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Dr Ian Fenty[1]
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Altimetry-observed shelf-edge currents off western Canada

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Along-track satellite altimetry data are used to study variations of the surface geostrophic currents over the shelf break and slope off western Canada in the past three decades. The study finds that the surface current is poleward in winter and equatorward in summer off South Vancouver Island, but poleward year round elsewhere. Large seasonal current anomalies are found in strong El Nino and La Nina years. The seasonal current anomalies show statistically significant correlation longshore. There is statistically significant correlation between the seasonal current anomalies and the longshore wind anomalies off Vancouver Island and off Oregon, implying the importance of regional and remote winds.

4

Could Sea Level Rise Cause Coastal Erosion on Turkey's Northern and Southern Coasts?

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Coastal erosion can occur from many factors, such as increasing wind speeds on the sea surface and increasing the intensity of the waves, local sea-level changes, currents, and sedimentation. This study aimed to determine that sea-level rise on Turkey's southern and northern coasts does not cause coastal erosion. For this purpose, sand mining/nourishment/subsidence investigations were made using ESA's Sentinel-1 data. The change of coastlines was determined, primarily in the coastal erosion zones of Antalya-Konyaaltı in the Mediterranean and Sakarya-Karasu in the Black Sea (2015-2022).). Sea level data obtained from the CTOH Along-Track Sea Level Anomalies regional products (X-TRACK) and Copernicus Marine Environment Monitoring Service (CMEMS) improved altimetry data simultaneously. Thus, the relationship between sea-level rise and coastal erosion was examined, and coastal collapses caused by coastal erosion were determined. In addition, the time-dependent variation of the coastline was determined.

3

Statistical decompositions of coastal surface currents and sea surface heights and evaluation of their performance

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Recent efforts to observe sea surface height (SSH) fields at less than kilometer spatial resolution using various satellite missions have spurred interest in understanding how well balanced and unbalanced motions can describe the ocean surface current field at finer scales, particularly in coastal regions characterized by complex flows under multiple driving forces (e.g., tides, winds, and low-frequency signals). In this study, we investigated the Helmholtz physical decomposition and wave-vortex decomposition to delineate the balanced and unbalanced motions of coastal surface currents while considering their reasonable justifications individually. The observed and simulated coastal surface currents do not exhibit an evident decomposition of balanced and unbalanced motions when wave-vortex decomposition is applied. Wave-vortex decomposition may not always be valid in coastal regions in which (1) the isotropy, spatial homogeneity, temporal stationarity, and statistical zero-correlations of the current components may not be guaranteed, and (2) multiple geophysical signals and footprints of driving forces are present. In contrast, the stream function obtained from the Helmholtz physical decomposition can be used as a proxy for balanced motions when the variance of vertical currents is weak, except for near-inertial variance. We believe that the Helmholtz decomposition in the physical domain will provide better insights into the dynamical decomposition than that in the spectral domain and can be applied to the analysis of upper ocean dynamics, including the propagation of unbalanced motions and vertical and horizontal structures of ageostrophic currents. Based on our study, SSH fields observed at a very high spatial resolution in upcoming satellite missions will complement ocean current fields at finer scales, particularly in coastal regions characterized by a complex flow geometry.

5

Fully Focused SAR Altimetry and Innovative River Level Gauges for Coastal Monitoring – the FFSAR-Coastal Project

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The recently developed technique of "fully focused" processing of SAR altimeter data provides opportunities for exciting new applications, as it provides hitherto unachievable along-track resolution of up to (and in some cases less than) tens of metres.

The objective of the FFSAR-Coastal Project is to apply the SMAP Fully Focused SAR (FFSAR) altimetry processor on Sentinel-3A and Sentinel 3B data and evaluate the potential of FFSAR altimeter data to make a significant new contribution to coastal and estuarine monitoring systems.
Two different environments are being considered:

- The Severn Estuary and river: A highly dynamic mixed tidal estuary environment, the confluence between a river and its estuary experiencing large tidal range and strong tidal currents.
- The lower Rhone Delta and Camargue: A low lying, flat river delta and wetland environment, susceptible to inundation and rising water levels.

By studying these two very different environments, the potential applicability and benefits offered by FF SAR altimeter data in other coastal, estuarine and delta locations will be demonstrated.
Innovative in situ lidar water level gauges, provided by vortex.io will be used for validation.

DTU Space have implemented the SMAP (Standalone Multi-Mission Altimetry Processor), developed by CLS, and applied it to Sentinel 3A and 3B altimeter data for the two regions in the study (Severn Estuary and Rhône delta). Initial results have helped to identify the optimum processing choices, which have then been applied to generate time series of data for selected tracks, and these data validated against in-situ data. The in-situ data comprise data from existing tide gauges, but also from four newly installed innovative "micro-gauges" provided by vortex.io, two in each region.

Subsequent analysis will then investigate the capability of FFSAR altimeter data to capture small scale physical signals (surface gradients, currents, roughness signatures) in highly tidal regions and to detect and measure tidal asymmetry/gradients across estuaries not seen with conventional altimetry. For the Rhône delta the analysis will focus on the ability of FFSAR data to accurately map different low lying channels and filaments.

Drone campaigns with an embedded LiDAR altimeter are planned to provide high resolution sea level measurements, synchronised to satellite overpasses, to provide a water level profile between the micro-gauge location and the satellite ground track.

FFSAR-Coastal is funded by ESA under the EO Science for Society Programme – Open Call.

6

Improving SAR Altimeter Processing Over the Coastal Zone - The ESA HYDROCOASTAL Project

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The objectives of the HYDROCOASTAL project, funded by the European Space Agency under the EO Science for Society programme, are to enhance our understanding of interactions between the inland water and coastal zone, between the coastal zone and the open ocean, and the small scale processes that govern these interactions. The project also aims to improve our capability to characterize the variation at different time scales of inland water storage, exchanges with the ocean and the impact on regional sea-level changes

To achieve these aims, the HYDROCOASTAL project team has developed and implemented new SAR altimeter processing algorithms for the coastal zone and inland waters, and with these processed Sentinel 3A, 3B and Cryosat-2 data to generate to generate an initial 2-year Test Data Set for selected regions. The performance of these new algorithms has been evaluated, by statistical analyses and comparison against in situ data. From this analysis, the best performing algorithms have been identified and a processing scheme implemented to generate a global scale coastal zone and inland water altimeter data set.

A series of case studies are now assessing these products in terms of their scientific impacts. All the produced data sets will be available on request to external researchers, and full descriptions of the processing algorithms are available via the project web-site

The presentation will provide an overview of the HYDROCOASTAL project, describe the different SAR altimeter processing algorithms that have been implemented and evaluated in the first phase of the project, and present results from the evaluation of the initial test data set. It will also present early results from coastal zone impact studies.

7

Portagauge and Satellite Sea level monitoring system for the Southwest Indian Ocean – PASS-SWIO

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Madagascar currently has very limited tidal prediction capability (primarily based on model data) and no national sea level monitoring capability. There is only one functioning tide gauge, whilst an earlier tide gauge, in the cyclone-prone north of the island, was swept away several years ago.
Working closely with Malagasy partners, the Direction Générale de la Météorologie (DGM), PASS-SWIO aims to establish a sea level monitoring system for Madagascar based on the deployment of a low-cost relocatable tide gauge (Portagauge).
Financially it is impractical for Madagascar to install multiple tide gauges at all points of interest along their extensive coastlines, nor can they be maintained on the multi-decadal timescales that are required to derive robust estimates of long-term sea level trends. Yet, tidal information is vital for the safety of communities, infrastructure and commerce, and since short-term hazards can be exacerbated by long-term increases in sea level, knowledge of longer-term change is also essential.
Longer-term sea level variability, including trends associated with Climate Change, can be derived from satellite altimetry data. However, for these 'absolute' sea level measurements, calculated relative to an ellipsoidal reference frame, to be meaningful for planning and adaptation purposes they require correction for vertical land motion and 'ground-truthing' to some known fixed point on land. Vertical land motion is traditionally measured by GNSS receivers via the detection of positioning and timing information from a constellation of navigational satellites. The recent GNSS interferometric reflectometry (GNSS-IR) technique exploiting the signal-to-noise ratio, allows sea level to be inferred relative to the same geodetic reference frame as satellite altimetry. Co-location of GNSS receivers with conventional tide gauge sensors (which measure relative to some fixed point on land), allows short-term tide gauge and GNSS-IR measurements to be connected to satellite altimetry, which can substitute for long-term observations from tide gauges.
The Portagauge, which uses GNSS-IR alongside a conventional radar gauge, will be deployed at Toamasina port on the NE coast of Madagascar. DGM will be trained to maintain and operate the Portagauge, and to carry out processing and analysis of tide gauge and satellite altimeter data (Jason-2, Jason-3, Sentinel-3A and 3B). They will cross validate portagauge data against satellite data and generate analysis of tidal and non-tidal sea-level characteristics for the Madagascar coastal region, including seasonal signals, inter-annual variability and trends. The PASS-SWIO team will also work with agencies and key users in Madagascar to define a road map to establish a long-term, sustainable, national sea-level monitoring system for the country. It will be important to ensure that the planned capacity development meets key requirements, complements existing capability and is sustainable, considering resource requirements. The project will provide a model sea level monitoring system for developing island states and coastal nations, based on low-cost tide gauges and satellite data.
PASS-SWIO is funded by ESA under the EO Science for Society Programme – Open Call.

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Assessment of renewable wave energy resources in the French façade coastal zone using high-resolution altimetry products

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An assessment of the wave energy potential is given for the French facade coastal zone, which is characterized by high energy swell generated by remote westerly wind systems, which is also affected by the strong wave-current interactions that take place in the area where tidal currents are of the order of 2 m/s. The study comprises the period from January 2018 till December 2020 encompassing the region 50° N, 36° N, 12° W, 0° E.
In order to estimate the energy period, required for the computation of the wave power density from the altimeter Ku band significant wave height and radar backscatter coefficient the empirical model of Gommenginger et al. (2003) is applied.
Taking advantage of the increased time and spatial coverage of high-resolution satellite altimetry data from the Sentinel-3A and -3B processed with the SAMOSA+ model-retracker the feasibility of high-resolution satellite altimetry-based assessment of wave renewable energy potential in the coastal zone is examined.

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An improved ship detection scheme experimented on Sentinel 3 – SRAL data: an approach based on robust statistics

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The detection of vessels is considered an attractive byproduct of satellite radar altimetry, because it may complement the conventional tracking systems with the possibility to build long-term global statistics of ship traffic based on relatively small and manageable datasets of freely available data.
The potentiality of SAR altimetry for the detection of ships has already been demonstrated with Cryosat2 data, and today Sentinel-3 is the first operational mission offering global SAR coverage with a constellation of two satellites.
Thanks to the enhanced azimuth (along-track) resolution available in the synthetic aperture radar (SAR) mode, the radar altimeter on board the Sentinel-3 satellite could be beneficial to other applications than ocean topography. In particular, this work studies the performance of algorithms for the automatic detection of ship targets from SAR mode data. Altimeter data could be regarded as an additional non-cooperative source for vessel traffic surveillance systems or to map global traffic patterns over long periods of time. In addition, the pre-processing of altimeter data by reliable detection algorithms, filtering out signal outliers from the sea surface response, largely contributes to enhance geophysical products that are typical in ocean topography studies (e.g. mean sea level).
This work proposes a processing chain based on mathematical morphology filtering and robust statistics to estimate the structured background and detect target signatures from radargrams. The detection stage is followed by an additional binary morphological filtering phase that is useful to estimate target characteristics, such as the height. The robust algorithm is compared with respect to non-robust techniques through detector-receiver operating characteristic (ROC) curves estimated from a real radargram data set. The study shows that robust statistics outperform non-robust ones, with i) better background estimate with low target signal leaking thus improving target signal to background ratio and ii) improved rejection of false alarms. The study finally provides a first attempt to validate the analysis comparing detected target contacts with automatic identification system (AIS) data.
In future work, the analysis will be improved by enlarging the ground truth data set with new data from Sentinel-3 and AIS, in new areas. Additional techniques based on machine learning algorithms will be also considered and tested.

9

Baltic SEAL: new insights into the mean and variability of the sea level in the Satellite Altimetry era

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For sea level studies, coastal adaptation, and planning for future sea level scenarios, regional responses require regionally-tailored sea level information. Global sea level products from satellite altimeters are now available through the European Space Agency's (ESA) Climate Change Initiative. However, these global datasets are not entirely appropriate for supporting regional actions. For the Baltic Sea region, complications such as coastal complexity and sea-ice restrain our ability to exploit altimetry data opportunities.

This presentation highlights the opportunities offered by such regionalised advances, through an examination by the ESA-funded Baltic SEAL project (http://balticseal.eu/). We present the challenges faced, and solutions implemented, to develop new dedicated along-track and gridded sea level datasets for Baltic Sea stakeholders, spanning the years 1995-2019. Advances in waveform classification and altimetry echo-fitting, expansion of echo-fitting to a wide range of altimetry missions, and multi-mission cross calibration, enabled all mission data to be integrated into a final gridded product.

This gridded product provides new insights into the Baltic Sea's mean sea level and its variability to be gathered. A Mean Sea Surface dataset was developed, in addition to an analysis of sea level trends in the region (using both tide gauge and altimetry data). The Baltic SEAL absolute sea level trend at the coast better aligns with information from the in-situ stations, when compared to current global products. A pronounced sea level trend gradient which increases towards the North-East was found. There is a strong correspondence between season-specific sea level trends and a decreasing trend in westerly wind forcing. The spatial and temporal density of the data allows for a robust comparison between the sea level time series and relevant climate indices such as the North Atlantic Oscillation, with implications for regionalising global climate change impacts.

These investigations highlight the potential of regionalised products for the Baltic Sea region, and beyond. The availability of multi-mission along-track data and gridded data offers a wide range of opportunities, from supporting local ocean circulation research, to storm surge monitoring.

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Global coastal attenuation of wind-waves observed with radar altimetry

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Coastal studies of wave climate and evaluations of wave energy resources are mainly regional and based on the use of computationally very expensive models or a network of in-situ data. Considering the significant wave height, satellite radar altimetry provides an established global and relatively long-term source, whose coastal data are nevertheless typically flagged as unreliable within 30 km of the coast. This study, recently published in Nature Communications (Passaro et al., 2021), exploits the reprocessing of the radar altimetry signals with a dedicated fitting algorithm to retrieve several years of significant wave height records in the coastal zone. We show significant variations in annual cycle amplitudes and mean state in the last 30 km from the coastline compared to offshore, in areas that were up to now not observable with standard radar altimetry. Consequently, a decrease in the average wave energy flux is observed. Globally, we found that the mean significant wave height at 3 km off the coast is on average 22% smaller than offshore, the amplitude of the annual cycle is reduced on average by 14% and the mean energy flux loses 38% of its offshore value.

In the attached plot: Density plots of the ratios between wave parameters computed in the coastal zone over the globe and the corresponding parameter computed offshore. The parameters considered are the mean Significant Wave Height (SWH) (a), the amplitude of the annual cycle (b), and the average wave energy flux (c). A second-degree polynomial is fitted to the data and plotted in red. The 95% confidence interval of the fit is shown with red dashed lines.

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Coherent modes of coastal sea level variability from altimetry and tide gauge observations

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Sea level dynamics in the coastal zone can differ significantly from that in the open ocean. The presence of the continental slope, shallow waters and the the coastlines give rise to a variety of processes that mediate the response of coastal sea level to open-ocean changes and produce distinct spatiotemporal sea level patterns. Yet how exactly this interplay occurs and, more importantly, the extent to what coastal sea level variations differ from open-ocean variability remain poorly understood. In this work, we use coastal altimetry observations in combination with tide gauge data to determine patterns of coherent coastal sea level variations and the degree of decoupling between such variations and open-ocean changes.

In a first step, we apply Bayesian mixture models to identify clusters of correlated tide gauge observations that explain a significant fraction of the coastal sea level variability. Using altimetry data, we find high regional coherency of along-shore coastal sea level variations, indicating common underlying mechanisms that cause these correlations.

In light of previous research, we confirm that the correlation structures of these coherent patterns are often confined to the continental slopes, particularly in extratropical regions. In regions like the northeastern US continental shelf, correlations decrease with increasing water depth, indicating a decoupling of shelf sea and open-ocean variability. We investigate how these differences between coastal and open ocean sea level variations change as a function of time scale, i.e., from monthly or interannual variations to long-term trends, and validate these results against tide gauge observations. We derive across-shore correlation length scales that provide insights into the space scales of coastal sea level dynamics and are useful to understand how well gridded products can resolve such processes.

We discuss possible causes of the coherent sea level fluctuations, such as wind forcing, coastally trapped waves, and large scale climate modes. The results motivate further research to better understand the driving mechanisms behind these coherent sea level variations, as well as the pathways linking remote forcing to coastal changes.

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Vertical land motion reconstruction reveals nonlinear effects on relative sea level

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Vertical land motion (VLM) is a major contributor to relative sea level change (RSLC) and represents a key constraint for coastal SL-reconstructions and projections. However, the sparse and inhomogeneous distribution of direct point-wise VLM observations and the effect of nonlinear processes such as earthquakes complicate the analysis of VLM in time and space along the coastline. Thus, in order to overcome the limitations of data-availability and to account for time-variable VLM, we develop a new Bayesian approach to estimate continuous time- and space-resolving (3D) VLM over the period 1995-2020.

We apply a multistage method (based on Bayesian Principal Component Analysis and transdimensional regression) to a global network of quality controlled VLM observations (GNSS data and differences of satellite altimetry and tide gauge observations), to extract common modes of variability and secular background trends. The estimated pattern represent a superposition of large scale VLM fingerprints, including linear motion signatures, e.g., the glacial isostatic adjustment (GIA), as well as regional coherent responses to earthquakes or mass loading changes, which exhibit inter-annual to decadal variability.

We apply the VLM reconstruction to perform a coastal SL trend budget analysis, disentangling the contribution of VLM and absolute SLC over 1900-2150. Recently employed RSLC reconstructions, which are statistically constrained by the GIA-VLM signature only, indicate significant biases when compared to century-long tide gauge RSLC measurements adjusted for the observation-informed VLM estimate. While VLM explains up to 34% of the variance of present-day RSLC, projected SLC will be dominated by the average absolute SLC. Still, regional-scale projected SLC will be substantially controlled by VLM, as it explains 50% of the variance of RSLC deviations from the global mean and accounts for 30% of the RSLC uncertainties. Thus, hitherto underrepresented time-variable VLM significantly limits regional RSLC projections, corroborating the need to incorporate observation-based VLM in sea level studies.

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Wind as driver of dub-annual Sea level anomalies on South Brazil and Patagonian Shelf

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Sea level anomaly (SLA) differ in strength and variability not only depending on the region, but also with temporal scales. The drivers of SLA behave similarly and can be found e.g. at the low-frequencies by atmospheric pressure pattern as well as on the high-frequency end by tides, wind and waves. In the study area, the Patagonian/Brazil continental shelf, SLA show higher variability in small temporal periods from days to weeks on the shelf, driven by tides, wind, fresh water discharge of large river mouths. Previous studies showed that seasonal SLA correlate well with wind forcing as well as with river discharge in vicinity of large river runoffs e.g. the Rio de la Plata. However, so far, little is known about wind forcing contributing to SLA over the entire shelf on higher frequencies.

This contribution consists of a comprehensive analysis of altimetry-based SLA from Copernicus provided in daily resolution on a 0.25° x 0.25° grid in order to investigate wind-driven impacts on different temporal scales. Additional dataset are used for validation and comparison, namely SLA from Reanalysis ORAS5, tide gauge data from GESLA-3, and satellite-based wind data from Copernicus. In order to guarantee a fair comparison, consistent handling of ocean tides and atmospheric effects is ensured by an adding or removal of DAC (Dynamic Atmosphere Correction) as well as removal of tides.

This coherence study shows that the shelf SLA are more affected by the along-shore than the across shore wind speed component. Along-shore wind speed shows significant agreement with the SLA in all periods resolved by the products (>20d) in coastal and shelf regions, remarkably in the surrounding of the Rio de la Plata region. EOF-analysis of shelf SLA revealed that the SLA reconstructed from 2. EOF (after 1. EOF describing annual cycle), which includes 10% of shelf variability, is correlating with along-shore wind speed in periods between 20 - 70d. Within this period, coherence is highest for around 70d in certain shelf areas. Furthermore, low coherence areas can be observed e.g. along the shelf break and at river mouths, where other features prevail as driver of SLA over wind.

This presentation will demonstrate that in addition to the existing studies about the seasonal cycle, SLA on higher frequency show significant agreement with wind forcing, which can further be associated with certain wind directions. The study will show ability and limits of existing gridded SLA and wind products to access sub-annual ocean dynamics.

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Improving coastal water altimetry retracking by incorporating spatial dependency of waveforms

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With the launch of the operational Sentinel series of the European Copernicus programme, the algorithms to obtain highly precise water level estimates over coastal seas need to become more robust, efficient and fit for automated use. Here we propose a 2D retracking method, which instead of a retracking gate as a point in the 1D waveform, seeks a line (referred to as a retracking line) in a 2D radargram. By finding such a retracker line, each radargram can be segmented into two parts: the left (front) and right hand side (back) of the retracking line. This can be interpreted as a binary image segmentation problem in a more straightforward representation, in which spatial constraints are considered. We formulated this problem using Markov Random Fields (MRF), which explicitly model the interaction between different constraints and auxiliary sources of information in a radargram. In such a formulation, we deal with a Bayesian framework with the goal of finding a specific labeling structure of the image which maximizes the posterior estimation of the MRF (MAP-MRF). We evaluate our method using UF-SAR and FF-SAR processed radargrams of Sentinel 6 altimetry data (track no. 196) over the coast of De Koog in the Netherlands and validate our results against in situ data.

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Improving estimates of significant wave height in coastal zones from Sentinel 3 SAR altimetry using a data driven method (RiwiSAR-SWH)

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This study proposes a data driven method to determine SWH using the Sentinel 3 data for both oceanic and coastal zones. For this purpose, we propose a method based on the rise time and the width of a waveform, called RiwiSAR SWH (rise time width model for SAR SWH), which is free from the complexity of the SAR physical model and estimates SWH over the coastal area and open ocean in a relatively straightforward manner. The method is employed over different regions in the coastal zone of the North Sea. The results are validated against in situ buoy data and compared with SWH estimates from SAMOSA+, SAMOSA++ and the Sentinel 3 Ocean retracker . The validation shows that the proposed method can determine SWH with accuracy ranging from 0.25m to 0.91m for different locations in the North Sea . Moreover , we obtain reliable SWH to within 1 km from the coast, which is
an improvement of more than 40% compared to existing methods.

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An Improved of Satellite Altimetry Data Processing Along the Algerian Coast

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In coastal systems, shorter spatial and temporal scales make ocean dynamics particularly complex, so the coastal domain represents a challenging target for processing of satellite altimetry data.
The main objectives of this paper are to improve the altimetric measurement in coastal areas by analyzing the main problems related to atmospheric corrections that must be applied to this measurement to obtain a precise surface height.
The processing of Saral/AltiKa Geophysical Data Records with in-house developed algorithms, including: re-tracking which is important for the last 7 km next to the coast; a more accurate wet troposphere correction (decontaminated correction) and better modelling of atmospheric effects permit us to determination the sea surface height over the Algerian coast.

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SARAL Altimeter-collected SSH Validation and Calibration using Algerian Tide Gauges

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Altimetric calibration is the process of quantitatively defining and comparing the altimetric measurements with known and controlled inputs, determined by independent means like tide gauge. SARAL/AltiKa satellite data processing, permit us to determine the sea surface height over the Algerian coast. Three Tide gauge stations in Algiers, Jijel and Oran are installed along the Algerian coast. These sites are located near a repeating ground track of SARAL/AltiKa then; they offer several advantages as validation sites of the altimeter sea surfaces.
This work aims to present the initial validation results using 20 cycles of SARAL/ALtiKA, pass # 273 over Algiers tide gauge, pass # 216 over Jijel tide gauge, and pass # 029 over Oran tide gauge. The objective of this experiment is to continuously monitor the absolute bias of the altimetric measurement systems.
The tide gauge measured could differ from sea level at the comparison point if the observations are apart from each other. Therefore, the altimetry observations are trans-located to the tide gauge location to overcome this difference by correcting the geoid difference between the observation points. The absolute bias is 5.84 cm, 6.95 cm and 6.23 cm at Oran and Algiers calibration sites respectively.

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Accurate Dynamic Topography by Satellite Altimetry and Marine Geoid Model

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Accurate determination of dynamic topography (DT) allows quantification of more realistic sea levels, and it also allows deeper insight into the sub-mesoscale dynamics of marine processes. The determination of DT has previously been limited due to unattainable high-resolution geoid models. The Baltic Sea countries however have cooperated (through gravity measurement campaigns and modeling techniques) to derive an accurate high-resolution NKG2015 quasi-geoid model. As a result, this study explores a method that derives DT by employing both a geodetic approach that utilizes satellite altimetry (SA) data and also from an oceanographic approach that uses hydrodynamic models (HDM). The high-resolution geoid is the key source that links these two approaches. The study site is that of the entire Baltic Sea for the period 2017–2019. For the geodetic approach, DT is computed using the along-track SA from multi missions (obtained from Baltic+SEAL retracker) that includes Sentinel-3A (S3A), Sentinel-3B (S3B) and Jason-3 (JA3) in conjunction with the NKG2015 geoid model. The vertical datum of HDMs are often undisclosed, thus a method is applied using geoid referred tide gauges (TG), that corrects the HDM. Once the vertical datum of both SA and HDM refer to the geoid a comparison of DT from both methods are performed. This comparison provides specific insight into the validation of the SA derived DT.
The results showed average discrepancies between SA and HDM within the range of ±20 cm, with RMSE of 9 cm (S3B) and 6 cm (S3A and JA6) and a standard deviation between 2–16 cm. The inter-comparison of SA missions' outcomes also confirmed that better results are obtainable by SAR mode (S3A and S3B) rather than with the LRM mode mission, although much larger discrepancies were found between filtered SA data and the corrected HDM with respect to those obtained for the S3A and S3B mission. This fact emphasizes that the JA3 dataset is affected by a higher measurement noise than S3A, and also that the SRAL instrument onboard the Sentinel-3 missions better solves the signal in the coastal band.
Due to the method employed utilizing different sources of data and multi-mission SA data it also allowed the identification of problematic issues/areas with SA, HDM, TG, and the geoid. For instance, geoid problems were discovered in the eastern section of the Baltic Sea, whilst potential TG data issues were found on the Swedish eastern coast. For SA it was observed that in the Gulf of Bothnia sea-ice may be problematic. Most importantly the comparison revealed that SA along-track data has the potential to show a more realistic variation of DT compared to that of HDM (which tended to generate an unrealistically smooth surface). Also, in most cases, the HDM tended to underestimate the DT.

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Sentinel-3 Topography mission Assessment through Reference Techniques – The ESA St3TART project

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The Copernicus Sentinel-3 Surface Topography Mission (STM), based on a constellation of two satellites, provides extremely valuable surface elevation information over inland waters, sea ice and land ice, thanks to its SAR altimeter which retrieves high-resolution along-track elevation measurements, and to its orbit that covers high-latitude polar regions. To ensure that these measurements can be used with confidence, and to maximize the return on investment of the Copernicus Sentinel-3 STM, adequate validation of the geophysical retrieval methods, processing algorithms and corrections must be performed, considering independent observations as Reference Measurements.

St3TART is an EU and ESA funded project led by NOVELTIS with a consortium of 17 European partners (CNES, DTU, NPI, vorteX.io, LEGOS, Hydro Matters, CLS, LOCEAN, IGE, SERTIT, GIS, CNR-IRPI, NPL, DT/INSU, IRD, M2C, SYRTE). It aims to generalize the concept of Fiducial Reference Measurements (FRM) for the Copernicus Sentinel-3 STM and to collect and distribute FRM data for the validation of the satellite mission over inland waters, sea ice and land ice. The provision of FRM will serve the validation activities of the ESA S3 Land Altimetry products, currently performed by the Sentinel-3 Mission Performance Centre, with the support of the Sentinel-3 Validation Team, for the sake of performance assessment and fitness-for-purpose of the Sentinel-3 STM Land core products. Those products cover inland waters, land-ice and sea-ice areas.

The objective of the St3TART project is not only to collect existing data or measure new observations during field campaigns, but to ensure that these observations meet the criteria of FRM standards and can be used in an operational way for the validation of the Sentinel-3 Land topography mission. Within the project, field campaigns are means to provide operational observations for the validation of the Sentinel-3 data.

In addition of the definition and consolidation of methods and protocols for the validation of the Sentinel-3 Altimetry Land products with FRM measurements, a roadmap will be drawn for the operational provision of FRM for the Sentinel-3 validation, considering the most relevant and cost-effective methods to be maintained, supported as far as possible or implemented. This will include guidelines for SI traceability, definition of the FRM measurement procedures, processing methods, and uncertainty budgets estimation. Several FRM campaigns have already been executed in sea ice covered region (Greenland) and on hydrological sites (on Garonne, Rhine and Po rivers), based on the first recommendations gathered in this roadmap.

A platform is under development to publicly disseminate the FRM data and measurements gathered within the St3TART project in order to facilitate the validation of the Sentinel-3 STM Land data products, with fully characterized and documented FRM processing and measurements. The St3TART project also supports the

community with the development of SCalSIT, a tool intended to help identifying in-situ Cal/Val sites over Inland Water Surfaces.
We will present the main objectives, tools and first outcomes of the project.

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Regional ocean modeling with data assimilation for improving Mean Dynamic Topography and sea level variability forecasting in the coastal ocean

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A 15-year reanalysis of circulation in the northeast U.S. coastal ocean has been completed using the Regional Ocean Modeling System (ROMS) and four-dimensional variational (4D-Var) data assimilation. The analysis downscales open boundary information from the Copernicus Marine Environmental Monitoring Service (CMEMS) global analysis and assimilates all available data from in situ instruments, coastal radars, and satellites.

Climatological data assimilation is used to compute coastal ocean Mean Dynamic Topography that significantly improves on the CNES CLS MDT on the continental shelf and in the Gulf of Maine, allowing the assimilation of Absolute Dynamic Topography to within a few kilometres of the coastline. Modeled sea level variability is highly coherent with tide gauge data throughout the domain and across all time scales from annual to daily, and is significantly more skillful than CMEMS.

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Assessment of coastal altimetry data along the coast of California

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Global average sea level is rising at an accelerated rate. However, coastal areas are more sensitive to ocean dynamics on local and regional scales. Regional trends often differ from the global average and are dependent on the time periods over which the trends are calculated. Moreover, nearshore sea levels may not be represented by offshore surface heights due to bathymetric constraints, wave-current interactions, and localized forcing. Thus, enhanced understanding of the relationship between regional signals and nearshore amplitudes and phasing is needed.

This work assesses regional variability in sea level oscillations, trends, and acceleration using the NASA Integrated Multi-Mission Ocean Altimeter Data for Climate Research level 4 gridded product, which is part of the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Program. This multi-mission, highly processed, 30-year sea level record reveals the historical context for examining high resolution coastal altimetry data that has become available in recent years.

Advances in regional reprocessing of altimetry data near coastlines using along-track, high-resolution (20 Hz, i.e., 300 m resolution) data from the Jason-1, 2, and 3 missions have yielded a novel dataset spanning January 2002 to December 2019 (Cazenave et al. 2022). This coastal product uses the Adaptive Leading-Edge Subwaveform (ALES) retracking method, applies additional adapted geophysical and environmental corrections, and has been validated in certain regions. Here we will assess the utility of this product along the southwest coast of the United States along the California coastline through comparison to in situ observations including tide gauges and pressure sensors, as well as existing numerical solutions for the region.

Finally, we investigate high resolution, along-track data from the Sentinel-6A/Michael Freilich mission in the same coastal California region making comparisons to data from the Jason missions in an effort to understand the improved observational capacity provided by Sentinel 6 near the coast relative to other satellite missions like Jason-2 and 3.

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Oceans Radar Altimetry With MAGAL Constellation

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The concept of a small radar altimeter (RA) constellation has already been proposed but not yet implemented due to technological limitations or high costs associated with the operation of such a constellation. Yet, some oceanic processes are still poorly understood due to the lack of adequate ocean sampling by past and current satellite altimetry missions. With the increase in popularity of the CubeSat concept and the current availability of low-cost and high-performance components, improving the space-time resolution of satellite altimetry with a constellation of small satellites becomes a possible scenario.
The MAGAL Constellation is a future constellation of small satellites carrying radar altimeters that aims to improve the understanding of ocean circulation variability on local, regional, and global scales by improving the spatiotemporal resolution of sea surface topography measurements. The measurements provided by MAGAL are expected to augment those from the operational RA missions to improve the collective data products with an enhanced data set over the open ocean, while also targeting the coastal processes. Four main use cases were selected, for which the sampling of the ocean with higher spatial and temporal resolutions is required: better characterization of the mesoscale variability at local and regional scales to support operational oceanography; eddy detection and tracking; monitoring of marine debris pathways, and the monitoring of the water level of inland water bodies.
To achieve these goals, MAGAL Constellation is being designed based on six CubeSats, no larger than 24U, flying into a single sun-synchronous ERM orbit with 97.4º inclination and at a ~500 km altitude, providing full coverage with a 5-day repetition cycle and distance between adjacent tracks of ~88 km at the Equator. The MAGAL platform will be miniaturized and manufactured in series, minimizing production, operational, and launching costs. The design process will take advantage of the new Space 4.0 industry to integrate readily COTS subsystems (navigation, tracking, cooling, and propulsion). A new small, lower power-consuming RA has been developed, operating at a frequency of 13 GHz, with a Frequency Modulated Continuous Wave (FMCW) architecture. To ensure an adequate observation footprint, a deployable dish antenna of at least 1.5 m diameter is required. The RA also embeds and provides additional data for range accuracy improvement and validation.
A prototype of the RA is already available and the first conducted field tests confirm the operation of all implemented features and functionalities. Preliminary results demonstrate both the data accuracy and the RA performance. Altitude tests through flight are already planned, together with the data validation through the MAGAL data center process and algorithms.
A Data Analysis Center (DAC) is being developed for data storage and processing, which will also include data from multiple sources (e.g. meteorology) to produce scientific and commercial information. The DAC front-end layer will also allow the display of the data in various graphical interfaces.
The project MAGAL Constellation (Nr. 033688) is co-financed by the European Regional Development Fund through COMPETE 2020, LISBOA 2020, and by FCT under the UT Austin-Portugal interface program.

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Coastal Low Resolution Mode Sea Level Data From CryoSat-2 on the Entrance to the Gulf of California

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Several studies have shown the usefulness of sea level data from the CryoSat-2 mission over oceanic and some coastal areas. The coastal regions whose validation presents the best results are those with high resolution measurements when the mission operates in SAR and SARin modes. However, large coastal extensions, in which only the low resolution mode (LRM) operates, still remain without validation. In this study we validated CryoSat-2 sea level anomalies (SLA) from LRM mode at 20 HZ (~350 m between measurements) with two tide gauges located at the entrance to the Gulf of California. One of them located in Cabo San Lucas (CSL), at the tip of the Baja California peninsula, and other in Mazatlán (MZ) on the mainland coast. CryoSat-2 SLAs are obtained after applying a series of geophysical corrections. Here we use the TPXO9 tidal model to correct for the tides and a percentage of the significant wave height (SWH) in place of the sea state bias (SSB). The percentage of SWH used is 7% and 9% for CSL and MZ respectively. The comparisons show good agreement in the SLAs in CSL and MZ, with standard deviations of the differences (SDD) lower than 0.09 m and correlations higher than 0.7 (95% of confidence level). Also, seasonal variability in CSL and MZ is described using the CryoSat-2 time series from 2011 to 2020, showing the presence of events such as El Niño (2015 to early 2016), La Niña (2011) and the warm event nicknamed the Blob (2014). Subsequently, the residual time series of CryoSat-2, after extracting the annual and semi-annual components, at 11 km from the coastline in CSL and 9 km in MZ, showed that MZ is more affected by El Niño/La Niña while CSL by the Blob/El Niño.

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Combining coastal altimetry and optical remote sensing to quantify drivers of coastline migration in the Wadden Sea

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Sea level rise has the potential to increase the probability of flooding of coastal areas with severe impacts on the local population and industries. However, coastline migration is not only caused by changes in absolute sea level, but also by vertical land motions that change the relative sea level and morphological processes that affect the sediment budget, such as sediment transport by wind, waves or currents. Each of these three groups of processes can individually cause the coastline to retreat or to prograde, and additionally they also interact with each other. If we want to know which consequences we can expect from future sea level rise, we need to know how to separate the effect of sea level changes on the coastline position from the effects of vertical land motions and of morphodynamics. Here, we approach this problem by combining the vertical sea surface heights from coastal altimetry measurements with horizontal coastline positions extracted from optical remote sensing images.
In this contribution we will present the data foundation for a case study for the barrier island of Terschelling (the Netherlands). The basis is formed by coastal sea surface heights from multi-mission radar altimetry processed using the ESA Earth Console, together with snapshots of coastline positions extracted from Landsat and Sentinel-2 optical imagery. Estimates of vertical land motions from GNSS enable us to link the altimetry observations to the recordings of nearby tide gauges. The comparison of altimetry and tide gauge measurements gives us insights into the nearshore sea surface height variability as a measure for the accuracy of sea surface height estimates directly at the coastline. Furthermore, a Digital Elevation Model from LiDAR and bathymetry observations is used to test the sensitivity of the coastline position to sea level height and beach slope. The combined evaluation of sea surface and topographic heights together with the horizontal shoreline positions will increase our understanding of climate change impacts. The methods designed in this case study serve as the basis for studies in other locations.

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Origin of Sea-level Changes on the Shelf of the Northwest Atlantic from Sentinel-3A SRAL

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The gap in understanding the changes of sea level on the continental shelf continues to hinder the linkage between the open ocean sea level and tide gauge records. Space-based observations are crucial in addressing this issue; however, conventional altimetry is significantly less reliable closer to the coast. SAR altimetry can help us bridge this gap to circumvent the resolution limitations of conventional altimetry. Recent studies have considered decadal changes from the tide gauge record; there has been less focus on shorter time-scales (higher frequencies), which carry a significant proportion of sea level variability in the coastal region. Similarly, SAR altimeter products have been underutilized for coastal monitoring studies despite the availability of CryoSat-2 and Sentinel-3A/B (both have a duration >5 years), in addition to the more recent Sentinel-6 Michael Freilich mission.

This work aims to address the limitations of previous studies by attributing the sea level change across the shelf to dynamic processes at various sub-interannual time-scales. Our region of interest is the Northwest Atlantic (specifically, Eastern seaboard of the U.S. and Atlantic Canada); this region has been flagged as a sea level rise hotspot at longer time-scales and contains high-quality in-situ observation infrastructure. We used SAMOSA++ coastally-retracked Sentinel-3A SRAL sea surface height anomaly in the coastal zone (within 250 km from the coast), in conjunction with hourly tide gauge and model sea level data, covering the period between 2016 and 2020. As the model, we used the output of GOFS/HYCOM, an eddy-resolving global ocean forecast system, to simulate the sea level and temperature-salinity profiles. In this study, we assess the sterodynamic component and its contributor processes: wind, freshwater discharge, steric advection and buoyancy. We analyzed the statistical relationship between these contributors and the altimeter/tide gauge time-series, establishing which contributors have the strongest relationship and their spatial pattern.

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Performance of Sentinel-3A SRAL on the Shelf of the Northwest Atlantic

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Despite Sentinel-3A providing a global SAR altimeter (SRAL) product for more than six years, there have been few applications to study the oceanography of the Northwest Atlantic (which includes the Atlantic coast of North America). The ability to increase along-track resolution and availability of SAR retrackers provides unprecedented opportunities to study more complex coastal regions like this with improved reliability.

This study evaluates the performance of Sentinel-3A SRAL over the shelf of the Atlantic coast of North America with multiple parameters considered. These include comparison with tide gauge data, obtaining decorrelation length scales, checking consistency at the crossovers, evaluating the influence of selected altimeter corrections on the observed variance, and suggesting optimal post-processing for oceanographic applications in this region. We studied both RADS 1 Hz and SAMOSA++ 1 Hz and 20 Hz products, in addition to 1 Hz ALES from TUM DGFI openADB. The results indicate similar performance to tide gauges for all products and increased consistency for SAMOSA++.

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On the assimilation of directional wave spectra in coastal wave model : upgrade of CMEMS-IBI

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The IBI forecasting system of the Copernicus Marine Service (CMEMS) provides high resolution wave products for the domain Iberian-Biscay-Ireland that includes coastal areas exposed to swell propagation and strong wind sea development in the Bay of Biscay. The objective of this work is to evaluate the impact of the assimilation of CFOSAT directional wave spectra on the prediction of integrated wave parameters. The CMEMS IBI model is based on the MFWAM model with a regional configuration of 5 km grid resolution. The model is forced by hourly IFS winds and boundary conditions from the globa model. The assimilation scheme is optimized in terms of correlation length for the observations. Assimilation test runs over a period from January to June 2022 have been performed, as well as a control mdoel run without assimilation. The validation of the results is implemented with independent altimeters and coastal wave buoys. Particular attention is considered to investigate the impact of the assimilation on dominant wave period and wave direction, particularly in coastal areas. We also evaluate the impact of using jointly surface currents forcing and the assimilation of directional wave spectra. We examined storm cases during winter 2022. Further comments and conclusions will be presented in the final presentation.

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Forecasting Of Absolute Dynamic Topography By Utilizing Machine Learning With Synergy Of Satellite Altimetry Data

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Increasing coastal activities due to navigation, marine engineering and recreational activities requires now more than ever accurate forecasting of sea level data. To accomplish this however firstly requires that various sources (e.g. hydrodynamic models, tide gauges and satellite altimetry) refer to a common vertical datum. This is usually performed by incorporating a high-resolution geoid model so that absolute dynamic topography is derived from all the sources. Once this is accomplished other prospects becomes possible. As a result, this study explores one step further by developing a method that utilizes prior results of accurate DT obtained for the Baltic Sea, along with a deep learning-based algorithms in order to spatio-temporally forecast absolute dynamic topography for the whole Baltic Sea.
The method is such that a 2D Convolutional Neural Network algorithms are utilized with input data that consists of sea surface temperature, wind components, sea level pressure and absolute DT from hydrodynamic models. The algorithms are trained with a data set from 2017–2019 and tested for 6 months in 2019. Results revealed that predicted and model DT with a spatial root mean square error of RMSE within ±4cm. The predicted data is also validated with Baltic+SEAL retracked SA data for the Sentinel 3A, Sentinel 3B and Jason 3 missions. The method is such that once satellite validation is within a reasonable threshold it can be included as another source of input for the forecasting process.

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Contribution of altimetry to the Gulf of Guinea climate resilience due to last decade sea level anomalies scenarios.

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The Gulf of Guinea (GoG), which stretches from Liberia to Gabon with reports of high vulnerability to coastal flooding caused by relative or climate-induced sea level rise, is an example of how coastal sea level changes remain poorly understood, in contrast to the global and regional average sea levels measured by satellite altimetry missions. These coastal areas with large human densities, low elevations, noticeable subsidence rates, and/or poor adaptation ability are most at risk. The relationship between equatorial Atlantic Ocean variability and the coastal region (1° coastal band off coast) of the GoG is investigated at interannual time scales from 1993 to 2021 (29 years) from recent altimetric products in order to understand its mitigation to sea level rise in a region where there are no reliable (non-existent) tide gauges data. The study focuses on the (extreme) warm and cold events that occur in both the GoG and the Atlantic Ninos and links them to the well-known Benguela Ninos occurrences that occur off the coast of Angola and Namibia. The trade winds relaxing in the western/central basin caused equatorial and subsequent coastal waves, which are generally accepted to be the cause of both catastrophes. A correlation between signals observed along the GoG with significant events depicted along the Angola-Namibian coastlines as the extraordinary Equatorial Atlantic Warming in 2010, 2012, and 2021 with the 2019 events depicted as the warmest in the last 40 years, which has never been reported in this region, using both altimetric monthly Sea Level Anomalies (SLA) and Sea Surface Temperature (SST) Anomalies. Interannual SLA along the equatorial domain are systematically analyzed, and it is found that they advance the West African coastal ones by 1 month, supporting the idea that equatorial wave dynamics are responsible for their creation and the northward propagation observed on the SLA attributed mainly to the Kelvin coastal trapped waves. Because of sparse in situ measurements and societal stresses due to the undergoing rising sea level facts, improved coastal altimetry geophysical corrections will be of great benefit to address sub-seasonal variability.

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Assessment of Sentinel-6A Data in a Complex Macrotidal Semi-enclosed Sea (Pertuis Charentais, France)

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After almost two years of acquisition, the performances of the new Sentinel-6 Michael Freilich (S6A-MF) altimeter are assessed by comparing SAR and LRM observations in the coastal zone. The study focuses on the S6A-MF track 70 crossing the semi-enclosed sea of the Pertuis Charentais (France), a macrotidal region characterized by the presence of numerous reflective Islands, large mudflats, varied sea-states and fine-scale ocean dynamic patterns.

We start by comparing the waveform distributions and the data availability of SAR and LRM modes in the area. In particular, the impact of mudflats on altimeter measurements is investigated by reconstructing the morphology of the scene during each satellite passage, thanks to a Digital Elevation Model (DEM) and a hydrodynamic model. Then, the accuracy of S6A-MF 20 Hz data, processed with standard GDR correction parameters, are evaluated in the region ; 1) Sea Surface Height (SSH) measurements are compared to those from the permanent tide-gauge of Aix Island, integrating geoid slopes from independent local GNSS surveys (using marine USV and buoys, see companion poster) and fine-scale horizontal gradients of ocean dynamics from a high-resolution hydrodynamic model (Tranchant et al., 2021) ; 2) Significant Wave Height (SWH) are confronted to output data of a local implementation of a spectral wave model.

First, results evidence the improved capabilities of SAR altimetry in such nearshore area, compared to LRM: waveforms are significantly less impacted by coastal features and measurements are valid and accurate up to few hundred meters from the coast. In particular, using the standard GDR correction parameters leads to a remarkable consistency between altimetric and tide-gauge data, unprecedented for the region. For instance, the relative SSH bias is associated with a standard deviation of 44.2 mm, which is reduced to 35.3 mm when modeled fine-scale ocean dynamic gradients are corrected for. Regarding the SWH in the nearshore area, preliminary results show a strongly reduced dispersion of SAR 20 Hz measurements (to an order of magnitude), which are also more consistent with numerical results.

Finally, we discuss recently developed low-cost GNSS buoys which were deployed during two S6A-MF overflights (June and October 2022), offering punctual assessments of Sentinel-6A data (SSH and SWH) as well as instrumental perspectives on the future SWOT long-term calibration and validation.

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Chupin, C., Ballu, V., Testut, L., Tranchant, Y. T., Calzas, M., Poirier, E., ... & Team FOAM Project. (2020). Mapping sea surface height using new concepts of kinematic GNSS instruments. Remote Sensing, 12(16), 2656.

Tranchant, Y. T., Testut, L., Chupin, C., Ballu, V., & Bonnefond, P. (2021). Near-Coast Tide Model Validation Using GNSS Unmanned Surface Vehicle (USV), a Case Study in the Pertuis Charentais (France). Remote Sensing, 13(15), 2886.

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GNSS Survey for Geoid Mapping in a Macrotidal Sea Involving Marine USV, Buoys and Hydrodynamic Modeling (Pertuis Charentais, France)

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Reliable geoid gradients are essentials for high-resolution processing of altimetry data and cal/val activities (where tide gauges observations and satellite tracks are not collocated). However, the resolution of global geoid models is still inadequate to map short scale undulations, and current Mean Sea Surface (MSS) models suffer from large errors in coastal regions. Moreover, conventional cal/val methods have to be upgraded in the scope of future SWOT 2D high-resolution Sea Surface Height (SSH) observations. Consequently, there is a pressing need to extend spatially our knowledge of coastal geoid and external techniques are necessary for determining geoid slopes and validating existing models in the coastal zone.

New opportunities have emerged with the improvement of GNSS processing techniques and the development of new GNSS systems. Chupin et Al. (2020) have demonstrated the ability of the Cyclopée system (a combination of a GNSS antenna and an acoustic altimeter) mounted on a marine USV to map SSH in motion with a centimeter accuracy. In parallel, the development of “low cost” GNSS buoys with geodetic accuracy (Pira et al., 2021) offers considerable potential to spatially extend our monitoring capabilities through multiple deployments within survey domains.

Two GNSS surveys were conducted (June and October 2022) in the macrotidal sea of the Pertuis Charentais (France), involving the use of a marine USV equipped with the Cyclopée system and the deployment of GNSS buoys in the vicinity of SARAL/AltiKa and Sentinel-6A MF ground tracks. In contrast to other cal/val sites, the presence of fine-scale coastal processes (non-linear tides, currents) can induce large uncertainties in the geoid mapping, even over small extents. In order to accurately remove the contribution of Dynamic Topography (DT) in kinematic SSH measurements, we developed a methodology based on the combined use of in-situ SSH acquisition and high-resolution hydrodynamic modeling. While GNSS buoys measurements give the contribution of DT at fixed points, fine-scale SSH gradients are corrected for from a regional numerical model (Tranchant et al., 2021).

The gridded geoid solution is evaluated through 1) a comparison to existing MSS and geoid models, including CLS15 (CNES/CLS), DTU18 (DTU), EGM2008 (NGA) and RAF20 (IGN) ; 2) a statistical investigation of misfit with SARAL/AltiKa and S6A-MF along-track residuals in the survey domain. In particular, we discuss small wavelength discrepancies and their implications in terms of error budget associated with the future SWOT calibration and exploitation.

References :

Chupin, C., Ballu, V., Testut, L., Tranchant, Y. T., Calzas, M., Poirier, E., ... & Team FOAM Project. (2020). Mapping sea surface height using new concepts of kinematic GNSS instruments. Remote Sensing, 12(16), 2656.

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Sea-Level Change Along the Norwegian Coast Between 2003 and 2018 From Satellite Altimetry, Tide Gauges, Hydrography, and Satellite Gravimetry

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Sea-level variations in coastal areas can differ significantly from those in the nearby open ocean. Monitoring coastal sea-level variations is therefore crucial to understand how climate variability can affect the densely populated coastal regions of the globe.

In this study, we focus on the sea-level variability along the coast of Norway using tide gauges, satellite altimetry, a network of eight hydrographic stations, and two satellite gravimetry missions over a period spanning 16 years (from 2003 to 2018).

At first, we evaluate the performance of the ALES-reprocessed coastal altimetry dataset (1Hz posting rate) by comparing it with the sea-level anomaly from tide gauges over a range of timescales.

We later assess the steric contribution to the sea level along the Norwegian coast. While longer time series are necessary to evaluate the steric contribution to the sea-level trends, we find that the sea-level annual cycle is more affected by variations in temperature than in salinity and that both temperature and salinity give a comparable contribution to the detrended and deseasoned sea-level variability along the entire Norwegian coast.

To conclude, we exploit the synergy between the ALES-reprocessed satellite altimetry dataset, the hydrographic stations, and two satellite gravimetry missions (GRACE and GRACE-FO) to quantify the mass contribution to sea level in the region. Preliminary results indicate a good agreement between the different instruments on intra-annual timescales.

A tentative conclusion from our study is that coastal regions poorly covered by in-situ instruments can benefit from our satellite-based approach to monitor and study sea-level change.

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Coastal Sea Level Change Near Greenland and Implications for the Mean Dynamic Topography

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Geostrophic coastal currents can be studied through satellite altimetry by computing the mean dynamic topography (MDT) which is the difference between the mean sea surface (MSS) and the geoid. The geoid is often considered stationary, however, due to the melting of the Greenland ice sheet, Greenland is experiencing an uplift causing changes in the local gravity field. Near the coast of Greenland these changes are expected to cause a negative sea level rise, which until recently hasn't been observed in altimetry-derived sea surface heights. Altimetry observations are challenging in this area due to the presence of sea ice, and reduced data quality near the coast. Changes in the MDT are dominated by changes in MSS on the global scale. This study compares the modelled geoid changes locally around Greenland with altimetric sea level trend changes and investigates the contribution of geoid changes to changes in MDT. Our findings indicate that there is a correlation between changes in the geoid and the observed sea level change near Greenland. This implies that geoid changes also influence the MDT, which can introduce an error to the altimetry-derived geostrophic coastal currents normally deduced from the slope of the MDT.

My PhD work will include a quality analysis and possible enhancing of coastal altimetry in coastal regions, both with respect to the presence of sea ice as in the case around Greenland, but also the importance of coastal retracking. The PhD work will study and develop methods to determine hydrodynamically consistent MDT in coastal regions with a particular focus on evaluation of the changes in the MDT during the altimetry era with a special focus on Greenland and the North Atlantic.

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Benefits of coastal altimetry for empirical ocean tidal models

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Ocean tide models provide an altimetry correction which is important for accurate determinations of sea surface processes, particularly in providing reliable sea level trend estimates. Recent advancements in empirical tide models based on satellite altimetry data have resulted in a significant reduction in tidal estimations in the coastal regions. EOT20, an Empirical Ocean Tide model developed at DGFI-TUM, is the only ocean tide model that currently benefits from using coastal dedicated altimetry processing when making estimations of tidal constituents along the coastal regions. A major driver of the reduction in error provided in the EOT20 model is the use of the ALES retracker which allowed for the reliable retrieval of sea level data closer to the coast, which is vital for the residual harmonic analysis used to derive ocean tide estimates. Although the performance of EOT20 resulted in a significant jump in accuracy in the coastal region relative to previous model iterations, several avenues of development were identified for which the model could be further improved. In that context, this presentation presents regional developments made to the EOT model aimed at further advancing the estimation of several tidal constituents as well as the derival of constituents previously not included in empirical tidal atlas'. These model developments aim at improving the ocean tide correction for along-track satellite altimetry with a particular focus being on the advancement of our understanding in the coastal regions.

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Detecting Coastal Flow Reversals Over the Gulf of Cádiz Using Multi-mission Altimetry Data

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Understanding and monitoring coastal circulation and sea-level variability is essential for the management of coastal areas, in particular regarding activities with potentially high socio-economic and environmental impacts. These activities might be affected further by the current changing-climate scenario. In this context, one of the main challenges of coastal altimetry is to achieve accurate observations related to the sea level, sea state and winds the closest to land. Ocean variability over coastal areas is highly controlled by local agents, such as wind and bathymetry; therefore, each different area must be analysed considering its own geophysical features. In this study, we focused on the coastal circulation along the western part on the northern margin of the Gulf of Cádiz (southwest of the Iberian Peninsula). There, the coastal flow is mainly alongshore, alternating between eastward and westward, driven by a combination of wind and alongshore pressure gradients. The objective is to demonstrate how coastal altimetry allows monitoring the variability of the flow reversals along the coast by analyzing the Absolute Dynamic Topography (ADT) cross-shore gradients resulting from coastal upwelling/downwelling. For this aim, we compared coastal flow direction from ADCP data and ADT cross-shore gradient from Sentinel-3A/3B altimetry data. Several periods from 2017 to 2022 were analyzed, depending on the ADPC data availability. Results show a strong statistical relationship (two-tailed Fisher test with p-value = 0.001) that support the use of the altimetry data for the study of the coastal circulation over the area.

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Coastal Sea State Uncertainty From a Triple Collocation Analysis of Observations During the Sentinel-6 Michael Freilich – Jason-3 Tandem Phase Experiment

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The growing satellite record of sea state observations is becoming increasingly important for climate change research, to improve ocean and weather forecasts and to inform climate change mitigation and investment strategies. In this context, coastal processes and impacts are of particular concern, driving a yet stronger research imperative. The Copernicus Sentinel-6 Michael Freilich (S6-MF) mission was launched in November 2020 by the European Space Agency to succeed Jason-3 (J3) as the long term satellite altimetry reference mission. S6-MF commissioning involved a unique 12-month Tandem Experiment during which S6-MF flew approximately 30 seconds behind J3 on the same ground tracks, resulting in an unprecedented global dataset of quasi-simultaneous collocated altimeter sea state measurements in Low-Resolution Mode (LRM) and Synthetic Aperture Radar (SAR) mode.

In this work, this unique dataset is examined to evaluate uncertainties in altimeter significant wave height (Hs) observations from the two missions in different operating modes and different sea state conditions. A particular focus is placed on the evaluation of uncertainties in the coastal zone by exploiting the large number of moored buoys located near the coast of the U.S. S6-MF and J3 data are compared with buoy measurements and reanalysis data using, amongst other methods, triple collocation (TC) analysis. Results indicate that, over both global and coastal oceans, J3 and S6-MF Low-Resolution Hs are almost identical, with near-zero bias, low RMS difference and very high correlation. This very high correlation precludes the use of triple collocation to the J3/S6-MF-SAR/buoy triplets. Comparing S6-MF SAR with J3 LRM and buoys confirms the positive sea-state dependent bias in SAR Hs. Triple collocation of J3, S6-MF and buoys reveals the sensitivity of measurement uncertainty to collocation criteria, particular in coastal areas. Further, we show how sea state dependence of measurement uncertainty varies between oceanic and coastal settings. In general, we find that steeper spatial gradients of sea state typically associated with coastal regions can hamper interpretation of TC analyses without undue consideration. These findings demonstrate the value of the Tandem Experiment to evaluate uncertainty and provide evidence of the stability and/or enhancements of new mission data contributing to the growing satellite climate record.

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An ICESat-2-based Assessment of Coastal Sea-level Trends and Variability

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Satellite altimetry continues to revolutionize ocean science, enabling precise observations of geocentric sea level with near-global coverage. However, altimetry has traditionally been challenged in the coastal zone (within ~20 km of land) due to the presence of land in the altimeter and radiometer footprint. With the 2018 launch of the laser altimeter onboard ICESat-2, new high-resolution observations of sea level at the coast are available. Given the nominal across-track footprint of ~15 meters, and along-track adaptive sampling between ~90 m and 7 km, ICESat-2 has the potential to fill the coastal data gap.

Here we assess the potential benefits of sea level measurements from ICESat-2 by comparing them to data from overlapping reference altimetry missions (Jason-3 and Sentinel 6/Michael Freilich) and in-situ observations at coastal tide gauges. On a global scale, ICESat-2 measurements agree well with these independent observations. Along coastlines, ICESat-2 provides much denser coverage with respect to both reference altimetry missions and tide gauges, albeit with higher noise levels.

Given the various strengths and weaknesses of the three observational systems (radar, laser, and in-situ), we leverage all three to investigate sea-level trends and variability along global coastlines. We assess how trends vary from the coast to the open ocean as well as the alongshore gradient. Given the short time series of ICESat-2 relative to timescales of natural ocean variability, we use radar altimetry to provide context regarding the persistence of trends. We investigate physical drivers, such as atmospheric forcing, using correlation analysis along with dynamical theory. We particularly focus on regions of disagreement in the observational systems, such as the Chesapeake Bay (U.S. Atlantic Coast), in order to highlight how specific observations are better able to measure different coastal processes.

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Potential Applications of SWOT High-Resolution Sea Surface Height Observations to Studying the Coastal Impact of Sea Level Rise

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The SWOT (Surface Water and Ocean Topography) mission is a high-resolution altimetry mission to be launched in December 2022. It will utilize the technique of radar interferometry for making observations of water elevation over a finite swath, creating 2 dimensional observations over a swath of ~ 100 km wide at resolution of ~ 50 m over land surface waters and ~ 2 km over the ocean. The mission's main goals are to measure the elevation of water surface to study small-scale ocean circulation and water storage of lakes and stream flow of rivers. In the open ocean, the mission's data of sea surface height (SSH) will resolve ocean eddies and fronts at scales as small as ~ 15 km, which play an important role in the vertical transfer of heat, salt, and nutrients. In coastal oceans, especially in low-lying coastlines, estuaries and river deltas, the high-resolution SSH observations will be used to study the interaction of the open ocean with coastal waters and rivers upstream with potential applications to the study of the impact of sea level change to storm surge, saltwater intrusions, and coastal landform changes such as river diversion. This presentation will also provide information on the SWOT mission status and its science program.

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Ship-borne SSH measurements using GNSS-R

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Satellite altimeters are unique tools that measures global SSH distributions, but their nadir observations are insufficient for spatial and temporal scales of coastal SSH. Ship-borne GNSS is a practical candidate for providing height observations with small scales. We have deployed GNSS receivers on two ferryboats in the Tsushima Strait (from Hakata to Pusan) and across the Kuroshio (from Tokyo to Hachijo-Jima), respectively. From the observed height of the GNSS antenna, SSH is determined by subtracting the distance of the antenna from the sea surface, which depends on the ship draft. Although the ship draft would change depending on the load weight and the ship speed, it does not affect SSH variations within the Tsushima Strait, since we can regard it as a constant during a cruise. Meanwhile, the draft could spatially change across the Kuroshio, since the ship load may vary at ports of call. Therefore, in this study, we dare to use GNSS signals reflected at the sea surface as GNSS Reflectometry (GNSS-R). Since the reflected signals always delay from the direct signals, the height of the antenna from the sea surface can be determined by the delay. Sea surface dynamic height (SSDH) is then determined from SSH by removing geoid height, since ship routes are not exactly repeated even route-fixed ferryboats. After tides and ship motions because of waves are removed by harmonic analysis and temporal averaging, respectively, along-track SSDH profiles are obtained two times a day, which can describe small-scale variations of the Kuroshio, the Tsushima current, and adjacent eddies.

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Coastal-to-open Ocean Exchange Processes in the California Current System from altimetry, ADCP and HFR data

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In the California Current System, a key eastern boundary upwelling regime, exchanges between the coast and open ocean are modulated by small-scale transient eddy features. We assess the observability of these features by the Sentinel 6/Jason-CS, Jason-3, AltiKa, and Sentinel-3 missions. We compare SAR-mode altimetry with Ku and C-band altimeter data from the high-resolution retracked altimeter data released as part of the ALES product. These data are evaluated in the context of archived in situ observations from shipboard acoustic Doppler current profiler measurements and from on-board thermosalinograph, as well as of high-frequency radar (HFR) current measurements. Underway CTD observations along multiple transects across an eddy collected in the summer of 2020 allow a useful comparison of altimetric sea surface height with in situ steric height. The data are used to assess the scales of variability that dominate cross-shelf exchange and the mechanisms responsible for coastal-to-open ocean exchange. Both ADCP and HFR analyses indicate that divergent, ageostrophic motions account for roughly half of the variability of currents at scales shorter than 70-100 km. At these scales, the HFR frequency-wavenumber spectrum indicates that the internal tides account for no more than 20% of the variance. Preliminary assessments suggest that a large fraction of the sub-inertial currents are indeed eddies. Results from the steric height calculations, however, suggest that only the variability at scales longer than about 60 km are observable by this constellation of altimeters. We will attempt to quantify the contribution of these altimeter-derived geostrophic currents to the offshore transport of tracers.

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An assessment of conventional and retracked Sentinel-3 data with implications for an updated coastal mean sea surface with associated errors in Norway

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The coastal mean sea surface (MSS) is a key quantity in oceanography and geodesy. Upon subtraction of the geoid the mean dynamic topography is obtained (MDT), from which geostrophic surface currents may be inferred. Furthermore, the coastal MSS is instrumental for the transformation between vertical reference frames on land and on sea.

The present study concerns the determination of the NMBU22 coastal MSS model with associated errors in Norway. It is an updated version of the NMBU18 model, which was based on 7 years (2010-2017) of SAR(In) data from Sentinel-3A, CryoSat-2, as well as Ka-band data from SARAL/AltiKa. NMBU22 is augmented with CryoSat-2 and Sentinel-3A/B data, covering a time period from 2010 to 2021 inclusive. NMBU22 is determined using the data-interpolating variational analysis (DIVA) tool. DIVA is based on the variational inverse method ,which is equivalent to optimal interpolation methods, but with the notable advantages that coastal boundaries are taken into account and that its numerical cost is close to independent of the number of data points.

An essential part of the data preparatory step is the assessment of the Adaptive Leading Edge Subwaveform (ALES) dedicated coastal altimetry product, applied to Sentinel-3 data. The ALES retracker is specifically aimed at reducing land contamination. We assess the temporal and spatial variability of both conventional and retracked datasets in terms of sea-level anomalies and MDT by comparison to the Norwegian network of permanent tide gauges, as well as to an extensive set of temporary tide-gauge observations in selected coastal areas. Further, we include MDT output from the NorKyst800 numerical ocean model in our comparison. Implications of the results for the updated MSS are discussed.

Finally, we assess NMBU22 MSS by comparisons to NMBU18 MSS as well as to the official coastal MSS product of the Norwegian Mapping Authority, state-of-the-art global MSS models as well as NorKyst800.

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The Role of the Applied Science User Community in Advancing Coastal Applications from Satellite Altimetry Measurements

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The applied science user community is a key and expanding component of the thirty year satellite altimetry mission partnership between NASA, CNES and other U.S. and international space and operational agencies. These missions measure sea surface height, surface height on large lakes and rivers, significant ocean wave height, surface wind speed, and sea ice height and thickness. Significant investment in developing, launching and operating these missions, and the high value of resulting data and information products, provide a rich resource for operational agencies, commercial interests, as well as the research community. Current flight missions include Jason-3 and Sentinel 6 Michael Freilich (S6MF). Future missions in development, including SWOT with advanced technologic capabilities, and Sentinel 6B, will extend the continuous record of consistent, calibrated data into the next decade. Partner agency Applications programs to expand the use of data and information products beyond the mission science objectives are intended to engage existing and potential non-research users such as decision makers, operational agencies, coastal managers, and others, enabling practical coastal decision support applications for societal benefit.

Efforts are underway by satellite mission partners to advance knowledge and understanding of mission capabilities, increase awareness of the utility of satellite assets and to grow the user community. Existing and emerging applications enabled by these missions, particulary with new technologies in play, include weather event predictions (such as hurricane intensity forecasts), coastal impacts assessments (storm surge, coastal currents), fisheries management, marine transport, and disaster risk management related to sea level change and flooding (both coastal and inland), among many others. Additionally, inputs from users and early adopters of mission data can stimulate the improvement of mission systems, models, and data product development.

Coastal altimetry applications are an important focus of these missions as the interface between the open ocean and surface hydrology regimes. Both S6MF and SWOT will provide data much closer to the coast and at higher resolution than traditional altimeter satellites, enhancing, for example, model predictions of the impact of sea level rise. These impacts include flooding of coastal infrastructure and communities, coastal dynamics and sea level interactions, coastal currents and wave fields, storm surge research. With SWOT, impacts due to interactions between inland water discharge and coastal sea level within estuaries will additionally be assessed. This information can also support adaptation efforts for population centers near the coasts.

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Improving Wet Path Delay Measurement in the Coastal Zone with the High Resolution Microwave Radiometer (HRMR) on Sentinel-6

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Sentinel-6 has taken over as the newest reference altimeter mission. It includes the AMR-C microwave radiometer for providing the wet tropospheric path delay correction. The AMR-C includes two key evolutions from the radiometer on the Jason-3 mission. The first is a special blackbody calibration system that is viewed by the radiometer approximately every 5 days and promises multi-year stability of wet path delay at the sub-mm level. This, in part, will reduce uncertainty on the global mean sea level trend derived from the Sentinel-6 mission. The other improvement is the high-resolution microwave radiometer (HRMR) which is an experimental payload that provides cm-level path delay measurements within 5km from land. The HRMR is the subject of this presentation.

The HRMR is a three-frequency microwave radiometer operating at 90, 130 and 166 GHz. It shares the same 1m aperture with the low-frequency 18-34 GHz radiometer, giving a beam width ranging from 3-5km between the 90-166GHz bands. The HRMR is used to provide water vapor sensitivity in the region from 5-50km from land, when the low-frequency channels, and their larger footprints, become contaminated by the warm land emission.

The HRMR retrieval algorithm uses a first guess path delay from the low-frequency radiometer to locally linearize the retrieval algorithm. Then the coastal path delay is retrieved from the HRMR channels. A final step blends the AMR PD with the HRMR PD using knowledge of the error in each approaching land.

We will describe the algorithm and performance. The path delay retrieval is shown to be better than 1cm within 5km from land.

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Round Robin Assessment of altimetry algorithms for coastal sea surface height data

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Multidecadal efforts have made possible the current record of ocean sea surface height variations, 30-year long, provided by high-precision altimeter satellites. These observations have greatly improved our knowledge of the open ocean and are now an essential component of many operational marine systems and climate studies. It is not the case in the coastal ocean, where satellite altimetry encounters different issues that make it more difficult to derive accurate geophysical data. However, monitoring coastal sea level changes at global scale is now a critical need that the too rare in-situ data cannot fulfill. This has motivated many efforts to bring the sea level retrieval by satellite altimetry as close as possible to the shore. The result of these efforts is now the availability of many new algorithms for retracking radar altimeter data, correcting sea surface heights and finally deriving sea level variations.

The main objective of this study, initiated and funded by the French space agency (CNES), is to objectively define the best set of altimetry algorithms for computing sea level anomalies (SLA) in coastal zones. We focus on Low Resolution Mode altimetry and aim for the creation of long-term time series spanning different missions. For the different processing components (retrackers, geophysical corrections, and auxiliary parameters, for a total of 21 algorithms), the relative quality of the different solutions is assessed with clearly defined metrics for variability, data availability, and impact on SLA as a function of distance to the nearest coast. The analysis is made at both global and regional scales for 3 specific zones: the Mediterranean Sea, the North East Atlantic and the East Australian coasts. In the regions considered, a comparison against available tide gauge data is also performed. This methodology is applied to Jason-2 and Jason-3 missions, and we determine which algorithms are the most limiting, and how results vary from one mission to the other.

The set of best performing algorithms near the coast will finally be presented, with the criteria used for the selection. This set will constitute the baseline algorithms for the generation of a new global Level-3 SLA product, that will also be presented.

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Evaluation of Retracked Sea Levels from Jason-2 Altimetry in Halmahera Sea, Indonesia

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This study examined sea levels of Jason-2 from several retrackers (i.e. Ice, Threshold, Improved Threshold, Fuzzy Logic, ALES, Ice3, Oce3, and Red3). Four years and a quarter data, from February 2011 to May 2015, were assessed over complex Halmahera Sea, Indonesia, particularly within 20 km from the land. Over tested region, altimetry range parameter is critical due to the complex local morphology (e.g. bays, straits, and many small islands). The results showed that most of the applied retrackers offer higher (>85%) percentage of reliable sea level data than the standard Maximum Likelihood Estimator-4 (MLE4) retracker (66%). Retracked sea levels were also in reasonably good agreement with in-situ data (mean correlation < 0.75), compared to standard MLE4 (mean correlation of 0.47). The best performance was found at a distance 10 km from land, with the highest correlation of 0.97 (from Ice3) and the smallest RMSE of 13 cm (from Ice). Based on the findings, it could be concluded that retracked sea levels were superior to standard sea levels, and have high potential for use in related coastal studies at Halmahera Sea and elsewhere with similar water condition such as a complicated coastal topography of Indonesia.

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Virtual altimetry tide gauges for sea level monitoring in the Gulf of Guinea

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Africa's coastal areas are generally low-lying and vulnerable to many impacts of climate change, such as mean sea level rise. The objective of this study is to analyse whether the lack of in situ sea level observations in this region can be, at least to some extent, filled in by satellite altimetry. The latter now provides series of about 3 decades of accurate measurements. In addition, thanks to recent advances in processing and instruments, observations have become reliable up to a few kilometres from the coast. These data, covering almost all of the world's coastal regions and freely available, could be used for several types of applications, in addition to existing tide gauges. In this study, we use the high-resolution coastal altimeter product X-TRACK/ALES to measure the tide and the long-term sea level changes in the Gulf of Guinea. This product provides sea level time series along the altimeter tracks with a resolution of ~350m. In our study area, at each intersection between one track and the coast, we define a virtual tide gauge station by averaging the 20 altimeter data points closest to the land. The data obtained are compared with those of the in-situ tide gauges available in the region. We find that the series of sea level anomalies of the virtual stations are in agreement with those of the tide gauge stations (correlation values between 0.58 and 0.78, root mean square differences between 5.6 and 8.3 cm). The virtual stations reproduce the observed tide with errors less or equal to 6.64 cm (i.e. 6% of the total signal). Part of the differences in tides between the two datasets are related to the difference in position between the two datasets in regions where the spatial distribution of the tide is complex. With regard to long-term sea level monitoring, we find, within errors, the same sea level trend values between most of the virtual stations and the corresponding tide gauges. Finally, this analysis reveals the significant contribution that we can expect from altimetry in terms of coastal sea level monitoring in the study area. Moreover, further improvements of the results obtained appear clearly possible through a better definition of the altimetry data editing strategy.

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Coastal Altimetry Datasets Performance in Indonesian Seas

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The development of a coastal altimetry retracker reflects the importance of the coastal region as a vital part of society. These developments aimed to address the shortcomings of satellite altimetry on the coast. However, only a few extensive studies have been conducted to quantify the performance of the coastal retracker.

In this study, two coastal datasets over a period spanning 18 years (from 2002 to 2020) for conventional altimetry (X-TRACK/ALES and ALES) and two SAR altimetry datasets (SAMOSA+ and SAMOSA++) along with a reference dataset (CMEMS) are being evaluated with selected tide gauge stations in Indonesia, a region important for global ocean circulation. In order to ensure the comparability of these datasets, a harmonization in correction models, frequency of observation, and sea-level parametrization is performed. This study is among the first to utilize the in-situ data situated at Indonesian seas.

We find that all datasets performed similarly at 5 selected tide gauges in Indonesia with an average correlation coefficient value of 0.875. Looking into the performance of each coastal retracker, ALES performs better than X-TRACK/ALES in all 5 stations, using median absolute difference as a metric (~ 7 cm in average). SAMOSA++ also performs slightly better than SAMOSA+ at 5 tide gauge in terms of the standard deviation of difference (~11 cm in average). However, one should note that the CMEMS data has comparable performance with all coastal retrackers, although it gets worse as it goes closer to the coast. This could be attributed to the more rigorous filter and smoothing process that was conducted on the CMEMS dataset.

In order to paint a more conclusive picture, additional 39 tide gauges stations spanning 12 years (2010 to 2022) will be used to evaluate the performance of all datasets, which it will have a further implication to understand the efficacy of altimetry retracking schemes on the coastal zone less than 10 km.

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Estuarine water level change from high resolution altimetry

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Tidal rivers and coastal-to-land sites are mostly affected by climate changes and are at multi-risks due to coastline retreat, flooding storms and river floods. New altimeter processing and new missions open new possibilities to observe fine-scale spatial changes in these regions.
In the present study, we first consider the improvement in sea level change detection obtained from unfocused SAR (USAR) and fully focused techniques (FF-SAR) along the Sentinel-3 and Sentinel-6 tracks in the Elbe estuary and tidal river. We show that the high variability at fine spatial-scale along-track in coastal zone is detected at best with 80 Hz frequency data obtained from FF-SAR processing. The agreement with gauges is highly dependent on the hydrodynamics, which causes departures from in-situ measurements larger than 20-30 cm for the binned altimeter data along-track. The dense in-situ network allows also comparison with GNSS-R derived water level. These departures are larger than in open sea and inland water, mainly due to differential tide and short-scale variability. Due to this expected high variability, this study shows that it is mandatory to increase the resolution of altimetry data along track to perform an instantaneous comparison with in-situ data to derive the accuracy of the altimeters.
We show that results depend also on the retracking method used, we compare results of same retracking method for USAR and FFSAR. For USAR data, the SAMOSA+ retracker applied at 20 Hz gives the best results with comparable departure as FFSAR.

The ability of the ocean modelling to reproduce this high variability at fine spatial-scale is then investigated using two regional ocean models for the Elbe estuary and tidal river, the HzG and the BSH models. Also for the ocean models this is a challenging region. Departures between ocean model and in-situ data are mainly ascribed to the tides and are reduced using de-tided data. Ocean modelled sea level is compared to nadir-altimetry along the satellite ground tracks.

While the coverage of nadir-altimeter is limited by the number of ground-tracks, the future SWOT mission provides a uniform coverage. In the second part of this study we investigate using simulations the signal expected from the SWOT mission. For this, SWOT data of the 1-day repeat are simulated using the two ocean models as input to the SWOT simulators for ocean (JPL-ocean) and hydrology (CNES hydrology). De-tided and not de-tided ocean model input cases are considered. The first case is preferable to derive reach-averaged outputs, while the second can be used for lower level output which may account for the tidal component, challenging for the wide-swath mission. Different methodologies to study level change and river discharge in the tidal river ad estuary from future SWOT data are considered and compared. Due to the differences between along-track altimetry and swath-altimetry, new methods to derive accuracy and precision of the measurements are considered.

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Comparison Between Copernicus Sentinel-3B SRAL Altimetry and Tide Gauge Records in the Antarctic Coasts

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Sea level measurements are of great importance for establishing the reference level, and they can be obtained using conventional tide gauges and since the 90s, satellite altimetry. Sea level records in Antarctica are rare and expensive. Besides, most of the time they can only be obtained in summer due to the extreme weather conditions during the rest of the year and the formation of the sea ice. We present here one of the longest time series of sea level available in Antarctica. The study area is located in Livingston Island, which is part of the South Shetland Island chain. This archipelago forms the northern boundary of the Bransfield Strait and the Antarctic Peninsula forms the southern boundary. Time series of sea level are obtained from pressure sensors and altimetry data. The oceanographic station is deployed off the coast of Johnson Cove, a remote location in Livingston Island (62°39'38.70"S; 60°22'11.62"W). As for the altimetry time series, the data used are from Copernicus Sentinel-3B (S3B) repository available in the ESA Earth Console Parallel Processing Service (P-PRO) (former GPOD). We used a crossover point between two S3B tracks (relative ascending orbit #0374 and descending #0109) near the tide gauge station (about 15 km). Data span about 3 years of continuous measurements (from November 2018 to December 2021). In-situ sea level data were obtained every 20 minutes with some gaps. Both time series are referred to the GRS80 ellipsoid enabling an absolute comparison. This work expands the concept of coastal altimetry to Antarctica, where very little information is available in terms of sea level measurements.

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New Advances in Altimetry Towards the Coast :

Example of the CTOH Coastal Sea Level Products

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Through different projects, the Center for Topographic studies for the Ocean and Hydrosphere (CTOH) contributes largely to advances in coastal altimetry and to its use in coastal applications. It has developed the X-TRACK software dedicated to the reprocessing of coastal altimetry data. X-TRACK is now a mature sea level product distributed worldwide by AVISO+ (https://www.aviso.altimetry.fr), cited in many scientific publications. It consists in long time-series of SLA from most altimetry missions, processed homogeneously, but also as long-track empirical tidal constants. The latter provides independent synoptic data on the coastal ocean for tidal studies, validation of tidal models or assimilation into tidal models.

In order to continue provide the most complete sea level datasets to coastal users, the CNES L2P Product (https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/along-track-sea-level-
anomalies-l2p.html) is now integrated into the X-TRACK processing chain: 12 altimetry missions, covering the 1992-2021 time period.

The CTOH contributes also, trought the high performance of X-TRACK software, to the development of new coastal sea level products specifically designed for climate studies, in close collaboration with ESA, TUM, CLS, NOC and SKYMAT. As part of the ESA Climate Change Initiative project, the Adaptive Leading Edge Subwaveform (ALES) Retracker (Passaro et al., 2014) and the X-TRACK software (Birol et al., 2017), previously validated and successfully applied to coastal sea level research, have been combined for the first time, in order to reprocess 18 years of sea level anomaly data (Jan. 2002 to Jan 2020) at a high frequency level (20 Hz) based on Jason missions. This new coastal sea level product called X-TRACK/ALES (https://climate.esa.int/en/projects/sea-level/data/) significantly extends the spatial coverage of sea level altimetry data in the coastal direction, now reaching a distance of 1.2-4 km from the coast on average (Birol et al., 2021). This is an unprecedented coastal coverage for any long-term altimetry data set, and then a significant contribution to the coastal research community. In addition, a new network of virtual altimetry-based stations in coastal areas of the world has also been derived from this dataset, providing new information on sea level change in the world coastal zones.

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Development of regional high-resolution hydrodynamic models in estuarian regions: the Seine and Elbe cases.

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Estuaries are generally complex and highly dynamical regions where river and ocean water masses meet, resulting in a mix of various processes, such as river flow, ocean tide, storm surges and local sea level variations. The interactions between the ocean flow and the river flow can produce distortions in the high-frequency variations of the water level measured in estuarian regions, especially in areas strongly influenced by ocean tides. In this context, hydrodynamic models are essential to remove the aliased high-frequency dynamical signals due to the ocean tide and storm surge from the satellite altimetry measurements over estuarine regions, in order to obtain high quality data.

In the frame of several projects (e.g. ST3TART) funded by the European Space Agency (ESA) and the French Space Agency (CNES), we developed high-resolution hydrodynamic model configurations with tide gauge data constraint, in order to simulate the interactions between the river flow and the ocean dynamics in the Seine (France) and Elbe (Germany) estuaries. This work built on the knowledge and experience gained from the previous works performed in the Seine and Gironde estuaries by the SWOT Science Team in the context of the preparation of the SWOT altimetry mission. This study was carried out with the aim to find the best model configuration and identify potential sources of uncertainties in order to provide accurate water surface elevations for the calibration and validation, or the correction, of satellite altimetry water surface height observations (e.g. Sentinel-3 and SWOT) in these areas. In this paper, we present the main results of the accuracy tests and model outputs validation that we performed using in-situ and satellite data with the aim to assess the model performance.

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Sentinel-6 : SAR improvements over LRM in the coastal zone

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Satellite altimetry is the tool of choice for monitoring sea-level rise. With accurate and continuous measurements of the global ocean for over 30 years, this technology is of utmost importance in a context of climate change, and more so when assessing environmental changes in the coastal zones.

The Sentinel-6 Michael Freilich altimetry mission extends the long series of satellite altimetry data of the Jason missions, and is the first mission that comprises both an historical nadir instrument operating in low-resolution mode (LRM) and a new Synthetic Aperture Radar (SAR), measuring the sea surface simultaneously. These double measurements are of utmost importance for enabling instrument bias assessment for ensuring continuity when transitioning from one instrument to the other and thus linking the new SAR technology with historical LRM altimetry records.

We use statistical analysis of along-track time series at both local and regional scales, geostrophic currents and machine learning techniques to assess the differences between LRM and SAR modes in the coastal zones. We confirm here that the continuity of the data is largely ensured by Sentinel-6 and that the SAR measurement performance (data availability, correlation with tide gauges) compared to the conventional mode in coastal areas is about 20% better in coastal areas. Clustering techniques show us the conditions of shoreline, bathymetry and neighbouring topography under which these improvements are more easily seen.

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Evaluating the new HRMR wet tropospheric correction from Sentinel-6MF over coastal regions

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The Sentinel-6 Michael Freilich (S6MF) satellite carries the Advanced Microwave Radiometer for Climate (AMR-C), with channels at 18.7, 23.8 and 34 GHz. Compared to the previous reference missions, this instrument further contains a High-Resolution Microwave Radiometer (HRMR) with channels at 90, 130 and 166 GHz, providing enhanced measurements of atmospheric parameters and better spatial resolution in coastal zones. The current S6MF products in baseline F07 provide two different wet tropospheric corrections (WTC): amr_wet_tropo, computed from AMR measurements alone, and rad_wet_tropo, computed from combination of AMR and HRMR measurements.
Building upon this new correction, this study aims at inspecting the differences between the two provided WTC and evaluating the actual impact of the HRMR in the computation of the WTC over coastal regions. The study is composed of three main parts: 1) assessment of the availability of each WTC; 2) analysis of the differences between them, function of distance to the coast; and 3) evaluation of these differences when compared with independent data, e.g., from GNSS coastal stations.
For this task, S6MF Climate-quality AMR Level 2 NTC (Non-Time Critical) Products, at 20 Hz, from EUMETSAT Data Centre have been used, available since 15 August 2022 (S6MF cycle 65, Pass 21), corresponding to the beginning of the F07 ground processor.
Regarding the availability of the WTC computed with a combination of AMR and HRMR over coastal zones (coastal processing), the data analysis shows that, on average, 25% of the rad_wet_tropo estimates are derived only with AMR data, which means that the remaining 75% of the S6MF coastal measurements consider HRMR data.
Concerning the differences between the two provided corrections (amr_wet_tropo versus rad_wet_tropo), the global differences are small (RMS of 0.1 cm), with a maximum RMS value of 0.9 cm for distances to the coast in the range 25-30 km. For distances to the coast smaller than 15 km or larger than 100 km, this RMS is 0.3 cm.
Additionally, an independent comparison with GNSS-derived WTC is being performed. This is a non-collocated comparison, between GNSS-derived WTC, at each station location and reduced to the sea level, and the S6MF-derived WTC at the location of each along-track measurement, in the vicinity of each GNSS station. This comparison reveals that, for distances from coast in the range 0-5 km, the two S6MF-derived corrections are not significantly different, and for distances to the coast in the range 5-20 km the correction with HRMR shows an improvement, when compared to the corresponding correction using only AMR data. Moreover, a small land contamination can still be observed in both corrections, up to about 25 km from the coast.
This independent assessment of reinforces the previous inter-comparison, showing that the most significant impact of including the HRMR holds for distances to the coast ranging from 5 to 20 km. This confirms the improved performance of the new S6MF WTC, mainly at coastal transitions, due to the better spatial resolution provided by the HRMR.

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SWOT early flight data status and plan for data product release

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The Surface Water and Ocean Topography (SWOT) mission aims to provide valuable data and information about the world's oceans and its terrestrial surface water such as lakes, rivers, and wetlands. SWOT is being developed jointly by NASA and Centre National D'Etudes Spatiales (CNES), with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency (UKSA). The mission is targeted for launch on Dec, 12th 2022 and is expected to make a revolution on our understanding of ocean, inland waters and coastal regions.

SWOT will indeed measure ocean surface topography and land surface water elevation with great accuracy, using inter-ferometry to achieve two-dimensional mapping for the very first time. In addition, SWOT will provide sigma0 maps at 250 m resolutions that will provide very valuable information to better understand the impact of local roughness variability on the nadir altimeter data. SWOT will also enable high resolution monitoring of coastal regions, including coastal currents, storm surges, and regional sea level change using the HR data mode.

During this presentation, we will provide early information on the actual SWOT flight operations and foreseen data products availability.

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BARRIER-LAGOON COASTS OF THE SVALBARD ARCHIPELAGO – 85 YEARS OF COASTLINE CHANGES (1936-2021)

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Due to climate warming the landscape of the Svalbard Archipelago is changing. New land is being revealed from under retreating glaciers; sediments and water released from the glaciers are creating new paraglacial forms. The extent of sea ice is decreasing - thus its protective role is diminishing, and coasts are exposed to erosion by waves and wind for longer periods of time.
Barrier-lagoon coasts, being directly under the influence of these dynamic changes, are a great predictor for describing the rates and processes that control the coasts around the Svalbard Archipelago. Here we present the first GIS-based inventory of the shoreline changes using multi-temporal satellite and aerial images. We used a Digital Shoreline Analysis System (DSAS) to identify and measure historical (1936-2021) changes in the coastline. Particular attention was paid on the formation of new spits which have turned into lagoons and on erosion of barriers leading to opening of coastal lagoon lakes. We analyzed coastal lagoons and discussed the role of storm events in the evolution of Arctic coasts.
We suspect that the supply of sediment from the glaciers and the still largely sea ice-protected coasts of northeast part of Svalbard are thus protected from erosion and extreme events creating conditions for coastal progradation. On contrary to the western part of Svalbard, where the warm West Spitsbergen Current occures, the climate is milder, and the longer open water season in autumn during storm season can lead to increased coastal erosion.

Keywords: DSAS, barrier-lagoon coasts, coastal evolution, Arctic, remote sensing.

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Toward Higher resolution Level-3 altimeter sea level products

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In 1998, first Level3 along-track, user friendly altimeter products have been developed with support from CNES and delivered to the users on AVISO+. The Level3 processing includes a homogenization of the SLA for the different altimeters (i.e. reduction of the global and regional biases), allowing the users to directly use the products without any pre-processing. They are widely used for different applications, including assimilation in numerical models. Since 2008, such products are generated and disseminated by the Copernicus Marine Service (CMEMS; previously MyOcean during its demonstration phase).
Since few years, efforts are done in order to improve the altimeter measurement in open ocean and coastal area. While the observation of the small mesoscale signal remains a challenge for the conventional altimeter measurement, new techniques and processing allow to significantly reduce the measurement errors and noises. Additionally, with the future altimeter missions as the large swath SWOT mission, the altimeter processing will face a new challenge be able to accurately process the signal at finer spatial scales.
A new generation of along-track products is under development with support from CNES (DUACS-RD project) and ESA (EO4SIBS project). They are derived from high resolution (20Hz) altimeter measurement and are specifically processed in order to solve finer scales up than the conventional 1Hz product and better sample the coastal areas. They merge recent developments that enable to optimize the Sentinel3 SAR altimeter processing (Boy 2017, Moreau,2018) and the Jason/Altika noise level (Zaron 2016, Tran 2019) and allow us to better exploit the fine-scale content of the altimetric missions. They also take into account improvements that are also done in geophysical corrections estimation (e.g. internal tide model [Zaron 2018]) and local Mean Sea Surface Estimation (e.g. Dibarboure et Pujol, 2019). Different experimental/samples datasets, with a nearly 1km (5Hz) sampling, are already available on AVISO+ (https://www.aviso.altimetry.fr/duacs), CMEMS (https://marine.copernicus.eu/). and EO4SIBS (http://www.eo4sibs.uliege.be/). They can be tested by users. New samples are also under preparation.
Additionally, an operational L3 5Hz production will start in CMEMS from late November 2022. We will present these experimental & operational 5Hz products.

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Integrating satellite altimetry, tide gauge and GPS data for regional sea level studies

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The relationship between satellite altimetry (SA) derived absolute sea level change rates and tide gauge (TG) observations of relative sea level change is essentially a local one, i.e. varies from point to point and from TG to TG. It has been investigated previously in littoral zones of the Mediterranean basin [Fenoglio-Mark, L., 2002; Fenoglio-Mark et al., 2012]. Other studies made use also of global positioning system (GPS) measurements of vertical land motion (VLM) in addition to TG and SA data [Rocco F.V., 2015; Zerbini et al., 2017], but the use of the first two measurement systems (SA and TG) is not synergistic with the GPS, as the latter is used only as a means of comparison. Moreover, Vignudelli et al., [2018] highlighted the difficulty of deriving spatially-consistent information on the sea level rates at regional scales. The paucity of collocated TG-GPS data and the lack of a well-established mathematical frame in which simultaneous and optimal solutions can be derived, have emphasized the difficulty of deriving spatially-consistent information on the sea level rates.
Earlier, a few authors dealt with the possibility to set locally isolated information into a coherent regional framework, using a constrained linear inverse problem approach [Kuo et al., 2004; Wöppelmann and Marcos, 2012], but the solution was valid only for regions of homogeneous (i.e. the same everywhere) absolute sea level rise (ASLR). The latter limitation has been recently removed by De Biasio et al. [2020]. A step in advance is now to develop an effective synergistic use of global positioning system (GPS) data, tide gauge measurements and satellite altimetry observations.
In this study GPS data are used as a real source of information on the relative VLM between pairs of TG and the absolute VLM of one of the TG, and not as mere term of comparison. Long, consistent and collocated tide gauge and GPS observations time series are extracted for a handful of suitable coastal locations in the Mediterranean Sea, and used in the original formulation of the constrained linear inverse problem, together with satellite altimetry data. Some experiments are conducted without GPS observations (traditional setup), and with GPS observations (the new proposed approach) Results are compared in order to assess the impact of GPS observations directly into the formulation of the constrained linear inverse problem.

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Towards validation of SWOT and new coastal processing algorithms: An altimetry and water level gauge case study in the Bristol Channel and Severn Estuary area.

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The Bristol Channel and Severn Estuary system is highly dynamic with one of the largest tidal ranges in the world. The varied coastline around these waters is well covered by a network of water level gauges (WLGs). This makes it an ideal area to test new algorithms in the coastal zone, for existing sensors, and for the validation of new sensors such as SWOT. The SWOT-UK and HYDROCOASTAL projects are using this area for these purposes.

For the SWOT-UK project a large dataset of WLG, CryoSat-2 and Sentinel-3 data are being gathered to validate water level and sea surface slope during the SWOT 90-day daily repeat cal-val mission phase. Additional in-situ instruments will be used to fill in gaps in the existing network. Satellite altimetry data have been compared with coastal WLGs as a quality assessment. Problems with the Sea State Bias correction in shallow waters and the effects of intertidal areas have been found. Looking at the slope along the satellite passes (across-channel), near-shore coastal dynamics and intertidal morphology have been seen to affect the comparison of the satellite and WLGs. These data will be used to develop a validation scheme for the 2D SWOT altimetry data, to determine the quality of the data in coastal and estuarine settings. This will highlight issues of how the coastal dynamics and morphology affect the comparison of the satellite and WLGs and how these features may be seen in the 2D SWOT data.

HYDROCOASTAL is an ESA funded project to explore both SAR and SARin altimeter measurements in the coastal zone and inland waters. In addition, optical data from Sentinel-2 MSI and Sentinel-3 OLCI instruments are used to produce river discharge products, in order to create new algorithms and evaluate their potential. The outcome of this project will enable a processing scheme to be used to create a global coastal zone and river discharge data set. The focus of HYDROCOASTAL in this region is to investigate SAR altimeter measurements in the coastal zone from new processing algorithms for CryoSat-2 and Sentinel-3. The WLG validation data will be used to assess these new altimeter measurements.

The results of a preliminary assessment of the WLG, CryoSat 2 and Sentinel 3 data will be presented. Followed by an exploration of effect of coastal dynamics and morphology on these data.

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Mapping Elevation and Elevation Changes in the German Coastal Zone

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The Federal Agency for Cartography and Geodesy (BKG) is the central service provider of topographic data, cartography, and geodetic reference systems for the German government. As the marine sector is constantly gaining importance, e.g. for the transport of goods or energy security, precise geodetic information become more and more important. In this context, BKG uses satellite altimetry to map and monitor the sea surface heights of the North and the Baltic Sea. In order to calibrate and validate the satellite observations, we performed measurements on the offshore research platform FINO2 as well as on two shipborne field campaigns during 2021 and 2022. In order to improve the spatial and temporal resolution of the altimetry data, we combine the altimetry observations with the output of a regional ocean model from Leibniz Institute for Baltic Sea Research (IOW). Here we present the first results of these activities and our strategy of combining satellite altimetry with different other observation techniques of sea level changes and land uplift to map and monitor elevation and elevation changes in the German coastal zone.

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Contribution of CryoSat-2, multi-mission synergies and AI methods to observe coastal current intrusions over the North-Western Mediterranean Sea

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For more than 30 years, satellite altimetry has been widely used to observe Sea Level Anomalies (SLA) associated to large scale ocean dynamics over the open ocean. The accuracy and precision of measurements have significantly progressed during the last 15 years thanks to advances in coastal-oriented data processing methods and the introduction of new measurement techniques from Ka-band (e.g. SARAL/AltiKa) and delay-doppler altimetry (aka SAR altimetry). SAR technology enable to characterize and monitor finer scale features closer to the coast compared to conventional pulse-limited altimeters. The ESA CryoSat-2 mission, initially developed for cryosphere applications, operates mainly in SAR closed-burst mode over the North-Western Mediterranean Sea. This is also the case of the Copernicus Sentinel-3 topography mission. The Mediterranean Sea is an area characterized by complex coastal and mesoscale dynamics, monitored by multi-sensor in situ instruments. This makes it a region with a high potential for altimetry coastal studies. In this respect, Casella et al. (2020) developed a random forest algorithm using conventional observations from Jason-2 and SARAL/AltiKa to characterize the frequency and intensity of intrusions of the Mediterranean Northern Current into the Gulf of Lion. We propose here to extend the Casella's approach by including new observations from Jason-3 as well as from Sentinel-3 and CryoSat-2 SAR altimetry missions. We first inter-compare the different datasets and focus our analysis on along-track data to assess the added-value of exploiting high resolution measurements. These datasets show a quite good agreement and complementarity, enabling to retrieve the general North-Western Mediterranean Sea circulation and mesoscale dynamics. Following this first step, the random forest algorithm is then applied to Jason-3, Sentinel-3 and adapt to the non-repetitive CryoSat-2 orbit to better observe coastal current intrusions over the Gulf of Lion. Meanwhile SWOT, this method will also be tested with the Copernicus Sentinel-6 data which are expected to provide the best quality data in coastal areas thanks to open-burst SAR acquisitions.

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Ocean waves observation from space: complementary approach from nadir, CFOSAT-SWIM and SAR wave mode systems.

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CFOSAT mission enables to access 2 types of data with complementarity skills to characterize waves near coasts. An optimal 1km resolution (5Hz) nadir estimation along track and a off nadir spectral content with a 70km/90km resolution.
The first type of product (nadir 5Hz) also exists for other missions (Jason-3, HY2B, CFOSAT and Altika) as demo product over 2021 (Aviso and CMEMS). It was shown to increase by 20% the number of valid data at less than 50km from the coasts notably inside lagoons, in all sea state conditions.
The second type of product (spectral) has a coarser resolution but provides a unique characterization of different types of sea states (directional swell or wind sea). Hence, this is complementary to Sentinel-1 wave mode which only gives swell information, only in weak winds conditions and often far from coasts (due to the wave mode mask).
The physical content of those products will be illustrated on some significant use cases.

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CryoSat: Mission Status and Future Challenges over the Coastal Zones

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CryoSat-2 was launched almost thirteen years ago and was the first European mission dedicated to the cryosphere with the objectives to monitor precise changes in the thickness of polar ice sheets and floating sea ice. The satellite carries the first Synthetic Aperture Interferometric Altimeter (SIRAL) which still remains one of the most innovative altimeters in space. Going beyond its ice monitoring objectives, CryoSat-2 has also demonstrated to provide a valuable source of observations over multiple surfaces, including the coastal ocean. Numerous CryoSat-based studies have been carried out over the last decade to optimize SAR/SARIN coastal processing algorithms. These innovations have been transposed into an operational framework to generate new thematic products so-called “Cryo-TEMPO Coastal Ocean”. The mission is expected to be extended until the end of 2025 with the scope to achieve new important objectives, to extend the synergy with other missions and integration into ocean models as well as to secure a unique long-term climate record at high latitude. One of main challenges for CryoSat is to better characterise small-scale variations and trends of sea ice thickness and sea level variations over the coastal polar domains, especially by exploiting its unique SARin capability. Scope of this paper is to describe the current mission status, show its main achievements and present future R&D challenges over the coastal zones. We will also provide an overview of recent product evolutions and new science results which are paving the way for the development of the CRISTAL Sentinel Expansion mission.

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The Cryo-TEMPO Coastal Ocean Thematic Data Product: a CryoSat-2 Regional Product for Ocean Applications

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Although primarily a cryosphere mission, CryoSat-2 has provided over a decade of key altimetry observations across a diverse range of scientific domains. The CryoSat-2 altimeter was a precursor of the development of Delay Doppler processing (the so called "SAR mode") for ocean applications. Compared to traditional nadir altimeters, SAR mode observations are characterized by a much smaller footprint, and hence higher along-track resolution, as well as reduced noise level. Over the oceans, these characteristics allows a more detailed representation of smaller structures (<100 km), as well as improved data coverage and precision closer to the coast. Despite these advantages, CryoSat-2 ocean observations remain somehow underutilized in the oceanography community.

The overarching aim of the Cryo-TEMPO project is to develop agile, robust and state-of-the-art CryoSat-2 Products, dedicated to specific Thematic Areas, and accessible to a broad range of users. The main goal of the Cryo-TEMPO Coastal Ocean Thematic Data Product (TDP) is to maximize the potential of CryoSat-2 observations over the ocean by implementing an ocean-specific processing chain based on the best performing methods and algorithms for coastal applications. These include, among others: the SAMOSA+ retracker, high-frequency adjustment (HFA) correction, iterative data editing, dedicated sea state bias (SSB) correction as well as regional mean dynamic topography (MDT) and tides. Cryo-TEMPO sea level anomalies are distributed with an associated transparent and traceable uncertainty.

The latest Cryo-TEMPO Coastal Ocean TDP is based on the official CryoSat-2 GOP baseline-C level1-b SAR and low resolution mode (LRM) observations over the Mediterranean and Black Sea region. The Coastal Ocean TDP spans from the beginning of the mission to present, with new observations processed and added to the database on a monthly basis. The second version of the product is currently available at the Cryo-TEMPO web portal (http://www.cpom.ucl.ac.uk/cryotempo/index.php?theme=coastaloceans). The data are also distributed and freely accessible via the ESA Cryosat science server (https://earth.esa.int/eogateway/missions/cryosat/data). Evolutions for the third version of the product will include an extension of the domain over the North Atlantic Ocean and the inclusion of CryoSat-2 SARIn observations along with SAR and LRM.

The current version of the product has been compared to the official GOP baseline-C products. Our results show that the Cryo-TEMPO Coastal Ocean TDP is characterized by lower variance (especially in the LRM regions of the domain), indicating improved accuracy. The largest impacts are from the SSB and HFA corrections, as well as from the iterative editing. The dataset was also compared with in-situ observations. These include tide gauges sea-level records from the western Mediterranean and surface velocities from the SOCIB HF-radar in the Balearic Sea. Comparison with the tide gauges SLA indicates a good consistency with the Cryo-TEMPO data. Correlations are in line with those previously reported for Sentinel-3A and Jason-3 (although with larger root mean square error). Comparison between satellite-based across-track geostrophic currents and those from HF radar also shows good consistency. With errors smaller than previously reported in the same region for the Saral-Altika altimeter.

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Analysis of Sea Level Variability in German Bight and Baltic Sea by Using Fully-Focused and Unfocused SAR Altimeter Products and GNSS Reflectometry

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Coastal zones are among the environments most affected and are multi-risk due to coastline retreat and pollution. Accurate knowledge of water heights is of major importance to analyze and understand drivers of sea level change and to plan coastal protection measures. Furthermore, it is still difficult to estimate ocean tides in coastal areas, and ocean tide errors continue to play an important role in correcting measured ranges from satellite altimetry.

In this study we evaluate the state of the art and dedicated coastal retrackers for Unfocused SAR (USAR) and FFSAR processing. The validation activities focus on the German Bight and Baltic Sea coastal region.

The project HYDROCOASTAL brings together coastal and inland water zone measurements from USAR altimetry. Several retrackers, dedicated to one or both zones are applied to CryoSat-2 and Sentinel-3A/B altimeter data. The University of Bonn contributes to the Hydrocoastal project with enhanced retracking and validation efforts. Additionally products available in EarthConsole are considered.

Although unfocused SAR altimetry processing provides improved results compared to conventional altimetry (CA), fully focused SAR(FFSAR) processing offers an improved along track resolution until 0.5 m. GNSS Reflectometry(GNSS-R) is additionally used for measuring the sea level change.

A cross-validation analysis of the SAR altimeter products is performed against GNSS-R data and tide gauge data. The study presents and discusses the validation results. The resulting statistics in terms of accuracy and precision are compared in few cases with the statistics output from the in-house validation strategy matrix.

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The relationship of Mean Sea Level Anomalies and Extreme Water Levels along the European Coasts

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Coastal flooding is a major natural hazard leading to large social, economic and environmental impacts. The understanding of the extreme total water levels and derived impact on coastal areas is crucial for preparedness and mitigate present and future coastal risk intensified in densely populated coastal areas. This work analysed 23 years (1993-2016) of multimission radar altimetry along with European coastal flooding database to investigate the role of mean sea level (MSL) contribution on the extreme total water levels in the European coastlines. Semi enclosed basins and micro tidal areas (Black Sea, Baltic and Mediterranean Sea) showed that monthly MSL contribution was even larger than astronomical tide and similar to the meteorological tide. In meso and macro tidal areas (North Atlantic and Bay of Biscay), the MSL contribution is lower than 20%, with the exception of the North Sea (>30%). The Baltic Sea is characterized by a positive significant correlation (r~0.7) between the annual cycle of MSL and the coastal flood event registered in the storm impact database. The positive MSL anomalies shows also a positive correlation (>95% of statistical significance) in the Central Mediterranean, North Atlantic, North Sea and Baltic Sea that expand to the Bay of Biscay and N-North Atlantic at >90% of the statistical significance.

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Comparison of in-situ measurements with satellite altimetry data and GLORYS reanalysis outputs in the Patagonia continental shelf along 44.7°S

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The Patagonia continental shelf is a vast region within the Southwestern Atlantic Ocean that is known for its high primary production rates and, consequently, for the wide biological diversity present there. In this study, we analyze in-situ measurements at 3 locations of the Patagonia continental shelf along 44.7°S, at 32, 150 and 378 km from the coast, respectively. The mooring closest to the coast provided one year of bottom pressure measurements with a temporal resolution of 2 minutes. The other two moorings provided 5 months and 18 months of zonal and meridional velocities recorded by upward-looking ADCPs, with a temporal resolution of 30 minutes. We conducted a comparison of these in-situ time series with satellite altimetry products and with the GLORYS global eddy-resolving physical ocean and sea ice reanalysis at 1/12° horizontal resolution that assimilates satellite altimetry data. Results show that GLORYS reanalysis reproduces better the SLA and the geostrophic velocities than the gridded satellite altimetry product in the analyzed section. The pressure time series retrieved at 32 km from the coast was highly correlated to GLORYS SLA (0.9 at a 95% confidence level), while the correlation with the gridded satellite product is much lower (0.4 at a 95% confidence level). Similar results were found when comparing the in-situ barotropic velocities to the satellite and the reanalysis velocities. Both data sets reproduce better the meridional velocity than the zonal velocity. These results suggest that GLORYS reanalysis reproduces better the frequencies lower than seasonal than the gridded satellite product. In fact, using GLORYS reanalysis intra-seasonal SLA, we were able to identify fast waves that propagate northward in the Patagonia continental shelf, traveling around 2000 km in 4 days, and that modulate the along-shore circulation in the section analyzed along 44.7°S.

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Towards a better knowledge of the coastal breezes in the Gulf of Cádiz: some advances from observations and models

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Coastal breezes are thermally driven flows formed in mid-latitude regions under fair-weather synoptic conditions. Under these situations, the thermal gradient between the sea and the ocean becomes important and produces onshore winds during daytime and offshore during the night. The impacts of these winds are broad and varied: they transport humidity, pollutants, and other physical properties in the coastal region; they can initiate convection (and even trigger the formation of storms), and they also drive the surface oceanic currents formed close to the coast, among others. From a societal point of view, the coastal breezes are crucial for wind power industry, air-quality forecasts, maritime sports, and simply for the refreshing impact that they cause in some warm areas in summer. Hence, a correct understanding of their physical characteristics is needed to correctly forecast them and to be able to investigate their future trends.

In this work, we present an observational analysis of the costal breezes in the Gulf of Cádiz, highlighting how the interaction with the background synoptic wind is very important for the final characteristics that the breezes have. The study includes observations from measurements obtained close to the sea but also using the mesoscale Weather Research and Forecasting (WRF) model. The findings from this work draw attention to the potential benefits that reliable altimetry wind data in coastal areas would have to improve the model evaluation and to increase the knowledge of these processes in marine regions with very scarce observational data.

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Validation and Use of Altimetry Products in the Southwestern Atlantic Continental Shelf

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The main objective of this work is to review the effort made by the group Southern Ocean PHYsical oceanograAphy (SOPHYA) from University of Buenos Aires to validate along track and gridded altimetry products and study the dynamics of sea level at different temporal scales on the Southwestern Atlantic Continental Shelf (SWACS), one of the largest shelves in the Southern Hemisphere.
Considering that the SWACS is characterized by large tide amplitudes, it is crucial to correct the altimetry data with an accurate tide model. This work has been done, obtaining that FES2014 is the best model on the mid-shelf, shelf-break and North of 42°S. In the estuary of the Río de la Plata, the main source of fresh water on the SWACS, the tide global models did not resolve adequately the 5 leading tide components and a regional model was needed. In this region, the wind influences the sea level, especially at sub-annual scales, and the Dynamic Atmospheric Correction (DAC) was also investigated. The main result was that the global model represents the spatial distribution but underestimated the values, especially in the upper estuary.
The gridded altimetry product was validated with tide gauges from PSMSL at annual scale along the coasts and used to analyze the seasonal cycle and long-term trends. The seasonal sea level in the SWACS is dominated by the density changes due to solar radiation, except north of 36°S where the wind variability is more important. Moreover, the seasonal sea level pattern derived from altimetry displays a cross-shore gradient that explains the seasonal geostrophic currents observed, being maximum in austral autumn and minimum in austral spring. On the SWACS, the sea level trend estimated with CMEMS and ESA_CCI products is 2.95 and 2.85 mm/yr (1993-2015), respectively and is dominated by the mass changes. The spatial pattern is almost homogeneous that it might indicate that the geostrophic currents are not changing.
Part of the effort to use altimetry in the study region was to deploy instruments under Jason tracks. A bottom pressure recorder was moored at 1.3 km from the nominal intersection of two tracks and 0.9 km from the coast. The results from the comparison between in situ and satellite data show that satellite data is more reliable using ALES retracking and tide model TPX08 as close as 4km from de coast. In addition, two bottom-mounted upward looking ADCPs were moored on the Jason-2 track #26 and two along 44.7°S. The velocity time series allowed to calculate the geostrophic transport and compared with altimetry in the north portion of SWACS obtaining high correlation at time scales longer than 20 days. It was also studied the interannual sea level variability and its geostrophic transport, observing that the wind in relation with Southern Annular Mode (SAM) is the main forcing. A similar analysis was done at 44.7°S. The region presents a barotropic circulation dominated by the meridional wind stress. In addition, the outer shelf is affected by an intra-seasonal signal that the gridded product cannot resolve.

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SAR, SARin, RDSAR and FF-SAR Altimetry Processing on Demand for Cryosat-2, Sentinel-3 & Sentinel-6 at ESA's Altimetry Virtual Lab

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The scope of this presentation is to provide an update on the ESA radar altimetry services portfolio for the exploitation of CryoSat-2 (CS-2), Sentinel-3 (S-3) and Sentinel-6 data from L1A (FBR) data products up to SAR/SARin L2 geophysical data products. At present, the following on-line & on-demand services compose the portfolio:

- The ESA-ESRIN SARvatore (SAR Versatile Altimetric TOolkit for Research & Exploitation) for CS-2 and S-3 services. These processor prototypes allow the users to customize the processing at L1b & L2 by setting a list of configurable options, including those not available in the operational processing chains (e.g., SAMOSA+/++ and ALES+ SAR retrackers).

- The ESA SAMPY for CryoSat-2 service. It allows the users to append the output of the SAMOSA+ retracker to official CryoSat-2 Level-2 GOP products. The retracker has been developed within the ESA Cryo-TEMPO project and is also available open source on GitHub at https://github.com/cls-obsnadir-dev/SAMPy.

- The TUDaBo SAR-RDSAR (TU Darmstadt – U Bonn SAR-Reduced SAR) for CS-2 and S-3 service. It allows users to generate reduced SAR, unfocused SAR & LRMC data. Several configurable L1b & L2 processing options and retrackers (BMLE3, SINC2, TALES, SINCS, SINCS OV) are available.

- The TU München ALES+ SAR for CS-2 and S-3 service. It allows users to process official L1b data and produces L2 products by applying the empirical ALES+ SAR subwaveform retracker, including a dedicated SSB solution.

- The Aresys FF-SAR (Fully-Focused SAR) for CS-2 & S-3 service. It provides the capability to produce L1b products with several configurable options and with the possibility of appending the ALES+ FFSAR output to the L1b products.

In the future, these services will be extended and the following new services will be made available: the Aresys FF-SAR service for Sentinel-6, the CLS SMAP S-3 FF-SAR processor (https://github.com/cls-obsnadir-dev/SMAP-FFSAR) and the ESA-ESTEC/isardSAT L1 Sentinel-6 Ground Prototype Processor.

All output data products are generated in standard netCDF format and are therefore also compatible with the multi-mission "Broadview Radar Altimetry Toolbox" (BRAT, http://www.altimetry.info).

The SARvatore Services have been migrated from the ESA G-POD (https://gpod.eo.esa.int/) to the Altimetry Virtual Lab, a community space for simplified services access and knowledge-sharing. It is hosted on EarthConsole (https://earthconsole.eu), a powerful EO data processing platform now also on the ESA

Network of Resources. This enables SARvatore Services to remain open for worldwide scientific applications (info at altimetry.info@esa.int).

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The BRAT and GUT Couple: Broadview Radar Altimetry and GOCE User Toolboxes

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The Broadview Radar Altimetry Toolbox (BRAT) is a collection of tools designed to facilitate the processing of radar altimetry data from all previous and current altimetry missions up to Sentinel-3 L1 and L2 products. A tutorial is included providing plenty of use cases on Geodesy & Geophysics, Oceanography, Coastal Zone, Atmosphere, Wind & Waves, Hydrology, Land, Ice and Climate. The Radar Altimetry Tutorial (RAT) can be consulted and downloaded at http://www.altimetry.info/radar-altimetry-tutorial/.

BRAT's last version (4.2.1) was released in June 2018. Based on the community feedback, the front-end has been improved and simplified. The capability to use BRAT in conjunction with MATLAB/IDL or C/C++/Python/Fortran, allowing users to obtain desired data bypassing the data-formatting hassle, remains unchanged. Several kinds of computations can be done within BRAT involving the combination of data fields, that can be saved for future use, either by using embedded formulas including those from oceanographic altimetry, or by implementing ad-hoc Python modules created by users to meet their needs. BRAT can also be used to quickly visualise data, or to translate data into other formats, e.g. from NetCDF to raster images.

The GOCE User Toolbox (GUT) is a compilation of tools for the use and the analysis of GOCE gravity field models. It facilitates using, viewing and post-processing GOCE L2 data and allows gravity field data, in conjunction and consistently with any other auxiliary data set, to be pre-processed by beginners in gravity field processing, for oceanographic, hydrologic and solid earth applications at both regional and global scales. Hence, GUT facilitates the extensive use of data acquired by the GRACE and GOCE missions.

In the current version (3.2), GUT has been outfitted with a graphical user interface allowing users to visually program data processing workflows. Further enhancements aiming at facilitating the use of gradients, the anisotropic diffusive filtering, and the computation of Bouguer and isostatic gravity anomalies have been introduced. Packaged with GUT is also GUT's Variance/Covariance Matrix (VCM) tool, which enables non-experts to compute and study, with relative ease, the formal errors of quantities – such as geoid height, gravity anomaly/disturbance, radial gravity gradient, vertical deflections – that may be derived from the GOCE gravity models.

In our continuous endeavour to provide better and more useful tools, we intend to develop synergies between BRAT and SNAP (the Sentinel Application Platform). This will allow our users to easily explore all the Sentinel data together. Any User or Space Agency are welcome to contribute to the evolution or the BRAT and GUT couple, especially in the preparation of future Altimetric and Gravity Missions.

BRAT and GUT toolboxes can be freely downloaded, along with text and video tutorials, ancillary material, auxiliary data and source code, at https://earth.esa.int/brat and https://earth.esa.int/gut.

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A Satellite Altimetry-Based Calibration of the Nearshore Wave Model SWAN and Assessment of Spectral Wave Climate in the Black and Azov Seas

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Detailed knowledge of the spectral wave climate is often necessary for all scientific and engineering applications in coastal and offshore areas. Currently, The long-term wave climate is evaluated by different studies and at different sea locations around the words. In the Black and Azov sea and several other regions, the wave climate is primarily assessed based on bulk wave parameters as the significant wave height and mean period. Nevertheless, these bulk parameters do not provide a reliable understanding of the wave characteristics in the case of combined seas in which the waves are multi-modal (spectra with several peaks). Furthermore, the used wave models are often not calibrated based on wave measurements. The rare calibrated models depend on buoy measurement's location, and their accuracy in areas in gaps of buoy measurements is unknown.
For an accurate assessment of the long-term spectral wave climate, the use of ocean observation data provided by satellites, radars and buoys can not be sufficient. Those data cover a short period and are also limited in time and space resolution. Due to those limitations, the only way for a detailed spatial assessment of the long-term spectral wave climate is the use of the spectral wave model. Thus, the only way to calibrate and evaluate the wave models' accuracy in the location where the buoy measurements are not available is using satellite altimetry observation as an ideal alternative; Noting that only studies based on the wave spectrum can describe complex sea state and provides a comprehensive representation of the existing wind and swell wave combinations. In the present study we present a detailed approach to ensure an accurate assessment of the spectral wave climate at spatial scales. The proposed method can be summarized in 4 main bases. The first base consists of the spatial calibration of the simulation wave nearshore model SWAN based on observations from seven altimetry satellites (Jason-3, Sentinel-3A, Sentinel-3B, Cryosat-2, SARAL/AltiKa, CFOSAT, and Hai Yang-2B). The second base consists of the validation and an uncertainty assessment of the calibrated model in estimating the directional spectral wave data in terms of wave frequency, energy, and direction. In the third base, we perform a spectral partitioning of the simulated directional wave spectra. Finally, we investigate the long-term spectral wave climate in the fourth base considering all the individual wave systems. The results show that the satellite altimeter observation significantly improved the default SWAN model at the spatial scale and for the whole sea domain. Thus, the calibration of the model reduced the underestimation of the total energy spectra in coastal locations without impacting the variance density distribution shape as a function of frequency and directions. The calibrated model allowed the development of the 42 years of spectral wave databases, which were statistically processed to set a detailed understanding of the spectral wave climate regime in the study area.
This study is a part of the project supported by The Scientific and Technological Research Council of Turkey (number 119N480) and the Russian Foundation for Basic Research (number 20–55–46007).

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Sea level along the world's coastlines can be measured by a network of virtual altimetry stations

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In the context of the ESA CCI Coastal Sea Level project, we have recently performed a complete reprocessing of high resolution (20 Hz, i.e., 350m) along-track altimetry data of the Jason-1, Jason-2 and Jason-3 missions over January 2002 to January 2020 along the coastal zones of Northeast Atlantic, Mediterranean Sea, whole African continent, North Indian Ocean, Asia, Australia and America. This reprocessing has provided valid sea level data in the 0-15 km band from the coast. A total of 750+ altimetry-based virtual coastal stations have been selected and sea level anomalies time series together with associated coastal sea level trends have been computed over the 2002-2020 time span. These virtual stations offer a unique tool for estimating sea level change close to the coast (typically up to 3 km to the coast but in many instances up to 1 km or even closer), especially in the coastal regions devoid from tide gauges. Results show that at about 90% of the virtual stations, the rate of sea level rise at the coast is similar to the rate offshore (15+ km away from the coast). In the remaining 10%, the sea level rate within 4-5 km from the coast is either faster or slower than offshore. In this presentation, we focus on a few coastal sites where the rate of sea level rise differs from that offshore. We discuss potential small-scale coastal processes (e.g., changes in shelf currents, waves, fresh water input from river runoff in deltas and estuaries, etc.) able to explain the observations. We also present preliminary comparisons of altimetry-based coastal sea level with outputs of a high-resolution oceanographic coastal model in the Golfe of Tonkin.

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ALBATROSS: Improving the bathymetry and ocean tide knowledge in the Southern Ocean with satellite observations

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The knowledge about bathymetry and ocean tides is at the crossroads of many scientific fields, especially in the Polar regions, as it has significant impact on the understanding of the coupled dynamical response of the ocean, sea ice and ice shelves system, as well as on the accuracy of ocean and ice parameters derived from satellite measurements. Tides in the Southern Ocean strongly influence the whole global ocean, and accurate and complete bathymetry information is crucial for tidal modelling, in particular under the Antarctic ice shelves.

The ALBATROSS project (ALtimetry for BAthymetry and Tide Retrievals for the Southern Ocean, Sea ice and ice Shelves), led by NOVELTIS in collaboration with DTU Space, NPI and UCL, is funded by the European Space Agency in the frame of the Polar Science Cluster in the EO4Society Programme, with the objective to foster collaborative research and interdisciplinary networking within polar Earth Observation.

ALBATROSS is a 2-year project (2021-2023) with several objectives: First, to improve the knowledge on bathymetry around Antarctica, considering decade-long reprocessed CryoSat-2 datasets, innovative information on bathymetry gradient location through the analysis of sea ice surface roughness characteristics, and the compilation of the best available bathymetry, ice draft, coastline and grounding line datasets in ice-shelf regions. Second, to improve the knowledge on ocean tides in the Southern Ocean through the implementation of a high-resolution hydrodynamic model based on the most advanced developments in ocean tide modelling, including data assimilation of satellite-altimetry tidal retrievals computed from the most recent and relevant satellite altimetry products to fill the gap between the 66°S-limited coverage of the Topex-Jason suite missions and the Antarctica coast.

This paper presents the most recent results obtained within the ALBATROSS project.

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Assessment of Coastal Changes in Tuktoyaktuk Peninsula (Canada) using Remote Sensing: General Framework

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The average rate of coastal change in the Arctic Ocean is -0.5 m/yr, despite significant local and regional variations, with large areas well above -3 m/yr. Recent data suggest an acceleration of coastal retreat due to the shorter sea ice season, higher storminess, warmer ocean waters and sea-level rise. Coastal permafrost makes the transition zone between Arctic landmasses and a seasonal and increasingly vulnerable coastal ecosystem. It is crucial to understand the linkage between the inland and nearshore zones, providing information on coastal processes and their climatic and biogeochemical, marine ecosystem and socio-economic impacts. The Tuktoyaktuk Peninsula (NWT, Canada) is a hotspot of shoreline retreat and an area with complex coastal dynamics. In this poster, we present the main framework of a PhD dissertation which aims to identify the shoreline evolution trends, controls, processes, dynamics and specific impacts in this sensitive region. The work will involve different remote sensing data and techniques, complemented by field observations, monitoring and modelling data, which will allow us to analyze and identify the factors driving coastal dynamics from 1950 to 2022. The study of detailed areas will validate the assessment of the controlling factors through the synergistic use of SAR, ICESat-2 Laser altimetry, UAS and field data. Specifically, Sentinel 1 SAR C-Band imagery will be used for D-InSAR analysis identifying terrain deformation and aiming at monitoring subsidence and IceSat2 LiDAR data will be used as a complementary tool to assess subsidence and coastal changes. It will also aim to identify the distinct roles of erosion, submersion and aggradation and their impacts on coastal dynamics and their implications for carbon and sediment fluxes.
This research contributes to the NUNATARYUK project funded by the European Union's Horizon 2020 Research and Innovation Program under grant agreement no. 773421 and from the Climate Change Preparedness in the North Program (Government of Canada).

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Dual-band altimetry from the Copernicus CRISTAL mission: its capabilities for coastal altimetry

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Within the expansion of the Copernicus Sentinel Constellation, the Copernicus polaR Ice and Snow Topography Altimeter (CRISTAL) mission is being developed as a key contribution to Europe's planned response to the need for monitoring of the polar regions. CRISTAL will fly to 88° latitude ensuring an almost complete coverage of the Arctic Ocean, as well as of the Antarctic ice sheet (like CryoSat-2, which is currently in its extended mission phase). CRISTAL's primary objective is to monitor the cryosphere (sea ice and its snow loading, land ice including glaciers) but the novel altimeter on board, called IRIS (Interferometric Radar Altimeter for Ice and Snow) is also expected to contribute significantly to oceanography and hydrology. IRIS will feature a dual Ku/Ka band SAR altimeter which is interferometric on the Ku channel, the first instrument of this kind in space and expected to enable enhanced measurement capabilities.

In this contribution we will discuss in detail the features that make IRIS on CRISTAL a very suitable instrument for coastal altimetry. First of all the simultaneous dual-band Ku/Ka approach with increased chirp bandwidth (500 Mhz) will allow enhanced range precision and this, combined with the SAR altimeter footprint, will also benefit the observations in the coastal zone. The interferometric capability of the Ku channel will allow the determination of sea level over complex coastal areas, as demonstrated with CryoSat-2. The simultaneous availability of Ku and Ka observation is also expected to facilitate the investigation of surface roughness-related effects, like the sea state bias.

For the CRISTAL mission, EUMETSAT is entrusted to operate the marine data centre generating operational global ocean products: ocean, coastal and SSH into the leads and over large lakes (e.g. Great Lakes). In this contribution we will also present EUMETSAT's preparatory activities and development plans to provide CRISTAL coastal thematic processing to the coastal community.

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A phase error in Sentinel-3 Individual Echoes, and

how to correct the error in post processing

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Vignudelli et al. [On Assessing the Performances of Sentinel-3 Radar Altimetry in Sheltered Coastal Regions: Case-Study of the Grado-Marano Lagoon System in the Northern Adriatic Sea], (in this conference) alludes to a phase error in Sentinel-3 Ku SRAL IQ data. This poster explains how this was discovered, where it comes from, and how the phase error can be corrected in post processing.

The phase error was first noticed with specular echoes from the salar de Uyuni (reference Abileah and Vignudelli 2021). A specular echo should have a discreet beat frequency. Equivalently, there should be a constant phase change in the 128 fast time IQ samples. But instead of a constant, the phase change is as shown in the Figure. (For plotting the mean is set to zero.) Satellites 3A (Figure 1) and 3B (Figure 2) are similar with the notable difference in the 'bump' at sample index 35.

This U-shaped phase error has been subsequently observed in several other locations – in day and night, and in northern and southern hemispheres. And the 3A-3B difference is also consistent from location to location. Furthermore, it is the same for every IE, regardless of echo position within a burst.

Whatever the cause, the error is easily corrected in post processing. A table of 128 phase shifts is derived from averaging thousands of IEs in a pass over salar d' Uyuni. A separate table exists for 3A and 3B. Each IE is phase corrected before the IQ data is used in further processing (e.g., with PISA, Delayed-Doppler, Fully-Focused SAR).

At the time of writing this abstract the effect of phase corrections on altimetry products (e.g., range) is under investigation. The poster will report the latest findings.

Abileah, R. and Vignudelli, S., doi:10.1016/j.rse.2021.112580

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On Assessing the Performances of Sentinel-3 Radar Altimetry in Sheltered Coastal Regions: Case-Study of the Grado-Marano Lagoon System in the Northern Adriatic Sea

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Sea level is an issue at the boundary line with land. It represents a potential threat to infrastructures and population living in low-elevation coastal areas. A slow rise of the sea level of few cm would make a difference to the land-sea interface, as present regional sea level trends associated to climate change are positive almost everywhere around the world (Wang et al., 2021): the sea would not retreat from land, making the land permanently lost. The satellite radar altimetry is the only measuring system capable of observing sea level changes independent of land. Unfortunately, using the classical open ocean altimetry sea level products, the number of valid data strongly decrease within 10–15 km from the coast, making those products not usable at land-sea interface. However, in the last years, there has been growing interest in improving the quality of altimeter data close to the coast. Considerable research has been carried out into overcoming to uncertainties in corrections and complexity of radar return and extending the capabilities of radar altimeters to measure sea level changes as close as possible to the coast. On average, the closest distance to the coast with valid sea level has been stated 3.5 km (Cazenave et al., 2022). Modern altimetry is now bringing new opportunities to extend the coverage to sheltered coastal regions. The availability of individual echoes stimulated the implementation of new processors (e.g., Delay-Doppler, PISA, Fully-Focused SAR, etc.). The burst-repetition frequency of Sentinel-3 enhances along track data at 80 Hz (i.e. every 89 m).
In this study we use high-resolution radar ranges that are estimated with two methods: 1) the Precise Inland Surface Altimetry (PISA) algorithm (Abileah and Vignudelli, 2021) and 2) the ESA GPOD/Earth Console® Altimetry service, using the default “Inland Water High product Resolution”. Radar range from PISA is corrected for a quadratic phase error in receiver window (also called U function phase error in fast time) that is explained in accompanying poster titled “A phase error in Sentinel-3 Individual Echoes, and how to correct the error in post processing”. We propose a new approach to identify bursts in sheltered coastal regions (e.g., coastal lagoons). This approach is based on Radar Cross Section (RCS) classification in specular, quasi-specular and non-specular behaviour. The idea is that specular surfaces have much higher signal-to-noise ratio than Brownian surfaces, therefore, retrieving more precise ranges. We use independent observations from the ICESat-2 lidar and from the Grado tide gauge to support the interpretation of the results.
The study area is the Grado-Marano Lagoon (Northern Adriatic Sea), which is an interesting laboratory where the continuum from sea to inland can be analysed, also in virtue of the favourable location of two Sentinel-3 altimeter tracks (and a Sentinel-6 track) as well as the availability of corroborative in-situ observations from a number of instruments, including tide gauges, wave and wind recorders that offer clear advantages for comparison and interpretation purposes.

Wang, J., Church, J.A., Zhang, X. et al., doi:10.1038/s41467-021-21265-6
Abileah, R. and Vignudelli, S., doi:10.1016/j.rse.2021.112580
Cazenave et al., doi:10.1038/s43247-022-00448-z

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Sea Level Variability at Several Time Scales in The Cuban Archipelago

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This paper characterizes the variability of the synoptic scale non-regular component of sea level related to extreme meteorological events, as well as sea level seasonality, monthly anomalies and long-term trend, from data series obtained at 15 stations of the National Tidal Network of Cuba, through numerical, statistical and spectral filtering methods, taking into account IOC manuals and guidelines. The synoptic maxima of the variations of sea level meteorological component are identified, which are located mainly at 0.22 CPD. The coefficients and spectral regression equation are determined from coastal and oceanic meteorological data. The mean annual cycle and characteristics of monthly sea level anomalies and the factors that generate them, mainly related to the occurrence of ENSO events, are determined, highlighting the events of increase in monthly mean values and remarkable alterations of the annual cycle with respect to the mean annual cycle. Long-term mean sea level trend in Cuba is determined, pointing out the existence of its acceleration since 2004.

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Joint Estimates of Coastal Sea-Level Trend and Vertical Land Motion in the Northern Gulf of Mexico

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The knowledge gap of exact vertical motion at tide gauges limits the quantification of geocentric sea-level variations and the corresponding land motion, which is insensitive to satellite altimetry. Here, we update an algorithm to reconstruct regional sea-level variations (dominant climate models and sea-level trends), separating the vertical motion at tide gauge locations in the northern Gulf of Mexico in the United States conflating over 100 years to tide gauge and 3 decades of satellite altimetry data. The reconstructed sea-level trends and the jointly estimated vertical land motion at tide gauge sties are then validated by independent measurements, including GPS land motion, and tide gauge sea-level records not used in the adjustment.

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Altimetry Marine Products at EUMETSAT: towards operational coastal products

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In view of the progress made by coastal altimetry methodologies and taking advantage of the capabilities of the SRAL and P4 altimeters on board of the Sentinel-3 and Sentinel-6 Missions operated by EUMETSAT, tailored coastal products are in the roadmap of evolutions at EUMETSAT. These products have been requested by the user community, operational and with latencies similar to the current Marine products. Different solutions are being considered and different studies will take place in 2023 to ensure that a solution compatible with an operational processing chain will be available in 2024.
In this presentation, we will be presenting EUMETSAT's roadmap activities and development plans to provide operationally the coastal user-community with consolidated coastal thematic processing based on Sentinel-3 and Sentinel-6 altimetry missions and on state-of-art coastal altimetry algorithms within the timeliness and performance expected by the coastal community.

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DUACS DT-2021 Reprocessed Altimetry Improves The Sea Level Retrieval In The Coastal Band Of The European Seas

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On December 2021, more than 29 years of Level-3 (L3) and Level-4 (L4) altimetry products were reprocessed, released and made freely available for users as the "DT-2021" version of the multi-satellite Data Unification and Altimeter Combination System (DUACS) products by the European Copernicus Program substituting the former "DT-2018". Currently, two types of altimetric L4 gridded products generated by the DUACS production system are available: the so called all satellite gridded products disseminated via the Copernicus Marine Service (CMEMS) project; and the two satellite gridded products distributed via the Copernicus Climate Change Service (C3S) project. The all satellite products are dedicated to the retrieval of mesoscale signals whereas the two satellite ones are dedicated to monitoring the long-term evolution of sea level, thus being suitable for using in climate applications.

In the latest release, new up-to-date standards have been applied and various geophysical correction parameters have been updated compared to the previous DT-2018 version in order to improve the product quality. The validation (quality check) of altimetry products is a key step in the data processing pipe to assess and characterise the errors associated with the altimetry measurements. This issue is crucial in the coastal zone. Different metrics are used to assess the quality of altimetry data. They mainly consist in the analysis of the SLA field at different step of the processing; check consistency of the SLA along the tracks of different altimeters and between gridded and along-track products; and comparisons with external in-situ measurements. In coastal areas, tide gauge measurements are commonly used.

This work focuses on improvements of the latest reprocessing of DUACS Delayed Time (DT) reanalysis in the retrieval of sea level in the coastal band of the European Seas with respect to the previously available reprocessed products. To do that, we conduct an inter-comparison of L4 global altimetry gridded products and in-situ tide gauges located along the European coasts from the Copernicus catalogue. The performance of the DT2021 processing all satellite and two satellite versions on the sea level retrieval is also assessed. The results confirmed that the DT2021 processing version better solves the signal in the coastal band. Compared to the previous DT2018 version, we obtained reductions in errors with tide gauges of 3%; and in the variance of the differences between the datasets of 5% for the all satellite dataset. Also, the number of valid data pairs used to conduct the inter-comparisons enhanced by 0.1% when using the DT2021 processing. This highlights the impact of the new DUACS DT2021 version on the coastal areas, that provides more valid measurements, located closer to the tide gauge sites, compared to DT2018 reprocessing.

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Ocean state reconstructions through remote-sensing, in-situ sparse observations and Deep Learning

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Artificial intelligence (AI) has grown significantly in recent years and is revolutionizing the field of data processing. In this work, we used a Deep Learning approach based on a Convolutional Neural Network (NN) to combine remote-sensing images: Chlorophyll, Sea Surface Temperature (SST), Sea Surface Height (SSH), and sparse in-situ observations to estimate the 3D state of the ocean. In the context of satellite oceanography, end-to-end architecture AI schemes are already available for space-time interpolation and short-term forecasting (Fablet et al., 2021). However, with the inclusion of in-situ observations, a further step towards comprehending/reconstructing 3D small-scale phenomena is possible. Studying the small features of the ocean is fundamental for understanding the vertical transport of nutrients and pollutants in a climate-change environment. We obtained significant improvements compared to the classical Optimal Interpolation scheme performing different Observing System Simulation Experiments (OSSE) based on realistic ocean model outputs. Finally, we explored the possible application in coastal scenarios through Sentinel-3 remote-sensing field

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Evaluation of CESat-2 ALT13 Inland Water Surface Height over Dez and Karkheh Dams

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Monitoring inland water levels is crucial for understanding hydrological processes to climate change impact leading to policy implementation. Accurate and detailed information on lake/reservoir water levels and temporal changes is required for water resource management and related studies. Also the inland water bodies such as reservoirs, lakes and rivers are important source of fresh water which is very important resource for the survival. So the monitoring of these resources also becomes one of the important task. Remote sensing altimetry has proved to be an excellent technique and very useful technology to precisely measure water levels of rivers, lakes, sea water and other inland water bodies. Although the Advanced Topographic Laser Altimeter System (ATLAS) onboard the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was primarily designed for glacier and sea-ice measurement, it can also be applied to monitor lake surface height by using ATLAS-13. ICESat-2 laser satellite has a very high ability to measure the thickness of polar snows, the height level of sea water and land, lakes, the height of forest trees and vegetation. ICESat-2 ATL13 products provide observations of inland water surface heights, which are suitable for water level estimation at a large scale. The atlas-13 product of ICESat-2 space-borne LiDAR. Here, we report an accuracy evaluation of the ICESat-2 laser altimetry data over two reservoirs in southwest of Iran using gauge data. The main goal of this research is to evaluate the accuracy of measuring the height of the water level of lakes using satellite altimetry ICESat-2 data. The water surface heights were derived from ICESat-2's strong beams data were analyzed and evaluated with the reservoir gauge observations of water level of Dez and Karkheh dam's lakes which located in the north of Khuzestan, Iran during 2018 to 2021. Statistical measurements were used to understand the agreement (R2= 0.99) among the datasets. An R2 value of 0.99 was observed between ICESat-2 derived water level and the reservoir gauge observations in both lakes. The results show that the ICESAT-2 satellite measures the water level of the lakes with very high accuracy.

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Estimating Greenland Ice Sheet melt with coastal altimetery

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We present a novel application of satellite altimetry to monitor ocean temperatures on the continental shelf around the Greenland Ice Sheet with the goal of better understanding past and better predicting future sea-level rise. Mass loss from the Greenland Ice Sheet is now responsible for about 20% of the total annual increase in global mean sea-level, a dramatic increase from the 1970's, 80's and 90's when the mass balance of the ice sheet was in a state of near equilibrium. About half of present-day ice sheet mass loss is due to enhanced surface runoff while the other half is due to glacier dynamics, mainly enhanced ice discharge by Greenland's more than 200 marine-terminating glaciers. Recent work has linked the interannual variability of Greenland's marine terminating glaciers to subsurface ocean temperature variability, specifically the temperatures of the relatively dense, warm and salty waters of subtropical origin (Atlantic Water) that control the intensity of submarine melt occurring along the ocean/glacier interface. Our preliminary analysis of satellite altimetry data in combination with a multi-year record of in-situ ocean data in the vicinity of Jakobshavn Glacier in Central West Greenland suggests that satellite altimetry data can indeed be used to infer Atlantic Water temperatures on Greenland's continental shelf. In particular, the thermal expansion set by interannual subsurface temperature variations induce sea-level variations of several centimeters, a signal which can be observed in an adequately-processed near-coastal multi-instrument satellite altimetry dataset. Prospects and requirements for employing satellite altimetry to monitor ocean temperatures in different sectors around Greenland will also be discussed.