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Consortium Members

ESA Sea Level Climate Change Initiative

# Product user guide

January 16, 2024

Nomenclature: SLACCI+_PUG_011_ProductUserGuide
Issue: 1.8

# Contents



# List of Figures

# 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

**PUG** Product User Guide

**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 | 10/01/23 | 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) |

## People involved in this issue:

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|---|---|---|
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## Acceptance of this deliverable document:

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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, SkyMAT 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) and The Climate Change Initiative Coastal Sea Level Team et al. (2020).

The present document provides the information about the different coastal sea level products and their use. The new updated version (v2.3; January 2024) of along-track coastal sea level time series and associated trends over 2002-2021 is presented below. This dataset differs from the previous v2.2 product by: (1) a temporal extension up to 30 June 2021 and (2) a new data processing with an improved coast detection and a strong along-track editing.

**We strongly recommend to the users to use this v2.3 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 v2.3 product. The previous version of the Product User Guide (PUG) in presented in annex A.

The v2.3 coastal sea level product provides a set of 1183 altimetry-based virtual coastal stations and associated sea level data which can be used for studying long-term coastal sea level trends (Cazenave et al. 2022). Figure 1 shows the regions covered by this version labeled R1 to R13.

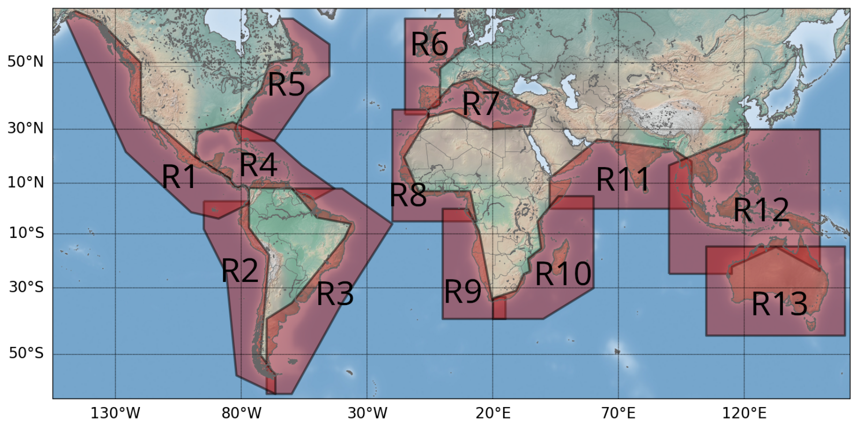


Figure 1: The regions covered by the along-track coastal sea level product. R labels refer to the regions numbers (see section 4.5.1)

# 2 Altimeter standards used for v2.3

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.

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

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. |
| **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; v2.3 product

During Summer 2023, a temporal extension of the v2.2 SL_cci+ coastal sea level dataset has been produced. It covers the period January 2002 to June 2021 (beyond that date, the WTC produced but the University of Porto (GPD+) is not available. Decision has been made to not use another correction in order to keep homogeneity, thus to limit the temporal extension to June 2021; the previous v2.2 product ended in December 2019). The new processing (v2.3) differs from the previous one in that the GDRs-F for Jason-3 are used instead of the older GDRs-D/T. The ALES retracking data (range and SSB) has been entirely recomputed using the GDRs-F from cycle 1 to 198 for Jason-3. The CTOH processing has 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 has been performed at CTOH in the northeast Atlantic area.

Preliminary inspection of this new data set shows a significant reduction of the data noise compared to the previous version, both in terms of the SLAs time series and trends. In particular, the trend uncertainties are reduced (average trend error in the first 2 km from the first valid point decrease from 1.16 mm yr$^{-1}$ to 0.83 mm yr$^{-1}$). Together with an improved coast detection, this new product leads to important an increase of the number of virtual coastal stations (1183) 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.

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 1183 virtual stations is 3.8 km with 223 sites at less than 2 km, 393 sites at less than

3 km and 1037 sites at less than 6 km from the coast (Fig. 3).

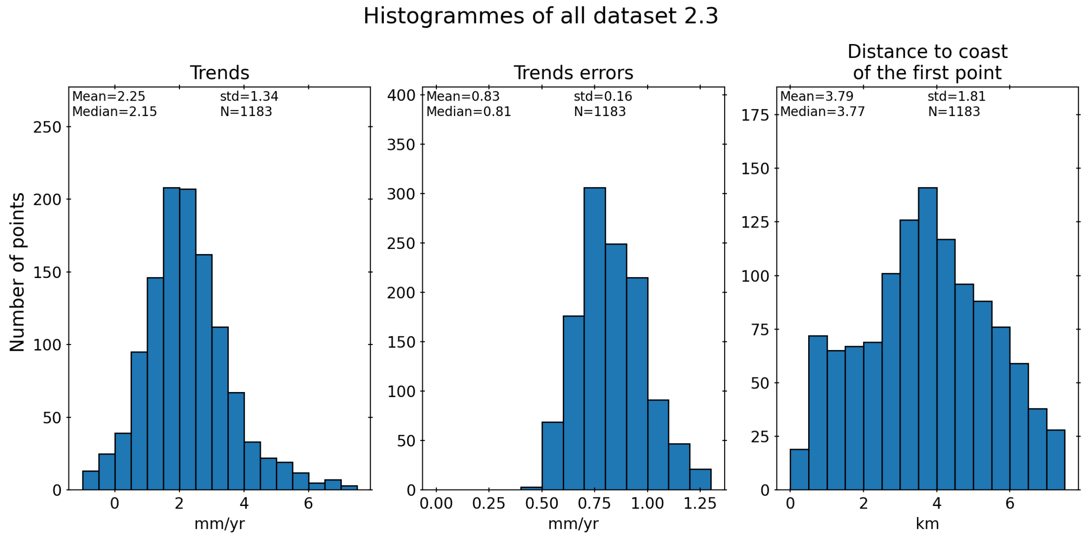


Figure 2: Histogram of trends and associated errors averaged in the first 2 km from the first valid point. And distance to coast of the first valid point for each virtual stations of the v2.3 dataset.

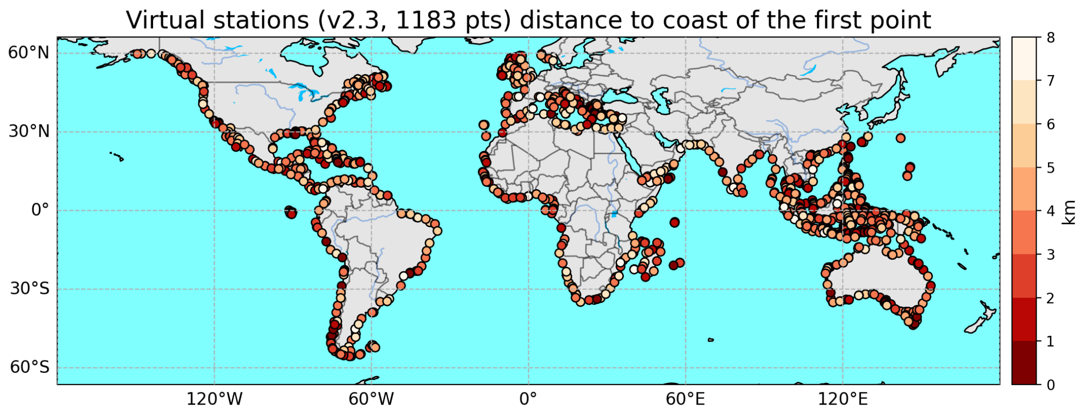


Figure 3: Map of the distance to coast of the first valid point for each virtual stations of the v2.3 dataset.

## 4.1 Improvement of the coast detection

In the previous versions the coast was identified if we observe a gap between successive points greater than 0.3° in the latitude variable. We now apply a two steps detection using a gap greater than 0.1° associated with a detection based on the distance to coast variable. This second step improves the detection of small islands.

## 4.2 New editing applied to the data

### 4.2.1 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 $\leq 1.5\,\mathrm{mm\,yr^{-1}}$

### 4.2.2 Along-track editing

A filter is applied to detect jumps between successive points. The details of this filtering are provided in part 4.3. After the jump filtering we remove points if there are gaps between successive points. This removal is detailed in part 4.4. We only keep tracks with a number of points ≥10 and with the distance to coast of the first point <8 km

## 4.3 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 1. Where $y$ is the SLA trend, $y_{err}$ the associated error and $x$ the index of the point.

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

### 4.3.1 First iteration

The detection is processed from coast to open sea and from open sea to the coast. The first part of the filter remove points that are detected in both direction (coast to open sea and open sea to coast), i.e. the jump is detected with the two neighbours of the points (Fig. 4).

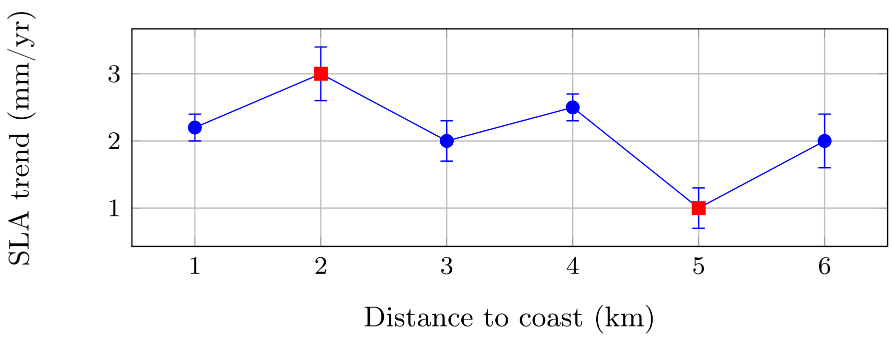


Figure 4: First iteration of the jump filtering. Red squares are detected in both direction

### 4.3.2 Second iteration

The detection is reprocessed after the first cleaning in both directions. A next step consists of removing points with a jump only with one of its neighbours (Fig. 5, top). We choose which one we delete before or after the jump if the difference of SLA between the point before the jump and its previous one is smaller or greater than the difference between the SLA of the point after the jump and the next one (Fig. 5, bottom). This iteration is repeated as long as we detect jump with the equation 1.

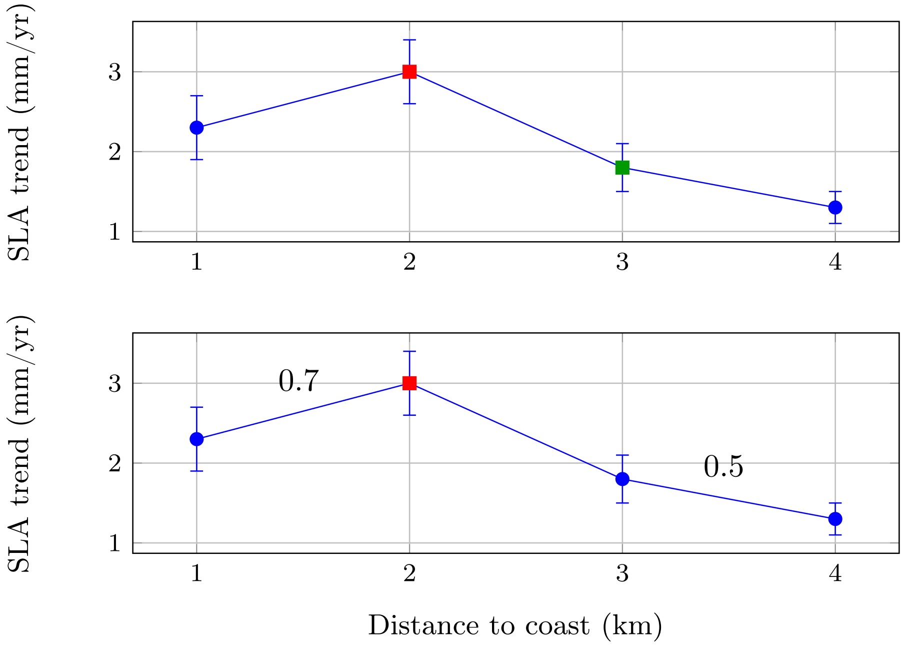


Figure 5: Second iteration of the jump filtering. On the top the red square is detected in the coast to open sea direction and the green one in the open sea to coast direction. On the bottom the red square is the deleted one because 0.7 > 0.5

## 4.4 Details of the gap editing

The first iteration removes points between the coast and the gap if there is more than one missing point in the first four points (Fig. 6).

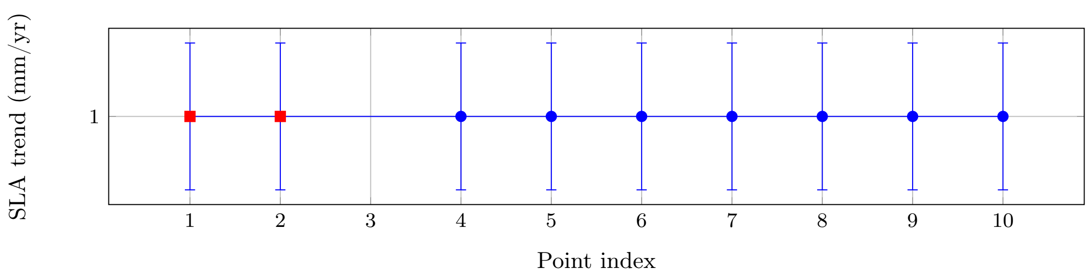


Figure 6: Edit of the gap near to the coast. The two first point are removed due to the missing point in the first four points.

The second iteration removes points between the coast and the gap if there are more than four missing points in the first thirty points (Fig. 7).

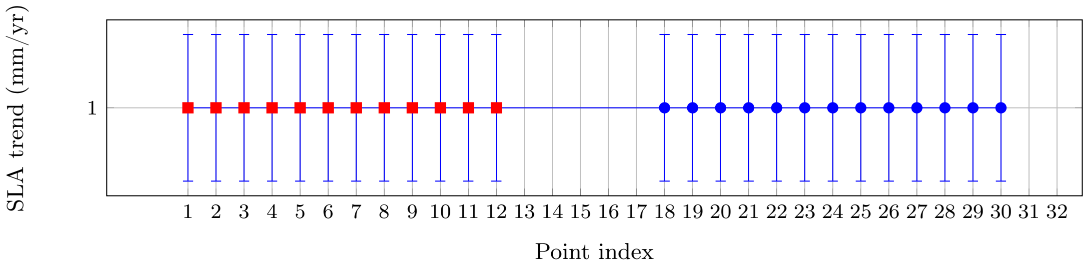


Figure 7: Edit of the gap in the first thirty points. The points 1 to 12 are removed due to the gap of more than four points before the thirtieth point.

The third iteration removes points between the gap and the open sea if there are more than four missing points in the last points after the thirtieth (Fig. 8).

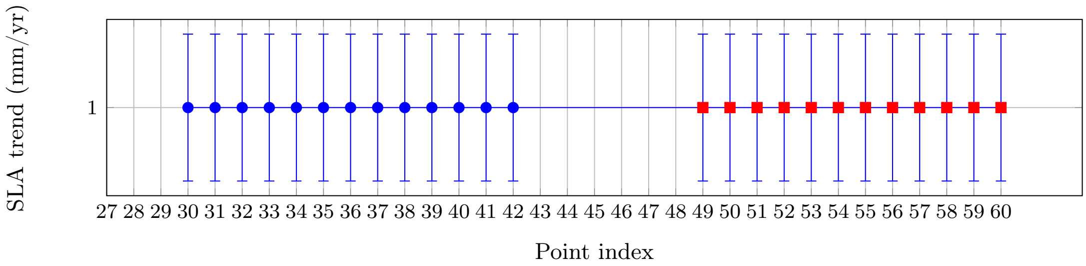


Figure 8: Edit of the gap after the thirtieth point. The points 49 to 60 are removed due to the gap of more than four points after the thirtieth point.

## 4.5 Nomenclature update

### 4.5.1 Region naming

The nomenclature used for this version 2.3 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, North Indian Ocean, 0°N/26,5°N, 42,5°E/99°E
R12, Southeast Asia, -25°N/30°N, 90°E/150°E
R13, 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 002 station number 1 in the Southeast America, produced on 2024/01/11 is found in a file whose name is:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-R3_JA_002_01-20240111-v2.3.nc

### 4.5.2 Global attributes

```
// global attributes:
:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Trends in the region R3" ;
: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 = "2024-01-11 generated by X-TRACK v1.06" ;
:references = "https://climate.esa.int/en/projects/sea-level/data/" ;
:trackink_id = "fcb8b8a2-ce32-4ffc-92c7-73603c66875b" ;
:Conventions = "CF-1.11" ;
:version = "X-TRACK/ALES" ;
:pass_number = "002" ;
:site_number = "01" ;
:product_version = "2.3" ;
:keywords = "satellite, ocean, coastal altimetry" ;
:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-R3_JA_002_01-20240110-v2.3.nc" ;
:naming_authority = "ESA CCI+" ;
:keywords_vocabulary = "NetCDF COARDS Climate and Forecast Standard Names" ;
:cdm_data_type = "Trajectory" ;
:date_created = "2024-01-11" ;
: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 = "-49.520" ;
:geospatial_lat_max = "-49.400" ;
:geospatial_lon_min = "-67.601" ;
:geospatial_lon_max = "-67.466" ;
: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" ;
```

### 4.5.3 Variables attributes

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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 = "-49.520" ;
        lat:lat_max = "-49.400" ;
    float lon(nbpoints) ;
        lon:_FillValue = NaNf ;
        lon:long_name = "Longitude" ;
        lon:sandard_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:lon_min = "-67.601" ;
        lon:lon_max = "-67.466" ;
    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 = "3.279" ;
        distance_to_coast:distance_to_coast_max = "19.825" ;
        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." ;
```

## 4.6 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/

# A Annex: Product User Guide of the previous versions

## 1. Introduction

In the context of the ESA's climate change initiative sea-level project, the Centre of Topography of the Oceans and the Hydrosphere (CTOH, http://ctoh.legos.obs-mip.fr) produces a Level 2P multi-mission altimeter along-track sea level product in some coastal regions. The product benefits from the spatial resolution provided by high-rate data, the Adaptive Leading Edge Subwaveform Retracker (ALES, *Passaro et al.*; 2014, 2015, 2017) and the post-processing strategy of the X-TRACK algorithm (*Birol et al.*, 2017, adapted to 20 Hz data as in *Birol and Delebecque*, 2014) both developed for the processing of coastal altimetry data, as well as the best possible set of geophysical corrections.

The main objective of this product is to provide accurate altimeter Sea Level Anomalies (SLA) time series as close to the coast as possible.

By merging X-TRACK and ALES altimetry processing tools, we compute 20-Hz along-track sea surface height (SSH) time series for Envisat, Jason-1, Jason-2 and Jason-3 missions and 40-Hz along-track SSH time series for SARAL/AltiKa mission. The X-TRACK software reprocesses corrections and parameters from delayed-time geophysical data records provided by space agencies (GDR products) and combines them with the ALES retracker product (range, sigma0 and sea state bias) to compute the SSH, after a robust editing of the measurements and corrections (described in Birol et al., 2017). The full data processing is explained in Birol et al. (2021) and Benveniste et al. (2020).

This document describes the information required to use the different coastal sea level products. Two recent updates (versions v2.1 and v2.2) of the initial version v1.1 of along-track coastal sea level time series and associated trends are presented below. They differ from the v1.1 product by: (1) a temporal extension up to 31 December 2019 and addition of American coasts, plus some new regions around Africa; and (2) new data selection and creation of a new set of virtual coastal stations. The v2.2 product is an updated version of v2.1, based on an optimization of the intermission bias calculation and improvement of some geophysical corrections. We strongly recommend to the users to use the v2.2 product.

Section 2 describes the altimeter standards used for the SLA computation; section 3 describes the regional along-track coastal sea level product valid for the two versions v2.1 and v2.2; section 4 presents the updates brought to the v2.2 product (compared to v2.1). Section 5 shows two examples of coastal sea level trends against distance to coast (version 2.2). These products provide a set of 756 altimetry-based virtual coastal stations and associated sea level data which can be used for studying long-term coastal sea level trends (Cazenave et al., 2022).

## 2. Altimeter standards used for v2.1 and v2.2

The Jason-1, Jason-2 and Jason-3 data used by the X-TRACK software are based, respectively, on the GDR-E and GDR-D products. The Envisat data used are the reprocessed GDR v2.1 and the SARAL/AltiKa data are from GDR-T. The range and sea state bias are provided by the ALES retracker product. The ocean tide and DAC corrections come from the RADS database. The wet tropospheric correction used is GPD+ (*Fernandes and Lazaro,* 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 below. Note that the mean sea surface used to compute the sea level anomalies is an area-averaged mean SSH and is thus not considered as an input dataset.

| **Parameter** | **Source** | **Jason-1** | **Jason-2** | **Jason-3** | **Envisat** | **SARAL** |
|---|---|---|---|---|---|---|
| L2 standards | GDR | GDR-E | GDR-E | GDR-D | GDR V2.1 | GDR-T |
| Altitude | GDR | Altitude of satellite | | | | |
| Range | ALES | 20 Hz ku band ALES corrected altimeter range (*Passaro et al.*, 2014) | | | | |
| Ionosphere | GDR | From dual-frequency altimeter range measurements, further filtered by X-TRACK | | | From GIM model (Iijima et al. 1999) | |
| Dry troposphere | GDR | From ECMWF model | | | | |
| Wet troposphere | GPD+ | GPD+ radiometer correction (*Fernandes and Lazaro*, 2016) | | | | |
| Sea state bias | ALES | Sea state bias correction in ku band, ALES retracking (*Passaro et al.*, 2018) | | | | |
| Solid tide | RADS | From tide potential model (*Cartwright and Taylor*, 1971, *Cartwright and Eden*, 1973) | | | | |
| Pole tide | GDR | From *Wahr*, 1985 | | | | |
| Loading effect | RADS | From FES 2014 (*Carrere et al.*, 2012) | | | | |
| Atmospheric correction | RADS | From MOG2D-G high frequencies (*Carrere and Lyard,* 2003) + inverse barometer | | | | |
| Ocean tide | RADS | From FES 2014 (*Carrere et al.*, 2012) including ocean tide, long period equilibrium tide, S1 tide | | | | |

## 3. Along-track coastal sea level anomalies and trends: Jan. 2002-Dec. 2019; v2.1 product

The coastal sea level trend product is product is a 18-year-long, high-resolution (20 Hz), along-track sea level dataset in coastal zones of thirteen regions shown in Figure 1: Northeast Atlantic, Mediterranean Sea, West Africa, Benguela, Southeast Africa, North Indian Ocean, Southeast Asia, Australia, Northwest America, Gulfstream, Caribbean, Atlantic South America and Humboldt. The present reprocessing has consisted of recomputing altimeter ranges of high-resolution (20 Hz, i.e., 300 m resolution) along-track altimetry data of the successive missions Jason-1, 2 and 3 over the **January 2002-December 2019 time span**, using the Adaptive Leading-Edge Subwaveform (ALES) retracking method. The ALES retracking also retrieves one of the geophysical corrections applied to the range measurements, the so-called sea state bias, that depends on the significant wave height, also derived from the radar echoes. Additional post-processing consists of applying adapted geophysical corrections for the coastal zones, dedicated inter-bias missions, editing, etc. This new data set, validated against tide gauges where possible, provides coastal sea level anomalies and sea level trends against distance to the coast, every 300 m along track, over January 2002 to December 2019. With this reprocessing, it is possible to provide reliable sea level time series around global coastlines. Hereinafter, we define as **'virtual' coastal stations** the sites where the Jason tracks cross the coastline. The data validation step used same criteria as for product v1.1. Note that for product v2.1, we have updated the virtual stations located within 6 km from the coast. This has led to the production of 756 virtual stations (Cazenave et al., 2022). Figure 2 shows the closest distance to the coast reached by the first valid point along the satellite tracks in the study regions.

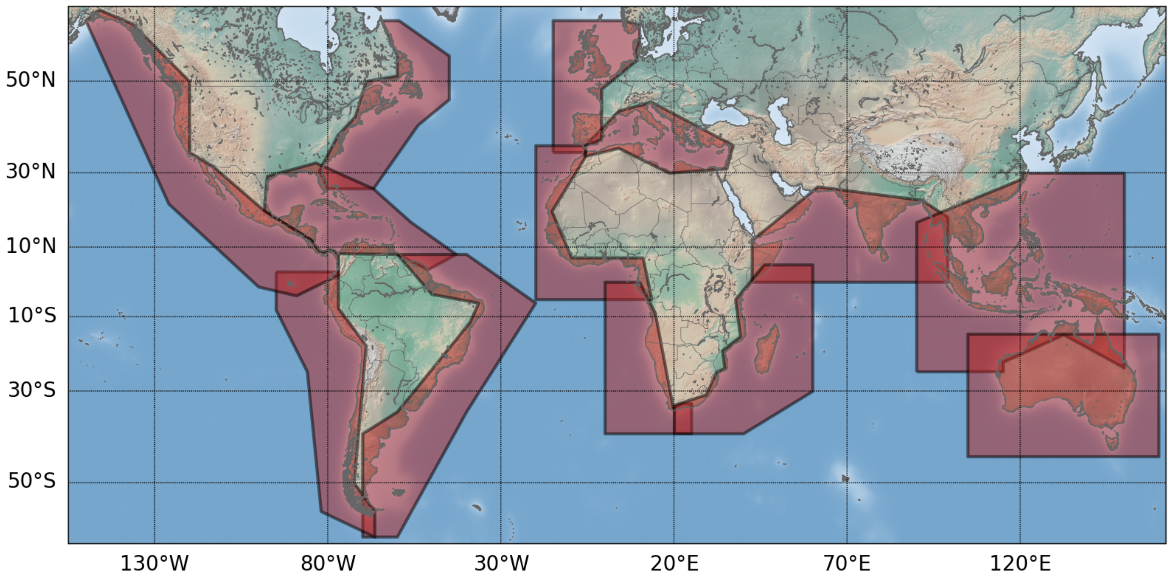


**Figure 1: The regions covered by the along-track coastal sea level product.**

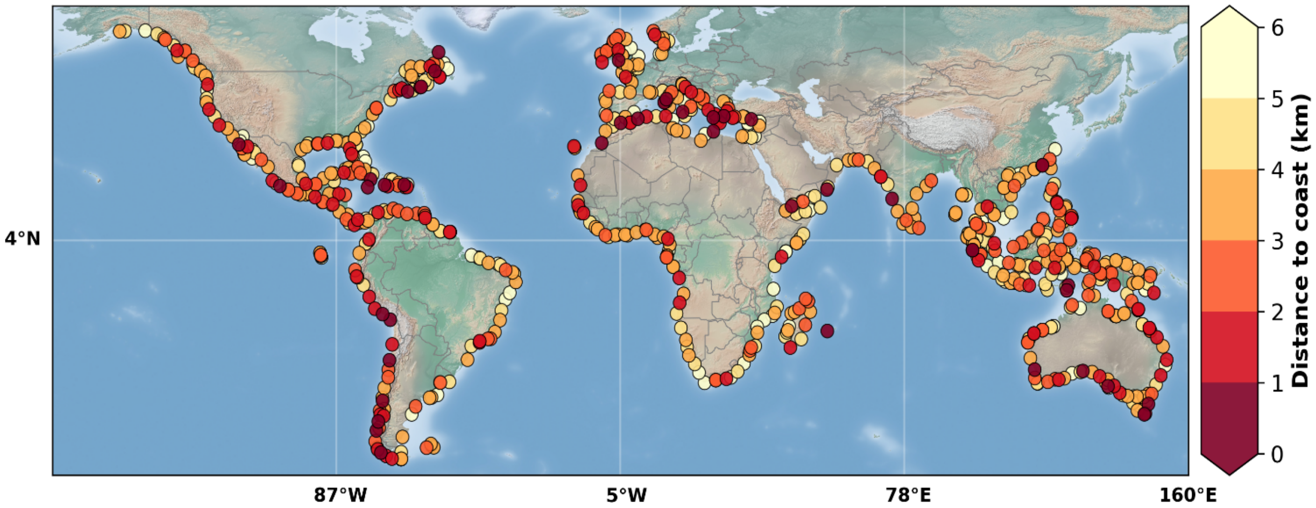


**Figure 2: Closest distance (km) to coast reached by the first valid point along the Jason tracks for the 756 selected virtual stations.**

## 3.1. Nomenclature update

The nomenclature used for this version **2.1 product** is:
ESACCI-SEALEVEL-IND-MSLTR-MERGED-<ZONE>_JA_<PassNumber>_<StationNumber>-<ProductionDateYYYYMMDD>-fv02.1.nc

Where <ZONE> is one of:

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

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

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

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

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

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

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

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

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

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

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

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

HUMBOLDT for Southwest America, -59°N /3°N, -95°E /66.5°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 222 station number 2 in the North East Atlantic Ocean, produced on 2022/01/24 is found in a file whose name is:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-**NE_ATL**_JA_**222_02**-20220124-fv02.1.nc

## 3.2. Format

NetCDF (network Common Data Form) 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. The NetCDF libraries define a machine-independent format for representing scientific data. Please see Unidata NetCDF pages for more information, and to retrieve NetCDF software on: https://www.unidata.ucar.edu/software/netcdf/

## 3.3. Data handling variable

| Variables | Description |
|---|---|
| **lat** | Latitude of each 20 Hz point |
| **lon** | Longitude of each 20 Hz point |
| **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. |
| **time** | Time of measurements (days since 1950-01-01) |
| **sla** | Monthly sea level anomaly (SLA) time series over 1 January 2002 to 31 December 2019 derived from the original 10-day X-TRACK/ALES SLA 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. |
| **local_sla_trend** | Sea level trends 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 coefficients). |

## 3.4. NetCDF Header update; v2.1 product

### 3.4.1. Global attributes; v2.1 product

Product name = ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_035_01-20220124-fv02.1.nc

// global attributes:

:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Trends in the region " ;

:institution = "ESA, CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;

:source = "Jason-1 GDR-E, Jason-2 GDR-D, Jason-3 GDR-D, RADS 4.0, ALES" ;

:history = "2022-01-18 generated by X-TRACK v.1.06" ;

:references = https://climate.esa.int/en/projects/sea-level/data/"" ;

:tracking_id = "bb6907ce-1906-42c2-8df1-acf89b190b23" ;

:Conventions = "CF-1.7" ;

:version = "X-TRACK/ALES" ;

:pass_number = "035" ;

:site_number = "01" ;

:product_version = "2.1" ;

: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" ;

:keywords = "satellite, ocean, coastal altimetry" ;

:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_035_01-20220124-fv02.1.nc" ;

:naming_authority = "ESA CCI+" ;

:keywords_vocabulary = "NetCDF COARDS Climate and Forecast Standard Names" ;

:cdm_data_type = "Trajectory" ;

:comment = "These data were produced at LEGOS as part of the ESA SL_CCI+ project." ;

:date_created = "2022-01-24" ;

: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 = "36.1577 " ;

:geospatial_lat_max = "36.2846 " ;

:geospatial_lon_min = "-6.26852 " ;

:geospatial_lon_max = "-6.18904 " ;

:geospatial_vertical_min = "0" ;

:geospatial_vertical_max = "0" ;

:time_coverage_start = "2002-01-01" ;

:time_coverage_end = "2019-12-31" ;

:time_coverage_duration = "P18Y" ;

:time_coverage_resolution = "P1M" ;

:standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Convention Standard Name Table v67" ;

: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 = "350 m" ;

:geospatial_lat_units = "degrees_north" ;

:geospatial_lon_units = "degrees_east" ;

:key_variables = "local_sla_trend" ;

}

## 3.5.

### 3.5.1. Variables attributes

variables:

float distance_to_coast(nbpoints) ;

distance_to_coast:_FillValue = 1.844674e+19f ;

distance_to_coast:long_name = "Distance to GSHHS 1.3 coastline" ;

distance_to_coast:units = "m" ;

distance_to_coast:distance_to_coast_min = 4053.74f ;

distance_to_coast:distance_to_coast_max = 19888.5f ;

distance_to_coast:comment = "Distance along track to a reference point at the coast " ;

float lat(nbpoints) ;

lat:long_name = "Latitude" ;

lat:standard_name = "latitude" ;

lat:units = "degrees_north" ;

lat:lat_min = 36.1577f ;

lat:lat_max = 36.2846f ;

float lon(nbpoints) ;

lon:long_name = "Longitude" ;

lon:standard_name = "longitude" ;

lon:units = "degrees_east" ;

lon:lon_min = -6.26852f ;

lon:lon_max = -6.18904f ;

double time(nbmonth) ;

time:_FillValue = 99.9999 ;

time:units = "days since 1950-1-1" ;

time:calendar = "julian" ;

time:long_name = "Time" ;

time:standard_name = "time" ;

float local_sla_trend(nbpoints) ;

local_sla_trend:_FillValue = 1.844674e+19f ;

local_sla_trend:long_name = "Geographical distribution of sea level trends" ;

local_sla_trend:standard_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 2002-01-01 and 2019-12-31" ;

float local_sla_trend_error(nbpoints) ;

local_sla_trend_error:_FillValue = 1.844674e+19f ;

local_sla_trend_error:long_name = "Geographical distribution of sea level trends errors" ;

local_sla_trend_error:units = "mm/year" ;

local_sla_trend_error:add_offset = 0.f ;

local_sla_trend_error:scale_factor = 1.f ;

float sla(nbpoints, nbmonth) ;

sla:_FillValue = 1.844674e+19f ;

sla:units = "m" ;

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. 2015) - 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 Edden 1973) - geocentric ocean tide (FES 2014 from RADS, Carrere et al. 2012) - 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."

## 4. V2.2 product: Updated along-track coastal sea level anomalies and trends; Improvement of the intermission bias calculation and improvement of the corrections applied in the SSH calculation

In this update, we optimized the calculation method of the intermission bias.
The bias Jason-1/Jason-2 and Jason-2/Jason-3 are now directly calculated on the SLAs of the individual missions. We filter and edit the SLAs before calculating the bias on the SSH. In addition, the smoothing parameters are also increased, via 4°x4° boxes and smoothed on 3 neighbouring boxes in all directions.
The v2.2 update also corrects a problem detected in the interpolation of the corrections applied to the SSH calculation very close to the coast. This problem has mainly affected the dry tropospheric correction at the few closest points to the coast where significant coastal relief is observed. This has impacted trend estimates when the satellite approaches the coast (about 73 coastal sites among the 756 sites). Figure 3 compares the coastal trend behaviour before and after the correction (i.e., between v2.1 and v2.2). However, on average, the impact on trends values is small.

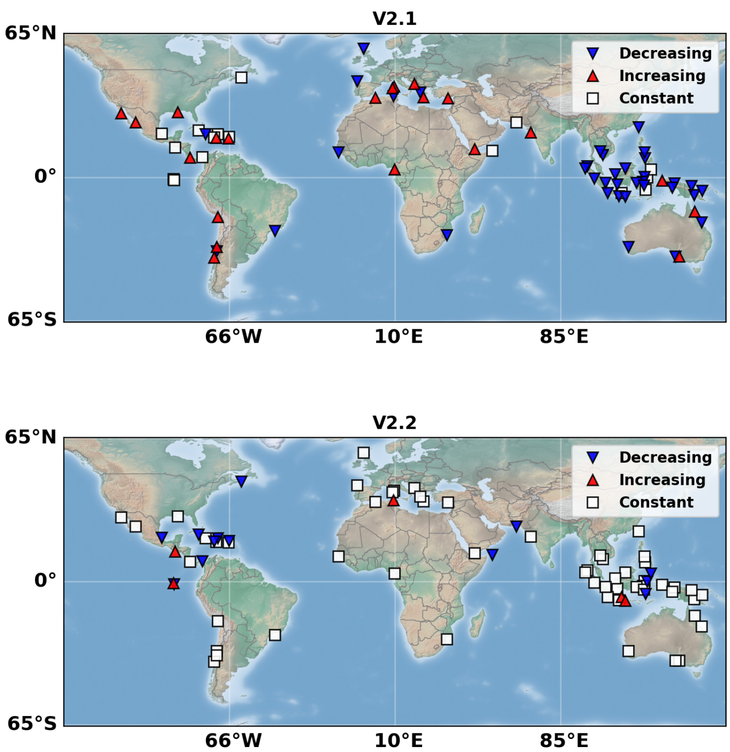


**Fig 3. Behaviour of the trends approaching the coast where the trends behaviour has changed between V2.1 (top panel) and V2.2 (bottom panel). Red triangle upward means the trend along-track increases from open ocean to the coast. Blue triangle downward means the trend along-track decreases close to the coast. White squares correspond to constant trends all along the track.**

## 4.1 Global Attributes; v2.2 product

Product name = ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_035_01-20221220-fv02.2.nc
// global attributes:
:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Trends in the region NE_ATL" ;
:institution = "ESA, CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
:source = "Jason-1 GDR-E, Jason-2 GDR-D, Jason-3 GDR-D, RADS 4.0, ALES" ;
:history = "2022-12-20 generated by X-TRACK v.1.06" ;
:references = "https://climate.esa.int/en/projects/sea-level/data/" ;
:tracking_id = "076f9cb0-8d05-4bd8-9081-33ee0b978224" ;
:Conventions = "CF-1.7" ;
:version = "X-TRACK/ALES" ;
:pass_number = "035" ;
:site_number = "01" ;
:product_version = "2.2" ;
: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" ;
:keywords = "satellite, ocean, coastal altimetry" ;
:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_035_01-20221220-fv02.2.nc" ;
:naming_authority = "ESA CCI+" ;
:keywords_vocabulary = "NetCDF COARDS Climate and Forecast Standard Names" ;
:cdm_data_type = "Trajectory" ;
:comment = "These data were produced at LEGOS as part of the ESA SL_CCI+ project." ;
:date_created = "2022-12-20" ;
: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 = "36.1577 " ;
:geospatial_lat_max = "36.2846 " ;
:geospatial_lon_min = "-6.26852 " ;
:geospatial_lon_max = "-6.18904 " ;
:geospatial_vertical_min = "0" ;
:geospatial_vertical_max = "0" ;
:time_coverage_start = "2002-01-01" ;
:time_coverage_end = "2019-12-31" ;
:time_coverage_duration = "P18Y" ;
:time_coverage_resolution = "P1M" ;

:standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Convention Standard Name Table v67" ;
: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 = "350 m" ;
:geospatial_lat_units = "degrees_north" ;
:geospatial_lon_units = "degrees_east" ;
:key_variables = "local_sla_trend" ;
}

## 4.2 Variables attributes; v2.2 product

variables:
float distance_to_coast(nbpoints) ;
distance_to_coast:_FillValue = 1.844674e+19f ;
distance_to_coast:long_name = "Distance to GSHHS 1.3 coastline" ;
distance_to_coast:units = "m" ;
distance_to_coast:distance_to_coast_min = 4053.74f ;
distance_to_coast:distance_to_coast_max = 19888.5f ;
distance_to_coast:comment = "Distance along track to a reference point at the coast " ;
float lat(nbpoints) ;
lat:long_name = "Latitude" ;
lat:standard_name = "latitude" ;
lat:units = "degrees_north" ;
lat:lat_min = 36.1577f ;
lat:lat_max = 36.2846f ;
float lon(nbpoints) ;
lon:long_name = "Longitude" ;
lon:standard_name = "longitude" ;
lon:units = "degrees_east" ;
lon:lon_min = -6.26852f ;
lon:lon_max = -6.18904f ;
double time(nbmonth) ;
time:_FillValue = 99.9999 ;
time:units = "days since 1950-1-1" ;
time:calendar = "julian" ;
time:long_name = "Time" ;
time:standard_name = "time" ;
float local_sla_trend(nbpoints) ;
local_sla_trend:_FillValue = 1.844674e+19f ;
local_sla_trend:long_name = "Geographical distribution of sea level trends" ;
local_sla_trend:standard_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 2002-01-01 and 2019-12-31" ;
float local_sla_trend_error(nbpoints) ;
local_sla_trend_error:_FillValue = 1.844674e+19f ;
local_sla_trend_error:long_name = "Geographical distribution of sea level trends errors" ;
local_sla_trend_error:units = "mm/year" ;
float sla (nbpoints, nbmonth) ;
sla:FillValue = 1.844674e+19f ;
sla:units = "m" ;
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, Carrere et al. 2012) - 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."

## 5. Examples of sea level trends against distance to coast

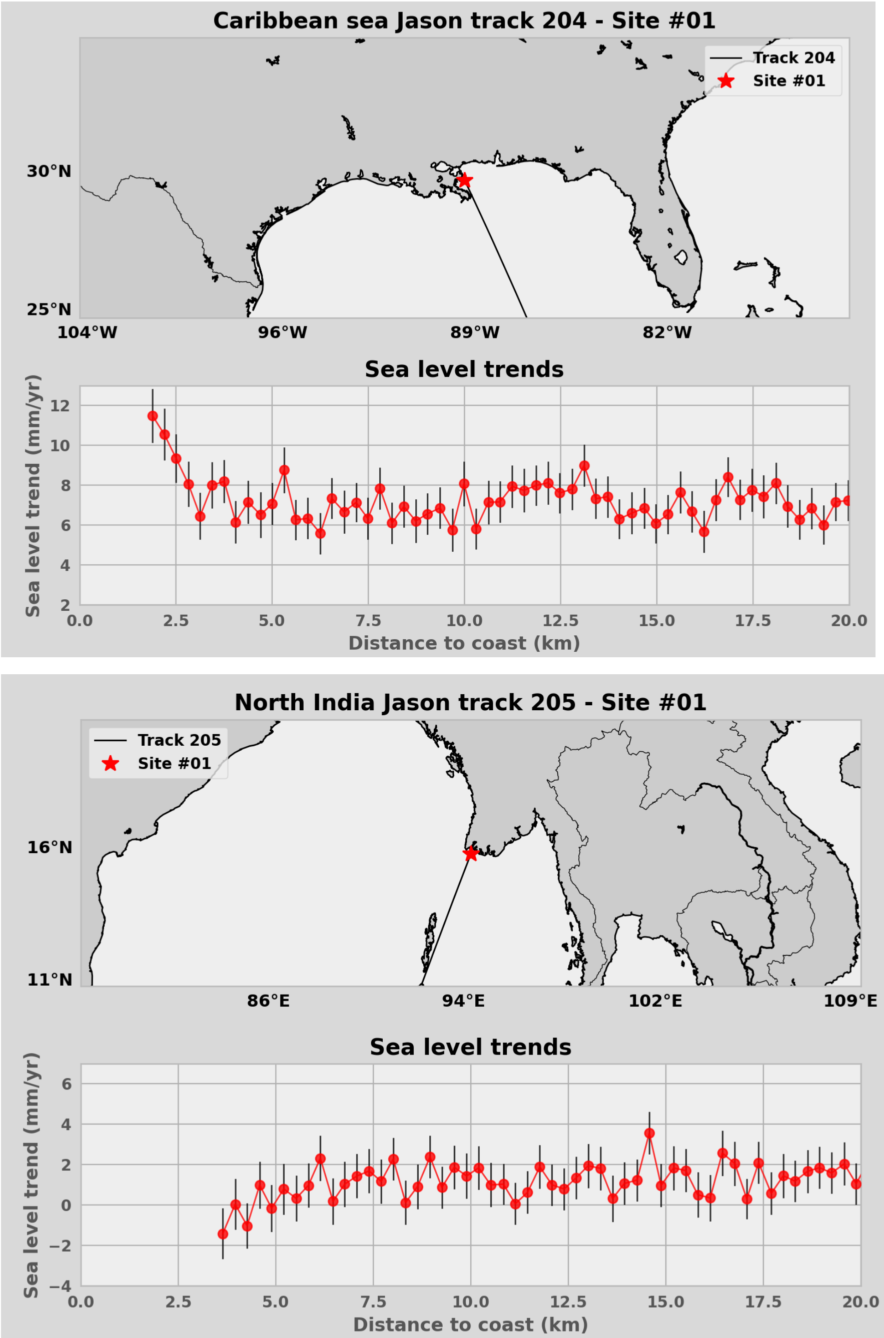


Fig 4. Sea level trends against distance to coast from the version 2.2.
Upper panel: Mississippi delta. Lower panel: Irrawaddy delta.

# References

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