COPAS Annual Report Sentinel-3A/B altimetry/tide gauges comparison

Copas eyes on our Ocean

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Change Log

Version	Date	Changes
1.0	April 24, 2024	First Draft
1.1	May 27, 2024	First Delivered Version
2.0	July 19, 2024	Second Delivered Version
2.1	August 26, 2024	Final version

Table of Content

List of Figures

Acronyms

DAC	Dynamic atmospheric correction.
FES	Finite element solution.
GC	GLOSS/Clivar.
GIA	Glacal isostatic adjustment.
GLOSS	Global sea level observing system.
LRM	Low Resolution Mode.
MSS	Mean sea surface.
NRT	Near real time.
NTC	Non time critical.
PDGS	Payload Data Ground Segment.
PLRM	Pseudo LRM.
PSMSL	Permannent service for mean sea level.
SAR	Synthetic aperture radar.
SARM	SAR Mode.
SSHA	Sea surface height anomaly.
STC	Short time critical.
TG	Tide gauge.
USO	Ultra stable oscillator.
VLM	Vertical land motion.

1 Introduction

This is the annual report on comparisons between ocean surface topography retrievals from Sentinel-3A and Sentinel-3B and tide gauge measurements for measures until the end of the year 2023. The work presented here was performed in the framework of the Mission Performance activities from COPAS (Copernicus Altimetry Service) project. It aims to complement the long-term stability analysis available in the NTC cyclic reports with a comparison with independent sea level measurements from tide gauges. Despite the limited precision of comparisons at individual stations (which are affected by high noise levels), averaging over a large tide gauge network reduces the noise and allows the identification and characterization of long-term drifts and/or discontinuities (or jumps) in altimetry-based sea level time series.

A particular focus was given this year to estimate the consistency of the method to compare altimetry and tide gauge data. The study was carried out on some parameters (described in **3**) and results are consistent with uncertainties given in **4**.

This report is structured in three main chapters:

- chapter **2** describes the datasets and the comparison method
- chapter **3** illustrates uncertainties associated with the method (colocation and interpolation),
- chapter **4** summarizes the main results regarding Sentinel-3 comparisons to tide gauges,

2 Data and methods

This chapter of the report describes the data and the method used to perform the comparisons between altimetry and tide gauges. Section 2.1. describes the in-situ and altimeter data used in the present analysis while section 2.2. provides an overview of the comparison methodology.

2.1. Data description

2.1.1. Tide gauges network

In-situ data coming from two distinct tide gauges networks are used in the present analysis:

- the GLOSS/Clivar core network retrieved from the legacy data portal maintained by the University of Hawaii (https://uhslc.soest.hawaii.edu/),
- the PSMSL network retrieved from the Permanent Service for Mean Sea Level (https://psmsl.org/)

The GLOSS/Clivar network provides hourly sea level data from approximately 300 stations (although data availability may vary over time). This network is designed to provide an evenly distributed sampling of the world's coastlines [2]. The PSMSL network is a more complete database, but only provides low frequency measurements (monthly averages) [4]. The geographical distribution of stations in the PSMSL network is uneven, with many more stations are available in the northern hemisphere than in the southern hemisphere.

Maps of in-situ stations locations for both networks are shown in Figure 1.

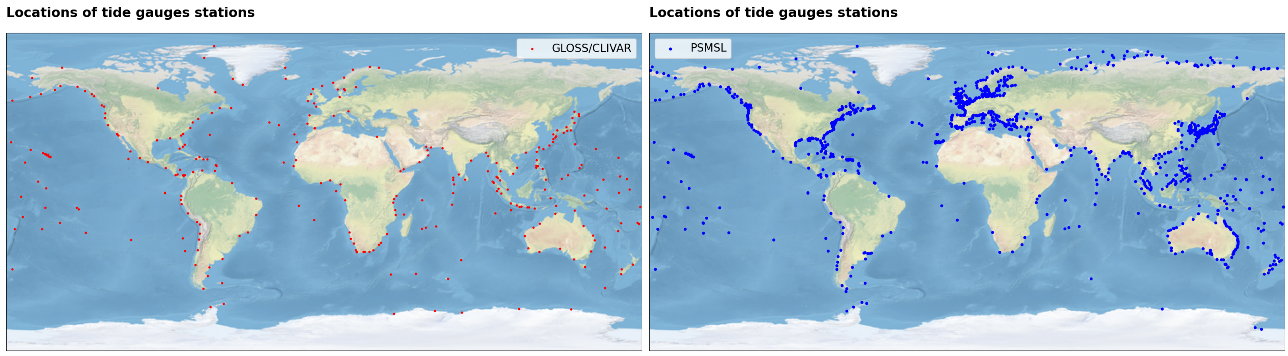

Figure 1 – Locations of tide gauges stations used in this analysis for the GLOSS/Clivar [left] and PSMSL [right] networks

2.1.2. Tide gauges pre-processing

Tide gauges measure sea level relative to a local datum. To obtain sea surface height measurements comparable to those obtained from altimetry, tide gauge measurements must be pre-processed to remove the following signals:

ocean tides as the name suggests, tide gauges were designed to measure tides with a high frequency sampling. Such signals are not observed by altimeters where tidal signals are aliased. On altimetry, tidal signals are removed using a tide model, and a similar tidal removal algorithm must be applied on tide gauges measurements,

- on GLOSS/Clivar hourly measurements a 71-hour Demerliac low-pass filter is applied to remove high frequency tidal effects;
- on PSMSL monthly means this is already applied prior to computing PSMSL monthly means and no further pre-processing is required;
- on both datasets (GLOSS/Clivar and PSMSL data) long-period ocean tides are corrected using the FES14b model [5], which is also used to correct altimetry data.

dynamical atmospheric correction atmospheric response to pressure (inverse barometer) and wind forcing are also corrected from in-situ measurements

- on GLOSS/Clivar hourly data we apply the high frequency (T<20 days) part of the outputs of the Mog2d model [3] plus static inverse barometer from ECMWF atmospheric pressure fields;
- on PSMSL since these are already monthly means, only the monthly average inverse barometer effect is applied.

Pole Tides This is a new correction added this year in tide gauge measurements. The same model as the one used to correct pole tides in official SSHA L2 marine products is used to correct tide gauge measures for pole tides.

vertical land motion tide gauges measure sea level relative to a local datum, any unknown vertical movement of this datum will impact measured sea level and bias the comparisons to altimetry. We account for the Glacial Isostatic Adjustment (GIA) part of these movements using a model (ICE5G/VM4 [7]).

Finally, high frequency tide gauge time series from stations of the GLOSS/Clivar network are filtered and resampled by averaging over one Sentinel-3 cycle window. Tide gauge time series defined on less than 80% of the altimetry period are discarded from the analysis.

2.1.3. Altimetry data

The Sentinel-3 data used in the present analysis are EUMETSAT-Marine Level-2 products. The current performance assessment (chapter 4) is based on the latest reprocessing campaign of the Sentinel-3A and Sentinel-3B missions, using processing baseline BC005.02 over the entire period.

The performances of official L2 marine product is assessed in this report: the SSHA field is the one available in those products. It is estimated following the classical equation:

$$SSHA = Orbit - Range - \sum Corrections - MSS \tag{1}$$

Only 1Hz altimetry measurements are used when comparing to tide gauges, all measurements are edited following the Cal/Val editing procedure which is described in NTC cyclic validation reports (available from https://user.eumetsat.int/resources/service-statuses/sentinel-3-altimetry-reports).

For each cycle, Sentinel-3 altimetry observations are averaged on a grid of 1° by 1° bins.

2.2. Altimetry versus tide gauges comparison method

The method used to compare tide gauge and altimetry observations follows the principles described in [8]. It consists of two main steps:

- Colocation of TG and altimetry measurements
- Estimation of TG-altimetry slope and uncertainty

2.2.1. Collocation and global bias estimaion

After pre-processing tide gauges and altimetry observations (see section 2.1.2.), the next step is to co-locate one altimetry time series at each tide gauge site. For each tide gauge, the colocated altimetry time series is the one with the highest correlation coefficient within a radius of 300 km around the tide gauge position. Further data selection criteria are applied to the most correlated altimetry time series:

- the correlation between altimetry and tide gauges should be greater than 0.7,
- the standard deviation of the differences between altimetry and tide gauge should be lower than 10 cm,
- the maximum difference between altimetry and tide gauge should be lower than 12 cm at each time step

This results in a set of colocated altimetry and tide gauges time series pairs. The time series of SSHA differences are computed for each pair and centered (mean removed). The global bias estimation is computed by averaging all centered SSHA differences time series.

2.2.2. TG/Altimetry uncertainty estimation

To estimate the drift between tide gauges and altimetry time series and its uncertainty, the comparison between TG and altimetry observations uses the uncertainty budget described in [1]. The uncertainty budget depends on the altimetry mission (and the geophysical standards used), on the in-situ network, and implicitly on the length of the time series. Specifically, the construction of the altimetry-TG uncertainty budget contains the following sources of errors:

Annual and sub-annual correlated errors the exact origins of these errors are unknown, they are directly estimated from altimetry-TG time series. We suspect TG and altimeter measurement errors and/or collocation errors of both datasets to significantly contribute to these errors. They are therefore dependent on the altimetry mission considered as well as the in-situ network used. The associated uncertainties are measured as the standard deviation of the altimetry-TG difference noise at the respective timescales (6-months and 1-year).

Inter-annual to decadal correlated errors The exact origins of these errors are unknown but they principally affect the TG data (i.e., TG networks averaging method, long-term stability of TG time series, etc.). The uncertainties have been estimated in [1] by taking the standard deviation of the altimetry-TG drift distribution for periods lengths of 3 and 10 years, divided by the square root of the number of independent tide gauges.

Drifts uncertainties correspond to the uncorrected vertical land motions (VLM) in the tide gauges data pre-processings. These uncertainties only depend on the in-situ network and are assumed to be non-correlated between tide gauges. The global trend uncertainty is $\sigma/\sqrt{N}$ where σ is the average VLM uncertainty for each TG and N is the number of tide gauges.

Table 2 provides a synthesis of the uncertainty budget used to estimate bias drift uncertainties for this report.

Time correlation	Network	Uncertainty at 1σ level [mm]	
		Sentinel-3A (SAR/PLRM)	Sentinel-3B (SAR/PLRM)
$\lambda = 6$ months	GC	2.4/2.6	3.5/3.0
	PSMSL	4.6/4.8	4.0/3.4
$\lambda = 1$ year	GC	0.9/0.9	0.9/0.9
	PSMSL	1.0/1.0	1.4/1.7
$\lambda = 3$ years	GC/PSMSL	1.0	
$\lambda = 10$ years	GC/PSMSL	1.0	
drift	GC/PSMSL	0.2 mm/yr	

Table 2 – Uncertainty budget for the estimation of GMSL drifts between altimetry and TG networks (GLOSS/Clivar and PSMSL). Value derived from estimations made in 2024 [1].

This year, a particular work was performed to assess the robustness and consistency of the method. Several sensitivity studies were carried out to test the impact of the colocation method and the number of available tide gauges on the regional and global comparison between altimetry and tide gauge data. Results of this study are summarized in **3**.

3 Uncertainty Budget of the comparison method

This section will focus on the sensitivity of the processing chain to different parameters :

- The method used to obtain tide gauges and altimetry colocated data,
- The method used to interpolate tide gauges data on altimetry location,
- The threshold applied on the altimetry / tide gauges correlation,
- The threshold applied on the standard deviation of differences between altimetry and tide gauges measurements,
- The number of available tide gauges in the global comparison.

The idea is to estimate how consistent are trends and associated uncertainties resulting from this processing chain of comparison between altimetry and tide gauges data.

The results presented in this section are obtained only with S3A SAR dataset and the GLOSS/Clivar TG network to simplify the first version of the sensitivity study.

3.1. Colocation and interpolation methods

The data selection from both measurement system (altimetry and TG) is the first step of this comparison. Both datasets need to be co-located and TG data need to be interpolated on altimetry positions.

Three colocation methods are implemented in the current processing chain :

- Best correlation from gridded altimetry data with respect to the TG data,
- Interpolation of gridded altimetry data on TG positions,
- Interpolation of along track altimetry data on TG positions.

Three TG interpolation methods are also implemented:

- Linear interpolation,
- Mean filter,
- Median filter.

The synthesis of results obtained with all those methods is presented in Figure 2.

The variability observed in relative trends between altimetry and TG data depends on the interpolation method of TG data on altimetry positions. It is illustrated through the standard deviation of trends obtained with different co-location methods with one interpolation method.

- Linear interpolation: standard deviation of $0.47\ mm.yr^{-1}$,
- Mean filter: standard deviation of $0.15\ mm.yr^{-1}$,
- Median filter: standard deviation of $0.25\ mm.yr^{-1}$.

Moreover, with one colocation method, there are disparities observed depending on the interpolation method: similar results are often obtained with mean and median filters, but a linear interpolation seems to give different results.

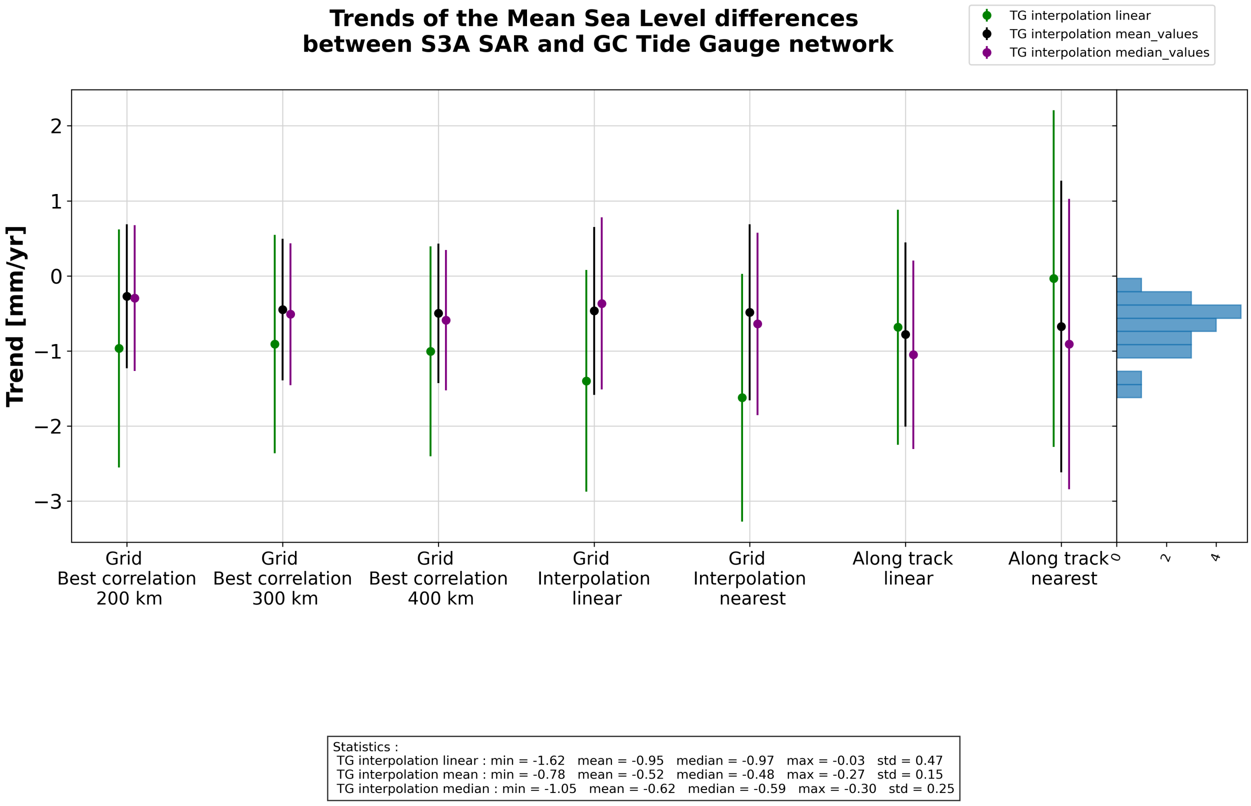

Figure 2 – Comparison S3A SAR with Gloss/Clivar : all colocation & interpolation methods

Differences in relative trends between altimetry and Tide Gauges are still in the 90% C.L. interval given by the estimated uncertainty budget.

3.2. Correlation Threshold

In this section, we will look at the sensitivity of the results (trend and associated uncertainty of differences between altimetry and Tide Gauges) to the threshold applied on the correlation between both time series.

Results of this study are summarized in Figure 3. The sensitivity of the trend is really low (standard deviation equal to $0.11\ mm.yr^{-1}$). A similar conclusion is obtained with associated uncertainties (standard deviation equal to $0.26\ .yr^{-1}$).

Trends and uncertainties are not significantly dependant to the threshold applied on the correlation between altimetry and tide gauge time series. However, the uncertainty is a little more sensitive to the correlation

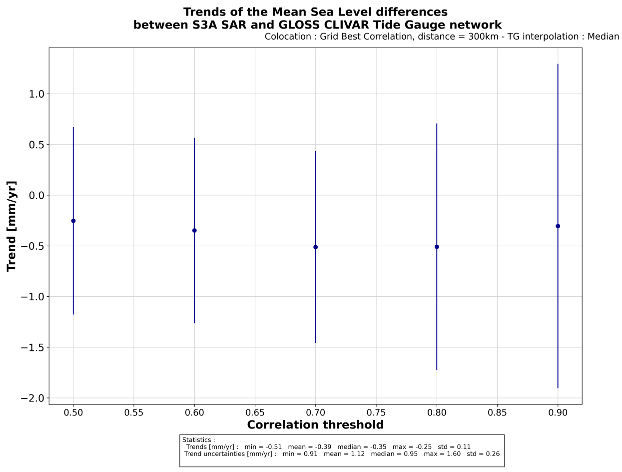

Figure 3 – Comparison S3A SAR with Gloss/Clivar : trends and associated uncertainty depending of the correlation threshold

threshold than the relative trend.

3.3. Standard Deviation of differences

Regarding the threshold applied on the standard deviation of differences between altimetry and tide gauge data, results are summarized in Figure 4.

Relative trends and associated uncertainties are not sensitive to this threshold. The standard deviations are equal to $0.05\ mm.yr^{-1}$ for trends and $0.00\ mm.yr^{-1}$ for associated uncertainties.

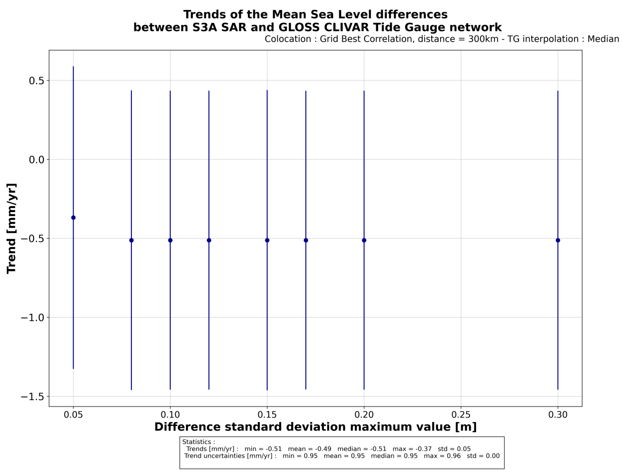

Figure 4 – Comparison S3A SAR with Gloss/Clivar : trends and associated uncertainty depending of the standard deviation of differences threshold

3.4. Number of Tide Gauges

Finally, we looked at the sensitivity of trends and associated uncertainties to the number of available Tide Gauges in the global comparison between altimetry and TG.

In this section, we performed a series of global comparison after removing at random 5% of available Tide Gauges and compute the relative trend and associated uncertainty of the global comparison.

Results are presented in Figure 5. The median values of trends and associated uncertainties obtained with those results match with the one obtained with the global comparison presented in Figure 7 (left).

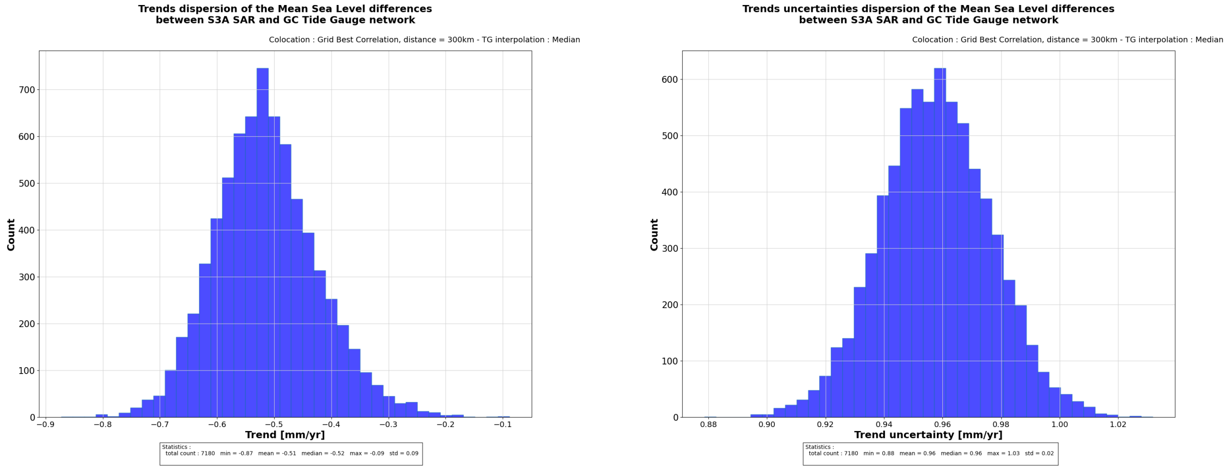

Figure 5 – Histogram of trends [left] and trend uncertainties [right] obtained by removing 5% of available Tide Gauges

The standard deviation obtained for trend uncertainties is equal to $0.02\ mm.yr^{-1}$.

The standard deviation obtained for trend values is equal to $0.09\ mm.yr^{-1}$ which is way below (one order of magnitude) the values of the uncertainties given by the global comparison.

Removing 5% of available Tide Gauges from the global comparison does not have a significant impact on the estimation of the trend or its associated uncertainty.

4 Stability assessment of Sentinel-3 versus tide gauges

In this chapter, we summarize the main results of the comparisons between Sentinel-3A/B altimetry measurements and tide gauges. Note that the latest version of Sentinel-3 data is used. Figure 6 illustrates the total number of tide gauges available (with both GLOSS/Clivar and PSMSL networks) in bright colors, and the number of tide gauges used in the global comparison (after selection with criteria presented in 2.2.1.).

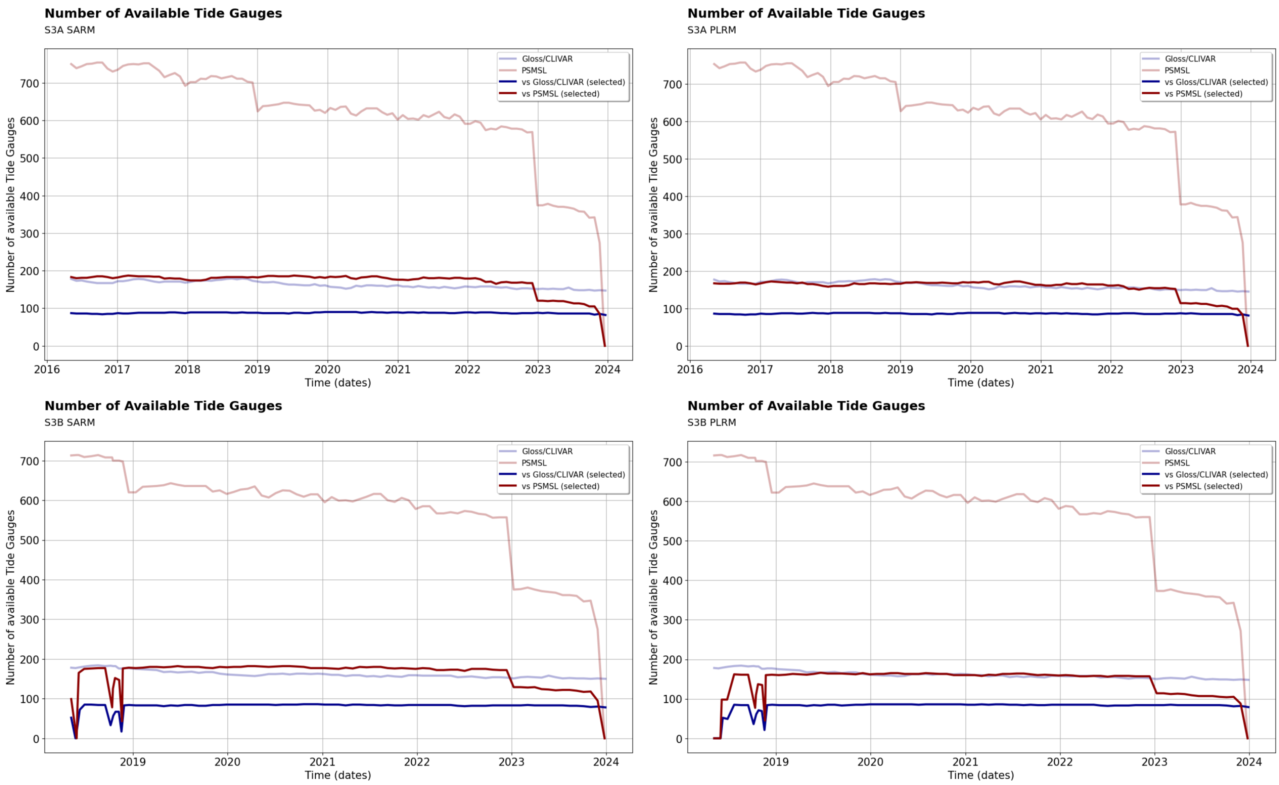

Figure 6 – Number of tide gauges used in the comparison with Sentinel-3A (up) Sentinel-3B (down) for the SARM (left) and PLRM (right) networks

4.1. Sentinel-3A

The global mean bias of Sentinel-3A with respect to tide gauges is shown on figure 7 for the SARM and figure 8 for PLRM. On those figures, dashed lines show the raw time series of compared data and solid lines show a 6-months filtered time series.

The Sentinel-3A drift relative to GLOSS/Clivar tide gauges is $-0.6\ mm.yr^{-1}$ in SARM and $-0.3\ mm.yr^{-1}$ in PLRM within a $\pm 0.9\ mm.yr^{-1}$ confidence interval ($90\% C.L.$) for both modes. For PSMSL tide gauges, the estimated drift is $0.1\ mm.yr^{-1}$ for both modes within a $1.4\ mm.yr^{-1}$ (in SARM) and $1.5\ mm.yr^{-1}$ (in PLRM) confidence interval ($90\% C.L.$).

No significant drift of Sentinel-3A is observed when comparing to tide gauges.

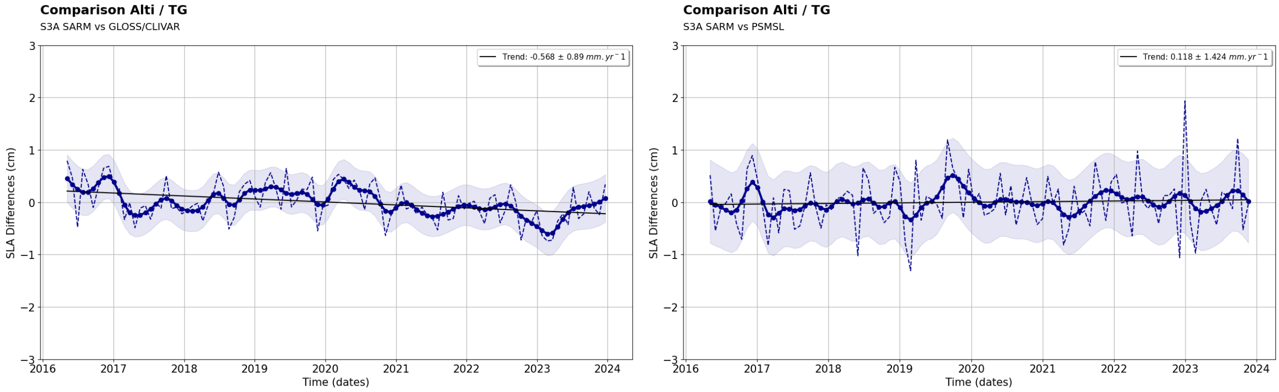

Figure 7 – Global bias between Sentinel-3A SARM and tide gauges for GLOSS/Clivar [left] and PSMSL [right] networks

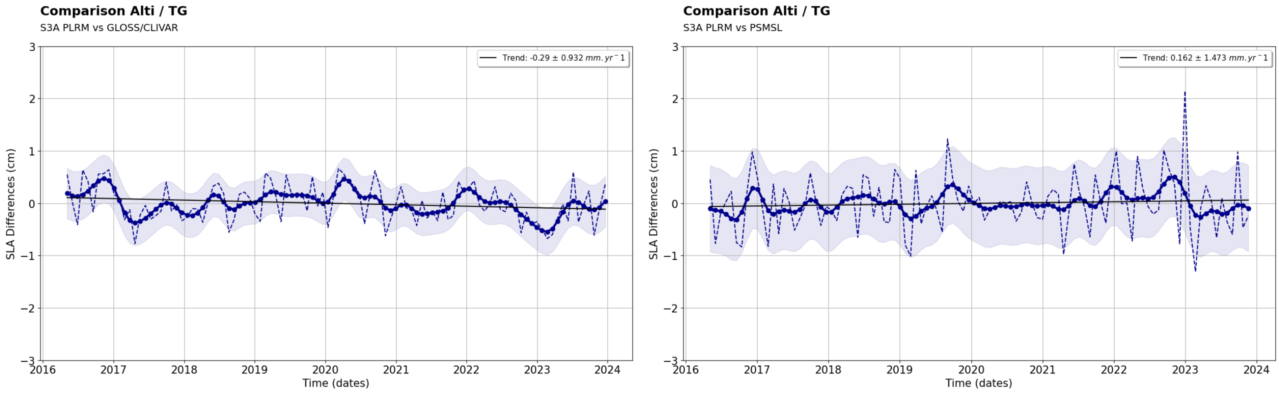

Figure 8 – Global bias between Sentinel-3A PLRM and tide gauges for GLOSS/Clivar [left] and PSMSL [right] networks

4.2. Sentinel-3B

The global mean bias of Sentinel-3B with respect to tide gauges is shown on figure 9 for SARM and figure 10 for PLRM. Note that for Sentinel-3B all estimated uncertainties are higher than for Sentinel-3A due to the shorter time series.

The Sentinel-3B drift relative to GLOSS/Clivar tide gauges $-0.7\ mm.yr^{-1}$ for both modes within a $1.6\ mm.yr^{-1}$ (in SARM) and $1.4\ mm.yr^{-1}$ (in PLRM) confidence interval ($90\%C.L.$). When comparing to PSMSL tide gauges, estimated Sentinel-3B drifts are $0.7\ mm.yr^{-1}$ in SARM and $1.1\ mm.yr^{-1}$ in PLRM within a $1.9\ mm.yr^{-1}$ (in SARM) and $1.7\ mm.yr^{-1}$ (in PLRM) confidence interval ($90\%C.L.$).

As for Sentinel-3A, no significant drift of Sentinel-3B is observed when comparing to tide gauges.

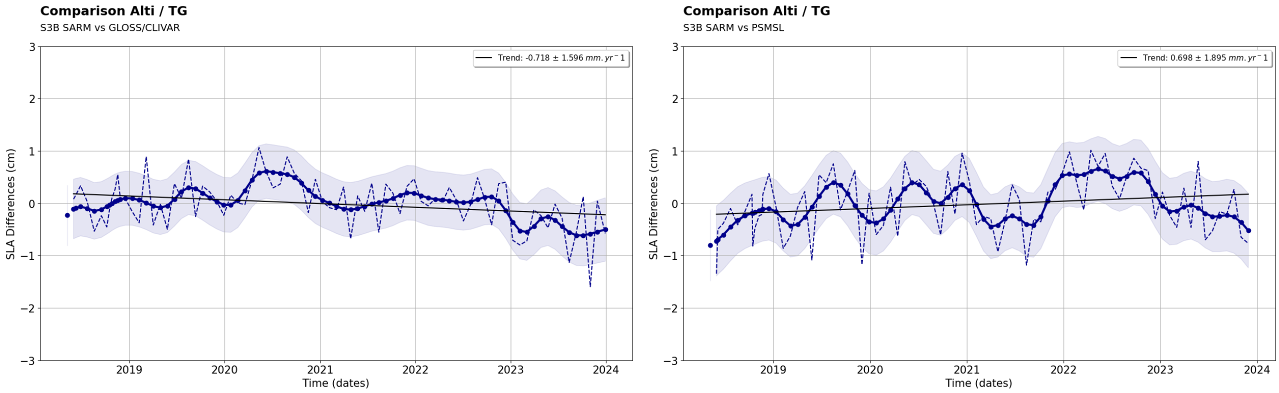

Figure 9 – Global bias between Sentinel-3B SARM and tide gauges for GLOSS/Clivar [left] and PSMSL [right] networks

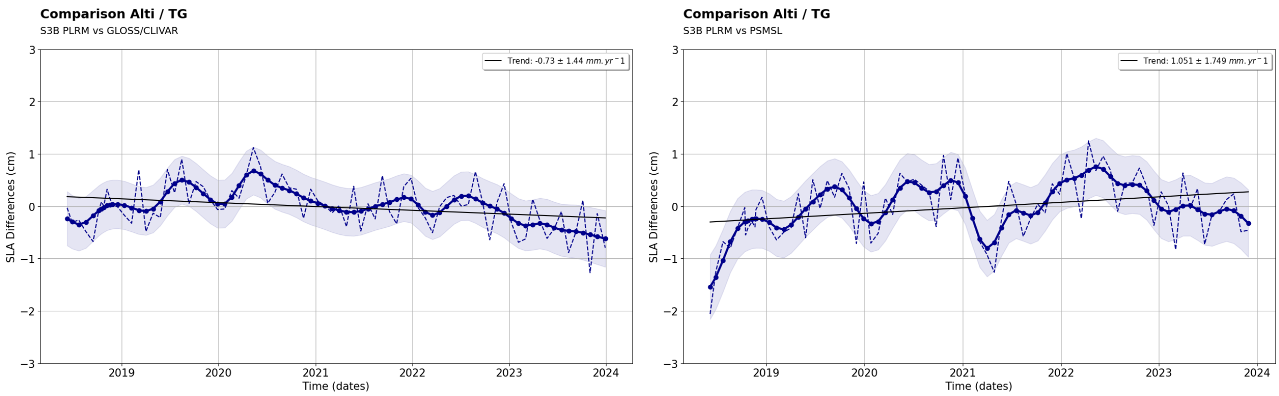

Figure 10 – Global bias between Sentinel-3B PLRM and tide gauges for GLOSS/Clivar [left] and PSMSL [right] networks

5 Conclusions

Tide gauges provide an independent measurement of sea surface height. Many stations provide high quality, uninterrupted records. This is extremely valuable for the verification of the long-term stability of satellite altimetry records.

In this report we assessed the stability of Sentinel-3A and Sentinel-3B missions with respect to two networks of tide gauges: Gloss/CLIVAR and PSMSL. *We show that until 2023 December, no significant drift (90% C.L.) of Sentinel-3A or Sentinel-3B can be detected with respect to tide gauges, either for SARM or PLRM data.* Bias drift estimates are summarized below:

	Sentinel-3A		Sentinel-3B	
	SARM	PLRM	SARM	PLRM
GLOSS/Clivar	-0.9 $\pm$ 1.5	-0.8 $\pm$ 1.5	0.0 $\pm$ 1.9	-0.1 $\pm$ 1.9
PSMSL	0.1 $\pm$ 1.4	0.5 $\pm$ 1.4	1.1 $\pm$ 1.9	1.1 $\pm$ 1.6

Table 3 – bias drifts estimate for Sentinel-3A and Sentinel-3B SARM and PLRM data for comparisons with GLOSS/Clivar and PSMSL networks (in mm/yr)

We also document (chapter **3**) how choices made in the comparison method between Altimetry and Tide Gauges induce modifications in final results (trend and associated uncertainty).

Uncertainty levels associated with comparisons between altimetry and tide gauges remain high, especially for short periods. Such uncertainties have different origins:

- altimetry/tide gauge colocation,
- stability of tide gauge datums,
- residual tidal or DAC errors in coastal altimetry,

All of which contribute to the final uncertainty estimates. Over recent years, many tide gauges have been equipped with GPS beacons. GPS measurements will provide better datum stability for tide gauge data, thus reducing the uncertainty of such comparisons. New co-location methods should also be investigated, in order to reduce local high-frequency discrepancies between altimetry and tide gauges. That would also contribute to lowering uncertainty levels, which is crucial to verify that altimetry reaches recently updated scientific stability requirements [6].

References

[1] M Ablain, N Taburet, L Zawadzki, R Jugier, and M Vayre. Salp annual report (2017) of mean sea level activities, 2018. URL https://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/SALP-RP-MA-EA-23189-CLS_AnnualReport_2017_MSL.pdf.

[2] Patrick C. Caldwell, Mark A. Merrifield, and Philip R. Thompson. Sea level measured by tide gauges from global oceans as part of the joint archive for sea level (jasl) since 1846, 2001. URL https://www.ncei.noaa.gov/archive/accession/JIMAR-JASL.

[3] L. Carrère and F. Lyard. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations. *Geophysical Research Letters*, 30(6), 2003. doi: https://doi.org/10.1029/2002GL016473. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002GL016473.

[4] Simon J. Holgate, Andrew Matthews, Philip L. Woodworth, Lesley J. Rickards, Mark E. Tamisiea, Elizabeth Bradshaw, Peter R. Foden, Kathleen M. Gordon, Svetlana Jevrejeva, and Jeff Pugh. New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, 29(3): 493, 2013. doi: 10.2112/jcoastres-d-12-00175.1. URL https://doi.org/10.2112/jcoastres-d-12-00175.1.

[5] F. H. Lyard, D. J. Allain, M. Cancet, L. Carrère, and N. Picot. Fes2014 global ocean tide atlas: design and performance. *Ocean Science*, 17(3):615–649, 2021. doi: 10.5194/os-17-615-2021. URL https://os.copernicus.org/articles/17/615/2021/.

[6] Benoit Meyssignac, Michael Ablain, Adrien Guérou, Pierre Prandi, Anne Barnoud, Alejandro Blazquez, Sébastien Fourest, Victor Rousseau, Pascal Bonnefond, Anny Cazenave, Jonathan Chenal, Gerald Dibarboure, Craig Donlon, Jérôme Benveniste, Annick Sylvestre-Baron, and Nadya Vinogradova. How accurate is accurate enough for measuring sea-level rise and variability. *Nature Climate Change*, 13(8):796–803, August 2023. doi: 10.1038/s41558-023-01735-z. URL https://doi.org/10.1038/s41558-023-01735-z.

[7] W.R. Peltier. GLOBAL GLACIAL ISOSTASY AND THE SURFACE OF THE ICE-AGE EARTH: The ICE-5g (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, 32(1):111–149, May 2004. doi: 10.1146/annurev.earth.32.082503.144359. URL https://doi.org/10.1146/annurev.earth.32.082503.144359.

[8] G. Valladeau, J.-F. Legeais, M. Ablain, S. Guinehut, and N. Picot. Comparing altimetry with tide gauges and argo profiling floats for data quality assessment and mean sea level studies. *Marine Geodesy*, 35 (sup1):42–60, 2012. doi: 10.1080/01490419.2012.718226.