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ESA Sea Level CCI+

Sea Level in Coastal Areas: User Requirements Document

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1. Introduction

The Sea Level project of the Climate Change Initiative (Phase I and II during 2011-2019) has been the opportunity to produce an accurate, homogeneous and stable sea level climate Data record (FCDR and ECV products). This production has been performed after gathering the User Requirements related to the sea level ECV. The SL_cci URD (available at: http://www.esa-sealevel-cci.org/webfm_send/235) includes a review and an analysis of the requirements provided within existing documents that come from Global Climate Observing system (GCOS), World Meteorological Organisation (WMO), World Climate Research Program (WCRP) on the one hand, and from the Climate Modelling Group (CMUG). The requirements coming from the Ocean Surface Community are also presented as well as the list of requirements dedicated to climate applications to be applied to the Sea Level variable. In particular, the SL_cci URD includes a description of the user requirements for the coastal areas, including the results of a survey dedicated to the coastal sea level.

The extension of the SL_cci activities (SL_cci+, started in 2019) focuses on computing high-resolution sea level anomalies and associated trends in coastal areas, validating and interpreting the products as well as characterizing sea level uncertainties on a global, regional and coastal scales. In this context, this document presents the update of the user requirements related to the coastal altimeter sea level products.

2. Requirements for the satellite observing system

The objective of the project is to develop a database of coastal sea level products in a number of world coastal zones selected for their vulnerability to global warming and sea level rise, using retracked data from LRM altimetry missions and SAR altimetry from the Sentinel 3A and 3B missions, as well as dedicated coastal geophysical corrections. This will be performed by combining the retracked altimeter range data using the ALES (Adaptive Leading Edge Subwaveform) retracker (Passaro et al, 2015) with the XTRACK system developed at LEGOS (Birol et al., 2017, 2020).
A new version of the X-TRACK processing chain has been developed, with main objective to integrate different efforts that have been recently made by the international altimetry community to enhance the capabilities of satellite altimetry along world coastlines. The most advanced processing algorithms and corrections available are combined into a new product for the present project. The ALES retracker has proven its efficiency in retrieving more coastal sea level observations than other retrackers, particularly when using high-rate (i.e., 20-Hz) altimeter measurements instead of the standard (1-Hz) data (Passaro et al., 2018 a,b ; Xu et al., 2018). On the other hand, geophysical corrections, in particular the wet

tropospheric and tidal corrections, have also been improved in the coastal domain. For the present project, acknowledging climate user needs, we propose to develop new X-TRACK/ALES L3 (i.e., along-track) and L4 (i.e., gridded) multi-mission products, combining the best spatial resolution provided by high-rate data, the best possible set of geophysical corrections (defined after a dedicated inter-comparison study), the post-processing strategy of X-TRACK and the advantage of the ALES retracker.
An homogeneous, long-term multi-mission coastal sea level product has been first computed from Jason-1,2,3, Envisat, SARAL/Altika, and Sentinel-3A & 3B missions for all the selected areas. All these data will then be combined in regional gridded products in a 'seamless' global grid approach with varying spatial resolution (higher resolution near the coast).
The focus was made on the period 2002 to present time when independent measurements (e.g. Argo, GRACE) are available to assess the physical processes. The CryoSat-2 mission is not included mainly due to its long repeat cycle that prevents us to estimate reliable trends, and new missions (Jason-3 and Sentinel-3A) are used to extend the database. Other altimetry missions (TOPEX-Poseidon, ERS-1, ERS-2, GFO, CryoSat-2) have been integrated in the global gridded Climate Data Record (CDR) developed within the previous phase of the SL_cci project and the operational production of this CDR has now been taken over by the European Copernicus Climate Change Service (C3S).

Considering the Earth Observation/EO and modelling communities, the requirements for sea level ECV data in coastal areas can be split into:

- Length (> 1 decade) and continuity of the sea level records
- Observation type
- Good temporal and spatial resolution
- Error characterization
- Quasi global coverage
- Easy access to the data

2.1. Record Length

The length and continuity of the Sea-Level ECV is undoubtedly the most pressing requirement of the EO and modeling communities since the longer the record, the easier to distinguish changes caused by anthropogenic forcing from the natural (internal) climate variability. In terms of global mean and the availability of a 25-year-long sea level record (Ablain et al., 2017, Legeais et al., 2018), this is already achievable (Marcos et al., 2017, Slangen et al., 2017). At regional scale, recent results suggest that the anthropogenic forcing begins to emerge in some regions but that the natural variability remains dominant. At local scale, the questions are still open. We expect that a ~20-year-long record can allow us to separate longer-term trends from the natural interannual variability. In addition, combination with other multi-sources datasets (i.e., Argo for the steric contribution, tide gauges, etc.) will offer constrains on the various processes active in the coastal zones and on their lifetime.

2.2. Observation Type

In the original proposal, we wrote:
“Ideally what is required for science and applications in the coastal areas is a gridded product of coastal sea level, with the highest possible resolution over the longest possible time span. Since the present project deals with multi-mission altimetry products, the coastal sea level record will have high-resolution along-track (<2 km for the LRM missions, a few hundred metres for the SAR data), and coarser resolution for the gridded product (10 km or better). We intend also to provide a 'seamless' gridded sea level product covering the global oceanic areas from the open ocean to the coast by adapted linkage of the existing SL_cci grids and other sea level gridded products (e.g., from AVISO, C3S) with the coastal sea level products developed in the present project.
In addition to the along-track & gridded coastal products, and seamless global grids with increasing spatial resolution to the coast, we intend to provide maps of coastal sea level trends over the selected study zones for the period 2002 to present.”

On the basis of the work already performed, we consider that the main novel product of this project is the high-resolution (20 Hz) along-track sea level anomalies in the close vicinity of the coast (within 20 km from the coast) and associated coastal sea level trends.
It will not be possible to compute high-resolution gridded sea level trends in the close vicinity of the coast due to the loose coverage of the satellite tracks over the long-term (2002-present).

The studied world coastal zones have been selected for their vulnerability to global warming and sea level rise and are listed in the following table:

Region name	Lat min	Lat max	Lon min	Lon max
Mediterranean Sea	30	46	-6	37
North East Atlantic	35	60	-15	10
Western Africa	-5	36.6	-20	13.5
North Indian Ocean	0	26.5	42.5	99
Southeast Asia and North Australia	-25	30	90	150
South Australia	-45	-15	105	160
Benguela	-40	0	0	25
South East Africa	-40	5	20	60

2.3. Spatial and temporal resolution

It is expected to produce coastal sea level time series with the following spatial resolution:

- Along-track high resolution (~1 km) coastal sea level anomalies, mission by mission products.
- Along-track monthly times series of sea level anomalies, starting in 2002 to present, along coastal portions of tracks in a set of edited and validated coastal sites of the selected regions,

2.4. Along-track coastal sea level trends derived from these edited monthly sea level anomalies at selected coastal sites. Accuracy

The accuracy of the sea level data at the coast depends on a number of factors, including the quality of the ALES retracker and accuracy of the coastal geophysical corrections. In terms of trend, the requirement would be an accuracy of 1-2 mm/yr over 15 years or longer.

2.5 Available coastal sea level products at the date of June 2021

A preliminary product (version 1.1) of coastal sea level time series over June 2002 to May 2018, and associated trends, has been published in November 2020 in Nature Scientific Data (Climate Change Initiative Coastal Sea Level Team (The), Coastal sea level anomalies and associated trends 2 from Jason satellite altimetry over 2002-2018, Nature Scientific Data, 7, 357, https://doi.org/10.1038/s41597-020-00694-w, 2020).

A version 2.0 product extending the spatio-temporal coverage (whole African continent, in addition to the other regions considered in the v 1.1 product -see Figure 1-; time span from January 2002 to December 2019) has been recently produced. Its validation is in progress.

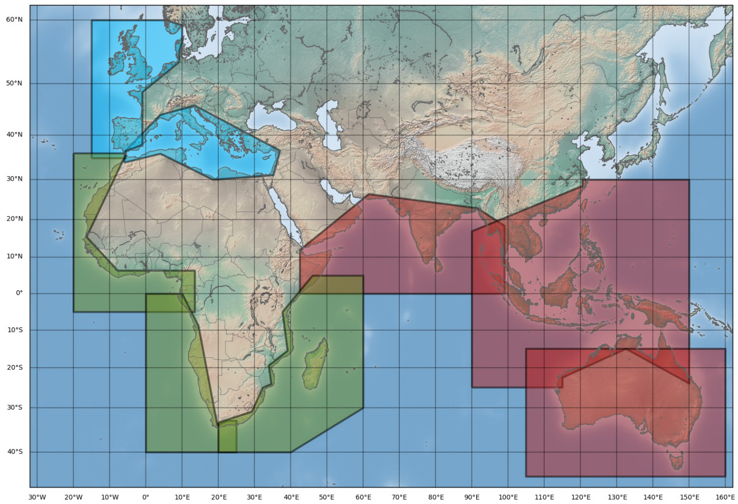

Fig.1: Map of the regions were coastal sea level time series and trends over 2002-2020 are available

3. Requirements for the validation

To validate the coastal sea level trends provided by the project, two methods can be used:

- Comparison with tide gauges
- Comparison with high resolution ocean simulations

Tide gauges provide the only direct measurements of coastal sea level against which the altimetry product can be validated. Tide-gauge observations, however, are spatially sparse, and thus they only allow for a validation at a very limited number of locations. This is an issue because the spatio-temporal scales of sea-level changes greatly vary from region to region according to bathymetric and regional climate conditions, meaning that a good match between altimetry and tide-gauge observations at one location cannot be extrapolated to other locations. In addition to this issue, tide gauges are located on the coast and hence they only measure coastal relative sea-level. This is another issue because, as mentioned above, coastal sea level can differ significantly from open-ocean sea level, but altimetry observations need to be validated also in the open ocean. These issues will be addressed by using high-resolution ocean models, which provide estimates of sea-level changes with good spatial coverage. Moreover, because of their fine resolution, they should be able to resolve many of the small-scale processes that are important for coastal sea level. Such models also enable us to investigate how sea-level changes evolve as we move from the open ocean to the coast. Finally, in doing the validation, it is important to quantify and account for the uncertainty associated with our estimates of sea-level changes, particularly for the trend.

3.1. Comparison with tide gauges

The validation should be done globally (contingent upon tide-gauge data availability) for both the sea-level variability and the long-term trends. This assessment will also include rigorous uncertainty estimation for the trends.

- In designing the validation strategy, a number of issues merit consideration. First, it is important to recognize that variability and trends in sea-level are driven by different mechanisms and hence have different spatial length scales; the former is largely associated with internal variability in the ocean-atmosphere system the latter is the superposition of various processes causing global mean and regional sea level variations (i.e., ocean warming and land-ice melting, fingerprints of land ice melt and mass redistribution), plus local processes occurring at the coast (wind, waves and atmospheric pressure forcing, small-scale shelf currents, fresh water input from rivers). This implies that the agreement between altimetry observations and other types of data (e.g., tide gauges and models) might be different depending on the temporal scales of variability that one is looking at. This means that a good agreement in terms of trend does not imply the same for the variability and vice versa, and hence the validation needs to be conducted specifically for each temporal component.
- Secondly, the regimes of sea-level variability can be very different between the coastal zone and the deep ocean, which demands that we validate both coastal and open-ocean altimetry observations. A further reason for the distinction between coast and open ocean is the need to explicitly assess the performance of the new coastal altimetry products in the coastal zone.
- Third, the main source of information on long-term sea-level changes comes from tide gauges, but those are strongly affected by vertical land motions. Hence, when comparing rates of sea-level rise from altimetry and tide gauges it is important to account for the contribution of land motion by using, for example, GNSS data wherever possible, otherwise the altimetry and tide-gauge rates are not directly comparable. Finally, in assessing the uncertainty associated with sea-level trend estimates, it is crucial to account for altimetry errors, serial correlation in the sea-level time series, and the effects of decadal variability, which is largely unresolved due to the relatively short altimetry record.

An inventory of tide gauge equipped with GNSS stations located close (<1 km) from satellite tracks crossing the coast will be performed shortly.

3.2. Comparison with high resolution ocean simulations

In the original proposal, we wrote:

"Together with tide gauge observations (but with sparse coverage), the only information to compare the coastal products delivered in this project comes from ocean reanalyses. The following suite of activities will be performed

- *Statistically quantify the differences observed between the altimetry-based coastal products and open ocean sea level variations at interannual time scale using ocean numerical models*
- *Characterize the dominant modes of temporal and spatial variability*
- *Characterize uncertainties*
- *Test the potential of altimetry to observe such signals at the coast*

For that purpose, we intend to use available ocean reanalyses, based on the community NEMO ocean model in various configurations. In particular:

- *'Climate-type' global experiments, with 0.25° resolution (used in the IPCC CMIP6 project). Outputs are available from the OCCIPUT project (Sérazin et al., 2015). An ensemble of 50 realizations are available, forced by observed wind and fluxes over 1960-2015. Uncertainties are also available.*
- *Other numerical experiments operationally provided by the Copernicus Marine Service (CMEMS) and MERCATOR-Ocean. These numerical simulations use different high-resolution versions of NEMO (a global version at 1/12°, and regional versions over the northeast Atlantic and Mediterranean Sea at 1/12° and 1/36°, allowing to have information very close to the coast (within a few km) (see section 3 below).*
- *The ECMWF ocean reanalyses, in particular ORA-S5 (https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets).*

Focusing on interannual variability and trends, we will compare the model-based and altimetry-based signals from the open ocean to the coast. For each study region, we will investigate the respective roles played by internal modes of variability and small-scale processes and human induced forcing factors acting in coastal zones."

However, further investigation shows that the data-model comparison is limited. This is due to the lack of resolution of available ocean models. The table below summarizes what is currently available:

Model	From	Region	Geographical area	Spatial resolution	Temporel resolution	Period covered

MEDSEA_REANALYSIS_PHYS_006_004	CMEMS & MED-MFC	Mediterranean	30.17°N-45.94°N 6°W-36.25°E	1/16°x1/16° ~ 6-7 km	daily monthly	1987-01-01 to 2018-12-31 **32 yrs**
MEDSEA_ANALYSIS_FORECAST_PHY_006_013_EAS5	CMEMS	Mediterranean	30.17°N-45.94°N 6°W-36.25°E	1/24°x1/24° ~ 4 km	hourly daily monthly	2018-04-01 to Present **~2 yrs**
corsica_MARS3D	IFREMER	Corsica	40.7164°N - 43.3149°N 8.1452°W-9.9408°W	360 x 484 m ~ 400 m	3-hourly monthly	Jan 2014 to Dec 2018 **5 yrs**
NEMO	LEGOS	Atlantic African coasts	31°S–16°N; 25°W–African coasts	1/12°x1/12° ~ 8-9 km	monthly	Jan 1993 to Dec 2015 **23 yrs**
GLOBAL_REANALYSIS_PHY_001_030	CMEMS & MERCATOR	Global	Global-ocean	1/12°x1/12° ~ 8 km	Daily monthly	Jan 1993 to 2018-12-25 **~26 yrs**
Symphonie	LEGOS/LA	Vietnam	0.5993°S – 24.07°N ; 98.981°E – 124.7616°E	3.5 km x 3.5 km	monthly	Jan 2009 to Dec 2018 **10 yrs**

Our coastal sea level product has a resolution of 300-350 m along track. As seen on the table above, available models do not have the required resolution to perform valuable comparisons, except the MARS3D model in the western Mediterranean Sea. However, preliminary analyses of the MARS3D model show strong bias in terms of trends that are not understood yet. Discussion with IFREMER (at the origin of the model are ongoing to further solve the problem).

Although the Symphonie model around Vietnam has a resolution of 3.5 km only, comparisons with our coastal results are also underway

4. Requirements for the understanding of the different processes

Preliminary results from the CCI Bridging Phase suggest different trend behaviours close to the coast compared to offshore (Marti et al., 2019). If real, the observed higher or lower trends reported in the 5 to 10 km to the coast may reveal the signature of small-scale processes acting only close to the coast, such as small scale shelf currents, trend in waves, wind and atmospheric pressure forcing, fresh water input from rivers in estuaries…

To explain observed trends at the coast, a number of auxiliary data sets are needed in the studied coastal zones:

- Temperature T and salinity S fields
- High-resolution wind and waves data
- Surface pressure P data
- River discharge data in estuaries
- Bathymetry
- …..

In general, such coastal observations do not exist. However, at some locations, data sets are available, for example sea surface salinity SSS and sea surface temperature SST in the Mediterranean Sea. In addition, coastal T/S fields can be found on the COPERNICUS Marine Service (CMEMS).

Winds and waves in the coastal zone can be derived from retracked altimetry data at the same points as the sea level anomalies (hence same spatio-temporal coverage and resolution -20 Hz-).

Global gridded data sets of waves and winds are also available (e.g., from reanalyses) but the resolution may not be high enough to quantify processes close to the coast. We will have to examine whether downscaling can be performed. Other data bases exist, e.g., the **Integrated Surface Dataset (Global)** from NOAA (https://catalog.data.gov/dataset/integrated-surface-global-hourly-data), composed of worldwide surface weather observations from over 35,000 stations, though the best spatial coverage is evident in North America, Europe, Australia, and parts of Asia. Parameters included are: air quality, atmospheric pressure, atmospheric temperature/dew point, atmospheric winds, clouds, precipitation, ocean waves, tides and more. For some stations, data may go as far back as 1901, though most data show a substantial increase in volume in the 1940s and again in the early 1970s. Currently, there are over 14,000 "active" stations updated daily in the database.

Finally, high-resolution, numerical ocean models can also be used to study coastal processes. E.g., the IBI ocean simulation with a resolution of 1/36° in the Atlantic - Iberian Biscay Irish sector (http://cmems-resources.cls.fr/documents/PUM/CMEMS-IBI-PUM-005-001.pdf).

For river discharges in estuaries, in situ data exist at some locations but the coverage is far from being optimal. When in situ data sets are unavailable, altimetry-based

river discharges (deduced from river water height after adapted calibration) will be used where available (http://hydroweb.theia-land.fr/).
An inventory of available data sets with information on location, record length, time and space resolution, etc. will be done shortly.

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