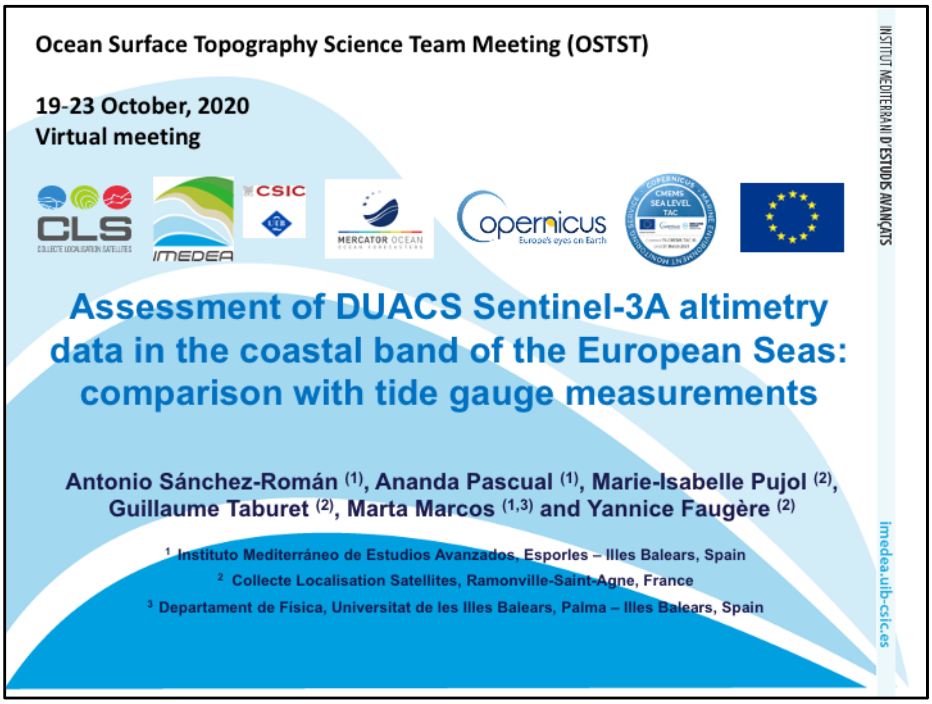


In this work we present an assessment of CMEMS/DUACS along-track (Level-3) altimeter regional operational products in the European Seas using in-situ tide gauges from the Copernicus Marine Environment Monitoring Service (CMEMS) catalogue. **The aim is to validate Sentinel-3A SAR mode SLAs against the equivalent in-situ tide gauge measurements.** To perform such assessment, 6-hour time series of tide gauge measurements will be compared with 1 Hz along-track altimetry data from the Sentinel-3A satellite mission. This inter-comparison has been also conducted by using SLA from Jason-3 satellite mission in order to investigate the improvements of Sentinel-3A mission over the latter in the coastal band.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Introduction

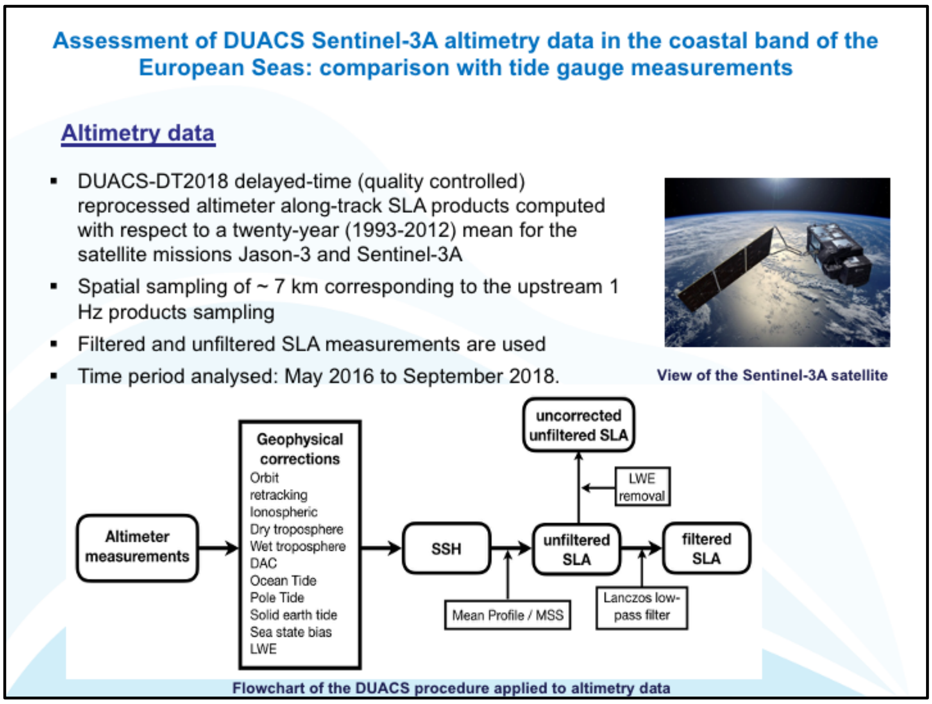
The Sentinel-3A satellite was launched on February 2016 as part of the European Union Copernicus Programme. It became fully operational on July 2016. Its main objective is to measure sea surface topography, global surface temperature, and global surface colour with high accuracy and reliability to support ocean forecasting systems, environmental monitoring and climate monitoring. The Sentinel-3A on board altimeter, synthetic aperture radar altimeter (SRAL), is based on the synthetic aperture radar mode (SARM).

View of the Sentinel-3A satellite

Sentinel-3A data is processed by EUMETSAT (https://www.eumetsat.int) which freely distributes level 1 and level 2 products. These products are in a second step reprocessed through the DUACS (Data Unification and Altimeter Combination System) altimeter multi-mission processing system (https://duacs.cls.fr). The DUACS system provides directly usable, high quality near-real-time (NRT) and delayed time (DT) global and regional altimeter products. Main processing steps include product homogenization, data editing, orbit error correction, reduction of long wavelength errors (LWE), and production of along-track and mapped sea level anomalies.

The DUACS processing is based on the altimeter standards given by L2P (Level-2 Plus) products. They include the most recent standards recommended for altimeter global products by the different agencies and expert groups such as OSTST) and ESA Quality Working groups.

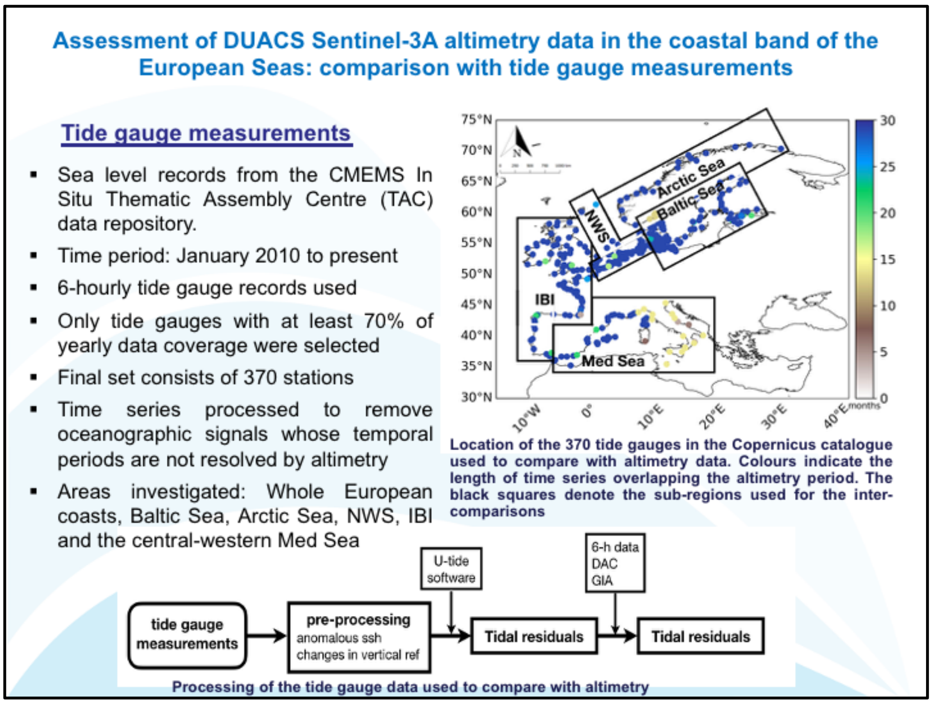
More than 25 years of level-3 (L3) and level-4 (L4) altimetry products were reprocessed and recently delivered as DUACS DT 2018 version. DUACS-DT2018 L3 products for repetitive altimeter missions are based on the use of a mean profile that allows collocating the SSH of the repetitive tracks and retrieving a precise mean reference in order to compute Sea Level Anomaly (SLA). SLAs are often used instead of Absolute Dynamic Topography, computed as the differences between SSH and the geoid height, because the geoid is not perfectly known at scales smaller than 150 km from space gravity missions. To solve this, a MSS model is used, which is based on altimetry data, and it contains the sum of the geoid height and the Mean Dynamic Topography. The along-track SLA products are thus affected by the aforementioned uncertainties in the geoid surface model and also by (i) instrumental errors; (ii) environmental and sea state errors; and (iii) precision of geophysical corrections. The latter are applied to the altimeter measurement to remove part of the physical signal that is not of interest or that need to be reduced for part of the processing. These elements introduce errors on the measurements.



DUACS-DT2018 along-track (Level-3) regional altimetry products for the European Seas were released by CMEMS in 2018. We use delayed-time (quality controlled) reprocessed altimeter along-track SLA products computed with respect to a twenty-year (1993-2012) mean for the satellite missions Jason-3 and Sentinel-3A. These products have a spatial sampling of around 7 km corresponding to the upstream 1 Hz products sampling. Filtered and unfiltered SLA measurements are provided. In this work we have used both. Unfiltered SLA is the row SLA (i.e. not filtered) measured by the instrument. Filtered SLA is computed in DUACS procedure by applying a Lanczos low-pass filter with a cut-off wavelength of around 40 km to SLA measurements. The aim is to remove the noise signal and short wavelength affected by the noise. Filtered SLA is not sub-sampled in order to keep the 1 Hz full resolution.

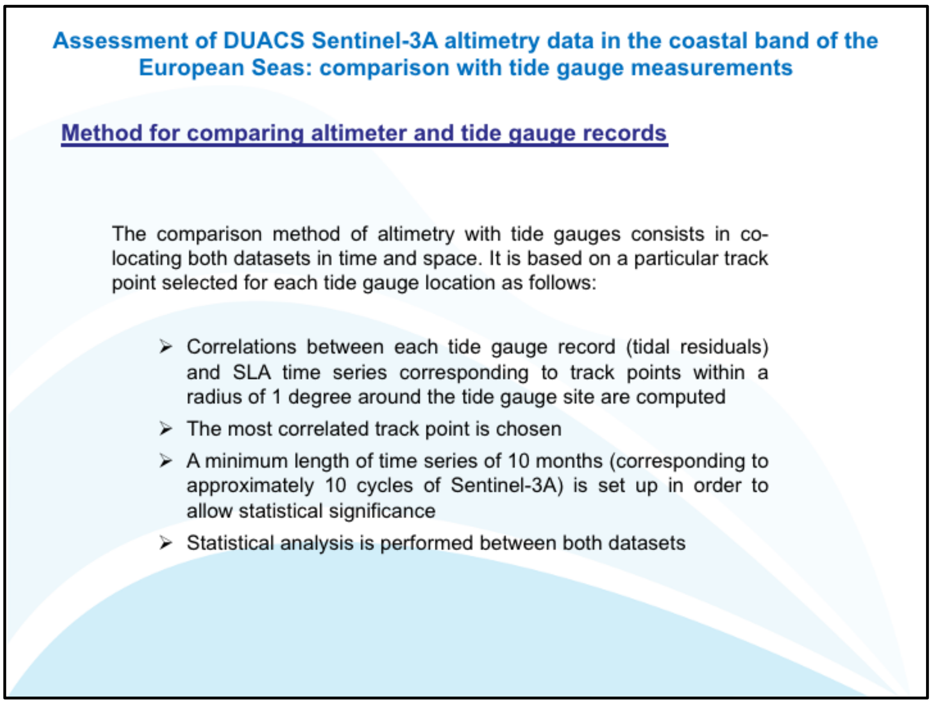
We used low-rate (1 Hz) SLAs instead of high-rate (i.e. 20 Hz SLAs) due to their higher accuracy, despite of the larger spatial resolution of the latter.

The flowchart explains the DUACS procedure applied to the altimetry data. It is based on the altimeter standards given by L2P (Level-2 Plus) products.

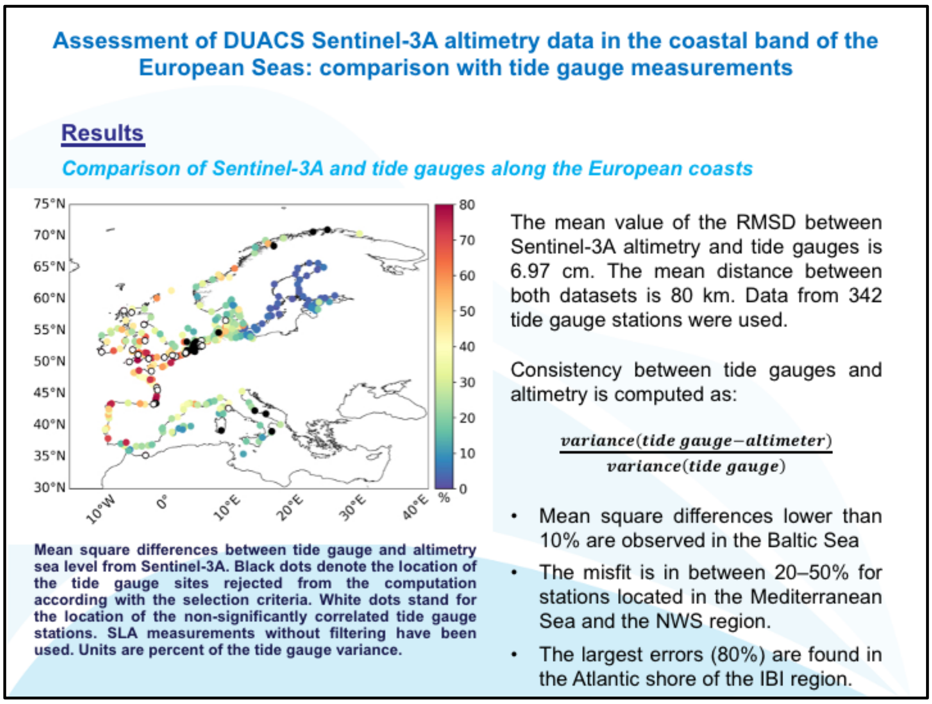


Sea level records used to compare with satellite altimetry were obtained from the CMEMS In Situ Thematic Assembly Centre (TAC) data repository. This dataset covers the time period spanning from January 2010 to present. 6-hourly tide gauge records were used according to the following procedure (see flowchart): the 445 tide gauge stations located in the European seas' domain were initially considered for this study. Quality flags of the tide gauge records were checked and observations with anomalous SSH data (values larger than 3 times the standard deviation of the time series) or changes in the vertical reference of the tide gauge were rejected. Also, tide gauge time series exhibiting a large variance (more than 20 cm^2) with respect to altimetry data were removed, as they are considered not representative of ocean sea level changes and are likely related to local features (e.g. river discharge). Moreover, only tide gauges with at least 70% of yearly data coverage were selected in order to allow the analysis of the seasonal signal. The final set consists of 370 stations. Before they can be compared with altimeter data, tide gauge measurements have to be processed in order to remove oceanographic signals whose temporal periods are not resolved by altimetry, thus avoiding important aliasing errors. First, tidal components were removed from the sea level records by using the u-tide software. Notice that the annual and semiannual frequencies are kept in the tidal residuals since they are included in the altimetry data.

For consistency with satellite altimetry data, the atmospherically-induced sea level caused by the action of atmospheric pressure and wind was removed from the tidal residuals. We used the DAC available at the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) website. The DAC data are provided as 6-h sea level fields on a 1/4° x 1/4° regular grid covering the global oceans. For each tide gauge site, the nearest grid point was selected and used to remove the atmospherically-induced sea level from observations, previously converted into 6-hourly records. Finally, 6-hourly tidal residuals were corrected for vertical movements associated with glacial isostatic adjustment (GIA) by using the Peltier mantel viscosity model (VM2).



Co-located altimeter and tide gauge measurements are analysed in terms of RMSD and variance of the time series. RMSD metric is commonly used to examine along-track altimeter data quality. In addition, the robustness of the results is investigated by using a bootstrap method, which allows to estimate quantities related to a dataset by averaging estimates from multiple data samples. To do that, the dataset is iteratively resampled with replacement. 10^3 iterations are used to ensure that meaningful statistics such standard deviation can be calculated on the sample of estimated values; thus allowing to assign measures of accuracy to sample estimates.



The consistency between altimetry and tide gauge data computed as follows:

$$\frac{variance(tide\ gauge - altimeter)}{variance(tide\ gauge)}$$

where the variance of tide gauge is associated with the variance of the signal. Consistency is expressed here as the mean square differences between both datasets in terms of percentage of the tide gauge variance. Notice that the minimum length of the time series is 10 months to allow statistical significance to the inter-comparison

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Results

Improvements of Sentinel-3A over Jason-3

Time series of SLA (cm) obtained from the most correlated Sentinel-3A track points (blue dots) and tidal residuals (orange dots) time series at each station site. The mean value of each time series has been subtracted for comparison purposes.

	Sentinel-3A*	Jason-3*	Impr.
RMSD (cm)	6.89 (0.17)	7.97 (0.21)	13 %
var TG (cm^2)	150 (6)	138 (5)	
var ALT (cm^2)	124 (5)	117 (5)	
var TG-ALT (cm^2)	47 (3)	64 (3)	25 %
data pairs	6037	6172	
stations	270		
distance TG (km)	79 ± 33	87 ± 33	9 %

*SLA measurements without filtering

( ) denotes the uncertainties (error bars) computed for rmsd and variance from the bootstrap method using 10^3 iterations.

The rmsd and variance are larger than the uncertainties, so they are significant from the statistical point of view

We conduct an equivalent analysis on Jason-3 data. Jason-3 satellite mission has an orbit repeat cycle of 9.91 days whilst Sentinel-3A presents a repeat cycle of 27 days. Thus, to make the inter-comparisons between both satellite missions with in-situ tide gauge observations comparable, SLA from Jason-3 is sub-sampled to retain every third point along the tracks in order to emulate the Sentinel-3A cycle. Moreover, the common tide gauge stations (270 stations) to both satellite missions are used. The results obtained for the whole European coasts are summarized in the table.

The RMSD between Jason-3 and tide gauge time series shows a mean value of 7.97 cm whereas it is reduced to 6.89 cm for the inter-comparison using the Sentinel-3A dataset. Overall, results from the Jason-3 satellite mission are consistent with those obtained for Sentinel-3A in terms of spatial distribution .

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Results

Improvements of Sentinel-3A over Jason-3

This table displays the improvements (%) of Sentinel-3A over Jason-3 for the inter-comparisons with tide gauges conducted in the European coasts and the different sub-regions investigated. SLA measurements without filtering have been used:

	European coasts	Med. Sea	IBI region	NWS region	Baltic Sea
RMSD (cm)	13 %	23 %	9 %	15 %	9 %
var TG-ALT (cm^2)	25 %	40 %	18 %	29 %	17 %
Distance TG (km)	9 %	9 %	10 %	17 %	---
Common stations	270	38	81	55	88

To further investigate the impact of SAR technology on the quality of Sentinel-3A data close to coast, we analyse how the measurement noise affects the retrieval of SLA in both missions. Also, the impact of the LWE processing on the quality of altimetry along-track products is assessed.

In the IBI and NWS regions, 81 and 55 common tide gauge stations to Sentinel-3A and Jason-3 missions are respectively identified. The analysis conducted with these stations shows a mean RMSD of 6.62 cm and 10.31 cm respectively for the comparison with Sentinel-3A, whilst the mean values for the inter-comparison using the Jason-3 dataset are 7.31 cm for the IBI region and 12.22 cm for the NWS region. Thus, Sentinel-3A satellite mission improves respectively the errors with tide gauges in both regions by 9% and 15%.

In the Baltic and Mediterranean seas, where generally lower errors are observed, we identified respectively 88 and 38 common tide gauge stations to both missions; showing a mean RMSD of 5.69 cm and 3.47 cm for the comparison with Sentinel-3A, whilst the mean values for the inter-comparison using the Jason-3 data are 6.24 cm and 4.49 cm, respectively. Thus, Sentinel-3A satellite mission improves the errors with tide gauges in both regions by 9% (23%) in the Baltic (Mediterranean) Sea.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Results

Impact of the measurement noise on the retrieval of SLA in the coastal area

This table displays the inter-comparisons altimetry – tide gauges using Lanczos low-pass filtered SLA and SLA measurements without filtering for Sentinel-3A and Jason-3 satellite missions. Common tide gauge stations for each satellite mission have been used.

These results confirm that SRAL instrument better solves the signal in the coastal band than altimeters on board Jason-3 even when filtered SLA is used.

European coasts	Sentinel-3A		Jason-3		improv. filtered S3-A	improv. filtered J-3
	unfiltered	filtered	unfiltered	filtered		
RMSD (cm)	6.97 (0.19)	6.95 (0.19)	8.72 (0.25)	8.52 (0.25)	0.3 %	2.3 %
var TG (cm²)	149 (5)		146 (6)			
var ALT (cm²)	121(7)	119 (7)	121 (5)	114 (5)	- 2 %	- 6 %
var TG-ALT (cm²)	49 (3)	48 (3)	76 (4)	72 (4)	1 %	5 %
data pairs	7119		6228			
stations	340		277			
distance TG (km)	80 ± 36		87 ± 34			

To check the impact of the measurement noise on the SRAL instrument on board the Sentinel-3A mission, the inter-comparison between satellite altimetry and in-situ tidal records in the European coasts is repeated but using the Lanczos low-pass filtered SLA available in the altimetric products. Outcomes are then compared with the inter-comparison previously conducted. The table summarizes the results. Notice that the same tide gauge sites and data points for the inter-comparisons using filtered SLA and SLA measurements without filtering from the Sentinel-3A mission are used to make outcomes comparable.

The variance of altimetry data diminishes by 2% when using the filtered data. This is an expected result due to higher frequencies being subtracted from the SLA time series in the filtering procedure. This fact decreases the RMSD by 0.3% when comparing filtered SLA with tide gauge records with respect to that obtained when using the SLA without filtering. Moreover, the variance of the differences between both datasets is also reduced by 1% when using the filtered data. However, it is worth noting that the improvements in the inter-comparisons (RMSD reduction) when using filtered SLA are negligible.

This procedure is repeated by using the Jason-3 dataset (see the table). A reduction threefold larger (6%) in variance of filtered SLA with respect to the SLA without filtering is observed. This underscores the expected larger measurement noise in the unfiltered SLA from Jason-3 Low Resolution Mode mission compared to the SAR mission. As a result, a RMSD improvement two points in percentage larger (2.3%) is obtained when using filtered data. Also, the variance of the differences altimetry – tide gauge diminishes by 5% when using the Jason-3 filtered data, this representing a reduction five times higher than that obtained for the Sentinel-3A mission.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

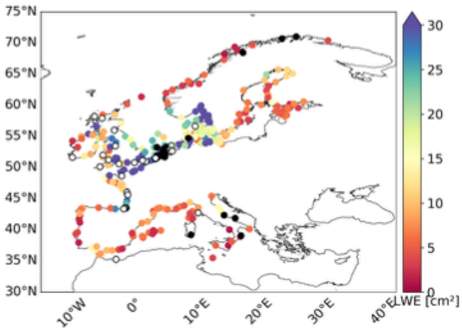
Results

Impact of the LWE correction applied on satellite altimetry

We investigate the possible impact of the LWE correction applied to Sentinel-3A and Jason-3 datasets on both the retrieval of SLA in the coastal zone and the inter-comparisons with in-situ measurements performed. To do that, LWE correction applied on SLA is subtracted from the altimetry time series in order to obtain uncorrected SLA as follows:

$$SLA_{uncorr} = SLA - LWE$$

Low values close to 0 cm^2 are obtained for most of the tide gauge sites located in the Baltic and Mediterranean Seas, as well as in the southernmost part of the IBI region; whereas larger variability exhibiting values larger than 25 cm^2 are found in the north-easternmost part of the latter and in the NWS region.



Variance (cm^2) of LWE correction applied on SLA measurements (without filtering) from the Sentinel-3A dataset along the European coasts. Black dots denote the location of the tide gauge sites rejected from the computation according with the selection criteria. White dots stand for the location of the non-significantly correlated tide gauge stations.

SLA in DUACS-DT2018 processing is provided to data users after removing several disturbances affecting the altimeter measurements such as high frequency oceanic signals, ocean tides, and LWE. To minimize errors related to the latter, a LWE reduction algorithm based on Optimal Interpolation is applied. This optimal-interpolation based empirical correction contributes to remove high frequency variability in the altimetry SLA due to noise (errors in corrections) and high frequency signals close to the coast that are not fully corrected by the application of the corrections to minimize the other two aforementioned errors.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Results

Impact of the LWE correction applied on satellite altimetry

This table displays the inter-comparisons altimetry – tide gauges using SLA measure_ ments (without filtering) with and without the LWE correction for Sentinel-3A and Jason-3 missions. Common tide gauge stations for each satellite mission have been used.

LWE correction leads to better agreement between the altimeter datasets and the tide gauges. A larger improvement (larger impact of LWE correction) is obtained for the Sentinel-3A data with respect to Jason-3.

European coasts	Sentinel-3A		improv. corrected S3A	Jason-3		improv. corrected J3
	LWE corrected	LWE uncorrected		LWE corrected	LWE uncorrected	
RMSD (cm)	6.94 (0.19)	7.67 (0.20)	10 %	8.61 (0.24)	8.84 (0.25)	3 %
var TG (cm^2)	148 (5)	159 (6)		145 (6)	147 (6)	
var ALT (cm^2)	120 (5)	152 (6)	- 21 %	120 (5)	144 (6)	- 16 %
var TG-ALT (cm^2)	48 (3)	59 (3)	18 %	74 (4)	78 (4)	5 %
data pairs	7170			6386		
stations	337			278		
distance TG (km)	80 ± 33			87 ± 33		

The RMSD between corrected SLA from Sentinel-3A (Jason-3) and tide gauge records (see table) diminishes by 10% (3%) with respect to that obtained when using uncorrected SLA. In addition, the variance of the differences between both datasets reduces by 18% (5%) when using corrected SLA. Thus, LWE correction leads to better agreement between the altimeter datasets and the tide gauges. We have considered the same tide gauge sites and data points for the inter-comparisons using corrected and uncorrected SLA from the Sentinel-3A mission in order to make outcomes comparable. The same applies to the Jason-3 dataset.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Conclusions

- ✓ We have validated the Sentinel-3A L3 along-track DUACS dataset in the coastal area of the European Seas over a period of two and half years by comparing the equivalent SLAs derived from 6-hour sampled tide gauges over the same period. Tide gauge records disseminated on CMEMS were used.
- ✓ The mean value of the RMSD between 1 Hz SLA from Sentinel-3A and tide gauges for the whole European coasts was 6.97 cm. It showed some variability according to the different regions investigated. The assessment was also conducted by using altimetry data from Jason-3 for inter-comparison purposes. The Sentinel-3A dataset showed lower RMSD and variance (altimetry - tide gauge) in the European coasts.
- ✓ The impact of the measurement noise on the SRAL instrument was checked by repeating the inter-comparisons but using filtered SLA. Results showed that the variance of altimetry data diminished by 2% when using filtered SLA from Sentinel-3A. As a consequence, an error 0.3% lower when comparing filtered SLA with tide gauge records with respect to that obtained when using the unfiltered data was obtained. Also, the variance of the differences between both datasets reduced by 1% when using the filtered data.

Assessment of DUACS Sentinel-3A altimetry data in the coastal band of the European Seas: comparison with tide gauge measurements

Conclusions

- ✓ The outcomes from the Jason-3 dataset confirmed the better results obtained from filtered SLA, although much larger discrepancies between filtered and unfiltered SLA when comparing with tide gauge records were found with respect to those obtained for the Sentinel-3A mission. This fact emphasizes that Jason-3 dataset is affected by a higher measurement noise than Sentinel-3A; and also that SRAL instrument on board the Sentinel-3A mission better solves the signal in the coastal band.
- ✓ The impact of the LWE correction applied to satellite altimetry was also assessed. The RMSD between LWE corrected SLA from Sentinel-3A and tide gauge records was 10% lower than that obtained when using uncorrected SLA; and the variance of the differences between both datasets also reduced by 18%. Thus, LWE correction leads to better agreement between the altimeter datasets and the tide gauges. Similar results were obtained for the Jason-3 mission.

Acknowledgements

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