value is not significant on a statistical point of view because it was computed with a small set of values, the estimation is consistent with (Ablain, et al., 2009) which estimated a 0.5mm RBU between the Jason-1/Jason-2 GMSL records.

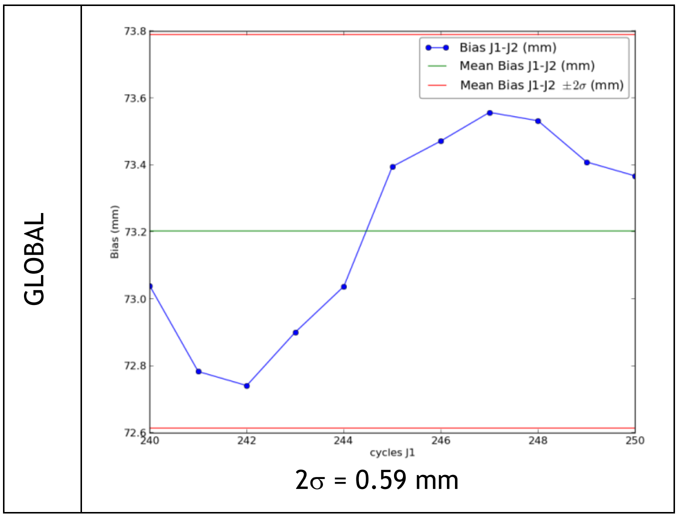

Figure 1: Biases between Jason-1 and Jason-2 Global MSL over the calibration phase (20 cycles).

2.2.1.2. Simulated data

In the previous section, the Relative Bias Uncertainty (RBU) was estimated over a calibration phase - with real Jason-1/Jason-2 data – to 0.59mm. However, this estimation is not statistically significant as it is limited by the duration of the calibration phase. In this section, we used

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[4] The calibration phase covers cycles 240-259 for Jason-1, 1-20 for Jason-2

synthetic GLORYS-based MSL data to simulate the scenario of a calibration phase between two missions. This way, we were able to generate a large set of relative biases and estimate accurately the uncertainty.

Mercator's oceanic reanalysis GLORYS provides model-based weekly ¼° Sea Level Anomaly grids. Synthetic altimetric data was generated by interpolating GLORYS in time and space on Jason-1 ground-tracks (which are identical to Jason-2 over the calibration phase). Global MSL records were then computed from this data.

Synthetic altimetric data is however significantly smoother than real measurements. In order to compute an accurate RBU estimate, synthetic MSL records should contain realistic high frequency signals. A white noise would not be realistic as these signals correspond to physical variations of the sea level as well as measurement/processing errors. They are thus correlated in time. Therefore, a random high frequency correlated noise was added to the synthetic MSL records so that it contains the same signals as the real ones (see Annexe A -).

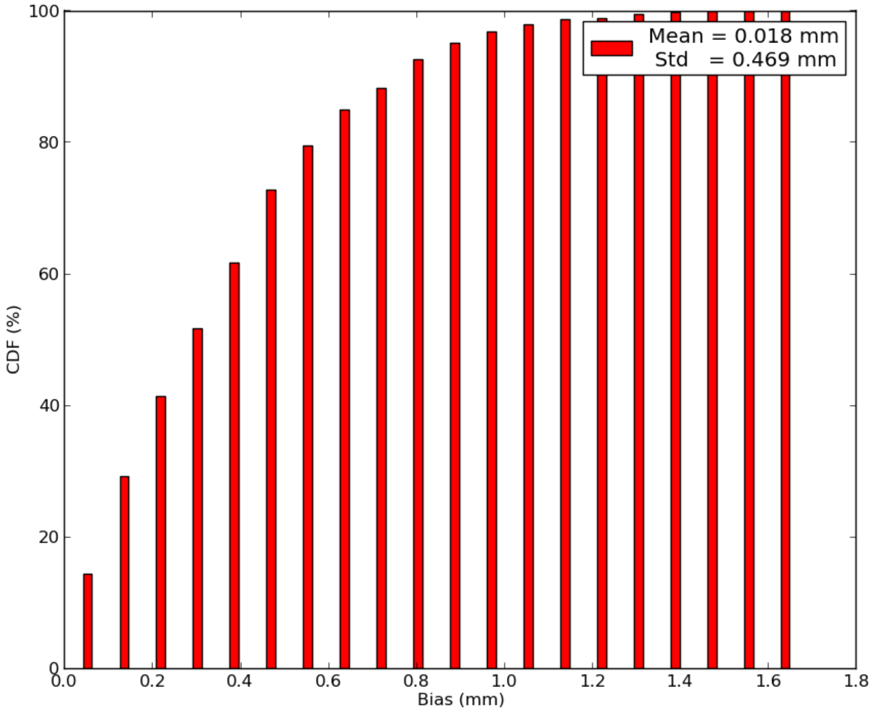

Figure 2: Cumulative distribution of the absolute bias -in the reference scenario-computed over 1000 tests

With this random noise addition, two different synthetic GMSL records were generated. A correlation close to 0.8 has been forced between them[5]. With this method, we were able to compute realistic Global MSL time series simulating the measurements of two missions during their calibration phases. We were then able to compute the relative bias a significant number of times.

Results are gathered in the cumulative histogram Figure 2. The x-axis represents the relative bias classes in millimeters, and the y-axis the cumulative population in each class. The distribution shows that in 95% of all tests the uncertainty remains below **0.9mm**, which is consistent with 2.2.1.1 where the estimate reached **0.59mm** with real data. This value leads to the same conclusions: **the RBU GMSL records measured by two missions with an intercalibration phase (reference scenario) is low.**

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[5] 0.8 is an estimation of the correlation between two missions during a calibration phase based on real Jason data.

The minimal RBU that can be reached in the reference scenario was estimated between 0.59mm and 0.9mm with a 95% confidence. This impact on the Global MSL uncertainty may be assumed as low. We will see in the following section that this low impact is mainly reached thanks to the calibration phase which ensures the correlation between the errors of the two missions.

2.2.2. Working scenario: no calibration phase

2.2.2.1. Estimation of the Relative Bias Uncertainty using real data

In the previous section, the Relative bias Uncertainty (RBU) of two missions benefiting from a calibration phase was estimated. This uncertainty, below 0.9mm, was our minimal reference as calibration phases ensures consistency between measures and between their errors. In this section, we placed ourselves in the scenario of two missions not benefiting from such a phase. It should be noted that the altimeters/platforms of the two missions are also different, which was not the case in the reference scenario. This adds a source of uncertainty. However, one may reasonably argue that the uncertainty due to ground tracks is relatively more significant.

In this configuration, several real datasets could have been considered. Indeed, it corresponds to many available pairs of satellites: Jason-1/Envisat, Jason-2/Altika, Geosat Follow-On/ERS-2… We chose the first one as it provides a common period of several years.

As in 2.2.1.1, the relative bias was computed over 9-cycles. However, here, the time series were large enough to provide a statistically significant RBU estimation. Results in Figure 3 show that when using different orbits and altimeters/platforms, the RBU of two missions in the working scenario reaches **2.9mm**. This corresponds to an increase included in [220%,400%] compared to results obtained with the reference scenario, see 2.2.1.

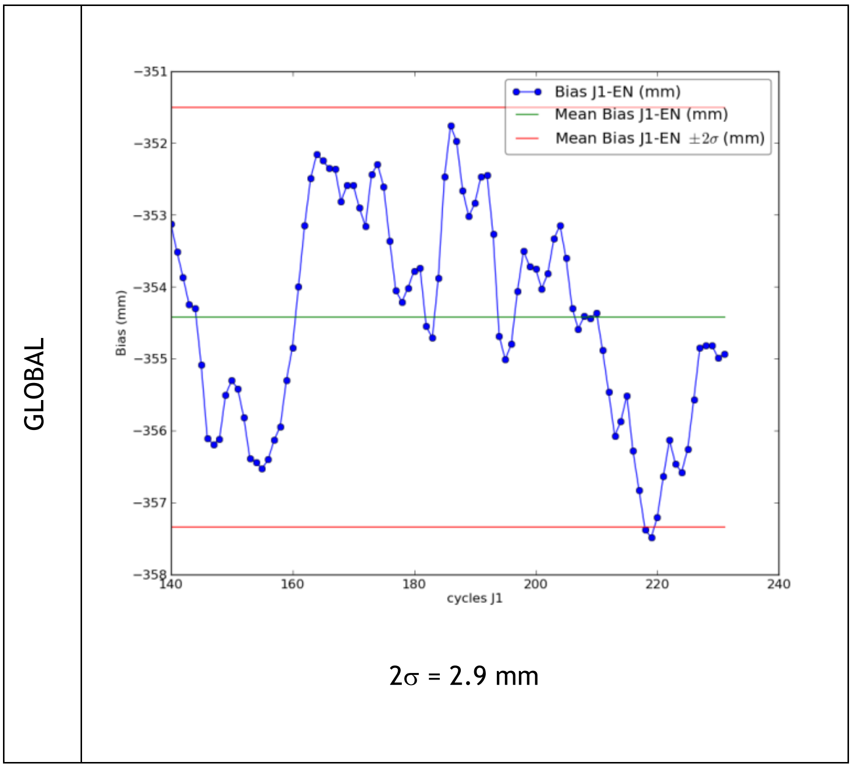

Figure 3: Relative biases between Jason-1 and Envisat Global MSL over 100 Jason-1 cycles.

This estimation proves that **the absence of a calibration phase has a strong impact on the Global MSL uncertainty**. In this configuration, the uncertainty is mainly due to two components: oceanic variability (negligible in the reference scenario) and measurement errors. Both are due to the difference of ground tracks. To a lesser extent, the component due to measurement errors is also due to the differences in altimeters and platforms, though this has not been demonstrated. In the next section, using simulated data, we decomposed the contribution of both components on this 2.9mm RBU estimate.

2.2.2.2. Decomposition of the Relative Bias Uncertainty

In the working scenario, the use of real data provided an accurate estimation of the Relative Bias Uncertainty (RBU). In this section, we used simulated data with similar techniques as in 2.2.1.2, but for a different purpose. We did not aim here at re-estimating the RBU but decomposing the estimation into its two main components.

In the context of the working scenario, the impact of oceanic variability is no longer negligible. Indeed, the ocean state changes between the passages of the two satellites. For similar reasons, corrections errors such as ocean tide or ionosphere are uncorrelated between both missions as they depend on time and space and the ground tracks are different. We thus separated the RBU induced by the oceanic variability and by the measurements errors.

2.2.2.2.1. Uncertainty induced by oceanic variability

In order to estimate the uncertainty induced by the ocean state change between the passages of the two satellites, GLORYS data was interpolated on Jason-1 and Sentinel-3A ground tracks. It was important here to use the same original data[6] for both satellites as we only want to estimate the impact of the different space-time sampling.

Then, we computed Global Mean Sea Level records over a hundred Sentinel-3A cycles time-period for both missions with the synthetic data. The Jason-1 simulated GMSL time series was interpolated on Sentinel-3A’s[7]. Finally, relative biases were computed by shifting a 9-cycles average window.

Results are available Figure 4 and show a distribution centered near zero with an extremum reaching 0.5mm. The 2-sigma value has been estimated to **0.35mm** which is low compared to the 2.9mm uncertainty estimated in 2.2.2.1. In other words, **oceanic variability has a low contribution (about 12%) on the Global MSL uncertainty in the working scenario**.

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[6] The GLORYS reanalysis plays the role of a “virtual” ocean state that both satellites measure through their specific ground track

[7] This step is compulsory as Sentinel-3A cycles last 27 days whereas Jason-1 cycles last 10 days

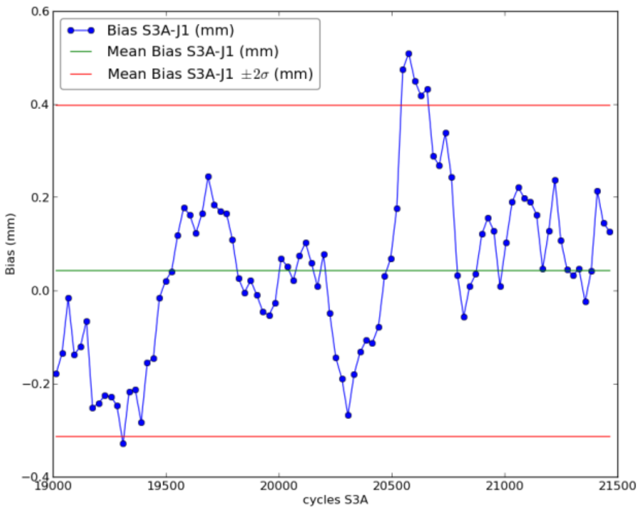
GLOBAL	 2σ = 0.35 mm

Figure 4: Relative biases between GLORYS-based simulated Jason-1 and Sentinel-3A Global MSL over 100 Sentinel-3A cycles

This result was expected as oceanic variability has mainly a local impact in strong currents regions (Agulhas, Gulf Stream, Kuroshio…), but its global impact on GMSL, and thus its contribution to RBU, is limited.

As this component represents only 12% of the total 2.9mm RBU, we expect to find a large contribution – close to 88% - of the measurement errors. The next part was thus mainly used to confirm the validity of our methodology based on simulated data.

2.2.2.2.2. Uncertainty induced by altimetric measurements errors

The Global MSL RBU was estimated to 2.9mm with real Jason-1/Envisat GMSL data. We aimed here at estimating the contribution of measurements errors on this uncertainty.

For this, two different random correlated noises were added to two identical synthetic GMSL records. Then the corresponding relative bias was computed. This operation was repeated a significant number of times.

Results are gathered in the cumulative histogram Figure 5. The distribution shows that in 95% of all tests the method inaccuracy remains under **2.5mm** (which is the value we expected on the basis of the two previous sections).

The total RBU -if we combine the components induced by oceanic variability (0.35mm, see 2.2.2.2.1) and measurement errors (2.5mm) - reaches 2.85mm. Thus, 12% is due to the ground-track difference and 88% to uncorrelated measurement errors. These results are consistent with the total RBU estimate of 2.9mm computed with real data between Envisat and Jason-1, see 2.2.2.1. It confirms that **the synthetic Global MSL we computed is realistic and validates the use of synthetic data**.

Errors committed by corrections such as ocean tide, ionosphere, troposphere… have time-space dependencies. Thus, over a cycle, these errors are uncorrelated between two missions if they do not have a calibration phase because the ground tracks are different. To a lesser extent, the two altimeters/platforms being different also contributes to the decorrelation of errors. As uncorrelated errors add up to each other, **measurement errors have a strong impact on the MSL Relative Bias Uncertainty when missions do not benefit from a calibration phase.**

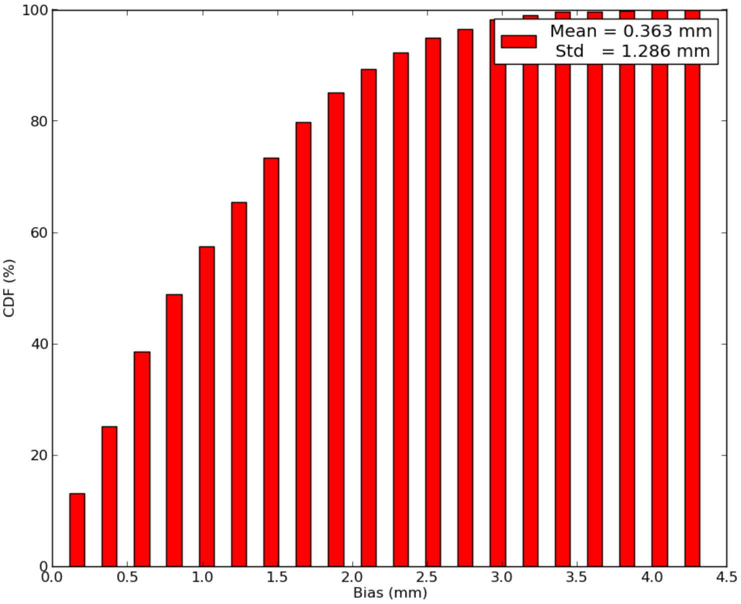


Figure 5: Cumulative distribution of the absolute relative bias -in the working scenario- computed over 1000 tests. The bias simulates the uncertainty due to measurements errors

2.2.3. Intermediary conclusions: Global Mean Sea Level Relative Bias Uncertainty

The Relative Bias Uncertainty (RBU) of two altimetric missions has been estimated under two configurations corresponding to Jason-1/Jason-2 (or Jason-2/Jason-3) and the Jason-2/Sentinel-3 scenario (or Jason-3/Sentinel-3, objective of this study). Results obtained with these configurations are synthesized in Table 1. To summarize, the uncertainty on the linking increases from 0.9 mm in the reference scenario to about 3 mm using Sentinel-3 (or Envisat, Altika, etc…). The question is to assess whether or not this increase is acceptable for climate studies. Results were included in Table 1 for each scenario and each kind of data (real and simulated). For the reference scenario (reference), the RBU is less than 1 mm whereas -in the case of the working scenario (Jason/Sentinel-3)- the RBU almost reaches 3 mm regardless of the data type (real and simulated).

	Simulated data		**Real data**	
	Missions	Bias uncertainty (mm)	Missions	Bias uncertainty (mm)
Ref. scenario	Jason/	0.9	Jason-1/	0.6

	Jason		Jason-2	
Work. scenario	Jason/ Sentinel-3	0.35+2.5	Jason-1/ Envisat	2.9

Table 1: Summary of RBU estimations with the different methods

RBU is expressed here as a distance. However, in our case, it is more interesting to analyze the impact of RBU on MSL trend uncertainty. This may be compared to **the user requirements for the Global Mean Sea Level trend which is lower or equal to 0.3 mm/yr over a 10-year period (SLCCI_URD_005)**.

The positions in time of mission changes are known for past missions. For future missions (Jason-3, Sentinel-3A), we assume a common change in June 2015. The RBU may thus be converted into a function of time that corresponds to the trend uncertainty. The function may be found by applying the Least Square Estimator formula to Heaviside functions which model RBUs. For instance, in the case of one mission change:

$$Trend\ Uncertainty(t) = \frac{6 * RBU * t_C(t - t_c)}{t(t^2 - P^2)}\ for\ t \geq t_c\ , 0\ for\ t < t_c$$

Where:

- t is the time,
- RBU the Relative Bias Uncertainty,
- t_c the time of mission change,
- P the sampling period

In our case, there are two mission changes, hence the formula is more complicated.

Figure 6 shows how RBU propagates on the MSL trend uncertainty in the Jason-1/Jason-2/Jason-3 (reference) and the Jason-1/Jason-2/Sentinel-3a (working) scenarios. The RBU values that have been used are the one computed with simulated data (see Table 1Table 2). It shows the 0.9mm RBU induced by Jason-1/Jason-2 calibration phase results in a 0.12mm/yr maximum trend uncertainty. Then, switching from Jason-2 to Jason-3 (ref. scenario) results in a 0.13mm/yr maximum trend uncertainty. However, switching from Jason-2 to Sentinel-3a (work. scenario) results in a 0.26mm/yr maximum trend uncertainty, close to user requirements.

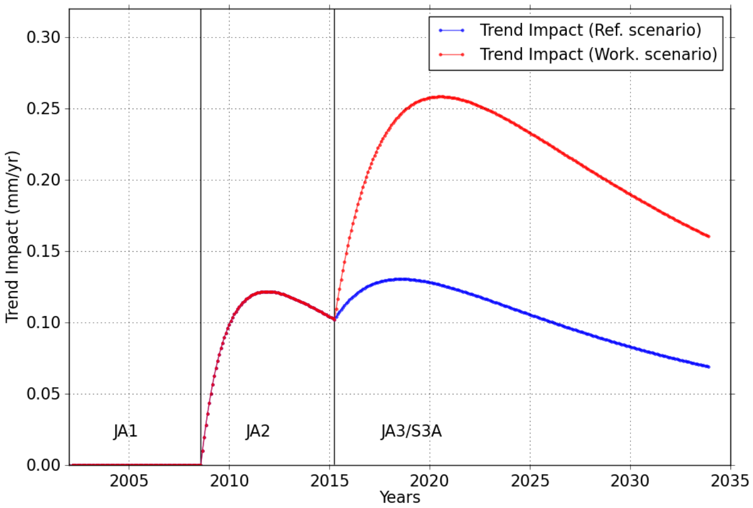


Figure 6: Impact of relative biases uncertainties on the trend uncertainty of Ja1/Ja2/Ja3 (Ref. Scenario) or Ja1/Ja2/S3a (Work. Scenario) GMSL time series

Therefore, this study leads to the conclusion that it is necessary to conserve the historical TOPEX/Jason ground track to compute an accurate and continuous Global MSL record. This allows the minimization of the Relative Bias Uncertainties impact thanks to calibration phases. Linking the TOPEX/Jason1/Jason2 Global MSL record with Sentinel-3 would induce an error of about 3 mm impacting the trend uncertainty by about 0.26mm/yr. This level of error is not acceptable regarding MSL user requirements since it is not the only source of trend uncertainty.

2.3. Impact on the Global Mean Sea Level evolution uncertainty

In the previous part, 2.2, the impact of using Sentinel-3A instead of a Jason mission on GMSL Relative Bias Uncertainty was estimated. In this part, the uncertainties due to the space-time sampling differences between Jason-2 and Sentinel-3A ground tracks on the global MSL evolution, including the long-term evolution (trend) and inter-annual signals, was estimated.

For this, the synthetic GMSL records on Sentinel-3A and Jason-2 ground tracks, described above, were used. Since the aim is to isolate the impact of ground tracks, no correlated error was added: everything happens as if both altimeters were measuring the same ocean state, with the same errors. Then, the difference between both time series after interpolating Jason-2 cycles on Sentinel-3A ones was computed. The difference is plotted Figure 7 (blue dots) along with the corresponding mid-term (green line: 6 months low-pass filter) and long-term evolutions (red line).

Results show the mid-term evolutions may reach 0.9mm locally with a 0.28mm standard deviation (so a **0.56mm 2-sigma value**). User requirements concerning interannual variations specify a maximum of 0.5mm uncertainty. Here, only semi-annual evolutions were represented because the time series was too short to compute interannual evolutions. One cannot directly compare the 0.56mm semi-annual uncertainty to the required interannual uncertainty of 0.5mm. It is expected that the uncertainty on high-frequency signals is higher than on low-frequency ones. However, we may conclude **the mid-term impact on GMSL evolution is low but significant**.

A **0.05 mm/yr** trend is estimated on the difference between Jason-2 and Sentinel-3. **Thus, the impact of ground tracks on GMSL long-term evolutions is low compared to the 0.3 mm/yr specified by user requirements, but is not negligible.**

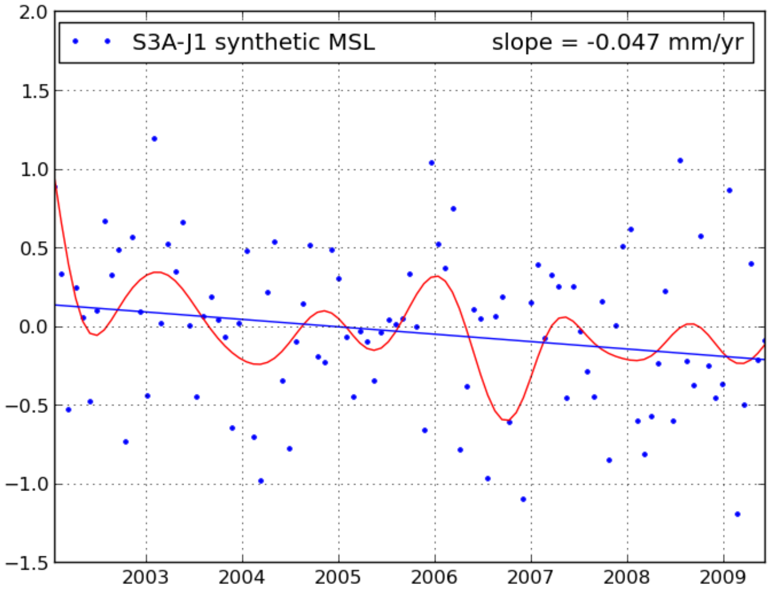


Figure 7: Difference between synthetic GLORYS-based GMSL on Jason-2 and Sentinel-3A ground tracks interpolated on Sentinel-3 cycles

2.4. Intermediary conclusions: impact on Global Mean Sea Level uncertainty

Section 2 focuses on the impact of the new Sentinel-3 ground track (different from the historical TOPEX/Jason ones) on the Global MSL time series in terms of long-term scales (i.e. long-term trends, inter-annual signals).

The section leads to the conclusion that it is necessary to conserve the historical TOPEX/Jason ground track to compute the Global MSL time series. This allows the minimization of the Relative Bias Uncertainties impact thanks to calibration phases. Linking the TOPEX/Jason1/Jason2 Global MSL record with Sentinel-3 would induce an error of about 3 mm impacting the trend uncertainty by about 0.3mm/yr. This level of error is not acceptable regarding MSL user requirements.

The impact of ground track on Global Mean Sea Level evolution uncertainty is low, at both mid-term and long-term levels. It may however not be neglected, mostly because it adds up with other sources of uncertainty such as relative bias or other systematic errors.

If the Global uncertainty is due to the difference in ground tracks, it necessarily means that the regional impact is also significant. This was studied in the following section.

3. Impact on Regional Mean Sea Level

3.1. Overview

In the previous section, the long-term impact of the new Sentinel-3 ground track on the Global MSL time series was studied. However, the global uncertainty is necessarily caused upstream by regional uncertainties. **User requirements UR-SLCCI-GEN-02 concerning the regional Mean Sea Level provides an upper limit of the local trend uncertainty, over a grid mesh of 50-100 km, of 1mm/yr.**

Therefore, two geographic areas were focused on: Mediterranean and North Atlantic Basins. These basins have been selected because the Mediterranean Sea is semi-enclosed, with the appropriate size to approach the limits of altimetry accuracy. North Atlantic is the place of significant local oceanic variability thanks to strong currents such as the Gulf Stream. Both will thus be impacted by the new Sentinel-3 ground track.

There are no specific URs for whole basins, but this enabled us to study in greater detail the accuracy loss due to ground track differences by decreasing progressively the scale of interest. In both regions, the study in section 2.2 was repeated, i.e. the Relative Bias Uncertainty (RBU) was estimated at basins scale.

Finally, the impact of the new Sentinel-3 ground track on regional MSL trends was estimated in a 1°x3° grid mesh in order to be compared to URs.

3.2. Impact of space-time sampling on the Regional MSL Relative Bias Uncertainty

We aimed here at estimating the Relative Bias Uncertainty (RBU) on regional MSL measured by Sentinel-3 and Jason missions.

The technical explanations will be limited as the methodology is based on section 2.2. The only technical difference is the use of masks to limit the computations on the areas of interest: Mediterranean and North Atlantic Basins.

First, the minimal RBU that can be achieved on the linking of two Regional Mean Sea Level (RMSL) time series was estimated. As in 2.2.1, this reference RBU may be achieved in the scenarioof two missions benefiting from a calibration phase. Second, this reference RBU was used to compare it to the working scenario, i.e. when there is no calibration phase.

3.2.1. Reference scenario: calibration phase

The description of the modus operandi is detailed in 2.2.1. The computation of Global Mean Sea Level RBU, in the reference scenario, was repeated focusing on two regions. Jason-1/Jason-2 real data were used, over the calibration phase, to compute the Regional RBU. The time-period is however limited, which makes the results not significant. The use of simulated data was thus again considered, but it has been left aside, as it is described in the corresponding part.

3.2.1.1. Real data

The use of real data over the calibration phase enables a rough estimation of the regional MSL RBU. However, the calibration phase is limited to 20 cycles. Because the computation of the bias requires at least 9 cycles, this result should be taken with caution.

As in 2.2.1.1, the bias was computed using a 9 cycles window on RMSL that is shifted from 1 cycle iteratively. The set of biases was plotted Figure 8 in the two regions of interest. Corresponding 2-

sigma values, **2.3mm** over the Mediterranean Basin and **2.2mm** over the North Atlantic basin, are similar in both regions.

With the same data, the Global RBU had been estimated to 0.59mm, see 2.2.1.1. **The RBU is thus multiplied by a factor 4 when reducing the area of interest from the globe to a basin over a calibration phase.**

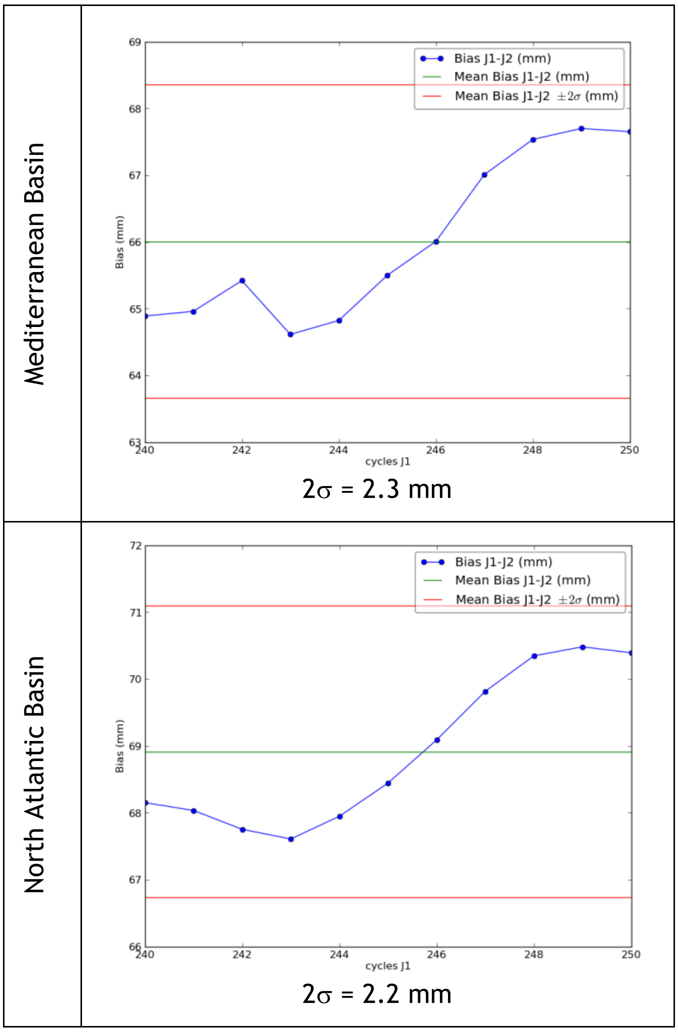


Figure 8: Relative bias between Jason-1 and Jason-2 Regional MSL over the calibration phase. Top: Mediterranean Basin, bottom: North Atlantic Basin.

3.2.1.2. Simulated data

In the previous section, the impact of ground track on RMSL linking was estimated over a calibration phase, using real data. However, the restricted duration of this phase did not allow a statically significant estimation. In 2.2.1.2, the matter was solved using simulated data but the difficulty was to simulate realistic high frequency signals which are not include in the GLORYS ocean reanalysis.

This solution was not repeated here. The reasons are high-frequency signals contained in Regional MSL time series are different from signals in Global MSL and specific two each region of interest. This would have thus taken too much time for few extra information.

Therefore, only use real data was considered, see 3.2.1.1, to estimate RBU with the reference scenario, on a regional scale.

3.2.2. Working scenario: no calibration phase

This scenario corresponds to the linking of Sentinel-3 with a reference mission. Section 2.2.2 was repeated focusing on two regions. We aimed here at stressing the impact of linking MSLs from two altimeters deprived of calibration phase, thus committing uncorrelated errors, on the Regional Mean Sea Level uncertainty.

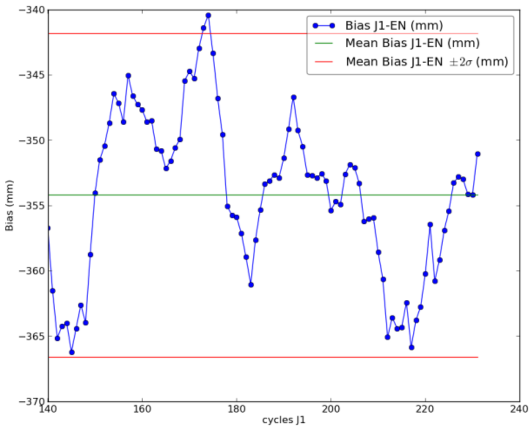
3.2.2.1. Estimation of the Relative Bias Uncertainty using real data

As in 2.2.2.1, we aimed at estimating the Relative Bias Uncertainty (RBU) with real Envisat and Jason-1 data. Indeed, the absence of a calibration phase is also typical of this mission pair. As we are not limited by the short length of a calibration phase, we were able to compute the bias between the two RMSL records over a hundred cycles to benefit from a statistically large set of values that is plotted for both regions on Figure 9.

The use of real Envisat and Jason-1 data shows a strong RBU -in the working scenario- in Mediterranean (**12mm**) and North Atlantic Basin (**9.1mm**). (Cazenave, et al., 2002), merging 6 years of TOPEX/Poseidon data with ERS-1 data, have reported a trend uncertainty of 1.5 mm/year in the Mediterranean Sea. The T/P / ERS-1 scenario is similar to the Jason-1/Envisat one. So if we convert the 12mm uncertainty into a trend uncertainty on a 6-years period (by simply dividing), we obtain a 2mm/yr uncertainty, which is consistent with (Cazenave, et al., 2002).

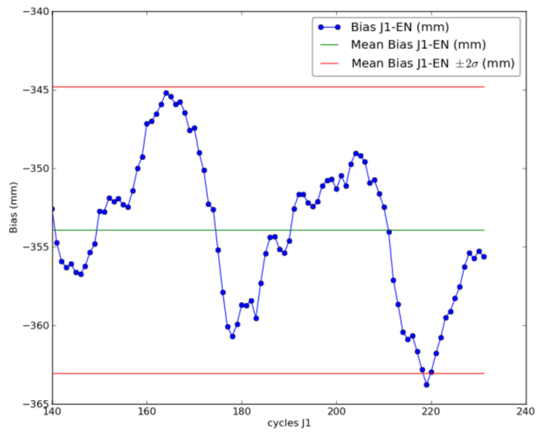
Compared to the **2.9mm** RBU obtained with Global MSL, the Regional MSL RBU is multiplied by **4** (resp. **3**) in the Mediterranean Basin (resp. North Atlantic Basin). These factors are consistent with the reference scenario (a factor 4 had been estimated, see 3.2.1.1). It suggests the RBU –in the absence of a calibration phase- is not evenly distributed on the globe. This shows the impact depends on the size of the area as well as the local oceanic variability.

Mediterranean Basin



2σ = 12 mm

North Atlantic Basin



2σ = 9.1 mm

Figure 9: Biases between Jason-1 and Envisat Regional MSL over 100 J1 cycles. Top: Mediterranean Basin, bottom: North Atlantic Basin.

3.2.2.2. Decomposition of the Relative Bias Uncertainty

The use of real data provides an accurate estimation of the Relative Bias Uncertainty (RBU) in the working scenario. In this section, we aimed at decomposing the estimation into its two main components: oceanic variability and measurement errors, see 2.2.2.2 for further details.

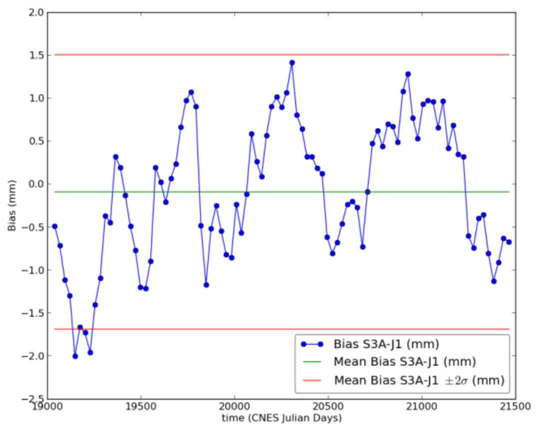
3.2.2.2.1. Uncertainty induced by the oceanic variability

In order to estimate the RBU induced by the ocean state change between the passages of the two satellites, GLORYS data was used, as in 2.2.2.2.1.

Regional Mean Sea Level time series over a hundred Sentinel-3A cycles time-period has been computed for both satellites, with synthetic data, over the two areas of interest.

On Figure 10 are plotted the relative biases for the Mediterranean and North-Atlantic basins. The time series, centered around zero, varies in the [-2mm, 2mm] interval. Corresponding RBUS are **1.6mm** in the Mediterranean and **2.2mm** in North Atlantic basin.

Mediterranean Basin



2σ = 1.6 mm

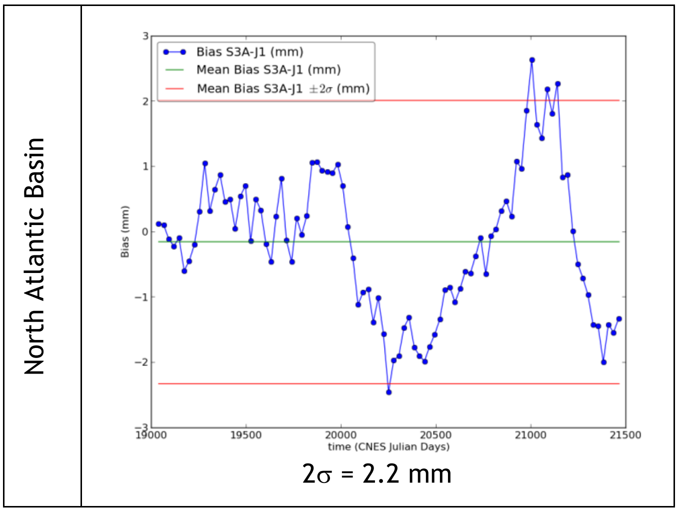


Figure 10: Relative Biases between Jason-1 and Sentinel-3A Regional Mean Sea Level over 100 S3A cycles. Top: Mediterranean Basin, bottom: North Atlantic Basin.

It has been shown in 2.2.2.2.2 that, in the Global case, 12% of the linking uncertainty was due to oceanic variability. According to the results in the regional case, and by comparison to real data results (see 3.2.2.1), the contribution of oceanic variability varies in the interval [13%, 24%]. Therefore, depending on the area of interest, its impact may be twice more important than in the global case.

3.2.2.2.2. Uncertainty induced by Altimetric measurements error

The impact of measurement errors on Global MSL RBU using simulated data, used in 2.2.2.2.2, was not repeated on Regional MSL because of the difficulty of simulating measurements errors in a regional case. Moreover, it has been shown in Impact on the MSL Relative Bias Uncertainty2.2 that results are consistent with real data, thus this part would not provide additional information.

3.2.3. Intermediary Conclusions

Uncertainties in the linking of two missions –in terms of Regional MSL- were estimated in two configurations: the first simulating the Jason-2/Jason-3 linking and the second the Jason-2/Sentinel-3A (or Jason-3/Sentinel-3A) linking. The geographical areas of interest were the Mediterranean and the North Atlantic Basins.

Results are gathered in Table 2. The impact of the ground-track was isolated (second column) from the total uncertainty (third column). In reference scenario, as we focused on the calibration phase, impact of oceanic variability was disregarded and set to 0. In the working scenario, however, it was computed in 3.2.2.2.1 using simulated data. The total uncertainty was computed using real Jason-1/Jason-2 data (resp. Jason-1/Envisat data) in the reference scenario (resp. working scenario). Results of the Global study were also recalled here.

Results show the RBU induced by oceanic variability without a calibration phase is approximately 4 times larger at basin scales than at global scale. The proportion of the RBU due to oceanic variability compared to the total RBU are approximately conserved between the global and basin scales, particularly in the Mediterranean Sea.

	Relative Bias Uncertainty induced by oceanic variability (mm)				Relative Bias Uncertainty induced by oceanic variability + measurements errors (mm)			
	Missions	Global	Medit. Basin	North Atl. Basin	Missions	Global	Medit. Basin	North Atl. Basin
Ref. Scenario *(calibration phase)*	Jason / Jason (simu)	**0**	**0**	**0**	J1/J2 (real)	**0.6**	**2.3**	**2.2**
Work. Scenario *(no calibration phase)*	Jason / S3 (simu)	**0.35**	**1.6**	**2.2**	J1/EN (real)	**2.9**	**12**	**9.1**

Table 2: Impact of calibration phases when linking two missions on MSL trend uncertainties

As for

Figure 6, Figure 11 shows how RBU propagates on the Regional MSL trend uncertainty in the Jason-1/Jason-2/Jason-3 (reference) and the Jason-1/Jason-2/Sentinel-3a (working) scenarios. The RBU values that have been used are the one computed with real data (see Table 2Table 2). It shows that in the Mediterranean (resp. North Atlantic) Basin, the 2.3mm (resp. 2.2mm) RBU induced by Jason-1/Jason-2 calibration phase results in a 0.31mm/yr (resp. 0.3mm/yr) maximum trend uncertainty. Then, switching from Jason-2 to Jason-3 (ref. scenario) results in a 0.33mm/yr (resp. 0.32mm/yr) maximum trend uncertainty. However, switching from Jason-2 to Sentinel-3a (work. scenario) results in a 0.96mm/yr (resp. 0.76mm/yr) maximum trend uncertainty.

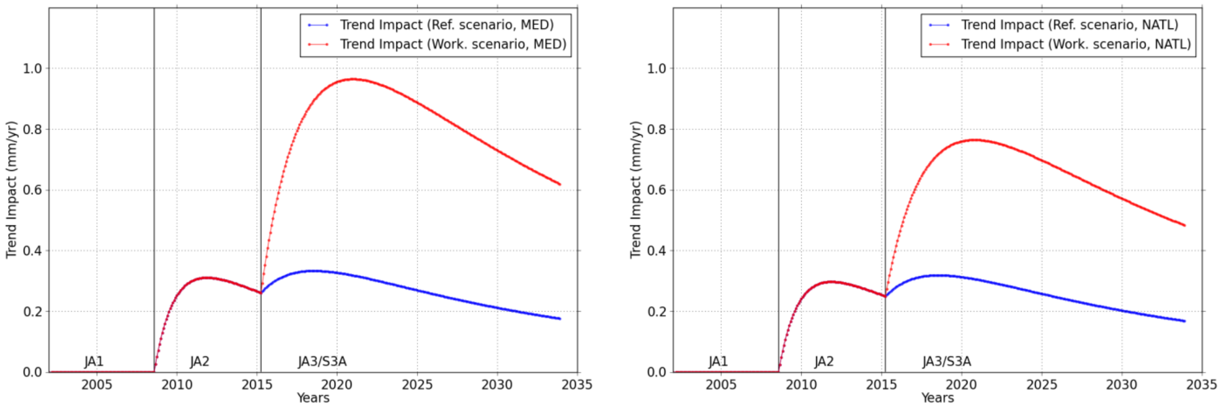


Figure 11: Impact of relative biases uncertainties on the trend uncertainty of Ja1/Ja2/Ja3 (Ref. Scenario) or Ja1/Ja2/S3a (Work. Scenario) regional MSL time series. Left: Mediterranean basin. Right: North Atlantic basin

It is difficult to conclude on the impact at this scale as no requirements have been provided in this case. However, it has been provided in a 50-100km grid mesh (UR-SLCCI-GEN-02): an uncertainty below 1mm/yr is required. In the working scenario, this UR is nearly reached at basin scale while the uncertainty is expected to be lower than at a 100km scale.

The study shows linking two missions without a calibration phase has a very strong impact on the MSL trend uncertainty at basin scale as the uncertainty is of the order of the UR in a 50-100km grid mesh.

3.3. Impact of space-time sampling on the Regional Mean Sea Level evolution uncertainty

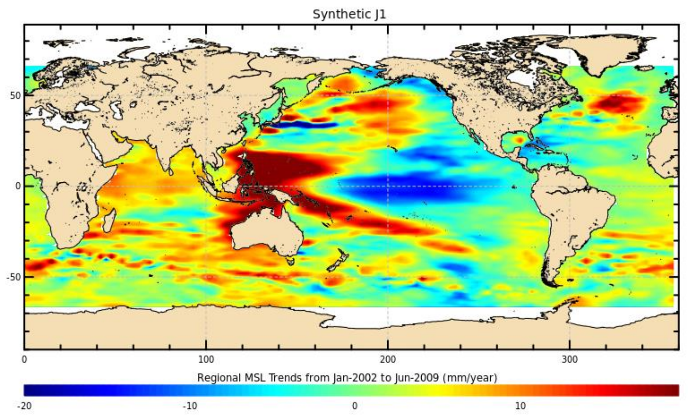
In the previous part 3.2 the impact of using Sentinel-3A instead of Jason-3 (for instance) on the linking of the two corresponding sets of Regional Mean Sea Level was estimated at a basin scale. In this part, the uncertainty regarding the Regional Mean Sea Level long-term evolution (trend) was estimated at a lower spatial scale: 100-350km.

Using the Sentinel-3A and Jason-1 synthetic Sea Level Anomalies, regional MSL trend grids were computed for both missions over the [Jan-2002, Jun-2009] period, see Figure 12. One may criticized the computation of MSL trend maps on 7.5 years, first because it is not an integer[8], second because at least 10 years are generally required to compute MSL trends. The reasons for this are the Jason-1 ground track starts in Jan-2002 and the version of GLORYS we used (2V1) stops in 2009. Because of time limitations and the fact that differences between the two maps are more interesting here than the values of individual maps, the data has not been extended to a more appropriate time-period.

The map in the bottom panel shows the difference of maps in the upper panels. According to the values (this is not visible on the map for visibility purposes), the contribution of ground track to regional MSL trend uncertainty may reach 9.5 mm/yr locally (in a 1°x3° grid mesh). These values are relatively high but are mainly located in areas where the oceanic variability is substantial (Agulhas, Kuroshio, Gulf Stream …etc). The histogram corresponding to map (above it), gathering all boxes values, shows **95% of values are below 2.5mm/yr**.

User requirements UR-SLCCI-GEN-02 ask for an uncertainty below 1mm/yr over a grid mesh of 50-100 km. The grid mesh that has been used is larger than the one used in URs, and yet the uncertainty is 2.5 times larger than the required upper limit. **Using Sentinel-3 or Jason ground tracks has thus a very strong impact on regional Mean Sea Level evolution trend uncertainty.**

Synthetic Jason-1 Regional MSL Trend



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[8] To compute MSL trends, a round number of years is generally required because it cancels the effect of semi-annual and annual signals on the value

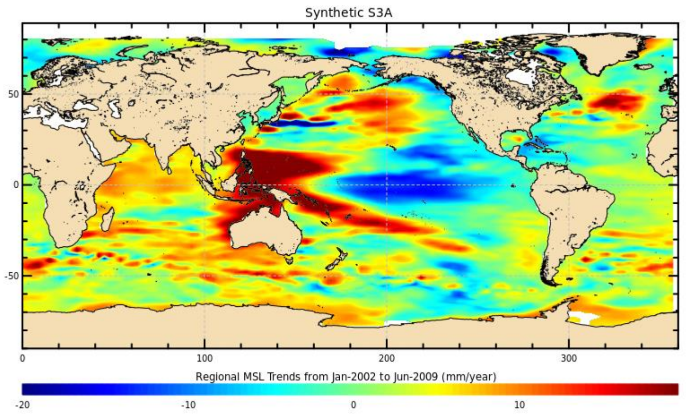
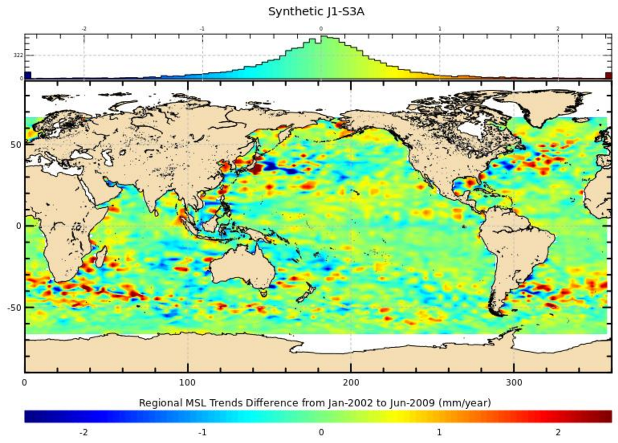
Synthetic Sentinel-3A Regional MSL Trend	
Difference between synthetic regional MSL trends	

Figure 12 : Jason-1 (top panel) and Sentinel-3A (mid panel) synthetic Regional MSL trend maps over 2002-2009. Bottom panel: maps difference and corresponding histogram. *Nb: GLORYS2V1 does not provide data over the Mediterranean Sea*

4. Conclusions and Recommendations

This study aimed at considering the possibility that the “reference” Global Mean Sea Level time series –using TOPEX and Jason missions – could be extended with Sentinel-3 measurements.

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, it will not be the case between Sentinel-3 and any of the Jason missions. So 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?

First, the Relative Bias Uncertainty (RBU) has been estimated in the most accurate case, i.e. when there is a calibration phase. This scenario may be found with Jason-1/Jason-2 (or Jason-2/Jason-3 in the future). This gives the minimal uncertainty that may be achieved when linking two missions. Then, the RBU has been estimated in the working configuration, i.e. without any calibration phase.

Results show that in the working configuration, the impact of RBU on the Global MSL trend reaches 0.26mm/yr, versus 0.13mm/yr in the reference configuration. This value represents only one component likely to increase the Global MSL trend uncertainty. However –under the working configuration-, user requirements (UR-SLCCI-SPC-01: 0.3mm/yr) are already nearly reached.

The regional RBU has also been computed on two basins: Mediterranean and North Atlantic. The RBU reaches respectively 2.3mm and 2.2mm in the reference scenario for 12mm and 9.1mm in the working scenario.

It has been demonstrated that –in the absence of a calibration phase- 88% of the uncertainty on the MSL linking is due to the decorrelation –between the two missions- of measurement errors while the remaining 12% is due to oceanic variability. This result stresses that correlation of measurement errors, induced by calibration phases, are crucial for the accuracy of MSL relative bias.

After having estimated the impact of altimetric missions MSL linking, the impact of Sentinel-3 and Jason different space-time samplings on the Global and Regional Mean Sea Level trend has been estimated. Results show that the uncertainty on the Global MSL trend - if Sentinel-3 or Jason-1 ground-track is considered- reaches **0.05mm/yr**, i.e. 17% of the user requirements. This uncertainty is low but may not be neglected. At regional scale, MSL trend uncertainty has been estimated to **2.5mm/yr** which is elevated compared to user requirements. This stresses the oceanic variability itself is a strong source of regional MSL trend uncertainty.

As a conclusion, using missions without calibration phase has a strong impact on both the Global and the Regional MSL uncertainty. The decorrelation of measurement errors due to the absence of calibration phase is the main source of uncertainty. However, the sampling of oceanic variability also has a strong impact on the Regional Mean Sea Level trends and –to a lesser extent- on Global MSL trends. Therefore, even if Sentinel-3 were proved to provide more accurate Mean Sea Level measurements than Jason-3, the uncertainty generated by linking this mission to a Jason MSL time series would not meet user requirements.

RECOMMENDATIONS

This study shows that linking Sentinel-3 to the reference Mean Sea Level time series makes it impossible to respect the user requirements UR-SLCCI-SPC-01 concerning Global Mean Sea Level trend uncertainty (<0.3mm/yr). The main reason is that it is important to remain consistent in the errors we commit to minimize sources of uncertainty.

The different sampling of oceanic variability –induced by the difference of ground tracks- prevents from meeting user requirements UR-SLCCI-GEN-02 concerning regional Mean Sea Level trends uncertainty (<1mm/yr)

To the extent possible, the use of Sentinel-3 in the reference Mean Sea Level records should therefore be avoided. It is necessary to conserve the historical TOPEX/Jason ground track to compute MSL time series and MSL trend maps.

The present study is to be published in the year in a peer reviewed publication to be determined with reference: L. Zawadzki, M. Ablain, A. Guillot, “Accuracy of the mean sea level continuous record with future altimetric missions: Jason-3 versus Sentinel-3a”

5. Acknowledgment

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Annexe A - **Addition of a realistic Jason-1-type noise in the synthetic altimetric data**

The Mercator Global Oceanic Reanalysis GLORYS provides model-based weekly ¼° maps. Synthetic altimetric data has been generated by interpolating GLORYS in time and space on Jason and Sentinel-3A ground-tracks. However, the synthetic altimetric data is significantly smoother than the real altimetric data measured by, for instance, Jason-1. This is confirmed by comparing de-trended Global MSL (GMSL) time series plots on Figure 13 (top and middle). The first one represents the GMSL computed from the real Jason-1 measurements after a 6-months low-pass filtering and the subtraction of semi-annual and annual signals. The second was computed with the synthetic GLORYS-based Jason-1 measurements. Accordingly, corresponding wavelet analyses show the low frequency (over 1 year period) signals are similar in both time series. However, high frequencies (below 10 months period) are missing in the synthetic GMSL.

Wavelet analyses quantify the frequencies and the corresponding amplitudes that are missing in the synthetic signal. If the high-frequency signal that needs to be added were a white noise, its characteristics would be an 8-month period associated with a 3mm standard deviation. In order to generate a correlated noise with the same characteristics, a random unbiased and normalized white noise vector v_N was first generated with the same dimensions as the time series. Then, instead of multiplying it with a variance -as we would do if we needed an uncorrelated white noise- a covariance matrix was used. Its diagonal contains the 9 mm^2 variance which is spread over the matrix - perpendicularly to the diagonal - with a Gaussian function. The Gaussian is tuned with the correlation period - 8 months in our case, see ***Eq 1***.

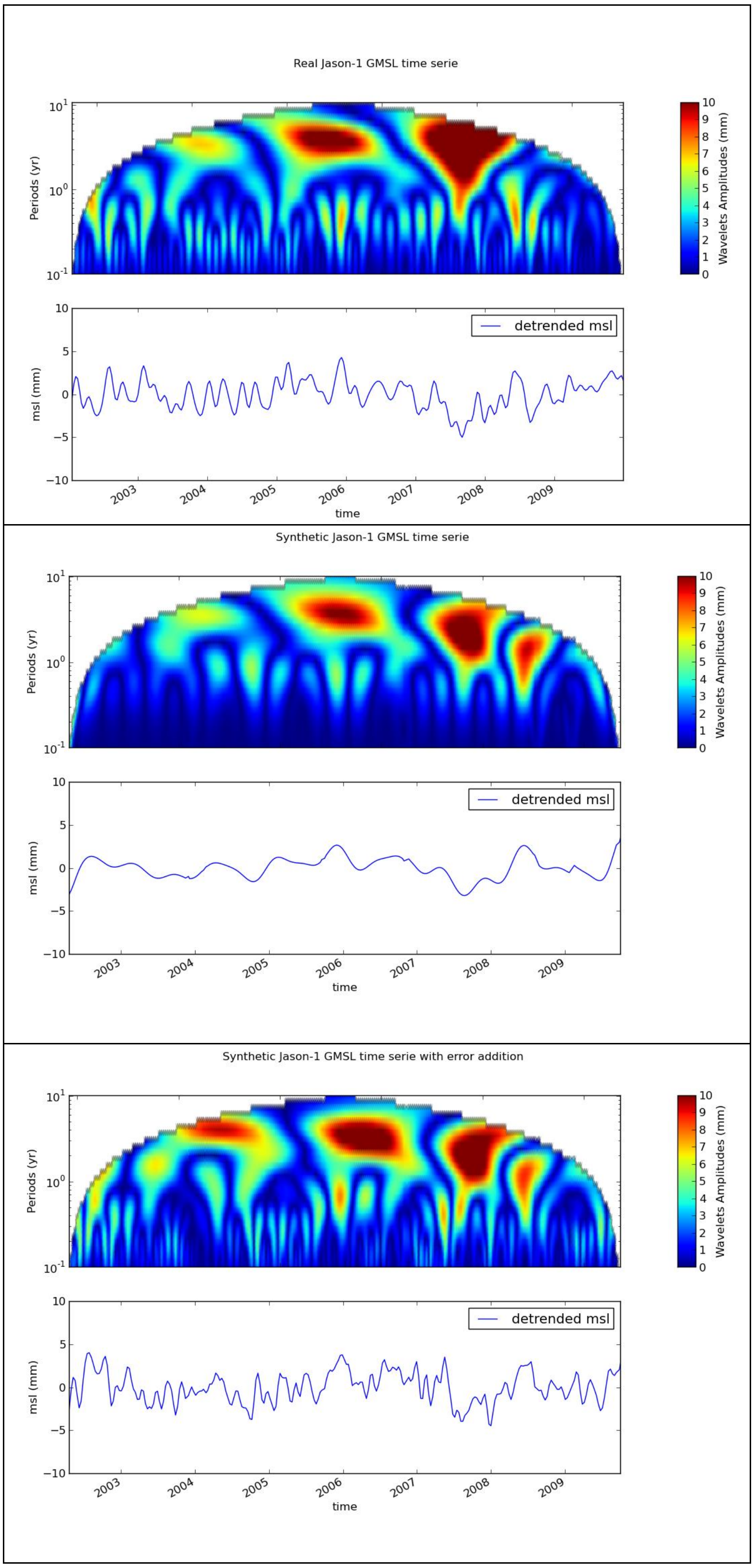
$$\boldsymbol{C} = \boldsymbol{\sigma}^2 * \boldsymbol{e}^{-\left(\frac{X}{L}\right)^2}$$

Eq 1: C is the covariance matrix, σ^2 the variance, X the time matrix and L the correlation period

The final correlated noise is the combination of this vector with the covariance matrix as in *Eq 2*. *nb: The square root of the covariance matrix is computed using a Jordan reduction.*

$$\boldsymbol{N_C} = \boldsymbol{v_N} * \boldsymbol{C^{1/2}}$$

Eq 2: Nc is the correlated noise, vn the white noise and C the covariance matrix



Real Jason-1 GMSL time serie

Synthetic Jason-1 GMSL time serie

Synthetic Jason-1 GMSL time serie with error addition

Figure 13: Addition of a correlated noise in the synthetic GLORYS-based Jason-1 GMSL. Top: Real Jason-1 GMSL filtered and adjusted time series. Middle: Synthetic Jason-1 GMSL filtered and adjusted time series. Bottom: Synthetic Jason-1 GMSL filtered and adjusted time series after high-frequency signal addition