Copernicus Climate Change Service

Product Quality Assessment Report (PQAR)

Sea Level
Version vDT2024

Issued by: CLS/Françoise Mertz, Maxime Ballarotta

Date: 03/03/2025

Ref: C3S2_D312b-WP2-FDDP-SL-V3.0-202411-PQAR-of-vDT2024-v1.1

Official reference number service contract: 2022/C3S2_312b_MOi/SC1

Contributors

CLS

Françoise Mertz

Maxime Ballarotta

Victor Quet

History of document modifications

Version	Date	Description of modification	Chapters / Sections
V1.0	15/11/2024	Creation of document describing the validation of the vDT2024 dataset	all
V1.1	03/03/2025	Document revised in line with recommendations by independent review, and finalised for publication.	all

List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
SL-V3.0	Sea Level measured by Altimetry and derived variables – daily dataset	CDR	DT2024	202411
SL-V3.0	Sea Level measured by Altimetry and derived variables – monthly dataset	CDR	DT2024	202411

Related documents

Reference ID	Document
C3S_ATBD	Mertz F., Mambert P., Lefèvre, F. (2025) C3S Sea Level Version vDT2024: Algorithm Theoretical Basis Document, E.U. Copernicus Climate Change Service, Document ref. D312b-WP2-FDDP-SL-v3.0-202411-ATBD-of-vDT2024-v1
C3S_PQAD	Mertz F., Lefèvre, F. (2024) C3S Seal Level Version DT2024: Product Quality Assurance Document. E.U. Copernicus Climate Change Service. Document ref. C3S2-D312b-WP1-PDDP-SL-v3.0-202406-PQAD-of-vDT2024-v1.1_Final
C3S_TRD	Mertz, F., Taburet G., Ghantous M., Lefèvre F. (2025) C3S Sea level, Version vDT2024: Target Requirements and Gap Analysis Document. Issue 2.1. E.U. Copernicus Climate Change Service. Document ref. C3S2-D312b-WP3-TRGAD-2024-SL-v3.0-202411-v3.1
C3S_PQAR_2021	Taburet G., Legeais, J-F., Lefèvre, F., Ghantous, M., Meyssignac, B. LLovel, W. (2023) C3S Sea level, Version DT2021: Product Quality Assessment Report. E.U. Copernicus Climate Change Service. Document ref. WP2-FDDP-2022-09_C3S2-Lot3_PQAR-ofvDT2021-SeaLevel-products_v1.2

Acronyms

Acronym	Definition
ADT	Absolute Dynamic Topography
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CDR	Climate Data Record
CMEMS	Copernicus Marine Monitoring Environment Service
CNES	Centre National des Etudes Spatiales
DHA	Dynamic Height Anomaly from *in situ* T/S profiles
DUACS	Data Unification And Combination System
vDT2021/ DT2024	DUACS Delayed-Time reprocessed sea level products version DT2021 (previous version of the C3S products) and DT2024 (currently distributed by C3S)
EAN	Estimated Accuracy Numbers
ECV	Essential Climate Variable
ESA	European Space Agency
GDR	Geophysical Data Record
GIA	Glacial Isostatic Adjustment
GRACE	Gravity Recovery And Climate Experiment
ICDR	Intermediate Climate Data Record
ITRF	International Terrestrial Reference Frame – the geodetic reference frame used to provide precisely measured parameters concerning Earth’s surface and motion.
MDT	Mean Dynamic Topography
MSL	Mean Sea Level
MSS	Mean Sea Surface
OSR	Copernicus Marine Service Ocean State Report
PSMSL	Permanent Service for Mean Sea Level
SALP	Service d’Altimétrie et de Localisation Précise from CNES
SLA	Sea Level Anomaly
SSH	Sea Surface Height
TP	Topex/Poseidon

General definitions

Sea Level	Level of the sea surface
Sea Level Anomaly	Anomaly of sea level compared to a mean sea level
Climate Data Record	Climate Data Records (CDRs) are robust, sustainable, and scientifically sound climate records that provide trustworthy information on how, where, and to what extent the land, oceans, atmosphere and ice sheets are changing.
Fundamental Climate Data Records	Long-term data record of calibrated and quality-controlled data designed to allow the generation of homogeneous products that are accurate and stable enough for climate monitoring.
Interim Climate Data Record	A temporal extension to the CDR for more recent data, using the baselined CDR algorithm and processing environment but whose consistency and continuity have not been verified.
DUACS	Data Unification and Altimeter Combination System: operational multi-mission production system of altimeter data developed by CNES/CLS.
Level 1 data	These data are timestamped and geographically located, and are also expressed in the appropriate units, and checked for quality.
Level 2 data	These data are corrected for instrument errors and errors due to atmospheric signal propagation and perturbations caused by surface reflection. Geophysical corrections are then applied (solid earth, ocean and pole tides, etc.).
Level 3 data	These data are validated (bad or spurious data are removed from the records), cross-calibrated (i.e. calibrated to a reference mission), along-track data.
Level 4 data	These are multi-satellite (cross-calibrated), gridded data

Table of Contents

Scope of the document

This Product Quality Assessment Report (PQAR) contains the results from the quality assessment described in the Product Quality Assurance Document [C3S_PQAD] for the Sea Level products version DT2024 (vDT2024). These products include daily maps of both observed sea level and derived geostrophic currents and monthly maps of observed sea level and derived eddy kinetic energy, and are produced by CLS from instruments onboard altimetry satellites.

Executive summary

The quality of the delayed-time C3S sea level products produced by the Data Unification and Altimeter Combination System known as DUACS (version DT2024) has been assessed by comparison with independent measurements (*in situ* and satellite) and in coordination with other projects (CNES SALP and Copernicus Marine Service). The altimeter standards have been specially defined for the production of the C3S sea level CDR. The DUACS vDT2024 sea level products are the latest version delivered.

The main results of the validation are:

1. **Sea Level Anomalies (SLA) and Absolute Dynamic Topography (ADT)**:
    - **Long-term sea level trend** - This can be monitored with the C3S products. The uncertainty of the mean sea level trend over the global ocean has been estimated to be of the order of 0.4 mm/yr (Ablain et al., 2019). On a regional scale, the averaged local sea level trend uncertainty related to the instrumental observing system only has been estimated at 0.83 mm/yr with values ranging from 0.78 to 1.22 mm/yr (the uncertainty related to the natural ocean variability has to be added; Prandi et al., 2021).
    - **Sea level errors for mesoscale signals -** In the C3S products, these errors vary between 1 cm² in low variability areas to 20.89 cm² in high variability areas. Wavelengths accessible with gridded products are larger than ~200 km.
    - **Along-track Sea Level Anomalies (SLA) and Absolute Dynamic Topography (ADT) -** The SLA and ADT fields also include uncorrelated residual noise measurement errors that are spatially and temporally variable. They are correlated with wave height, though differ from one altimeter to another. Characteristic mean noise values over the global ocean vary between 2-4 cm rms for raw measurements and 0.7-2.3 cm for filtered products. The presence of this measurement noise limits the observability of wavelengths shorter than ~65km (global mean value for the L3 along-track data).

2. **Geostrophic currents:**
    Geostrophic currents derived from altimeter gridded products are usually underestimated when compared to *in situ* observations. Errors on geostrophic currents have been estimated to range between 11 and 17 cm/s depending on the ocean surface variability.

3. **Estimated Accuracy Numbers:**
   The Estimated Accuracy Numbers (EAN) are representative of the signatures of different error signals in the products, including both uncorrelated (i.e. noise) and correlated (spatial and temporal scales) error signals and are examined through looking at measurement noise, mesoscale errors, geostrophic current errors, observable wavelength errors and Mean Sea Level errors at climate scales. These EANs are specific to the DUACS vDT2024 altimeter products and are described in this document. Overall:
    - The GMSL record now achieves stability performances of ±0.3 mm/yr at the 90 % confidence level (C. L.) for its trend and ±0.05 mm/yr^2 (90 %C. L.) for its acceleration over the 29-years of the altimetry record.
    - The radiometer Wet Troposphere Correction (WTC) and the high-frequency errors with timescales shorter than 1-year are the major contributors to the GMSL uncertainty over periods of 10-years (30–70 %), both for the trend and acceleration estimations.
    - For longer periods of 20-years, the Topex/Poseidon (TP) data quality is still a limitation but more interestingly, the International Terrestrial Reference Frame (ITRF) realisation uncertainties become dominant over all the others sources of uncertainty.

This document is structured as follows - Section 1 lists the products involved in the quality assessment. Section 2 describes the validation results obtained with the approach described in the [C3S_PQAD]. This includes the comparison of the altimeter data with independent measurements (derived from *in situ* instruments and other altimeter missions), along with more in-depth information on the EANs. The objective is to provide a first estimate of the errors of the products and the associated uncertainties distinguishing different spatial and temporal scales. Section 3 provides additional validation approaches. In addition to the systematically performed validation, the assessment of the DUACS sea level products is also complemented by specific studies in coordination with other projects (e.g. Copernicus Marine Service, CNES SALP) that aim to characterize the errors for specific fields, wavelengths and timescales. This includes the reference to past studies that have contributed to improve the characterization of errors, and the description of the global and regional Mean Sea Level (MSL) trends. Section 4, the compliance of the validation results with user requirements is discussed.

1. Product validation methodology

This Product Quality Assessment Report applies to the C3S sea level vDT2024 product. This includes the full reprocessing of the sea level Climate Data Record (C3S vDT2024 CDR), produced with the DUACS version vDT2024 of the production system.

The gridded sea level product is produced for the global ocean and includes several ocean variables:

- The Sea Level Anomalies (SLA)
- The geostrophic velocities derived from the SLA
- The Absolute Dynamic Topography (ADT)
- The absolute geostrophic velocities derived from the ADT

The validation results are mainly presented for the SLA since the other variables are directly derived from the SLA (calculating the gradient of the SLA to produce the velocities and adding the static Mean Dynamic Topography (MDT) to produce the ADT).

A full description of the validation methodology is described in the Product Quality Assurance Document [C3S_PQAD].

2. Validation results

2.1 Summary of the developments in the C3S vDT2024 sea level products

The C3S vDT2024 sea level CDR has benefited from several developments since the previous version. They include the new L2P vDT2024 altimeter standards following expert recommendations (Kocha et al., 2023).

2.2 Internal validation and Quality Control

Numerous processing steps are required to produce the gridded sea level maps from the level 2 along-track measurements. They are described in detail in the Algorithm Theoretical Basis Document [C3S_ATBD]. Each processing step is followed by dedicated validation and quality control analyses. The metrics used are described in the Product Quality Assurance Document [C3S_PQAD]. The results of this internal validation are compiled into dedicated reports which are analysed by altimetry experts for each ICDR production (temporal extension of the sea level record) and for the CDR production (full reprocessing of the time series). These reports are for internal use and are not distributed. Many diagnoses are calculated about editing, monitoring of along-track (L3) mean SLA with and without orbit error for each mission, monitoring of gridded (L4) mean SLA, etc. Some examples are shown in Figure 1 (the percentage of points per pass rejected by the editing process over time) and in Figure 2 (daily mean of L3 SLA for each mission over time).

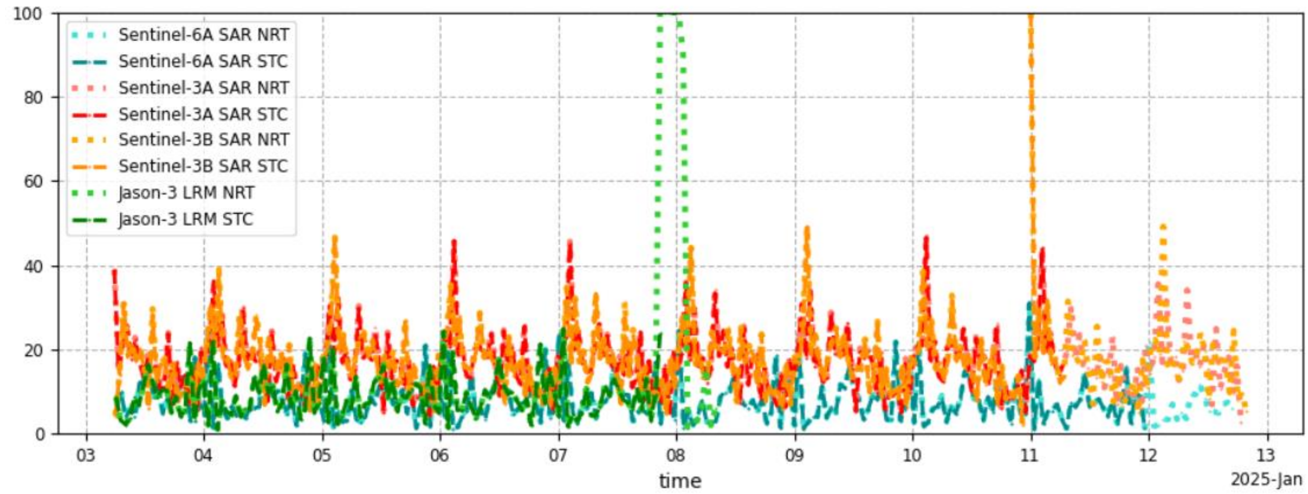


Figure 1: Percentage of rejected points for L2P over ocean by satellite half-orbit. For C3S, only Short Time Critical (STC) datasets are used.

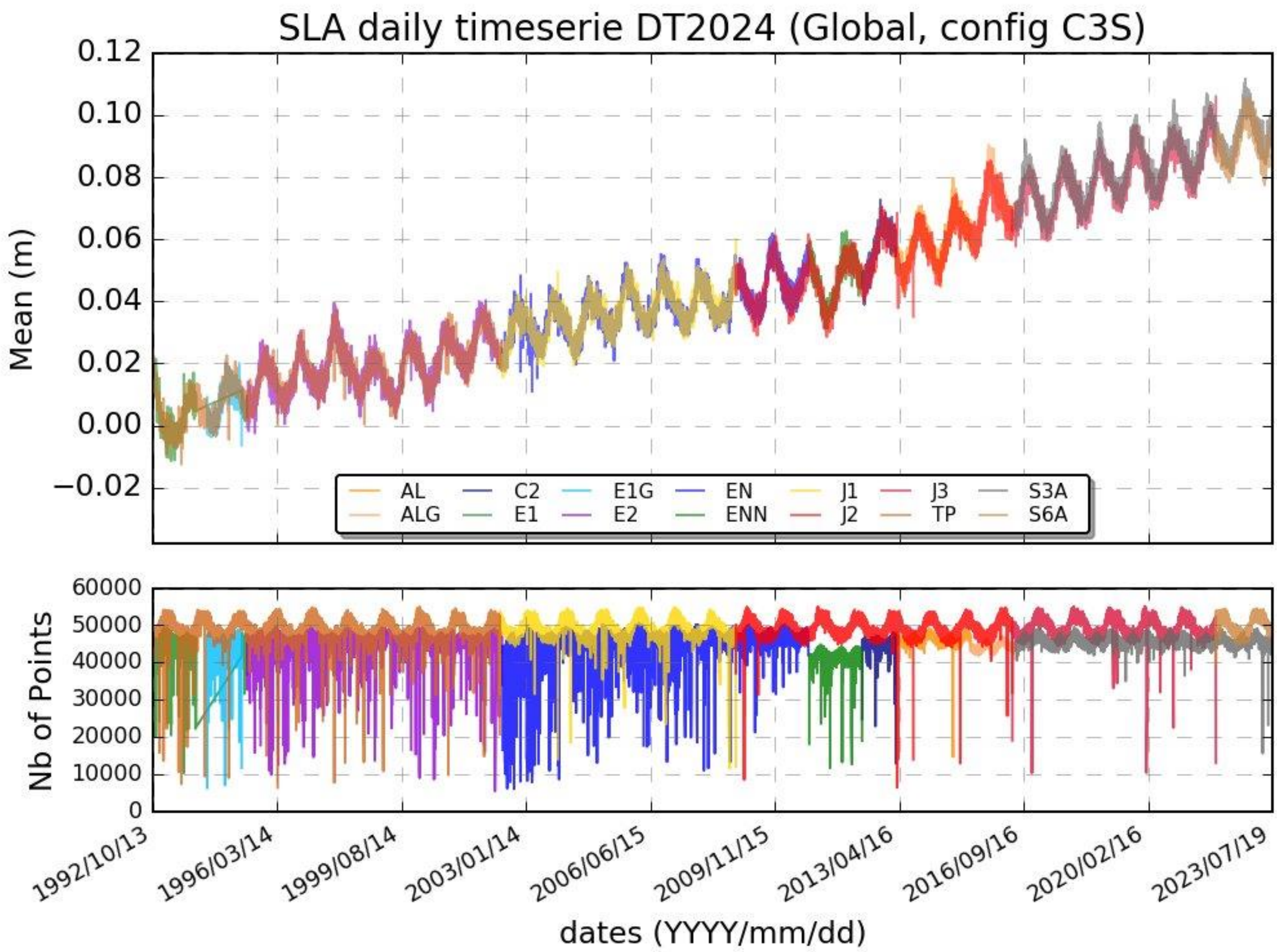


Figure 2: Means of Sea Level Anomaly (SLA) for each mission per day (days for which the number of points exceeds 500) in cm with the number of points.

2.3 Sea Surface Heights from tide gauges

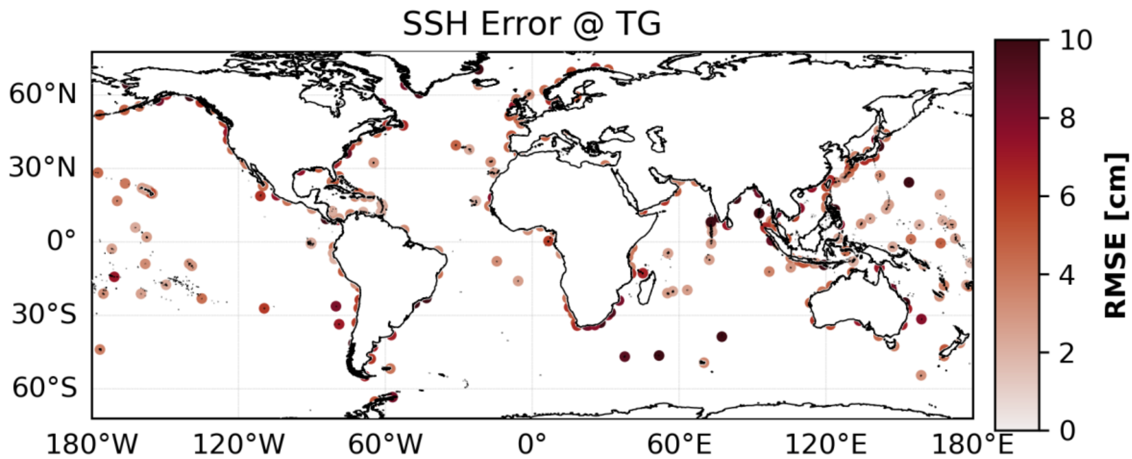
Tide Gauges (TG) from the GLOSS/CLIVAR[1] have been used for SLA gridded products validation over the Global Ocean and for the period 1993-2020. The sea surface height measured by the tide gauges is compared to the daily mean SLA field given by gridded altimeter products (the method is described in [C3S_PQAD]).

2.3.1 Variance

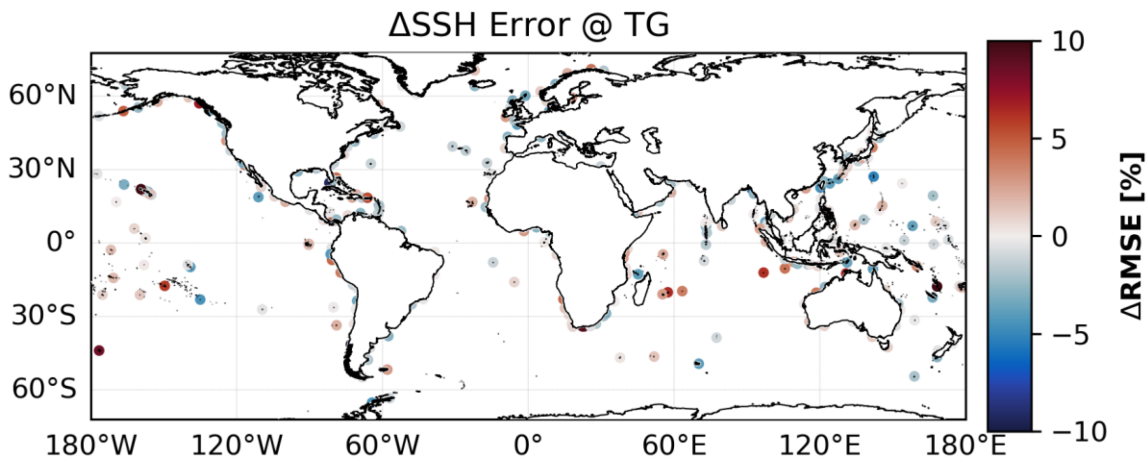
Figure 3 presents the RMS of the difference between the vDT2024 sea level anomaly gridded product and an independent TG dataset. It also illustrates the inhomogeneity of the SLA gridded product error in coastal areas. The SLA gridded product errors vary between ~1 cm to more than 10 cm. The comparison of altimeter SLA and independent TG measurement shows improved results when the altimeter product vDT2024 version is considered rather than the previous one (vDT2021) (Figure 3b). The Root Mean Square Error (RMSE) between altimetry and TG is especially reduced along part of the European and Japanese coasts. In those regions, the reduction in the variance of the differences between altimetry and TGs ranges between 0.2% to more than 5% of the TG signal. In some other

[1] https://gloss-sealevel.org [last access 2024/11/07]

coastal areas, degradation is however observed. This is the case in the south Pacific Ocean and Indian Ocean. Nevertheless, these degradations are observed for stations where the differences between altimetry and TG reaches less than 1% of the TG signal.



A



B

Figure 3: Panel A - RMS of the difference between global gridded DUACS vDT2024 sea level anomaly and independent tide gauge measurements over the period 1993 to 2020 (units: cm); Panel B - difference of RMSE between vDT2024 and vDT2021 global C3S gridded products. Negative values (i.e., blue colour) indicates a reduction of error in vDT2024 products.

2.3.2 Detection of drift

The stability of the C3S sea level CDR vDT2024 can be further estimated by comparison with the *in situ* tide gauges. The trend of the difference is estimated over the total altimeter period (Figure 4) and amounts to -0.13 mm/yr (GIA corrected). Given the uncertainty associated with the method of comparison, this value cannot be distinguished from 0 mm/yr and no drift is found in the altimeter record over the 30 year period. Note that the C3S vDT2024 products are not corrected for the TOPEX-A instrumental drift (see section 3.2).

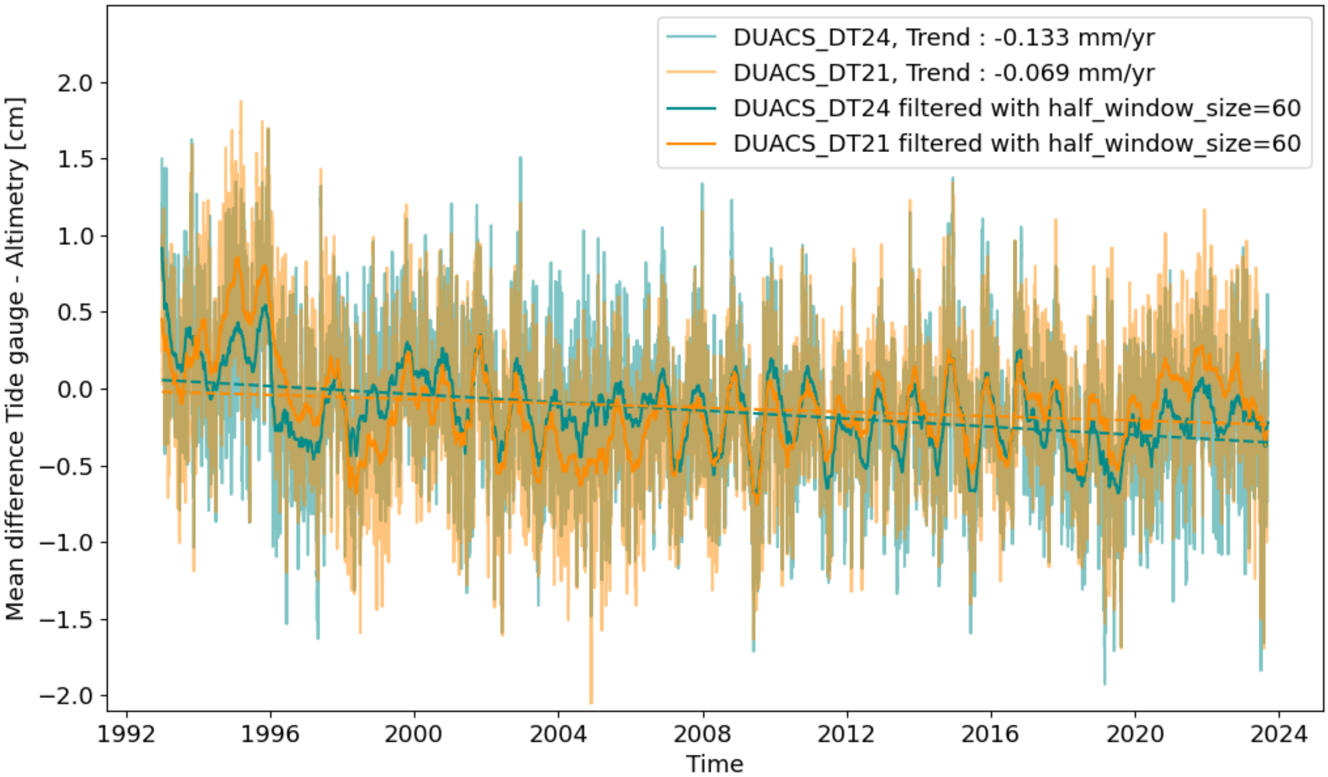
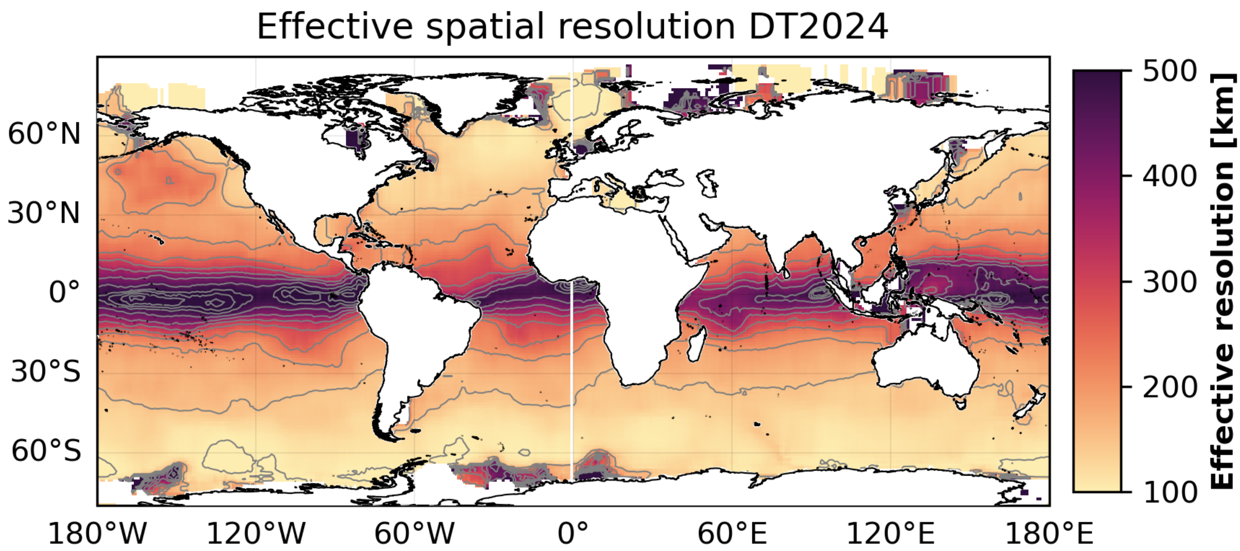


Figure 4: Mean SLA differences between the tide gauges and the C3S sea level CDR vDT2021 (yellow curve) and between the tide gauges and the C3S sea level CDR vDT2024 (blue curve) during the total common period of the sea level record (1993 – 2023) and with 60 days filtered curves. The trend of the differences has been adjusted over the entire period.

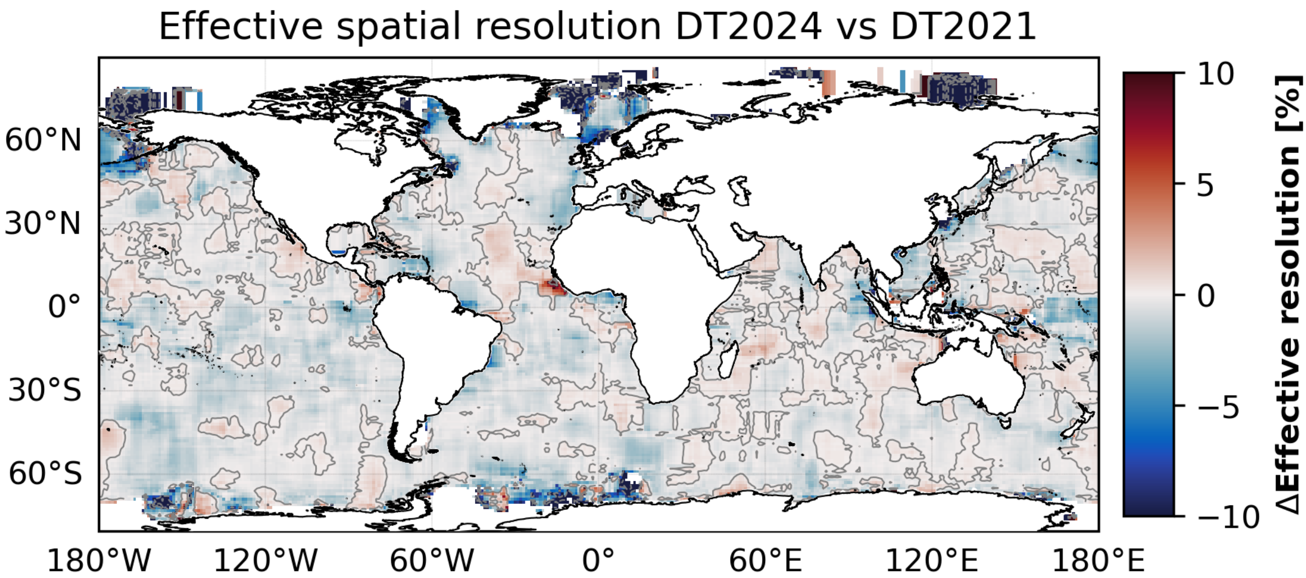
2.4 Effective resolution

The errors observed at mesoscales also highlight the L4 product spatial resolution capability. As discussed in Pujol et al. (2016), the effective resolution of the SLA gridded product is constrained by the altimeter sampling capability and mapping methodology used. In order to estimate the spatial resolution of the gridded products, an evaluation has been carried out based on a spectral approach. A full description of this approach can be found in Ballarotta et al. (2019).

Figure 5 (panel A) shows the global map of the effective spatial resolution of the vDT2024 global maps computed over the period from 2018-01-01 to 2018-12-31, where Saral/AltiKa data were used as an independent dataset. The resulting mean spatial resolution of the global gridded SLA is about 200 km at mid-latitudes. The Observable wavelength increases in the equatorial band to reach ~500 km. The comparison with the spectral content computed from full-resolution Saral/AltiKa 1 Hz along-track measurements (not reported here) shows that a large part of the energy observed in along-track measurements at wavelengths ranging from 200 to 65 km is missing in the SLA gridded products. The loss reaches nearly -40% at wavelength of 200 km and rapidly increases at shorter wavelengths. Overall, the vDT2024 SLA gridded C3S products have a similar resolution to the previous vDT2021 C3S products.



A



B

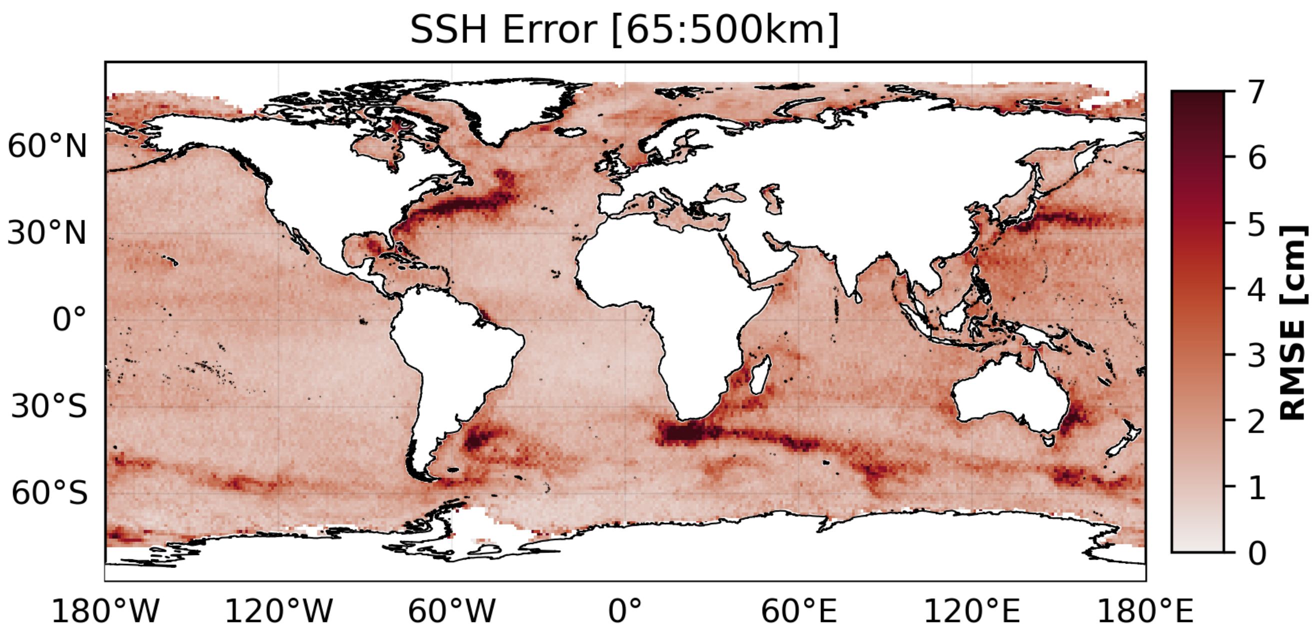
Figure 5: Effective spatial resolution (in km; Panel A) and gain / loss of effective resolution between vDT2024 and vDT2021 products (Panel B).

2.5 Independent altimeter along-track measurements

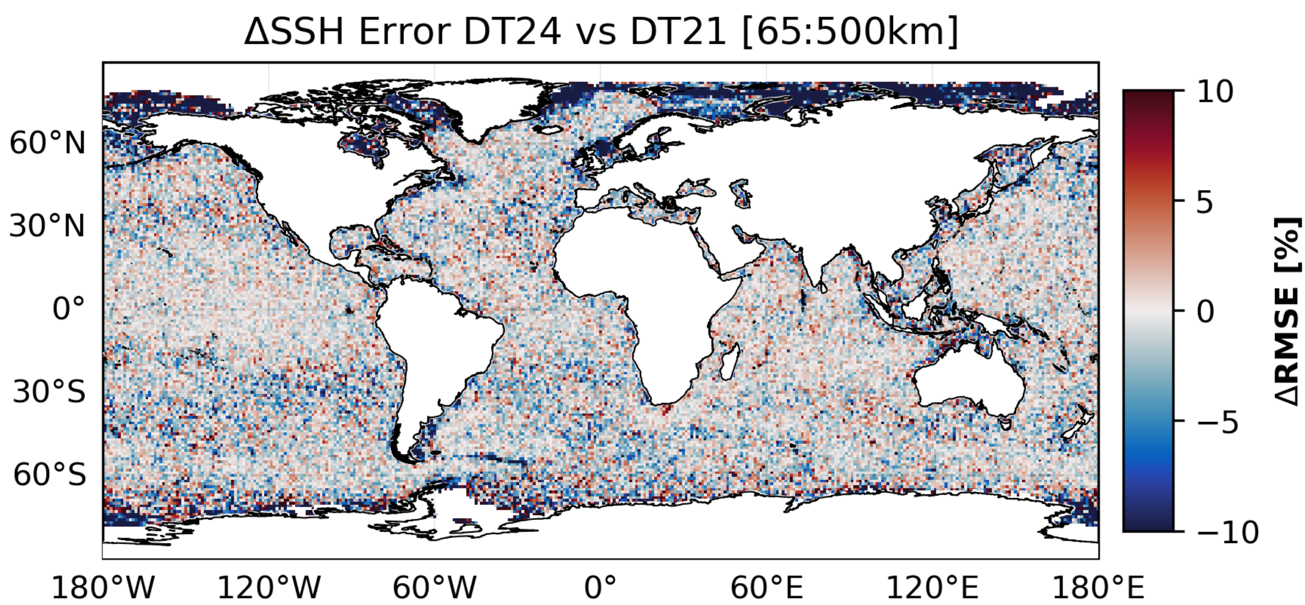
Table 1 and Figure 6 (Panel A) present the Root Mean Square (RMS) of the difference between the vDT2024 sea level anomaly gridded product and the independent SARAL-DP/ALtiKa along-track measurements over the period from 2018-01-01 to 2018-12-31 (the method is described in [C3S_PQAD]). It illustrates the inhomogeneity of the SLA gridded product error for the mesoscale signal, particularly between low and high variability areas. Figure 6 (Panel B) compares the mapping error between the vDT2024 and vDT2021 C3S reprocessing. On Figure 6 (Panel B), a blue pattern indicates a reduction in mapping error, while a red pattern means an increase of mapping error in the new vDT2024 reprocessing. Overall, the new reprocessing reduces the error. Compared to the previous version of the products (i.e., vDT2021), this error is reduced (up to 8% in coastal areas). The SLA gridded product errors in other areas are estimated to be between 2 to 5 cm², with higher values in high variability coastal areas. This error is globally reduced by approximately 1% to 2% compared to the previous version of the products.

Table 1: Variance of the differences between gridded (L4) vDT2024 two-sat-merged products from DUACS and independent SARAL-DP/AltiKa (ALG) along-track measurements over 2018 for different geographic selections. Unit: cm². In parenthesis: variance reduction (in %) compared with the results obtained with the vDT2021 products from DUACS. Statistics are presented for all wavelengths (left column) and wavelengths ranging between 65-500 km (right column).

	mapping_err_var [cm²] all wavelengths	**mapping_err_filtered_var [cm²] wavelengths [65-500] km**
global (lat between 60° and -60°)	18.38 (-1.39%)	4.73 (-1.25%)
coastal	24.16 (-10.61%)	5.83 (-7.74%)
offshore_high variablity	50.96 (-0.49%)	20.88 (-0.33%)
offshore_low variability	13.78 (-2.96%)	2.93 (-1.35%)
equatorial_band	14.22 (-1.18%)	3.20 (-0.62%)



A



B

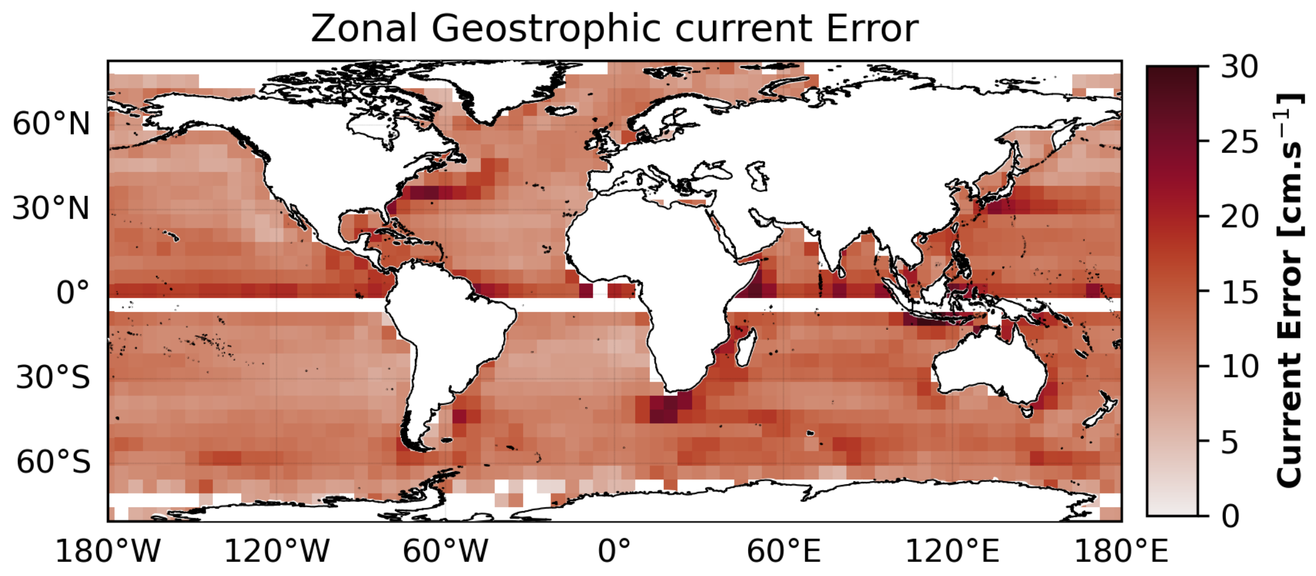
Figure 6: vDT2024 Sea Level Anomaly comparison to estimates from other independent sensor systems, and estimates from the most recent product version. Panel A shows the RMS of the difference between global gridded vDT2024 C3S sea level anomaly and independent SARAL-DP/AltiKa along-track measurements over the period 2018-01-01 to 2018-12-31 (units: cm). Panel B shows the difference of RMSE between vDT2024 and vDT2021 global gridded products. Negative values (i.e., blue colour) indicates a reduction of error in vDT2024 product.

2.6 Surface velocities from surface drifting buoys

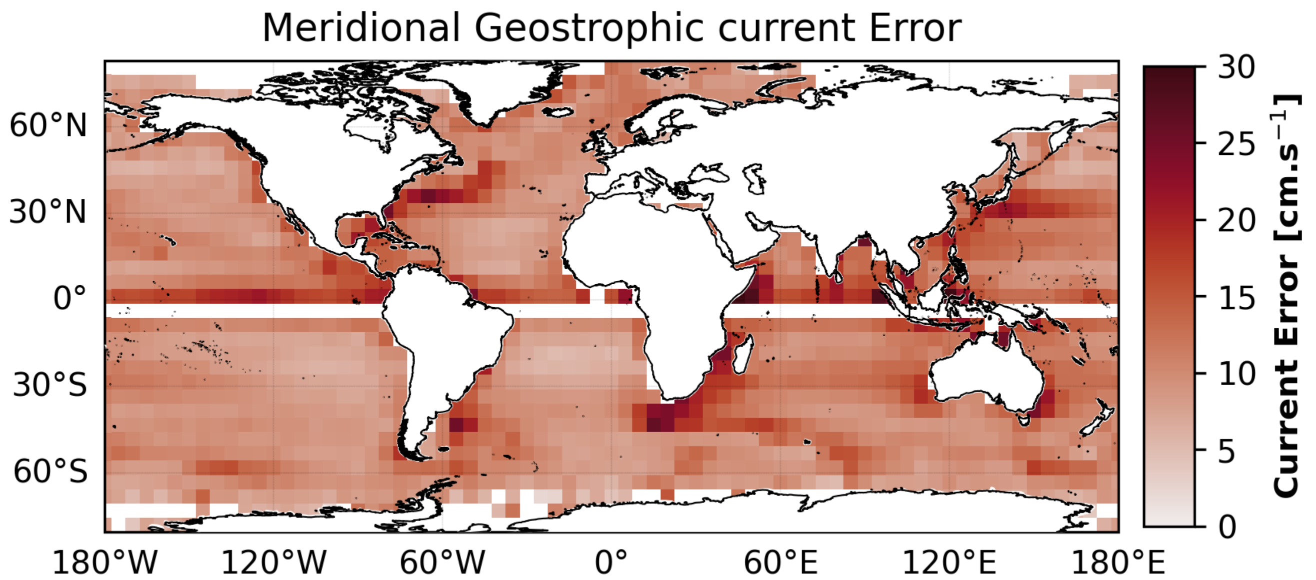
The geostrophic currents are calculated by applying the geostrophic balance equation to the SLA and ADT fields (see [C3S_ATBD]). Meanwhile, the absolute surface currents in the product are calculated using the principle of geostrophy from gridded SLA/ADT products. The quality of these products strongly depends on the quality of the SLA/ADT field and on the methodology used to estimate the derivates.

The comparison with drifter measurements gives an indication of the errors on geostrophic current products. The distribution of the speed of the current (not shown) shows a global underestimation of the current in the altimeter products compared to the drifter observations, especially for currents with medium and strong intensities (> 0.2 m/s). Figure 7 shows the zonal and meridional RMS differences in 5° x 5° boxes between AOML drifters and absolute geostrophic current products over the period 1993-2020. The equatorial band was excluded from the analysis, since the geostrophic approximation does not lead to an accurate estimation of the currents in this area. Elsewhere, the RMS of the differences is around 11-12cm/s (12.1 cm/s for zonal –11.2cm/s meridional– component). Locally, the RMS of the differences is higher and it reaches 18 cm/s over high variability areas.

The difference with the previous version (vDT2021 standards) of the products is shown in Figure 8 (Panel A). In this Figure, it can be observed that the reduction of the error is mainly found at mid-latitude (5-10%). Larger errors are found for the zonal component at high latitude, especially in the Southern hemisphere.

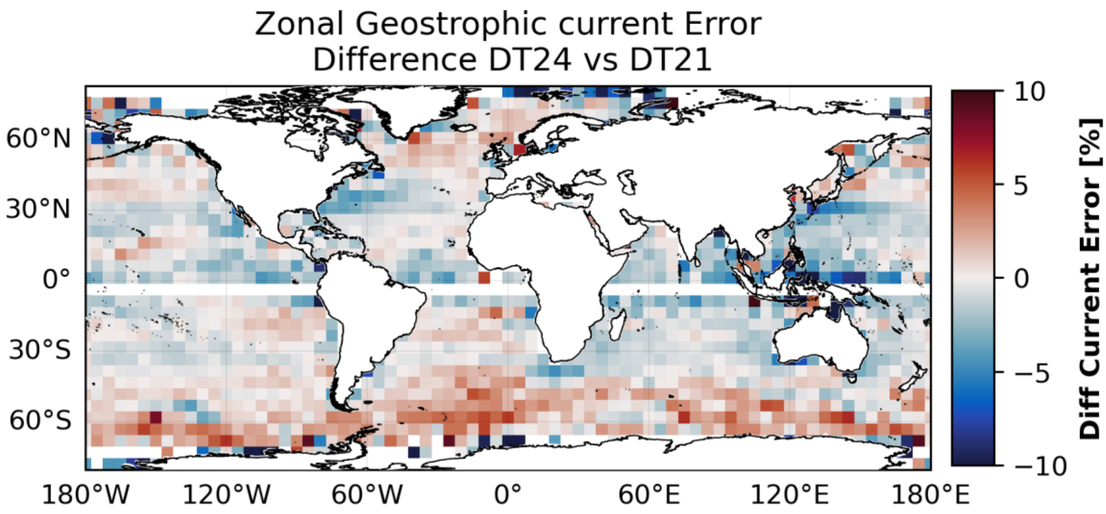


A

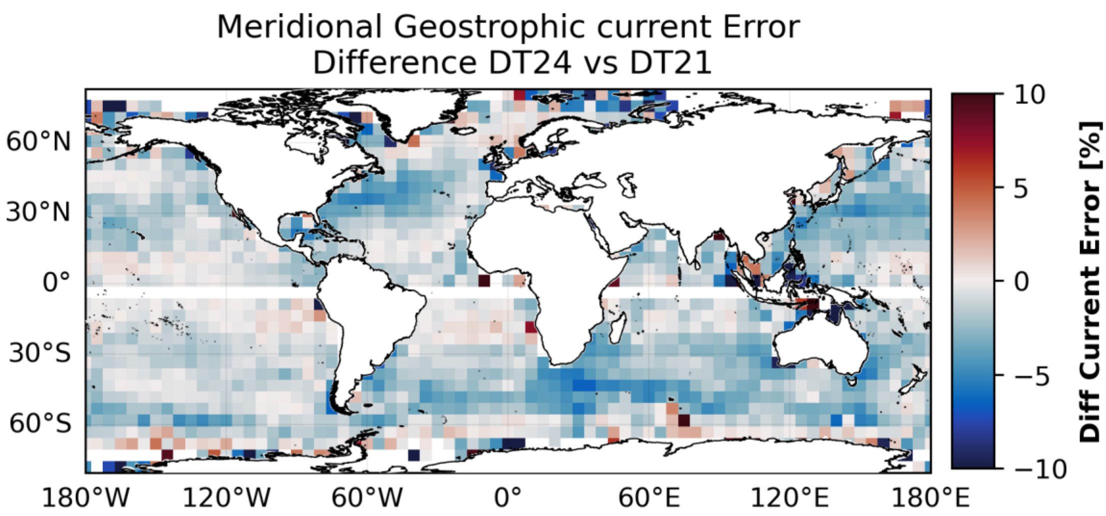


B

Figure 7: Zonal (Panel A) and meridional (Panel B) RMS of the difference between vDT2024 geostrophic current and drifter measurements over the period 1993-2019 (units: cm/s).



A



B

Figure 8: Zonal (Panel A) and meridional (Panel B) difference of RMSE between vDT2024 and vDT2021 gridded geostrophic current products (units: %). Negative values (i.e., blue colour) means a reduction of error in vDT2024 products.

2.7 Estimated Accuracy Numbers

The following Estimated Accuracy Numbers (EAN) are representative of the signatures of different error signals in the products, including both uncorrelated (i.e. noise) and correlated (spatial and temporal scales) error signals. These EANs are specific to the DUACS vDT2024 altimeter products.

The compliance with user requirements is detailed in section 4.

Measurement Noise:
The level of noise, for 1hz, vary from a mission to another and vary between 2 and 3.6 cm rms for non-filtered SLA and 0.85 to 1.53 cm rms for filtered SLA, see Table 2. This gives us the confidence level of each mission when integrated into the mapping process. A summary of the measurement noise (i.e., uncorrelated error) is given in Table 2.

Table 2: Mean 1Hz measurement noise observed for the different altimeters used for along-track (L3) DUACS products (used to produce the C3S CDR). Noise for raw measurements (in bold) and filtered (low-pass filtering; cut-off 65km) SLA (in brackets) are indicated. Unit: cm rms.

	Global Ocean
Sentinel-6MF	**2.3 (0.98)**
Sentinel-3A	**2.0** (0.85)
Jason-3	**2.6** (1.11)
Jason-2	**2.6** (1.11)
Cryosat-2	**2.6** (1.11)
SARAL/AltiKa	**2.0** (0.85)
Topex/Poseidon	**2.6** (1.11)
Jason-1	**2.6** (1.11)
Envisat	**2.6** (1.11)
ERS-1	**3.6** (1.53)
ERS-2	**3.6** (1.53)

<u>Mesoscale:</u>

For merged maps (L4 products), EAN were estimated using the results of comparisons between maps and independent along-track data. Results are summarized in Table 3. A full description is given in section 2.4.

It is important to note that the results obtained with this method are representative of the quality of the gridded products when only two altimeters are available. **The C3S products are not dedicated to the retrieval of mesoscale signals**. The performance is expected to be increased with the use of the all-satellite merged sea level products distributed by the Copernicus Marine Service. These products include all available altimeter missions, and the mesoscale errors should thus be lower since the products benefit from an optimal ocean surface sampling (see section 3.3).

Table 3: Variance of the differences between gridded (L4) vDT2024 two-sat-merged products and independent SARAL-DP/AltiKa drifting phase along-track measurements for different geographic selections (unit = cm²). Statistics are presented for wavelengths ranging between 65-500 km and latitudes between -60° and 60°.

	AL [2018]
Reference area*	1
Dist coast > 200km & variance < 200 cm²	2.9
Dist coast > 200km & variance > 200 cm²	20.89
Dist coast < 200km	5.8

** The reference area is defined as [330, 360°E]; [-22, -8°N] and corresponds to an area of very low-variability in the South Atlantic subtropical gyre where the observed errors are small*

<u>Geostrophic current:</u>

EANs for geostrophic currents are deduced from comparisons between L4 altimeter products and drifter measurements. A summary is presented in Table 4 (see also section 2.6).

Table 4: RMS of the differences between DUACS vDT2024 geostrophic current (L4) products and independent drifter measurements (unit = cm/s). In brackets: percentage mean square reduction compared with the results obtained with the vDT2021 products. Statistics have been computed for latitudes between -60° and 60°and between 1993 and 2020.

Selection criteria	**zonal**	**meridional**
Global excluding equatorial band	12.07 (-1%)	11.21 (-2%)
High variability areas	17.98 (-2%)	18.01 (-4%)
Low variability areas	11.36 (0%)	10.34 (-2%)

Observable wavelengths:

The along-track (L3) product is delivered at a 1Hz sampling frequency (not subsampled) and gridded (L4) products are delivered at 1/4° for global products. Nevertheless, this spatial sampling is not representative of the effective spatial resolution of the products. Along-track products used to produce the gridded products are affected by measurement noise that limits the observation of small scales as discussed in section 2.4. The resolving capacity of gridded products is directly linked to the altimeter constellation state and mapping method as discussed in Section 2.4. The effective resolution of the products is summarized in and is fully discussed in Ballarotta et al (2019).

Table 5: Effective mean spatial and temporal resolution of the DUACS vDT2024 global products (L3 & L4) over the global ocean.

	L3 products	**L4 global products**
Observable Spatial Wavelengths (km)	> ~65	> ~180
Observable Temporal Wavelengths (days)	-	~33

MSL trend & climate scales:

The estimate of the MSL errors at climate scales has benefited from the ESA SL Climate Change Initiative (CCI) project (see the synthesis inTable 6 and in Table 7).

The GMSL record now achieves stability performances of ±0.3 mm/yr at the 90 % confidence level (C. L.) for its trend and ±0.05 mm/yr^2 (90 %C. L.) for its acceleration over the 29-years of the altimetry record. Thanks to an analysis of the relative contribution of each uncertainty budget contributor, i.e., the altimeter, the radiometer, the orbit determination, the geophysical corrections, Guérou et al., (2023) identified the current limiting factors to the GMSL monitoring stability and accuracy. They found that the radiometer Wet Troposphere Correction (WTC) and the high-frequency errors with timescales shorter than 1-year are the major contributors to the GMSL uncertainty over periods of 10-years (30–70 %), both for the trend and acceleration estimations. For longer periods of 20-years, the Topex/Poseidon (TP) data quality is still a limitation but more interestingly, the errors and uncertainties associated with how the International Terrestrial Reference Frame (ITRF) is defined (ITRF realization uncertainties) becomes dominant over all the others sources of uncertainty.

Table 6: Estimated uncertainties at climate scales observed for DUACS DT sea level products at global scale. The sources of uncertainties are based on the work of Ablain et al. (2019). The values in blue are the ones updated in Guérou et al., (2023).

Source of uncertainties	**Type of errors**	**Uncertainty (1σ)**	**Method / References**
Altimeter noise / geophysical corrections	Correlated errors λ =2-months	$u_\sigma = 1.7$ mm over TP period $u_\sigma = 1.2$ mm over J1 period $u_\sigma = 1.1$ mm over J2 period $u_\sigma = 1.0$ mm over J3 period	This paper (Sect. 2.3)
Geophysical corrections / orbit	Correlated errors λ =1-year	$u_\sigma = 1.4$ mm over TP period $u_\sigma = 1.2$ mm over J1 period $u_\sigma = 1.1$ mm over J2 period $u_\sigma = 1.1$ mm over J3 period	This paper (Sect. 2.3)
Radiometer WTC	Correlated errors λ =5-years	$u_\sigma = 1.1$ mm over TP, J1, J2 periods $u_\sigma = 1.8$ mm over J3 period	Legeais et al. (2014) Thao et al. (2014) This paper (Sect. 2.3)
Orbits determination	Correlated errors λ =10-years	$u_\sigma = 1.12$ mm over TP period $u_\sigma = 0.5$ mm over Jasons period	Couhert et al. (2015); Rudenko et al. (2017)
Intermissions calibration offsets	Bias	$u_\Delta = 2\,mm$ for TP-A/B $u_\Delta = 0.3\,mm$ for TP/J1 $u_\Delta = 0.1\,mm$ for J1/J2 $u_\Delta = 0.2\,mm$ for J2/J3	This paper (sec. 2.2.1)
International Terrestrial Reference Frame (ITRF)	Drift	$u_\delta = 0.1\,mm/yr$ over 1993-present	Couhert et al. (2015)
Global Isostatic Adjustement (GIA)	Drift	$u_\delta = 0.05\,mm/yr$ over 1993-present	Spada (2017)
Topex-A/-B altimeter drift	Drift	$u_\delta = 0.7\,mm/yr$ over TP-A period $u_\delta = 0.1\,mm/yr$ over TP-B period	Ablain et al. (2017)

Table 7: Estimated errors at climatic scales observed on sea level DUACS DT products (L3 & L4). (Guérou et al., 2023; Prandi et al., 2021) with respect to the GCOS requirements from [Ablain et al., 2019], [WCRP Global Sea Level Budget Group, 2018] and [Prandi et al., 2021]).

Spatial scales	Temporal scales	Altimetry errors	User Requirements
Global MSL	Long-term evolution (30 years)	0.3 mm/yr	0.1 - 0.3 mm/yr[1]
Regional MSL	Long term evolution (> 10 years)	1.22 mm/yr[2]	< 1 mm/yr

[1] Depending on the applications

[2] Only the uncertainty related to the instrumental observing system has been considered.

3. Application(s) specific assessments

3.1 Global and regional MSL trends and sea level uncertainties

The stability of the MSL record is ensured by the use of a reference mission (TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3). Sentinel-6A replaced Jason-3 as the reference mission since 4th April 2022. The associated input L2P products are first cross-calibrated to ensure continuity of the mean sea level between these missions. This relies on the measurements of the two altimeters during the tandem phase when both instruments measure the same place with a time difference of a few seconds, therefore measuring the same sea state. This bias reduction takes into account both global and regional biases; the results are checked in detail since this step is crucial for climate signals. Details are presented in Pujol et al. (2016).

The stability of the MSL has been assessed by comparison with the *in situ* tide gauge measurements (see previous section) and the associated MSL trends are discussed in the next section.

Error budget: An error budget dedicated to the main spatio-temporal scales (i.e., global and regional, long-term – (5 – 10 years or more) , inter annual (<5 years) and seasonal) was initially established within the ESA Sea Level Climate Change Initiative (SL_cci). **Error! Reference source not found.**The latest version of the uncertainty budget (associated with L2P vDT2021 products) is published in Guérou et al. 2023 and will be updated for v2024DT C3S products next year. Additional contributions to the improved uncertainty estimates can be found in the SL_cci error report [SL_cci CECR], the SL_cci Product Validation and Intercomparison Report [SL_cci PVIR] and in Pujol et al. (2016) and Legeais et al. (2018).

Trend of the global MSL: It is based on the latest C3S sea level products for the period 1993-2022 amounts to an average rise of 3.5 mm/yr with an error of +/- 0.4 mm/yr (Figure 9). The altimeter MSL trend is corrected for the Glacial Isostatic Adjustment (GIA, -0.3 mm/yr) to take into account the volume change of the ocean basins due to the Post Glacial Rebound (Peltier, 2004; Tamisiea and Mitrovica, 2011).

Guérou et al (2023) have provided a comprehensive description of the uncertainties in the satellite global MSL trend and acceleration by estimating the error covariance matrix for the global MSL record. This has allowed them to derive a 90% confidence interval for the global MSL record, and then to estimate the associated trend uncertainty**. The uncertainty of the global MSL during the total altimetry period is +0.3 mm/yr at a confidence interval of 90%** (**Table 6**; Guérou et al., 2023; Ablain et al., 2019; WCRP Sea Level Budget Group, 2018). This level of uncertainty remains greater than the target requirements (see [C3S_TRD]).

The largest source of uncertainty associated with the Global Mean Sea Level parameters' (trend and acceleration) over 30 years are the ITRF, the wet tropospheric correction and high-frequency correlated noise (Meyssignac et al. 2023). There are other sources of uncertainties and all are currently adressed by the altimetry community. In particular, there are still some open questions about the TOPEX period (especially TOPEX-A), and there are some on-going work to correct a potential drift in TOPEX-A data in vDT2024 C3S products.

3.2

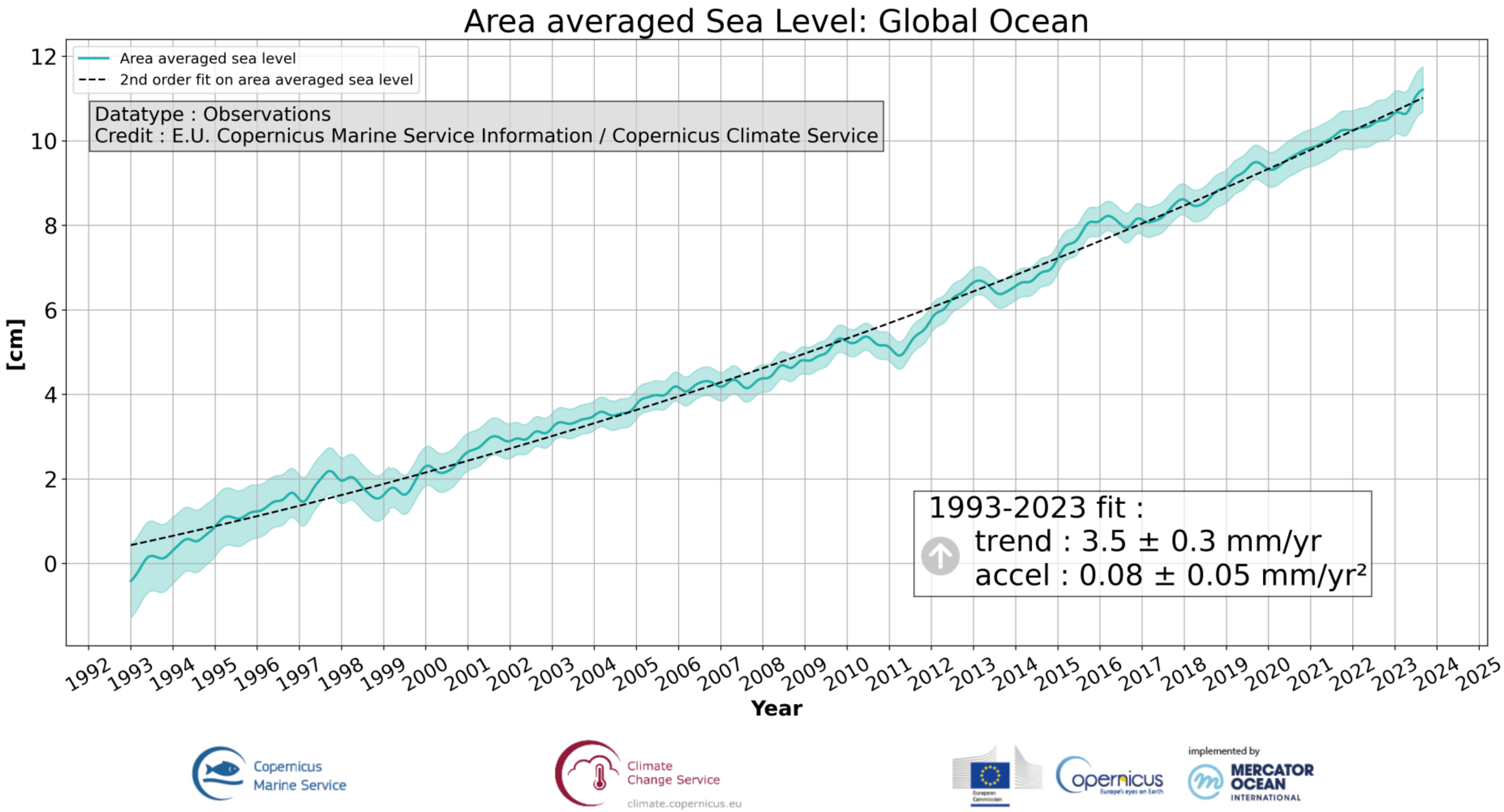


Figure 9: Temporal progression of the global mean sea level from the C3S vDT2024 two-satellite merged product for the period 1993 - 2023 with low-pass filtered MSL anomalies (and without annual and semi-annual signals) relative to the 1993-2012 mean. The MSL curve has been corrected by -0.3 mm/yr for the glacial isostatic adjustment using the ICE5G-VM2 model (Peltier et al., 2004).

The regional mean sea level trends are estimated from the daily C3S sea level maps covering the altimetry era from January-1993 to February-2024 (see Figure 10). The observed variations are generally considerably larger than those observed at global scale (values range between -5 mm/yr and +5 mm/yr around the 3 mm/yr global estimate). This is explained by the large local variability generated by regional changes in winds, pressure, and ocean currents, all averaged out to a global scale (e.g. Stammer et al., 2013). The altimeter MSL trends during the altimetry era exhibit large scale variations with amplitudes reaching up to +8 mm/yr in regions such as the western tropical Pacific Ocean and the Southern Ocean.

The regional sea level trend uncertainty has an average estimate of 0.83 mm/yr with local values ranging from 0.78 to 1.22 mm/yr depending on the region. These values are only related to the errors associated with the altimeter instrumental observing system (Prandi et al., 2021). The orbital solution remains the main source of error (Couhert et al., 2014) with large spatial patterns at the hemispheric scale. Furthermore, errors are higher during the first decade (1993-2002) as the Earth gravity field models are less accurate for this period. Additional errors are still observed, e.g., for the radiometer-based wet tropospheric correction in tropical areas, other atmospheric corrections at high latitudes, and high frequency corrections in coastal areas.

Note that due to the production process being dedicated to homogeneity and stability, the C3S sea level products have been used for the production of the Copernicus Marine Service Ocean Monitoring Indicators (global and regional MSL), which are described in the annual Ocean State Report (OSR). For example, the most recent OSR report (von Schuckmann et al., 2024) used the vDT2021 product to derive the reported global and regional indicators.

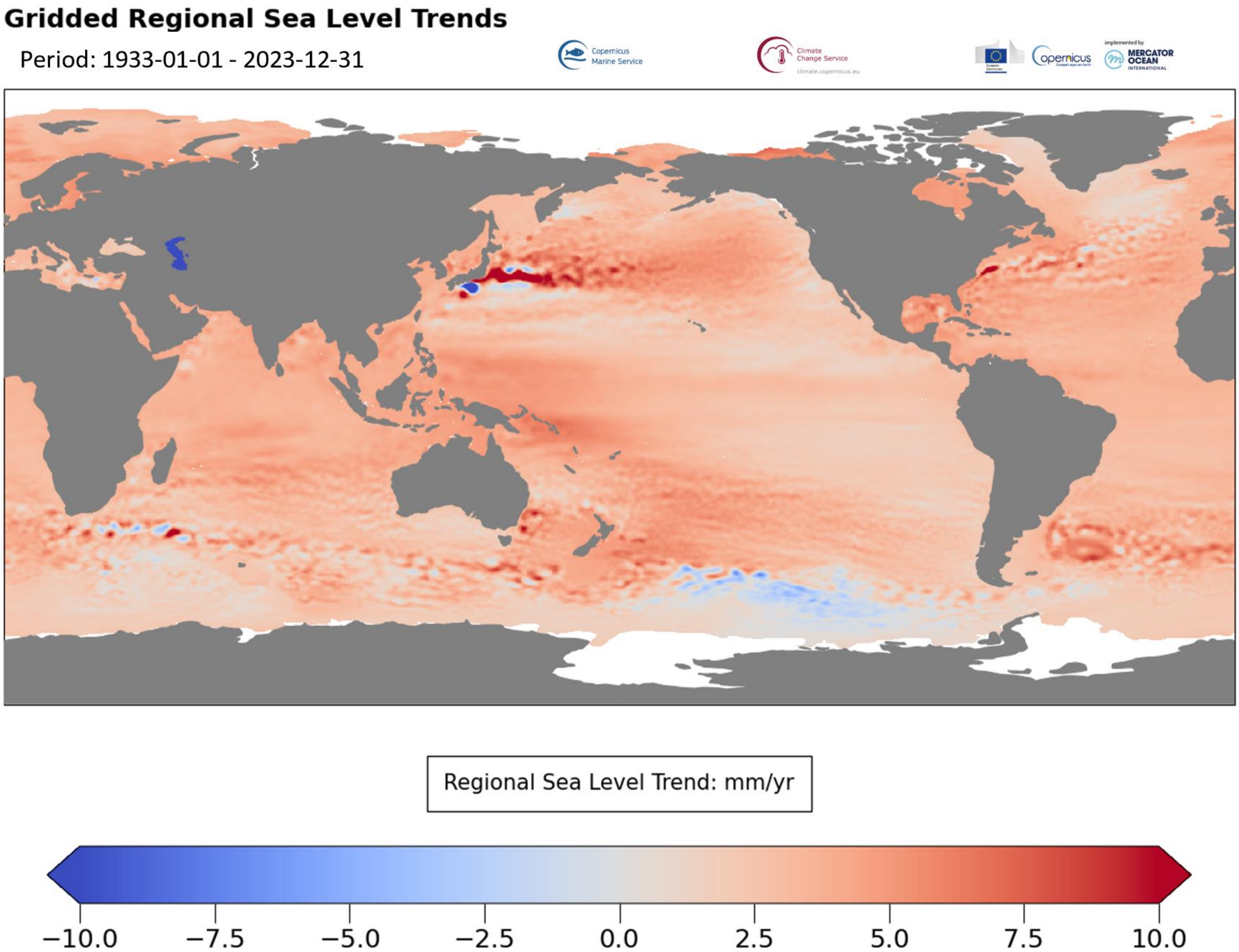


Figure 10: Regional MSL trends of the C3S two-satellite merged product during the altimetry era. No GIA correction has been applied to the altimeter data.

Mesoscale signals

Regarding the mesoscale signals, the measurement noise mainly consists of instrumental (altimeter) measurement errors and can be quantified by spectral analysis of the SLA. The uncorrelated measurement error is a consequence of the instrumental white noise linked to the Surface Wave Height. For conventional radar altimeter measurements, the inhomogeneity of the sea state within the altimeter footprint also induces an error, manifesting as a "bump" in the wavenumber spectrum of the SLA. A full understanding of this "bump" of spectral energy (Dibarboure et al, 2014) awaits. The mean 1Hz measurement noise for the different altimeters is summarized in Table 2.

The presence of measurement noise in the along-track products limits the observability of the shorter mesoscales. The wavelength where the signal can be distinguished from the noise has been found (by SLA power spectrum density analysis) to be variable in space and time (Dufau et al., 2016; Ballarotta et al., 2019). The mean value was found to be nearly 65 km.

3.2 The TOPEX-A instrumental drift correction

The most notable error that affects the first 6 years (January 1993 to February 1999) of the Topex/Poseidon GMSL measurements is due to an instrumental drift of the TOPEX-A altimeter.

Work is on-going (currently lead by teams at the JPL, CNES and in CLS) to assess a potential drift of the TOPEX-A instrument, and document a correction to be applied to new L2P vDT2024 products to obtain the most accurate GMSL record possible. By convention, the global mean sea level had previously been set to zero for 1993. However, the proposed correction of the TOPEX-A instrumental drift has been chosen so that it is null at the end of the lifetime of the TOPEX mission in 1999. With this approach, the corrected GMSL does not equal zero in 1993 (see Figure 5), but this approach is preferred to ensure the continuity of the initial and corrected GMSL after 1999 (e.g. for ocean modellers).

3.3 The C3S and Copernicus Marine Service sea level products

Two types of sea level altimetric gridded products generated by the DUACS production system are currently available:

- Global and regional (European seas) gridded products generated and disseminated in the framework of the Copernicus Marine service (CMEMS).
- Global gridded product generated in the framework of the Copernicus Climate Change (C3S) service, and disseminated both via C3S and CMEMS. No regional product is available for C3S.

This section presents the particularities of the sea level gridded datasets produced by two distinct approaches. The CMEMS approach focuses on the mesoscale mapping capacity of the altimeter data together with the stability of the overall dataset, whereas the C3S products focus solely on the stability of the global and regional Mean Sea Level (MSL), even if this implies potential reduction of the spatial sampling of the ocean.

The first difference between both datasets is related to the number of altimeters used in the satellite constellation. All available altimeters are included in the CMEMS products whereas a fixed number of altimeters (two) are included in the C3S products. Previous studies (Dibarboure et al., 2011; Pascual et al., 2006) underscored the necessity of using a minimum of a two-satellite constellations for the retrieval of mesoscale signals. Within the production process, the long-term stability and large-scale changes are built upon the records from the reference missions (TOPEX-Poseidon, Jason-1, Jason-2 and Jason-3, Sentinel-6A) used in both CMEMS and C3S products.

In CMEMS products, the additional missions (e.g. up to four additional missions in 2017) are homogenized with respect to the reference missions. These additional missions contribute to improve the sampling of mesoscale processes, provide high-latitude coverage, and increase the product accuracy. In addition, mesoscale errors are also reduced in the CMEMS products due to the improved ocean surface sampling thanks to the use of all satellites available in the constellation. However, the total number of satellites strongly varies during the altimetry era and some biases may appear with the introduction of a new satellite tracking on a drifting orbit, which may affect the stability of the global and regional MSL.

In C3S products, even if the spatial sampling is reduced with less satellites, the risk of introducing such anomalies associated with new systems is thus reduced, and the stability is improved. Note that in the CMEMS products, the stability is ensured by the use of the same reference missions.

While the level 2 altimeter standards used to compute the sea level anomalies in the CMEMS and C3S products are identical, a second difference between these products arises from the reference used to compute the Sea Level Anomalies: either a Mean Sea Surface (MSS) for all missions in the C3S products, or a mean profile of sea surface heights used along the theoretical track of the satellites with a repetitive orbit in the CMEMS products. These mean profiles increase the local accuracy of the sea level estimates, but the combined use of both MSS and mean profiles for successive missions in the CMEMS merged products could lead to some biases affecting the sea level stability. Even if this has a minor impact at global scale, the stability of the regional MSL can be affected, particularly in the Mediterranean Sea and Black Sea (not shown here). So, the systematic use of only MSS for all missions contributes to ensure the MSL stability in the C3S products. Meanwhile, the mesoscale accuracy of the CMEMS products is increased with the use of the mean profiles for repetitive missions.

The last difference between these products concerns the temporal and spatial scales used in the mapping process (Optimal Interpolation). It has been reviewed specifically for the CMEMS production and is different in the C3S and CMEMS sea level products. In CMEMS, the spatial and temporal scales have been re-estimated as the altimeter constellation (number of satellites in flight simultaneously) varies over time. In recent times, the large number of altimeters has made it possible to better sample surface topography spatially and temporally, which is why these scales for CMEMS have been revisited, in contrast to C3S, where the constellation is stable over time (2 satellites).

Because mission revisit times in the all-satellites (CMEMS) constellation are shorter than in two-satellites (C3S) constellation, temporal decorrelation scales are shorter in CMEMS than in C3S. Spatial scales, on the other hand, are more or less the same.

In conclusion, with the best spatial sampling, the all-satellite CMEMS gridded merged products should be preferred for oceanic mesoscale applications and data-assimilation, while the C3S two-satellites gridded merged products should be used for climate applications including mean sea level change, variability and oceanic circulation.

Further details regarding the choice of a two-satellites merged constellation for the climate-oriented C3S sea level products and of a homogeneous mean reference field for all missions are presented in [C3S_PQAR_2021]. This comparison was made for a previous C3S product (vDT2018) but remains valid for the current C3S product (vDT2024).

Note that additional differences may appear in the future between CMEMS and C3S products with respect to specific missions (e.g. the Jason-CS/Sentinel-6 mission could be processed differently according to their use in Copernicus Marine Service or C3S production with either SAR or Low Resolution Mode data being used). This will further differentiate the Copernicus Marine Service and C3S products, requiring users to carefully assess which product series best suits their use case needs.

3.4 Sea Level Closure Budget Approach

A quality assessment of the C3S sea level data has been performed by comparing the version vDT2018 of the C3S sea level product with independent observations of the sea level contributors and by testing the closure of the sea level budget. Details of the validation results obtained at global and regional scales are reported in [C3S_PWAR_2021] and are also presented in Legeais et al. (2020). This approach contributes to a better characterization of potential anomalies or drifts in the input data. For instance, this has allowed the estimation of the impact of the TOPEX-A instrumental drift on the global MSL drift. Note that the sea level budget closure quality assessment has not been applied for this project to the two latest versions (DT2021 and DT2024) of the C3S sea level global dataset.

4. Compliance with user requirements

All the validation studies performed on the C3S vDT2024 delayed-time sea level products have been described in the previous sections (see the methodology in the [C3S_PQAD]). The obtained results have allowed us:

- To better characterize the differences between the existing sea level dataset collections (two-satellite and all-satellite merged altimeter products);
- To better characterize the errors of the sea level record at different spatial and temporal scales; and
- To improve the estimation of the associated uncertainties.

Details on the error budget estimation at climate scale can be found in Guérou et al (2023) and Prandi et al., 2021 and the associated user requirements are presented (for more detail see Table 6, Table 7, the C3S Target Requirement Document [C3S_TRD] and the SL_cci User Requirements Document [SL_cci URD]).

The error in the global MSL remains higher than what is requested (as detailed by Meyssignac et al., 2023) for some applications (e.g. estimate of the Ocean Heat Content and the Earth Energy Imbalance). The magnitude of this error is not expected to be significantly reduced without major improvements to some altimeter standards or instrumental corrections. For instance, a reprocessing of the TOPEX-A measurements may significantly affect the estimation of the global MSL and reduce the associated uncertainty (for more details, see previous section, Dieng et al., 2017 and Guérou et al, 2023).

The error in the estimation of the interannual signals of the global MSL also remains higher than the requirements. The presentation of Quet et al., 2024 shows preliminary results about the new uncertainty budget associated with the new L2P vDT2024 products.

Regarding the error of the regional MSL trend, the contributors are listed in the previous sections and there is a regional aspect to the magnitude of some errors. The error remains smaller than the requirements in some parts of the ocean, but much greater values are found in other regions.

5. References

Ablain M., Larnicol G., Faugere Y., Cazenave A., Meyssignac B., Picot N., Benveniste J., 2012, Error Characterization of Altimetry Measurements at Climate Scales, in Proceedings of the "20 Years of Progress in Radar Altimetry" Symposium, Venice, Italy, 24-29 September 2012, Benveniste, J. and Morrow, R., Eds., ESA Special Publication SP-710, 2012. DOI:10.5270/esa.sp-710.altimetry2012

Ablain M., A. Cazenave, G. Larnicol, M. Balmaseda, P. Cipollini, Y. Faugere, M.J. Fernandes, O. Henry, J.A. Johannessen, J. Legeais, B. Meyssignac, N. Picot, M. Roca, S. Rudenko, M.G. Scharffenberg, D. Stammer, G. Timms, P. Knudsen, O. Andersen, and J. Benveniste, 2015. Improved Sea Level record over the satellite altimetry era (1993-2010) from the Climate Change Initiative project. Ocean Sci., 11, 67-82, DOI:10.5194/os-11-67-2015, 2015.

Ablain M., R. Jugier, L. Zawadki, and N. Taburet.: The TOPEX-A Drift and Impacts on GMSL Time Series (poster), Ocean Surface Topography Science Team meeting, 2017. Available at: https://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/Poster_OSTST17_GMSL_Drift_TOPEX-A.pdf . Last access: 16/01/2020.

Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, A., Cazenave, A., and Picot, N.: Uncertainty in Satellite estimate of Global Mean Sea Level changes, trend and acceleration, Earth Syst. Sci. Data, 11, 1189-1202, https://doi.org/10.5194/essd-11-1189-2019 , 2019.

Ballarotta, M., Ubelmann, C., Pujol, M.-I., Taburet, G., Fournier, F., Legeais, J.-F., Faugère, Y., Delepoulle, A., Chelton, D., Dibarboure, G., and Picot, N.: On the resolutions of ocean altimetry maps, Ocean Sci., 15, 1091–1109, https://doi.org/10.5194/os-15-1091-2019 , 2019.

Beckley, B. D., Callahan, P. S., Hancock III, D. W., Mitchum, G. T., and Ray, R. D.: On the "cal mode" correction to TOPEX satellite altimetry and its effect on the global mean sea level time series, J. Geophys. Res.-Oceans, 122, 8371–8384, DOI: 10.1002/2017JC013090, 2017.

Blazquez, A., B Meyssignac, JM Lemoine, E Berthier, A Ribes, A Cazenave, Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: implications for the global water and sea level budgets, *Geophysical Journal International*, Volume 215, Issue 1, October 2018, Pages 415–430, https://doi.org/10.1093/gji/ggy293

Chambers, D.P., Cazenave, A., Champollion D., Dieng, H., Llovel, W., Forsberg, R. von Schuckmann, K., Wada, Y. (2017): Evaluation of the Global Mean Sea Level Budget between 1993 and 2014. Surv Geophys (2017) 38:309–327, DOI: 10.1007/s10712-016-9381-3.

Chen, X., Zhang, X., Church, J. A., Watson, C. S., King, M. A., Monselesan, D., Legresy, B., and Harig, C.: The increasing rate of global mean sea level-rise during 1993–2014, Nat. Clim. Change, 7, 492–495, https://doi.org/10.1038/NCLIMATE3325, 2017.

Cheng, L., K., E., Trenberth, J. Fasullo, T. Boyer, J., Abraham and J., Zhu, 2017. Improved estimates of ocean heat content from 1960 to 2015. *Science Advances,* 3, 3, DOI: 10.1126/sciadv.1601545.

Couhert A.; L. Cerri; JF Legeais; M. Ablain; N. Zelensky; B. Haines; F. Lemoine; W. Bertiger; S. Desai; M. Otten; Towards the 1 mm/y Stability of the Radial Orbit Error at Regional Scales. Advances in Space Research, 2014. doi:10.1016/j.asr.2014.06.041

Decharme, B., and H. Douville (2006), Introduction of a sub‐grid hydrology in the ISBA land surface model, *Climate Dyn.*, 26, 65–78.

Dibarboure G., Pujol M.-I., Briol F., Le Traon P.Y., Larnicol G., Picot N., Mertz F. & Ablain M. (2011) Jason-2 in DUACS: Updated System Description, First Tandem Results and Impact on Processing and Products, Marine Geodesy, 34:3-4, 214-241, DOI: 10.1080/01490419.2011.584826

Dibarboure, G., F. Boy, J.D. Desjonqueres, S. Labroue, Y. Lasne, N. Picot, J.C. Poisson and P.Thibaut: Investigating Short-Wavelength Correlated Errors on Low-Resolution Mode Altimetry, J. Atmospheric Ocean. Technol., 31, 1337–1362. doi:10.1175/JTECH-D-13-00081.1, 2014

Dieng, H. B., Cazenave, A., Meyssignac, B., & Ablain, M. (2017). New estimate of the current rate of sea level rise from a sea level budget approach. Geophysical Research Letters.

Dufau, C., Orstynowicz, M., Dibarboure, G., Morrow, R., and La Traon, P.-Y.: Mesoscale Resolution Capability of altimetry: present & future, J. Geophys. Res, 121, 4910–4927, doi:10.1002/2015JC010904, 2016.

Faugere Y., Durand C., Carrere L., Ubelmann C., Ballarotta B., Dibarboure G. : Impact of internal tide correction on the DUACS maps accuracy, Presentation OSTST2019,

https://ostst.aviso.altimetry.fr/fileadmin/user_upload/OSTST2019/TID_01_DUACS_IT_Impact-Faugere.pdf (last access: 21 Nov 2024)

Guérou, A., Meyssignac, B., Prandi, P., Ablain, M., Ribes, A., and Bignalet-Cazalet, F.: Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty, Ocean Sci., 19, 431–451, https://doi.org/10.5194/os-19-431-2023, 2023

Gouretski, V., and Reseghetti, F. (2010), On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database, Deep Sea Res., Part I, 57 (6), 812 - 833, doi:10.1016/j.dsr.2010.03.011.

Kocha, C., Lievin, M., Pageot, Y., Rubin, C., Philipps, S., Dibarboure, G., Denis, I., Guinle, T., and Nogueira Loddo, C.: 30 years of sea level anomaly reprocessed to improve climate and mesoscale satellite data record. OSTST meeting., https://doi.org/10.24400/527896/a03-2023.3804, 2023.

Legeais J.-F., M. Ablain and S. Thao. Evaluation of wet troposphere path delays from atmospheric reanalyses and radiometers and their impact on the altimeter sea level. Ocean Science, 10, 893-905, 2014. doi: 10.5194/os-10-893-2014. http://www.ocean-sci.net/10/893/2014/os-10-893-2014.pdf

Legeais, J.-F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J. A., Scharffenberg, M. G., Fenoglio-Marc, L., Fernandes, M. J., Andersen, O. B., Rudenko, S., Cipollini, P., Quartly, G. D., Passaro, M., Cazenave, A., and Benveniste, J.: An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative, Earth Syst. Sci. Data, 10, 281-301, https://doi.org/10.5194/essd-10-281-2018, 2018.

Legeais, J.-F., Llowel, W., Melet, A. and Meyssignac, B.: Evidence of the TOPEX-A Altimeter Instrumental Anomaly and Acceleration of the Global Mean Sea Level. In: The Copernicus Marine

Environment Monitoring Service Ocean State Report, Issue 4, J. Oper. Oceanogr., vol 13, Issue Sup 1, s77, 2020.

Leuliette, E.W., and J.K. Willis. 2011. Balancing the sea level budget. *Oceanography* 24(2):122–129, https://doi.org/10.5670/oceanog.2011.32.

Levitus S., et al. (2012), World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. Geophys. Res. Lett., 39, L10603. doi:10.1019/2012GL051106.

Lievin M., Kocha C., Courcol B., Philipps S., Denis I., Guinle T., Nogueira C., Loddo, Dibarboure G., Picot N., Bignalet-Cazalet F.: Reprocessing of Sea Level L2P products for 28 years of altimetry missions, Presentation OSTST2020, https://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2020_Reprocessing_L2P_2020.pdf (last access: 1 July 2021), 2020.

Llovel, W., Willis, J. K., Landerer, F. W., Fukumori, I., Deep-ocean contribution to sea level and energy budget not detectable over the past decade. Nature Climate Change, 2014. DOI: 10.1038/nclimate2387.

Llovel, W., Purkey, S., Meyssignac, B. *et al.* Global ocean freshening, ocean mass increase and global mean sea level rise over 2005–2015. *Sci Rep* **9,** 17717 (2019). https://doi.org/10.1038/s41598-019-54239-2

Marzeion, B.; Jarosch, A.H.; Hofer, M. , 2012 , Past and future sea-level change from the surface mass balance of glaciers , *The Cryosphere* , **6** , 1295 - 1322 , DOI: 10.5194/tc-6-1295-2012.

Meyssignac B., Ablain M., Guerou A., Prandi P., Barnoud A., Blazquez A., Fourest S., Rousseau V., Bonnefond P., Cazenave A., Chenal J., Dibarboure G., Donlon C., Benveniste J., Sylvestre-Baron A., and Vinogradova N.: How accurate is accurate enough for measuring sea-level rise and variability, Nature Climate Change, https://doi.org/10.1038/s41558-023-01735-z, (2023).

Mulet S., Jousset S., New regional mean dynamic topography of Mediterranean and Black Sea from altimetry, gravity and *in situ* data , Presentation OSTST2020, https://meetings.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2020_JOUSSET_MULET_MDT.pdf (last access: 1 July 2021), 2020.

Mulet, S., Rio, M.-H., Etienne, H., Artana, C., Cancet, M., Dibarboure, G., Feng, H., Husson, R., Picot, N., Provost, C., and Strub, P. T.: The new CNES-CLS18 global mean dynamic topography, Ocean Sci., 17, 789–808, https://doi.org/10.5194/os-17-789-2021 , 2021.

Pascual, A., Faugere, Y., Larnicol, G., and Le Traon, P.-Y.: Improved description of the ocean mesoscale variability by combining four satellite altimeters, Geophys. Res. Lett., 33, L02611, doi:10.1029/2005GL024633, 2006.

Peltier R. (2004). 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 (32:111-149).

Prandi P, Philipps S, Pignot V, Picot N (2015) SARAL/AltiKa global statistical assessment and cross-calibration with Jason-2. Mar Geod 38(S2):297–312

Prandi, P., Meyssignac, B., Ablain, M. Spada, G., Ribes, A. & Benveniste, J., Local sea level trends, accelerations and uncertainties over 1993-2019. Sci Data 8, 1 (2021). https://doi.org/10.1038/s41597-020-00786-7

Pujol, M.-I., Faugère, Y., Taburet, G., Dupuy, S., Pelloquin, C., Ablain, M., and Picot, N.: DUACS DT2014: the new multi-mission altimeter data set reprocessed over 20 years, Ocean Sci., 12, 1067-1090, doi:10.5194/os-12-1067-2016, 2016.

Purkey, S. and G. C. Johnson, 2010. Warming of the Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. Jour. Clim., DOI: 10.1175/2010JCLI3682.1.

Quet, V., Mangilli A., Prandi P., Kocha C., Dibarboure G., 2024, LONG TERM ASSESSMENT OF THE GLOBAL MEAN SEA LEVEL RECORD AND ASSOCIATED UNCERTAINTIES BASED ON NEW L2P DT 24 PRODUCTS, 30 Years of Progress in Radar Altimetry Symposium, September 2024.

Rio, M. H., S. Guinehut, and G. Larnicol (2011): New CNES ‐ CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry, and *in situ* measurements, J. Geophys. Res., 116, C07018, doi:10.1029/2010JC006505.

Roemmich, D. and J. Gilson, 2009: The 2004-2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. *Progress in Oceanography*, **82,** 81-100.

Sérazin, G., B. Meyssignac, T. Penduff, L. Terray, B. Barnier, and J.-M. Molines (2016), Quantifying uncertainties on regional sea level change induced by multidecadal intrinsic oceanic variability, Geophys. Res. Lett., 43, 8151–8159, doi:10.1002/2016GL069273.

Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B. et al., 2012, 'A reconciled estimate of ice-sheet mass balance',Science338(6111), 1183–1189 (DOI: 10.1126/science.1228102).

[SL_cci CECR] SL CCI Error Characterization Report: https://climate.esa.int/media/documents/SLCCI-ErrorReport-030-2-2.pdf

[SL_cci PVIR] SL CCI Product Validation and Intercomparison report https://climate.esa.int/media/documents/SLCCI-PVIR-073_SL_cciV2-1-1.pdf

[SL_cci URD] SL CCI User Requirements Document https://climate.esa.int/media/documents/SLCCI-URD-004_1-6.pdf

Stammer D, Cazenave A, Ponte RM, Tamisiea ME, 2013 Causes for contemporary regional sea level changes. Annu. Rev. Mar. Sci, 5. doi: 10.1146/annurev-marine-121211-172406.

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

Von Schuckmann, K., Moreira, L., Cancet, M., Gues, F., Autret, E., Baker, J., Bricaud, C., Bourdalle-Badie, R., Castrillo, L., Cheng, L., Chevallier, F., Ciani, D., de Pascual-Collar, A., De Toma, V., Drevillon, M., Fanelli, C., Garric, G., Gehlen, M., Giesen, R., Hodges, K., Iovino, D., Jandt-Scheelke, S., Jansen, E., Juza, M., Karagali, I., Lavergne, T., Masina, S., McAdam, R., Minière, A., Morrison, H., Panteleit, T. R., Pisano, A., Pujol, M.-I., Stoffelen, A., Thual, S., Van Gennip, S., Veillard, P., Yang, C., and Zuo, H.: The state of the global ocean, in: 8th edition of the Copernicus Ocean State Report (OSR8), edited by: von Schuckmann, K., Moreira, L., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G., Copernicus Publications, State Planet, 4-osr8, 1, https://doi.org/10.5194/sp-4-osr8-1-2024, 2024.

Watson, C. S., White, N. J., Church, J. A., King, M. A., Burgette, R. J., and Legresy, B.: Unabated global mean sea level over the satellite altimeter era, Nat. Clim. Change, 5, 565–568, DOI: 10.1038/NCLIMATE2635, 2015.

WCRP Global Sea Level Budget Group: Global Sea Level Budget 1993-Present, Earth Syst. Sci. Data, 10, 1551–1590, https://doi.org/10.5194/essd-10-1551-2018 , 2018.

Zawadzki, L., Ablain, M. (2016) Accuracy of the mean sea level continuous record with future altimetric missions: Jason-3 vs. Sentinel-3a, Ocean Sci., 12, 9-18, doi:10.5194/os-12-9-2016, 2016.

Copernicus Climate Change Service

ECMWF – Robert-Schuman-Platz 3, 53175 Bonn, Germany

Contact: https://support.ecmwf.int/

climate.copernicus.eu copernicus.eu ecmwf.int