# HYDROCOASTAL

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

## ESA Contract 4000129872/20/I-DT

### *Case study: Saline intrusion in the Ebro Delta*

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# 1. Introduction

In the Ebro Delta the saline intrusion is currently dominated by the river discharge (Sierra et al., 2004). However, other factors such as river bathymetry and climatology play a non-neglectable role (Sierra et al., 2004). In fact, it was found that anomalies in wind speed have a strong correlation with anomalies in saline intrusion (Sierra et al., 2004). Moreover, the saline intrusion is affected by the conditions in the river-mouth, that is the interaction between the river and the sea. Disregarding the turbulent conditions that the waves create, the higher the contact between the freshwater coming from the river and the saltwater from the sea, the higher the saline intrusion will be.

Currently, the relative height of the Ebro Delta with respect to the sea is slowly decreasing due to sea level rise (SLR), subsidence, sediment shortage and coastal erosion due to wave dynamics. All these factors can be brought together to build a relative sea level rise (RSLR) (Fatorić and Chelleri, 2012). The subsidence is a natural phenomenon that has been aggravated by the anthropogenic activities in the area (Fatorić and Chelleri, 2012), and the reduction in the sediment brought by the river has been extremely reduced in the last century after the construction of the Mequinensa dam at about 130 km from the river mouth (Sierra et al. 2004). Before the construction of big dams along the Ebro River, the sediment input compensated the natural coastal erosion, but currently there is no compensation and coastal erosion is transporting the eroded land to the lateral bays in the Delta, thereby making the river mouth bigger (Fatorić and Chelleri, 2012). Regarding the effect of sea level rise, it was found that with an increase between 0,5 to 1 m, most of the Delta would be flooded (Fatorić and Chelleri, 2012). In addition, a study, which investigated the effects of the mean sea level rise in soil salinity and rice production in the area of the Ebro Delta, found that if we considered the SLR interval predicted by the Representative Concentration Pathways (RCP) 8.5, by the end of the century the soil salinity would increase by 2 to 3 times, and the rice production would suffer a reduction between 5 and 30 % (Genua-Olmedo et al., 2016).

The objective of this study is to assess the possibility of calculating the SLR close to the Delta using altimetry data from Sentinel-3, in order to improve empirical models which only consider the river discharge (Sierra et al., 2004, Ibañez et al., 1996). Since the difficulties of measuring the sea level close to the coast are already known, the intention of this study is to compare the SLR at the bays surrounding the Ebro Delta with the SLR calculated up to 30 km from the coast.

# 2. Sea water level time series

## 2.1. Regions of interest

To investigate the SLR close to the Ebro Delta, we chose two regions of interest (ROI): the Alfacs and the Fangars bay which are shown in Figure 1. The ROI corresponding to Alfacs bay can be subsequently divided in two regions, the inside and the outside of the bay. In addition, Figure 1 includes the number of the Sentinel-3 tracks that go over these ROIs.

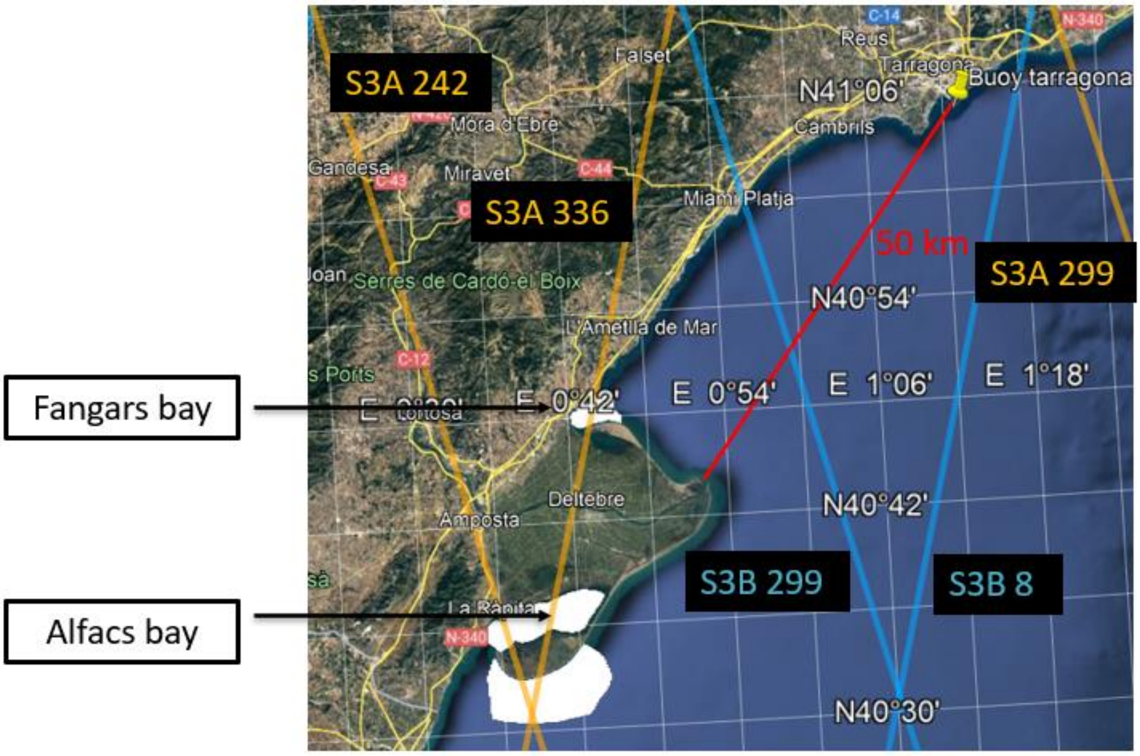



*Figure 1. Regions of interest close to the Ebro Delta.*

## 2.2. L2 and L3 algorithm description

To obtain the sea water level time series we used three different retrackers, so that we could investigate which one yielded the time series with less amount of noise. The three retrackers used were the Hydrocoastal Spatio-Temporal Altimeter Retracker for SAR altimetry (STARS) developed by the University of Bonn and the ESA's L2 SAMOSA 2.5 and OCOG retrackers.

To translate the altimetry range to water level we applied the following equation:

$$\text{water level} = \text{altitude} - \text{retracked range} - \text{geoid} - \text{corrections}$$

The geoid used in this equation is the official Spanish geoid called EGM08-REDNAP which has the ellipsoid WGS84 as reference. Regarding the corrections, the chosen ones considering the proximity to the coast are:

- Wet tropospheric correction (model, at measured altitude)
- Dry tropospheric correction (model, at measured altitude)
- Ionosphere correction (GIM)
- Sea state bias correction
- Ocean tide + non equilibrium correction
- Dynamic atmosphere correction
- Solid earth tide correction
- Pole tide correction

It is important to underline that since the along track resolution of S3 is 300 m, for each date we could get more than one water level.

Regarding the L3 algorithm, we start by filtering out some outliers. This is done by fitting all the L2 water levels to a normal distribution and discarding those points which are outside three standard deviations from the expected value of the gaussian. Next, we fit the water levels of each date to another gaussian, we take the expected value as the water level for that date, and the standard deviation as the uncertainty. Notice that if we only have one point per date, the uncertainty will be zero and thus become meaningless. Therefore, the uncertainty should be always given together with the numbers of points used in the calculation.

## 2.3. Noise quantification

The noise of the time series is calculated by first measuring the sea level difference between neighboring points (only to the right), calculating the corresponding absolute values, and finally obtaining the average. This is called AASLD:

$$\text{AASLD} = \text{average}(\text{abs}((\text{sea level difference}))$$

## 2.4. Sea level rise calculation

Since there is no standard method to calculate sea level rise, we implemented three methods commonly used in the literature. The three methods have in common the first two steps. First, the monthly average is calculated, and then, the water levels of missing months are guessed using linear interpolation. In the case the missing month is at the sides of the data, the corresponding date is simply deleted.

The differences of the three methods are the following:

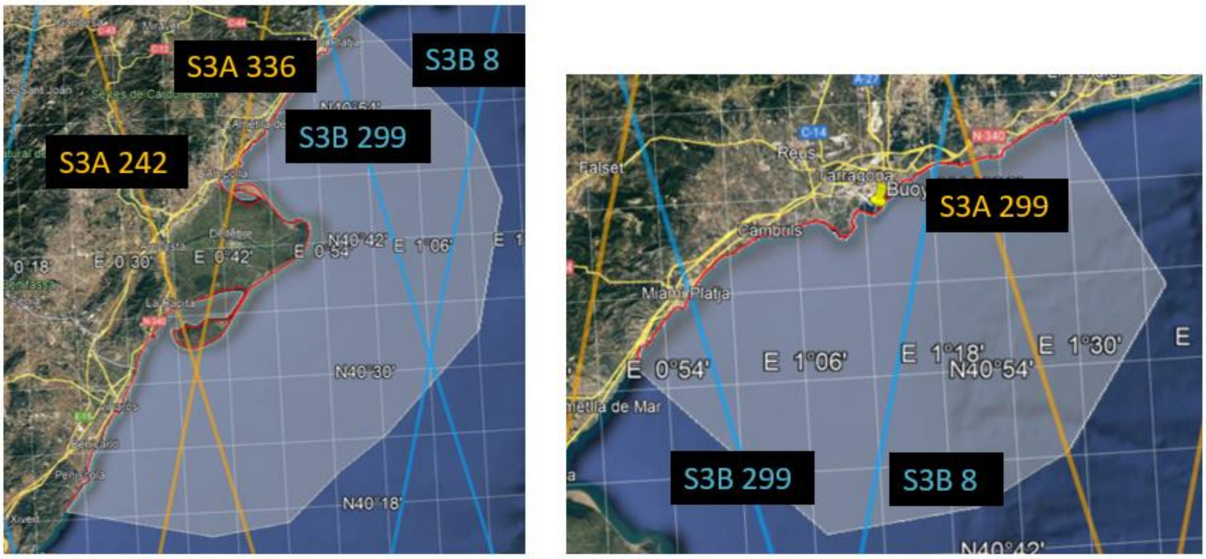
- Method 1 (LR): a simple linear regression.
- Method 2 (L + S): the data is fitted to a model which represents a line plus a sinusoid with the frequency of a year,

$$\text{sea level} = a + b \cdot t + c \cdot \sin 2\pi t + d \cdot \cos 2\pi t$$

- Method 3 (Lowpass + LR): first, a low pass filter is applied, specifically the Butterworth filter with a cut-off frequency of 1 Hz, a sample frequency of 12 Hz, and order 10. Then, like method 1, a simple linear regression is done.

## 2.5. Influence of the distance to the coast

The influence of the distance to the coast on the sea level rise was analyzed by investigating




two ROIs, which are displayed on Figure 2. One ROI was defined close to the buoy of Tarragona, so that we could compare it to the gauge data, and another ROI was defined surrounding the Ebro Delta.

*Figure 2. Regions of interest to analyze the influence of the distance to the coast on the sea level rise.*

The influence of the distance to the coast was studied using two approaches. The first approach looks at how the noise of the data changes with the distance, and the second approach looks at how the sea level rise changes. In order to perform these calculations, the data points were classified in boxes according to the distance to the coastline, which is displayed as a red line bordering the coast in Figure 2. Due to the resolution of 300 m for S3, we chose to build boxes with a separation of 1 km to the coast.

# 3. Results

## 3.1. Noise quantification

Table 1 shows the noise of the time series for the three ROIs calculated with the three retrackers. The noise retrieved from the range estimated by the STARS retracker from the University of Bonn is lower than the one retrieved from the range estimated by the SAMOSA 2.5 and OCOG retrackers from ESA. Regarding the number of points, the STARS retracker shows a slightly higher number of them. These results are aligned with the hydrocoastal project's previous results.

Consequently, the following of this analysis will be based on the STARS retracking estimates.

| | AASLD (m) – Number of points | | |
|---|---|---|---|
| Retrackers | Alfacs bay (inside) | Alfacs bay (outside) | Fangars bay |
| UBO | 0,16 – 173 | 0,11 – 174 | 0,20 – 86 |
| ESA OCEAN | 1,67 – 172 | 0,76 – 172 | 0,55 – 84 |
| ESA OCOG | 2,22 – 172 | 1,43 – 172 | 1,45 – 84 |

*Table 1. Noise measurements of the sea level time series close the Ebro Delta.*

## 3.2. Sea Level Rise close to the Delta

The different values of sea level rise calculated with the three methods using the time series obtained with the retracker of Bonn are shown in Table 2. On the one hand, the results indicate that the third method has the lowest uncertainty. On the other hand, the uncertainties are of the same or one order higher than the corresponding values and indicate that the sea level rise could be either negative or positive.

| | Sea level rise (mm/year) | | |
|---|---|---|---|
| Methods | Alfacs bay (inside) | Alfacs bay (outside) | Fangars bay |
| LR | 0,7 ± 6,0 | 1,0 ± 5,1 | 2 ± 12 |
| L + S | 0,6 ± 5,3 | 0,8 ± 3,8 | 3 ± 11 |
| Lowpass + LR | -0,6 ± 2,8 | -1,6 ± 2,6 | -0,7 ± 3,7 |

*Table 2. Sea level rise measurements for the ROIs close to the Ebro Delta.*

## 3.3. Influence of the distance to the coast

The noise of the data in the ROI close to Tarragona and to the Ebro Delta are displayed on Figure 3 and Figure 4 respectively. In Figure 3 we can observe that, in general, the noise retrieved from the STARS retracker is lower than the one retrieved from the L2 ESA retrackers, especially at a distance below 6 km from the coast; between 6 and 10km L2 ESA retrackers show a lower level of noise but at a distance to the coast over 10km the STARS retracker depicts lower level of noise. With respect to the results on the ROI close to the Ebro Delta, Figure 4 shows similar results i.e. the STARS retracker is less sensitive to the proximity to the coast in comparison to the ESA retrackers.

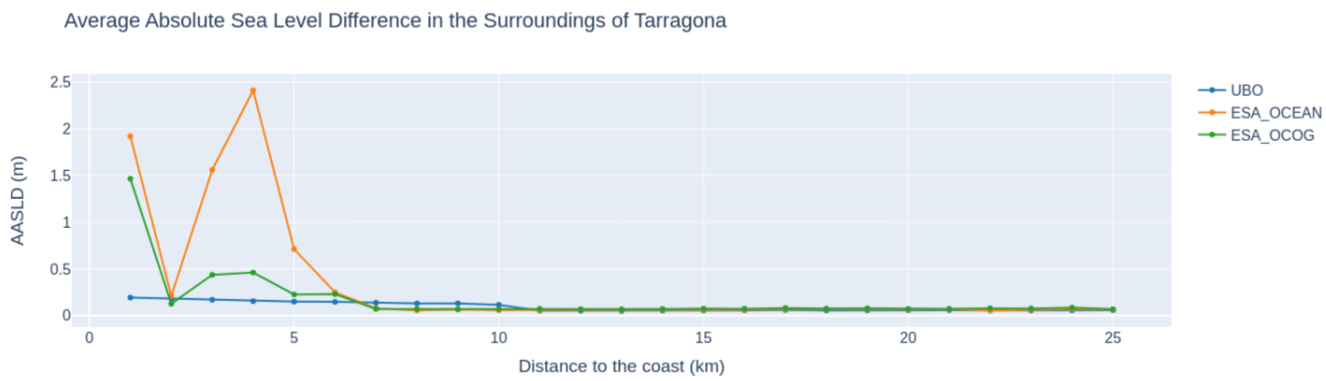



*Figure 3. Different retrackers' noise dependence on the distance to the coast close to Tarragona.*

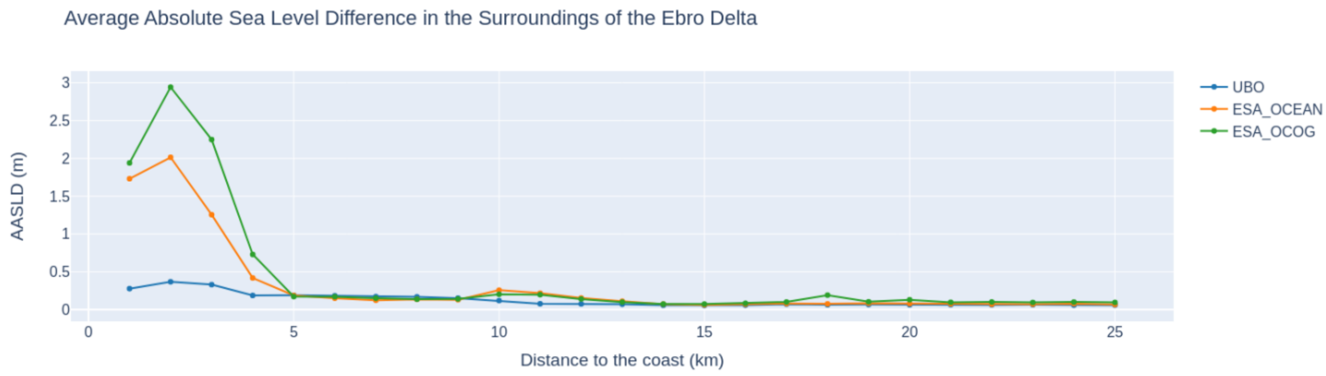



*Figure 4. Different retrackers' noise dependence on the distance to the coast close to the Ebro Delta.*

The influence of the distance to the coast in the estimation of SLR is shown on Figure 5 and Figure 6 for the ROI of Tarragona and Ebro Delta respectively. For all the retrackers the uncertainty in SLR is reduced when increasing the distance to the coast.

For the Bonn retracker, in Tarragona area, at the furthest (30 km) and closest (1 km) points to the coastline, the calculated sea level rise are 5,0 ± 3,7 mm/year and 9,8 ± 8,3 mm/year respectively (see Figure 5). In the Ebro Delta they are -2,3 ± 3,6 mm/year and 0,12 ± 9,98 mm/year respectively (see Figure 6). These results seem to be contradictory among them with a positive trend in Tarragona but a negative trend in the Ebro Delta. However, the uncertainty of these results is of the same order of magnitude of the estimated SLR.

Furthermore, these results show that increasing the distance to the coast, even if important to reduce the noise of the data, it does not suffice to obtain SLR estimations with acceptable uncertainties. These large uncertainties might be related to the relative short time span of the sea level time series. In the next Section we will try to investigate the impact of the length of the measurements on the sea level rise estimation uncertainty.

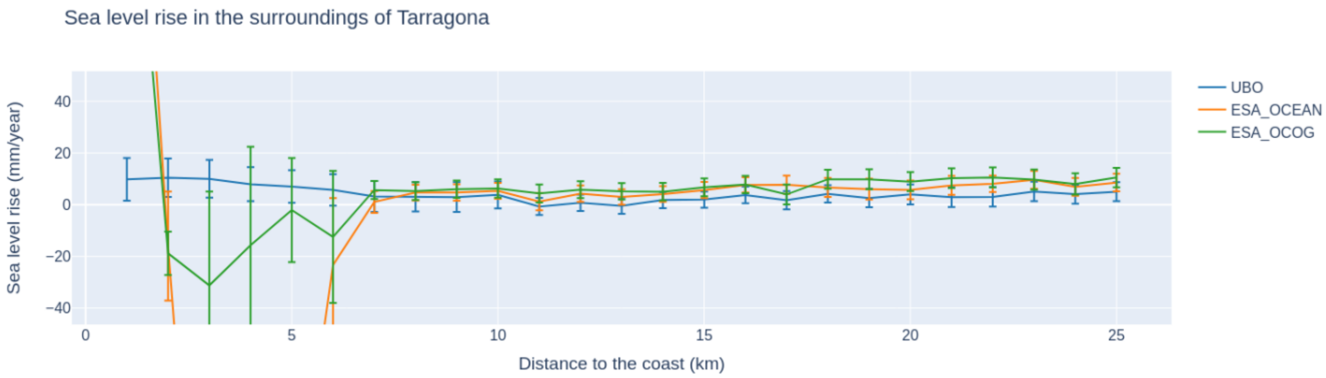



*Figure 5. Dependence of the sea level rise on the distance to the coast for the ROI close to Tarragona.*

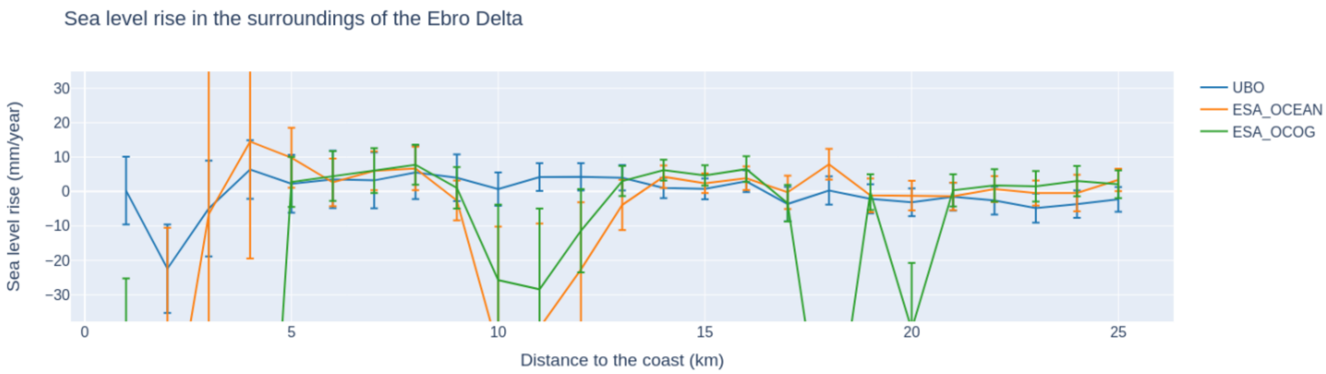



*Figure 6. Dependence of the sea level rise on the distance to the coast for the ROI close to the Ebro Delta.*

# 4. Necessary time span to calculate the sea level rise

This section uses in situ data to determine which is the necessary time span to obtain a SLR estimation with an uncertainty below the mm range.

## 4.1. Methodology

With the objective of investigating how the number of months taken in the calculations affect the uncertainty in the obtained sea level rise, we analyzed the gauge data of a buoy located in Tarragona, 50 km away from the Ebro Delta as indicated in Figure 1. This gauge station was chosen since it was the closest station to the Ebro Delta which publishes the data openly to the public. The data was provided by Puertos del Estado.

In comparison to the data available of S3, which is only available from April 2016, the gauge station started operating on the January of 1993. Therefore, it allows us to make sea level rise predictions with a time span of more than 25 years.

To investigate the sea level rise dependence on the time span, we first calculated the sea level rise using the entire time series using the three previously mentioned methods. Then, instead of taking the entire span we calculated the sea level rise for a time window with a certain number of months. We did this in steps of one month for two types of windows. A window starting on 1993 and increasing in size along the direction of time, which we called “starting from the left”, and a window starting on 2020 and increasing in size along the opposite direction of time, which we called “starting from the right”.

## 4.2. Results

The sea level rise calculations using the gauge data of the Tarragona buoy and calculated with the three aforementioned methods are shown in Table 3. We can observe that the third method, that is the one with the low pass filter, continues to yield the lowest uncertainty. In addition, with this method the uncertainty is one order of magnitude lower than the corresponding value, which brings confidence to their validity.

| | Calculation method | | |
|---|---|---|---|
| | LR | L + S | Lowpass + LR |
| Sea level rise (mm/year) | 5,67 ± 0,52 | 5,50 ± 0,41 | 5,55 ± 0,28 |

*Table 3. Sea level rise calculated from the gauge data of the buoy in Tarragona.*

Regarding the study on the dependence of the time span on the sea level rise, the results are displayed on **Figure 7**. It is important to underline that the currently available time span of S3 is only of 84 months. As we can observe, for a number of months below 100 the sea level rise values are unstable, and the corresponding uncertainty of the same order of magnitude. It's not until we cross 125-150 months that the uncertainty goes below 1 mm.

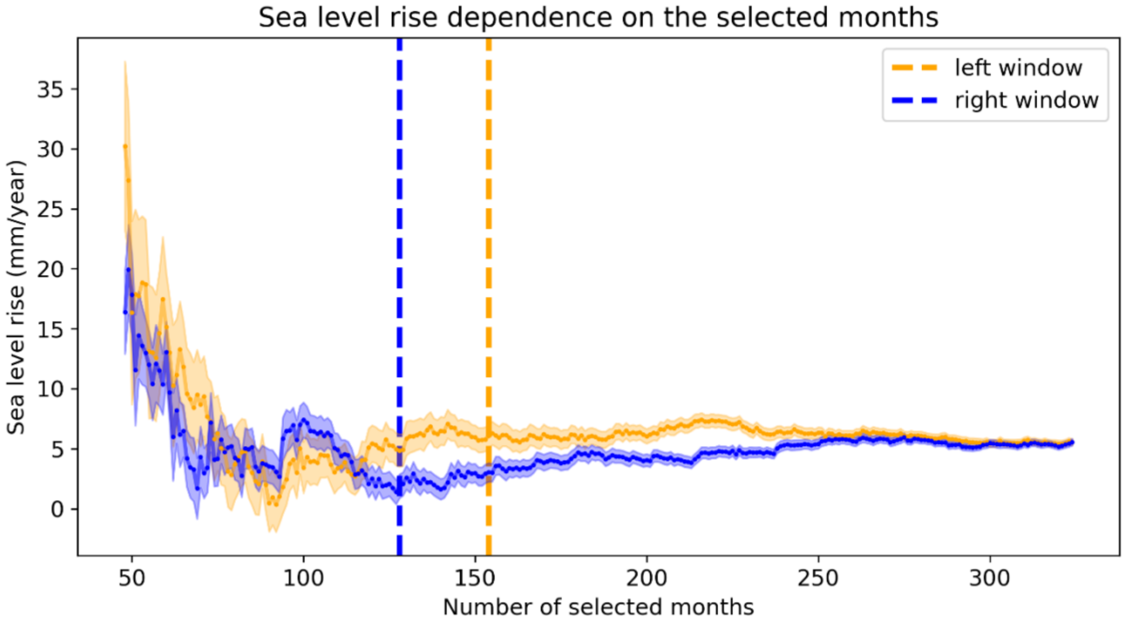



*Figure 7. Sea level rise dependency on the time span measured for the data from the buoy of Tarragona. The dashed vertical lines indicate the number of months at which the uncertainty (the shadow) reached a value below 1 mm.*

# 5. Conclusions

## 5.1. Study Case Outcomes

The noise in sea surface height of Hydrocoastal UBO retracker has proven, in general, to be lower than the one from the SAMOSA and OCOG estimates available in L2 ESA operational products, and it also has slightly better results regarding the number of points.

We implemented three methods to estimate sea level rise, the method with the lowest uncertainty was to apply a low pass filter before estimating sea level rise by linear regression to monthly estimates of sea level. The sea level rise estimates close to the Ebro Delta were -0,6 ± 2,8 mm in Alfacs bay (inside), -1,6 ± 2,6 mm in Alfacs bay (outside) and -0,7 ± 3,7 mm in Fangars bay. A decrease of sea level is not expected as all studies in the Mediterranean region are estimating positive increases in the order of 3 mm per year. Being the uncertainties of the same order of magnitude (or higher) than the corresponding values, it indicates that the sea level rise could be either negative or positive. Consequently, we did a small study to investigate whether these results were related to the relatively short time span of the sea level estimates.

Our results indicate that for a number of months below 100 the sea level rise values are unstable, and the corresponding uncertainty of the same order of magnitude. In order to obtain an estimation of SLR with an accuracy below 1 mm, we would need more than 10 years of data (currently available time span of S3 is only of 84 months).

Despite the technical challenge, an accurate determination of SLR is crucial to model the saline intrusion in delicate regions such as the Ebro Delta. An increase in sea level would not only change the water depth at the mouth of the river, but it would also lead to a potential flooding of the whole Delta, and thus to salinity reaching deeper into the river.

It is important to underline that the flooding of the Delta is not only caused by the sea level rise, thus a next generation model should consider the complex behavior which represents it. This includes the erosion of the coast due to extreme events, the reduction of sediment content to compensate the erosion, and the sinking of the Delta caused by the compression of its land due to its own weight, i.e., subsidence.

## 5.2. Recommendations

In our study area, both Hydrocoastal L2E products for inland and coastal areas showed improved performances compared to baseline L2 products.

The impact of the improved coastal products in sea level rise estimation could not be properly evaluated due to the relatively short time series duration (it was estimated that at least 10 years are needed to get estimations with acceptable levels of uncertainty). With the current length of data records, SLR derived from Hydrocoastal products seem to diverge from baseline products even at relatively large distance from the coast. It would be recommended to assess the impact of the improved products in SLR estimations in other areas to confirm these preliminary results and revise them when longer datasets are available.

# 6. References

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