On the absolute sea level at the Swedish west coast estimated by VLBI, GNSS, and tide gauges

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G. Elgered and R. Haas

Abstract We analyse the existing ten year time series of sea level observations at the Onsala Space Observatory. A time series of ten years is however too short to result in a stable value for a linear trend. Therefore we compare the sea level data acquired at Onsala with those from the nearby tide gauge station Ringhals. The tide gauge at Ringhals started operations in late 1967. Using Ringhals sea level data we estimate a linear trend for the relative sea level of 0.54 mm/year. Space geodesy observations using Very Long Baseline Interferometry (VLBI) from 1980 to 2020 and Global Navigational Satellite Systems (GNSS) from 1994 to 2020 have resulted in estimates of the land uplift of 2.9 mm/year and 2.7 mm/year, respectively. Combining the relative sea level trend at Ringhals with the land uplift at Onsala result in an estimate of 3.3 mm/year for the linear trend of the absolute sea level for this region. This is in agreement with recent estimates for the linear trend of the global sea level rise during this time period.

Keywords sea level, tide gauge

1 Introduction

The geodesy Very Long Baseline Interferometry (VLBI) radio telescopes and the Global Navigational Satellite Systems (GNSS) stations at the Onsala Space Observatory are all located within a few hundred metres from the Kattegat coastline. Therefore, a collaboration begun with the Swedish Meteorological and Hydrological Institute (SMHI) to install a tide gauge station at the observatory (see Figure 1). SMHI is responsible for the national observational network of sea level in Sweden and the data are available by open access. This station has been operational since June 2015 and its characteristics have been presented at an earlier EVGA meeting (Elgered et al., 2019). There is now a time series of the relative sea level for almost ten years. It is still a bit short to combine with geodetic height data to assess long term trends in the absolute sea level. However, the tide gauge station Ringhals, located 20 km south-south-east of Onsala has been operational since 1 November 1967. In the following we present observational data from these two stations and combine the results with recent estimates of the land uplift from VLBI and GNSS in order to derive a value for the linear trend of the absolute sea level rise in this region.

Fig. 1 The tide gauge station at the Onsala Space Observatory.

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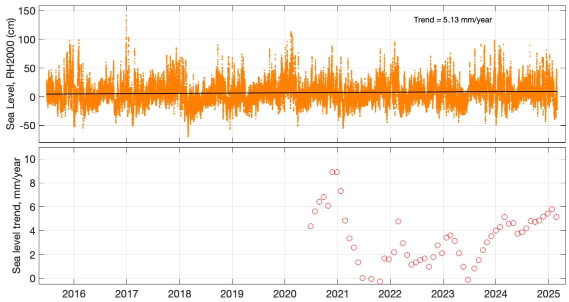

Fig. 2 Sea level observations at Onsala (top). The estimated linear trend from the start to a specific date show that seasonal and yearly variability is significant (bottom).

2 Onsala tide gauge

The tide gauge station is equipped with several sensors, three radar sensors, one laser sensor, and two pneumatic sensors (Elgered et al., 2019). The official sensor is the CS476 radar. Hourly values of the sea level are archived and available via the SMHI web pages (open access). We show the complete time series, from 00 UT 24 June 2015 to 24 UT 28 February 2025, in Figure 2. Starting five years from the first observation we also present estimates for the linear trend when adding one more month of data for each estimate. We note that the variability is significant, also towards the end of the time series, and conclude that the changing weather conditions, mainly in terms of pressure and winds from year to year, have a large influence on the overall trend.

The sea level at Onsala has roughly varied between half a metre below to one and a half metre above the average sea level. The variations are dominated by changes in weather, i.e., the pressure and the direction and the speed of the wind. An example when the weather conditions are rather stable is presented in Figure 3. The tidal signal is hence rather weak, a typical peak-to-valley difference of about 20 cm.

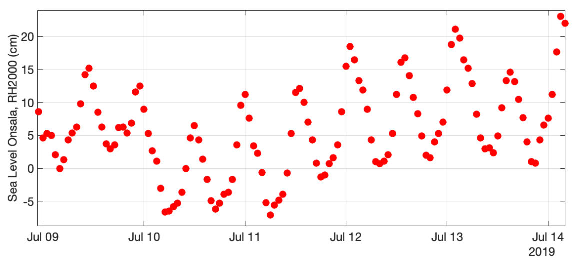

Fig. 3 An example time series of the sea level at Onsala during five days in July 2019 when the weather conditions were rather stable and the tides are clearly visible.

3 Comparison: Sea level at Onsala and Ringhals

We use the existing simultaneous data (from June 2014 to February 2025) to assess the question of how representative the Ringhals tide gauge station is for the corresponding one at Onsala. The Onsala and Ringhals stations provide 84,819 and 84,329 data points, respectively. This corresponds a coverage of 99.86 % and 99.29 %, respectively. Before the comparison is done, we select only data points that are acquired on the same hour resulting in 84,235 data points, corresponding to 99.2 % of the total period. The sea level observations at Ringhals are shown in Figure 4. When comparing Figure 2 and Figure 4 we see an overall agreement but a difference in the sea level trends of about half a mm/year: 5.13 mm/year at Onsala and 5.61 mm/year at Ringhals.

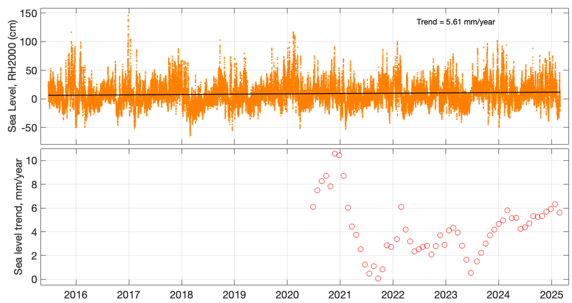

Fig. 4 Sea level observations at Ringhals, c.f. Figure 2.

The mean sea level averaged over this time period is 7.1 cm at Onsala and 9.0 cm (RH2000) at Ringhals. The observations are shown together with their differences in Figure 5. We note that occasionally during high sea level, the difference is large with higher values at Ringhals.

This effect is studied further using Van de Casteele diagrams in Figure 6. The horizontal error bars in the right graph indicate the formal uncertainty assuming a gaussian distribution.

The reason for the differences during high sea level is not known. The high sea levels occur during storms,

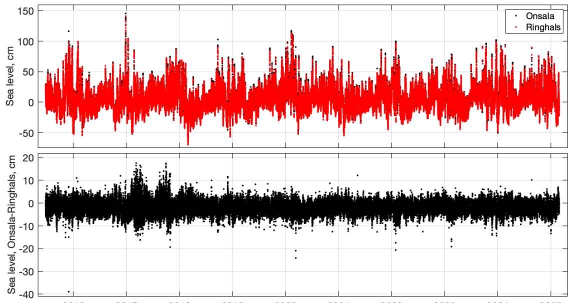

Fig. 5 Sea level observations at Onsala and Ringhals (top) and their differences (bottom).

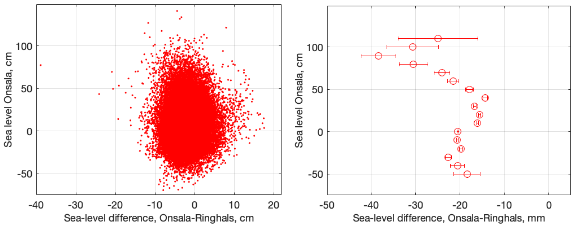

Fig. 6 Van de Casteele diagrams showing the differences in sea level at Onsala and Ringhals. Individual hourly observations are shown in the left graph and mean values for 10 cm intervals in the sea level at Onsala are shown in the graph to the right.

and we may speculate that the local environment, i.e., the location of the tide gauge station relative the shape of the coastline, plays a role during these occasions, see Figure 7. We estimated the sea level trends also by ignoring values of the sea level at times when one or both sites observed a sea level above a certain level. However, we find that the difference of the half mm/year remains in all cases.

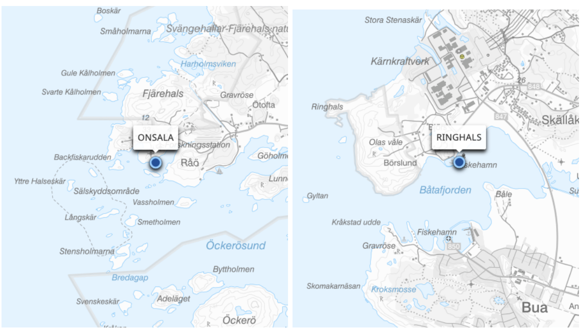

Fig. 7 The locations of the tide gauge stations at Onsala and Ringhals; © maps Lantmäteriet.

4 The absolute sea level

There are several geodetic reference markers in and around the Onsala tide gauge well. Levelling of the markers in the well relative to those in the bedrock are carried out roughly on a yearly basis. All markers are, however, not visited every time. The reference marker 827a is located on the mounting plate of the main radar sensor CS476 and the markers 827 b, c, and d, are also located in the well, see Figure 8.

These results are presented in Table 1. They show a standard deviation in the range from 0.3–0.5 mm relative to the the reference marker 822, in the bedrock close to the well.

Table 1 Levelling results to the reference points in the well

	Height in RH2000[a]			
Date	827a (m)	827b (m)	827c (m)	827d (m)
2015-02-01	2.54617	–	–	–
2015-08-13	2.545	2.487	2.544	2.487
2016-08-05	–	–	–	2.4872
2017-06-01	–	2.4870	2.5446	2.4878
2017-07-26	–	–	–	2.488
2017-08-11	–	–	–	2.4876
2019-08-20	2.5453	2.4872	2.5447	2.4877
2020-03-31	–	–	–	2.4868
2020-10-05	2.5451	2.4865	2.5440	2.4878
2021-03-12	–	–	–	2.4868
2021-07-06	2.5459	2.4874	2.5450	2.4878
2024-08-13	2.5458	2.4870	2.5447	2.4877
Mean	2.5456	2.4870	2.5445	2.4875
SD[b] (mm)	0.47	0.30	0.41	0.43

[a] Assuming that the reference marker 822 is at 2.1064 m
[b] SD: Standard Deviation

The complete time series of the relative sea level at Ringhals is shown in Figure 9. The linear trend estimated from these data is 0.54 mm/year. We also note a slight increase in the rate when including the data from the last ten years. This in agreement with the higher rates observed at Onsala and Ringhals using the observations from 2015 to 2025 only.

In order to derive trends in the absolute sea level the relative results need to be corrected for any ongoing vertical motion of the Earth's crust. In northern Europe this long term trend is dominated by the glacial isostatic adjustment since the last ice age, see

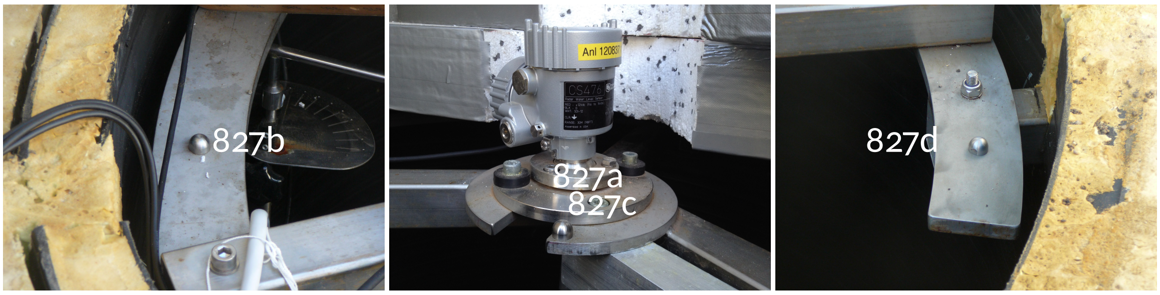

Fig. 8 Reference markers in the well. Marker 827a was first measured in February 2015. The additional markers 827b, 827c, and 827d were added thereafter and were first measured on August 13, 2015.

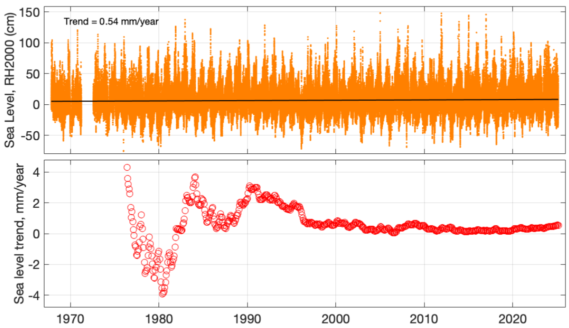

Fig. 9 Top: The complete time series of sea level observations at Ringhals. Bottom: The estimated linear trend from the start in 1967 to a specific date.

e.g. Kierulf et al. (2021). Geodetic observations as summarized in ITRF2020 (Altamimi et al., 2023) give an estimated uplift of:

- 2.7 mm/year using GNSS data (1994–2020)
- 2.9 mm/year using VLBI data (1980–2020)

It is reasonable to believe that these values for the uplift of the Earth's crust are rather constant over a several decades. This is different from the sea level trends.

Assuming that the sea level measured at Ringhals, during the 57 years of operation, is representative also for Onsala, and that the uplift at Onsala is approximately equal to that at Ringhals, means that an overall linear trend of the regional absolute sea level has been approximately 3.3 mm/year averaged over the period 1967–2025.

5 Conclusion

The sea level at a specific site or region show large variations, depending on the variability of the weather conditions from season to season and from one year to another, compared to the expected values for the long-term trends. Therefore, stable and reliable values for any trends can only be obtained by averaging either over a very large area or over a long time. The absolute sea-level rise from 1967 to 2025 in the Onsala / Ringhals area of Kattegat has been 3.3 ± 0.2 mm/year. We also see an indication that there is an acceleration towards the end of the time series. If this is true it is consistent with recent results reported for the global sea level trend (Hamlington et al., 2024).

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