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Consortium Members

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1. Introduction

This document presents the main results achieved during the first phase of the ESA Sea Level CCI (SL_cci+) project during 2019-2022. The activities have focused on the estimate of coastal sea level trends based on altimeter measurements and the analysis of the trend evolution when getting close to the coast, and the production of a first estimate of the uncertainties of the mean sea level trends and accelerations at regional scale. The activities performed within the three CCN option work listed.
The list of the datasets produced by the team is provided with the associated user statistics and the scientific peer-reviewed publications produced by the team are also presented.
At last, perspectives for future activities are provided.

2. Achievements of the SL_cci+ project (2019-2022)

During the first phase of the ESA Sea Level CCI+ project, the activity has focused on the estimate of the sea level close to the coast in order to assess whether the sea level trends at the coast are similar to what can be observed further offshore in the open ocean.

Reprocessed altimeter 10-day Sea Level Anomalies have been computed in all the coastal regions illustrated in Figure 1. Measurements are available along the tracks of the Jasons altimeter missions at 20 Hz (about 300m along-track distance between two consecutive measurements) during the period January 2002- January 2020.

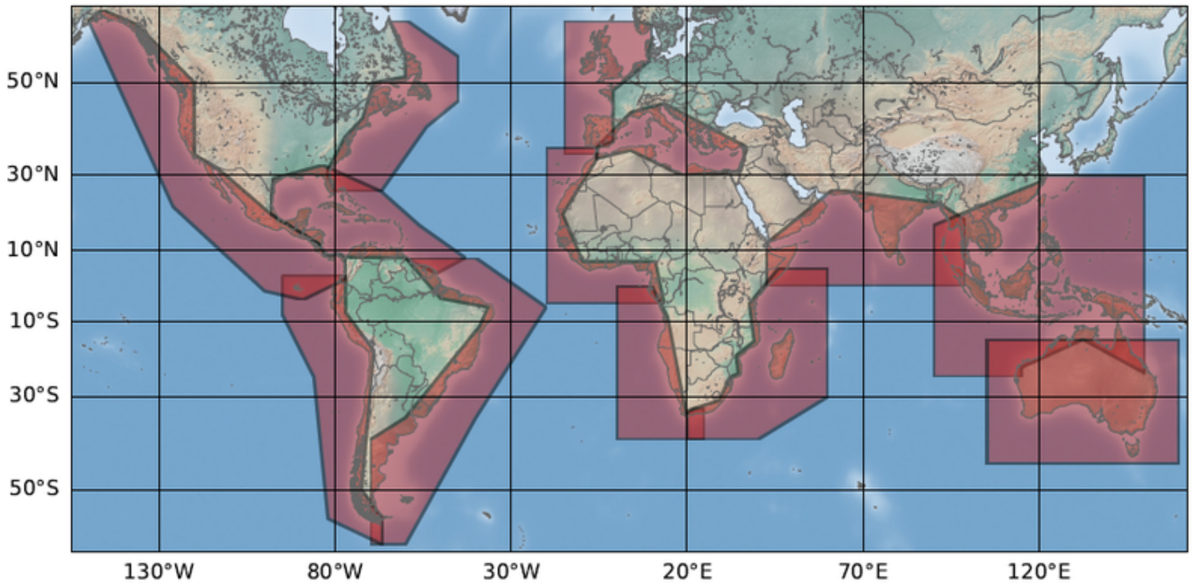

Figure 1: Regions covered in SL_cci+ v2.1

Further validation and editing have led to the production of the v2.1 dataset of monthly sea level anomalies and associated trends at 756 selected coastal sites located in almost all the world coastal ocean (see Figure 2) covering 2002-2020.

Extended validation has been performed, especially by comparison with independent measurements from tide gauges networks.

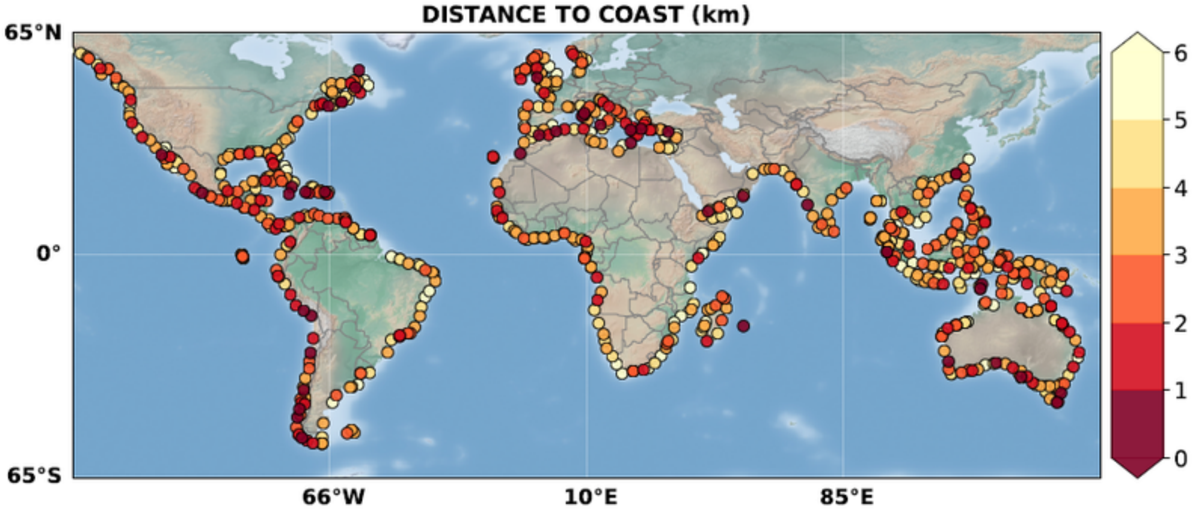

Figure 2: *Closest distance to coast reached by the first valid point along the track at the 756 coastal sites (called 'virtual coastal stations') selected in the v2.1 processing.*

The mean sea level trends observed at the 251 virtual stations located at less than 3.5 km from the coast are shown in Figure 3 during 2002-2020, superimposed with the C3S sea level trends during the same time span.

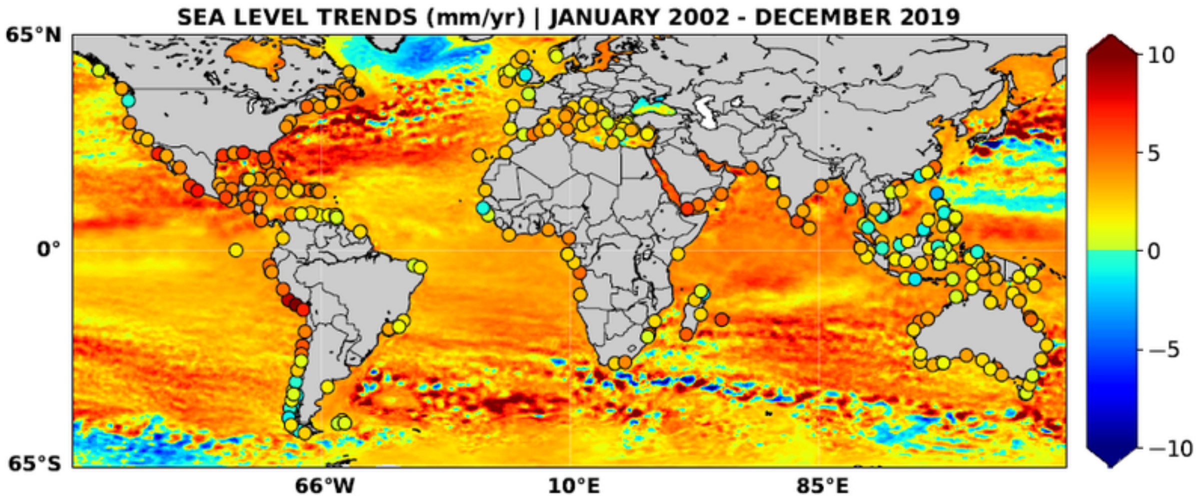

Figure 3: *Coastal mean trends (average over the first 2 km along the track) computed over January 2002 to December 2019 for the 251 virtual stations located at less than 3.5 km from the coast. The background map represents the C3S sea level trends over the same time span.*

In more than 80% of cases, the sea level trend at the coast is similar to the open ocean trend (considered here at a distance of 15 km from the coast). In the other 20%, we note smaller trend than offshore for ¾ of the sites. This is particularly seen in the southeast Asia region. The remaining sites show slightly larger trends in the last few km to the coast compared to the open ocean. The different trend behaviours are presented in Figure 4 as well as a map synthesizing the results (Figure 5).

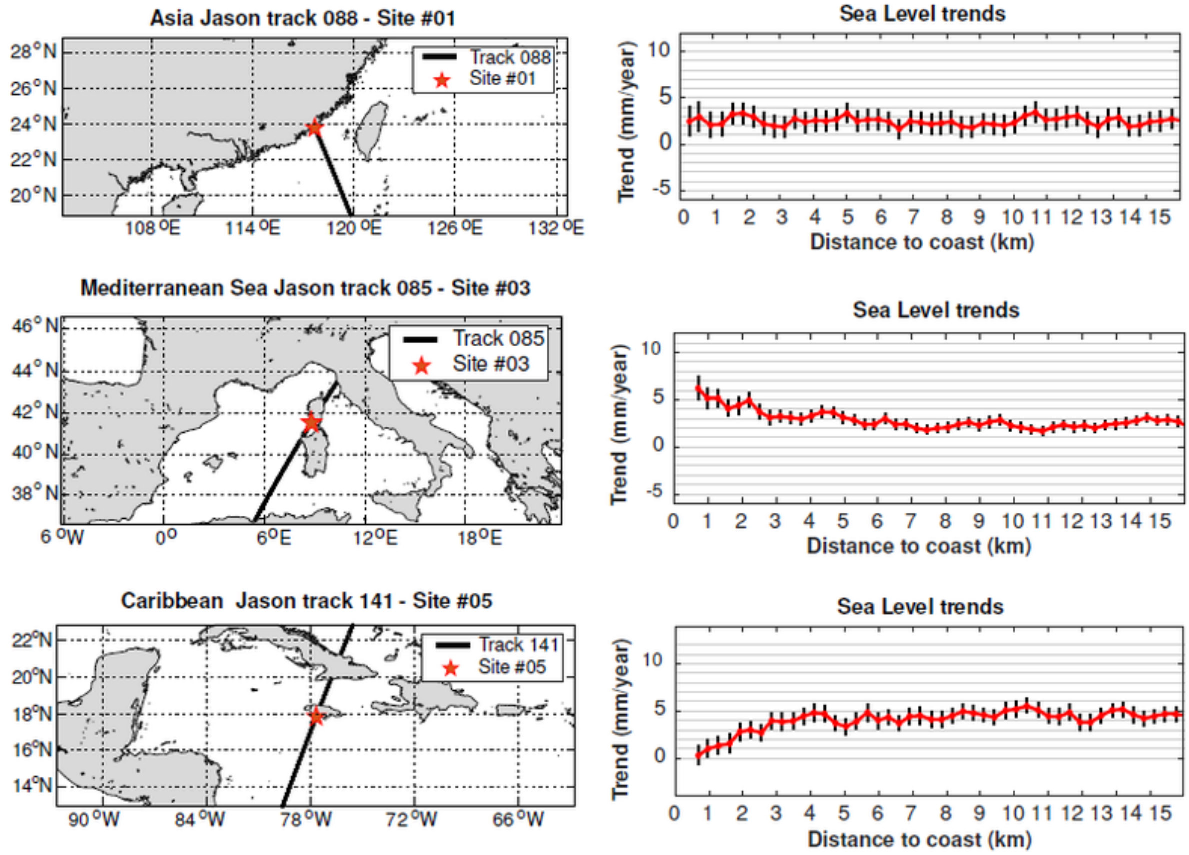

Figure 4: *Examples of sea level trend behaviours approaching the coast (constant, increasing and decreasing).*

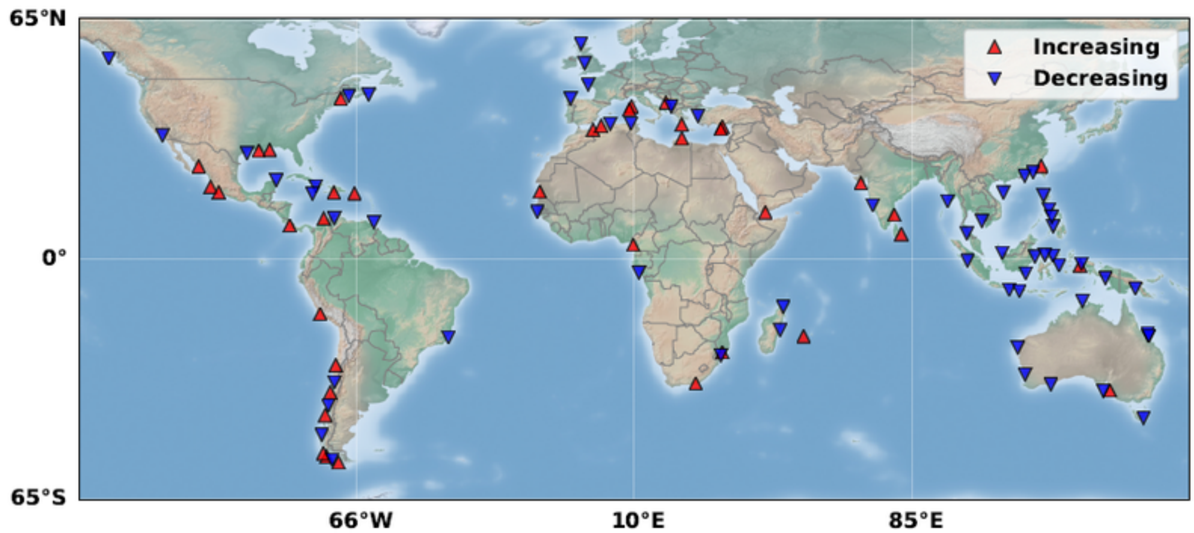

Figure 5*: Sites where coastal trends differ from offshore trends. Red/blue triangles correspond to increasing/decreasing trends near the coast.*

Figure 6 shows the statistics concerning the trend behaviours near the coast for all studied regions, illustrating that no specific regional bias can be observed.

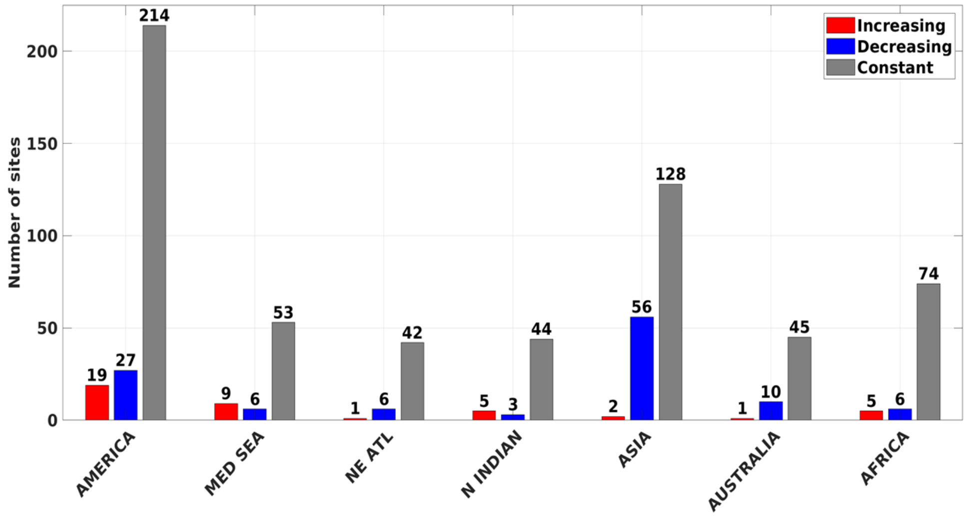

Figure 6: *Trend behavior near the coast for all studied regions. Grey, blue and red bars indicate constant, decreasing and increasing trend compared to open ocean trend.*

The network of virtual coastal stations proposed here should be of invaluable interest for estimating present-day (absolute) sea level rise along the world coastlines, especially in regions devoid from in situ tide gauges. This is illustrated in *Figure 7* with the distribution of the 271 virtual stations located within 3.5 km from the coast and of current tide gauges that have monthly sea level data over the study time span (with not more than 24 months of missing data).

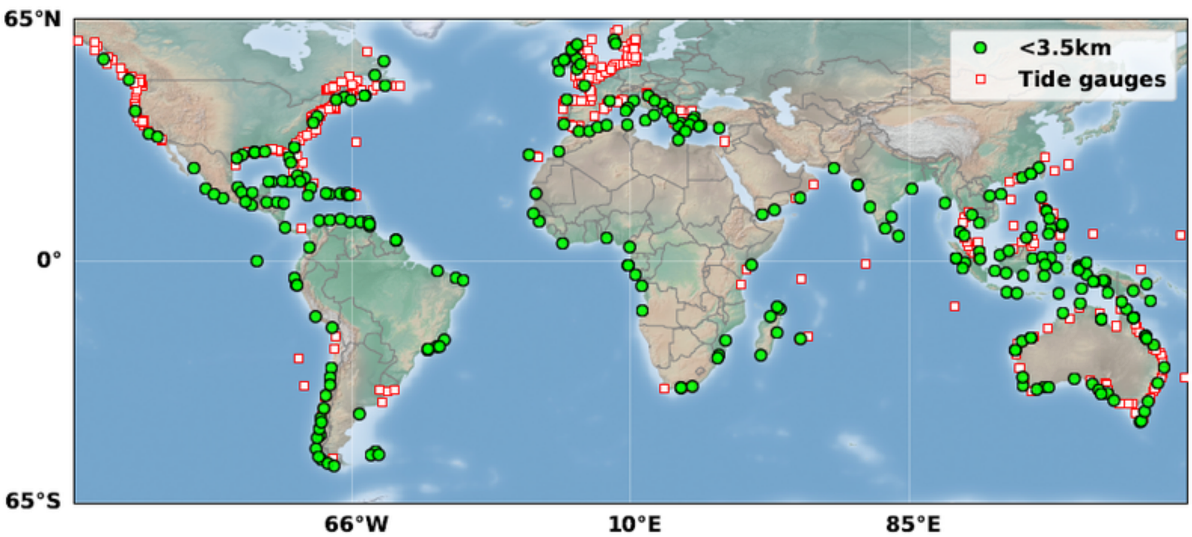

Figure 7: Network of 271 virtual coastal stations located within 3.5 km from the coast (green dots) with tide gauges (from PSMSL) having monthly data over 2002/01-2019/12 (with only 24 months of missing data; 400 sites; white/red squares)

In addition, the work has also focused on the estimate of **uncertainties associated to regional sea level trends**. We use the approach developed by Ablain et al. (2019) based on the estimate of an error budget which is then used to estimate error covariance matrices. These matrices are introduced into the ordinary least squares formulation to update the distribution of model parameters, leading to a more accurate estimation of uncertainties.

We regionalise the error budget and perform an uncertainty estimation at each grid step. Errors fall into three categories: biases, correlated errors or drifts. Each corresponding to a given covariance structure which is scaled to account for local error levels.

We perform an analysis to estimate the uncertainty affecting regional sea level trends and accelerations. Results are shown on Figure 8, at the 90% confidence level.

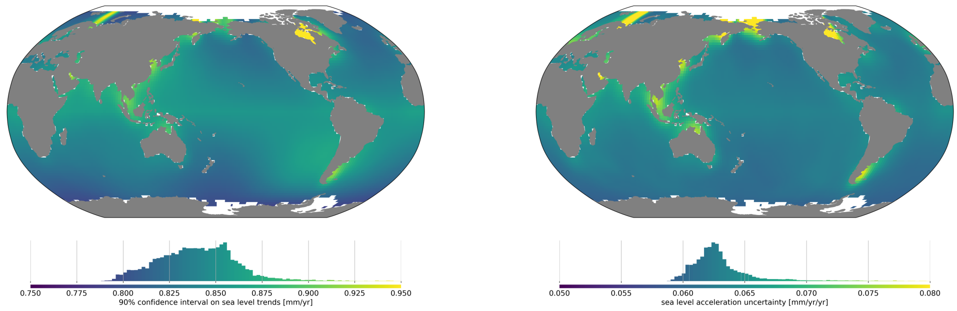

Figure 8: *90% confidence interval on regional sea level trends (left) and accelerations (right)*

How much of the global ocean is experiencing significant rise or acceleration is maybe a more important information. Based on the C3S sea level grids, corrected for the TOPEX-A drift, we estimate regional sea level trends and accelerations. Our results suggest that 98% of the ocean is experiencing significant rise, while 70% is experiencing a significant acceleration. The corresponding maps are shown on Figure 9. However, one should note that we consider only errors related to the altimetric system (orbit stability, measurement noises, …). As a result, significant accelerations mainly result from low frequency natural ocean variability, which is not considered in this study.

These results are presented in full details in Prandi et al., Local sea level trends, accelerations and uncertainties over 1993-2019. Sci Data 8, 1 (2021). https://doi.org/10.1038/s41597-020-00786-7.

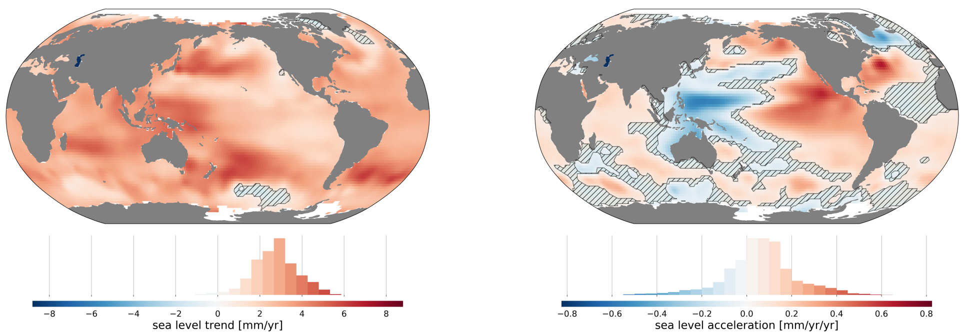

Figure 9: *Maps of sea level trends (left) and accelerations (right), non-significant areas are hatched*

In addition, three options have been contracted within the project with the Contract Change Notifications (CCN). The first task has focused on the validation of the estimate of the steric sea level, which has contributed to the phase 1 of the ESA CCI Sea Level Budget Closure project.

Within the second CCN, comparisons with tide gauges data have allowed us to produce a regional dataset of vertical land movements (VLM), which are one of the major sources of error of the coastal sea level. The regularly spaced coastline profile has been derived by spatial interpolation of sparse VLM obtained by sea level trend differences between the SL_cci+ altimeter coastal data and tide gauges. Figure 10 and Figure 11 show the interpolated VLM in the two selected macro-regions.

When considered, these VLM allow the estimate of the relative sea level at the coast, which is the quantity of interest when discussing coastal impacts.

The approach of interpolating VLM derived from altimetry and tide gauges differences alone remains limited due to the relatively low coverage in some areas (e.g. Italy, the Baltic region and large parts of Indonesia). Secondly, the Philippines and subduction zones (i.e., west of Sumatra) are affected by high spatial or temporal VLM variability, which cannot be represented by a smooth interpolated surface of linear VLM. Thus, extending the database by adding GNSS observations and increasing the number of observations in time can strongly increase the robustness of the results and enhance the resolution VLM processes.

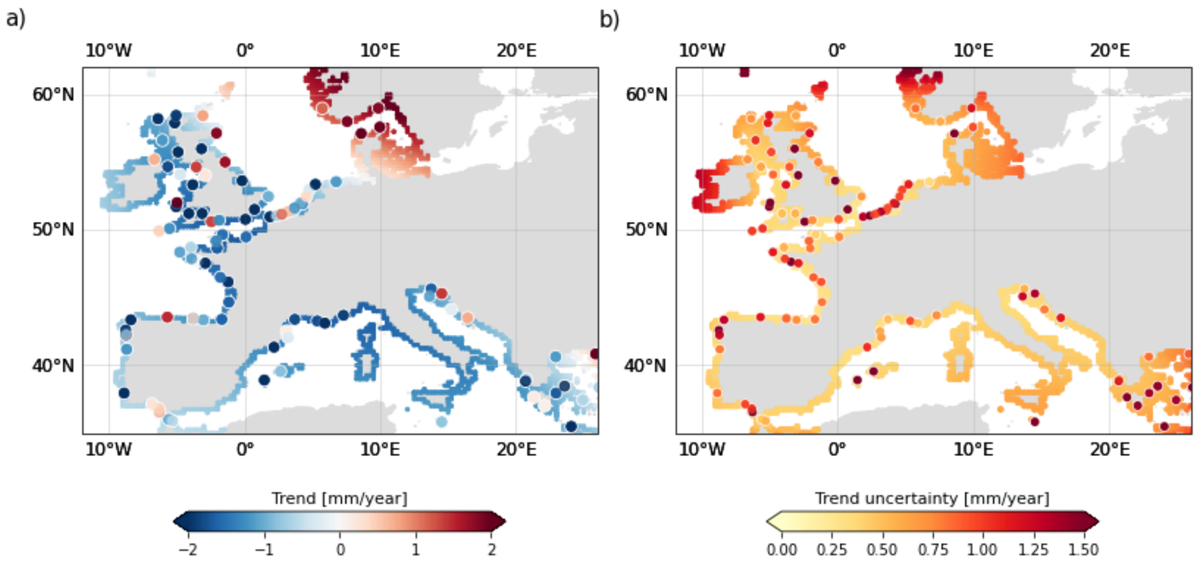

Figure 10: *Continuous VLM (a) and uncertainties (b) along the European coastline. In addition to the continuous interpolated estimate, we show the satellite vs tide gauges VLM and uncertainties (white edge-colours).*

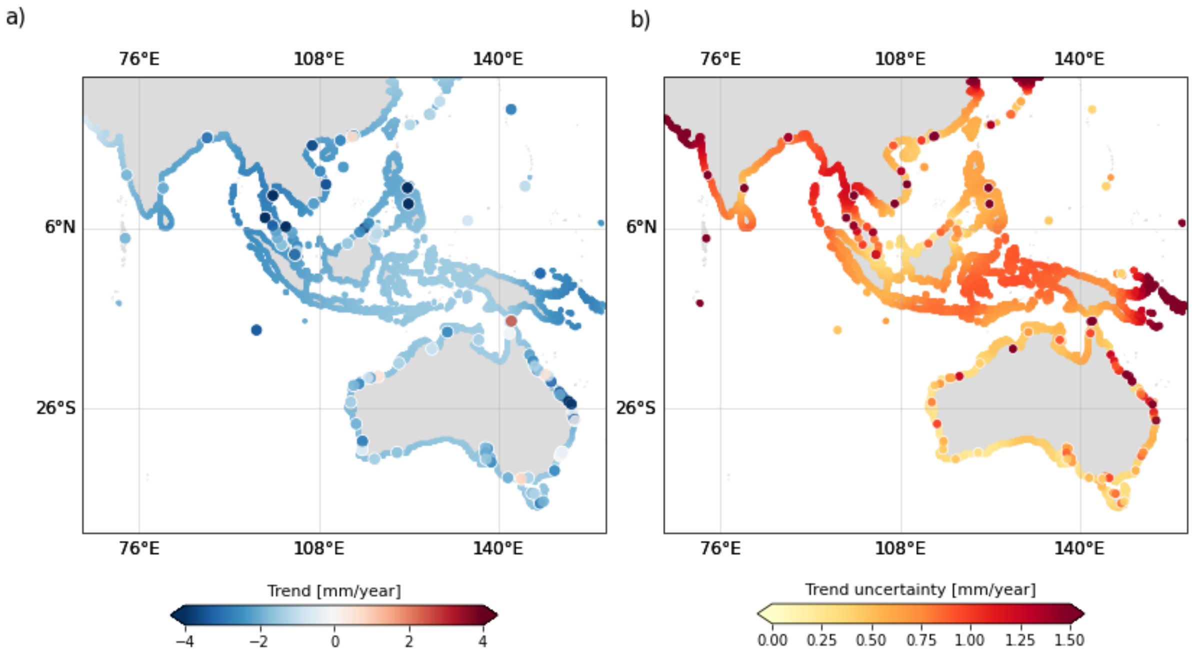

Figure 11: *Continuous VLM (a) and uncertainties (b) on Oceania and South-East Asia. In addition to the continuous interpolated estimate, we show the satellite vs tide gauges VLM and uncertainties (white edge-colours).*

Tide gauges have also been used as independent references to assess the quality of the SL_cci+ dataset with regards to another sea level product (CNES/AVISO L2P21). This has also allowed the estimate of VLM, which will contribute to reduce the uncertainty on the relative mean sea level.

At last, the SL_cci+ project partly focuses on the production of altimeter coastal sea level datasets and the analysis of the sea level rise at the coast. One of the input data required for this production is the GPD+ we troposphere correction (correction of the radar altimeter range for the wet troposphere path delay). In order to plan the temporal extension of the SL_cci+ dataset production, the third CCN has dealt with the production of this GPD+ correction close to present days for different altimeter missions (SARAL/AltiKa, Jason-3, Sentinel-3A and Sentinel-3B).

3. SL_cci+ Datasets

The SL_cci+ coastal sea level datasets are available for the users in the ESA Open Data Portal (https://climate.esa.int/en/odp/#/dashboard) and all sea level datasets are presented in the collection: https://catalogue.ceda.ac.uk/uuid/56c94cb1410f4f2b8a41729c0e558617.

Regarding the coastal datasets, this includes the v1.1 10-day coastal sea level dataset covering all regions from the Jason missions and also from the Envisat and SARAL/Altika missions.

The v2.1 **dataset of monthly sea level trends at virtual stations** is available here: https://doi.org/10.17882/74354

4. Data download user statistics

The ESA Open Data Portal download statistics of the sea level CCI datasets during the period Q2 2019 – Q1 2022 are presented below:

Dataset	Users	Accesses	Size
Arctic_MSLA/20161024/	4	1853	272.3 MiB
DTU_TUM_Arctic_Antarctic_MSLA/20170720/	12	500	4.7 GiB
FCDR/v2.0/	107	8188	811.6 GiB
IND/v1.1/	16	55	187.7 MiB
IND/v2.0/	205	122296	8.4 GiB
L4/MSLA/v1.1/	35	634	1.5 GiB
L4/MSLA/v2.0/	224	25514	47.1 GiB
XTRACK_ALES_SLA/ENVISAT_SARAL/SLA/v1.1/	1	394	5.5 GiB
XTRACK_ALES_SLA/SLA/v1.1_202006/ (10 days SLA in all regions)	**63**	2837	146.6 GiB
XTRACK_ALES_SLA/Trends_SelectedSites/v1.1_202006/	**50**	7860	169.3 MiB

Dataset from SEANOE repository (https://doi.org/10.17882/74354)	Users	-	-
XTRACK_ALES_SLA virtual stations (cumulated v1.1 and v2.1)	**108**		

5. Publications

The **9 publications** produced by the Sea Level CCI+ team within phase 1 of the project (2019-2022) is presented in https://climate.esa.int/en/projects/sea-level/publications/ and are listed below. In addition, the activity of the project has been advertised in **international conferences and workshops**. Up to **33 abstracts have been submitted by the team to 16 conferences**.

Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, A., Spada, G., Benveniste, J., Cazenave, A., and Picot, N.: Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration, Earth Syst. Sci. Data, 11, 1189–1202, https://doi.org/10.5194/essd-11-1189-2019, 2019.

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

Dieng, H.B., A. Cazenave, Y. Gouzenes, B.A. Sow, Trends and inter-annual variability of altimetry-based coastal sea level in the Mediterranean Sea: Comparison with tide gauges and models, Advances in Space Research, 2021, https://doi.org/10.1016/j.asr.2021.06.022.

Gouzenes, Y., Léger, F., Cazenave, A., Birol, F., Bonnefond, P., Passaro, M., Nino, F., Almar, R., Laurain, O., Schwatke, C., Legeais, J.-F., and Benveniste, J.: Coastal sea level rise at Senetosa (Corsica) during the Jason altimetry missions, Ocean Sci., 16, 1165–1182, https://doi.org/10.5194/os-16-1165-2020, 2020.

Marti F., Cazenave A., Birol F., Passaro, M. Leger F., Nino F., Almar R., Benveniste J. and Legeais J.F., Altimetry-based sea level trends along the coasts of western Africa, Advances in Space Research, published online 24 May2019, https://doi.org/10.1016/j.asr.2019.05.033, 2019.

Passaro M., Hemer M., Quartly G.D., Schwatke C., Dettmering D., Seitz F.: Global coastal attenuation of wind-waves observed with radar altimetry, Nature Communications (2021), https://doi.org/10.1038/s41467-021-23982-4

Prandi, P., Meyssignac, B., Ablain, M. Spada, G., Ribes, A. & Benveniste, J., Local sea level trends, accelerations and uncertainties over 1993-2019. Sci Data 8, 1 (2021). https://doi.org/10.1038/s41597-020-00786-7

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 stations for measuring sea level along the world coastlines, Communications Earth and Environment, 2022, In press.

In addition, valorisation of the SL_cci+ dataset has been made through different external projects, including:

- A master internship completed (in 2021) on the long-term coastal sea level changes observed along the East Australian coast (a publication is under preparation),
- A PhD in collaboration with the University of Douala (Cameroun) on the long-term coastal sea level variability in the Gulf of Guinea : driving processes and societal risks (a publication is under preparation),
- A PhD on the sea level in the Caribbean Sea : driving processes and response to climate change (model projections).

6. SL_cci+ perspectives

A phase 2 of the SL_cci+ project is expected during the period 2022-2024. Within this phase, the proposed SL_cci+ activity is to provide a temporal and spatial extension of the coastal sea level dataset of monthly sea level trends at virtual stations and to characterize the observed sea level trends behaviour close to the coast. Different approaches are envisaged to investigate the origin of these behaviours using available measurements. Comparison with other altimeter sea level product will be performed and investigations will be carried out on potential links with external parameters such as the proximity with estuaries. Analysis of the associated physical processes will be done thanks to high resolution regional model output when available. The challenge is that both long time span and high resolution are required for such analysis and very few ocean models are available with such constraints.

Regarding the regional sea level trends uncertainties, the activity has focused on the characterization of the sea level trends and accelerations based on the estimate of a satellite error budget and the computation of a matrix of the variance/covariance errors (considering the instrumental errors only). The next step is a better characterization of the regional mean sea level trend uncertainties by estimating the spatially correlated mean sea level errors at regional scale. In addition of the progress expected on this task during the next phase of the project, suggestion is made to include this activity together with the production of the estimate of the Ocean Heat Content variable which requires the estimate of associated uncertainties.

This dataset of regional mean sea level uncertainties will have to be updated in the future along with the temporal extension of the sea level time series, and especially when a new altimetry mission is included in the constellation. A specific framework should be identified to ensure the update of this work (frequency to be clarified).

It is also envisaged to adapt the framework developed for the regional mean sea level trends uncertainties to local scales, allowing the provision of realistic uncertainties of the sea level trends at virtual stations.

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