HYDROCOASTAL

SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level

Case Study: Impact Assessment Report on the Bristol Channel and Severn Estuary (SKYMAT/NOC/SatOC)

Deliverable D3.1

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1. Introduction

1.1. The HYDROCOASTAL Project

The HYDROCOASTAL project is funded under the ESA EO Science for Society Programme and aims to maximise the exploitation of SAR altimeter measurements in the coastal zone and inland waters, by evaluating and implementing new approaches to process SAR data from CryoSat-2, Sentinel-3A and Sentinel-3B.

This case study examines the Bristol Channel and Severn Estuary, which have one of the largest tidal ranges in the world, ranging between 10 m at the entrance to the channel, to approximately 14 m at the eastern end of the channel. The key objective of this impact assessment report is to establish if the new retrackers improve the satellite's performance compared with what is otherwise available. The outcome of this analysis will determine if more valid data points are captured closer to the coast, and if the accuracy of the observations close to the coast has improved. In a wider context, the satellite's improved performance will enable a better understanding of interactions and processes between river discharge and coastal sea level.

The products analysed in this HYDROCOASTAL Impact Assessment Case Study are the HYDROCOASTAL SAR altimeter final products, generated for the project by isardSAT, from an implementation of L1a to L2 processing software on a Virtual Machine provided to the project by Earth Console on their "G-BOX" system. Two re-trackers were implemented by isardSAT, the DTU MWaPP software for inland waters, and the UBonn STARS retracker for coastal zones. For the region covered by this study, output from both retrackers is available. In additional, the L2 output from the standard ESA product (which used the SAMOSA2 retracker), together with the geophysical correction fields, were interpolated onto the same along-track locations as the products were produced by the UBonn and DTU re-trackers (see Garcia-Mondejar et al, 2020, for description of processing algorithms)

We assess the three retrackers (U. Bonn, DTU and operational ESA) for Sentinel 3A/B (S3A/B) and CyroSat-2 (CS2) by validating these satellite observations against tide gauges measurements. The outcome of this validation will enable us to assess the potential beneficial impact of these new datasets, compared to what is otherwise available.

This analysis is divided into two sections, the first examines each retracker in terms of its noise from uncorrected sea surface height as a function of distance to the coast. The second part investigates the validation of the altimetry observations against tide gauge measurements.

1.2. Scope of this Document

This document is the Impact Assessment Report (IAR) for HYDROCOASTAL and it corresponds to the deliverable D3.1 and D3.2 of the project. The scope of this report is to compile and assess the main findings of the impact activities.

1.3. Document Organisation

- Section 1: A short introduction defining the scope of this report.

- Section 2: The results of the noise performance for each retracker from uncorrected sea surface height as a function of distance to the coast the L2 products in the coastal zones (CZ).
- Section 3: The results of the validation activities for the L2 product in the Bristol Channel/Severn Estuary
- Section 4: Summary and Recommendations

1.4. Reference Documents

HYDROCOASTAL Proposal: SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level. Proposal, January 2020

2 Uncorrected Sea Surface Height (USSH)

Each of the three retrackers (U. Bonn, DTU and ESA) were assessed by investigating their observational noise as a function of distance to the coast. Uncorrected Sea Surface Height (USSH) is defined as “Altitude” minus “Range”, whereas the observational noise is defined as the absolute successive differences in USSH along each track. The USSH noise is then binned at 1 km resolution as a function of distance to the coast.

Figure 2.1.1 shows the noise level (m) from USSH observations for Sentinel 3A as a function of distance to the coast. Three retrackers were analysed; the operational ESA retracker, U. Bonn and the DTU retrackers. A summary of the analysis is shown in Table 2.1, here the noise level is substantially higher across all retrackers at 1 km from the coast. In general, the U. BONN has the lowest noise level.

Table 2.1 Summary of the Sentinel 3A noise level (m) from USSH observations as a function of distance to the coast.

	Distance to the Coast (km)			
	1 km	2 km	Varied Distance (specified below)	
ESA	0.18	0.05	0.03 (4 to 10 km)	
U. BONN	0.05	0.03	0.02 (3 to 9 km)	0.01 (10 km)
DTU	0.12	0.07	0.06 (3 to 9 km)	0.07 (10 km)

For Sentinel 3B, Figure 2.1.2 shows the results of the noise level (m) from the three retrackers as a function of distance to the coast. A summary of the analysis is shown in Table 2.2, here the noise level is substantially higher across all retrackers at 1 km from the coast. Despite the noise spike at 10 km from the coast, U. BONN had the lowest noise level.

Table 2.2 Summary of the Sentinel 3B noise level (m) from USSH observations as a function of distance to the coast.

	Distance to the Coast (km)					
	1 km	2 km	Varied Distance (specified below)			
ESA	0.20	0.07	0.08 (3 to 4 km)	0.06 (5km)	0.04 (6km)	0.03 (7 to 18 km)

U. BONN	0.04	0.03	0.02 (3 to 9 km)	0.02 (4 to 9km)	0.03 (10 km)	0.01 (11 to 18 km)
DTU	0.12	0.06 to 0.07 (2 to 18 km)				

The noise level analysis was repeated with CryoSat-2 observations (Fig 2.1.3) using the three retrackers and are summarised in Table 2.3. Again, the noise level at 1 km was higher across all retrackers. In spite of a spike in the noise level at 10 km, U. BONN had the lowest noise level. The highest noise level at 1 km from the three satellites (Tables 2.1, 2.2 and 2.3) was the ESA retracker.

Table 2.3 Summary of CryoSat-2 noise level (m) from USSH observations as a function of distance to the coast.

	Distance to the Coast (km)			
	1 km	2 km	Varied Distance (specified below)	
ESA	0.21	0.07	0.04 to 0.05 (3 to 18 km)	
U. BONN	0.05	0.04	0.03 (3 to 10 km)	0.02 (11 to 18 km)
DTU	0.12	0.06 to 0.07 (2 to 18 km)		

The number of valid observations for Sentinel 3 and CryoSat-2 are shown (Fig 2.1.1 to 2.1.3, bottom middle panel). The U. BONN consistently has the smallest number of valid observations compared with the DTU and ESA for Sentinel 3A whereas the number of valid observations for all three retrackers are very similar for Sentinel 3B. However, it has been reported that the number of valid observations for CryoSat-2 were dramatically lower for U. BONN compared with the other two retrackers due to a software bug in the processing. This bug was fixed for Sentinel 3A and Sentinel 3B and the data reprocessed, but due to constraints of time, it was not possible to reprocess Cryosat-2 data. In addition, the “spike” in the noise level at 10 km from the coast from the U. BONN retracker is a known consequence of the processor algorithm which implements a new mode at 10 km from the coast.

To sum up, except for a spike in noise level at the 10 km from the coast, U. BONN has a consistently lower noise level compared with the DTU and ESA retrackers for all three satellites. However, the relatively good performance of U. BONN in terms of noise comes at the cost of a lower number of valid observations for S3A and CryroSat-2. Finally, we note that the noise level at 1 km from the coast is considerably higher than at 2 or more km away from the coast. Therefore, we chose not to include data that are less than 2 km from the coast for validation of altimetry against tide gauges.

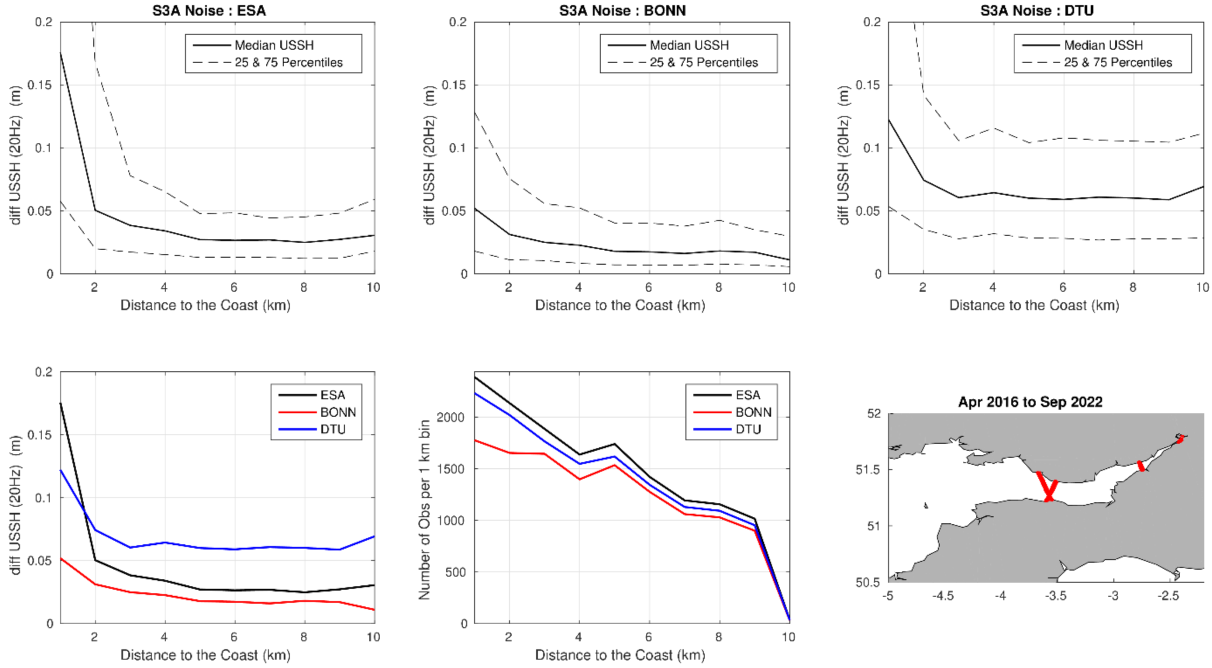


Figure 2.1.1 Results for Sentinel 3A, using ESA, U Bonn, and DTU retrackers, for the Bristol Channel and Severn Estuary (U.K.): top panel showing the noise of the uncorrected sea surface height (USSH) as a function of distance to the coast; bottom panel (left) represents the USSH comparison between the retrackers; bottom middle panel illustrates the number of valid observations as a function of distance to the coast; bottom right shows a spatial map of the S3A tracks.

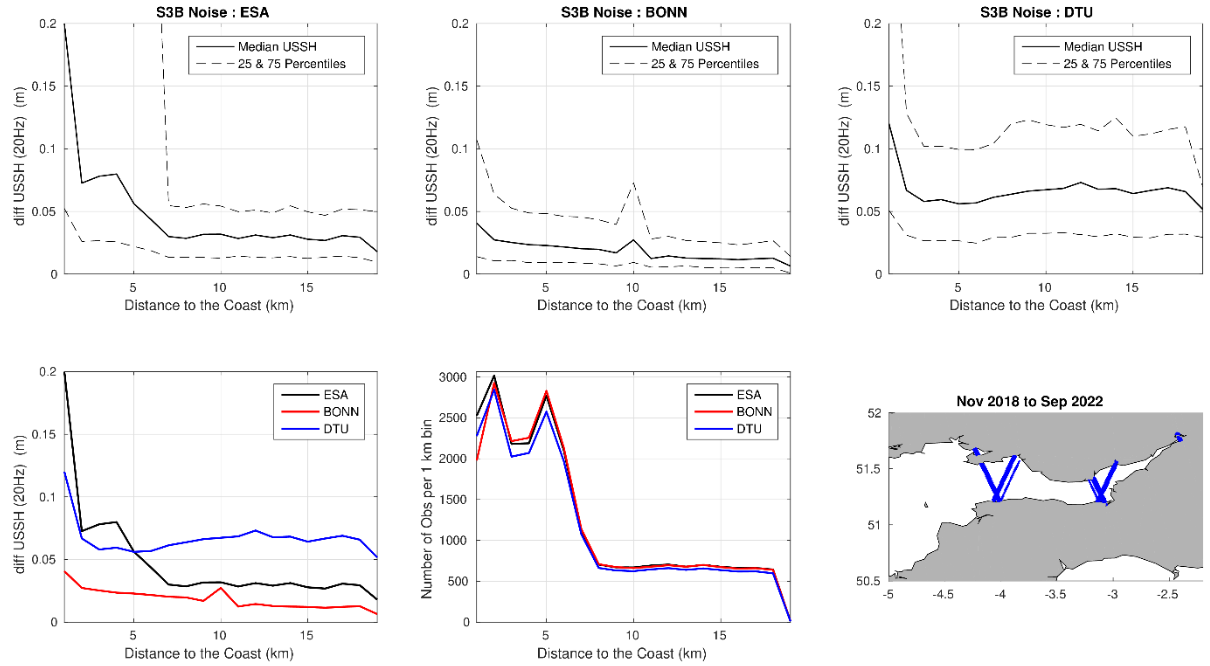


Figure 2.1.2 Same as Fig. 2.1.1 but showing Sentinel 3B results.

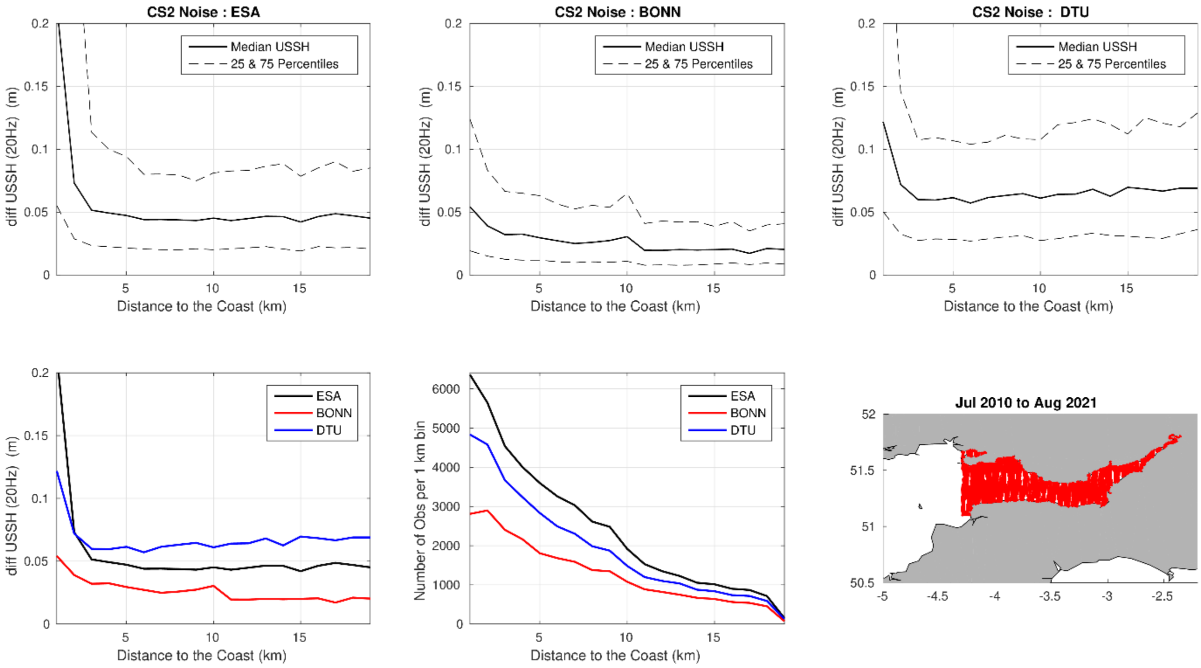


Figure 2.1.3 Same as Fig. 3.1.1 but showing CryoSat-2 results.

3 The results of the validation activities for the L2 product in the Bristol Channel/Severn Estuary

3.1 Comparison of Sentinel 3 using TWLE and SLA observations against tide gauge data

This section compares tide gauge observations against altimetry measurements. Seven tide gauge locations were selected along both sides of the Bristol Channel and Severn Estuary (Figure 3.1.1). These tide gauge datasets were downloaded from three sources, the Environment Agency (U.K), British Oceanographic Data Centre and National Network of Regional Coastal Monitoring Programmes (U.K). However, due to the distribution of the tide gauge locations and the altimetry S3A/B tracks, no one tide gauge could make a direct comparison between S3A and S3B. Any uncertainty in the ocean tide models will reflect large errors in the analysis due to the very high tidal range. Therefore, the analysis is carried out using two methods. The first method examines the total water level envelope (TWLE) derived from the altimetry against tide gauge observations and the second method explores altimetry sea level anomaly (SLA) observations where the ocean tide is removed from both the altimetry and tide gauge observations. The altimetry TWLE observations are defined in Equation 1 and the altimetry SLA measurements are defined in either Equation 2 or 4. As part of the validation process, data from three retrackers (U. BONN, DTU and ESA) are examined to determine which retracker has the best performance against tide gauge observations. We did not apply the dynamic atmospheric correction (DAC) to either the altimetry or tide gauge measurements.

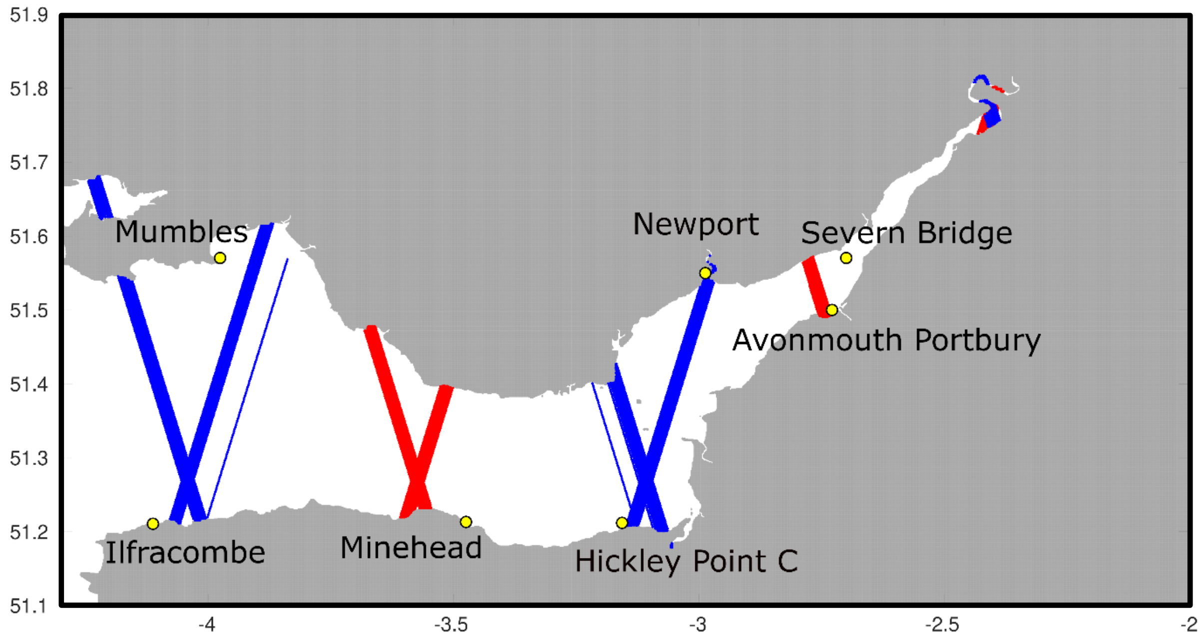


Figure 3.1.1 Location of the seven tide gauges and the S3A(Red) and S3B (Blue) tracks that are used in this analysis.

3.2 Tide Gauge processing

For SLA consistency, we derive a predicted tide gauge model using harmonic analysis which has the same number of tidal constituents to that of each altimeter's ocean model. Hence, S3A/B uses both FES 2014 and GOT4.1 ocean model, whereas CS2 uses FES 2004 ocean model from the Ice processor. In this way, we are comparing "like" with "like". Please note, the operational CryoSat-2 observations use FES 2014 ocean model.
The FES 2014 ocean model contains 34 tidal constituents. These tide constituents are as follows: 2N2, EPS2, J1, K1, K2, L2, La2, M2, M3, M4, M6, M8, Mf, MKS2, Mm, MN4, MS4, MSf, MSqm, Mtm, Mu2, N2, N4, Nu2, O1, P1, Q1, R2, S1, S2, S4, Sa, Ssa and T2. However, two long hydrodynamic period waves, that is, Mtm and MSqm tidal constituents were not available for the tide gauge harmonic analysis. The GOT4.10 uses 10 tide constituents, these are as follows: Q1, O1, S1, K1, N2, M2, S2, K2, M4, P1. These 10 tide constituents were applied to the tide gauge harmonic analysis. Likewise, for FES 2004 ocean model CryoSat-2 Ice Processor, the tidal constituents were used for the CryoSat-2 validation.

To get a perspective of the large tidal range, Fig. 3.2.1, 3.2.2 and 3.2.3 show examples of the harmonic analysis applied to the tide gauge data. The 34 FES 2014 tidal constituents used in Fig. 3.2.1 show that some of the tide is still left within the residuals (SLA). However, if the full harmonic analysis (59 tidal constituents) is applied to the same tide gauge, then the residuals improved (Fig. 3.2.2). The periodic and relatively large amplitude spikes within the improved residuals may be an oscillating seiche and may not necessarily be tide signal. At this preliminary stage of the analysis, it does appear that the FES 2014 ocean model may not fully recreate the astronomical tides.

The availability of tide gauge dataset is from January 2017 to September 2022. The harmonic analysis was carried out for each tide gauge on a yearly basis, where the yearly mean was removed. In addition, the data were quality controlled (QC), such that a QC flag was raised if a SLA (i.e. residual, Observation minus Predicted Model) observation was greater than 3 STD's away from the yearly mean. This QC flag did not mean that this was a bad observation, however each tide gauge was also visually assessed where a QC flag had occurred. This can be seen in the residuals in Fig. 3.2.1 (bottom panel) as an example.

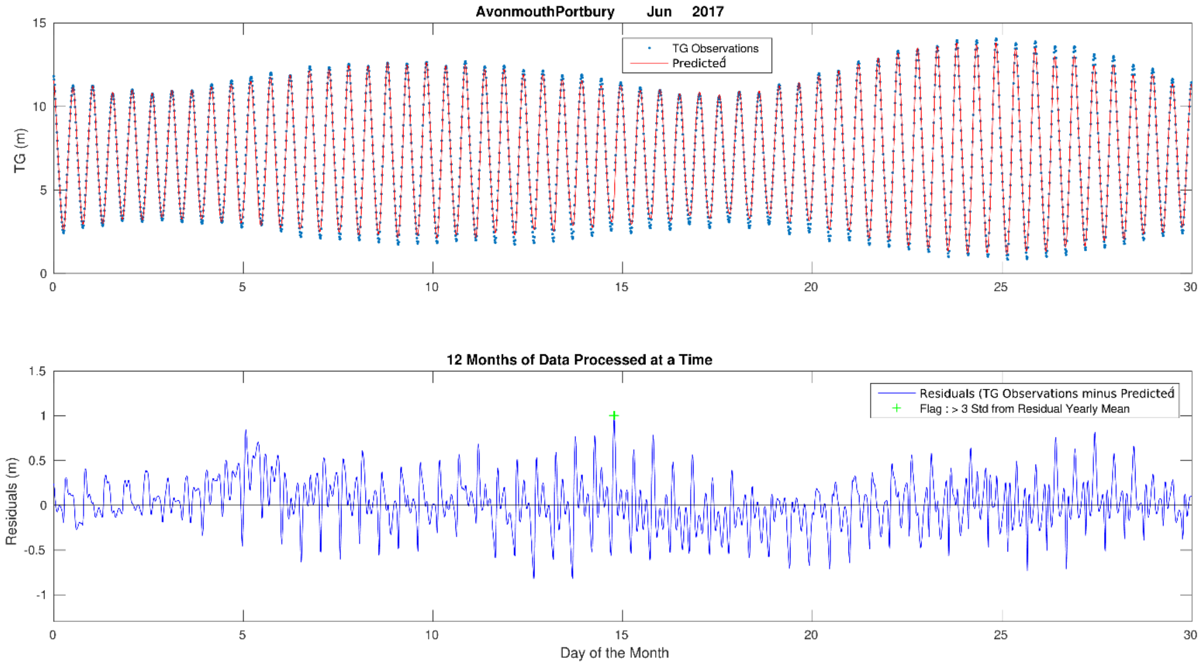


Figure 3.2.1 An example of the tide gauge timeseries at Avonmouth Portbury. The top panel represents the tide gauge observations (blue) with the derived predicted model (red). In this case the derived predicted model is using the maximum amount of tide constituents based on the FES 2014 ocean model. The bottom panel shows the residuals, that is, SLA (Observation minus predicted) the green cross illustrates a quality control flag given to any residuals that are greater than 3 STD's away from the yearly mean.

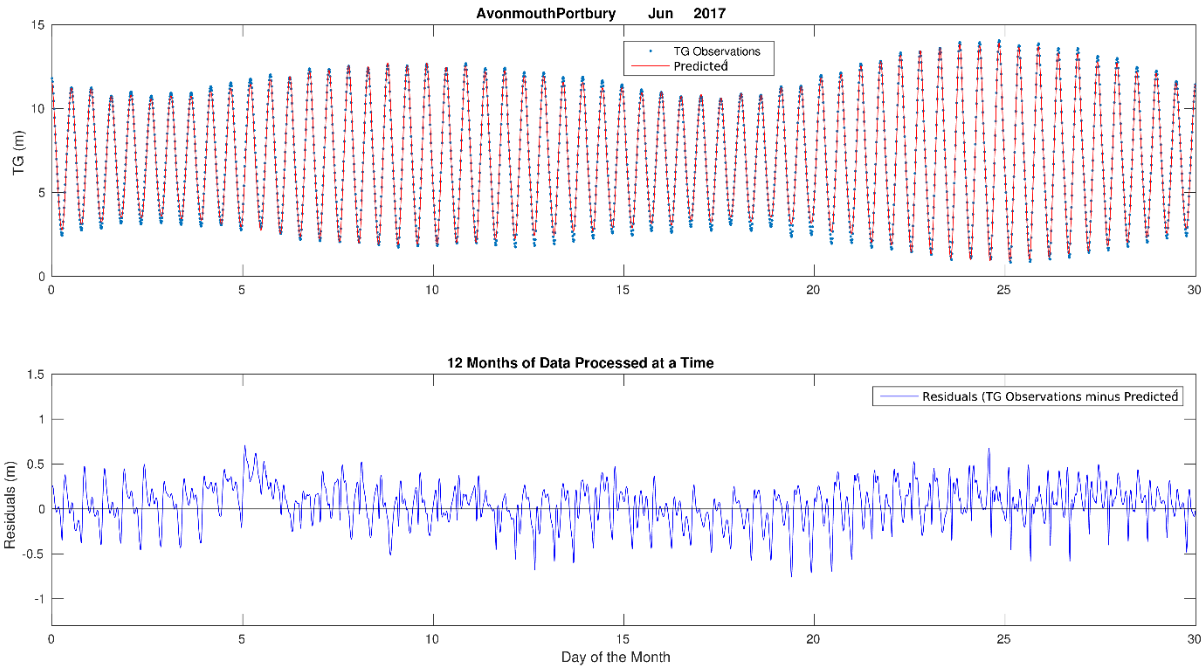


Figure 3.2.2 Same as Figure 3.2.1, except we use the full harmonic analysis to remove the ocean tide. Here the derived predicted model (red) required 59 tidal constituents compared with using the FES 2014 model tidal constituents.

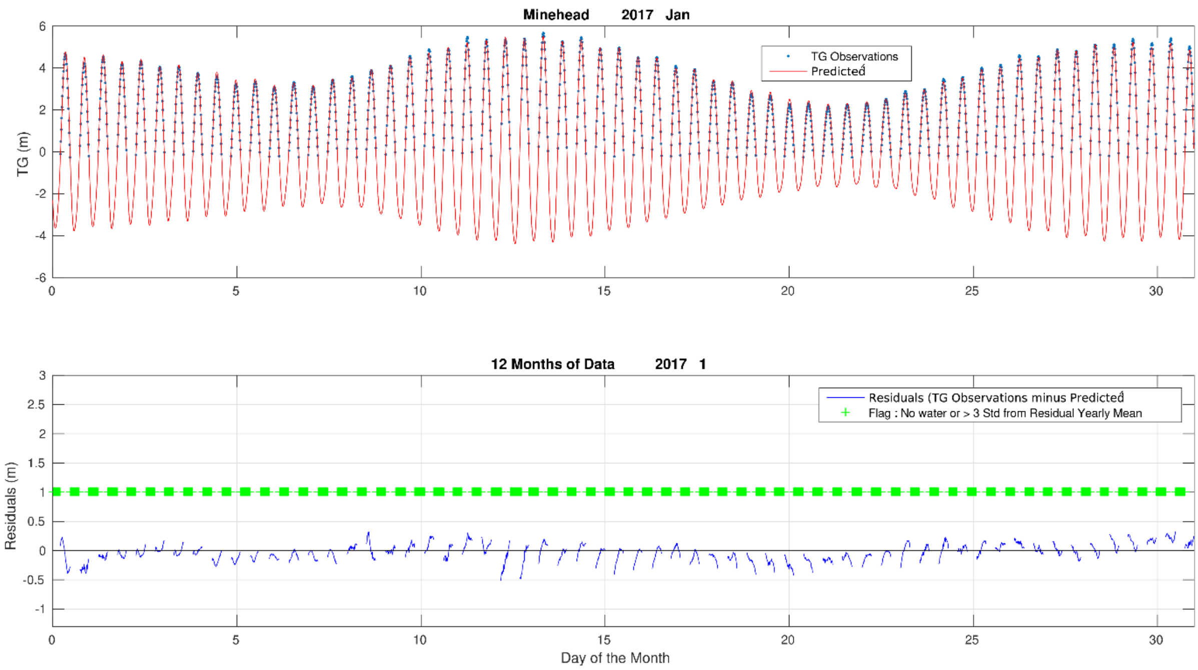


Figure 3.2.3 Same as Figure 3.2.1 but illustrates Minehead tide gauge that only has half cycles recorded. The green crosses (bottom panel) indicate no water or any residuals that are greater than 3 STD's away from the yearly mean.

Satellite data were extracted between 2 to 15 km from each tide gauge location. Within this sub-sample of satellite observations, the "closest approach to the coast" was calculated for each altimetry observation and then used for part of the analysis. The altimetry data were averaged in time to coincide with the tide gauge timestep interval (10 min at the Severn Bridge tide gauge and 15 min at the other tide gauges
As part of the processing, the following altimetry parameters are used to derive TWLE and SLA observations (Eq.1 to Eq.4).

The corrections used to compute the along-track SLA were extracted from the HYDROCOASTAL L2E data set provided by isardSAT.
The following equations relate to using the FES 2014 models (i.e., load tide and ocean tide)

```
TWLE_fes   = alt
                  - range
                  - GIM_ion
                   -wet_trop
                  - dry_trop
                  -solid_earth_tide
                  - load_tide_fes              (Sol 2)
                  - sea_state_bais
                  -MSS                                            (1)
SLA        = TWLE - Pure ocean_tide_fes         (Sol 2)
                  - geocentric_polar_tide
                  - ocean_tide_non_eq                                   (2)
```

Please note that the FES 2014 ocean tide model has the load tide component which is part of the TWLE as well as having the ocean tide non equilibrium applied. Therefore, we create a "Pure" ocean tide using equation 3.

"Pure" ocean tide = ocean_tide_fes (sol 2) + ocean_tide_non_eq - load_tide (sol 2) (3)

Normally, equation 4 would be used to derive SLA (see below)

```
SLA        = alt  -range
                  -GIM_ion
                  -gpd_wet_trop
                  -gpd_dry_trop
                  -solid_earth_tide
                  -sea_state_bais
                  -ocean_tide_fes          (Sol 2)
                  -geocentric_polar_tide
                  -MSS                                            (4)
```

Hence, SLA (Eq. 2) minus SLA (Eq. 4) equals zero.

As previously mentioned, the yearly mean was removed from both tide gauge and altimetry data to minimise any possible errors from mean sea surface (MSS) within the Bristol Channel and the Severn Estuary. In addition, trend and seasonal and semi-seasonal cycles were also removed from both tide gauge and altimetry datasets.

3.3 Investigating the performance of three corrections used within Sentinel 3 processing

Before proceeding, we need to know which geophysical corrections perform the best within the Bristol Channel and Severn Estuary. Thus, we compare three corrections used within Sentinel 3 processing where the SLA altimetry measurements are compared against tide gauge data. We repeat the comparison for the following cases: first, with and without the sea state bias (SSB) correction applied (using the FES2014, and the WTC/DTC from the University of Porto); second, we compare the WTC/DTC from the University of Porto against the "Model at zero altitude" where the FES2014 and SSB corrections are applied. Last, we compare the FES 2014 ocean tide model against GOT4.10 tide model where the WTC/DTC from the University of Porto and SSB correction are applied.

The preliminary analysis (Fig. 3.3.1a) showed that the SSB correction applied to the altimetry provided very little to no improvement in terms of the standard deviation of the differences (STDD) between the SLA satellite observations and the tide gauge measurements. In addition, there was very little evidence to show that the WTC/DTC from the University of Porto correction improved the SLA STDD compared with the WTC/DTC Model (Fig. 3.3.1b). However, the comparison in Fig. 3.3.1c showed that the FES 2014 ocean tide model (34 constituents) provided a much lower SLA SSTD compared with using GOT 4.1 ocean tide model (10 constituents). Figure 3.3.2, like Fig. 3.3.1, shows the same results of STDD but as a percentage of their corresponding tidal range. Even though the STDD look high (approximately 0.35 m), the percentages (with respect to their tidal range) show that this STDD uncertainty represents approximately 2 to 2.5% of the sea level signal. These initial results also show that the University of BONN retracker has a lower overall SLA STDD compared with the other two retrackers (DTU and ESA). We repeated this analysis by examining the average correlations across the seven tide gauges (Fig. 3.3.3). The results showed an overall improvement when the SSB was applied, a small improvement when WTC/DTC from the University of Porto for two of the retrackers (BONN and DTU) and very large increase in correlation when the FES 2014 was applied. Thus, based on these initial STDD and correlation comparisons, we decided to use SSB, WTC/DTC from the University of Porto and FES 2014 ocean tide corrections for the next step in the analysis.

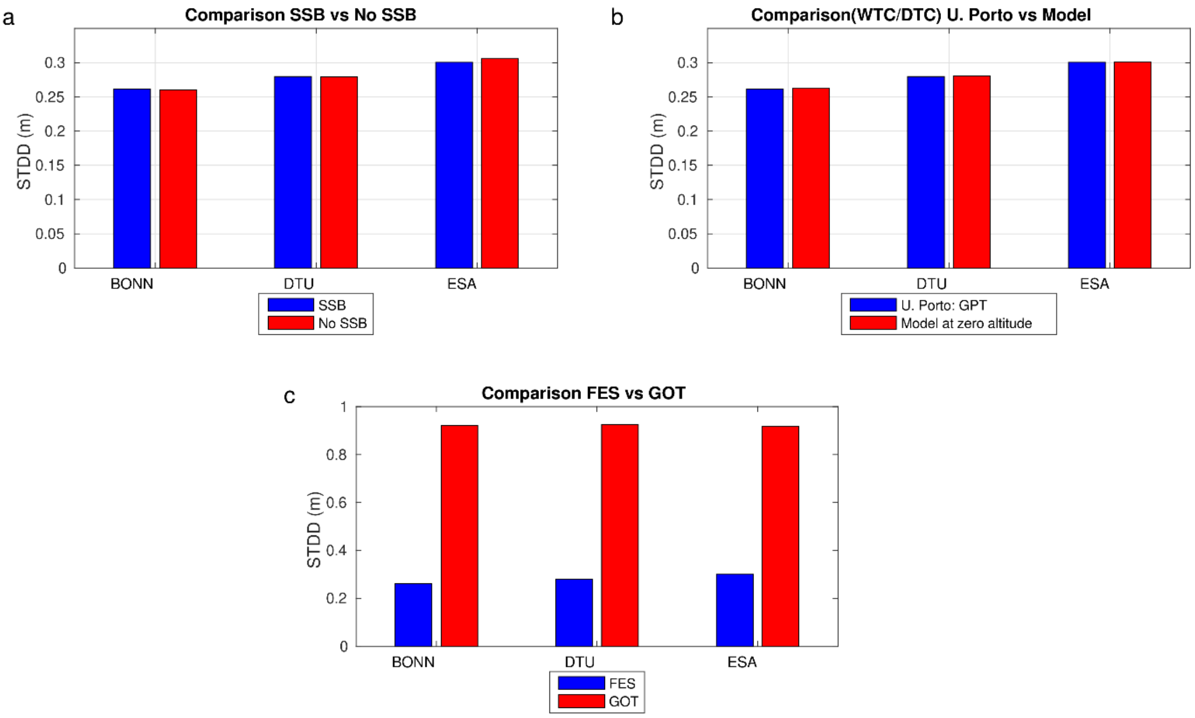


Figure 3.3.1 Average SLA STDD over the seven tide gauges from Sentinel-3A/B data for the cases: (a) SSB correction vs no SSB correction (both corrected using FES2014 and the WTC/DTC from the University of Porto); (b) WTC/DTC from the University of Porto vs that from Model (both corrected using FES2014 and with the SSB correction applied); and (c) FES2014 vs GOT4.10 (both corrected using the WTC/DTC from the University of Porto and with the SSB correction applied).

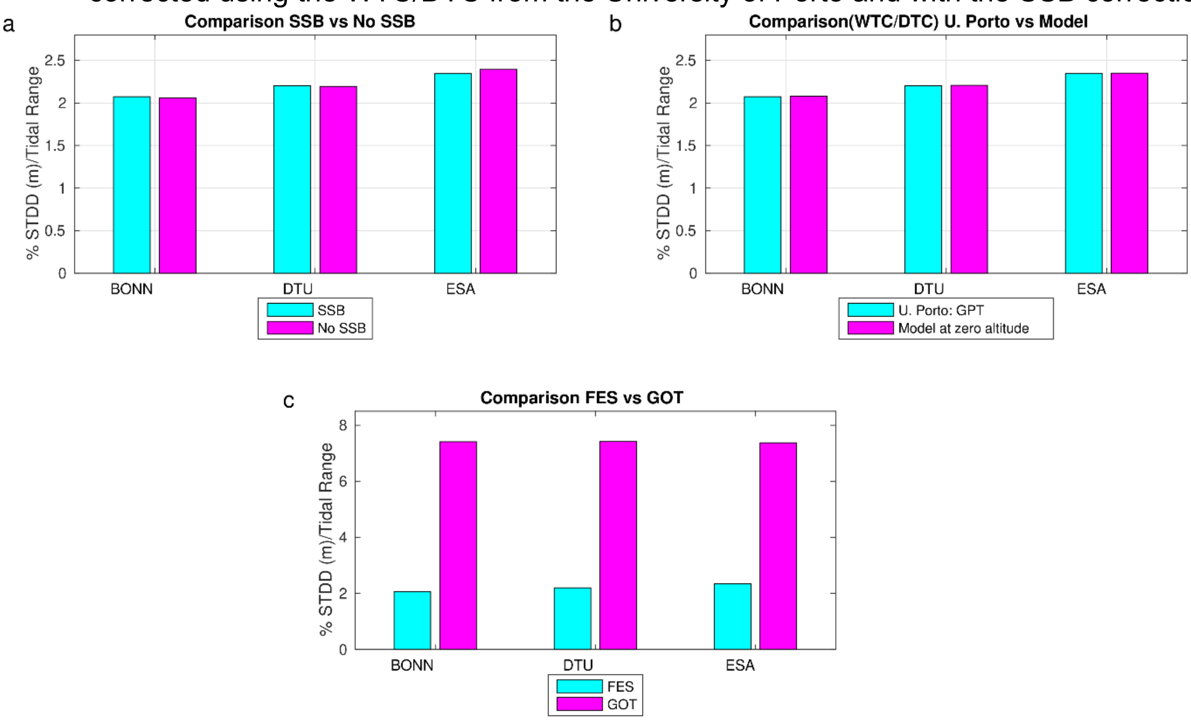


Figure 3.3.2 Average percentages of SLA (i.e. STDD/Tidal Range) over the seven tide gauges from Sentinel-3A/B data for the cases: (a) SSB correction vs no SSB correction (both corrected using

FES2014 and the WTC/DTC from the University of Porto); (b) WTC/DTC from the University of Porto vs that from the Model (both corrected using FES2014 and with the SSB correction applied); and (c) FES2014 vs GOT4.10 (both corrected using the WTC/DTC from the University of Porto and with the SSB correction applied).

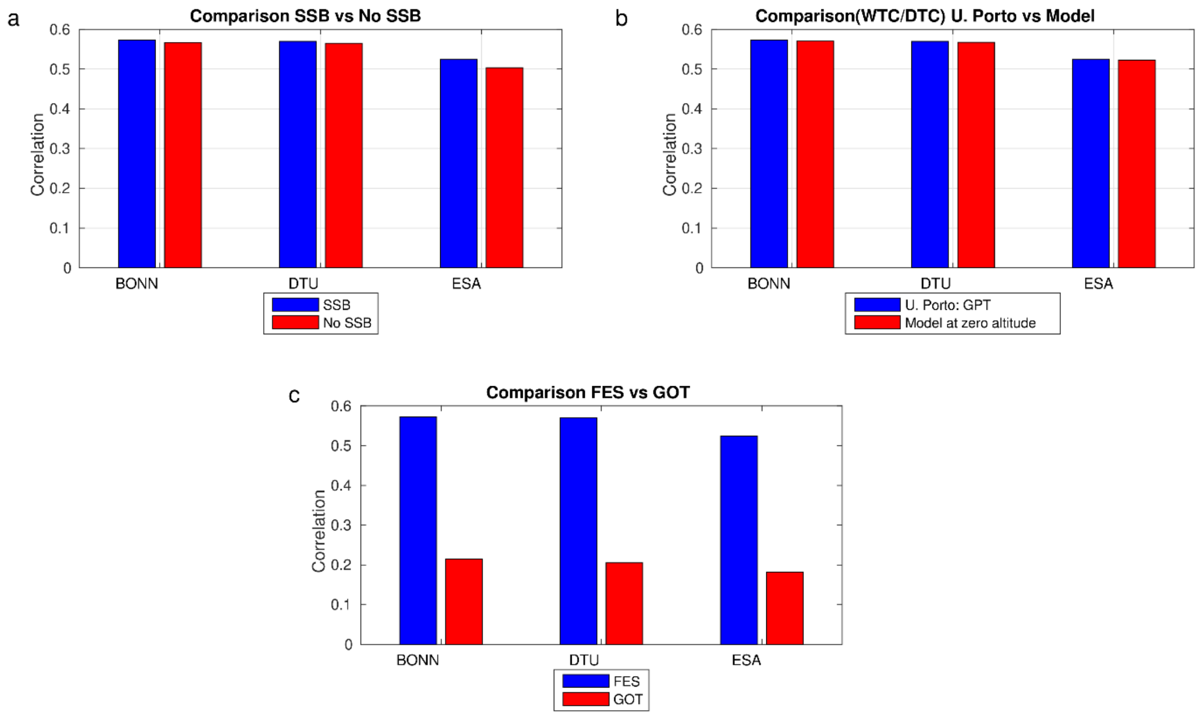


Figure 3.3.3 Average correlation of SLA (i.e. STDD/Tidal Range) over the seven tide gauges from Sentinel-3A/B data for the cases: (a) SSB correction vs no SSB correction (both corrected using FES2014 and the WTC/DTC from the University of Porto); (b) WTC/DTC from the University of Porto vs that from the Model (both corrected using FES2014 and with the SSB correction applied); and (c) FES2014 vs GOT4.10 (both corrected using the WTC/DTC from the University of Porto and with the SSB correction applied).

3.4 Comparison of Sentinel 3A and B TWLE observations against tide gauge data

As previously mentioned, there is a large tidal range within the Bristol Channel/Severn Estuary, and some evidence that the FES 2014 derived from 34 tidal constituents may not remove the tidal signal completely to calculate the sea level anomaly (SLA). Therefore, we separate the validation analysis into two categories: the total water level envelope (TWLE) and the SLA; and compare these observations with the tide gauge data. In addition, the altimetry data are extracted between 2 to 15 km and averaged in time and space that coincides with the tide gauge temporal sampling.

The TWLE allowed us to have a unique perspective into how the retrackers perform against tide gauge observations without removing the ocean tide signal. Here, the SSB, WTC/DTC from the University of Porto correction were applied to derive the TWLE observations (Eq. 1). Correlation as a function of distance to the coast for each tide gauge is displayed in Fig. 3.4.1 where the data are binned at 1 km intervals. The correlations between TWLE and tide gauges are generally very high, this is not surprising as most of the sea level signal is due to the ocean tide. However, there are differences between the three retrackers (U. BONN, DTU and ESA). The DTU retracker correlation with tide gauges appears to not deteriorate when approaching the coast. In addition, DTU was the most consistent retracker across the seven tide gauges. DTU retracker had a slightly lower number of observations at four tide gauge locations (Minehead, Ilfracombe, Mumbles and Newport) compared with the other two retrackers. The worst performance was that of the ESA retracker. In Figure 3.4.2, the average correlation (a) and STDD (b) between TWLE and tide gauge observations across the seven tide gauges are shown. These results indicate that DTU had highest average correlation of 0.97 and lowest STDD of 0.59 m as well as having the smallest range of values (i.e., whiskers). Finally, Table 3.4.1 complements Fig. 3.4.2 representing a breakdown of the individual tide gauges in terms of correlation and STDD. The brackets represent the percentage value as a proxy for the uncertainty (i.e., STDD/Tidal Range) at each tide gauge location and mean absolute deviation (MAD) is also displayed. The DTU retracker shows in general, more consistent correlations over all tide gauges including the percentage value and the MAD estimation. However, the U. Bonn retracker outperformed DTU for the tide gauge at Mumbles.

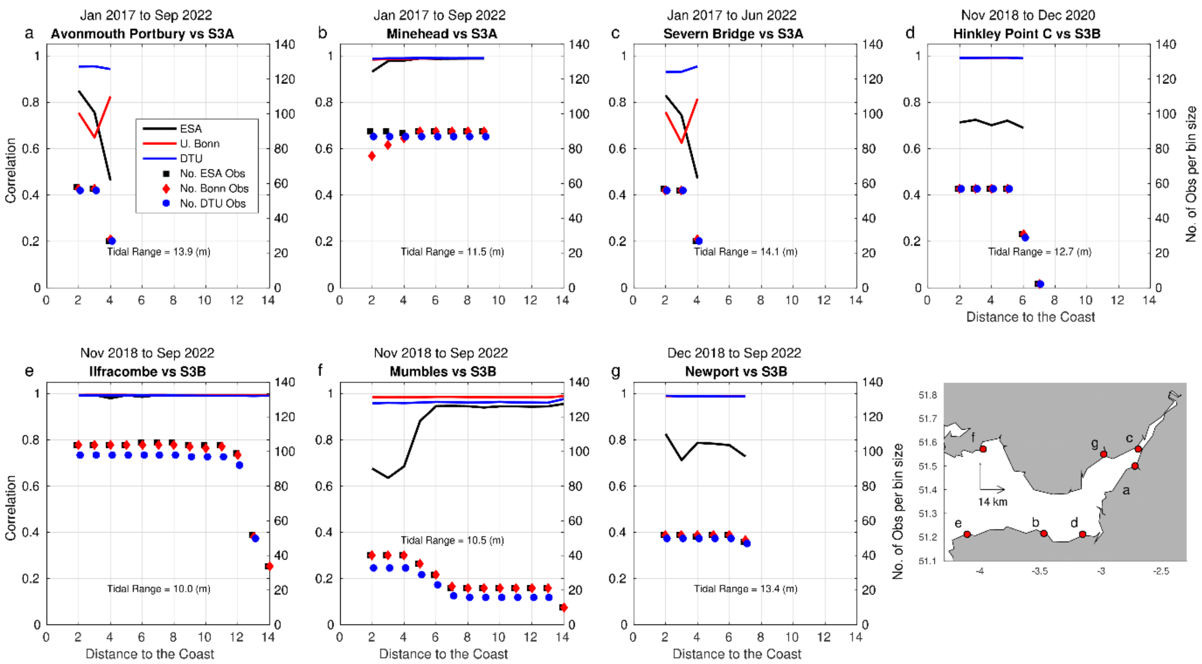


Figure 3.4.1 The correlation and STDD between altimetry (TWLE) and seven tide gauges as a function of distance to the coast within the Bristol Channel and Severn Estuary, U.K. The data is binned at 1 km intervals. Each plot has two Y axes, the left shows the correlation, and the right Y axis gives the number of valid observations. The tide range for the Minehead tide gauge is only an estimate as only the top half tidal cycles are recorded.

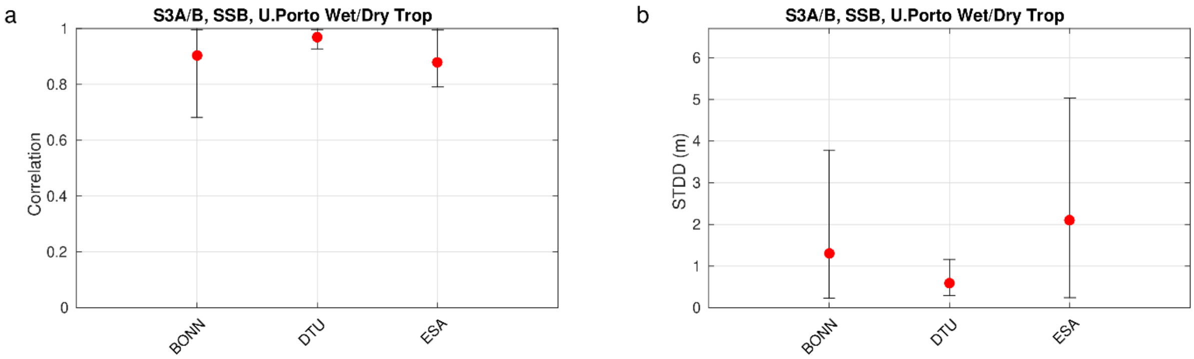


Figure 3.4.2 The correlation (a) and STDD (b) between tide gauge observations and S3A/B TWLE measurements (SSB, DTC/WTC from UPorto corrections) averaged over 2-15 km from the coast. Red filled in circles denote average over the seven tide gauges while the whiskers represent the range of values. Here, no FES 2014 ocean tide correction was applied.

Table 3.4.1 The correlations and standard deviation differences (STDD) between the TWLE altimetry observations against tide gauges measurements using three retrackers (U. Bonn, DTU and ESA) within the Bristol Channel and Severn Estuary, U.K. The value in the brackets represents the percentage value as a proxy for the uncertainty (i.e., STDD/Tidal Range) at each tide gauge location. The ranges represent ±1 Mean Absolute Deviation (MAD). All observations are between 2-15 km from each of the tide gauge locations. The highest correlation(s) at each tide gauge are highlighted in red.

Tide Gauge	Altimeter	U. Bonn (m)		DTU (m)		ESA (m)	
		Corr	STDD±1 MAD	Corr	STDD±1 MAD	Corr	STDD±1 MAD
Avonmouth Portbury	S3A	0.68	3.8(27)±2.0	0.95	1.1(08)±0.8	0.83	1.9(14)±1.4
Minehead	S3A	0.98	0.3(03)±0.3	0.98	0.3(03)±0.3	0.97	0.3(03)±0.3
Severn Bridge	S3A	0.70	3.7(27)±2.0	0.93	1.2(08)±0.8	0.81	2.0(14)±1.4
Hinkley Point C	S3B	0.99	0.3(02)±0.2	0.99	0.3(02)±0.2	0.79	5.0(40)±4.2
Ilfracombe	S3B	0.99	0.2(02)±0.2	0.99	0.3(03)±0.2	0.99	0.2(02)±0.2
Mumbles	S3B	0.99	0.3(03)±0.3	0.96	0.5(05)±0.4	0.83	2.6(25)±2.1
Newport	S3B	0.99	0.4(03)±0.3	0.99	0.5(03)±0.4	0.91	2.7(20)±2.3

3.5 Comparison of Sentinel 3A and B SLA observations against tide gauge data

This next section examines the SLA altimetry measurements against the seven tide gauges. FES 2014 ocean tide was applied to the altimetry observations (see Eq. 2), including the WTC/DTC from the University of Porto and SSB correction. Fig. 3.5.1 shows the correlation as a function of distance to the coast. The correlations are a lot lower than TWLE showing little change or an increase in correlation towards the coast. The ESA retracker shows more correlation variability as a function of distance to the coast compared with the other two retrackers. This is consistent in Fig. 3.5.2a where the range in correlations (shown by the whiskers) of the ESA retracker averaged across the seven tide gauges is larger compared with the other two retrackers. The STDD also illustrates that ESA has the biggest range in Fig. 3.5.2b. Here, the correlation from the average of seven tide gauges for U. BONN, DTU and ESA

is, respectively, 0.57, 0.57, 0.52 and their corresponding STDD(m) is 0.26, 0.28 and 0.30. Thus, the U. BONN retracker gives the best agreement with the tide gauge SLA observations, followed very closely by the DTU retracker. Table 3.5.1 shows that although U. BONN had the best average correlation and STDD, DTU had five out of the seven tide gauges with the highest correlation between the three retrackers, and these five tide gauges also had the same STDD values compared with U. BONN.
As a check, we repeated the analysis (Fig. 3.5.3) such that only 2 to 8 km of altimetry data were extracted around each tide gauge location. The correlation and STDD between the altimetry TWLE (a, b) show that the averaged correlation from seven tide gauges for U. BONN, DTU and ESA retrackers gave 0.87, 0.91 and 0.82, respectively, whereas the averaged STDD (m) gave 1.45, 0.77 and 2.70. Likewise, the average SLA (c, d) correlation and STDD from seven tide gauges using the U. BONN, DTU and ESA retrackers gave 0.51, 054 and 0.44, respectively, whereas the averaged STDD (m) gave 0.27, 0.28 and 0.34. When these results were compared with altimetry data that were extracted between 2 to 15 km, the greater coverage appeared to improve the results.

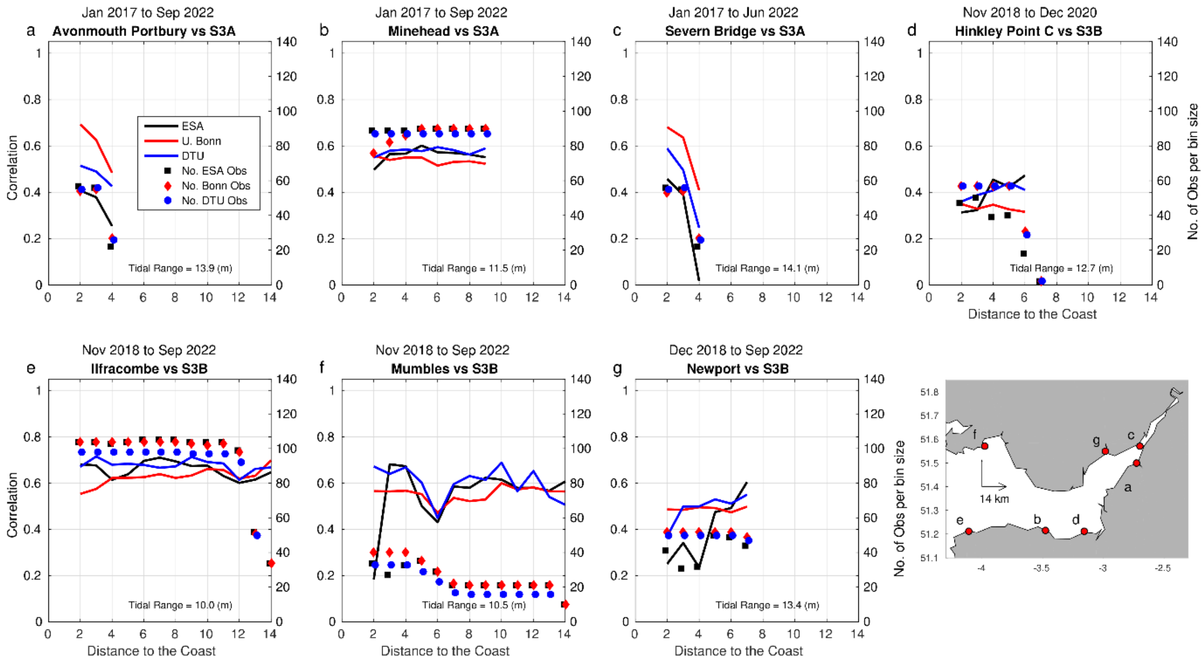


Figure 3.5.1 The correlation between altimetry (SLA) and seven tide gauges as a function of distance to the coast within the Bristol Channel and Severn Estuary, U.K. The data is binned at 1 km intervals. Each plot has two Y axes, the left shows the correlation, and the right Y axis gives the number of valid observations.

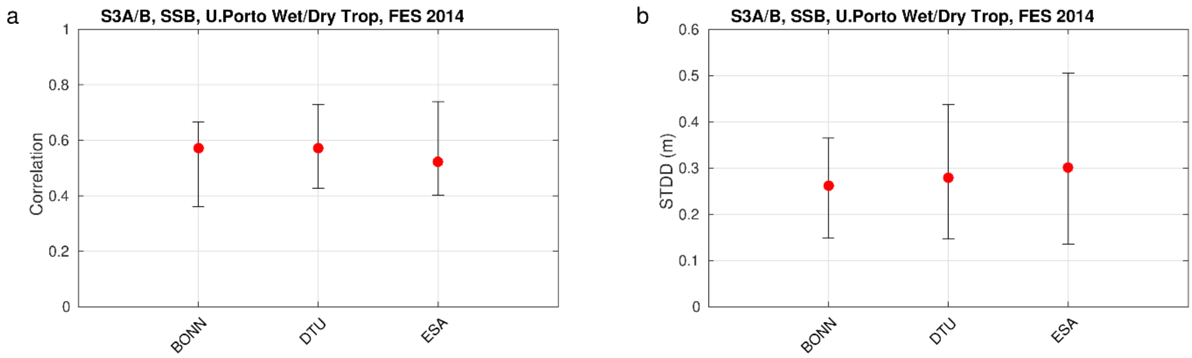


Figure 3.5.2 Correlation (a) and STDD (b) between SLAs from S3A/B (SSB, DTC/WTC from UPorto, and FES 2014 ocean tide correction) and tide gauge data for SLAs averaged over 2-15 km from the coast. Red filled in circles denote average over the seven tide gauges while the whiskers represent the range of values.

Table 3.5.1 The correlations and standard deviation differences (STDD) between the SLA altimetry observation against tide gauge measurements using three retrackers (U. Bonn, DTU and ESA). The value in the brackets represents the percentage value as a proxy for the uncertainty (i.e. STDD/Tidal Range) at each tide gauge location. The ranges represent ±1 Mean Absolute Deviation (MAD). All observations are between 2-15 km from each the tide gauge location. The highest correlation(s) at each tide gauge are highlighted in red.

Tide Gauge	Altimeter	U. Bonn (m)		DTU (m)		ESA (m)	
		Corr	STDD±1 MAD	Corr	STDD±1 MAD	Corr	STDD±1 MAD
Avonmouth Portbury	S3A	0.67	0.4(03)±0.3	0.54	0.4(03)±0.3	0.41	0.5(04)±0.4
Minehead	S3A	0.55	0.2(02)±0.2	0.58	0.2(02)±0.2	0.60	0.2(02)±0.1
Severn Bridge	S3A	0.66	0.4(03)±0.3	0.55	0.4(03)±0.3	0.41	0.5(04)±0.4
Hinkley Point C	S3B	0.36	0.3(02)±0.2	0.43	0.3(02)±0.2	0.40	0.3(02)±0.2
Ilfracombe	S3B	0.67	0.2(02)±0.1	0.73	0.1(01)±0.1	0.74	0.1(01)±0.1
Mumbles	S3B	0.59	0.1(01)±0.1	0.61	0.2(02)±0.1	0.56	0.2(02)±0.1
Newport	S3B	0.52	0.3(02)±0.2	0.56	0.3(02)±0.2	0.55	0.3(02)±0.2

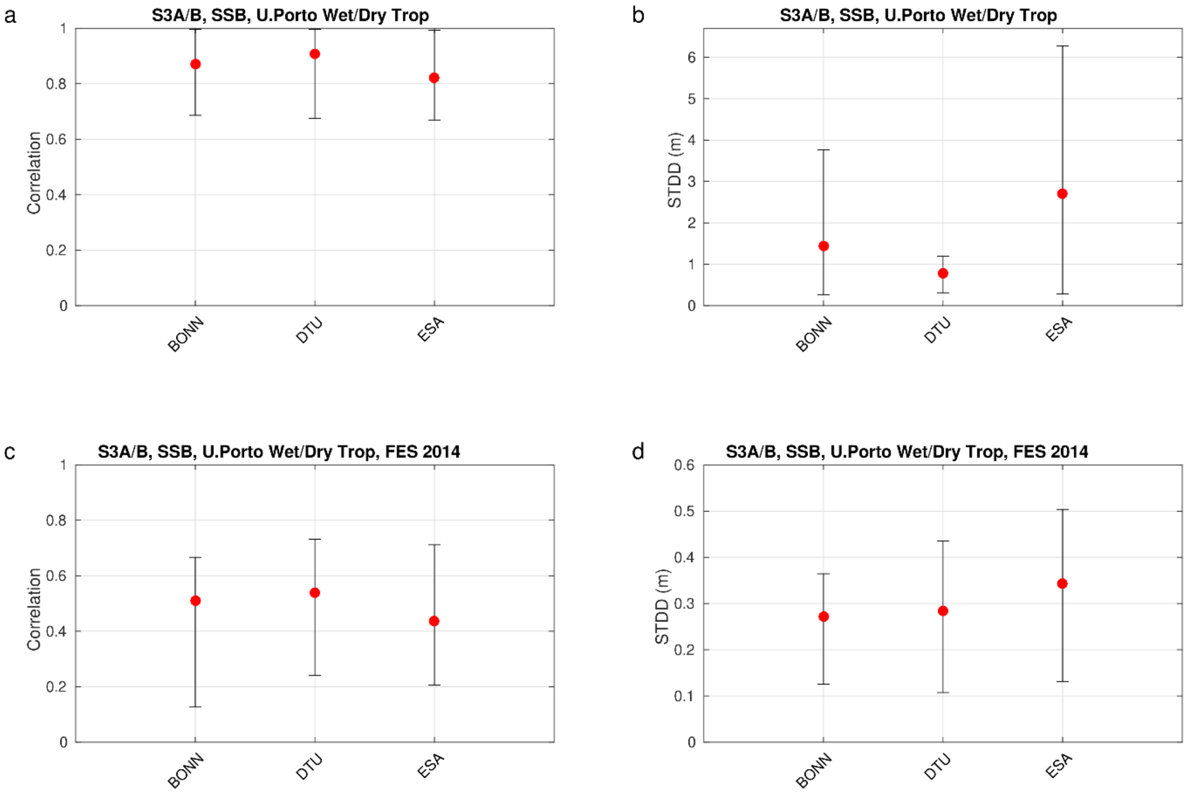


Figure 3.5.3 Correlation (a) and STDD (b) between tide gauge and S3A/B TWLE (hence, no FES 2014 ocean model applied) observations (SSB, DTC/WTC from UPorto corrections) averaged over 2-8 km from the coast. Likewise, the correlation (c) and STDD (d) for SLA include the FES 2014 ocean model. Red filled in circles denote average over the seven tide gauges while the whiskers represent the range of values.

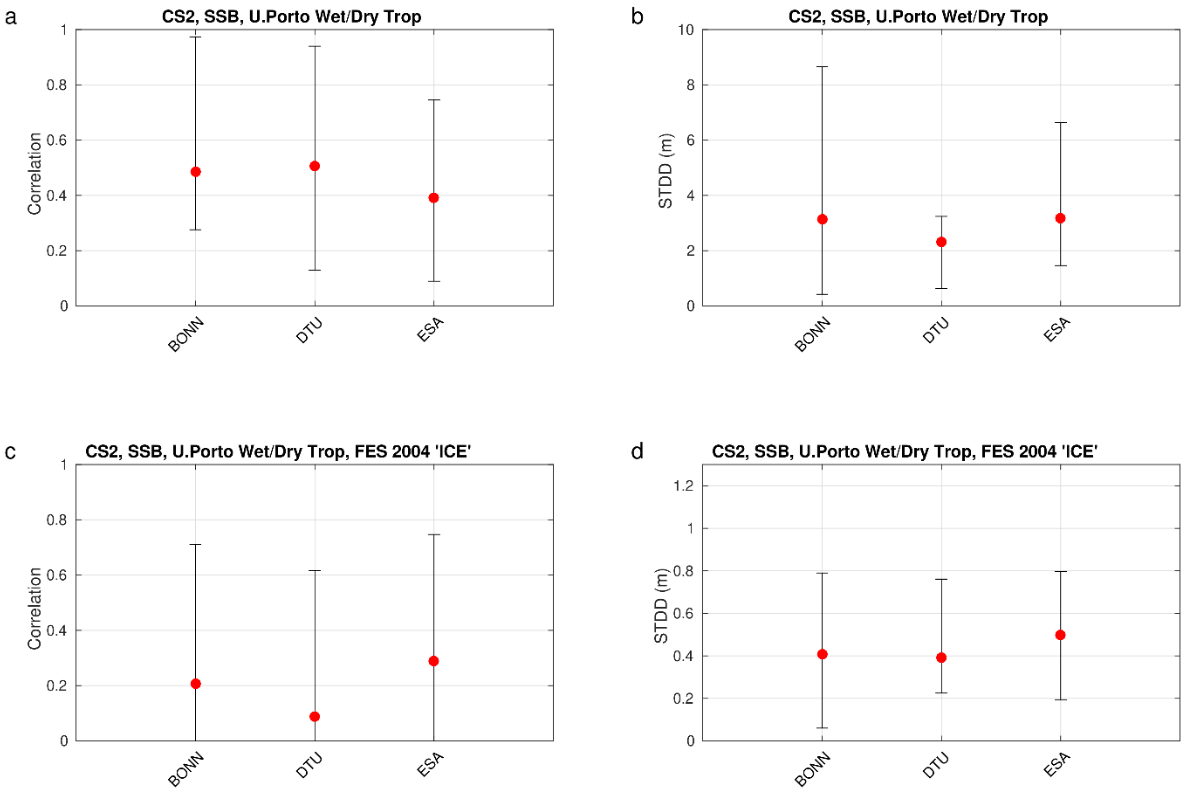
3.6 Comparison of CryoSat-2 using TWLE and SLA observations against tide gauge data

We would like to point out here that the SLA altimetry observations are calculated from the CryoSat-2 ice processor, which applies the FES 2004 ocean tide model. This version of FES has a similar number of tide constituents to that of GOT4.10 ocean model.

The correlation and STDD between the altimetry TWLE measurements and tide gauges are shown in Figure 3.6.1 (a, b). The averaged correlation from seven tide gauges for TWLE using the U. BONN, DTU and ESA retrackers gave 0.59, 0.61 and 0.49, respectively, whereas the averaged STDD (m) gave 3.13, 2.34 and 3.32, respectively. Similarly, the average SLA correlation and STDD is shown in Figure 3.6.1 (c, d). Here, the averaged correlation from seven tide gauges for SLA using the U. BONN, DTU and ESA retrackers gave 0.42, 0.07 and 0.23, respectively, whereas the averaged STDD (m) gave 0.51, 0.54 and 0.84.

The CryoSat-2 TWLE correlations appear to be a lot lower compared with Sentinel 3 observations, this may be affected by the non-repeating orbit as well as the sea surface may have aliasing of the tidal signal. The correlation of SLA against tide gauges is very poor, this reason is likely to be explained by the FES 2004 ocean model not being good enough for the Bristol Channel and the Severn Estuary.

Figure 3.6.1 Correlation (a) and STDD (b) between tide gauge and CS2 TWLE (hence, no ocean model applied) observations (SSB, DTC/WTC from UPorto corrections) averaged over 2-15 km from the coast. Likewise, the correlation (c) and STDD (d) for SLA include the FES 2004 ocean model. Red filled in circles denote average over the seven tide gauges while the whiskers represent the range of values.



3.7 Potential beneficial impact of the new Sentinel 3A /B and CryoSat-2

The results of the validation have paved the way to determine the potential beneficial impact of these new datasets. The S3A/B data, extracted between 2 to 15 km from each tide gauge location and averaged in time to coincide with the tide gauge timestep interval, show that both the U. BONN and DTU retrackers outperformed the operational ESA retracker in terms of higher correlation and lower STDD with respect to tide gauge measurements (Fig 3.4.2 and 3.5.2).

The CryoSat-2 TWLE data did not perform well against tide gauge observations compared with S3A/B data. This is probably related to the non-repeating orbit within the Bristol Channel and Severn Estuary. However, the CryoSat-2 TWLE comparison with tide gauge observations gave better results for the DTU retracker compared with the ESA retracker (see Fig 3.6.1 a & b). The 2004 tide model used to derive the

SLA observations for CryoSat-2 was limited by the number of tidal constituents and shown to be no good when comparing against tide gauge measurements.

Although the ESA retracker had a higher number of observations close to the coast for all satellite data (Fig 2.1, 2.2 and 2.3), the analysis later showed it to have lower correlations compared with the U. BONN and DTU retrackers. This implies that the new retrackers are extracting more reliable data than the operational ESA retracker.

S3A/B showed, as a function of distance to the coast, both the U. BONN and DTU retrackers had higher correlations close to the coast compared with the operational retracker ESA (Fig.3.4.1 and 3.5.1), leading to a higher accuracy closer to the coast.

4 Summary and Recommendations

- Uncorrected Sea Surface Height (USSH) data were used to calculate noise as a function distance to the coast.
- U. BONN had a consistently lower noise level compared with the DTU and ESA retrackers, although a spike occurred in noise level at the 10 km from the coast.
- Data less than 2 km of the coast were not included in the validation analysis as there was a dramatic deterioration in the USSH noise level at 1 km from the coast.
- The validation of the retracker output using total water level envelope (TWLE) and SLA was based on seven tide gauges.
- Preliminary investigation showed that sea state bias correction; wet and dry tropospheric corrections from the University of Porto and FES 2014 ocean model will be used for the validation of Sentinel 3A/B and CryoSat-2 against tide gauge data.
- For consistency with the altimetry data, the derived predicted ocean tide model from each tide gauge was used to remove the tide component but were constrained to the same number as used in FES 2014 for Sentinel 3A/B observations or FES 2004 for CryoSat-2 measurements. However, it was found that the variance of the residuals (Observations minus predicted model) from tide gauge records was significantly reduced when a full harmonic analysis was carried out using 59 tidal constituents. This implies that the FES 2014 (with 34 constituents) does not capture the whole tidal signal and may not be good enough for the SLA validation. The number of tidal constituents used for FES 2004 with CryoSat-2 is considerably less than FES 2014 and therefore the derived SLA will not be appropriate for the Bristol Channel / Severn Estuary region.
- Due to the uncertainty of the altimetry tide models, the analysis was separated into two components, using the altimetry TWLE and SLA where the Ocean model was FES 2014 (containing 34 tidal constituents).
- The DTU retracker outperformed the U. BONN and the ESA from the TWLE validation against the tide gauge data for both S3A/B and CryoSat-2 datasets.
- U. BONN retracker had the overall best performance for the SLA validation against tide gauge observations using Sentinel 3 data. However, the DTU retracker had a better performance from five out of the seven tide gauge stations.
- For completeness, the Sentinel 3 data were extracted between 2 to 8 km instead of 2 to 15 km around each tide gauge location and the results showed a small deterioration in correlation and STDD.

- CryoSat-2 data validation showed lower correlation and higher STDD values with the TWLE analysis. It is not clear why this occurred, but this may be affected by the non-repeating orbit where the tidal signal is not sampled adequately as each pass will be at a different distance and location with respect to the tide gauge. The Severn Estuary is so highly dynamic (mostly because of the large tidal range) that there is a lot of variability on small spatial and temporal scales. Thus, each pass will be subject to different dynamics and small-scale features of sea level variability with respect to the reference tide gauge location. The SLA validation was very disappointing with very low correlation and high STDD values. This is most likely due to the FES 2004 ocean tide model applied in the ice processor which is not appropriate for the Bristol Channel/Severn Estuary.
- A “caution” should be in place when using the derived SLA for S3A/B observations in the Bristol Channel and Severn Estuary because the FES 2014 ocean model may have limitations. Thus, it should be stressed that this caution is not related to the re-tracker’s performance.
- Both DTU and U, BONN retrackers outperformed the operational ESA retracker, for S3A/B which included more reliable observations and better accuracy close to the coast.
- The USSH noise level as a function of distance to the coast shows some differences in performance between S3A and S3B. However, this could not be validated as no tide gauge location coincided with both S3A and S3B tracks.
- The S3A/B correlations against tide gauge observations improved when the SSB correction was applied in the Bristol Channel and Serven Estuary. More future work is needed to have confidence that the SSB correction is applicable to the inland waters.
- A small improvement occurred when WTC/DTC from the University of Porto was applied using the U. BONN and DTU retrackers compared with the standard the WTC/DTC Model at Zero Altitude. We recommend that WTC/DTC from the University of Porto continue to be applied in future work which will improve with time and to act as an independent check.
- Given the similarity in performance in the DTU and U. BONN retrackers, we recommend use of the DTU re-tracker close to the coast to provide continuity with the water levels for the inflowing rivers (which are also provided by the DTU re-tracker).
- For future work, the DTU re-tracker should be implemented into new datasets in the coastal and inshore regions.

5 References

Garcia-Mondejar et al., (2020). Algorithm Theoretical Basis Document, October 2020. HYDROCOASATAL Project Report for ESA