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Consortium Members

ESA Sea Level Climate Change Initiative

Product user guide

July 04, 2025

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Issue: 2.0

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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)
2.0	04/07/25	New coastal product v3.0: geographical extension to other coastlines and to small tropical islands of low elevation. Reorganisation of the production chain and small improvements of the post-processing. Adding of the filtered variable of the averaged SLA in the 10 first points variable: `sla_mean_10pts_filt`	L. Leclercq, A. Cazenave (LEGOS)

People involved in this issue:

Written by:	L. Leclercq, A. Cazenave, F. Léger (LEGOS)	04/07/2025
Checked by:	F. Birol (LEGOS), J.-F. Legeais (CLS)	
Approved by:	J.-F. Legeais (CLS)	04/07/2025 

Acceptance of this deliverable document:

Accepted by ESA:	S. Connors	 Digitally signed by Sarah Connors Date: 2025.07.10 09:51:41 +01'00'

Distribution

Company	Names	Contact details
ESA	S. Connors	sarah.connors@esa.int
CLS	J.-F. Legeais	jlegeais@groupcls.com
	P. Prandi	pprandi@groupcls.com
	S. Labroue	slabroue@groupcls.com
	A. Mangilli	amangilli@groupcls.com
	V. Quet	vquet@groupcls.com
LEGOS	A. Cazenave	anny.cazenave@univ-tlse3.fr
	B. Meyssignac	benoit.meyssignac@univ-tlse3.fr
	F. Birol	florence.birol@univ-tlse3.fr
	F. Niño	fernando.nino@univ-tlse3.fr
	F. Léger	fabien.leger@univ-tlse3.fr
	L. Leclercq	lancelot.leclercq@univ-tlse3.fr
	L. Tolu	lena.tolu@univ-tlse3.fr
NOC	S. Jevrejeva	sveta@noc.ac.uk
	A. Wise	anwise@noc.ac.uk
DGFI-TUM	M. Passaro	marcello.passaro@tum.de

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 (v3.0; June 2025) 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 v2.4 product (released in November 2024) by a spatial extension. It also uses the new improved FES22 ocean tide model instead of FES14 model in the previous versions. And it has been a slight change in the editing (outlier removal) and a new variable have been added (`sla_mean_10pts_filt`)

We strongly recommend to the users to use this v3.0 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 v3.0 product.

The v3.0 coastal sea level product provides a set of 1634 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 R20) covered by this version.

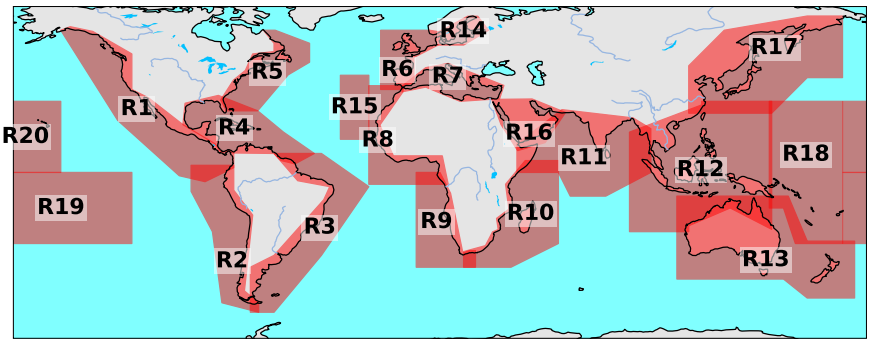

Figure 1: The regions covered by the along-track coastal sea level product v3.0. R labels refer to the regions numbers (see section 4.3.1)

2 Altimeter standards used for v3.0

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	CNES	From FES 2022 Lyard et al. in prep.		
Atmospheric correction	RADS	From MOG2D-G high frequencies (Carrère and Lyard 2003) + inverse barometer		
Ocean tide	CNES	From FES 2022 Lyard et al. in prep. 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.
sla_mean_10pts_filt	Averaged SLA time series over the first 10 nearest points to the coast with a 6 months rolling mean filter.
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; v3.0 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 1634 virtual stations is 3.7 km with 399 sites at less than 2 km and 596 sites at less than 3 km from the coast (Fig. 3).

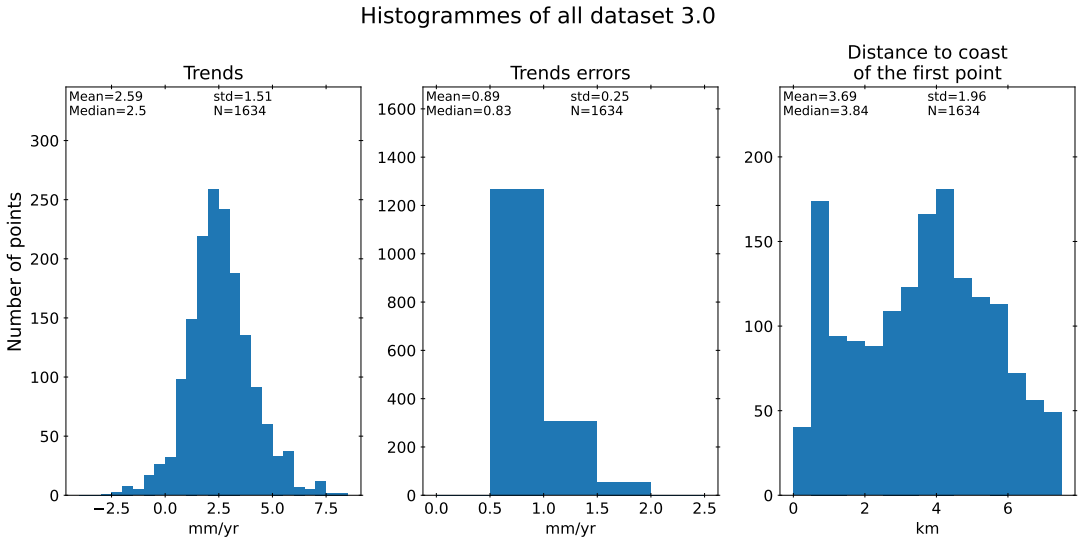

Figure 2: Histograms: trends and associated errors along-track averaged over 2 km from the closest valid point to the coast, and distance to coast of the first valid point, for each virtual stations of the v3.0 dataset.

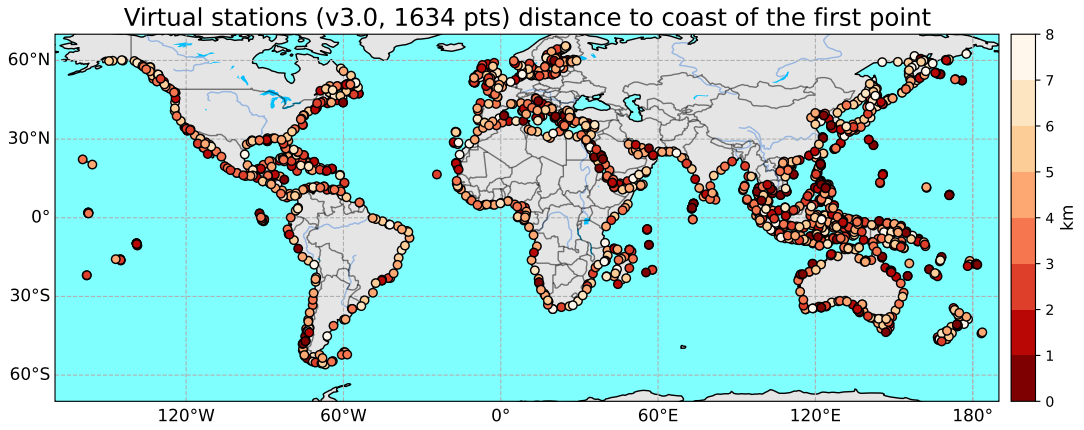

Figure 3: Map of the distance to coast of the first valid point for each virtual stations of the v3.0 dataset.

4.1 X-Track processing changes

4.1.1 Spatial extension

In the v3.0 dataset the spatial coverage has been extended with 7 new regions: Baltic Sea, Azores islands, Red Sea and Persic Gulf, North West Pacific Ocean, Western tropical Pacific Ocean,

Central Pacific and Hawaii islands. In addition the North Indian Ocean region and the Australian region have been extended to integrate respectively the whole Maldives islands and the New Zealand.

4.1.2 Use of FES22 tide corrections

The X-Track processing is integrating the new FES22 ocean tide altimeter correction from Lyard et al. in preparation.

4.2 Improvement of the post-processing

In v3.0 the outliers removal is slightly modified by implementing parametric variance function based on the approach from (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:

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

Where $\hat{E}(y|x)$ is the rolling mean over 12 months of the time series and $\sqrt{\widehat{Var}(y|x)}$ is the standard deviation function. We obtain the squared deviation from the rolling mean estimate:

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

The variance function is:

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

With:

$$\hat{E}(\hat{e}^2|x) = roll\_mean((y - \hat{E}(y|x))^2) \tag{4}$$

4.3 Nomenclature update

4.3.1 Region naming

The nomenclature used for this version 3.0 product is the following:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-<ZONE>_JA_<PassNumber>_<StationNumber>-<ProductionDateYYYYMMDD>-v3.0.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

R14, for Baltic Sea, 53.75°N/66.9°N, 9°E/30.5°E
R15, for Azores islands, 14°N/41°N, -20°E/32°E
R16, for Red Sea and Persic Gulf, 9°N/31°N, 31.9°N/54.4°N
R17, for North West Pacific Ocean, 25.25°N/66°N, 115°N/179.9°N
R18, for Western tropical Pacific Ocean, -30°N/30°N, 149°N/179.9°N
R19, for central Pacific Ocean, -30°N/0°N, -179.9°N/-120°N
R20, for Hawaii islands, 0°N/30°N, -179.9°N/-150°N
<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 2025/06/18 is found in a file whose name is:
ESACCI-SEALEVEL-IND-MSLTR-MERGED-R3_JA_011_02-20250618-v3.0.nc

4.3.2 Global attributes

```
// global attributes:
:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Anomaly 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, CNES database" ;
:history = "2025-06-18 generated by cci_sealevel processing chain git tag
cci_20250618" ;
:references = "https://climate.esa.int/en/projects/sea-level/data/" ;
:tracking_id = "01294032-f880-4128-944e-309baebc9625" ;
:Conventions = "CF-1.11" ;
:pass_number = "002" ;
:part_number = "05" ;
:product_version = "3.0" ;
:keywords = "satellite, ocean, coastal altimetry" ;
:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-R1_JA_002_05-20250618-v3.0.nc" ;
:naming_authority = "ESA CCI+" ;
:keywords_vocabulary = "NetCDF COARDS Climate and Forecast Standard Names" ;
:cdm_data_type = "Trajectory" ;
:date_created = "2025-06-18" ;
: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" ;
string :project = "Sea Level Climate Change Initiative - European Space Agency" ;
:geospatial_lat_min = "16.939" ;
:geospatial_lat_max = "17.070" ;
:geospatial_lon_min = "-100.583" ;
:geospatial_lon_max = "-100.530" ;
:time_coverage_start = "2002-01" ;
:time_coverage_end = "2021-06" ;
:time_coverage_duration = "P19.5Y" ;
:time_coverage_resolution = "P10D" ;
:standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Convention
Standard Name Table v91" ;
```

```
: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 = "sla" ;
: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" ;
```

4.3.3 Variables attributes

```
variables:
  int64 nbpoints(nbpoints) ;
    nbpoints:units = "count" ;
    nbpoints:long_name = "points number" ;
  float lat(nbpoints) ;
    lat:_FillValue = NaNf ;
    lat:long_name = "Latitude" ;
    lat:standard_name = "latitude" ;
    lat:units = "degrees_north" ;
    lat:lat_min = "16.939" ;
    lat:lat_max = "17.070" ;
  float lon(nbpoints) ;
    lon:_FillValue = NaNf ;
    lon:long_name = "Longitude" ;
    lon:standard_name = "longitude" ;
    lon:units = "degrees_east" ;
    lon:lon_min = "-100.583" ;
    lon:lon_max = "-100.530" ;
  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 = "4176." ;
    distance_to_coast:distance_to_coast_max = "1980.3" ;
    distance_to_coast:comment = "Distance along track to a reference point at
    the coast" ;
  int64 nbmonths(nbmonths) ;
    nbmonths:units = "count" ;
    nbmonths:long_name = "months number" ;
  double sla(nbpoints, nbmonths) ;
    sla:_FillValue = NaN ;
    sla:units = "m" ;
    sla:long_name = "X-TRACK/ALES monthly sea level anomaly" ;
    sla:standard_name = "sea_surface_height_above_mean_sea_level" ;
```

```
    string 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 2022 from CNES) - geocentric pole tide height (Wahr 1985 (J1/2)
    and Desai 2015 (J3)) - 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 local_sla_trend(nbpoints) ;
    local_sla_trend:_FillValue = NaN ;
    local_sla_trend:long_name = "Sea level anomaly trend as calculated by OLS
    regression" ;
    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 anomaly between 2002-01-01 and 2021-06-30" ;
  double local_sla_trend_error(nbpoints) ;
    local_sla_trend_error:_FillValue = NaN ;
    local_sla_trend_error:long_name = "Standard deviation of the OLS estimator of
    sea level trend" ;
    local_sla_trend_error:units = "mm/year" ;
  double sla_mean_10pts(nbmonths) ;
    sla_mean_10pts:_FillValue = NaN ;
    sla_mean_10pts:units = "m" ;
    sla_mean_10pts:long_name = "Sea level anomaly averaged over the 10 nearest
    points to the coast" ;
    sla_mean_10pts:standard_name = "sea_surface_height_above_mean_sea_level" ;
    sla_mean_10pts:comment = "X-Track/ALES monthly sea level anomaly averaged
    over the 10 first nearest point to the coast" ;
  double sla_mean_10pts_filt(nbmonths) ;
    sla_mean_10pts_filt:_FillValue = NaN ;
    sla_mean_10pts_filt:units = "m" ;
    sla_mean_10pts_filt:long_name = "Sea level anomaly averaged over the 10 nearest
    points to the coast with a 6 month filter" ;
    sla_mean_10pts_filt:standard_name = "sea_surface_height_above_mean_sea_level" ;
    sla_mean_10pts_filt:comment = "X-Track/ALES monthly sea level anomaly averaged
    over the 10 first nearest point to the coast with a 6 month rolling mean filter"
  int64 time(nbmonths) ;
    time:long_name = "Time" ;
    time:standard_name = "time" ;
    time:units = "days since 1950-01-01" ;
    time:calendar = "proleptic_gregorian" ;
```

5 Examples of along-track SLAs and trends (v3.0)

A full catalogue of the along-track SLAs and trends (v3.0) is available with the dataset.

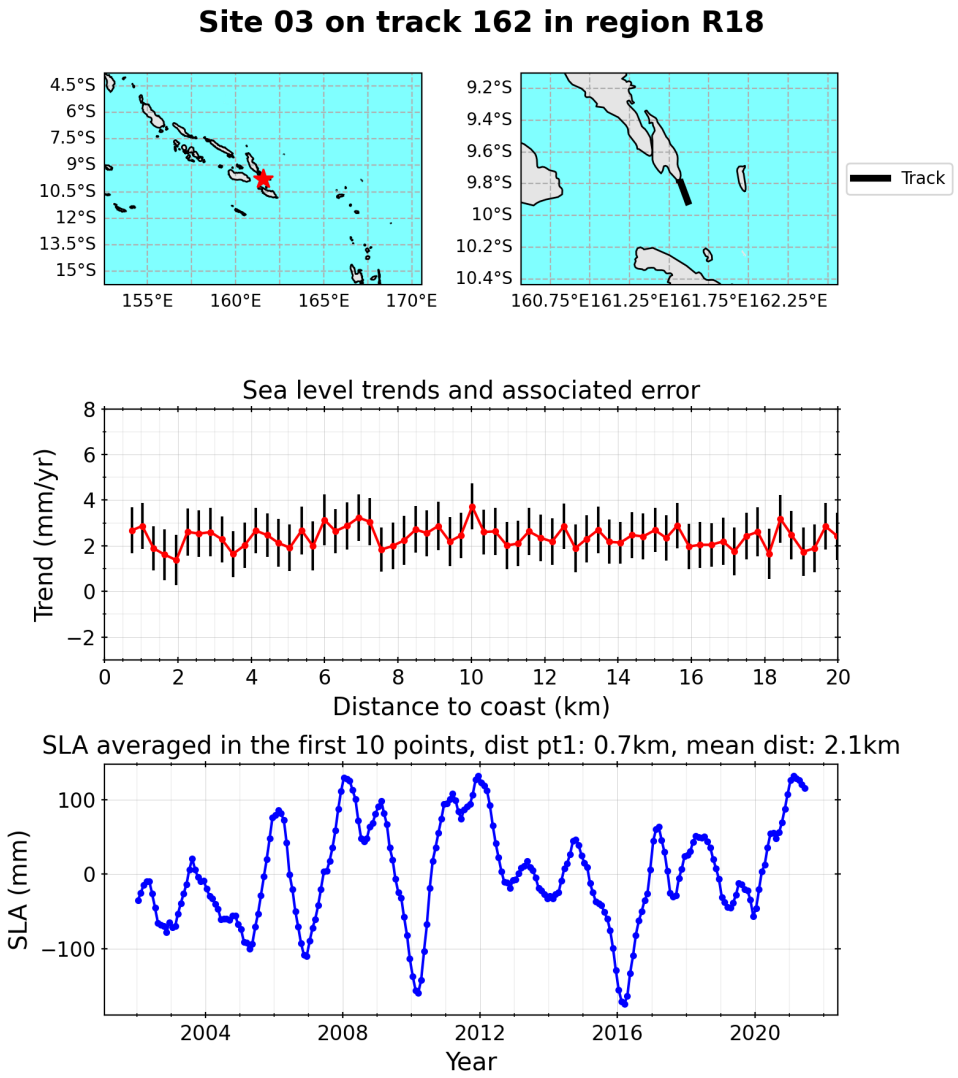

Figure 4: Example in the south of Malaita (Solomon Archipelago) (top panel): Sea level trends against distance to coast (middle panel) and SLA time series averaged over the first closest 10 points to the coast (bottom panel).

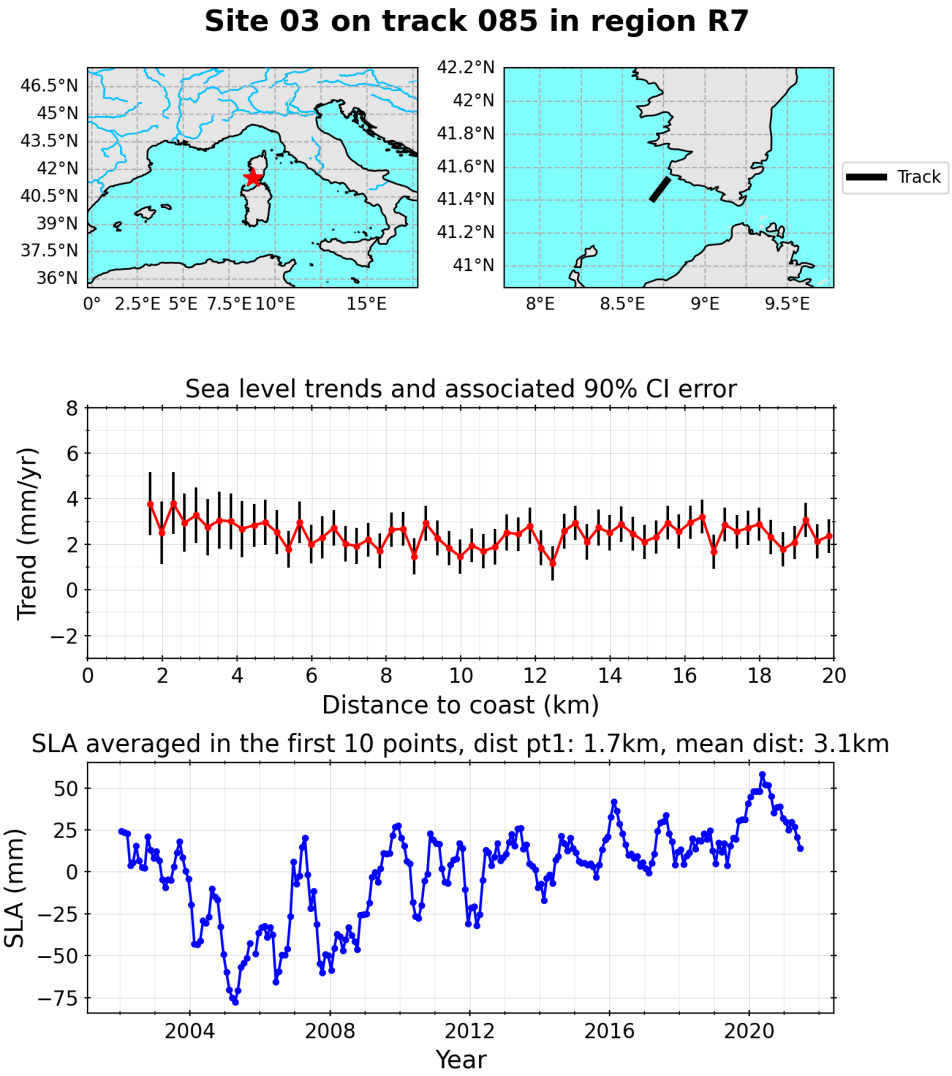

Figure 5: Example at the Senetosa site (south Corsica island): Sea level trends against distance to coast (middle panel) and SLA time series averaged over the first closest 10 points to the coast (bottom panel).

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/`

References

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Birol, F. and C. Delebecque (2014). "Using High Sampling Rate (10/20Hz) Altimeter Data for the Observation of Coastal Surface Currents: A Case Study over the Northwestern Mediterranean Sea." In: *Journal of Marine Systems* 129, pp. 318–333. DOI: 10.1016/j.jmarsys.2013.07.009.

Birol, F., F. Léger, M. Passaro, A. Cazenave, F. Niño, F. M. Calafat, A. Shaw, J.-F. Legeais, Y. Gouzenes, C. Schwatke, and J. Benveniste (2021). "The X-TRACK/ALES Multi-Mission Processing System: New Advances in Altimetry towards the Coast." In: *Advances in Space Research* 67.8, pp. 2398–2415. DOI: 10.1016/j.asr.2021.01.049.

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