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1. Introduction

In the initial SL_cci+ proposal to ESA, we described potential links with the Global Modelling & Research Community. We suggested that the Climate Research Community be involved through effective existing international collaborations in which the proposers are currently involved. This includes:

- The **ESA CCI Sea Level Budget Closure project** (SLBC_cci) involving 10 different European partners, including LEGOS. The project has for objective to analyze in an integrative context recent results obtained by the ESA CCI programme for the sea level, glaciers and ice sheets ECVs, in order to assess whether the global mean sea level budget is closed. This project includes several climate modeling teams.
- The **World Climate Research Programme (WCRP) 'Sea Level Budget' Group** (90 scientists from 50 institutions worldwide). This community has been involved during the past 2 years in assessing the global sea level budget over the altimetry era. A first assessment (led by A. Cazenave and B. Meyssignac) has been recently published (The WCRP Global Sea Level Budget Group, 2018; names and affiliations given in annex). Yearly updates with the same international community are planned. This project also involves several climate modeling teams worldwide, including non-European experts.
- Participants to the **ISSI workshop** entitled **'Understanding the relationship between coastal sea level and large scale ocean circulation'** organized by the proposers in March 2018 in Bern (Switzerland) (http://www.issibern.ch/workshops/coastoceanproc/). The objective was to discuss the various mechanisms that drive coastal sea level and how sea level changes at the coast is linked to open ocean sea level changes. In effect, many atmospheric and oceanographic factors associated with both large-scale and local variability can influence coastal sea level on time scales from hours to multi decades. Previous studies have pointed out differences between observed (by tide gauges) sea level behaviour at the coast and adjacent shallow & deep ocean regions. Short spatial-scale processes can arise from coastally trapped waves and currents, localized tidal resonances, bathymetric control, local atmospheric forcing and other factors such as river fresh water input. These processes that depend on location and timescale may have significant impact on coastal sea level. Identifying these various influences is essential for understanding, simulating, and predicting coastal sea level variability and change, an issue of key societal concern in the context of a changing climate. The ISSI workshop had several objectives: (1) review our current understanding of coastal sea level changes and variability, from seasonal to multi-decadal time scales, and characterize the impact of large-scale open ocean processes on coastal sea level; (2) review available observing systems informing on sea level in coastal areas and identify gaps and uncertainties; (3) assess the ability of ocean syntheses in estimating coastal sea level variations and of atmosphere-ocean global coupled models in projecting future changes. The workshop outcomes included: (1) better understanding of the forcing factors that affect coastal sea level, and of the role of large-scale climate signals, (2) identification of a set of priorities for the development of an optimal and integrated (satellite and ground-based) coastal observing system, with focus on coastal altimetry; and (3) development of strategies to increase model capabilities to forecast short-term processes and project longer-term coastal changes. A book edited by Springer just appeared (https://www.issibern.ch/workshops/coastoceanproc/index.php/sssi75/).
- Other planned collaborations will be conducted with different international institutes involved in coastal sea level research, again on a volunteer and open scientific exchange basis.

In addition, the proposal to ESA indicated that 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.

In this update version, we present :

(1) a validation of the coastal sea level trend at the Senetosa (Corsica) site using the high-resolution MARS3D model provided by IFREMER

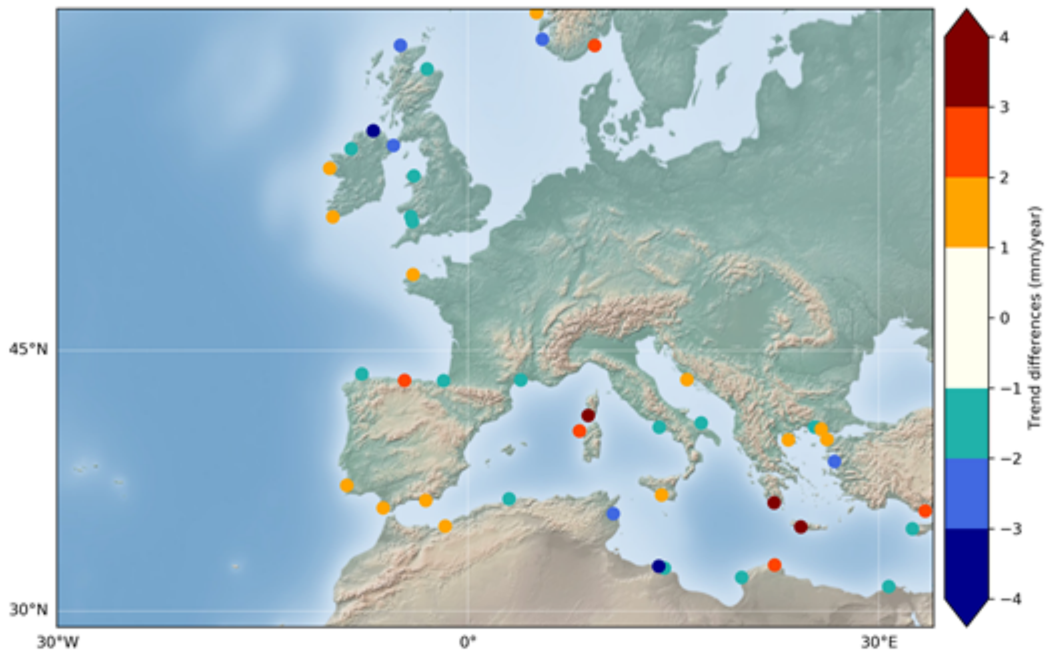
(2) a comparison between coastal sea level anomalies (SLAs) produced recently by the project (data published in November 2020 in Nature Scientific data) with tide gauge in the Mediterranean Sea

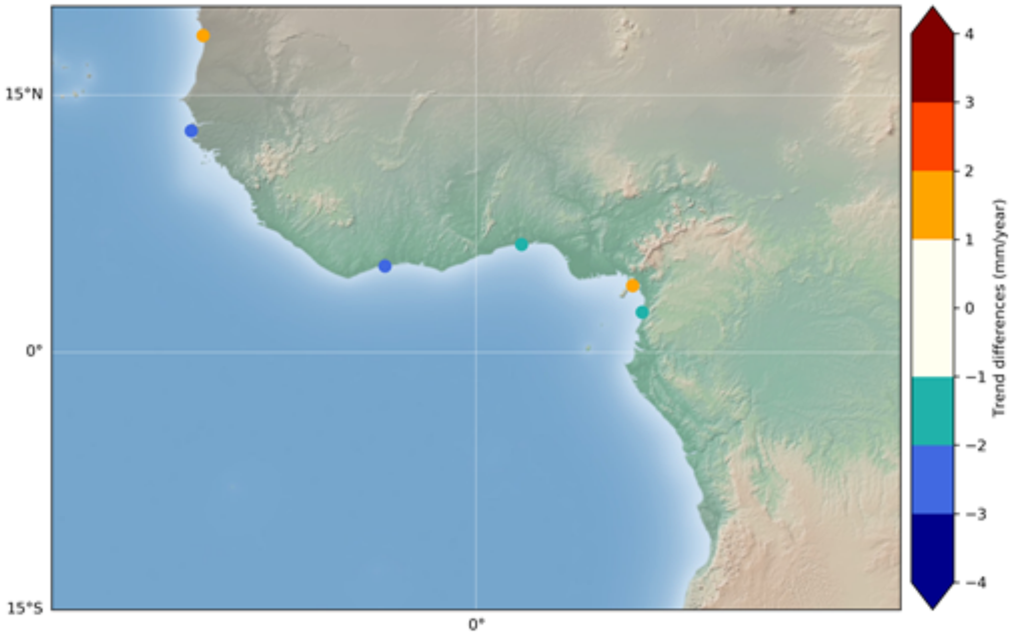
(3) Short-term perspective to quantify coastal processes using in situ data from the JERICO-RI European project for further comparison with coastal sea level trends estimated in the CCI project.

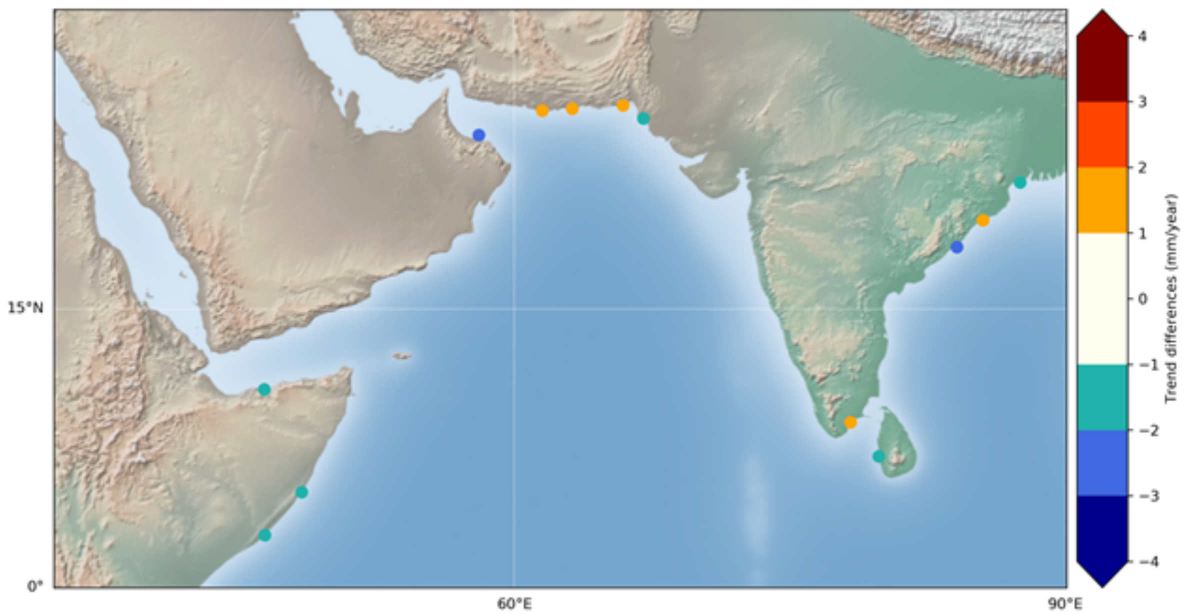
2. Study of sea level processes causing departures between coastal and open ocean sea level trends

2.1. SL_cci+ coastal regions

Recent results on coastal sea level trends (The Climate Change Coastal Sea Level Team, 2020; Birol et al., 2021) indicate that only a few sites (20% among the 429 studied) present sea level trends at the coast departing from open ocean trends. This is illustrated on the figures below for the different studied regions.




15°N
0°
15°S
0°
4
3
2
1
0
−1
−2
−3
−4
Trend differences (mm/year)


15°N
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4
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−3
−4
Trend differences (mm/year)

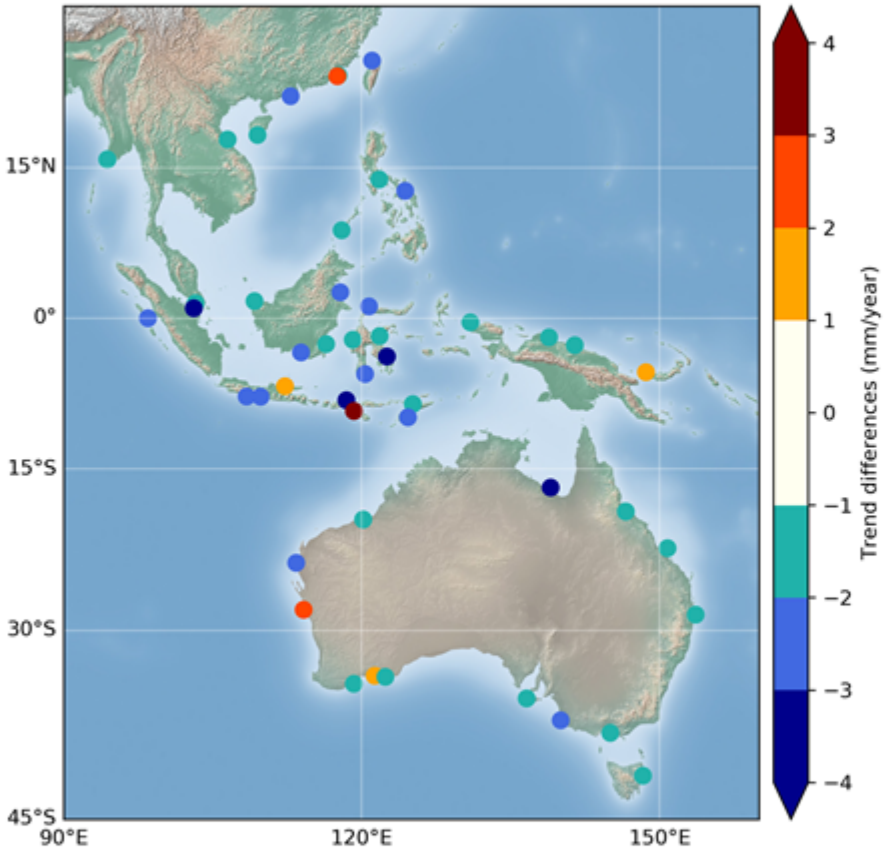


Figure 1: *Differences in sea level trends between the coast (averaged trends over 2-km along-track from the closest valid point to the coast) and the 14-16 km average, offshore. White points correspond to no significant differences (within +1/-1 mm/yr) between open ocean and coast. Orange-red-brown / green-blue dots correspond to coastal trend increase/decrease at the coast. Results from the Climate Change Coastal Sea Level Team (the), "Sea level anomalies and associated trends estimated from altimetry from 2002 to 2018 at selected coastal sites". Nature scientific Data, 7, 357, https://doi.org/10.1038/s41597-020-00694-w, 2020.*

2.2. The Senetosa case

A detailed study has been performed for the Senetosa site (south Corsica, Mediterranean Sea) (Gouzenes et al.; 2020) to understand the causes of the observed difference. The study showed that neither the errors in the geophysical corrections applied to the altimetry data (i.e. sea state bias/ssb, wet tropospheric correction, dynamic atmospheric correction/dac, ocean tide plus ocean loading tide), nor the errors in the ALES retracking (by comparing with the MLE4 standard retracker used for Jason altimeter missions) could explain the trend increase in the last 3-4 km to the coast. We concluded that some small scale physical process may be responsible for the trend increase towards the coast. We evaluated the contribution of waves but concluded that trend in waves was too small and active too close to the coast (last 1 km) to explain the reported trend increase. In a recent study, Dieng et al. (submitted, 2021) investigated this further and examined the effect of sea water temperature and salinity close to the coast, using high resolution (400 m) data from the MARS-3D model developed by IFREMER (France) and suggest that the trend increase in the last 3-4 km to the coast could be due to the steric contribution of SLA in close relation to the evolution of bathymetry near the coast.

Fig.2 compares SLA trends against distance to the coast with the bathymetry from the MARS-3D model and ETOPO2, available with a spatial resolution of about 400 m and 3.5 km respectively interpolated at the position of the along-track SLA points. We note that SLA trends and bathymetry are highly correlated, with trend increase corresponding to seafloor depth decrease. However, the exact cause of this correlation remains unknown. We further analysed the evolution of temperature T and salinity S of the MARS-3D model, calculated over the 2014-2018 period (the only time span available from the model). For that purpose, we interpolated the model T/S data along the 085/03 Jason track, computed the T/S trends as a function of depth and distance to the coast. Corresponding 2-D maps are shown in Fig.3a and Fig.3b. We note an increase of the temperature trend with depth as the distance to the coast decreases. This indicates a thermocline deepening close to the coast (Fig.3a). An opposite effect is observed for the salinity trend with a sinking of the halocline (Fig.3b). These physical characteristics (increasing temperature trends and decreasing salinity trends) occur in the last ~4 km to the coast (as previously observed for the change in bathymetry and SLA trend increase). Such a behaviour indicates a decreasing trend in sea water density (with sinking of the pycnocline) which in turn leads to an increasing sea level trend. We computed the steric sea level by integrating over depth the T/S anomalies and expressed it as a function of distance to the coast. This is illustrated in Fig.4 which compares the altimetric SLA trends (calculated over the period June 2002 - May 2018) and the steric SLA of the MARS3D model (calculated over the period January 2014 - December 2018). Unfortunately, the steric trend computation cannot be performed over 2002-2018 due to model data unavailability. Besides the altimetric trends computed over a time span as short as 4 years (2014-2018) are too noisy to provide reliable results, as shown in Gouzenes et al. (2020) (the unstable trend estimate over short periods is due to high frequency noise in the X-TRACK/ALES product). Thus, the good agreement noted between steric and SLA trends may be fortuitous. Hence, the only conclusion we can draw so far is that, if the steric trend behaviour is a long-lived feature, change in T/S nearby Senetosa may be invoked to explain the SLA trend increase towards the coast. This could be eventually related to the presence of a wind-driven small-scale coastal current nearby the Senetosa shoreline, as shown in Gouzenes et al. (2020).

The observed seafloor depth decrease close to the Senetosa coast may influence the sea water density distribution (i.e. the isopycnal lines), with a direct impact on the SLA trend increase. Lazure and Dumas (2008) showed that in shallow coastal areas, the dynamics of the thermal and haline structures of the upper ocean is quite complex due to the spatial and temporal variability of wind stress and heat fluxes. The latter induce turbulent mixing that causes temperature and salinity variations within the surface layers and consequently, density stratification. However, our results remain limited due to the very short period (2014-2018) of temperature and salinity data from the MARS3D model, and therefore of the steric component.

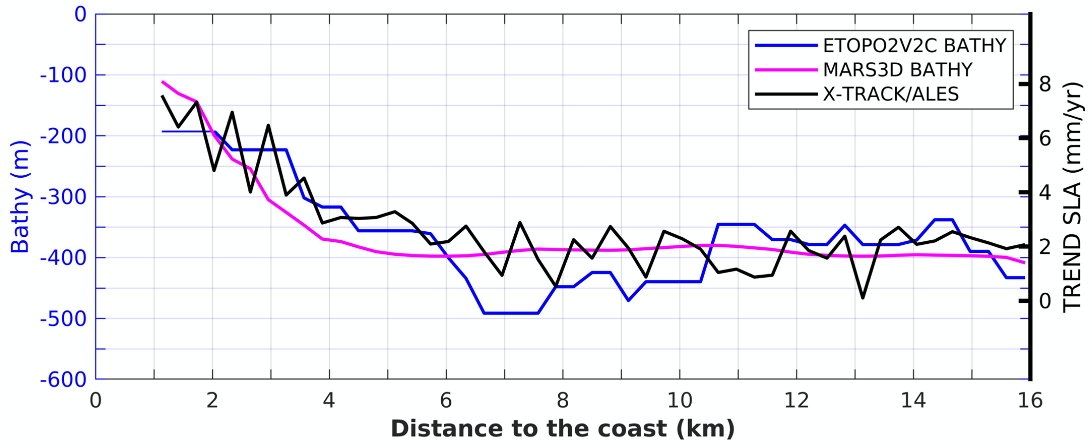


Fig.2: Comparison of the evolution of the SLA trend of X-TRACK/ALES (calculated over the period June 2002 - May 2018) with the profile of the bathymetry along the altimeter track over the first 16 km of the coast, for site 085/03 near Senetosa.

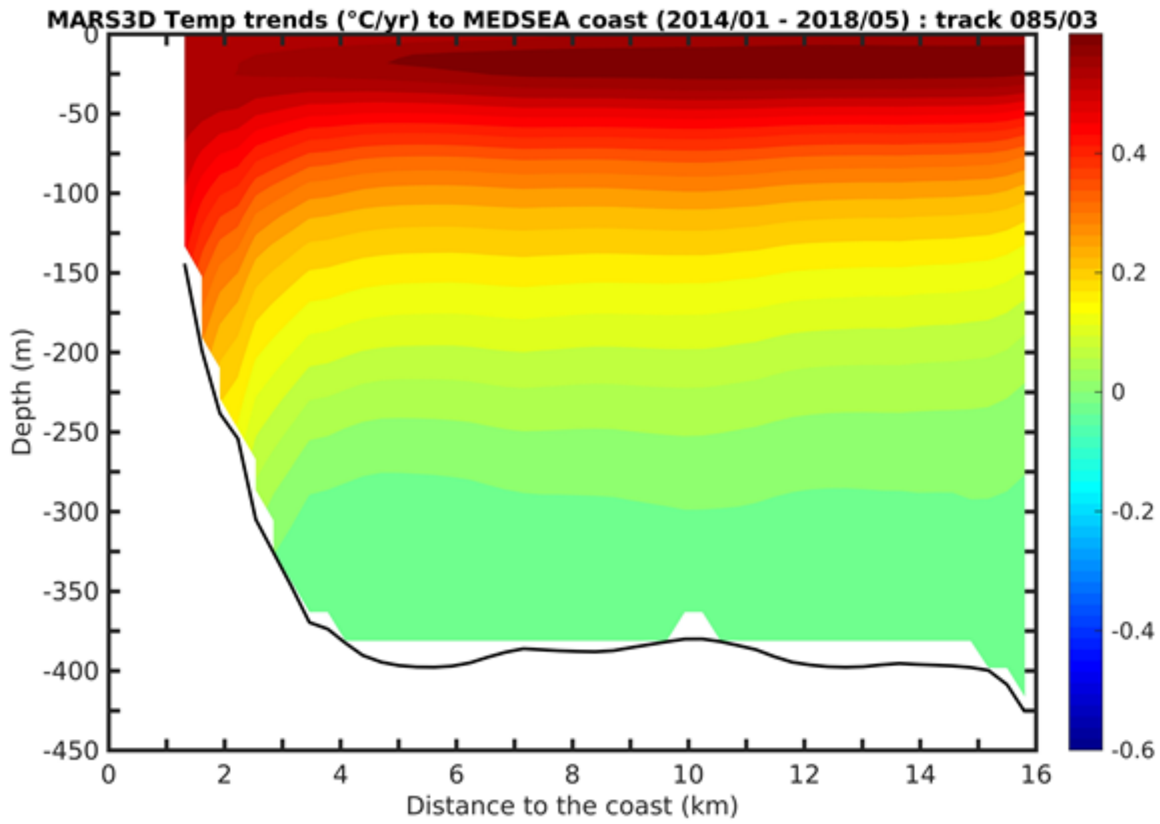


Fig.3a: Temperature trend map of the MARS3D model (calculated over the period January 2014 - December 2018) as a function of depth and distance at the coast along the altimeter track over the first 16 km of the coast, for site 085/03 near Senetosa.

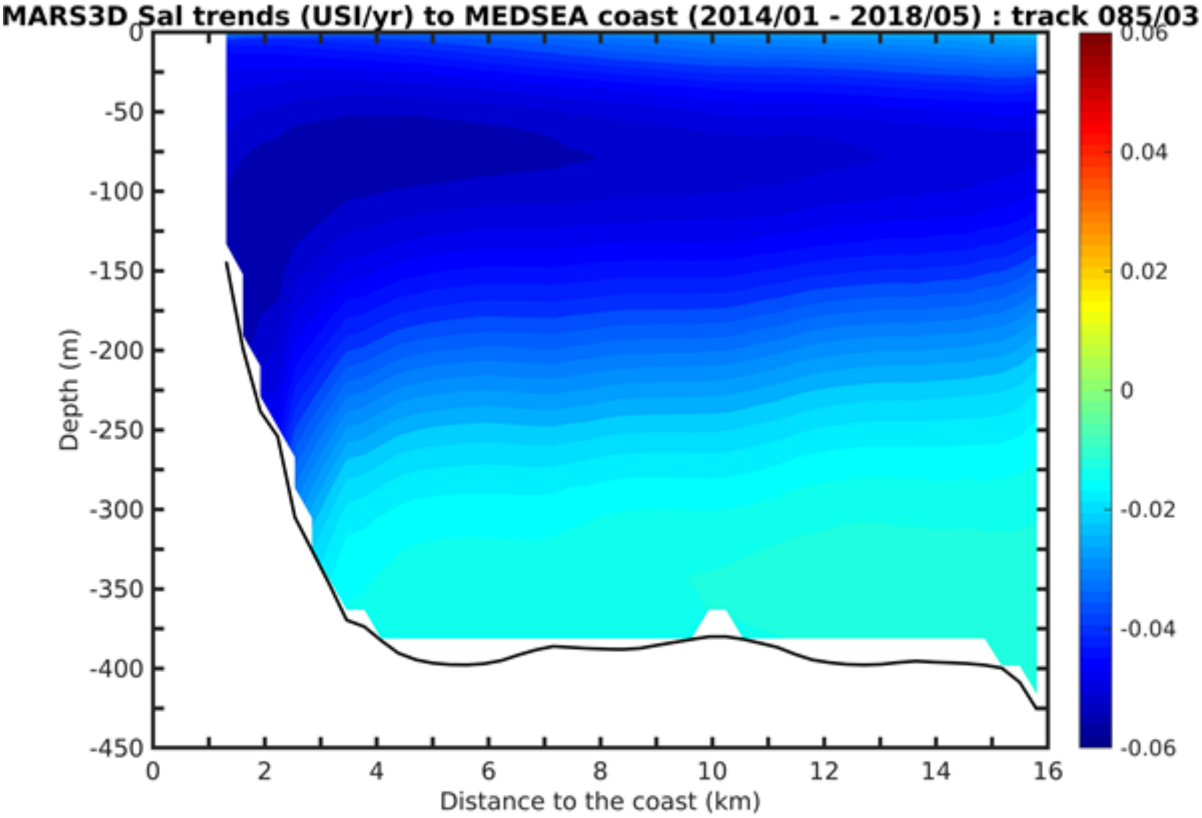


Fig.3b: Salinity trend map of the MARS3D model (calculated over the period January 2014 - December 2018) as a function of depth and distance at the coast along the altimeter track over the first 16 km of the coast, for site 085/03 near Senetosa.

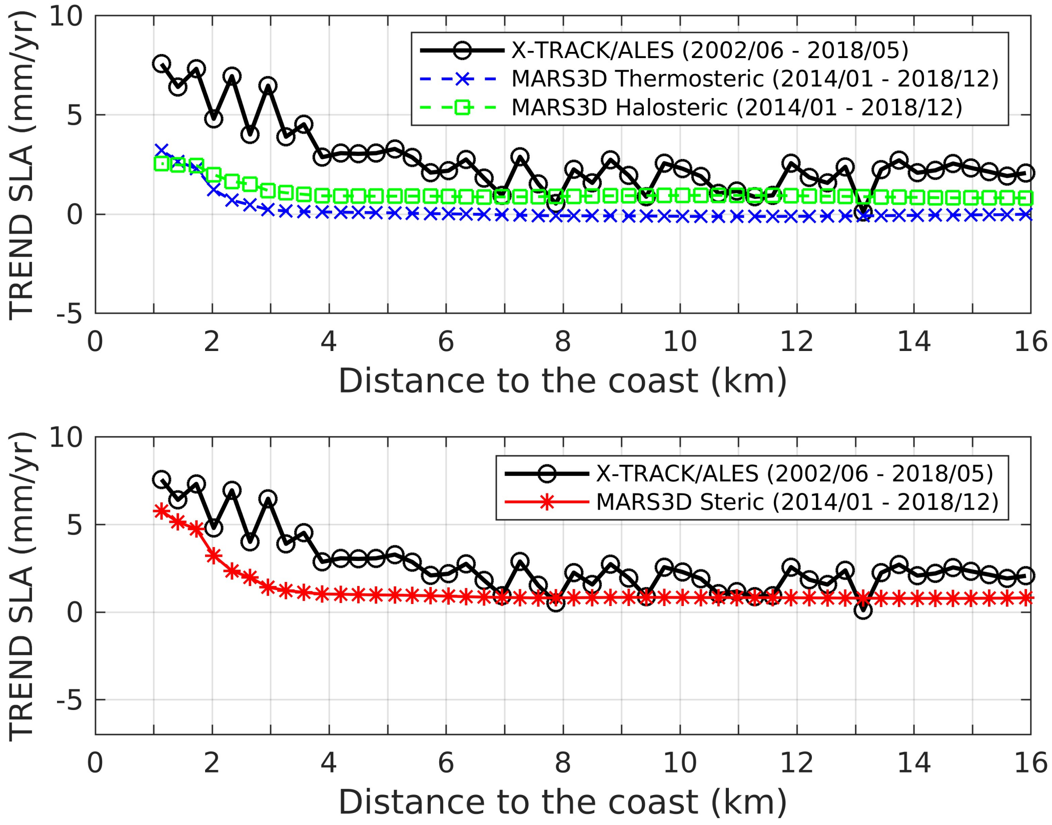


Fig.4: Comparison of the evolution, along the altimeter track over the first 16 km of the coast, of the X-TRACK/ALES SLA trend (calculated over the period June 2002 - May 2018) with : *(above)* that of the thermosteric and halosteric component ; and *(below)* that of the steric component (calculated over the period January 2014 - December 2018 and estimated using temperature and salinity data from the MARS3D model) for site 085/03 near the coast of Senetosa.

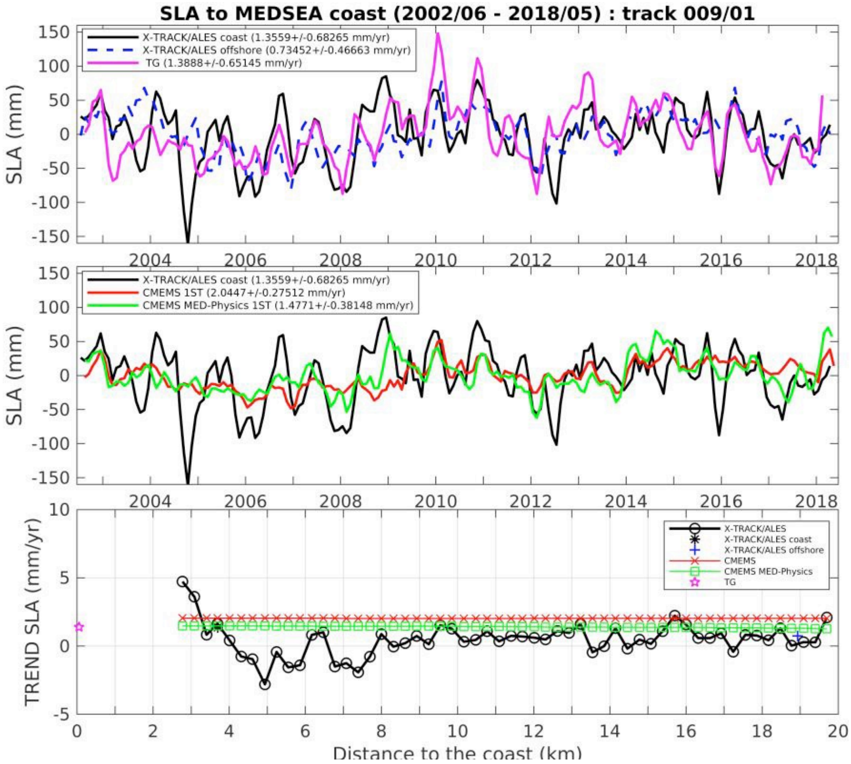
3. Comparisons with tide gauges in the Mediterranean Sea

An assessment of coastal SLAs (Birol et al., 2021) and coastal trends (Climate Change Coastal Sea Level Team (the), "Sea level anomalies and associated trends estimated from altimetry from 2002 to 2018 at selected coastal sites". *Nature scientific Data*, 7, 357, https://doi.org/10.1038/s41597-020-00694-w, 2020) has been performed in the Mediterranean Sea region by comparing with tide gauge data where available. This is an extension of the statistical validation performed by F. Calafat and A. Shaw in the Nature Scientific Data paper. Here we directly compare coastal SLAs and tide gauge time series. We selected a set of 15 coastal sites where the distance between the Jason track at the coast is less than 30 km from a tide gauge for which the in situ record at least partly covers the 2002-2018 time span. We compared the interannual variability and trends of the altimetry sea level anomalies and of the tide gauge data, in a band of 20 km from the coast. Fig.5 shows the location of the tide gauges considered for this comparison.

Fig.5. Map of the Mediterranean Sea showing the position of the altimeter tracks (lines in yellow), the sites studied (indicated numbers in yellow) and the TGs (circles in white).

A good agreement is found between the altimetry-based sea level time series and the tide gauge data at interannual time scales. In terms of trends, the comparison also shows general good agreement within the respective uncertainties. However, correcting for GNSS-based vertical land motions the few tide gauge sites located at a distance less than 50 km from a GNSS antenna, does not improve the agreement. Fig.6a,b shows two examples of SLAs from altimetry and tide gauges. For these two cases (9/1 and 185/1 tracks), the RMS of the TG minus altimetry time series are 41 mm and 34 mm respectively. The correlation between the TG and altimetry time series are 0.53 and 0.70 respectively.

(a)


SLA to MEDSEA coast (2002/06 - 2018/05) : track 009/01
X-TRACK/ALES coast (1.3559+/-0.68265 mm/yr)
X-TRACK/ALES offshore (0.73452+/-0.46663 mm/yr)
TG (1.3888+/-0.65145 mm/yr)
SLA (mm)
X-TRACK/ALES coast (1.3559+/-0.68265 mm/yr)
CMEMS 1ST (2.0447+/-0.27512 mm/yr)
CMEMS MED-Physics 1ST (1.4771+/-0.38148 mm/yr)
SLA (mm)
TREND SLA (mm/yr)
X-TRACK/ALES
X-TRACK/ALES coast
X-TRACK/ALES offshore
CMEMS
CMEMS MED-Physics
TG
Distance to the coast (km)

(b)

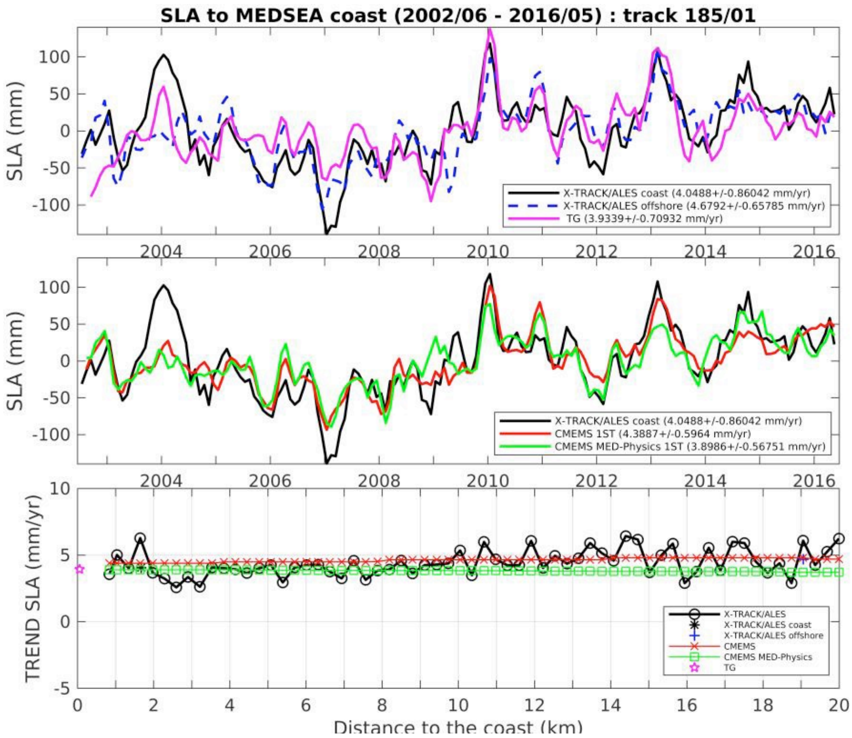


Fig.6. Comparison of SLA time series at two sites over the period June 2002 - May 2018: (upper panel) between X-TRACK/ALES at the coast and offshore with the TG; (middle panel) between X-TRACK/ALES at the coast, CMEMS/DT2018 L4 altimeter product (1st point at coast) and the CMEMS MED-Physics model (1st point at coast); (lower panel) the evolution of the SLA trend of our different products on the first 20 km of the coast along the altimeter track. (a) track 9/1, Monaco tide gauge ; (b) track 185/1, Rhodos tide gauge.

We also considered altimetry-based regional sea level grids of the Copernicus Marine Environmental Service (CMEMS) and model based gridded data from the CMEMS MED-Physics model (resolutions of 1.4° and 1/16° respectively) and interpolated the gridded data along the Jason tracks. CMEMS and model sea level time series are also shown in Fig.6. Unfortunately, the CMEMS and model data do not have the needed resolution to perform reliable comparison very close to the coast, preventing us to perform independent validation of the increase/decrease of altimetry-based sea level trends reported in the last 3-5 km to the coast at a number of sites.

4. Perspectives

4.1. Comparisons with ocean reanalyses

Example of assessment of satellite measurements through the impact of their assimilation in ocean reanalyses are already available (Ford, 2020). For systematic comparisons between altimetry data and model outputs, we are faced to strong limitations in terms of model temporal availability and resolution. The table below summarizes the properties of current available models.

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.

4.2. JERICO-RI (Joint European Research Infrastructure network for coastal Observatory)

JERICO-RI is a European project of the H2020 programme consisting of Coastal Observatories that integrate several observing platform types i.e. fixed buoys, piles, moorings, drifters, Ferrybox, gliders, HF radars, coastal cable observatories and the associated technologies dedicated to the observation and monitoring of the European coastal waters. This observing system of systems, is designed to provide high-quality data that are supporting knowledge development on the complex and often coupled physical, chemical and biological processes characterizing the coastal waters of European coastal seas. Fig.7 shows the regions (called super sites) where coastal observing systems are implemented.

Fig. 7: JERICO-RI super sites location (https://www.jerico-ri.eu/)

Although most coastal observatories of the JERICO-RI project are dedicated to biological observations, a few of them provide temperature and salinity measurements, sometimes currents, of high interest for the CCI coastal sea level project since these data allow quantifying coastal processes able to explain observed coastal sea level trends.

As an example, we show below the Western Mediterranean super site (Fig.8) and the available in situ measured parameters (Table 1).

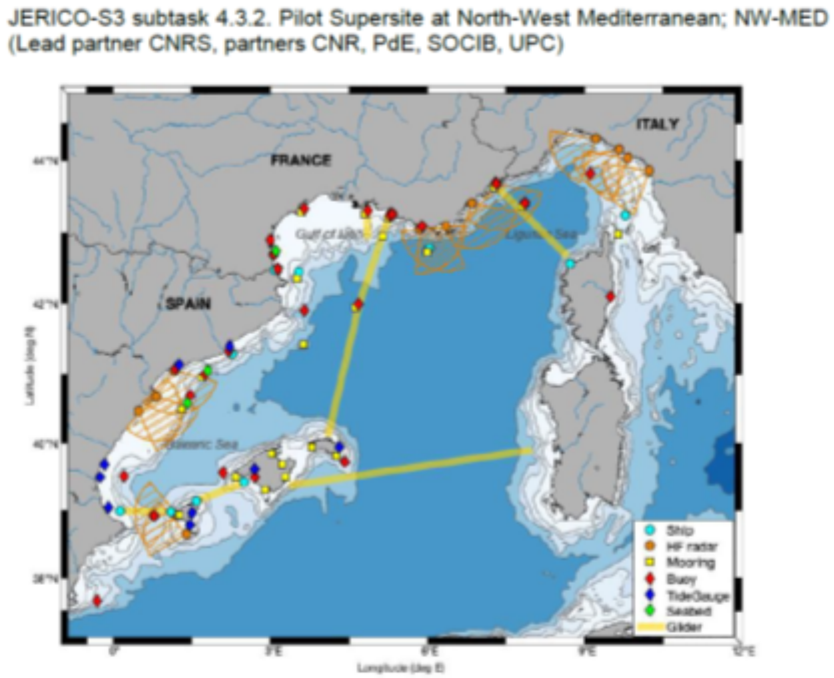


Fig. 8: Platforms and existing stations of the Western Mediterranean super site (https://www.jerico-ri.eu/)

Operational observation systems & platforms in the region	Operational status	Parameters
Ships (ILICO, SOCIB, CNR)	operational (different frequency)	Profiles: T, S, O_2, fluorescence Bottles: nutrients, carbonate, zooplankton, phytoplankton, genomics
HF radars (CNR, PdE, ILICO, SOCIB)	operational	surface currents (speed, direction)
Moorings (ILICO, CNR)	operational	T, S, O_2, currents, particle flux, images
Buoys (ILICO, PdE, UPC, SOCIB)	operational	meteorology, currents, waves, PAR, T, S, O_2, fluorescence, pH, pCO_2

Tide gauges (PdE, SOCIB)	operational	sea level
River stations (ILICO)	operational	Discharge, particles load, nutrients, metals
Seabed (UPC)	operational	T, S, depth, currents, waves, underwater sound. seismometer, video-camera, biodiversity
Gliders (ILICO, SOCIB)	operational	T, S, fluo, turbidity, O2, CDOM, BB700 (routinely), particles size, current motion (occasionally)
Numerical models (SOCIB, IFREMER, PdE, CNRS)	operational/semi-operational	(3D) T, S, currents, waves, sea level

Table 1: Type of measurements available from the Western Mediterranean super site

In the coming weeks, we will identify the JERICO data sets of interest for our project, considering the proximity of the JERICO stations and the Jason sites as well as the JERICO data coverage. Then, we will quantity the impact of density change (using in situ temperature and salinity data), currents and waves on altimetry-based coastal SLAs and trends.

This will represent the main contribution (together with the work already done for Senetosa) to the Climate Assessment work package of the CCI coastal sea level project.

5. Publications of the project

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.

Climate Change Coastal Sea Level Team (the), "Sea level anomalies and associated trends estimated from altimetry from 2002 to 2018 at selected coastal sites". Nature scientific Data, 7, 357, https://doi.org/10.1038/s41597-020-00694-w, 2020.

Dieng H.B., Cazenave A., Gouzenes Y. and Sow, A., Trends and inter-annual variability of coastal sea level in the Mediterranean Sea: Validation of high-resolution altimetry using tide gauges and models, submitted, Advances in Space Research, 2021.

Gouzenes, Y., F. Léger, A. Cazenave, F. Birol, P. Bonnefond, M. Passaro, F. Nino, R. Almar, O. Laurain, C. Schwatke, J.-F. Legeais and J. Benveniste. Coastal Sea Level rise at Senetosa (Corsica) during the Jason altimetry missions. *Ocean Sciences*, 16, 1–18, 2020 https://doi.org/10.5194/os-16-1-2020, 2020.

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Lazure P. and F. Dumas, An external–internal mode coupling for a 3D hydrodynamical model for applications at regional scale (MARS). Advances in Water Resources, 31, 2, 233-250, 2008, DOI: https://doi.org/10.1016/j.advwatres.2007.06.010

WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present, *Earth Syst. Sci. Data*, 10, 1551–1590, https://doi.org/10.5194/essd-10-1551-2018, 2018.

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