Consortium Members

ESA Sea Level CCI+

Product Validation Plan

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People involved in this issue:			
Written by:	A. Cazenave		
Checked by:	JF Legeais (CLS)		
Approved by:	JF Legeais (CLS)	24/06/2021	
Application authorized by:	J. Benveniste (ESA)	Date: 2021.06.25 '19:19:14 +02'00	Digitally signed by Jérôme Benveniste

Distribution:		
Company	**Names**	**Contact Details**
ESA	J. Benveniste A. Ambrozio, M. Restano	Jerome.Benveniste@esa.int; Americo.Ambrozio@esa.int; Marco.Restano@esa.int
CLS	J.-F. Legeais ; P. Prandi ; S. Labroue ; A. Guerou	jlegeais@groupcls.com ; pprandi@groupcls.com; slabroue@groupcls.com; aguerou@groupcls.com;
LEGOS	A. Cazenave ; B. Meyssignac ; F. Birol; F. Nino; F. Leger;	anny.cazenave@legos.obs-mip.fr; yvan.gouzenes@legos.obs-mip.fr; Benoit.Meyssignac@legos.obs-mip.fr; florence.birol@legos.obs-mip.fr; fernando.nino@legos.obs-mip.fr; fabien.leger@legos.obs-mip.fr;
NOC	F. Calafat	Francisco.calafat@noc.ac.uk;
SkyMAT Ltd	A. Shaw	agps@skymat.co.uk;
DGFI-TUM	M. Passaro J. Oelsmann	marcello.passaro@tum.de; Julius.oelsmann@tum.de;

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1. Objectives and overview

The objective of this document is to define the Product Validation Plan (PVP), describing the procedure used for the validation and user assessment of the SL_cci+ coastal sea level products (sea level anomalies and associated trends). The aim is to produce sea level measurements closer to the coast than with already existing altimeter dataset and the validation procedure is expected to show the added value of the SL_cci+ coastal sea level datasets.

Sea level trends computed from the combined XTRACK/ALES sea level anomalies for all missions will be validated with 3 approaches:

- Validation of altimetry-based sea-level variability and trends in the coastal zone against tide-gauge observations at a selected set of stations distributed across the globe.
- Comparison of altimetry sea-level observations with high-resolution ocean models, focusing on assessing the performance of the new altimetry product at ungauged coastal locations and understanding the differences between coastal and open-ocean sea-level changes.
- Quantification of coastal processes where data are available. This approach will help to explain (or not) the observed coastal trends. In case of success, this will represent a robust approach to validate the new coastal sea level products.

The world coastal zones studied in the SL_cci+ project have been selected for their vulnerability to global warming and sea level rise and are listed 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

Tide gauges provide the only direct measurements of coastal sea level against which the altimetry product can be validated. Hence, this task will yield a realistic estimate of the accuracy of altimetry-based sea level trends in the coastal zone. 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 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. It should be underlined that using high resolution models for the validation of altimeter coastal measurements has some limitations, especially related to the lack of spatial resolution of most of the available ocean models. The reduced period covered by some models also prevents us from validating the observed long-term trends. In the future, improving the spatial resolution and the length of the model output should allow improved validation results.

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, an important task to undertake.

We also plan to quantify coastal processes at the origin of the observed coastal sea level trends, where data are available. This will be a third type of validation, obviously the most robust (in case of successful comparison).

2. Type of validation diagnoses

2.1 Validation with tide gauges

This task will involve a global validation of the coastal altimetry products against a carefully-selected set of tide gauges. The validation will be conducted in terms of the sea-level annual cycle, inter-annual variability, and long-term trends.

A number of aspects deserve careful consideration when designing this validation activity. First, we note that, in general, altimetry measurements are not taken at the tide-gauge locations but at some ocean point nearby nor are they collocated in time with the tide-gauge observations. Therefore, some processing is necessary to obtain consistent altimeter/tide-gauge comparison pairs. To achieve this, we will follow the approach that we have successfully used in previous validation activities (Calafat et al., 2017; Passaro et al., 2018; Bouffard et al., 2018). Briefly, this approach consists of assigning the altimetry data to distance bands of a certain width, and then averaging the altimetry records falling within each band. The corresponding tide-gauge matching value is obtained by linearly interpolating the tide-gauge observations to the time of the corresponding altimetry pass. This procedure ensures that the altimetry and tide-gauge observations are comparable. Finally, we compare the two time series for each distance band and select the band with the maximum correlation as our best altimetry time series. Both hourly and monthly tide gauge measurements will be used in the comparisons.

The second point that requires attention is the fact that sea level from different tide gauges might be dominated by processes with very different length scales. This makes it difficult to assess the performance of the altimetry data since, for a given distance from the coast, the agreement will always be better at sites where sea level changes are associated with relatively large length scales. In addition, in regions with small length scales, it is difficult to determine whether differences between altimetry and tide gauge observations are due to land contamination in the altimeter footprint or to the fact that the altimeter and the tide gauge are measuring different sea level properties. To address this issue, we will extend the approach that we have developed in the SL_cci Bridging Phase to the global domain. Such approach involves using the high-resolution NEMO model to determine the decorrelation length scale at tide-gauge locations, and then select only the tide gauges where length scales are relatively large (developed within the SL_cci "Bridging phase"). We will use this technique to select a set of tide gauges covering different coastal areas across the globe and will compare the altimetry data against such stations.

Finally, the issue of vertical land motion affecting tide-gauge measurements, particularly the trends, needs special attention. To cope with it, we will use GPS data to adjust the tide-gauge trends for land motion, wherever a GPS station is collocated (or nearly so) with the tide-gauge station.

The following activities (sub-tasks) are planned for this task:

- Computation of the decorrelation length scale at available tide gauges using output from the NEMO model.
- Selection of tide gauges for the validation according to the coherence length scales derived from the NEMO model.
- Computation of consistent altimetry/tide-gauge comparison pairs.
- Comparison of the altimetry and tide-gauge observations in terms of the sea-level annual cycle characteristics (i.e., amplitude and phase), inter-annual variability (correlation and RMS difference), and trend.

2.2 Direct comparison between coastal sea level anomalies and tide gauge records in the Mediterranean Sea

A study has been recently performed to compare coastal sea level time series (focusing on interannual variability) and trends with sea level time series from nearby tide gauges in the Mediterranean Sea (Dieng et al., 2021). 14 sites have been selected on the basis that the Jason track crosses land at a distance less than 30 km from a tide gauge. Figure 1 shows the location of the 14 track portions and the tide gauges.

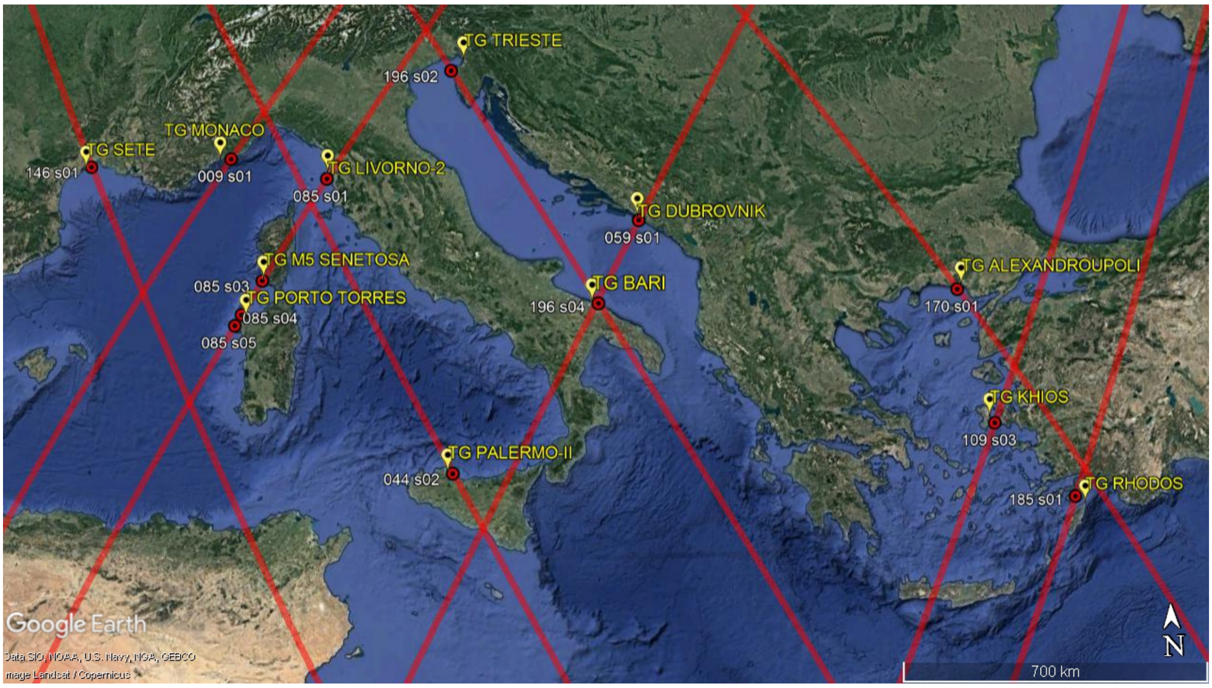

Figure 1: *Google Earth image of the Mediterranean Sea with the selected Jason tracks (red lines) and tide gauge sites (yellow symbols).*

In Figure 2 are shown coastal sea level time series from the CCI Coastal sea level project (product version 2.0, updated to 2020) with the nearby tide gauge records superimposed (from Dieng et al., 2021).

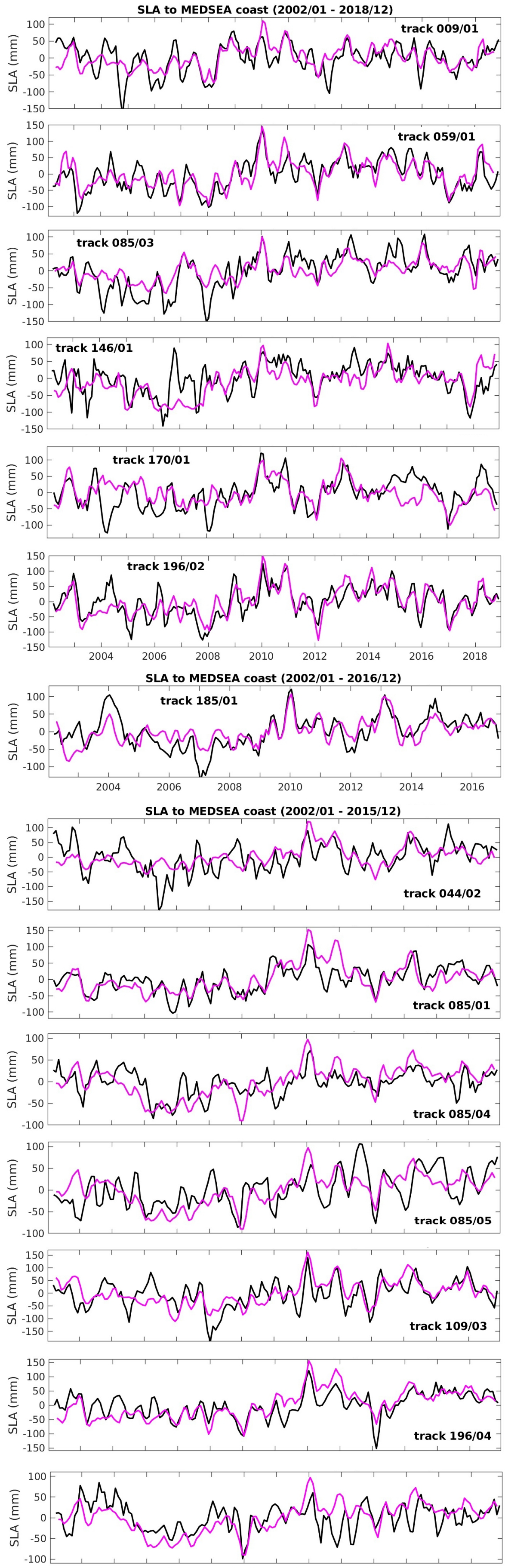
SLA to MEDSEA coast (2002/01 - 2018/12)
track 009/01
track 059/01
track 085/03
track 146/01
track 170/01
track 196/02
SLA to MEDSEA coast (2002/01 - 2016/12)
track 185/01
SLA to MEDSEA coast (2002/01 - 2015/12)
track 044/02
track 085/01
track 085/04
track 085/05
track 109/03
track 196/04
SLA (mm)

Figure 2: ***Coastal SLA time series (2 km averages; black) and tide gauge records (purple) at the 14 selected sites. (a) for tracks 9/1, 59/1, 85/3, 146/1, 170/1, 196/2 and 185/1. (b) for tracks 44/2, 85/1, 85/4, 85/5, 196/2 and 222/2.***

The RMS of the difference time series (altimetry minus tide gauge) are in the range 30-45 mm, with a mean value of 36 mm. This value is to be compared to the average square-root variance of the signal, on the order of 100 mm (or slightly larger).

An article (Dieng et al., 2021) has been published in Advances of Space Research.

2.3 Validation by comparing with high-resolution ocean models

At the beginning of the project, the following elements have been identified:

"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. We propose the following suite of activities:

- *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).*
- *The Iberian-Biscay-Irish (IBI) high-resolution (1/36°) ocean model along part of western European coasts*
- *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 where a specific analysis has been performed (Dieng et al., 2020).

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

2.3 Comparison with coastal processes

Another way of validating the computed coastal trends is to quantify coastal processes potentially responsible for the observed trends. Different coastal processes can be invoked:

- Water density changes due to coastal currents
- Water density changes due to fresh water input in estuaries and transport by river plumes
- Trends in wind, waves or atmospheric pressure

To quantify these coastal processes, a number of coastal data sets will be needed; in particular temperature and salinity data, wave data and meteorological data. Such data will be limited in time and space but at some location (in particular in the northern Mediterranean Sea), some data exist. In river estuaries and deltas, we will also use river discharge (where available) to correlate coastal sea level trends with trends in discharge. We will perform an inventory of available data for coastal process quantification. This work is in progress.

3. Input data for validation diagnoses

Different auxiliary data and model outputs will be needed to perform the validation:

-Tide gauge records in the vicinity of the satellite tracks (data from the Hawaii and Sonel networks)

- GNSS data to estimate vertical land motions

-Temperature and salinity fields in some coastal areas

- Meteorological data (surface winds, atmospheric pressure)

- Wave height

- Seafloor bathymetry

- River discharge in estuaries

Such data will not be available everywhere. Thus, the validation will be performed only at locations where data exist. Preliminary objective will be to focus on the North East Atlantic Ocean and the Mediterranean Sea where many types of data are available.

Preliminary work using bathymetry data indicate at some sites a clear correlation with the bathymetry. This is the case at the Senetosa site (calibration site of the Topex and Jason missions), located south of Corsica in the Mediterranean Sea. This is illustrated in the Figure 3 below.

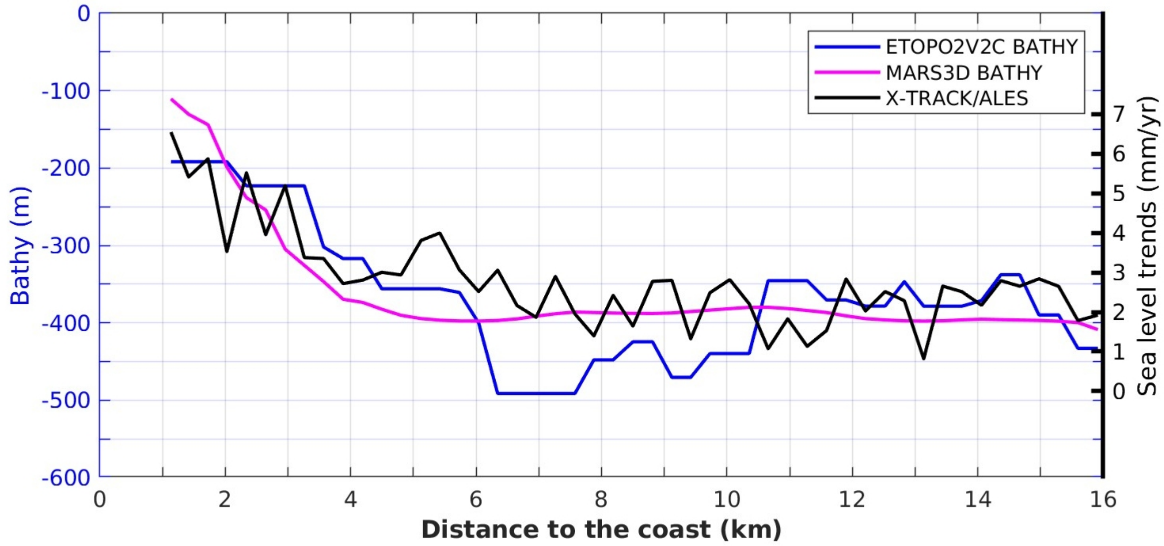

Figure 3***: Coastal sea level trends at Senetosa as a function of distance to the coast, computed from the 20 Hz X-Track/ALES product over 2002-2020 (black curve) (Dieng et al., 2021). Bathymetry interpolated along the Jason track (pink curve).***

The correlation between the two curves is striking. We note that the trend increase as the distance to the coast decreases corresponds to the increase in the bathymetric profile.

Similar comparisons are currently performed at other sites. However it appears that this is not always the case. Investigations to understand why are underway.

4. References

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