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Copernicus Climate Change Service

Algorithm Theoretical Basis Document

Sea Level Version DT2024

Issued by: CLS / Françoise Mertz, Fabien Lefèvre, Pascal Mambert

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Contributors

CLS
Françoise Mertz
Pascal Mambert
Fabien Lefèvre

History of document modifications

Document Version	Date	Description of modification	Chapters / Sections
1	30/01/2017	Creation to align with Version 2.0 CDR	All
1.2	13/03/2017	ECMWF comments taken into account	All
2	22/03/2018	Adaptation to the reprocessed C3S CDR v1 vDT2018	All
New round of documentation under the C3S2_312a_Lot3_METNorway contract, implementing a release of version DT2021 data.			
1.0	30/08/2022	Document revised, taking into account Independent review comments from draft iterations of the ATBD adapted to the reprocessed vDT2021 data.	All
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1.2	14/12/2023	Revised after remarks done during SRR on 12/12/2023	
New round of documentation under the 2022/C3S2_312b_MOi/SC1 contract, implementing a release of version DT2024 data and a new ATBD (this document) to accompany the product.			
1.0	07/08/2024	Document drafted, taking into account the existing ATBD and adapted to the reprocessed vDT2024 data, sent for independent review and approved as the draft ATBD.	All
	16/01/2025	Document revised, taking into account the existing draft ATBD and perspectives from independent review. Document finalized for publication as a Version 1.0.	All

List of datasets covered by this document

The present document applies to the C3S altimeter derived sea level Climate Data Record (CDR) and its temporal extensions (Interim CDR). The current version corresponds to the reprocessed DUACS Delayed-Time v**DT2024** products.

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP2-CDR-SL-v3.0-2024-11	Sea level gridded data from satellite observations for the global ocean from 1993 to present	CDR	vDT2024	30/11/2024
WP2-ICDRD-SL-v3.0		ICDR	vDT2024	Pending at time of publication

Related documents

This document is part of a suite of reports documenting the production of Version DT2024 (and previous) Sea Level datasets available within the C3S service, some of which are referenced here in the text. These documents, their preferred citation, and how they appear in this document's main text (their reference id) are outlined in the following table.

Reference ID	Document
C3S_TRD	Mertz F., Taburet G., Ghantous M., Lefèvre F. (2025) C3S Sea level, Version DT2024: Target Requirements and Gap Analysis Document. Issue 3.1. E.U. Copernicus Climate Change Service. Document ref. C3S2-D312b-WP3-TRGAD-2024-SL-v3.0-202411-v3.1.
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_PQAR	Mertz F., Ballarotta M., Lefèvre, F., Quet V. (2025) C3S Sea level, Version DT2024: Product Quality Assessment Report. E.U. Copernicus Climate Change Service. Document ref. C3S2-D312b-WP2-FDDP-SL-v3.0-202411-PQAR-of-vDT2024-v1.1
C3S_SQAD	Mertz F., Mambert P. (2025) Sea Level, Version DT2024: System Quality Assurance Document, Copernicus Climate Change Service. Document ref. C3S2-D312b-WP3-SQAD-SL-v3.0-202411-v1.1
C3S_PUGS	F. Mertz, G. Taburet and J.-F. Legeais, 2025, C3S Sea Level, vDT2024: Product User Guide and Specifications. Issue 1.0 E.U. Copernicus Climate Change Service. Document ref. WP2-FDDP-2024-11_C3S2-D312b-PUGS-of-vDT2024-SeaLevel-products_v1.1

Acronyms

Acronym	Definition
ADT	Absolute Dynamic Topography
CCI	ESA’s Climate Change Initiative
CDR	Climate Data Record
DUACS	Data Unification and Altimeter Combination System
ECV	Essential Climate Variable
EKE	Eddy Kinetic Energy
ESA	European Space Agency
GDR	Geophysical Data Record
L2P	Level-2 Plus
LWE	Long Wavelength Errors
MADT	Map of Absolute Dynamic Topography
MDT	Mean Dynamic Topography
MSLA	Map of Sea Level Anomaly
MSL	Mean Sea Level
MSS	Mean Sea Surface
OE	Orbit Error
SAD	Static Ancillary Data
SLA	Sea Level Anomaly
SSH	Sea Surface Height

General definitions

Sea Level	Level of the sea surface; this term is ambiguous and is used generically in this document.
Sea Level Anomaly (SLA)	Anomaly of sea level compared to a mean sea level, which has been approximated by the mean sea surface.
Absolute Dynamic Topography (ADT)	The difference between the Satellite's altitude above the geoid and the distance—called the "range"—measured by the altimeter; also called the dynamic topography (cf. sea surface height).
Mean Dynamic Topography (MDT)	The dynamical part of the mean sea surface, determined by subtracting the geoid from the mean sea surface.
Mean Sea Surface (MSS) or **Mean Sea Level (MSL)**	Long-term temporal mean of the observed sea surface height. For C3S, this is a gridded variable.
Geoid	The form the ocean surface would take if only gravitational and rotational forces were at work (i.e. excluding currents, atmospheric forcing and tides); it is an equipotential surface and is measured relative to the reference ellipsoid.
Sea Surface Height (SSH)	The difference between the Satellite's altitude above the reference ellipsoid and the distance—called the "range"—measured by the altimeter (cf. absolute dynamic topography; NB: the term "sea surface height" is sometimes used to refer to a different quantity in other contexts, such as ocean modelling).
Geostrophic current	The velocity component of the ocean currents which is due solely to the balance between the pressure gradient and the Coriolis force.
Reference ellipsoid	An arbitrary ellipsoid from which the satellite's altitude is measured; it is chosen to approximate the Earth's surface.

Reference missions	A specific satellite mission acquiring measurement data that serves as a baseline, or standard, against which measurements acquired by other satellite missions are calibrated, validated, and compared. Reference missions are crucial for ensuring the continuity, consistency, and accuracy of Climate Data Records.
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 (ICDR)	Dataset that has been forward processed, using the baselined CDR algorithm and processing environment, to extend the timeline of measurements originating with the CDR. Note that the consistency and continuity of the ICDR have not been verified, which the user must keep in mind.
DUACS	Data Unification and Altimeter Combination System: An operational multi-mission production system of altimeter data developed by CNES/CLS.
Level 1 data	These measurement data are timed and located, and are also expressed in the appropriate units, and checked for quality.
Level 2 data	These data are corrected for instrument errors, errors due to atmospheric signal propagation, and perturbations caused by surface reflection. Geophysical corrections are then applied (for example, corrections for solid earth, ocean and pole tides, amongst others).
Level 3 data	These data are validated (off-record data are edited), cross-calibrated (I.e. calibrated to a reference mission), along-track data.
Level 4 data	These are multi-satellite (cross-calibrated), gridded data.

Contents

Scope of the document

This document is the Algorithm Theoretical Basis Document (ATBD) for Sea Level (level 2) product, Version DT2024 (vDT2024), produced by Collecte Localisation Satellites (CLS)[1] from instruments on altimetry satellites. It describes the algorithms used to generate the Sea Level product, including the scientific justification for the algorithms selected to derive the product, an outline of the implemented approach and a listing of the assumptions and limitations of the algorithm.

Executive summary

This Algorithm Theoretical Basis Document summarises the procedures implemented to map altimetry-derived sea level anomaly data in the Data Unification and Altimeter Combination System (DUACS), which is used to produce the C3S sea level altimeter product version vDT2024. The product contains the following data:

- Sea level anomaly (SLA)
- Absolute dynamic topography (ADT).
- Absolute geostrophic velocity meridian component
- Absolute geostrophic velocity zonal component
- Geostrophic velocity anomalies meridian component
- Geostrophic velocity anomalies zonal component
- Ice flag
- Instrumental drift correction

The DUACS requires a suite of corrections to be input as pre-processing ancillary data (see Section 2), referred to as the altimeter standard[2]. For the C3S version vDT2024 sea level product, and all preceding versions, two missions are used: a primary reference mission and a secondary mission. The reference mission changes over time, however, to ensure consistency the replacement mission always follows the same orbit, therefore always samples the same part of the surface. The secondary mission is calibrated with respect to the primary mission (more information is presented in Section 1). An optimal interpolation algorithm is used to complete (or "flesh out") two-dimensional maps of sea level anomaly, with viable data values derived from the corrected and inter-calibrated along-track altimeter data. These maps are then used to generate the derived products, which are the absolute dynamic topography and geostrophic velocities. An overview of the process is described in Section 3.2 with specific details of the various algorithmic components given in Sections 3.3 to 3.7. Finally, an overview of the output data is provided in Section 4, together with the variable names as included in the data set. These are linked to their origins in the algorithm process.

[1] For more information on CLS, see https://www.cls.fr/en/ [last accessed 11th December 2024]

[2] The altimeter standard is a collection of algorithms and corrections determined upstream which relate to the functioning of the altimeter and its satellite carrier, for example the ionospheric correction, the satellite's orbit, and many others. They can change at any time and not just when a new CDR or ICDR is produced.

1. Instruments – satellite altimeters

The C3S version vDT2024 altimeter-derived sea level data products are based on a satellite constellation with a stable number of altimeters. This ensures the long-term stability of the ocean observing system's sea level estimates. Reference missions (Topex-Poseidon, Jason-1, 2, 3 and Sentinel-6MF) are used to ensure the long-term stability of the CDR and the Mean Sea Level (MSL).

There is also a second type of altimeter mission included in the products. These secondary missions are the complementary and opportunity missions depending on the time period of their operation (e.g. Cryosat-2). They provide additional information for the estimation of mesoscale signals and also increase the ocean coverage at high latitudes. The missions currently included in the production system are the Sentinel-6MF and Sentinel-3a mission pair. The complete altimetric satellite constellation used in the C3S Sea Level products is illustrated in Figure 1.

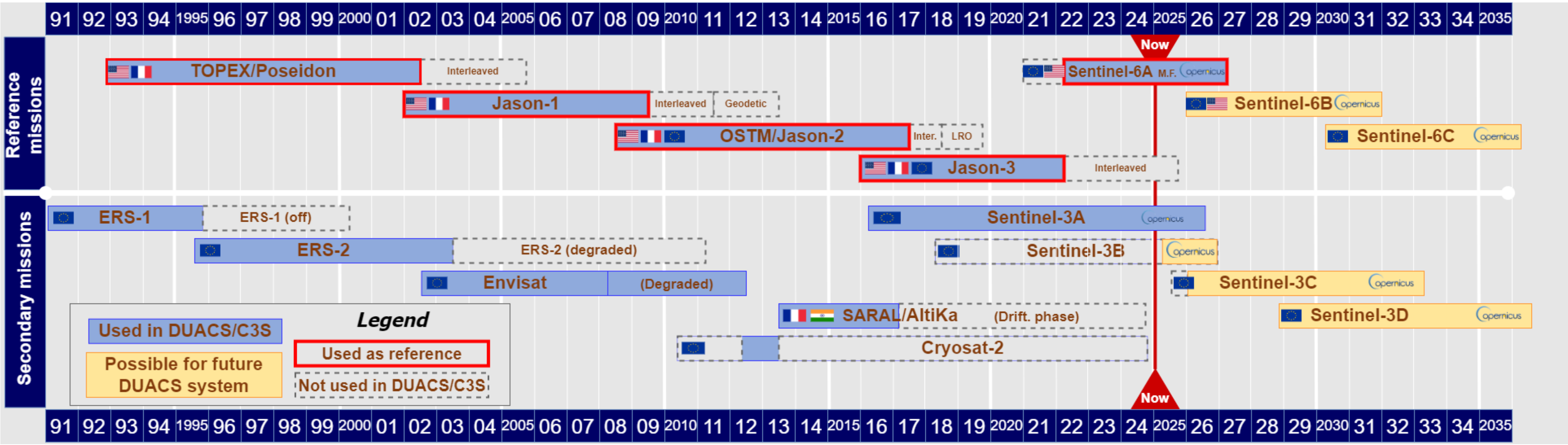

Figure 1. Overview of the availability period of the L2P products (input for the DUACS, and therefore the C3S production lines) for each altimetric mission. Missions can be categorized into 2 groups – Reference and Secondary missions.

2. Input and auxiliary data

The main input data for the altimeter-derived sea level production system are known as the Fundamental Climate Data Records (FCDR) within the Copernicus community (also called L2P within CNES/EUMETSAT). The FCDR sea level measurements have benefited from Calibration/Validation analyses and only validated data are made available. The FCDRs provide the required information to compute the along-track Sea Level Anomaly (SLA) such as the orbit solution, geophysical altimeter corrections (tides, dynamic atmospheric corrections, troposphere and ionosphere corrections, Sea State Bias) and the Mean Sea Surface used as a reference (see Section 3.3.1). The global and regional biases between the different missions are corrected by using altimeter measurements acquired during the commissioning phases (when two satellites measure the same ocean state). However, particular attention is paid to the content of the different (F)CDR products available in terms of standards and corrections for climate applications. For each data source it is verified that the FCDRs contain adequate information to employ the QA4EO principles[3] (quality indicator and traceability).

The production of the temporal extension of the sea level record (Interim Climate Data Record: ICDR) is entirely dependent on the availability of the FCDR/L2P input data. All altimeter standards (and in particular, the orbit solution) must be available for all altimeter missions processed within the C3S framework before production can begin. These altimeter missions can be seen in Figure 1.

[3] https://qa4eo.org/ [last accessed 3rd January,2025]

3. Description of the production system

3.1 The basics of altimeter measurement

The altimeter measures the altimeter range, which is the distance between the center of mass of the satellite to the surface of the Earth (see Figure 2). From this, the sea surface height (SSH) can be computed; this is the height of the sea surface above the reference ellipsoid. The satellite altitude, or orbit, refers to the distance of the center of mass of the satellite above a reference point. The reference point will usually be either a point on the reference ellipsoid or the center of the Earth.

$$SSH = orbit - range - correction \quad [1]$$

The corrections due to environmental conditions need to be applied in order to retrieve the correct sea surface height. The mean sea surface (MSS_P) is the temporal mean of the SSH over a period P. It is a mean surface above the reference ellipsoid, and it includes the geoid.

$$MSS_P = \langle SSH \rangle_P \quad [2]$$

The MSS used in the C3S products is available via the Aviso+ website[4].

The sea level anomaly (SLA_P) is the anomaly of the signal around the mean component. It is deduced from the SSH and MSS_P:

$$SLA_P = SSH - MSS_P \quad [3]$$

Mean dynamic topography (MDT_P) is the temporal mean of the SSH above the geoid over a period N.

$$MDT_P = MSS_P - geoid \quad [4]$$

The absolute dynamic topography (ADT) is the instantaneous height above the geoid. The geoid is an equipotential surface that would correspond with the ocean surface if the ocean was at rest (i.e. with no forcing other than gravity and the centrifugal force of the rotating Earth; Hughes and Bingham, 2008). Other forcings such as those by the wind, differential heating and precipitation, deviate the ocean's surface from the geoid. Thus, the departure from the geoid provides important information of the dynamic ocean.

The ADT is the sum of the SLA_P and MDT_P:

$$ADT = SLA_P + MDT_P - SSH - MSS_P + MDT_P \quad [5]$$

The reference period P considered can be changed, as described in Pujol et al. (2016). Many of the above terms are visualized in Figure 2.

[4] http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mss.html, with registration [last accessed 6th January, 2025]

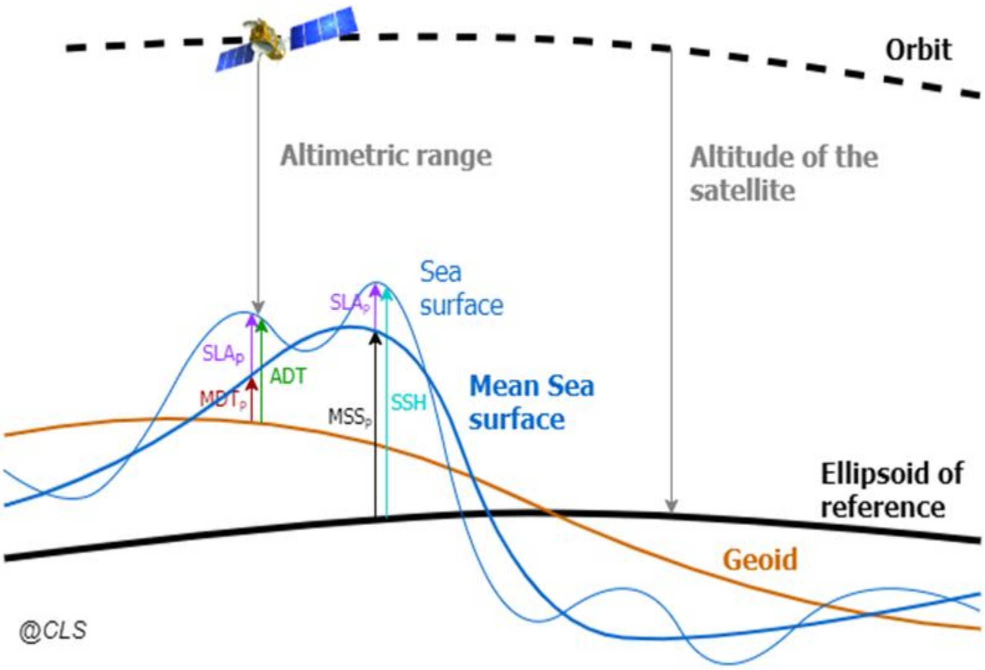

Figure 2. Schematic of the various quantities showing what they are measured relative to. The abbreviations are SSH: Sea Surface Height; SLA: Sea Level Anomaly; MDT: Mean Dynamic Topography; ADT: Absolute Dynamic Topography; MSS: Mean Sea Surface. The letter P subscript refers to the period over which the mean values are calculated.

3.2 Overview of the processing chain

The Sea Level C3S production chain is based on the DUACS that has been adapted to fulfill the C3S Target Requirements [C3S_TRD]. The current version of the product is version vDT2024, corresponding to the DUACS vDT2024 reprocessed delayed-time altimeter sea level products (see Figure 3).

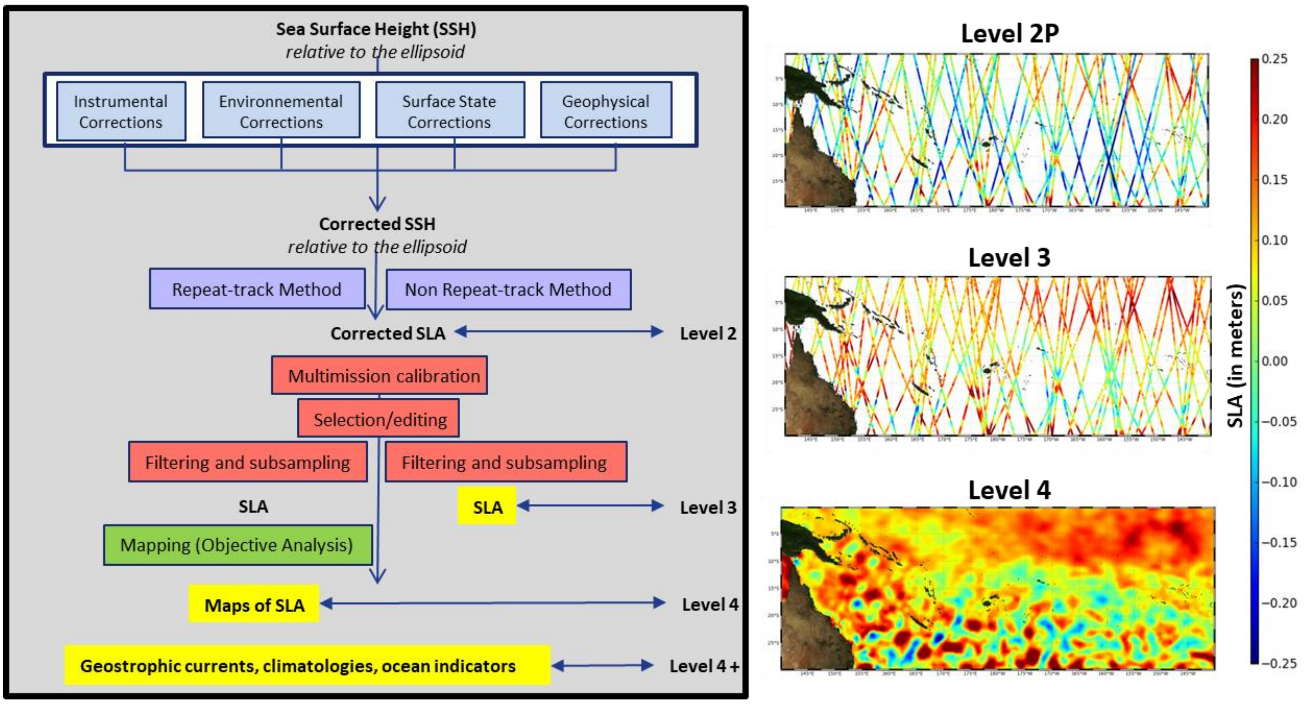

Figure 3. Architecture of the production system used for the version DT2024 data available through the C3S Climate Data Store. The panel on the left illustrates schematically the different steps used to produce the different datasets; on the right are examples of what each of these datasets looks like when plotted for the same sea state. Note that only the level 4 dataset (calculated using two satellites) is available through the C3S Climate Data Store.

The processing sequences can be divided into several key steps, from data acquisition to production of Sea Level ECV products and quality control. The following sections describe the algorithms used in each step (note that an algorithm can depend on another and can be used in different steps). The validation phases are described in detail in the Quality Assurance Document ([C3S_PQAD]). They are crucial for the uncertainty estimations. The key steps are summarized in the schematic in

Figure 4, and are detailed in the following subsections.

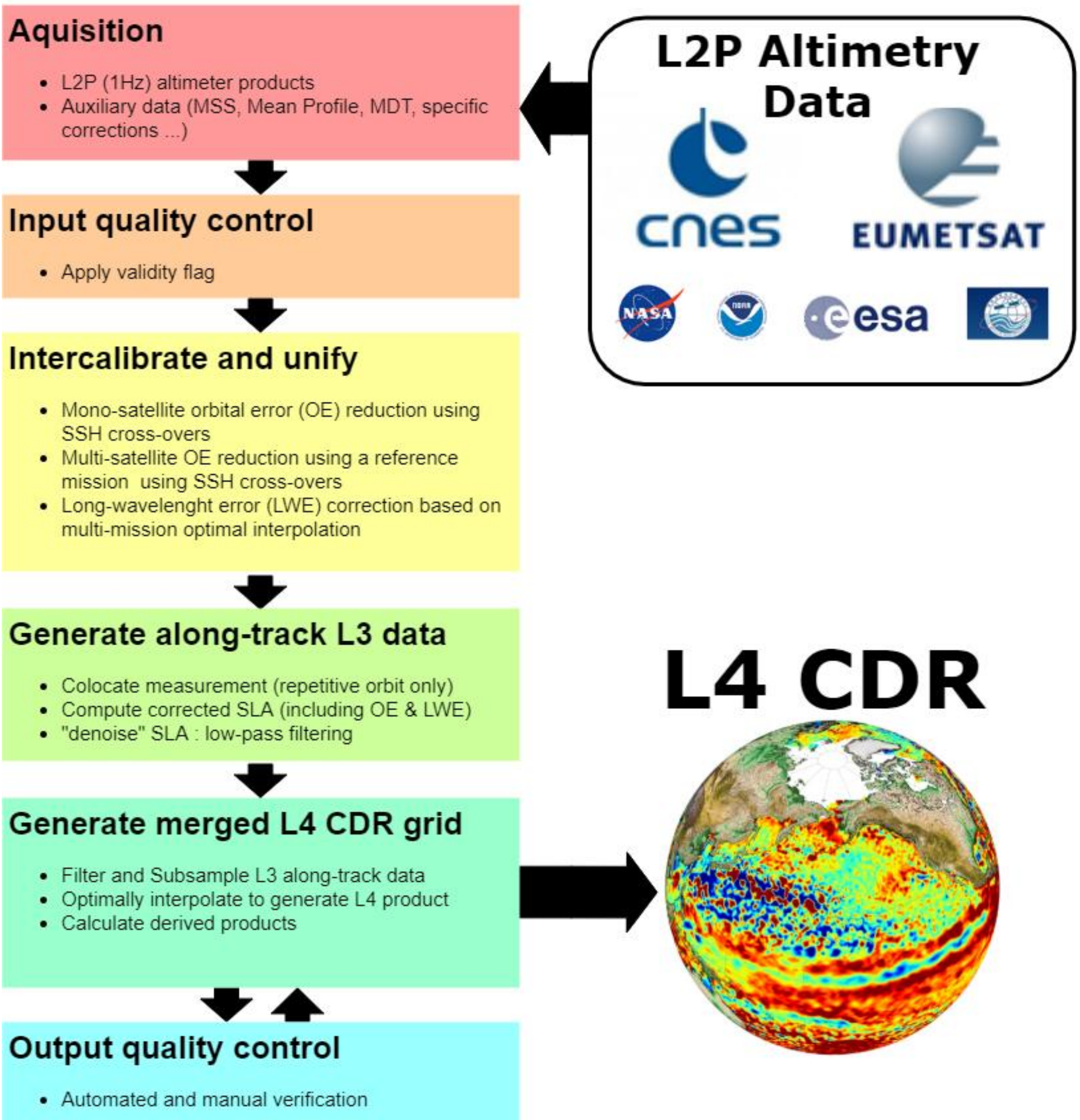

Figure 4. Schematic of the production process described in Section 3.

3.3 Acquisition

3.3.1 Summary

This step consists of acquiring input data for the system. The main input data are Level 2P altimeter products (these correspond to the Fundamental Climate Data Record for the C3S sea level product) provided by Space Agencies and CLS. For C3S, only Delayed-Time products are used. Other ancillary data (atmospheric forcing, MOG2D correction) are also acquired. Data are formatted, and synchronization is applied in order to freeze altimetry flow processing until reception of all ancillary data needed for complete processing. The resulting database of altimetry and auxiliary data are then used in the following steps. For information on how this upstream data is prepared, see the Aviso handbooks for the Sentinel[5] missions and for missions[6] other than Sentinel.

The L2P validation flags and regional and global biases are applied to guarantee that the processing chain uses the most accurate altimeter data.

3.3.2 Process description

The components used to generate the level 2P SLA and SSH are known as the altimeter standards. They are defined by the following formulae:

$$SLA = SSH - MSS \qquad [6]$$

and

$$SSH = Orbit - Range - \sum_{i=0}^{N} C_i \qquad [7]$$

The Sea Surface Height (SSH) is the height of the sea surface above the reference ellipsoid MSS, which is the Mean Sea Surface of the ocean over a long period. The Sea Level Anomaly (SLA) is the anomaly of the signal around the mean component.

The orbit corresponds to the distance between the satellite and the ellipsoid; the range is the distance measured by the altimeter between the satellite and the sea surface; and $\sum_{i=0}^{N} C_i$ is the sum of all the corrections needed to take the atmospheric effects, the geophysical phenomena and the sea-surface state into account. A list of these corrections can be found in the AVISO Handbooks[7].

The choice of the best altimeter geophysical corrections to produce the level 2P input products results from research and development activities carried out at CLS as part of a broader effort in altimetry in

[5] https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_L2P_S3_S6.pdf [last accessed 6th January, 2025].

[6] https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_L2P_all_missions_except_S3_S6.pdf [last accessed 6th January, 2025].

[7] https://www.aviso.altimetry.fr/fr/donnees/information-sur-les-produits/manuels-dutilisation-des-produits-aviso.html [last accessed 6th January, 2025].

conjunction with the Copernicus Marine Service[8], the CNES[9], and ESA[10], and thus falls outside of the purview of C3S.

Process output:

- Along-track SLA measurements for each processed mission.

3.4 Intercalibrate and unify

3.4.1 Summary

In this step, multi-mission cross-calibration is performed to ensure the consistency and accuracy of all the data flows from all satellites. This process uses empirical processes to minimize long-wave geographically correlated errors. After determining the crossover locations and differences, there are two separate calibrations to reduce them: (i) a dedicated method for orbit error reduction is applied by using a crossover minimization with a reference mission and (ii) a cross-calibration process is applied to reduce the residual long-wavelength error signal.

3.4.2 Compute crossover data

Crossover points are identified and located, and the altimetry parameters over them are interpolated.

Process input:

- Along-track data validated SSH.

Crossover points are where two satellite tracks intersect, whether they be mono-mission (the same satellite passes over the same point later in its cycle) or multi-mission (two satellites cross over the same point). These crossover points enable the calibration of the observations by comparing measurements for a place and time. To ensure that the comparison has meaning, crossover points are never more than ten days apart, a length of time less than that of the temporal variability of the ocean surface. The algorithm is divided into 2 main stages:

1. *Determine locations of mission path crossovers*

   For mono-mission analysis, the crossover locations are determined by the crossing of ascending and descending passes for a single mission. The geographic distribution of the crossover locations depends on the orbit characteristics of the processed mission. For multi-mission analysis, the crossover locations between two different missions are determined by the crossing of one pass of the reference mission with the passes of the secondary mission that are within the chosen temporal window. The passes can be either ascending or descending depending on the geographic distribution.

[8] https://marine.copernicus.eu [last accessed 25th November, 2024], formerly known as the Copernicus Marine Service (CMS)
[9] https://cnes.fr [last accessed 6th January, 2025].
[10] https://www.esa.int [last accessed 25th November, 2024]

2. *Interpolation of altimetry parameters at crossover location*

Once the crossover locations are identified, all altimeter fields (measurements, corrections and other fields such as bathymetry or MSS) are interpolated at crossover locations and dates. Most parameters are interpolated linearly, but the interpolation of the SSH is calculated using splines as it is highly sensitive to measurement noise and along-track variations in surface topography. Crossovers are then appended to the existing crossover database as more altimeter data becomes available. This crossover dataset is the input of the orbit error (OE) reduction method.

Process output:

- Interpolated SSH at crossover locations.

3.4.3 Compute mono-mission satellite orbit error

The orbit error is deduced from a single mission analysis of crossover SSH.

Process input

- Crossover data of the reference mission.
- Validated along-track SLA measurements.
- Processing parameters: Static Ancillary Data (SAD).

This algorithm deals with orbital error estimation deduced from crossover SSH differences in the case of a single mission. The orbital error reduction processing for a single mission is based on the regression of a sinusoidal model of the observations, which is given by the SSH crossover differences for a whole cycle of data. These observations are assumed to contain only orbital errors, whose variations are due to long wavelength errors and can be modelled by a sinusoid of 1 or 2 cycles per orbit revolution.

This algorithm is activated only for the mission chosen as the reference mission in the DUACS.

Further information on the model used can be found in Tai et al., 1986.

Process output

- Along-track orbit error.
- Along-track SLA corrected for orbital error.

3.4.4 Compute multi-mission OE

The orbit error is deduced from a multi mission analysis of the crossover SSH.

Process input

- Crossover data of two missions:
  - SSH crossovers corrected for orbital error for the reference mission,
  - SSH crossovers for the secondary mission.
- Validated along-track SLA measurements for the secondary mission.
- Processing parameters (SAD).

This algorithm deals with orbital error estimation deduced from crossover SSH differences. The orbital error estimation relies on the following assumption: there is an altimetric mission with a more accurate orbit than the other missions available in the Level 3 system—this is considered as the reference mission. All the other missions are considered as secondary missions and their orbital error is deduced from crossovers of the secondary mission with itself, added to crossovers with the reference mission, which has already been corrected for orbital error.

The orbit error for the secondary mission is estimated by fitting a cubic spline to the observations. This process consists of reducing orbit errors through a global minimization of (i) the crossover differences observed for the reference mission, and (ii) between the reference and other missions also identified as complementary and opportunity missions.

The process is described in detail in Le Traon et al., 1998

Process output

- Along-track orbit error for the secondary mission.
- Along-track SLA corrected for orbit error for the secondary mission.

3.5 Generate L3 Data

3.5.1 Summary

Once altimeter data are validated and inter-calibrated, different Sea Level Anomaly (SLA) products are generated using a reference field that is the Mean Sea Surface (MSS). Data are first projected on theoretical co-located track positions using precise cross-track projection and interpolation schemes. A final quality control processing is applied on these data to edit possible isolated and slightly erroneous measurements.

3.5.2 Compute SLA

The along-track SLA data are computed onto the satellite's theoretical track for each processed mission.

Process input

- Along-track SSH measurements corrected for orbit error.
- Processing parameters (SAD).

Along-track SLA are computed from the difference between the SSH observations minus the Mean Sea Surface (MSS), which is a pre-defined, gridded temporal mean of the SSH, calculated in the present version over a 20-year period from 1993 to 2013 (Schaeffer et al., 2012; Pujol et at., 2018a) and interpolated onto the satellite's theoretical track. The SSH observations are themselves interpolated onto the theoretical track as well, as there is an along-track deviation that must be corrected. Across-track deviations are considered small enough to ignore. The errors affecting the SLAs and MSS have different magnitudes and wavelengths. The computation of the SLAs and their associated errors are detailed in Dibarboure et al., 2011 and Pujol et al., 2016.

Process output

- Along track SLA measurements for each processed mission.

3.5.3 Validate SLA

This step involves validating the along-track SLA data.

Process input

- Along-track SLA measurements.
- Mean sea level anomaly multi mission reference maps.
- Processing parameters (SAD).

The aim of this step is to eliminate spurious residual data that could not be detected by previous validation steps. The along-track data are compared to mapped data, and the difference evaluated for each observation. These reference maps are produced in the same way as the maps in Section 3.6.3. However, prior to all the error correction, without fully resolving the smaller-scale signal and only using past data in the optimal interpolation; they are intended only to give a rough prediction of the mapped SLA. This enables local variability to be estimated, noting that these estimates are not intended for distribution.

The difference is then compared with a map of long-term SLA variance, calculated over 9 years of historic data. A variance representing the instrumental noise is added to the local variance, and the sum is inflated by a scalar factor depending on the distance from the coast. If the squared distance is greater than this, then the observation is rejected.

Process output

- Validated Along-track SLA measurements.

3.6 Generate merged L4 CDR grid

3.6.1 Summary

Finally, level 4 merged maps of SLA are produced by optimally interpolating the along-track, cross-calibrated L3 SLA products. The mapping process is refined to compute the SLA maps for a given date with realistic spatial and temporal correlation scales, producing a map of the measurements merging the observations from all altimeter missions required in the system. Specific algorithms are used to improve the mapping technique for climate applications.

3.6.2 Filter and subsample SLA

Here, a numerical filter is applied to the SLA measurements, which are then subsampled.

Process input

- Validated along-track SLA measurements.
- Processing parameters (SAD).

The aim of this algorithm is to reduce the high frequency content that cannot be properly retrieved mainly due to limitations in the altimetry spatial and temporal sampling, i.e. the altimeters cover only part of the Earth's surface, and the coverage varies with latitude. Thus, to prepare the data for the mapping process, the along-track SLA are low-pass filtered by applying a cut-off wavelength that varies smoothly with latitude using an empirically derived function (see Ducet et al., 2000). Wavelengths shorter than ~200km at the Equator and ~65km at latitudes above 40 degrees are suppressed. For use in the L4 gridded products, a latitude-dependent subsampling is applied in order to be commensurate with the filtering, so that only as many points as needed to represent the remaining spectral content are retained. The non-subsampled data is retained for the L3 along-track products which are delivered to users.

Further information can be found in Dufau et al., 2016; Pujol et al., 2016; Ducet et al., 2000.

Process output

- Filtered along-track SLA for each processed mission.
- Filtered and subsampled along track SLA for each processed mission.

3.6.3 Compute gridded SLA product

The daily mean MSLA grids and associated error are computed from SLA data.

Process input

- Filtered and subsampled along-track SLA measurements corrected for orbital error.
- Processing parameters (SAD).

A mapping procedure using Optimal Interpolation (OI: Bretherton et al., 1976) is applied to produce SLA maps (MSLA products) at a given date. The OI requires a good description of (i) the characteristics of the physical signal to be mapped (like realistic correlation functions) and (ii) the observation errors. Observation errors taken into account are two-fold: an uncorrelated component, and along-track long-wavelength correlated errors (Pujol et al., 2016). The procedure generates a map merging measurements from the altimeter missions prescribed in the system (Ducet et al., 2000). Combining data from different missions significantly improves the estimation of mesoscale signals (Le Traon and Dibarboure, 1999; Le Traon et al., 2001; Pascual et al., 2006). The MSLA products are computed, incorporating data 6 weeks either side of the computation date, weighting those closer to the computation date more heavily. An example map is shown in Figure 5.

The formal mapping error is an indicator of the representativeness of the gridded SLA, i.e. how well the mapped SLA represents the temporal and spatial scales implicit in the altimeter data (it is formal in the sense that it is not a measure of the accuracy of the gridded SLA, which can only be deduced by comparing against an independent observation). Also known as formal error variance, in practice, it corresponds to a local least-squares minimum of the error variance. It depends on (i) the constellation sampling capability (i.e. the spatial distribution and the density of the data used in the optimal estimation), (ii) the consistency of the spatial and temporal scales of the data with the sea surface variability, and (iii) the instrumental noise. These are described in Le Traon et al (1998) and Pujol et al (2016). The formal mapping error is usually low under the tracks of the different altimeters used in the mapping, and in between the tracks becomes higher with distance from the tracks. Higher formal mapping errors are also observed over high variability areas (where SLA variability is high). Figure 5 shows examples of the formal mapping error, with darker areas representing a higher error. The fundamental / core algorithm used for the mapping procedure is described in Pujol et al., 2016.
Further information can be found in Ducet et al., 2000 ; Le Traon et al., 1998 ; Le Traon et al., 2003 ; Pujol et al., 2016; Bretherton et al., 1976.

Process output

- Mean Sea Level Anomaly (MSLA) grids - Multi-mission daily mean MSLA on a regular longitude-latitude grid.
- Multi-mission daily mean formal mapping error grid for the MSLA Grid.
- Multi-mission daily mean formal mapping error grid for geostrophic velocities.

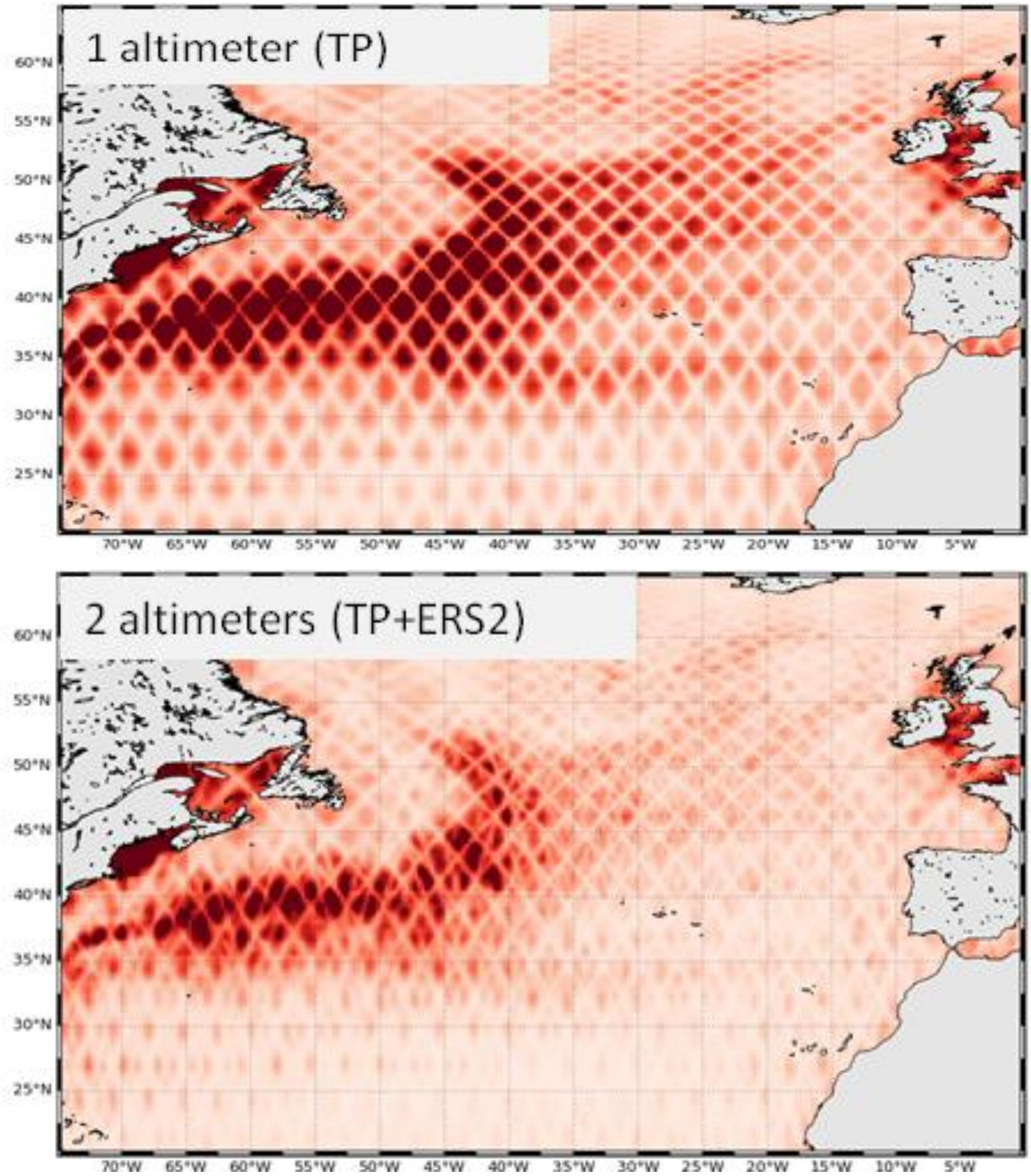

Figure 5. Formal mapping error over the gulf stream. The upper map shows the error calculated when only one mission is used to generate the mapped SLA, whereas for the lower map two missions are used. Darker means there is a greater formal mapping error; the satellite tracks are clearly visible as the lighter tracks and note the dark "diamonds" between tracks where the error is highest.

3.6.4 Compute L4 derived gridded products

Compute the derived products from MSLA grids.

Process input

- Geophysical parameters
    - Mean Sea Level Anomaly (MSLA) grids
    - Mean Dynamic Topography (MDT) (SAD)

The estimated map of SLA (MSLA) is used to generate other products such as geostrophic currents or a map of Absolute Dynamic Topography (MADT; more information in Taburet et al., 2021). An example is presented in Figure 6.

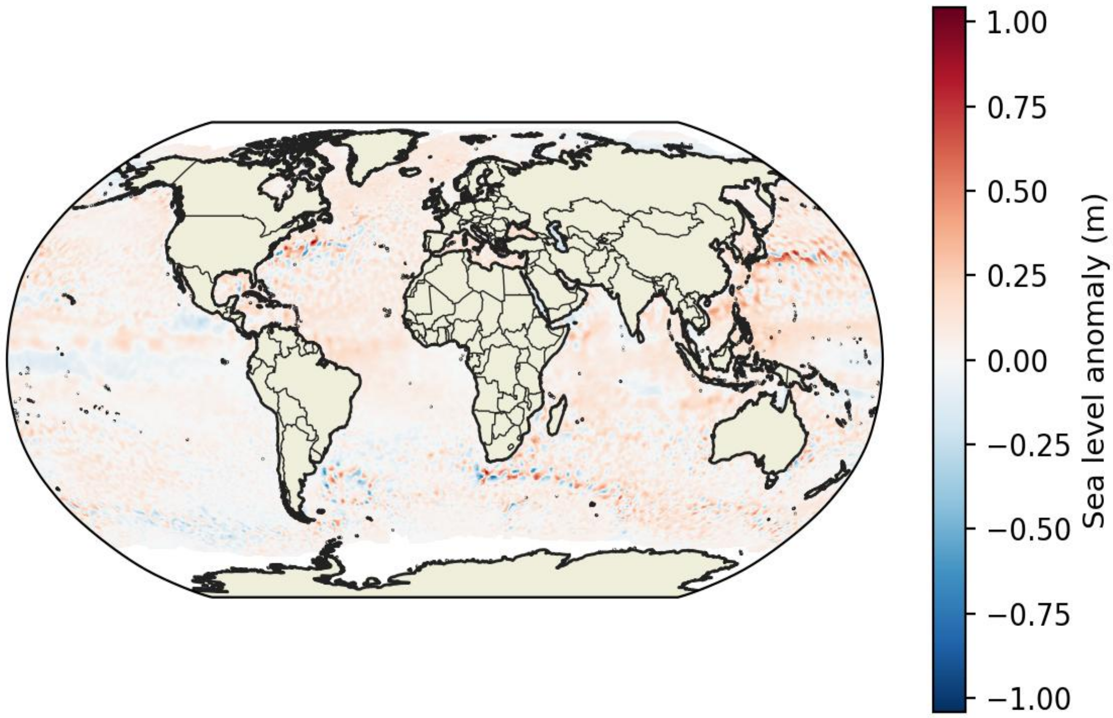

Figure 6. Example of Sea Level Anomaly Maps possible on data for the date 15/08/2010.

Geostrophic velocity anomalies are computed using finite differences. The geostrophic velocity (with u the zonal velocity and v the meridional velocity) is defined in terms of the gradient of the pressure (p) and the Coriolis parameter (f).

$$u = -\frac{1}{f\rho}\frac{\partial p}{\partial y} \; and \; v = \frac{1}{f\rho}\frac{\partial p}{\partial x} \; with \; f = 2\Omega \sin\Phi \qquad [8]$$

As the pressure gradient is approximately proportional to the gradient of the sea surface elevation, η ($p = \rho\eta g$), anomalies of geostrophic velocities are computed from sea level anomalies.

The anomaly of the geostrophic current disseminated to users is derived from gridded SLA field. It is computed using a 9-point stencil width (Arbic et al., 2012) for latitudes outside the ±5°N band. In the equatorial band, the Lagerloef method (Lagerloef et al., 1999) introducing the β plane approximation is used. The absolute geostrophic current is obtained by adding the mean geostrophic current, which is associated with the mean dynamic topography (MDT) to this anomaly. An example is presented in Figure 7.

The currents are then used to calculate the specific eddy kinetic energy (EKE), defined as

$$\frac{1}{2}(u^2 + v^2)$$

The geostrophic current anomaly is used to calculate the specific EKE which is in turn used to calculate the monthly mean eddy kinetic energy in Section 3.6.5.

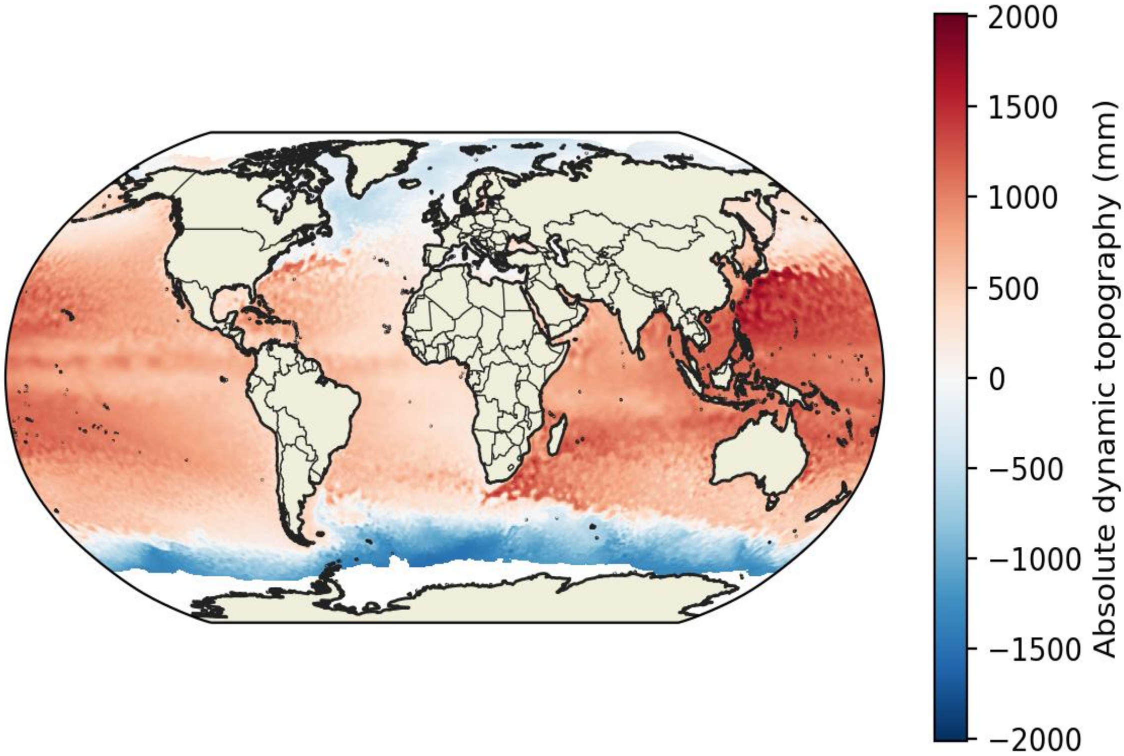

Figure 7. Example of Absolute Dynamic Topography map for 15/08/2010.

Further information can be found in Ducet et al., 2000; Lagerloef et al., 1999; Pascual et al., 2006; Pujol et al., 2016 and Faugere et al., 2022

Process output:

- Multi-mission Maps of Absolute Dynamic Topography (MADT) grid (Figure 7).
- Multi-mission grid of geostrophic velocity anomalies.
- Multi-mission grid of absolute geostrophic velocity (Figure 8).
- Multi-mission grid of Eddy Kinetic Energy (EKE)

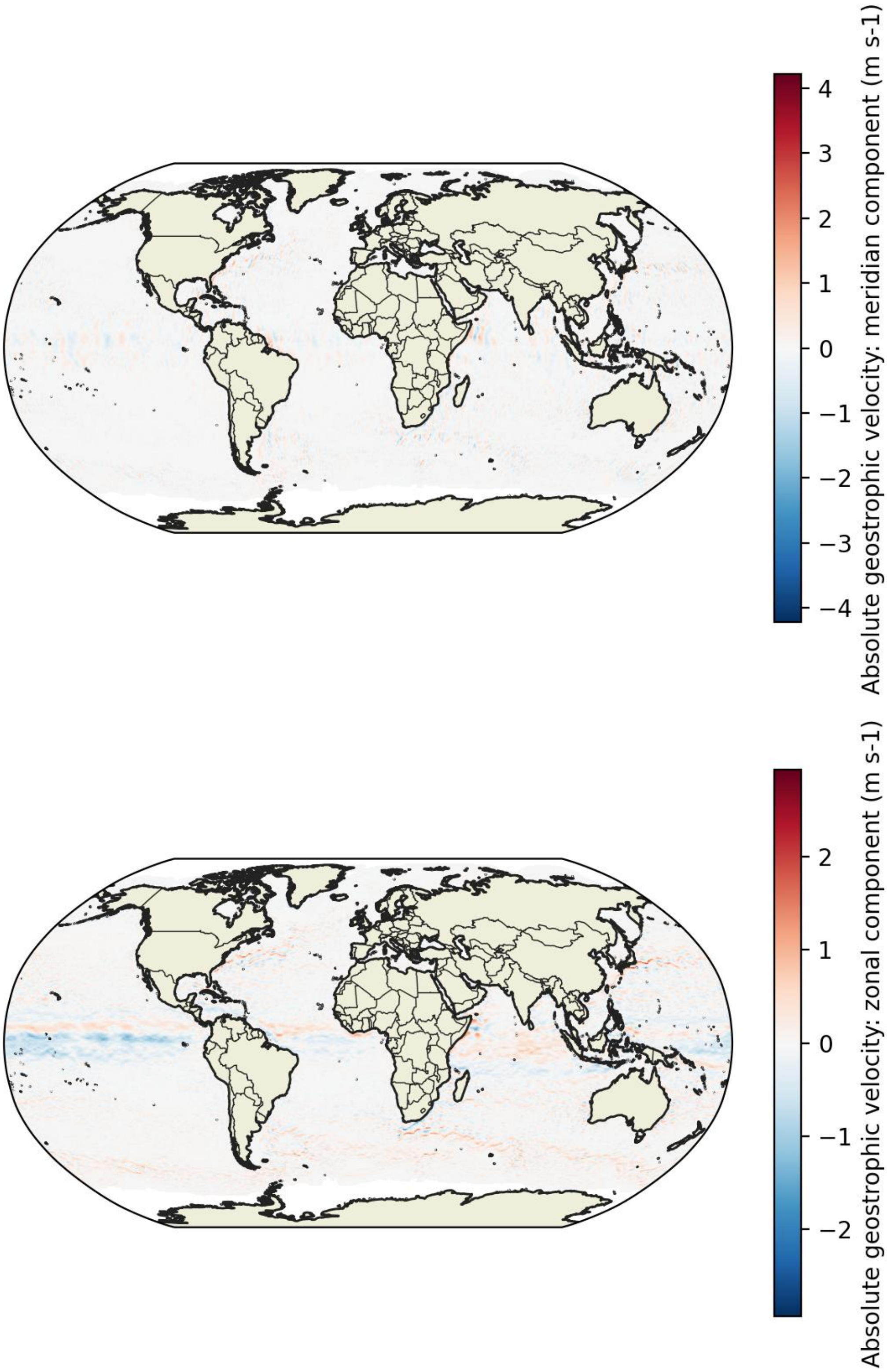

Figure 8. Example of Absolute geostrophic velocity meridional (top) & zonal (bottom) for 15/08/2010.

3.6.5 Compute climatological gridded products

Compute temporal means.

Process input

- Mean Sea Level Anomaly (MSLA) grids (see Section 3.6.3).
- Daily mean gridded EKE derived from SLA (see Section 3.6.4)

Monthly temporal means are calculated for each grid point using the daily mean fields as inputs. Means are only calculated for months with a complete series of daily fields. These monthly temporal datasets are delivered as point datasets.

Further information can be found in Taburet et al., 2019.

Process output

- Monthly mean gridded SLA and Eddy Kinetic Energy (EKE).

3.7 Output quality control

This represents the final step before the delivery of the products, and involves automated and manual verification, including the compiling and analysis of statistical quantities and visually inspecting maps. This task is described in more detail in the associated Product Quality Assurance Document (see [C3S_PQAD]) and in the Product Quality Assessment Report ([C3S_PQAR]).

For a detailed description of the SSALTO/DUACS see (Dibarboure et al., 2011 ; Pujol et al., 2016) and the Aviso website[11].

Each L4 variable is packaged into one dataset for each date, with the monthly products packaged separately.

3.8 Version development

Outlined in this document are the algorithms which produce version vDT2024 of the C3S Sea Level products. The first major version (v1.0, DT2018) was released in 2018, with iterative releases of improved, more accurate versions of data since. The present version (DT2024) has been improved with respect to the earlier version (DT2021), in particular by implementing a newer altimeter standard, resulting in a more accurate data set (Lievin et al., 2020; Faugère et al., 2022, Kocha et al., 2023). For this reason alone, the current version vDT2024 is to be preferred over the old one. The present version also includes a sea ice mask, and a correction for TOPEX-A when calculating global means. These are included as extra variables which the user is free to use or not, depending on their use case.

[11] The information available at the following URL: http://www.aviso.altimetry.fr/ searching information on SSALTO/DUACS MULTIMISSION ALTIMETER PRODUCTS. [Website last accessed 6th January, 2025].

3.8.1 Process description

The input quality control is a critical process applied to ensure that the processing chain uses the most accurate altimeter data. The L2P quality control consists of both simple raw data editing with quality flags or parameter thresholds, and on data editing algorithms based on the detection of erroneous artifacts, mono and multi-mission crossover validation, and macroscopic statistics to edit out large data flows that do not meet the system's requirements.

3.8.2 Further reading

Further information on calibration can be found in Benveniste et al., 2003; Vincent et al. 2003

4. Output Data

Parameters found in the output dataset are summarized in **Table 1**. They are available in NetCDF format, with a full description available in the Product User Guide and Specifications document ([C3S_PUGS]).

Table 1. Sea level data layers found in a single C3S sea level version vDT2024 data file, and their origins in the algorithm processing chain.

Variable	Attribute name in file	Description	Origin / Document Section
Sea level anomaly	sla	Sea surface height above the mean sea surface, referenced to the [1993, 2012] period. (Unit: m)	3.6.3
Absolute dynamic topography	adt	Sea surface height above the geoid computed as the sum of the sea level anomaly with the mean dynamic topography (Unit: m)	3.6.4
Absolute geostrophic velocity meridian component	vgos	Northward component of the absolute geostrophic current. (Unit: m/s)	3.6.4
Absolute geostrophic velocity zonal component	ugos	Eastward component of the absolute geostrophic current. (Unit: m/s)	3.6.4
Geostrophic velocity anomalies meridian component	vgosa	Northward component of the absolute geostrophic current anomaly. (Unit: m/s)	3.6.4
Geostrophic velocity anomalies zonal component	ugosa	Eastward component of the absolute geostrophic current anomaly. (Unit: m/s)	3.6.4
Sea level anomaly monthly mean	sla	Monthly mean of sea surface height above the mean sea surface, referenced to the [1993, 2012] period. (Unit: m)	3.6.5
Eddy kinetic energy monthly mean	eke	Monthly mean of specific eddy kinetic energy calculated from the sea level anomaly. (Units: cm^2/s^2)	3.6.5
Ice flag	flag_ice	Flag indicating the presence (flag = 1) or absence (flag = 0) of sea ice. This variable is only available in version vDT2021. (Dimensionless)	Externally sourced*
Instrumental drift correction	tpa_correction	This correction is not yet available for the current product version. This field will be updated once this correction is produced. This variable can be added to the gridded SLA to correct for the observed instrumental drift during the lifetime of the TOPEX-A mission (the correction is null after	Externally sourced*

		this period). This is a global correction to be added a posteriori (and not before) on the global mean sea level estimate derived from the gridded sea level map. It can be applied at regional or local scale as a best estimate (better than no correction, since the regional variation of the instrumental drift is unknown).	

*Note that the ice flag and the TOPEX-A instrumental drift correction are sourced externally. See Lavergne et al, 2019 for the sea ice, and WCRP, 2018; More information on their inclusion here may be found in the C3S Sea level version vDT2024 Product User Guide and Specification document (C3S_PUGS).

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Copernicus Climate Change Service

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

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