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Consortium Members

ESA Sea Level Climate Change Initiative

Product user guide

November 25, 2024

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Issue:	1.9

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Acronyms

ALES Adaptive Leading Edge Subwaveform

CLS Collecte Localisation Satellites

CTOH Centre of Topography of the Oceans and Hydrosphere

DAC Dry Atmospheric Correction

DGFI-TUM Deutsches Geodätisches Forschungsinstitut - Technische Universität München

ESA European Space Agency

GDR Geophysical Data Record

GPD+ GNSS derived Path Delay

GSHHG Global Self-consistent, Hierarchical, High-resolution Geography database

L2P Level 2 Plus

LEGOS Laboratoire d'Études en Géophysique et Océanographie Spatiales

NetCDF Network Common Data Form

NOC National Oceanography Center

RADS Radar Altimeter Database System

SLA Sea Level Anomaly

SSB Sea State Bias

SSH Sea Surface Height

WTC Wet Tropospheric Correction

Chronology of issues:

Issue:	**Date:**	**Reason for change:**	Author:
1.0	30/09/19	Initial version	F. Léger (LEGOS)
1.1	18/11/19	ESA review comments	J.-F. Legeais (CLS)
1.2	05/01/20	Extension with Jason-3 (J3)	F. Léger (LEGOS)
1.3	25/05/20	SLA and trends product at selected sites	Y. Gouzènes (LEGOS)
1.4	11/03/21	Temporal J3 extension + new zones	F. Léger (LEGOS)
1.5	15/04/21	Addition of Envisat and SARAL/AltiKa	F. Léger (LEGOS)
1.6	24/01/22	New coastal product v2.1: update of along-track coastal sea level time series and trends with temporal extension up to Dec. 2019 and addition of American coasts, plus some new regions around Africa; New data selection and creation of a new set of virtual coastal stations	Y. Gouzènes, A. Cazenave, F. Léger (LEGOS)
1.7	03/01/23	New coastal product v2.2: update of the v2.1 product based on a few minor improvements brought to the data	Y. Gouzènes, A. Cazenave (LEGOS)
1.8	10/01/24	New coastal product v2.3: temporal extension up to June 2021, use of GDR-F for J3, slight improvement of the SSB editing at 20 Hz and improvement of the coast detection associated with a strong editing during the post processing	L. Leclercq, A. Cazenave, F. Léger (LEGOS)
1.9	06/11/24	New coastal product v2.4: improvement of the post-processing and adding of the averaged SLA in the 10 first points variable: `sla_mean_10pts`	L. Leclercq, A. Cazenave (LEGOS)

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1 Introduction

In the context of the European Space Agency's (ESA) climate change initiative sea-level project, the project partners (CTOH, LEGOS, DGFI-TUM, NOC and CLS) have produced a Level 2 Plus (L2P) multi-mission altimeter along-track time series and associated trends product in the world coastal regions. The product benefits from the spatial resolution provided by high-rate along-track data (20 Hz, i.e. ≈350 m resolution), the Adaptive Leading Edge Subwaveform retracking (ALES, Passaro et al. (2014, 2015, 2018b)) and the post-processing strategy of the X-Track algorithm developed at CTOH/LEGOS (Birol et al. 2017), adapted to 20 Hz data and using the best possible set of geophysical corrections (update of Birol and Delebecque (2014)).

The main objective of this coastal sea level product is to provide accurate altimeter Sea Level Anomaly (SLA) time series as close as possible to the coast. By merging X-Track and ALES altimetry processing tools, we have computed 20 Hz along-track Sea Surface Height (SSH) time series for Jason-1, Jason-2 and Jason-3 missions covering the January 2002 to June 2021 time span. The X-Track software reprocesses geophysical corrections and parameters from delayed-time Geophysical Data Record (GDR) products provided by space agencies and combines them with the ALES retracked waveforms (range, sigma0 and Sea State Bias (SSB)) to compute 20 Hz along-track SSH time series, after a robust editing of the measurements and corrections (described in Birol et al. (2017)). The full data processing is detailed in Birol et al. (2021), The Climate Change Initiative Coastal Sea Level Team et al. (2020) and Cazenave et al. (2022).

The present document provides the information about the latest coastal sea level products and how to use them. The new updated version (v2.4; November 2024) of along-track coastal sea level time series and associated trends from January 2002 to June 2021 is presented below. This dataset differs from the previous v2.3 product (released in January 2024) by two new criteria: (1) at least more than 50% of data per mission, (2) an improvement of the editing (outlier removal).

We strongly recommend to the users to use this v2.4 product.

Section 2 describes the altimeter standards used for the SLAs computation. Section 3 describes the different variables of the dataset. Section 4 presents the updates brought to the v2.4 product. Section 6 presents the updates brought to the v2.3 product.

The v2.4 coastal sea level product provides a set of 1132 altimetry-based virtual coastal stations and associated sea level data which can be used for studying long-term coastal sea level trends. Figure 1 shows the regions (R1 to R13) covered by this version.

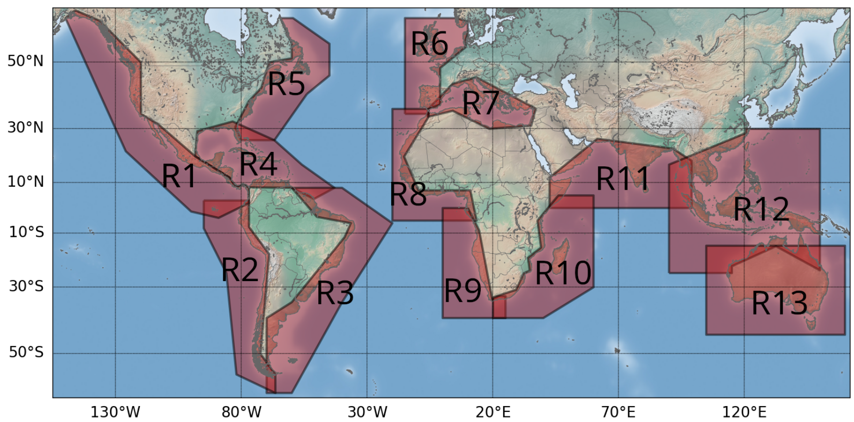

Figure 1: The regions covered by the along-track coastal sea level product. R labels refer to the regions numbers (see section 4.2.1)

2 Altimeter standards used for v2.4

The Jason-1, Jason-2 and Jason-3 data used by the X-Track software are based, respectively, on the GDR-E, GDR-D and GDR-F products of each mission. The altimeter range and SSB correction are provided by the ALES retracker product. The ocean tide correction and the Dry Atmospheric Correction (DAC) come from the Radar Altimeter Database System (RADS). The Wet Tropospheric Correction (WTC) used is the GNSS derived Path Delay (GPD+) (Fernandes and Lázaro 2016), provided by the University of Porto. The list of the parameters used in the computation of the SSH data is provided in the table 1. Note that the mean sea surface used to compute the SLAs is an area-averaged SSH and is thus not considered as an input dataset.

Parameters	Source	Jason-1	Jason-2	Jason-3
L2 standards	GDR	GDR-E	GDR-D	GDR-F
Altitude	GDR	Altitude of satellite		
Range	ALES	20 Hz Ku band ALES corrected altimeter range (Passaro et al. 2014)		
Ionoshere	GDR	From dual-frequency altimeter range measurements, further filtered by X-Track		
DAC	GDR	From ECMWF model		
WTC	GPD+	GPD+ radiometer correction (Fernandes and Lázaro 2016)		
SSB	ALES	Sea state bias correction in Ku band, ALES retracking (Passaro et al. 2018a)		
Solid tide	RADS	From tide potential model (Cartwright and Tayler 1971; Cartwright and Edden 1973)		
Pole tide	GDR	From Wahr (1985)		From Desai et al. (2015)
Loading effect	RADS	From FES 2014 (Lyard et al. 2021)		
Atmospheric correction	RADS	From MOG2D-G high frequencies (Carrère and Lyard 2003) + inverse barometer		
Ocean tide	RADS	From FES 2014 (Lyard et al. 2021) including ocean tide, long period equilibrium tide, S1 tide		

Table 1: Parameters used in the computation of the SSH

3 Data variables

Variables	Description
lat	Latitude of each 20 Hz point
lon	Longitude of each 20 Hz point
nbpoints	Index of each point (start from 1)
distance_to_coast	Distance to a reference point at the coast of each 20 Hz point. This reference point is the point of the track closest to the coastline (from GSHHG).
nbmonths	Index of time (start from 1)
time	Time of measurements (days since 1950-01-01)
sla	Monthly SLA time series over 1 January 2002 to 30 June 2021 derived from the original 10-day X-Track/ALES SLAs after post-processing at each 20 Hz point along-track (from 20 km offshore to the coast). Annual and inter-annual signals have been removed.
sla_mean_10pts	Averaged SLA time series over the first 10 nearest points to the coast.
local_sla_trend	Sea level trend computed from the monthly SLAs time series at each 20 Hz point in the along-track direction (from 20 km offshore to the coast).
local_sla_trend_error	Sea level trend error at each 20 Hz point in the along-track direction, based on the standard error of the slope regression coefficient (computed as the root square of the diagonal of the covariance matrix of the regression coefficient).

4 Along-track coastal sea level anomalies and trends: January 2002 - June 2021; v2.4 product

Figure 2 shows the distribution of the computed trends and associated errors, as well as distance to coast of the virtual stations. The average distance of the first valid point for the whole set of 1132 virtual stations is 4 km with 196 sites at less than 2 km, 325 sites at less than 3 km and 946 sites at less than 6 km from the coast (Fig. 3).

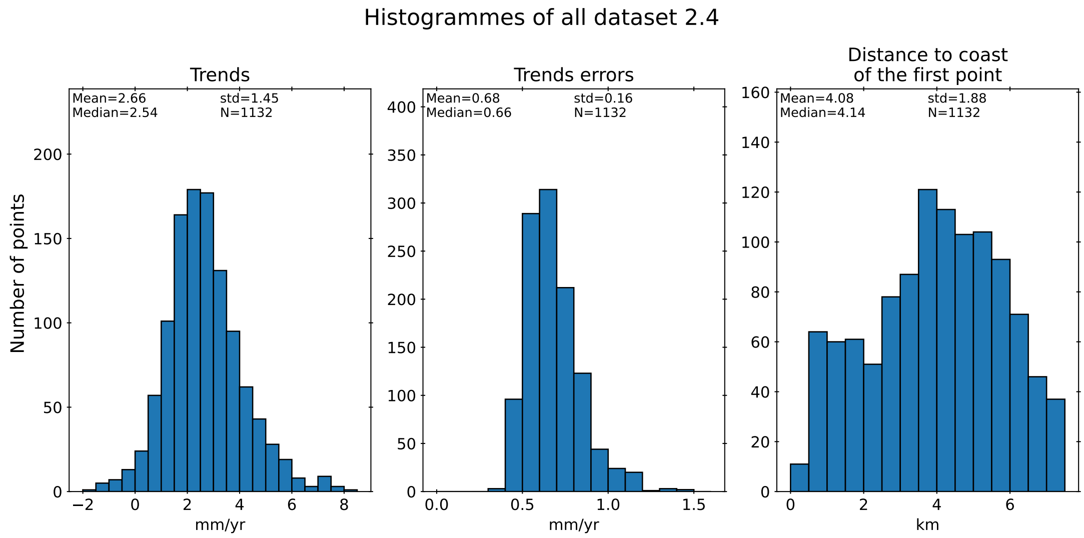

Figure 2: Histograms: trends and associated errors along-track averaged over 2 km from the closest valid point to the coast, and distance to coast of the first valid point, for each virtual stations of the v2.4 dataset.

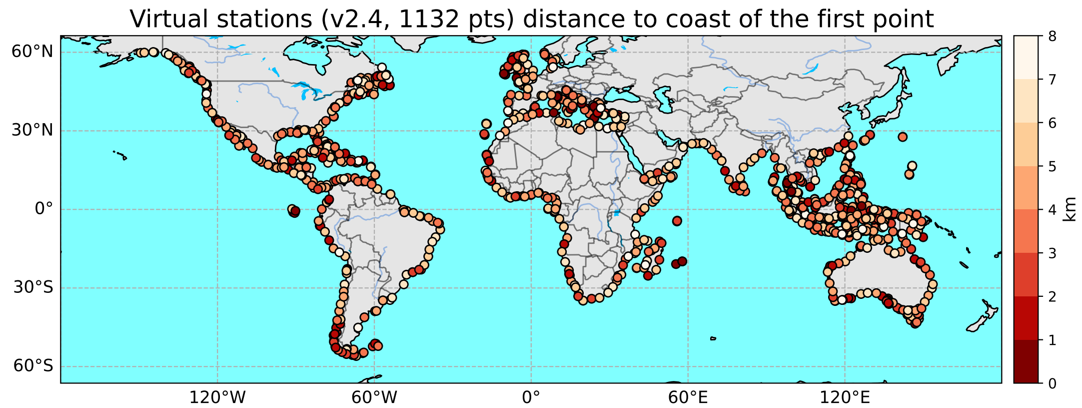

Figure 3: Map of the distance to coast of the first valid point for each virtual stations of the v2.4 dataset.

4.1 Improvement of the post-processing

To avoid problems of missing data during the Jason-1 mission leading to overweighting the data of Jason-2 and Jason-3 missions, a new criteria has been considered: points with less than 50% of valid data per Jason mission were discarded. This new criteria replaces the previous one that only considered points with at least 80% of available data in the whole time series. The new criteria should allow to have a more uniform distribution of valid data across the three Jason missions.

We also improved the outliers removal by implementing a non-parametric variance function based on lowess approach (Cleveland 1979). See also: `https://stats.stackexchange.com/questions/561120/predicition-interval-for-loess-smoothed-data`. This leads to removing data out of the interval:

$$\hat{E}(y|x) \pm 3 * \sqrt{\widehat{Var}(y|x)} \quad (1)$$

Where $\hat{E}(y|x)$ is the lowess fit of the time series and $\sqrt{\widehat{Var}(y|x)}$ is the standard deviation function. We obtain the squared deviation from the lowess estimate:

$$\hat{e}^2 = (y - \hat{E}(y|x))^2 \quad (2)$$

The variance function is:

$$\widehat{Var}(y|x) = \hat{E}(\hat{e}^2|x) \quad (3)$$

With:

$$\hat{E}(\hat{e}^2|x) = lowess((y - \hat{E}(y|x))^2) \quad (4)$$

4.2 Nomenclature update

4.2.1 Region naming

The nomenclature used for this version 2.4 product is the following:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-<ZONE>_JA_<PassNumber>_<StationNumber>-<ProductionDateYYYYMMDD>-v2.3.nc

Where <ZONE> is one of:

R1, for Northwest America, -3.9°N /61.5°N, -150°E /-77°E

R2, for Southwest America, -59°N /3°N, -95°E /66.5°E

R3, for Southeast America, -59°N /8°N, -70°E /-20°E

R4, for Caribbean region including Gulf of Mexico, 3.6°N /32.5°N, -98.45°E /-43°E

R5, for Northeast America, 26°N /60°N, -82.5°E /-45°E

R6, for the North East Atlantic Ocean, 35°N/60°N, -15°E/10°E

R7, for the Mediterranean Sea, 30°N/46°N, -6°E/37°E

R8, for West Africa, -5°N /36.6°N, -20°E /13.5°E

R9, for Southwest Africa, -40°N/0°N, 0°E/25°E

R10, for Southeast Africa, -40°N /5°N, 20°E /60°E

R11, for North Indian Ocean, 0°N/26,5°N, 42,5°E/99°E

R12, for Southeast Asia, -25°N/30°N, 90°E/150°E

R13, for South Australia, -45°N/-15°N, 105°E/160°E

<PassNumber> is the Jason track number

<StationNumber> is the site number on the track numbered from north to south

For example, the time series data associated with track 011 part number 02 in the Southeast America, produced on 2024/11/22 is found in a file whose name is:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-R3_JA_011_02-20241122-v2.4.nc

4.2.2 Global attributes

```
// global attributes:
:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Trends in the region R1" ;
:institution = "ESA, CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
:source = "Jason-1 GDR-E, Jason-2 GDR-D, Jason-3 GDR-F, RADS 4.0 (J1, J2),
RADS 4.2 (J3), ALES" ;
:history = "2024-11-22 generated by X-TRACK v1.06" ;
:references = "https://climate.esa.int/en/projects/sea-level/data/" ;
:trackink_id = "c48c1089-4a1d-469c-9901-948fe17a361e" ;
:Conventions = "CF-1.11" ;
:version = "X-TRACK/ALES" ;
:pass_number = "011" ;
:site_number = "02" ;
:product_version = "2.4" ;
:keywords = "satellite, ocean, coastal altimetry" ;
:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-R3_JA_011_02-20241122-v2.4.nc" ;
:naming_authority = "ESA CCI+" ;
:keywords_vocabulary = "NetCDF COARDS Climate and Forecast Standard Names" ;
:cdm_data_type = "Trajectory" ;
:date_created = "2024-11-22" ;
:creator_name = "CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
:creator_url = "https://climate.esa.int/en/projects/sea-level/data/" ;
:creator_email = "info-sealevel@esa-sealevel-cci.org" ;
:project = "Sea Level Climate Change Initiative - European Space Agency" ;
:geospatial_lat_min = "-2.513" ;
:geospatial_lat_max = "-2.154" ;
:geospatial_lon_min = "-42.704" ;
:geospatial_lon_max = "-42.576" ;
:time_coverage_start = "20020101" ;
:time_coverage_end = "20210630" ;
:time_coverage_duration = "P19.5Y" ;
:time_coverage_resolution = "P1M" ;
:standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Convention
Standard Name Table v83" ;
:license = "ESA CCI Data Policy: free and open access" ;
:platform = "Jason-1, Jason-2 and Jason-3" ;
:sensor = "Poseidon-2, Poseidon-3 and Poseidon-3B" ;
:spatial_resolution = "350m" ;
:geospatial_lat_units = "degrees_north" ;
:geospatial_lon_units = "degrees_east" ;
:key_variables = "local_sla_trend" ;
:comment = "These data were produced at LEGOS as part of the ESA SL_CCI+ project" ;
:summary = "This dataset contains 20 Hz regional sea level trends computed from
monthly sea level anomalies combining ALES retracker and post-processing strategy of
X-TRACK from 20 km offshore to the coast" ;
```

4.2.3 Variables attributes

```
variables:
  int64 nbmonths(nbmonths) ;
    nbmonths:units = "count" ;
    nbmonths:long_name = "month number" ;
  int64 time(nbmonths) ;
    time:long_name = "Time" ;
    time:standard_name = "time" ;
    time:units = "days since 1950-01-01" ;
    time:calendar = "proleptic_gregorian" ;
  int64 nbpoints(nbpoints) ;
    nbpoints:units = "count" ;
    nbpoints:long_name = "point number" ;
  float lat(nbpoints) ;
    lat:_FillValue = NaNf ;
    lat:long_name = "Latitude" ;
    lat:sandard_name = "latitude" ;
    lat:units = "degrees_north" ;
    lat:lat_min = "-2.513" ;
    lat:lat_max = "-2.154" ;
  float lon(nbpoints) ;
    lon:_FillValue = NaNf ;
    lon:long_name = "Longitude" ;
    lon:sandard_name = "longitude" ;
    lon:units = "degrees_east" ;
    lon:lon_min = "-42.704" ;
    lon:lon_max = "-42.576" ;
  double distance_to_coast(nbpoints) ;
    distance_to_coast:_FillValue = NaN ;
    distance_to_coast:long_name = "Distance to GSHHS 1.3 coastline" ;
    distance_to_coast:units = "m" ;
    distance_to_coast:distance_to_coast_min = "5.310" ;
    distance_to_coast:distance_to_coast_max = "47.478" ;
    distance_to_coast:comment = "Distance along track to a reference point
    at the coast" ;
  double local_sla_trend(nbpoints) ;
    local_sla_trend:_FillValue = NaN ;
    local_sla_trend:long_name = "Geographical distribution of sea level trends" ;
    local_sla_trend:sandard_name = "tendency_of_sea_surface_height_above_sea_level" ;
    local_sla_trend:units = "mm/year" ;
    local_sla_trend:comment = "Sea level trends computed from X-TRACK/ALES monthly
    sea level anomalies between 20020101 and 20210630" ;
  double local_sla_trend_error(nbpoints) ;
    local_sla_trend_error:_FillValue = NaN ;
    local_sla_trend_error:long_name = "Geographical distribution of sea level
    trend errors" ;
    local_sla_trend_error:units = "mm/year" ;
  double sla(nbpoints, nbmonths) ;
```

```
  sla:_FillValue = NaN ;
  sla:units = "m" ;
  sla:long_name = "X-TRACK/ALES Monthly Sea Level Anomalies" ;
  sla:standard_name = "sea_surface_height_above_mean_sea_level" ;
  sla:comment = "The sla are monthly averaged and annual and semi-annual cycles
  are removed. sla = altitude of satellite - 20 Hz Ku band ALES corrected altimeter
  range (Passaro et al. 2014) - altimeter ionospheric correction on Ku band
  (From dual-frequency altimeter range measurements) - model dry tropospheric
  correction (From ECMWF model) - GPD+ wet tropospheric correction
  (Fernandes et al. 2016) - sea state bias correction in Ku band
  (ALES retracking, Passaro et al. 2014) - solid earth tide height
  (From RADS, tide potential model, Cartwright and Taylor 1971,
  Cartwright and Eden 1973) - geocentric ocean tide (FES 2014 from RADS,
  Lyard et al. 2021) - geocentric pole tide height (Wahr 1985) - Atmospheric
  correction (From RADS, Carrere and Lyard 2003) - X-TRACK mean sea surface
  (Birol et al. 2017). Each corrective term is edited following Birol et al. 2017."
double sla_mean_10pts(nbmonths) ;
  sla_mean_10pts:_FillValue = NaN ;
  sla_mean_10pts:units = "m" ;
  sla_mean_10pts:long_name = "X-Track/ALES Monthly Sea Level Anomalies averaged
  over the 10 first nearest point to coast" ;
  sla_mean_10pts:standard_name = "sea_surface_height_above_mean_sea_level" ;
  sla_mean_10pts:comment = "SLA from the sla variable averaged over the 10 first
  nearest point to coast" ;
```

5 Examples of along-track SLAs and trends (v2.4)

A full catalogue of the along-track SLAs and trends (v2.4) is available with the dataset.

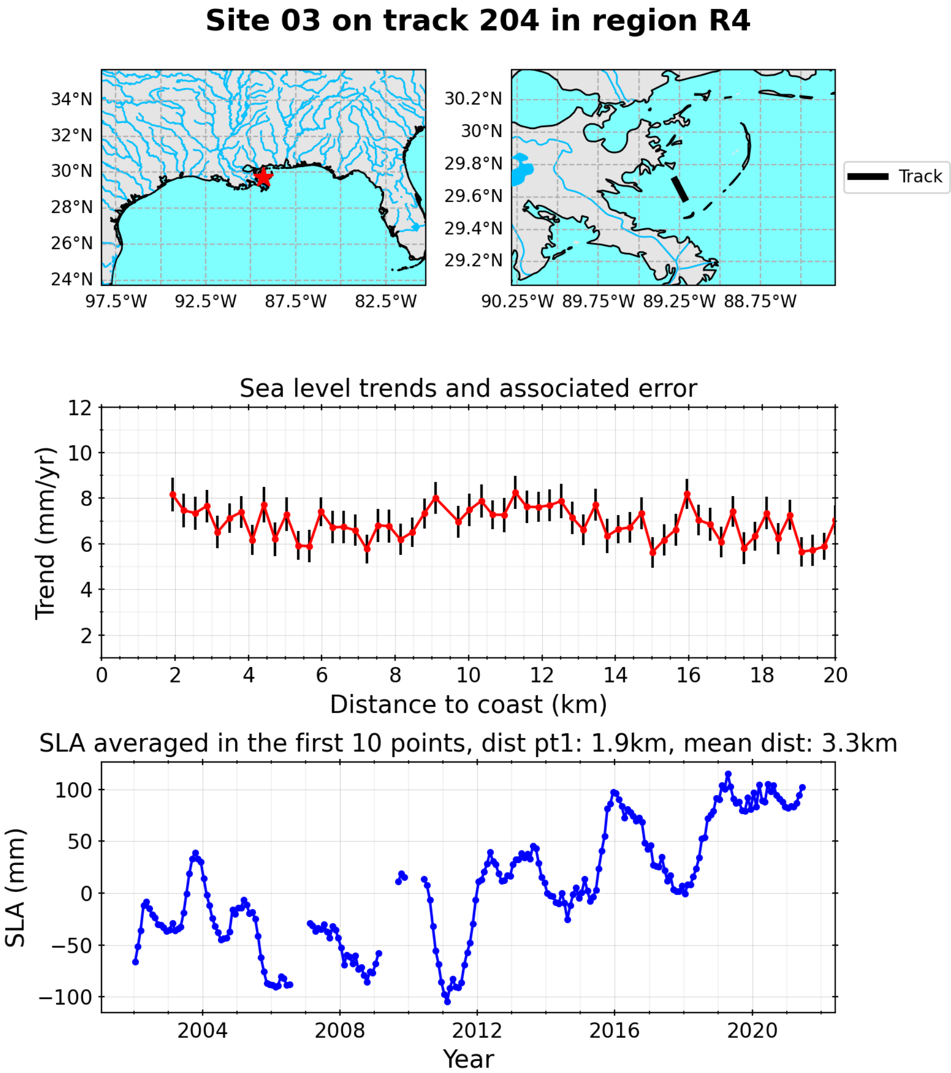

Figure 4: Example in the Mississippi delta (top panel): sea level trends against distance to coast (middle panel) and SLA time series averaged over the first 10 points (bottom panel).

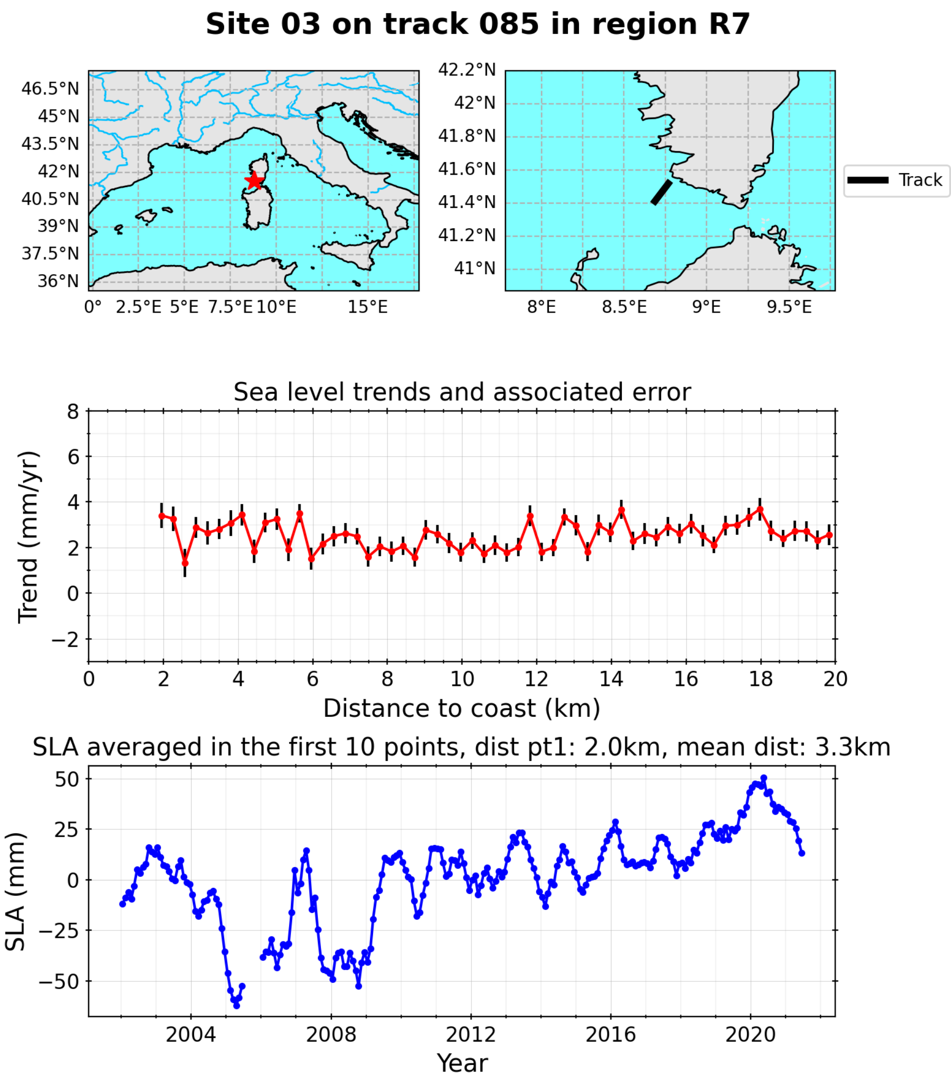

Figure 5: Example at the Senetosa site (south Corsica island): sea level trends against distance to coast (middle panel) and SLA time series averaged over the first 10 points (bottom panel).

6 Description of the previously released v2.3 product

During Summer 2023, a temporal extension of the v2.2 SL_cci+ coastal sea level dataset had been produced. It covered the period January 2002 to June 2021 (beyond that date, the WTC produced but the University of Porto (GPD+) is not available). Decision had been made to not use another correction in order to keep homogeneity. This limited the temporal extension to June 2021. The new processing (v2.3) differed from the previous one (v2.2) in that the GDRs-F for Jason-3 are used instead of the older GDRs-D/T. The ALES retracking data (range and SSB) had been entirely recomputed using the GDRs-F from cycle 1 to 198 for Jason-3. The CTOH processing had also slightly improved the SSB editing at 20 Hz (see Leger and Birol technical note, 8 August 2023) and re-estimated the intermission biases. A first validation step of the extended data set had been performed at CTOH in the northeast Atlantic area.

The v2.3 data set shows a significant reduction of the data noise compared to the v2.2 version, both in terms of the SLAs time series and trends. In particular, the trend uncertainties were reduced (the average trend error in the first 2 km from the first valid point decreased from 1.16 mm yr^{-1} to 0.83 mm yr^{-1}). Together with an improved coast detection, this product led to important an increase of the number of virtual coastal stations (1189) compared to the previous v2.2 version (756). This mostly concerns the Southeast Asia region where there are many small islands, hence many coastal sites.

6.1 Improvement of the coast detection

In version v2.2 the coast was identified when we had a gap between successive points greater than 0.3° in the latitude variable. In v2.3 a two steps detection was applied considering a gap greater than 0.1° and a criteria based on distance to coast. This allowed to detect more small islands.

6.2 New editing applied to the data

6.2.1 Editing based on the number of valid SLA data at each along-track point

We only keep along-track points where the percentage of valid data in the SLAs is ≥80 % and the SLA's trends error is ≤1.5 mm yr^{-1}

6.2.2 Along-track editing

A filter is applied to detect jumps between successive points. The details of this filtering are provided in section 6.3. After the jump filtering we remove points where there are gaps between successive points. This removal is detailed in section 6.4. We only keep tracks with a number of points ≥10 and with the distance to coast of the first point <8 km

6.3 Details of the jump filtering

The filtering is based on the difference of trends between two points. Detection of jumps along the track is based on the equation 5, where y is the SLA trend, y_{err} the associated error and x the index of the point.

$$|y(x) - y(x-1)| - |y_{err}(x) + y_{err}(x-1)| > 0 \quad (5)$$

6.3.1 First iteration

The jump detection is processed from coast to open sea and from open sea to the coast. In the first iteration the filter removes points for which we detected jumps in both directions (coast to open sea and open sea to coast, Fig. 6).

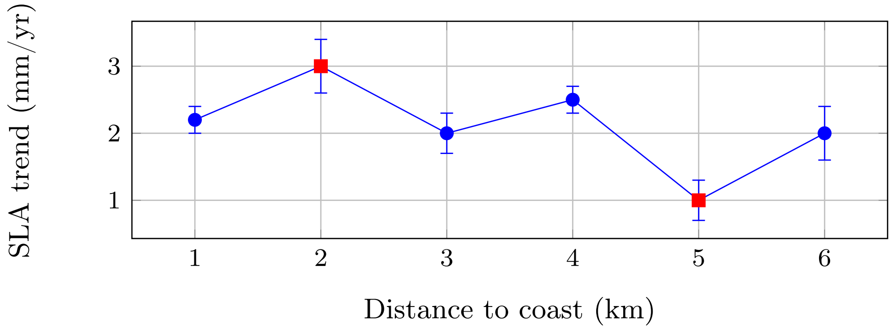

Figure 6: First iteration of the jump filtering. Red squares are detected in both direction

6.3.2 Second iteration

A second reprocessing is performed. It consists of removing points with a jump only between two successive points.

This iteration is repeated as long as we detect jumps based the equation 5.

6.4 Details of the gap (missing points) editing

A first iteration removes points between the coast and a gap when there is at least one missing point in the first four points (Fig. 7).

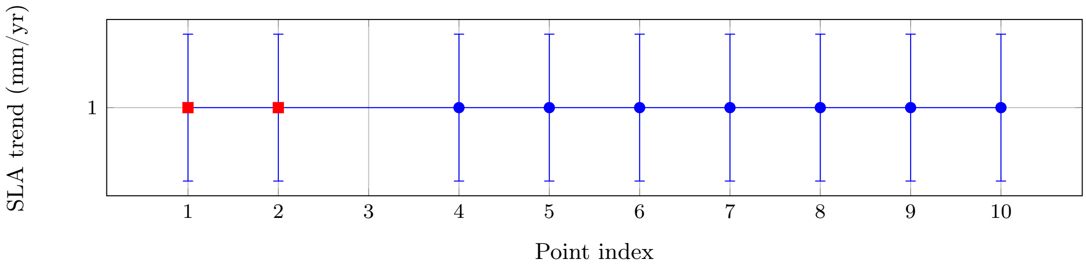

Figure 7: Missing points near to the coast. In this example the first two points are removed due to the missing point in the first four points.

A second iteration removes points between the coast and a gap when there are more than four missing points in the first thirty points (Fig. 8).

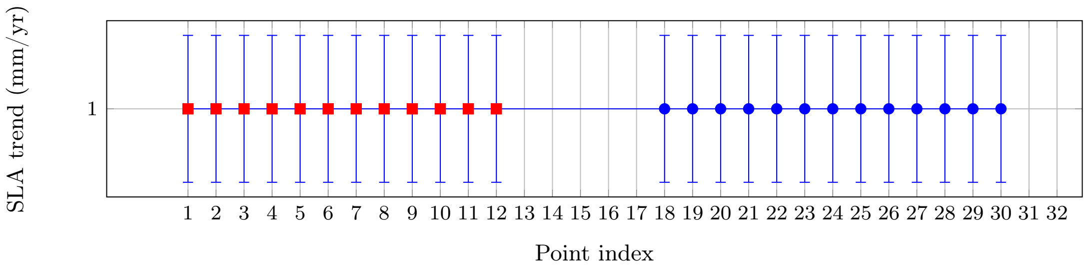

Figure 8: Gap before point 20. In this example points 1 to 12 are removed due to four missing points before point 30.

A third iteration removes points between the gap and the open sea if there are more than four missing points beyond point 30 (Fig. 9).

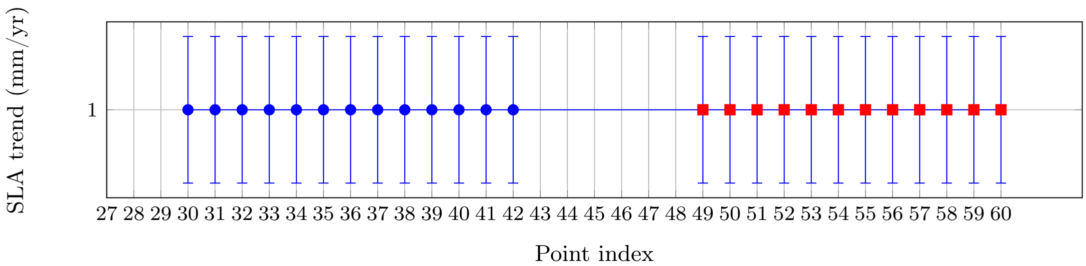

Figure 9: Gap beyond point 30. In this example points 49 to 60 are removed due to the gap of more than four points beyond point 30.

7 Format

Network Common Data Form (NetCDF) is an interface for array-oriented data access and a library that provides an implementation of the interface. The NetCDF library also defines a machine-independent format for representing scientific data. Together, the interface, library, and format support the creation, access, and sharing of scientific data. The NetCDF software was developed at the Unidata Program Center in Boulder, Colorado. Please see Unidata NetCDF pages for more information, and to retrieve NetCDF software on: `https://www.unidata.ucar.edu/software/netcdf/`

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