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Consortium Members

Product User Guide

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1.2	5/01/20	Extension with Jason-3	F. Léger (LEGOS)
1.3	25/05/20	SLA and trends product at selected sites (sec. 4)	Y. Gouzenes (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 (section 5).	Y. Gouzènes, A. Cazenave, F. Léger (LEGOS)

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List of Acronyms

ALES	Adaptive Leading Edge Subwaveform
ESA	European Space Agency
CCI	Climate Change Initiative
CTOH	Centre of Topography of the Oceans and Hydrosphere
GDR	Geophysical Data Record
GPD	GNSS Path Delay we troposphere correction
GSHHS	Global Self-consistent, Hierarchical, High-resolution Geography database
Level 2P	Level 2 Plus altimeter data (after editing and validation)
RADS	Radar Altimeter Database System
SLA	Sea Level Anomaly
SSH	Sea Surface Height
X-TRACK	Altimeter production system developed by CTOH

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.

This document describes the information required to use the different coastal sea level products. Section 2 describes the altimeter standards used for the SLA computation, section 3 describes the regional along-track coastal sea level product and section 4 presents the thematic product which consists in monthly post-processed and validated SLA and associated trends at selected coastal sites. This provides a set of altimetry-based virtual coastal stations which can be used for studying long-term sea level trends, while the regional coastal along-track product includes all the data and is recommended for studying coastal circulation.

2. Altimeter standards

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.*, 2015)				
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. Regional coastal along-track product

3.1 Definition

Currently, the J1+J2+J3 product is distributed with 8 datasets corresponding to 8 coastal regions (Benguela Current, Mediterranean Sea, North East Atlantic Ocean, North Indian Ocean, South Australia, Southeast Africa, Southeast Asia and West African Coasts). Regions are illustrated on the figure below. They consist in a 20 Hz along-track SLA time series projected onto reference tracks with a spatial interval of circa 320 m between consecutive points. The total time series is derived from the Jason-1, Jason-2 and Jason-3 missions and covers the period from 15 January 2002 to 31 January 2020. The time series have been corrected for the inter mission biases.

Envisat and SARAL/AltiKa product are distributed with only 6 datasets corresponding to 6 coastal regions (Mediterranean Sea, North East Atlantic Ocean, North Indian Ocean, South Australia, Southeast Asia and West African Coasts). The time series for Envisat cover the period from 30 September 2002 to 13 September 2010 and from 14 March 2013 to 04 July 2016 for SARAL/AltiKa.

3.2 Latest version of the product

The J1+J2+J3 regional coastal along-track sea level product is currently available in version 2.0. This new release replaces the previous version of the product (v1.1). The evolutions included in version 2.0 are the following:

- New coastal areas included (‘Benguela’ and ‘South-East Africa’),
- Northward extension of the ‘Western Africa’ area (in order to include the coast up to Gibraltar Strait) and slightly reduced in the South to adapt to the new ‘Benguela’ area,
- Temporal extension from June 2018 until January 2020,
- Improved estimate of the inter mission bias between two successive missions.

3.3 Nomenclature

The nomenclature used for these products is:

ESACCI-SEALEVEL-L3-SLA-<ZONE>-<MISSION>-<ProductionDateYYYYMMDD>-<ORBIT>-<PassNumberXXX>-fv<VersionNumber>.nc

Where <MISSION> is:

MERGED for multi-mission data J1+J2+J3

ENV for Envisat

SRL for SARAL/AltiKa

<ORBIT> is:

JA for Jason orbits

EN for Envisat and SARAL/AltiKa orbits

< VersionNumber> is:

01.1 for Envisat and SARAL/AltiKa products

02.0 for combined J1+J2+J3 products

And <ZONE> is one of Figure 1:

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, for the North Indian Ocean, 0°N/26,5°N, 42,5°E/99°E
S_AUSTRALIA, for South Australia, -45°N/-15°N, 105°E/160°E
SE_ASIA, for Southeast Asia, -25°N/30°N, 90°E/150°E
WAFRICA, for the West African Coasts, -5°N/36,6°N, -20°E/13,5°E
BENGUELA, for the Benguela Current area, -40°N/0°N, 0°E/25°E
SE_AFRICA, for Southeast Africa, -40°N/5°N, 20°E/60°E.

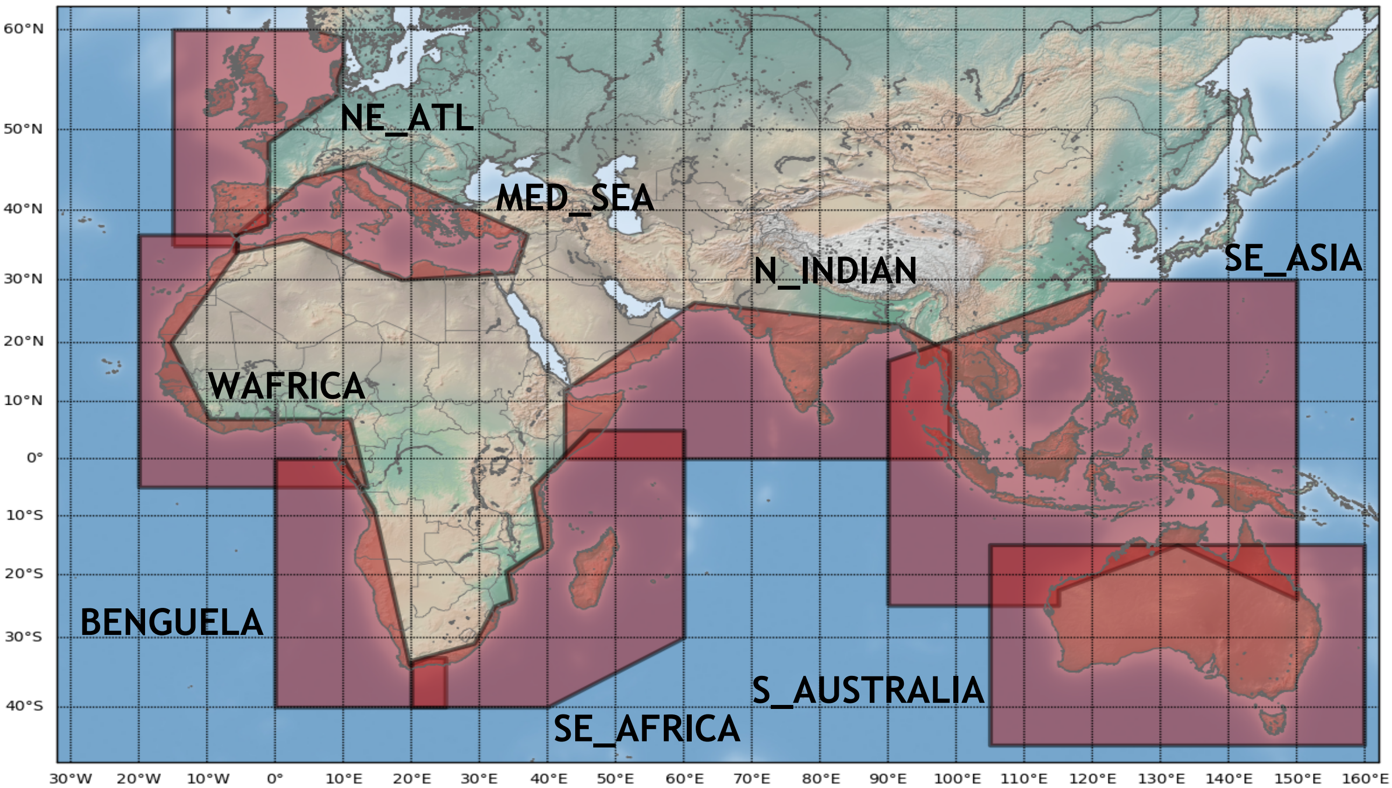

Figure 1: The regions covered by the coastal along-track product

For example, the J1+J2+J3 combined time-series data associated with track 222 in the North East Atlantic Ocean, produced on 2021/05/20 is found in a file whose name is:

ESACCI-SEALEVEL-L3-SLA-**NE_ATL**-MERGED-**20210520**-JA-**222**-fv02.0.nc

3.4 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/

3.5 Data handling variables

Names of variables in files	**Description**
lon	Longitude of the data point at 20 Hz resolution along the mean track
lat	Latitude of the data point at 20 Hz resolution along the mean track
cycle	Mission cycle number
missions_cycles	Original cycle number specific to each mission. It is discontinuous on the date of the change of mission.
sla	Sea Level Anomaly
ocean_tide	Oceanic tide includes the corresponding loading tide and equilibrium long-period ocean tide height from FES2014
dynamic_atmospheric_correction	Dynamic Atmospheric Correction, combining the low and high frequency effect of atmospheric pressure and wind on sea surface height from MOG2D-G
mean_sea_surface	X-TRACK Mean Sea Surface
dist_to_coast_gshhs	Distance to the nearest GSHHS coastline
mdt_cnes_cls18	Mean Dynamic Topography
time	Time of measurement at 20 Hz resolution
qual_flag	Quality flag if distance to the coast is lower than 4 km
Additional variables only for the multi-mission J1+J2+J3 products	
biasJ1J2	J1 J2 regional intermission bias
biasJ2J3	J2 J3 regional intermission bias

3.6 NetCDF header

Example for the Jason multi-mission product track 222 in the North East Atlantic Ocean zone

Product name = ESACCI-SEALEVEL-L3-SLA-NE_ATL-MERGED-20210520-JA-222-fv02.0.nc

3.6.1 Global attributes

```
// global attributes:
		:title = "SL_cci+ L3 X-TRACK/ALES Altimeter Sea Level Anomalies in the region NE_ATL" ;
		:institution = "ESA, CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
		:Conventions = "CF-1.6" ;
		:history = "2021-03-10 generated by X-TRACK v.1.03" ;
		:version = "X-TRACK/ALES 2.0" ;
		:pass_number = "222" ;
		:source = "Jason-1 GDR-E, Jason-2 GDR-D, Jason-3 GDR-D, RADS 4.0, ALES" ;
		:references = "https://climate.esa.int/en/projects/sea-level/data/" ;
		:tracking_id = "270b16ad-ccbe-49ec-85b4-a452872a10d7" ;
		:product_version = "2.0" ;
		:summary = "This dataset contains 20 Hz Level-3 regional sea level anomalies combining
ALES retracker and post-processing strategy of X-TRACK" ;
		:keywords = "satellite, ocean, coastal altimetry," ;
		:id = "DT-SLA-MERGED-20HZ" ;
		: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 = "2021-03-10" ;
		:creator_name = "CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
		:creator_url = "https://climate.esa.int/en/projects/sea-level/" ;
		:creator_email = "info-sealevel@esa-sealevel-cci.org" ;
		:project = "Sea Level Climate Change Initiative – European Space Agency" ;
		:geospatial_lat_min = "49.826 " ;
		:geospatial_lat_max = "59.3069 " ;
		:geospatial_lon_min = "-14.9914 " ;
		:geospatial_lon_max = "0.51267 " ;
		:geospatial_vertical_min = "0" ;
		:geospatial_vertical_max = "0" ;
		:time_coverage_start = "2002-01-15" ;
		:time_coverage_end = "2020-01-31" ;
		:time_coverage_duration = "P18Y" ;
		:time_coverage_resolution = "P9DT21H58M27.84S" ;
		: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 = "sea_surface_height_above_mean_sea_level" ;
```

3.6.2 Variables attributes

Variables:

```
	byte qual_flag(nbpoints) ;
		qual_flag:comment = "flag if distance to the coast is lower than 4 km" ;
		qual_flag:flag_meanings = "good, bad" ;
		qual_flag:flag_values = 0b, 1b ;
```

```
		qual_flag:long_name = "20Hz SLA quality flag" ;
	double biasJ1J2(nbpoints) ;
		biasJ1J2:_FillValue = 9.96920996838687e+36 ;
		biasJ1J2:units = "m" ;
		biasJ1J2:long_name = "J1 J2 intermission bias" ;
		biasJ1J2:comment = "J1 J2 regional intermission bias - 1°x1° box average. Mean regional
value is -0.053 m" ;
	double biasJ2J3(nbpoints) ;
		biasJ2J3:_FillValue = 9.96920996838687e+36 ;
		biasJ2J3:units = "m" ;
		biasJ2J3:long_name = "J2 J3 intermission bias" ;
		biasJ2J3:comment = "J2 J3 regional intermission bias - 1°x1° box average. Mean regional
value is -0.023 m" ;
	int cycle(nbcycles) ;
		cycle:long_name = "Cycle number" ;
		cycle:cyc_min = 1 ;
		cycle:cyc_max = 664 ;
		cycle:units = "count" ;
	int dist_to_coast_gshhs(nbpoints) ;
		dist_to_coast_gshhs:_FillValue = -2147483648 ;
		dist_to_coast_gshhs:long_name = "Distance to nearest coastline" ;
		dist_to_coast_gshhs:units = "m" ;
		dist_to_coast_gshhs:description = "Geodesic distances on WGS-84" ;
		dist_to_coast_gshhs:GMT_version = "4.5.9_r9889 [64-bit]" ;
		dist_to_coast_gshhs:add_offset = 0.f ;
		dist_to_coast_gshhs:scale_factor = -0.01f ;
		dist_to_coast_gshhs:comment = "Distance to nearest GSHHS 1.3 coastline in m" ;
	float lat(nbpoints) ;
		lat:_FillValue = 99.9999f ;
		lat:units = "degrees_north" ;
		lat:long_name = "Latitude" ;
		lat:short_name = "Lat" ;
		lat:lat_min = 49.f ;
		lat:lat_max = 60.f ;
		lat:add_offset = 0.f ;
		lat:scale_factor = 1.f ;
	float lon(nbpoints) ;
		lon:_FillValue = 99.9999f ;
		lon:units = "degrees_east" ;
		lon:long_name = "Longitude" ;
		lon:short_name = "Lon" ;
		lon:lon_min = -15.f ;
		lon:lon_max = 1.f ;
		lon:add_offset = 0.f ;
		lon:scale_factor = 1.f ;
	int mdt_cnes_cls_18(nbpoints) ;
		mdt_cnes_cls_18:_FillValue = -2147483647 ;
		mdt_cnes_cls_18:long_name = "mean dynamic topography" ;
		mdt_cnes_cls_18:units = "m" ;
		mdt_cnes_cls_18:creator_url = "https://www.aviso.altimetry.fr" ;
		mdt_cnes_cls_18:institution = "CLS, CNES" ;
		mdt_cnes_cls_18:processing_level = "L4" ;
		mdt_cnes_cls_18:product_version = "1.0" ;
		mdt_cnes_cls_18:summary = "Mean Dynamic Topography calculated from the combination
of altimetry, gravimetry (including GOCE and GRACE) and in-situ data. The reference time-period is 1993-
2012." ;
```

```
		mdt_cnes_cls_18:comment = "MDT_CNES_CLS18" ;
		mdt_cnes_cls_18:standard_name_vocabulary = "NetCDF Climate and Forecast (CF)
Metadata Convention Standard Name Table v37" ;
		mdt_cnes_cls_18:scale_factor = 1.e-06 ;
		mdt_cnes_cls_18:coordinates = "lon lat" ;
		mdt_cnes_cls_18:standard_name = "sea_surface_height_above_sea_level" ;
	short missions_cycles(nbcycles) ;
		missions_cycles:_FillValue = -99s ;
		missions_cycles:long_name = "Original cycle numbers of the concatenated missions" ;
		missions_cycles:cyc_min = 1 ;
		missions_cycles:cyc_max = 303 ;
		missions_cycles:units = "count" ;
		missions_cycles:comment = "This cycle number is specific to each mission. It is
discontinuous on the date of the change of mission." ;
	float sla(nbpoints, nbcycles) ;
		sla:_FillValue = 99.9999f ;
		sla:units = "m" ;
		sla:short_name = "SLA" ;
		sla:add_offset = 0.f ;
		sla:scale_factor = 1.f ;
		sla:comment = "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 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. " ;
		sla:long_name = "X-TRACK/ALES Sea Level Anomalies" ;
		sla:standard_name = "sea_surface_height_above_mean_sea_level" ;
	double time(nbpoints, nbcycles) ;
		time:_FillValue = 99.9999 ;
		time:units = "days since 1950-1-1" ;
		time:calendar = "julian" ;
		time:long_name = "Time of measurement" ;
		time:short_name = "Time" ;
	float ocean_tide(nbpoints, nbcycles) ;
		ocean_tide:_FillValue = 99.9999f ;
		ocean_tide:units = "m" ;
		ocean_tide:short_name = "Tide" ;
		ocean_tide:add_offset = 0.f ;
		ocean_tide:scale_factor = 1.f ;
		ocean_tide:long_name = "Global FES14 tide correction" ;
		ocean_tide:comment = "Geocentric ocean tide Includes the corresponding loading tide and
equilibrium long-period ocean tide height" ;
		ocean_tide:standard_name =
"sea_surface_height_amplitude_due_to_geocentric_ocean_tide" ;
	float dynamic_atmospheric_correction(nbpoints, nbcycles) ;
		dynamic_atmospheric_correction:_FillValue = 99.9999f ;
		dynamic_atmospheric_correction:units = "m" ;
		dynamic_atmospheric_correction:long_name = "Global Dynamic Atmospheric Corrections" ;
		dynamic_atmospheric_correction:short_name = "DAC" ;
		dynamic_atmospheric_correction:add_offset = 0.f ;
		dynamic_atmospheric_correction:scale_factor = 1.f ;
		dynamic_atmospheric_correction:comment = "Combined low and high frequency effect of
atmospheric pressure and wind on sea surface height from MOG2D-G" ;
```

```
    float mean_sea_surface(nbpoints) ;
            mean_sea_surface:_FillValue = 99.9999f ;
            mean_sea_surface:units = "m" ;
            mean_sea_surface:short_name = "MSSH" ;
            mean_sea_surface:mssh_period = "Cycles from 1 to 664 are used for the mssh computation"
;
            mean_sea_surface:add_offset = 0.f ;
            mean_sea_surface:scale_factor = 1.f ;
            mean_sea_surface:long_name = "X-TRACK/ALES Mean Sea Surface" ;
```

3.7 Example

Here you can find a basic example for reading and plotting the product using Python version 3.7. The output is shown in Figure 2 below; the code is shown in the following page. Python (http://www.python.org) is a free, general purpose programming language that is available on multiple operating systems including Linux, Windows and Mac OS (please note that the python 2.x series is deprecated and will not receive any further update after January 1, 2020).

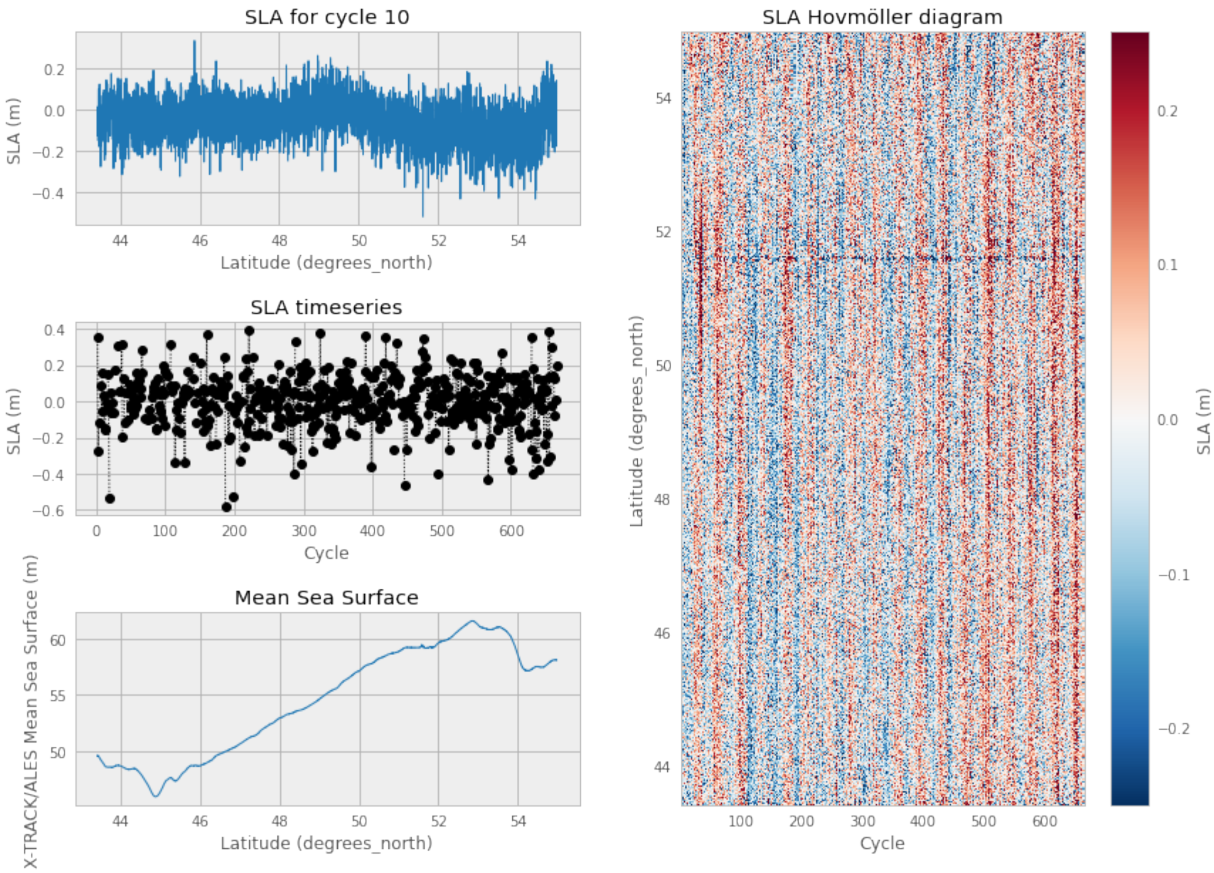

Figure 2: Output from the python example program

```
from netCDF4 import Dataset
import matplotlib.pyplot as plt


def read_variable_data(ncid, varname):
    data = ncid.variables[varname][:]
    longname = ncid.variables[varname].long_name
    shortname = ncid.variables[varname].short_name
    units = ncid.variables[varname].units
    return data, shortname, longname, units


# Open the ESA CCI SLA file.
ncid = Dataset("ESACCI-SEALEVEL-L3-SLA-NE_ATL-MERGED-20210520-JA-248-fv02.0.nc")

# get variables and metadata
latData, _, latLongName, latUnits = read_variable_data(ncid, "lat")
slaData, slaShortName, _, slaUnits = read_variable_data(ncid, "sla")
mssData, _, mssLongName, mssUnits = read_variable_data(ncid, "mean_sea_surface")

var = "cycle"
cycleData = ncid.variables[var][:]

# create figure window and plot
plt.figure(figsize=(14, 10))
ax = plt.subplot(3, 2, 1)
ax.plot(latData, slaData[:, 9])  # plot sla along latitude for cycle 10
ax.set_ylabel(slaShortName + " (" + slaUnits + ")")
ax.set_xlabel(latLongName + " (" + latUnits + ")")
ax.set_title("SLA for cycle 10")

ax = plt.subplot(3, 2, 3)
# plot timeseries of sla for the 10th point at lat[10]
ax.plot(cycleData, slaData[9, :], "ok:")
ax.set_xlabel("Cycle")
ax.set_ylabel(slaShortName + " (" + slaUnits + ")")
ax.set_title("SLA timeseries")

ax = plt.subplot(3, 2, 5)
ax.plot(latData, mssData)
ax.set_xlabel(latLongName + " (" + latUnits + ")")
ax.set_ylabel(mssLongName + " (" + slaUnits + ")")
ax.set_title("Mean Sea Surface")

cmap = "RdBu_r"  # colormap name
ax = plt.subplot(1, 2, 2)
pc = ax.pcolor(cycleData, latData, slaData, vmin=-0.25, vmax=0.25, cmap=cmap)
ax.set_xlabel("Cycle")
ax.set_ylabel(latLongName + " (" + latUnits + ")")
ax.set_title("SLA Hovmöller diagram")
cb = plt.colorbar(pc)
cb.set_label(slaShortName + " (" + slaUnits + ")")

plt.subplots_adjust(hspace=0.5)  # space between subplot

ncid.close()  # Close the NetCDF file.
plt.show()  # Show our completed plot
```

4. Along-track coastal sea level anomalies and trends; v1.1 product

4.1 Definition

The coastal sea level **trend** product is derived from the regional coastal along-track product in version 1.1. Thus, this product is a 16-year-long (June 2002 to May 2018), high-resolution (20 Hz), along-track sea level dataset in coastal zones of six regions: Mediterranean Sea, Northeast Atlantic, West Africa, North Indian Ocean, Southeast Asia and Australia. The new coastal sea level data set is based on the standards described in section 2 (i.e., complete reprocessing of raw radar altimetry waveforms from the Jason-1, Jason-2 and Jason-3 missions to derive satellite sea surface ranges as close as possible to the coast and optimization of the geophysical corrections applied to the range measurements). At each point of measurements along the tracks, the 10-day data are further averaged on a monthly basis, annual and semi-annual signals are removed and a new data editing is applied (based on a 2-sigma elimination of Jason cycles), at each 20-Hz sea level anomaly time series up to 20 km offshore. The corresponding monthly coastal sea level time series have been further analysed to compute sea level trends over the 16-year time span at each along-track 20-Hz point, from 20 km offshore to the coast. A severe selection (described in The CCI Coastal Sea Level Team, 2020) has been further carried out on all coastal portions of satellite tracks crossing land, leading to retain a set of 429 coastal sites of valid sea level time series and trend values.

This dataset is suitable for studying long-term sea level trends.

4.2 Nomenclature

The nomenclature used for this version 1.1 product is:
ESACCI-SEALEVEL-IND-MSLTR-MERGED-<ZONE>_JA_<PassNumber>_<SiteNumber>-<ProductionDateYYYYMMDD>-fv01.1.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 the West African Coasts, -8°N/20°N, -30°E/13,5°E

<PassNumber> is the Jason track number

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

For example, the time series data associated with track 222 site number 2 in the North East Atlantic Ocean, produced on 2020/06/02 is found in a file whose name is:

ESACCI-SEALEVEL-IND-MSLTR-MERGED-**NE_ATL**_JA_**222_02**-20200310-fv01.1.nc

4.3 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/

4.4 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 June 2002 to May 2018 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).

4.5 NetCDF header

4.5.1 Global attributes

Product name = ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_222_01-20200404-fv01.1.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 = "2020-04-04 generated by X-TRACK v.1.06" ;
:references = "http://www.esa-sealevel-cci.org/products" ;
:tracking_id = "ace2d682-e0da-42e8-ac8f-a366b638edc2" ;
:Conventions = "CF-1.7" ;
:version = "X-TRACK/ALES 1.1" ;
:pass_number = "222" ;
:site_number = "01" ;
:product_version = "1.1" ;
:summary = "This dataset contains 20 Hz regional sea level trends computed from sea level anomalies combining ALES retracker and post-processing strategy of X-TRACK" ;
:keywords = "satellite, ocean, coastal altimetry" ;
:id = "ESACCI-SEALEVEL-IND-MSLTR-MERGED-NE_ATL_JA_222_01-20200404-fv01.1.nc" ;
:doi = " " ;
: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 = "2020-02-06" ;
:creator_name = "CTOH/LEGOS, Toulouse Univ., CNRS, IRD, CNES, UPS, France" ;
:creator_url = "http://www.esa-sealevel-cci.org" ;
:creator_email = "info-sealevel@esa-sealevel-cci.org" ;
:project = "Sea Level Climate Change Initiative - European Space Agency" ;
:geospatial_lat_min = "55.2331 " ;
:geospatial_lat_max = "55.3515 " ;
:geospatial_lon_min = "-7.09489 " ;
:geospatial_lon_max = "-6.89854 " ;
:geospatial_vertical_min = "0" ;
:geospatial_vertical_max = "0" ;
:time_coverage_start = "2002-06-01" ;
:time_coverage_end = "2018-05-30" ;
:time_coverage_duration = "P16Y" ;
:time_coverage_resolution = "P9DT21H58M27.84S" ;
: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" ;

4.5.2 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 = 1586.44f ;
        distance_to_coast:distance_to_coast_max = 19717.8f ;
        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 = 55.2331f ;
        lat:lat_max = 55.3515f ;
float lon(nbpoints) ;
        lon:long_name = "Longitude" ;
        lon:standard_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:lon_min = -7.09489f ;
        lon:lon_max = -6.89854f ;
double time(nbcycle) ;
        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 mean 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 2002-06-01 and 2016-05-30" ;
float local_sla_trend_error(nbpoints) ;
        local_sla_trend_error:_FillValue = 1.844674e+19f ;
```

local_sla_trend_error:long_name = "Geographical distribution of mean 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, nbcycle) ;

sla:_FillValue = 1.844674e+19f ;

sla:units = "m" ;

sla:standard_name = "sea_surface_height_above_mean_sea_level" ;

sla:comment = "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 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." ;

4.6 Example

This monthly product allows to study long-term coastal trend in numerous sites. Fig.2 shows such an example that contains sea level anomalies and trends at site n°2 on track 20 in the Mediterranean Sea. From top to bottom, it shows a map of the site position on the track, the sea level trends at each 20-Hz point, expressed as a function of distance to the coast, starting from 15 km offshore, and superimposed trend errors, and finally sea level anomaly time series at the first six valid points from the coast. The monthly sea level anomalies also allow to recompute the trend over the desired period, for instance to compare with tide gauges at the coast.

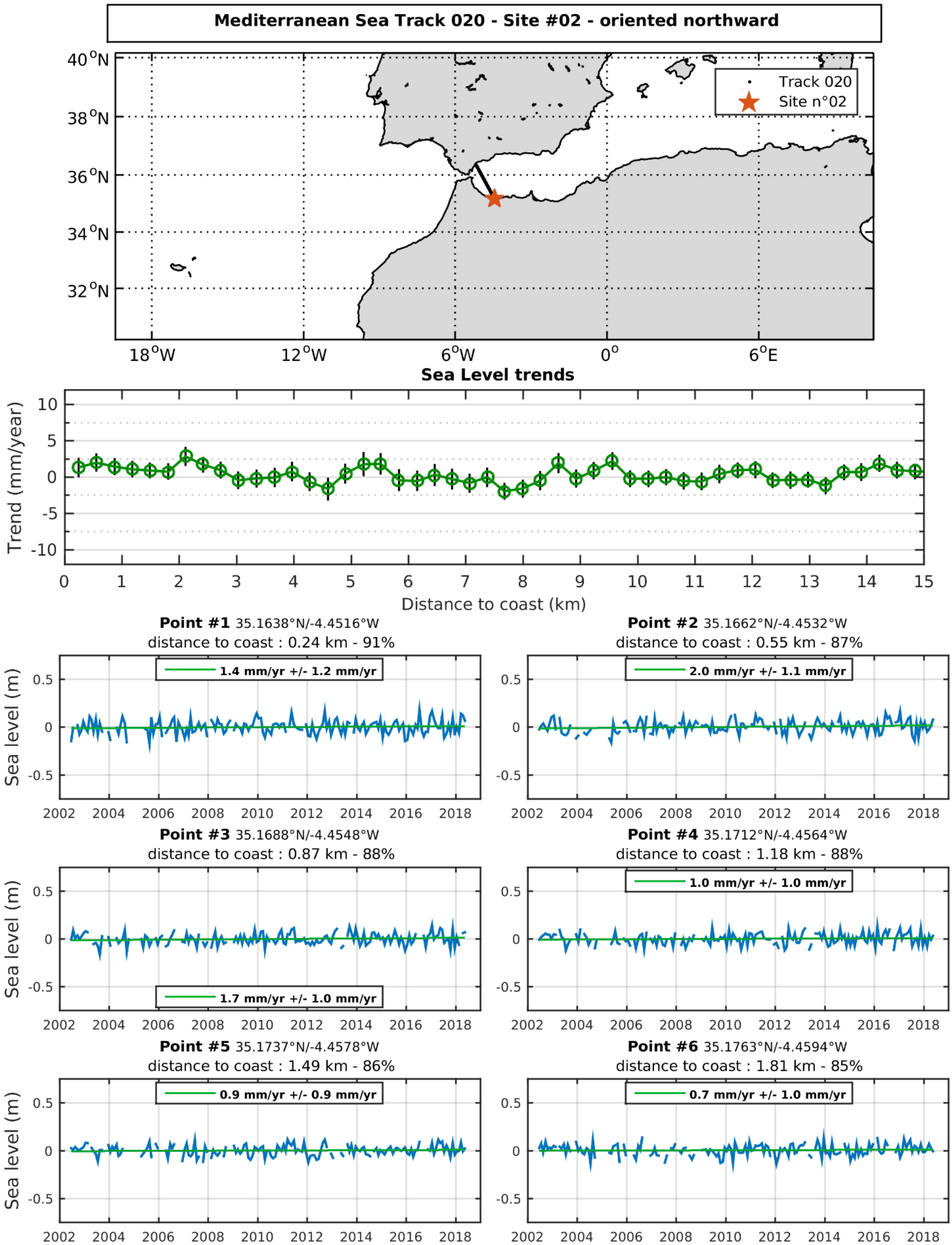
Mediterranean Sea Track 020 - Site #02 - oriented northward
Track 020
Site n°02
40°N
38°N
36°N
34°N
32°N
18°W
12°W
6°W
0°
6°E
Sea Level trends
Trend (mm/year)
Distance to coast (km)
Point #1 35.1638°N/-4.4516°W
distance to coast : 0.24 km - 91%
1.4 mm/yr +/- 1.2 mm/yr
Point #2 35.1662°N/-4.4532°W
distance to coast : 0.55 km - 87%
2.0 mm/yr +/- 1.1 mm/yr
Point #3 35.1688°N/-4.4548°W
distance to coast : 0.87 km - 88%
1.7 mm/yr +/- 1.0 mm/yr
Point #4 35.1712°N/-4.4564°W
distance to coast : 1.18 km - 88%
1.0 mm/yr +/- 1.0 mm/yr
Point #5 35.1737°N/-4.4578°W
distance to coast : 1.49 km - 86%
0.9 mm/yr +/- 0.9 mm/yr
Point #6 35.1763°N/-4.4594°W
distance to coast : 1.81 km - 85%
0.7 mm/yr +/- 1.0 mm/yr
Sea level (m)

Figure 3: ***Position (top), trends and trend errors (vertical bars) along-track as a function of distance to the coast (middle) and sea level anomalies time series of the 6 first points (bottom) for the site n°2 on track 20 in Mediterranean Sea; the % of valid data is indicated at the top of each plot.***

The product also allows global analyses to be performed (The CCI Coastal Sea Level Team, 2020), as illustrated in figure 3 showing differences between coastal trends (at the closest distance to the coast of the first valid point) and open ocean trends at each site. This map alo provides information on the location of the 429 selected sites.

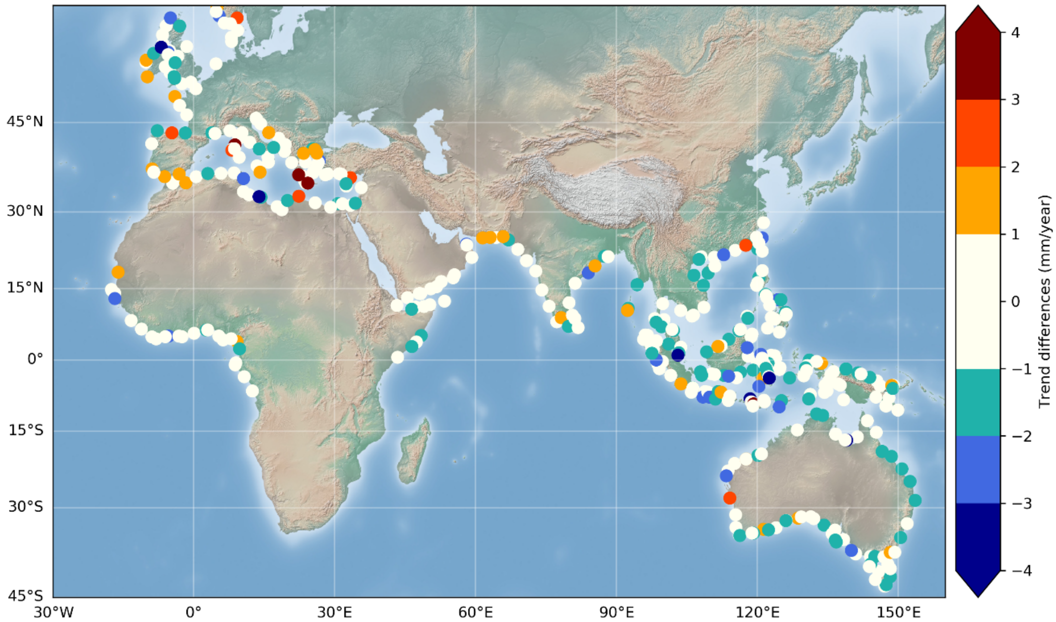

Figure 4: *Differences in sea level trends between an along-track band of 2 km from the closest valid point to the coast and the 14-16 km average, offshore. 'Cream' colour corresponds to no significant differences. Orange-red-brown and green-blue dots correspond to coastal trend increase and decrease respectively at the coast*

5. Updated along-track coastal sea level anomalies and trends (v2.1): Jan. 2002-Dec. 2019, extended to the American continent

In this update, the study regions have been extended, now including the Northeast Atlantic, Mediterranean Sea, Africa, North Indian Ocean, Southeast Asia, Australia and America. 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. Fig.5 shows the closest distance to the coast reached by the first valid point along the satellite tracks in the study regions.

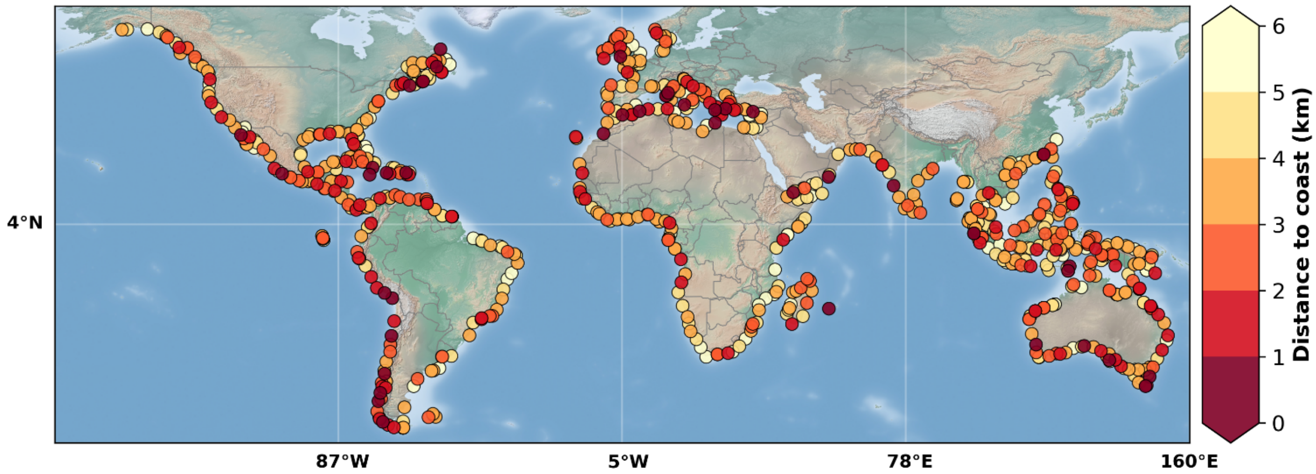

Figure 5: *Closest distance (km) to coast reached by the first valid point along the Jason tracks for the 756 selected virtual stations.*

5.1 Format and data handling variable update

The format and data handling variable are similar to product v1.1

5.2 Nomenclature update

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

The nomenclature is similar to product v1.1 with the following add in <ZONE>:

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

5.3 NetCDF Header update

5.3.1 Global attributes

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" ;

}

5.3.2 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." ;

6. Additional information and known issues

- The users are informed that the reference to Fernandes et al., 2015 mentioned in the “comment” attribute of the “sla” variable in the NetCDF data files should be instead Fernandes et al., 2016. This will be corrected in the next version of the datasets.
- It is clarified that the “spatial_resolution” global attribute available in the NetCDF data files corresponds to the posting rate (separation between two consecutive estimates in the along-track direction), which is on average around 350m.

7. References

Birol F. and C. Delebecque, 2014. Using high sampling rate (10/20 Hz) altimeter data for the observation of coastal surface currents: A case study over the northwestern Mediterranean Sea, *J. Mar. Syst.*, https://doi.org/10.1016/j.jmarsys.2013.07.009.

Birol F., N. Fuller, F. Lyard, M. Cancet, F. Niño, C. Delebecque, S. Fleury, F. Toublanc, A. Melet and M. Saraceno, F. Léger, 2017. Coastal applications from nadir altimetry: example of the X-TRACK regional products. *Advances in Space Research*, https://doi.org/10.1016/j.asr.2016.11.005.

Birol, F., F. Léger, M. Passaro, A. Cazenave, F. Niño, F. Calafat, A. Shaw, J.F. Legeais, Y.Gouzenes, C. Schwatke, J. Benveniste, 2021. The X-TRACK/ALES multi-mission processing system: New advances in altimetry towards the coast. Advances in Space Research, S0273117721001046, https://doi.org/10.1016/j.asr.2021.01.049.

Cartwright, D. E. and Taylor, R. J., 1971. New computation of the tide-generating potential. *Geophysical Journal of the Royal Astronomical Society*, 23, 45-74, https://doi.org/10.1111/j.1365-246X.1971.tb01803.x.

Cartwright, D. E. and Edden, A. C., 1973. Corrected Tables of Tidal Harmonics. *Geophysical Journal of the Royal Astronomical Society*, 33: 253-264. https://doi.org/10.1111/j.1365-246X.1973.tb03420.x.

Carrere, L., and Lyard, F., 2003. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing-Comparisons with observations. *Geophys. Res. Lett.*, 30(6), 1275, https://doi.org/10.1029/2002GL016473.

Carrere L., Lyard, F., Cancet, M., Guillot, A., Roblou, L., 2012. FES2012: A new global tidal model taking advantage of nearly 20 years of altimetry, in Proceedings of the “20 Years of Progress in Radar Altimetry” Symposium, Venice, Italy, 24-29 September 2012, Benveniste, J. and Morrow, R., Eds., ESA Special Publication SP-710, 2012. https://doi.org/10.5270/esa.sp-710.altimetry2012

The Climate Change Initiative Coastal Sea Level Team., Coastal sea level anomalies and associated trends from Jason satellite altimetry over 2002–2018. Sci Data 7, 357 (2020). https://doi.org/10.1038/s41597-020-00694-w

The Climate Change Initiative Coastal Sea Level Team, New network of virtual altimetry stations for measuring sea level along the world coastlines, submitted to Communications Earth and Environment, January 2022.

Fernandes, M., and Clara Lázaro, 2016. GPD+ Wet Tropospheric Corrections for CryoSat-2 and GFO Altimetry Missions. *Remote Sensing* 8 (10): 851. https://doi.org/10.3390/rs8100851.

Iijima B.A., I.L. Harris, C.M. Ho, U.J. Lindqwister, A.J. Mannucci, X. Pi, M.J. Reyes, L.C. Sparks, B.D. Wilson,(1999). Automated daily process for global ionospheric total electron content maps and satellite ocean altimeter ionospheric calibration based on Global Positioning System data. Journal of Atmospheric and Solar-Terrestrial Physics 61 1205-121, https://doi.org/10.1016/S1364-6826(99)00067-X.

Passaro M., Cipollini P., Vignudelli S., Quartly G., Snaith H., 2014. ALES: A multi-mission subwaveform retracker for coastal and open ocean altimetry. *Remote Sensing of Environment* 145, 173-189, https://doi.org/10.1016/j.rse.2014.02.008.

Passaro M., Fenoglio-Marc L., Cipollini P. 2015. Validation of significant wave height from improved satellite altimetry in the German bight. *IEEE Transactions on Geoscience and Remote Sensing* 53(4): 2146-2156, https://doi.org/10.1109/TGRS.2014.2356331.

Passaro M., Smith W., Schwatke C., Piccioni G., Dettmering D., 2017. Validation of a global dataset based on subwaveform retracking: improving the precision of pulse-limited satellite altimetry. *OSTST Meeting 2017*, Miami, USA.

Wahr, J. M., 1985. Deformation induced by polar motion. *J. Geophys. Res.*, 90 (B11), 9363– 9368, https://doi.org/10.1029/JB090iB11p09363.