Kartverket

Report 19/04811-19

Extreme water levels for Norway

Updated extreme value analysis based on data series up to and including 2022

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Author: Hilde Sande Borck and Oda Roaldsdotter Ravndal

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Summary: This report presents updated extreme still water levels for the Norwegian coast and Ny-Ålesund released in the spring of 2024. The extreme value analysis is done using the same approach as in 2015, using the ACER method, but extending the time series to also include observations from 2015-2022. Significant improvements in data quality have also been made since the last major revision in 2015 and new permanent tide gauges have been established. The results show minor changes in extreme still water levels compared to 2015, with reduced uncertainties, especially for tide gauges with shorter data series. A new high-end water level for local planning is introduced, combining the 1000-year extreme surge with the highest astronomical tide (HAT). The report also discusses limitations and future work, recommending continuous updates to the tidal model and data quality, and improved knowledge of how local effects influence extreme water levels. Further research is recommended on optimal data series length, detrending routines, and methods for extreme value analysis,

Keywords: Extreme value analysis, extreme water levels, return level, storm surge, tide gauge, tidal data, tidal zone

Cover photo: Bente Berggraf

Approved by: Nicolien Haasbroek

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Norsk sammendrag

Rapporten "Ekstreme vannstandsnivåer for Norge" beskriver ekstremverdianalysen Kartverket har gjort av vannstandsdata fram til og med år 2022. Dette resulterte i oppdaterte offisielle ekstreme vannstandsnivå for Norge, gyldige fra april 2024.

Omfang og begrensninger: Rapporten omhandler arbeidet med en oppdatert ekstremverdianalyse for vannstand for kysten av Norge og Ny-Ålesund. Kartverket har brukt ACER-metoden for å beregne ekstreme vannstandsnivåer med samme parameterinnstillinger som i 2015, men har utvidet datasettene med data fra det permanente nettverket av vannstandsmålere for årene 2015-2022. Det er gjort betydelige forbedringer i datakvaliteten siden forrige analyse og nye vannstandsmålere har blitt etablert, men fortsatt er det enkelte områder som ikke dekkes av dagens modell for vannstand eller av denne ekstremverdianalysen. I tillegg er det enkelte lokale effekter som ikke er tatt med, og det er verdt å merke at analysen heller ikke inkluderer bølgepåvirkning.

Resultater: Analysen viser at de ekstreme vannstandene langs norskekysten i liten grad har endret seg siden 2015. Det er noen lokale variasjoner. For eksempel har Andenes en 15 cm lavere 1000-års ekstremvannstand enn tidligere, mens Viker har en 5,5 cm lavere verdi. Generelt er usikkerheten i de ekstreme vannstandene redusert, spesielt for stasjoner med korte dataserier. Rapporten introduserer også et nytt øvre estimat for vannstand til bruk for blant annet kommunal planlegging, basert på en kombinasjon av 1000-års ekstrem stormflo og høyeste astronomiske tidevann (HAT).

Videre arbeid: Rapporten anbefaler kontinuerlige oppdateringer av tidevannsmodellen og datakvaliteten, samt videre forskning på optimal lengde av dataserier og forbedring av detrending-rutiner. Det foreslås også å undersøke alternative metoder for ekstremverdianalyse og å øke forståelsen av lokale effekter som kan påvirke ekstreme vannstander, inkludert fjorddynamikk og samspillet mellom elv og kyst.

1 Introduction

1.1 Background and scope

The Norwegian Mapping Authority operates the national permanent tide gauge network and is responsible for both data sets and products based on these observations, including the extreme still water levels, hereafter referred to as extreme water levels.

Extreme water levels are statistically calculated levels giving the present-day risk of inundation. These levels include tides and surges, as observed at the tide gauges along the coast of Norway but does not include other effects like waves. This is important information in local planning and building, in civil protection and special alerts, and for defining natural hazards, for instance when it comes to insurance claims.

The Norwegian Mapping Authority provides the official extreme water levels for the Norwegian coast and a few locations on Svalbard. A major revision of this product is considered every 5 years, this includes reviewing the methods and the selection of data, as well as adding the years of observed water level data since the last major analysis. Minor updates to the product are done continuously whenever the data available for a location is improved.

The last major revision of the extreme water levels for the whole coast of Norway was done in 2015 (Ravndal & Borck, 2016) in connection with the national sea level rise report. A new major revision was considered in 2020, but as the extreme water levels from 2015 (with the continuous updates) were considered to still be valid, it was decided to postpone the major revision and align it with the upcoming work to update the sea level rise report.

During the work with the sea level rise report (Simpson et al., 2024), commissioned by the Norwegian Environment Agency, it was decided that the extreme still water levels should be updated for the entire Norwegian coast, using the same methodology as in (Simpson et al., 2015) but with an improved knowledge base. In the dialogue with the Norwegian Environment Agency, it was furthermore decided that there was a need for a large impact – low probability level and that the methodology for this was to be determined. In this report, the basis for both deliverables is presented and discussed in more detail than in (Simpson et al., 2024).

Before presenting the results, we discuss the available data for the analysis, including the new data from 2015-2022, quality improvements and other changes of the data sets. The tidal zones and estimation of water level for the entire coast is then explained, before the preprocessing steps and preparation of times series for the analysis. These methods have not changed since 2015, but the zones have been improved and there are some new challenges with this approach for areas with a newly established permanent tide gauge.

We then discuss the results of the extreme value analysis which resulted in an updated official product for Norway valid from April 2024 including the new high-end water level estimate to be used as the large impact – low probability scenario, with a discussion in the appendix of different approaches considered.

Since it was decided to use the ACER-method (Skjong et al., 2013) also for this major revision, this report does not discuss different methods for extreme value analysis or other ways to estimate the water levels and the extreme values away from a permanent tide gauge. However, we include some observations and discussions of weaknesses of the approach used, a few tests, and some thoughts on future work.

1.2 Notations and abbreviations

Different communities use slightly different terms for the same thing or the same term for different things. We therefore try to identify the most important terms here, together with a list of abbreviations used in this report.

1.2.1 Important terms

Tide gauge, mareographs and water level or sea level station: Traditionally tide gauge or mareographs has been used for installations measuring the water level, but nowadays water level stations or sea level stations are also used. In Norway we talk about our network of water level stations, but as tide gauge is still mostly used in English, we use tide gauge in this report.

Modern high-quality data, historical data: Water level data collected in Norway after the modernization of the permanent tide gauge network around 1990 are described as *modern high-quality data* while *historical data* is typically used to denote data older than this. The exact year for the modernization varies from 1986 to 1992. Then the existing paper-based tide gauges were replaced by digital encoders, and the temporal sampling went from hourly to 10-minutes, and in 2007 to 1-minute.

Tidal zone model: The model used to define the tides along the Norwegian coast is a *tidal zone model*. It consists of polygons where the tide is expected to be similar enough to be modelled by the same time series. The tidal zone model is the basis for modelling water levels along the coast and includes information about what surge to use for this.

Water levels and still water levels: In this report the term *water levels* are used for the water level as observed at a tide gauge (water level gauge), which corresponds to the term *still water levels* in for instance (IPCC, 2022). This is the average water level without effects caused by wind waves, such as infragravity waves, wave setup and swash.

Extreme value analysis (EVA), extreme water levels, return levels, return period: An *extreme value analysis* is a method where the extremes in a statistical distribution are studied. One output from the *extreme value analysis* is *return levels* with their appropriate *return period*. There exist different methods for *extreme value analysis*, and it is performed on a number of applications. *Extreme water levels* are here used for the results from an extreme value analysis on the water level observations, giving the present-day risk of inundation. An *extreme water level* with a *return period* of 20 years, often referred to as a 20-year *extreme water level*, is a level that statistically occurs once every 20 years, or has a 1/20 probability of occurring any given year.

Observed surge, weather effect and residuals: The *observed surge* is the difference between the observed water level and the predicted tide at a given time, often also referred to as the (surge) *residuals* or *weather effect*.

Skew surge: The *skew surge* is the difference between the maximum observed water level and the predicted high-water closest in time.

Storm surge: An abnormally high surge that is typically observed during or in relation to a storm, resulting from (mainly) the effect of wind and low pressure.

1.2.2 List of abbreviations:

ACER: Average Conditional Exceedance Rate.
EVA: Extreme value analysis.
HAT: Highest astronomical tide.
MSL: Mean Sea Level.
$MSL_{1996-2014}$: The current, official Norwegian realization of MSL, using data from the period 1996 to 2014.
NMA: Norwegian Mapping Authority.
NN2000: The Norwegian vertical datum of 2000.

2 Data: Observations, models and preprocessing

Although the method of EVA is the same as the one performed in 2015, there has been significant changes in the data used for the analysis. We give a brief description of the data used for the analysis, the changes that have been made on the data series and the tidal zones since the last update and the pre-processing steps carried out before the EVA.

2.1 Observations from the Norwegian tide gauge network

The observations from the Norwegian tide gauge network are the foundation for the work described in this report. In this chapter we will describe the network and the regional differences in Norway, and the work done to improve the quality of the data since 2015.

2.1.1 Introduction to the network and observations used for the analysis

The Norwegian permanent tide gauge network consists, per April 2024, of 30 tide gauges, 29 of these along the Norwegian coast and one in Ny-Ålesund in Svalbard. Figure 1 shows an overview of the network. The tide gauges have mainly been installed in open areas, with little influence from rivers and estuaries. The year of installation, and thus the length of the observation series varies from tide gauge to tide gauge. Note that the newest tide gauges in the network were installed between 2021 and 2023 and are not yet used for EVA.

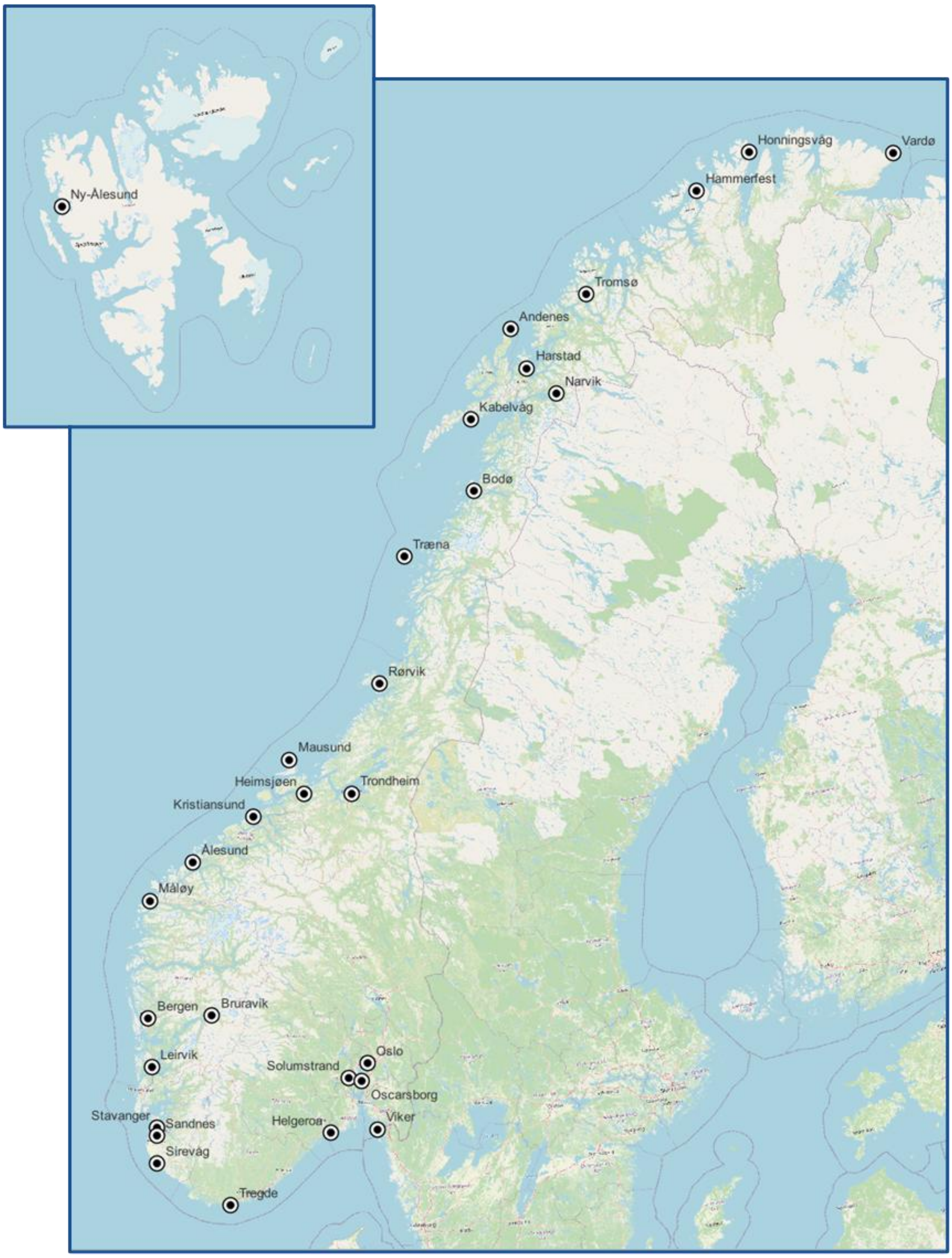

Figure 1: The Norwegian permanent tide gauge network as of April 2024

The tidal pattern, and hence the water level pattern varies significantly along the Norwegian coast. Figure 2 and Figure 3 shows the pattern of the total water level and of the surge, geographically sorted. In the southern part of the country, the water level is surge dominated, with a tidal amplitude of only a few centimetres close to Egersund on the south-western coast. The surge can be both positive and negative and is observed to be the highest in Oslofjorden. In western and northern Norway, the water level is tide dominated, with a tidal amplitude generally increasing northwards along the coast. In the southernmost tide gauges the effect of the diurnal tide is masked by the surge, while the diurnal tide is clearly visible as two peaks in the histograms in Figure 2 as we move west and north. We also observe that the total water level variation is increasing going north because of the increasing tidal amplitude.

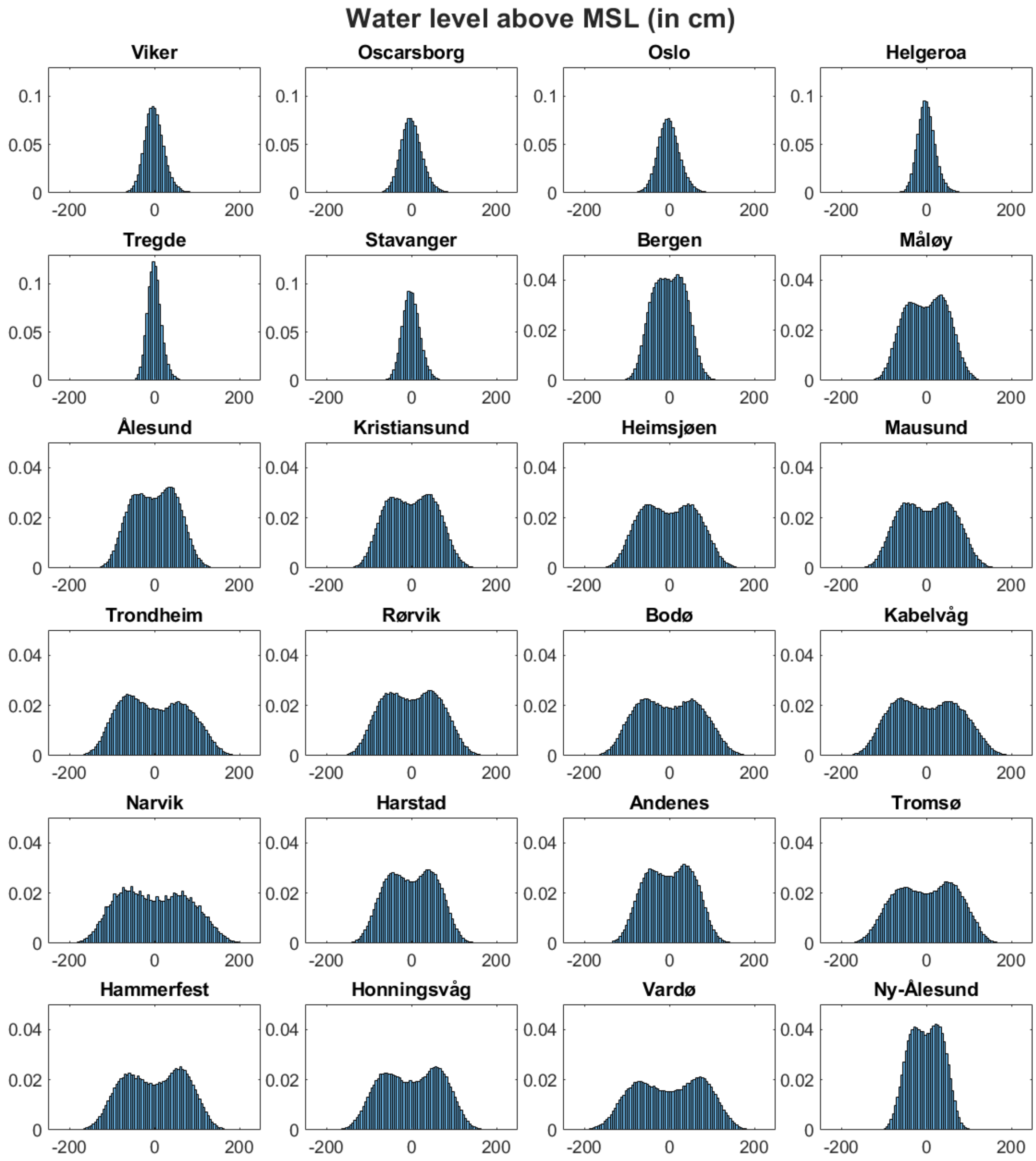

Figure 2: Normalized histogram plot of the water level in all the data series used. The plots have been sorted geographically. Due to the changing pattern of the data, the y-axis has a different resolution for locations south of Bergen.

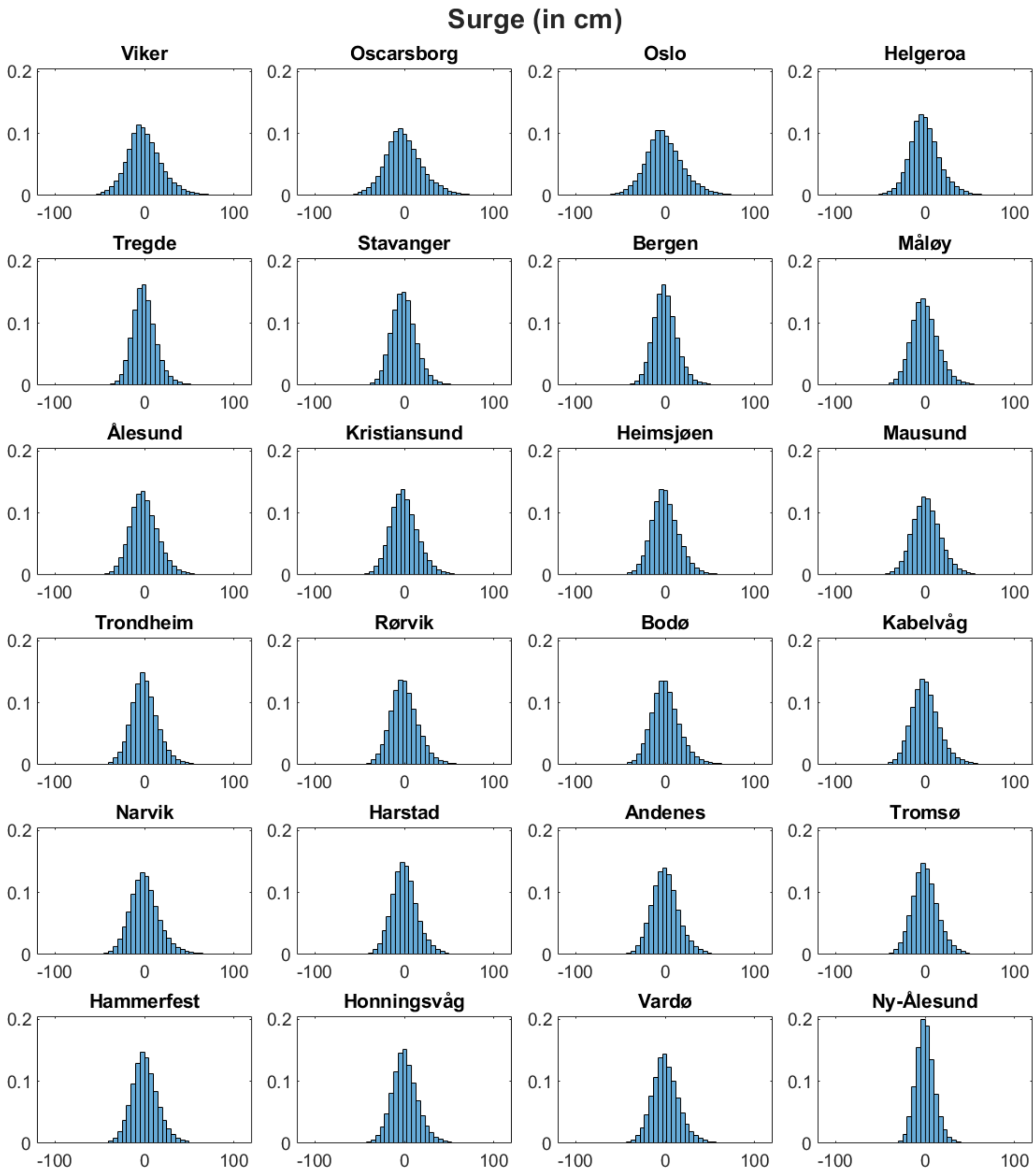

Figure 3: Normalized histogram plot of the surge in the last 31 years of the data series used. Plots have been sorted geographically.

2.1.2 Knowledge base and major changes since the last revision

The water level data used in this work has been collected over multiple decades, using different equipment and procedures. Figure 4 illustrates the length and the completeness of the time series from each permanent tide gauge used in the analysis. The previous analysis (Simpson et al., 2015) used data through 2014, for the analysis described here eight more years have been added.

In (Breili, 2022), a buddy check of the tide gauges was performed. This buddy check shows a significant quality improvement after approximately 1990 for all the tide gauges in that analysis. This corresponds to the time where the equipment at the tide gauges were changed, and we refer to data after this as modern high-quality data.

Although the older data has been quality controlled after they were digitized, there might still be errors in the data series. Errors could be related to the measurements themselves – a reference level not recorded properly, malfunctioning of tide gauge, timing errors related to the clock on the tide gauge, or to the digitization process – typing errors, misplacement of water level curves in time etc. The historical water level data are typically graphs recorded with a pen on paper, and the vertical and horizontal resolution will therefore vary with the tidal amplitude and equipment type. Although the full curve is available, generally only instantaneous hourly values were stored, which is different from the modern process, described in 2.3.1.

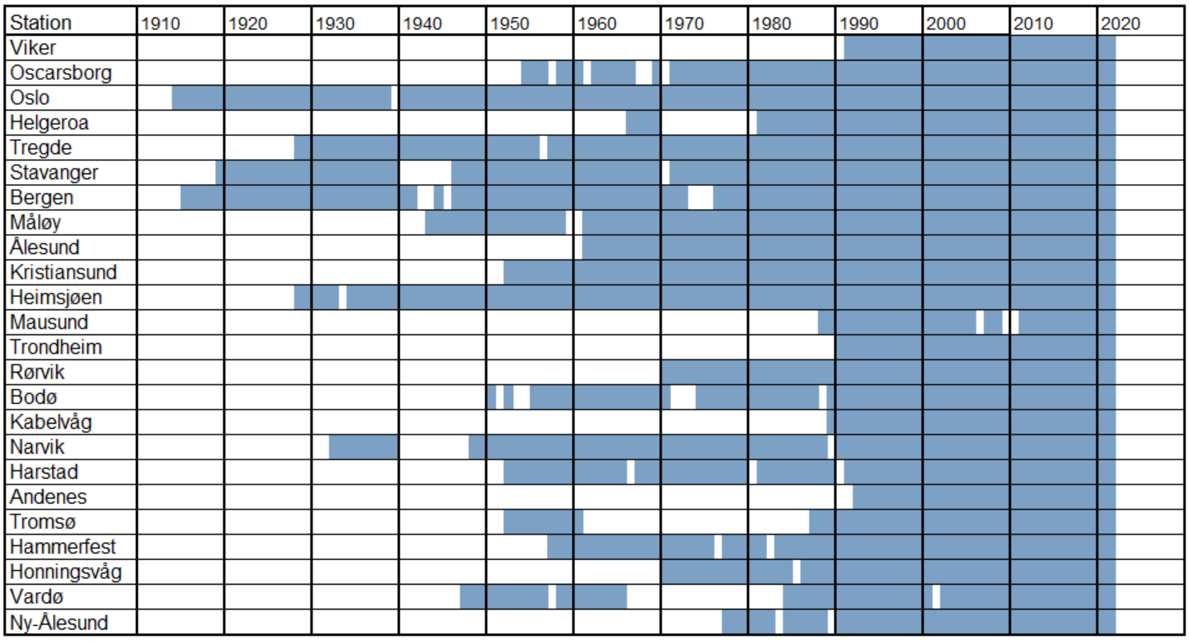

Figure 4: Length and completeness of observations used in the analysis.

Data from the tide gauge in Mausund was not included in the last revision as the length of the time series was too short. The tide gauge had at that time quality-controlled data only back to 2010. In the years since, as well as adding eight more years to the end of the series, older data spanning back to 1988 has been validated and corrected. This additional time series may still contain some timing errors, but reference levels, mean values and peaks are of sufficient quality to be used here. Visual control of the time series prepared for the EVA revealed some short periods with timing errors in January 2000 and December 2008 that has been discarded from the EVA-series.

The data series from Tromsø starts in 1952 but the tide gauge has been moved several times in this period. From 1961 to 1985, the tide gauge was located in an area with a higher tidal amplitude, and this period has therefore been removed from the EVA series, see A.2.

In 2019, work was carried out to correct and quality control the NMA’s permanent tide gauges. This was carried out on the modern, high-quality data, starting from 2008. The procedure uses measurements taken during routine maintenance visits at the tide gauge, and hence the data has been corrected all through 2022. Further description of the method can be found in (Voldsund et al., 2023) and a review of the procedure and quality control carried out can be found in (Taskjelle, 2023).

As a result of the calibration and quality control, the current Mean Sea Level ($MSL_{1996-2014}$) was updated on all the permanent tide gauges, keeping the same reference period. The changes in $MSL_{1996-2014}$ were small, not exceeding 0.5 cm anywhere. A complete list of the $MSL_{1996-2014}$ changes can be found in A.1.

As will be discussed in more detail in 2.3.2, some tide gauges are experiencing subsidence as shown in Table 1. This is now compensated for in the times series back to the late 1980's but was not corrected for in the data used for EVA in 2015.

2.2 Tidal zones and estimated water levels for the whole coast

NMA provides "observed" water level for other locations than the permanent tide gauges based on a tidal zone model. As time series of estimated water level data from this model are used for the EVA, we give an overview of the model, highlighting the changes since 2015 and areas of particular interest.

2.2.1 The tidal zone model and its knowledge base

The whole coast and parts of Svalbard is divided into so-called tidal zones where the tide is expected to be similar enough to be modelled by the same time series.

A tidal zone is a polygon with the following properties:

- A tide gauge for tidal data (permanent or temporal).
- A set of rules for how the tidal data from the nearby tide gauge should be adjusted.
- A permanent tide gauge for observed surge.

The model for estimating water level combines the observed surge and the modelled tide for the given location:

Estimated water level = Tides for the zone (calculated) + Surge (observed)

A knowledge base of several hundred time series from temporal tide gauges is used to determine the tidal zones. The tidal signals at these sites are compared to the tidal signal of nearby tide gauges to find the amplitude factor and time delay between them. The area is then divided into enough tidal zones to have a smooth transition from one tidal signal to the other. The bathymetry/topology in the area is used to identify areas with abrupt changes and to help decide where to divide the coast into zones. Figure 5 shows the knowledge base and the tidal zones for the Norwegian coast.

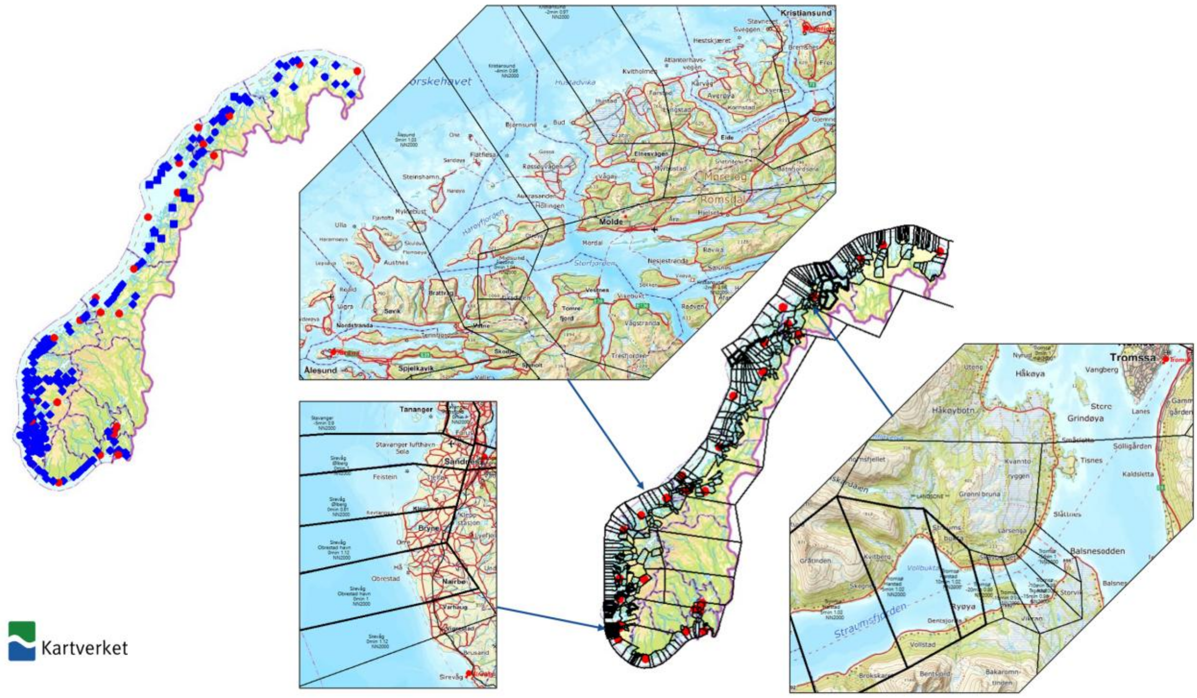

Figure 5: Illustration of the knowledge base (far left) and the tidal zones with examples from the coast from Ålesund tide gauge to Kristiansund tide gauge, the coast south of Stavanger with Sirevåg tide gauge and a narrow strait close to Tromsø tide gauge.

The tidal data is most often based on a permanent tide gauge but can be from a local observation site where we have at least 4 months of measurements. This is mostly the case in areas where the shape of the local tidal signal differs from the nearby permanent tide gauge, so that the tide is difficult to model.

Since the surge cannot be predicted, it requires data in real time. In the current model, the observed surge (observed water level - predicted tide) from the most representative nearby permanent tide gauge is used, without any rules or corrections. An illustration of the zones of influence of the different tide gauges along the Norwegian coast can be seen in Figure 6.

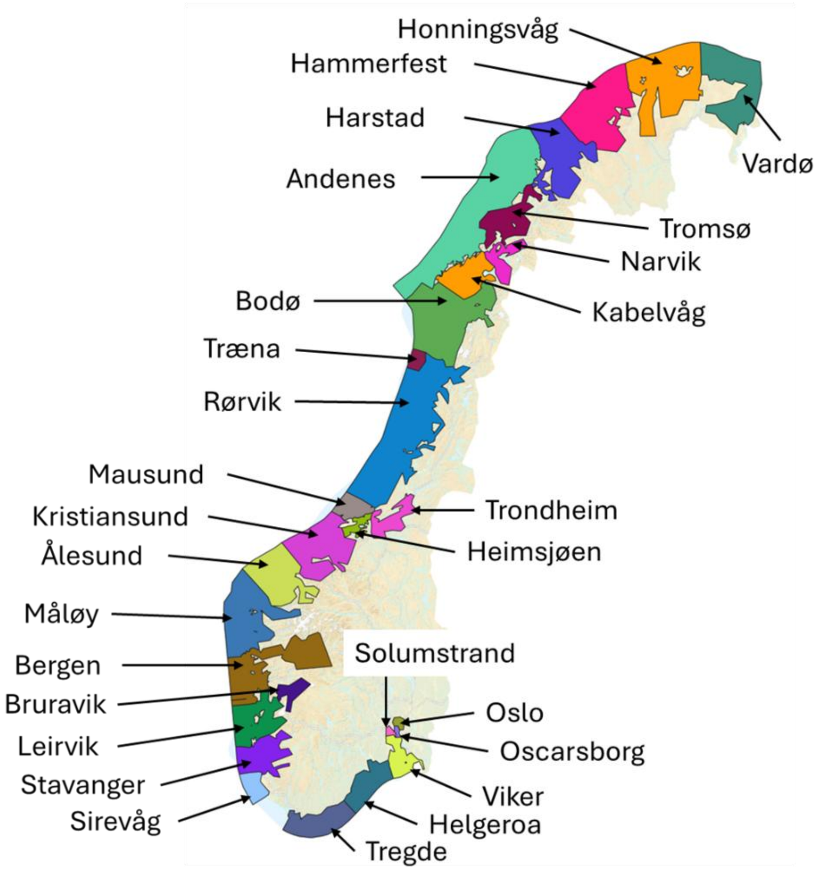

Figure 6: The areas where a permanent tide gauge is used to estimate the observed surge.

Most of the coast is covered by tidal zones but the model does not provide estimated water level everywhere. In Figure 6 these areas have been removed and can be seen, particularly on the south-western coast from Sirevåg to Lista. In addition, this concerns several small basins with narrow openings along the coasts. For a few tidal zones (Mo in Modalen and Straumsosen/Grunnvågen in Lindås) the model only provides tides and not the total water levels, as no permanent tide gauge can be assigned for the surge.

In addition to the Norwegian mainland, Norway also consists of the Svalbard archipelago and other territories in the Arctic and Antarctic regions. Most of these regions are not covered by the tidal zones. At Svalbard, only the areas around Ny-Ålesund (where there is a tide gauge) and Longyearbyen are covered by tidal zones with estimated water level and tides. In addition, tidal predictions are available for Jan Mayen, an island in the Artic Ocean with no permanent population.

2.2.2 Quality improvement and changes since 2015

The model for estimated water level is continuously updated as more observations become available, new data is analysed, or new information is provided. A polygon can be adjusted, or the set of rules tuned, to better fit the additional information and improve the quality of the model. Some smaller areas are no longer covered by the model as a closer look has revealed a basin where the model is not likely to provide good enough estimates or where NMA has received information contradicting the proposed model. The model will in general be more accurate close to the permanent tide gauges and less accurate further away. A map of the quality is available at (*Kvalitet på tidevann- og vannstandsdata*, 2024) with more information (in Norwegian only) about the quality flags introduced in 2023.

In 2015 all tide gauges in the model were permanent tide gauges, no local sites had been incorporated yet. Thus, the model has been improved quite a lot in the areas now using local sites, in particular for Hardangerfjorden. Furthermore, the option to use tides based on one permanent tide gauge and surge from a different one has been introduced, now used for instance around the Lofoten islands. In 2021 NMA updated the tidal constants for all permanent tide gauges and local sites used in the model, improving the tidal part of the model further.

Mausund was not included in the model until 2020, and from 2021 to 2023 the NMA installed 6 new permanent tide gauges, which has gradually been incorporated into the model. Sandnes has since December 2022 covered the inner parts of Gandsfjorden. Since the autumn 2023 the new tide gauge at Sirevåg made it possible to extend the tidal zone model from Tananger to Sirevåg. During the spring of 2024, Leirvik and Bruravik were fully incorporated in the tidal zone model for Hardangerfjorden and the surrounding area, improving the quality of the surge. In May 2024 the newest tide gauges, Træna (group of islands in Nordland) and Solumstrand (close to Drammen), were also included in the tidal zone model. So far Træna only covers the group of islands and the sea area for Træna municipality, and Solumstrand the inner part of Drammensfjorden.

2.3 Preprocessing of data series

The data collected from the permanent tide gauges go through different quality checks, filtering and other analysis or quality improvement before we end up with an hourly, detrended EVA series. The main steps and choices made are discussed here.

2.3.1 Filtering and down-sampling

A time series to be used for EVA is prepared for each tide gauge containing hourly data for the available years of observations. If there are less than half of the expected data points for a given year, this year is removed. The years included for each tide gauge are shown in Figure 4.

The EVA series are based on the historical data series and hourly down-sampled modern data up till the end of 2022. Down-sampling of the modern data (10 minutes or 1 minute) to hourly values are done following NMA's standard routines using Butterworth filters.

The time series prepared for EVA have undergone a visual quality control, checking for obvious errors that could impact the EVA. Data for some shorter periods have been discarded or tried corrected in the EVA-series for Bergen, Narvik, Oscarsborg and Stavanger, while several months of data from 1936 and 1941 was discarded for Heimsjøen. These corrections and discards have not been applied to the original data series (the historical series) as this visual control is not a full-scale quality enhancing work.

Hourly data has been chosen for the EVA to get a consistent time series as the historical data series registered in our database are hourly. It is also a time stamp recommended in literature, see e.g. (Arns et al., 2013).

2.3.2 Detrending

The tide gauge measures the water level relative to a fixed level, the tide gauge zero, connected to the land reference system through a defined tide gauge benchmark. The water level measurement is thus a relative measurement, combining both changes in the sea level and vertical land motion.

The land uplift caused by glacial isostatic adjustment is an important factor to consider when analysing long data series from the Norwegian coast. The NMA determines the land uplift which varies between 1mm/year and 5 mm/year along the coast (Simpson et al., 2024). This can be clearly observed in the historical data from Oslo shown in Figure 7 where the relative water level now is almost 50 cm below the average water level when the measurements started in 1914.

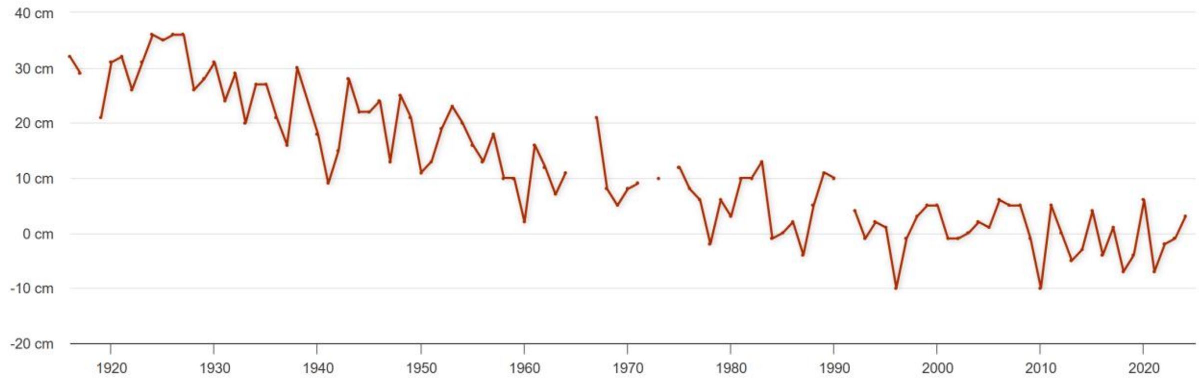

Figure 7: Historical yearly mean water level values (in cm above $MSL_{1996\text{-}2014}$) from the Oslo tide gauge, retrieved from NMA's website (Se havnivå, tidevann og vannstand, n.d)

In addition to the land uplift, the absolute sea level is rising along the Norwegian coast with a mean rate of 2.3 +/- 0.3 mm/year for 1960-2022 and 3.3 +/- 0.9 mm/year for 1993-2022 (Simpson et al., 2024).

Finally, some tide gauges are placed on unstable ground, causing subsidence, influencing the relative sea level measurement from that gauge. Since the late 1980's all permanent tide gauges in the NMA's tide gauge network are levelled every 3 years to monitor such effects. The analysis shows that there are 7 tide gauges that are subsiding slightly, see

Table 1, and the series experiencing subsidence are corrected for this in NMA's system.

Table 1: Tide gauges with local subsidence

Tide gauge	Starting year of correction	Rate (mm/year)
Viker	1991	0.3
Helgeroa	1988	0.22
Stavanger	1988	0.71
Mausund	2011	1.1
Trondheim	1990	0.85
Kabelvåg	1989	0.19

Honningsvåg	1989	0.15

When carrying out an EVA the data used for the analysis should be stationary. It is therefore important to remove any effects that could influence the stationarity of the series. In addition, to be able to only consider the effect of the storm surge on the water level observations, the data should be corrected to a common level. Because of the effects described above, removing the trend in time is an important step in obtaining more stationary data. In this report, only the trend in time has been corrected for.

There are different approaches when it comes to detrending data series. Some are discussed in (Bousquet & Bernardara, 2021) where a piecewise linear trend was chosen, while (Arns et al., 2013) suggested correcting using a yearly gliding mean. In (Simpson et al., 2015) a linear trend was used and it was decided to use the same approach in this update. The trends calculated on the same data series as the one used for the EVA can be seen in Figure 8. We note that these trends are similar to the ones calculated by the Permanent Service for Mean Sea level in (*Sea Level Trend Methods*, n.d.). However, one thing to be aware of is that as the data series are of different lengths, detrending them individually can lead to similar effects not being treated the same. This is visible when comparing two tide gauges with similar land uplift such as Oslo and Oscarsborg or Ålesund and Bergen in Figure 8.

Three of the tide gauges experiencing subsidence, Stavanger, Helgeroa and Mausund, have recorded data used for the EVA before the monitoring of subsidence started. They are likely to have experienced subsidence also before the correction starts, but with no monitoring, this cannot be corrected for. Some of the tide gauges might also have been in a different location without this being recorded correctly. These kinds of issues have not been considered when calculating the trend.

Another aspect to consider is that the data does not always show a linear trend, but other types of fluctuations over time. This is clearly visible in the time series from Bergen but also in other locations. (Chafik et al., 2019) and (Leijala et al., 2018) describes decadal variation in the North Atlantic and along the Norwegian coast that could be one reason for the observed pattern.

It is important to note that because of the different effects described above and the limitations described in the section below, one cannot consider the trends calculated here directly as the relative sea level change at the tide gauge. To obtain such estimates, one should refer to (Simpson et al., 2024).

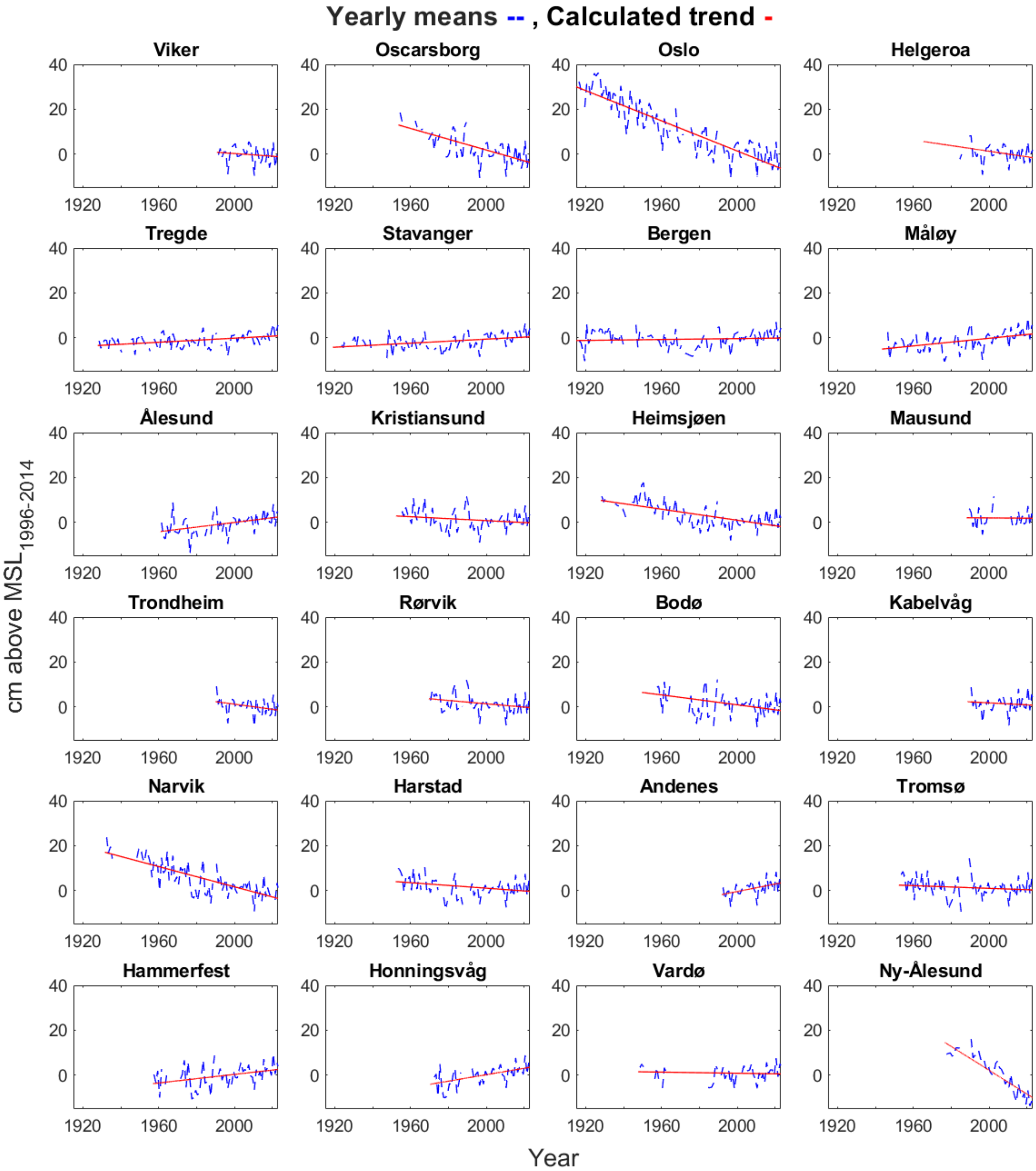

Figure 8: Overview of the trends (red) calculated for the EVA analysis as well as yearly means (blue) for the tide gauges considered here. Note that some years used in the EVA analysis do not fulfill the criteria for calculating the yearly mean, see for instance Helgeroa where the EVA analysis uses data from earlier years than the yearly means series.

2.3.3 EVA time series for each tidal zone

For any given tidal zone, we calculate the predicted tide according to the tidal zone model but without the time shift. This is based on the last EVA revision which concluded that the time shift could be ignored (Ravndal & Borck, 2016), hence reducing the number of unique time series to be analysed. No further analysis of this has been carried out in this revision. To get the EVA time series, we then add the surge from the appropriate tide gauge, found by subtracting the predicted tides from the detrended EVA time series. For tidal zones with surge from a newly established tide gauge, the EVA time series get the surge from another tide gauge with longer record, usually the tide gauge previously used for the surge in that area.

The EVA also includes the south-western coast from Lista to Sirevåg not yet covered by the model and two zones with no surge assigned. In these areas we are not able to estimate the water level at a given time of a given day at a sufficient high quality, but for the EVA we analysed several years of data and the timing of the individual events are less important as long as the number of peaks on average is representative for the area. The details of all the tidal zones where the EVA time series differs from the model are given in A.3.

There is no EVA time series for the other smaller areas (basins) not covered by the model, and NMA does not provide extreme water levels for these.

2.3.4 EVA surge series

For the large impact – low probability scenario, further described in 3.2, we use an EVA surge series. For this we use the observed surge at each of the tide gauges, often referred to as the (surge) residuals. In the analysis, the peaks within 12 hourly values were extracted, instead of every local extreme as for the water level data.

Normally, the skew surge is used in extreme value analysis of still water levels by indirect methods. The skew surge is less sensitive to the quality of the observations and the tidal predictions (Bousquet & Bernardara, 2021). Skew surge has thus been argued to be the best choice in tidal dominated regions (Williams et al., 2016).

We still prefer to use the observed surge because we have locally adapted high-quality tidal predictions, typically not available when doing regional or global EVAs. In addition, we have surge dominated areas with small tides, where the skew surge does not make sense, and areas with double high tides where skew surge would be difficult to define. An important objective of this EVA is a consistent product for the whole country, and we therefore analyse the observed surge.

To avoid problems in the surge data from errors in the timing of observations, which is a common problem for older data, we use only the modern data from 1992 onwards. The EVA surge series thus consists of 31 years of observed surge from 1992-2022 for each tide gauge, calculated by subtracting high-quality tidal predictions, including the predictable seasonal weather effect, from the high quality hourly observed water level used for the main EVA. Longer time series are often preferred for EVA, but in (Arns et al., 2013) it was shown that around 30 years of data could be as valuable as 100 years of data with the proper set-up. In this setting we conclude that using shorter time series of higher quality surge data provides the best EVA of the surge and at the same time ensures consistency between the tide gauges.

For this period, we have consistent 10 minutes series which could have been used, but hourly data was chosen mostly because it was used in the main EVA. A comparison of the EVA results using hourly versus 10 minutes data for the EVA of the surge can be found in E.2. For most tide gauges there are no observable differences in the results, while some tide gauges have some smaller differences.

3 Results

The results of the EVA for all tidal zones described in this report became the new official data set for extreme values for the Norwegian coast and Svalbard from 26th of April 2024 and included the new high-end extreme still water level based on EVA of surge data combined with HAT.

These data are part of the NMA product Water level data and water level information (*Vannstandsdata og vannstandsinformasjon - Kartkatalogen*, n.d.) available as a location-based search through the API for water level data (*Vannstand API - Kartkatalogen*, n.d.). A selection of the extreme water levels (given to NN2000) is part of an updated dataset containing the recommended data used for planning, published as an official dataset on Geonorge (*Det Offentlige Kartgrunnlaget*, n.d.) in June 2024.

3.1 The new national extreme water levels

The ACER-method has been applied to the EVA time series for each tidal zone along the coast to obtain extreme high and low water levels. As already mentioned, the different parameters are set using the same approach as in (Ravndal & Borck, 2016), see Appendix B.1 for further details including the ACER-plots for each tide gauge. Note that the focus of this work is on the extreme high water levels and that the analysis has not been optimized with respect to the extreme low water levels which are thus in general of lower quality. The rest of this discussion focuses only on the high extremes.

Figure 9 shows how the 200-year extreme water level vary along the coast, with the highest values in Vestfjorden and Ofoten, south of Lofoten, and in the north-eastern parts around Vardø. These are the areas with the highest tidal amplitudes, as illustrated in the middle figure. In the rightmost figure, the highest astronomical tide has been subtracted from the 200-year extreme water level to show the areas where the storm surges have the largest impact: In the south, particular around Oslofjorden, but also in Vestfjorden and Ofoten.

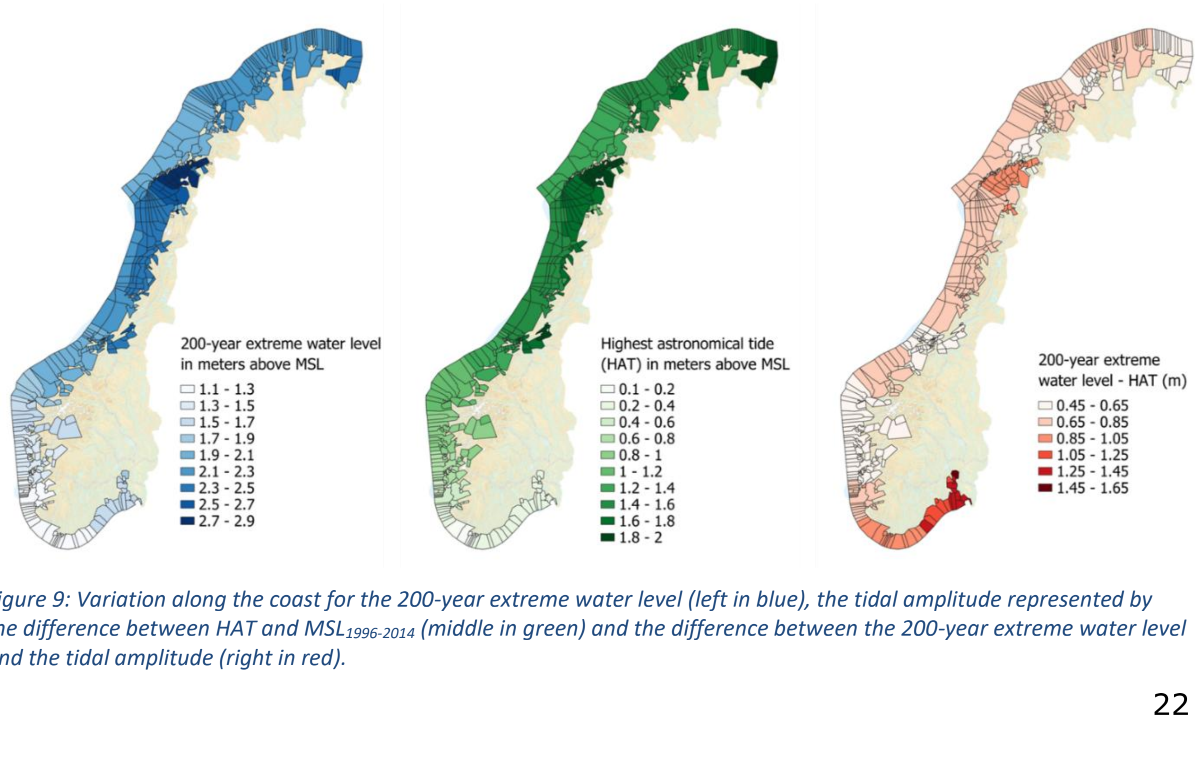

Figure 9: Variation along the coast for the 200-year extreme water level (left in blue), the tidal amplitude represented by the difference between HAT and $MSL_{1996-2014}$ (middle in green) and the difference between the 200-year extreme water level and the tidal amplitude (right in red).

The results include a confidence interval of 5 to 95 percent which reflects the uncertainty of the EVA, strongly dominated by the length of the analysed time series. Thus, zones based on the same tide gauge for the surge data, will have similar confidence intervals. This confidence interval does not reflect how well the estimated time series for this zone represents the physical conditions. In the same way as for the estimated tides and water level, the water level forecasts, and the extreme water levels are all based on the same model. Thus, they are consistent products, and the quality given to the estimated water level will define the quality of the forecasts and the extreme water levels as well. For the zones based on newly established tide gauges, the EVA relies on surge data from other tide gauges. Hence, the consistency between the estimated tides, water level and forecasts and the extreme water levels are not as strong here. See 4.2.3 for discussions of this effect. In A.3 we include details of where the extreme water levels series differ from the tidal zone model, and how this influences the quality of the extreme water levels. Plots of the new extreme high and low water levels, with confidence intervals, can be found in C.1 for the tide gauges.

The uncertainties of the extreme water levels are in general smaller than those from 2015. This is shown in Figure 10 where the 2015 values are compared to the new values for the 20-, 200- and 1000-year extreme water levels. This is as expected when adding 8 years of data, in particular for the tide gauges with shorter time spans. Andenes and Viker show a significant decrease in the uncertainties, while for other similar short series such as Trondheim, the added years of data does not impact the uncertainties much. A few tide gauges like Bergen and Harstad with generally small confidence intervals have larger uncertainties in the new numbers. See further discussions in 4.1.

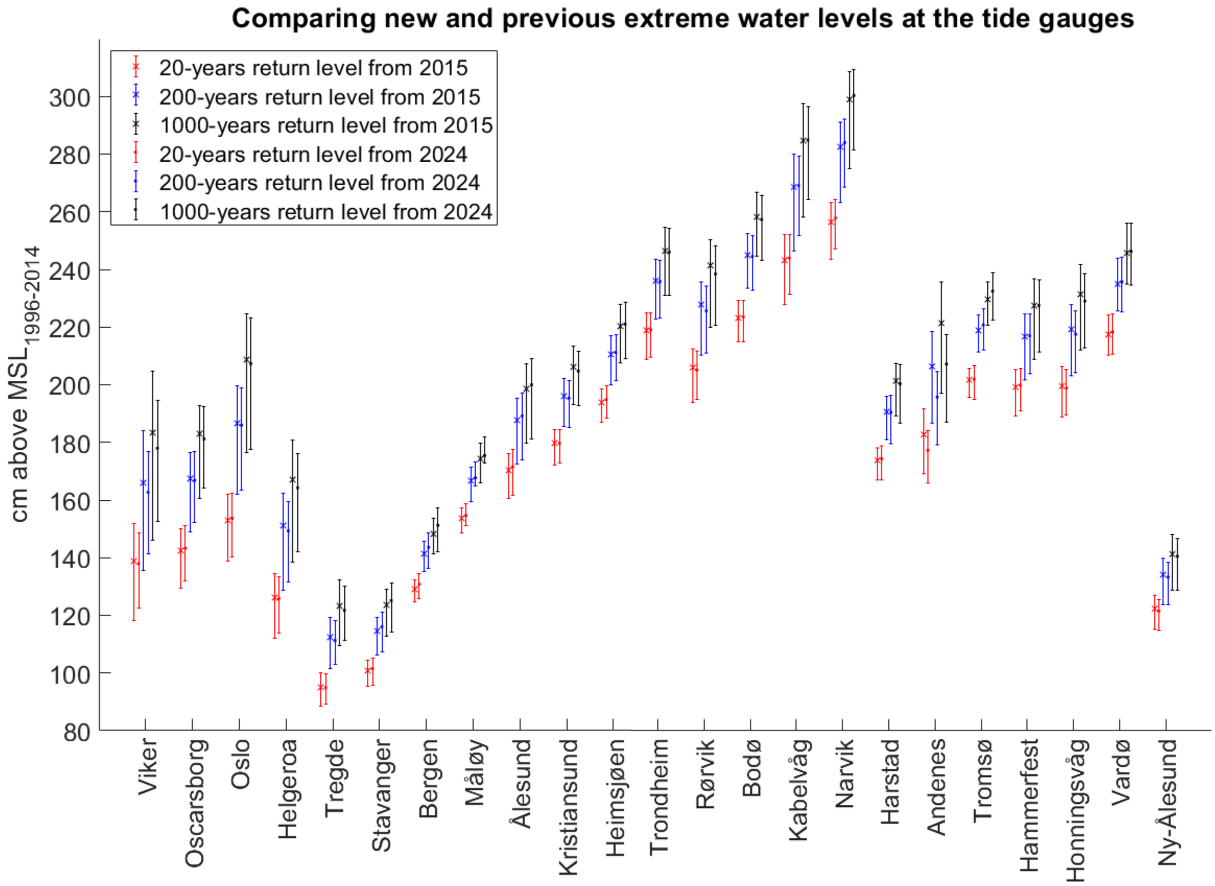

Figure 10: Comparing a selection of extreme water levels from 2015 with the new ones for each tide gauge.

The values of the extreme water levels have not changed much from the EVA in 2015. Andenes has the largest changes, with a 15 cm lower value for the new 1000-year extreme water level. For Viker the 1000-year extreme water level is 5.5 cm lower than in 2015, while for all other tide gauges the new 1000-year extreme water level is less than 3 cm higher or lower than the old ones.

Figure 11 shows the changes for Tromsø for which the EVA time series now have significantly less data than used in 2015, as discussed in 2.1.2 Removing the (wrong) data from a location with a larger tidal amplitude, has resulted in a slightly different fit of the ACER-curve with lower extreme values for the short return periods and slightly higher values for the long return periods. There is also a slight increase in the uncertainty as expected for a shorter time series.

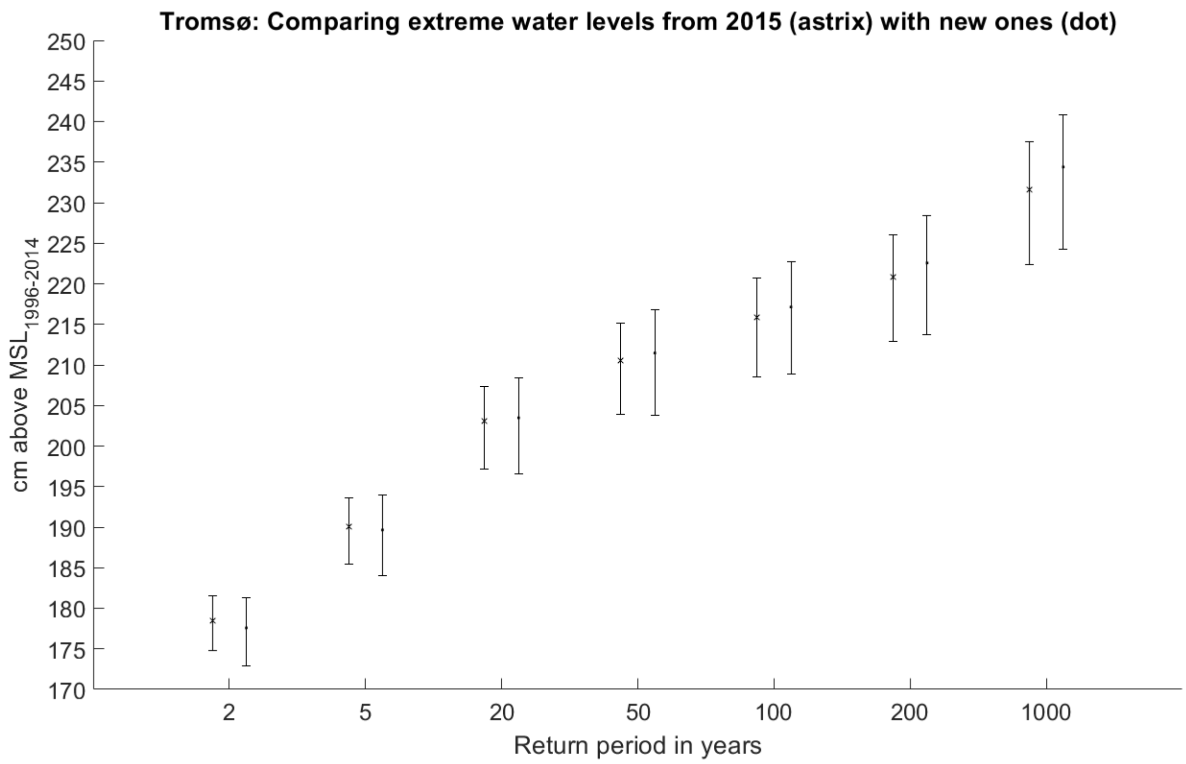

Figure 11: Tromsø extreme water levels from 2015 marked with x compared to the new ones marked with a dot where data from the other location has been removed.

The Mausund tide gauge is not included in Figure 10 because Mausund was not part of the 2015 EVA. At this location, the tidal zone model was then still based on Heimsjøen. The old extreme values from 2015 based on estimated water levels are compared to the new values based on observations from Mausund in Figure 12. As mentioned above, the confidence intervals mainly reflect the length of the analyzed time series and are therefore lower for the 2015 values than for the new values. However, the new extreme water levels based on Mausund is a better representation of the physical conditions at this location. The comparison shows that the earlier zone-based data was fairly good, though it seems to overestimate for the longer return periods. Similar changes can be seen for the surrounding tidal zones now based on Mausund.

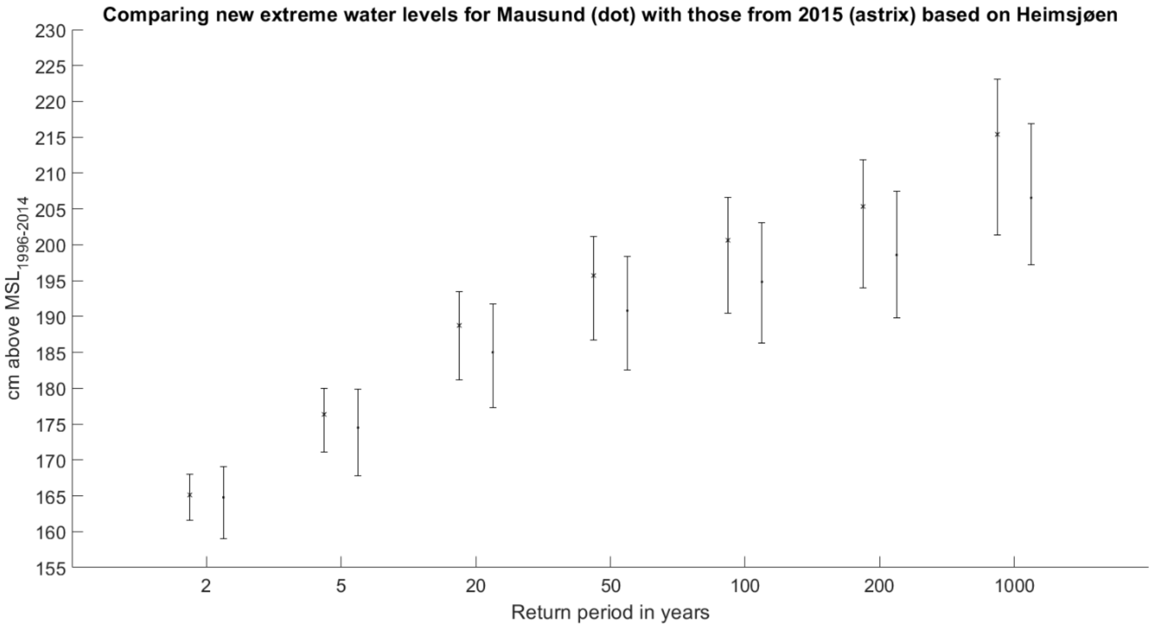

Figure 12: Extreme water levels for the zone where Mausund tide gauge is located. New values are based on observations from Mausund, while EVA 2015 is based on a longer time-series estimated based on Heimsjøen

Comparing the new results for the tidal zones along the coast with the existing values, we find the same pattern as for the permanent tide gauges with the largest changes for zones based on surge from Andenes tide gauge. For most of the quality improvements described in 2.2.2, the extreme water levels have improved accordingly.

3.2 Return levels for surge and a high-end extreme still water

The ACER-method has also been used to analyze the EVA surge series from each tide gauge. Both high and low return levels for surge have been calculated, see B.4 for the corresponding ACER-functions.

A few high return levels for the surge with confidence intervals are included in Figure 13. As expected, the geographical pattern is quite different from that of the water level extremes, with the highest surges in the Oslofjorden region. It is well known that the tides are larger south of the Lofoten islands than to the north. This is clearly also the case for the surge, likely due to the direction of the coast facing more north here, as noted in (Simpson et al., 2024).

As the EVA surge series used are all the same length, it is also interesting to note the differences in the uncertainties for these return levels. For the tide gauges in Oslofjorden the uncertainties are larger for the larger surges. This seems also to be the case for Ålesund and Kristiansund compared to the nearby tide gauges, however, Bodø, Kabelvåg and Narvik are among the higher surges, but with smaller confidence intervals. See also 4.2.4 for further discussion and comparison to the uncertainty of the extreme water levels.

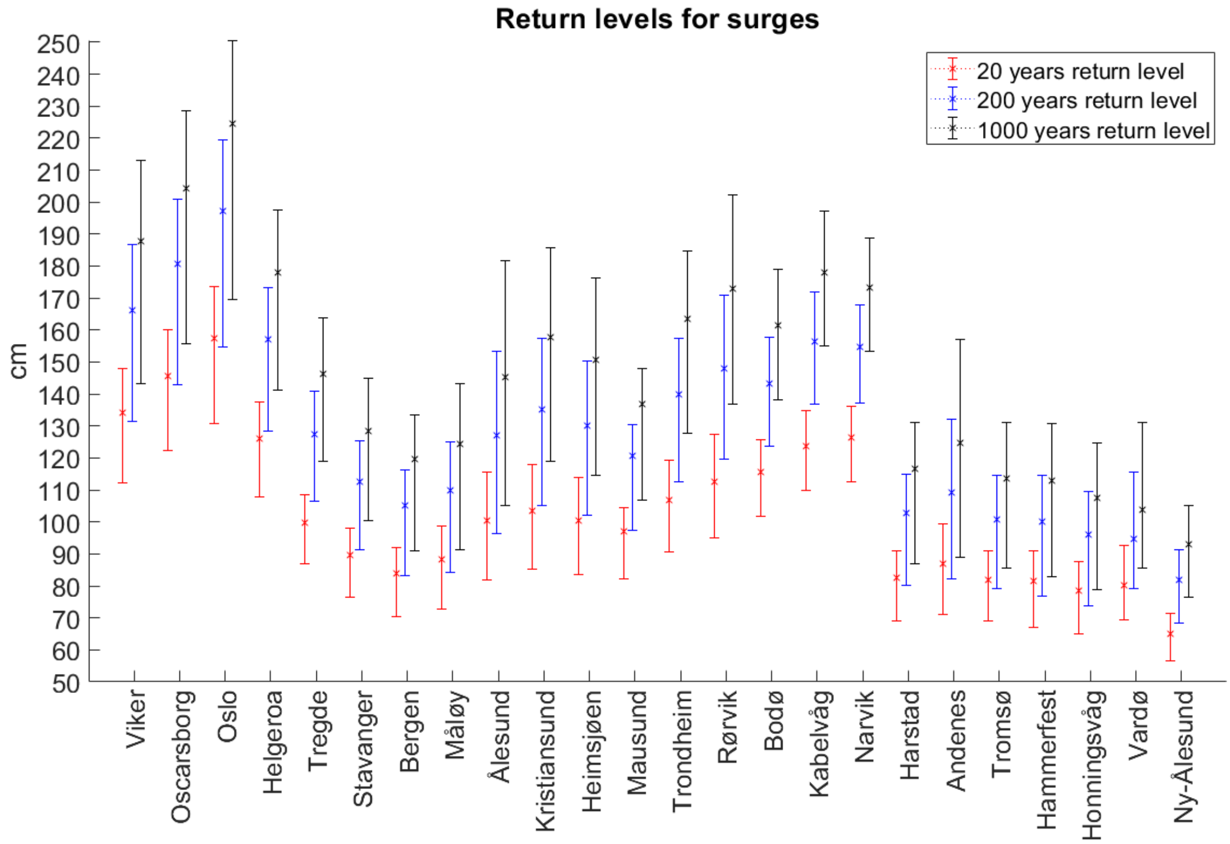

Figure 13: High return levels for surge for the network of permanent tide gauges in Norway

The only use of the return levels for surge is for the high-end extreme still water level, and the rest of this discussion is limited to this product. The recommended high-end extreme water level has been defined as the local HAT with the 1000-year return level for surge from the nearby tide gauge added. See Appendix D for a discussion of different strategies for defining this. Figure 14 shows the high-end still water level for each of the tide gauges, with the confidence intervals of the 1000-year high surge indicated.

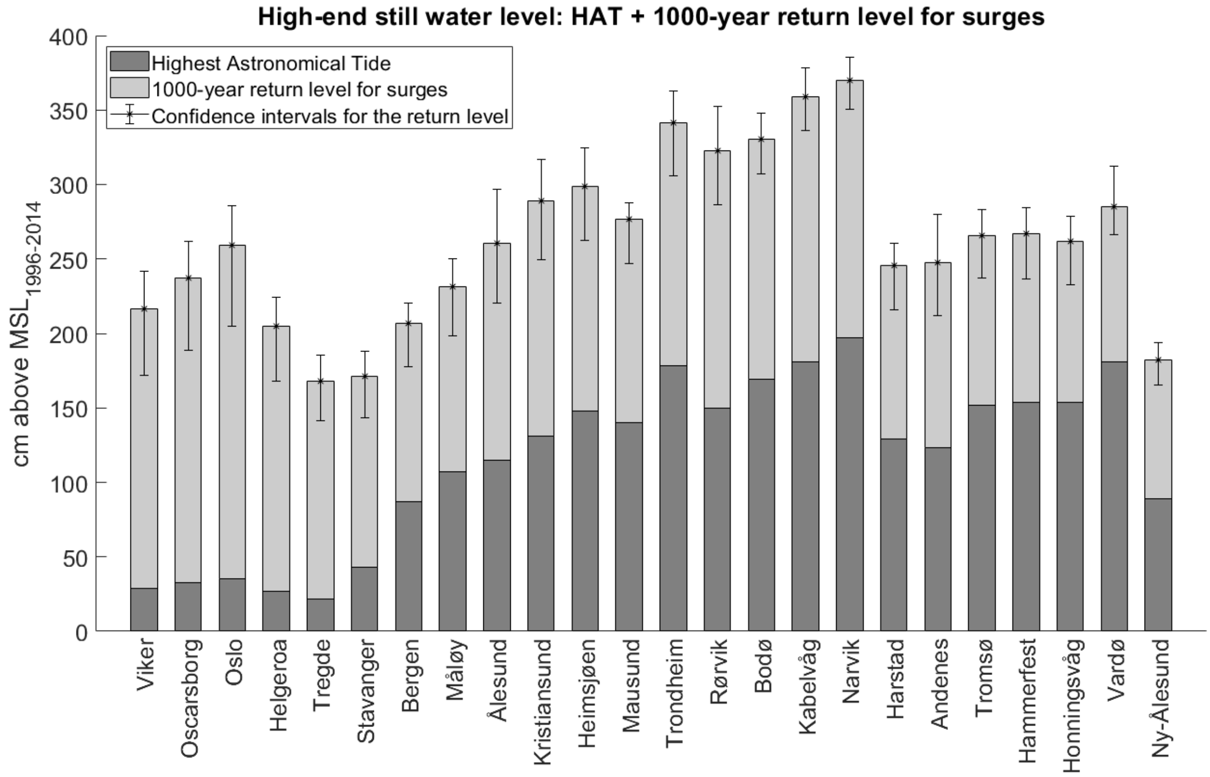

Figure 14: The high-end extreme water level estimate defined as HAT with the 1000-year return level for surge added for each of the permanent tide gauges along the coast

The values for the high-end estimate along the coast are shown in Figure 15. The pattern is similar to the one seen for the tide gauges, as expected since the 1000-year return level for the surge from the most representative nearby tide gauge is added to the local HAT which is changing more gradually along the coast. The figure also includes the changes of this estimate compared to the approach used in 2015, described in Appendix D. It can be clearly seen that the former approach was more conservative than the current high-end extreme water level, but that the level of conservatism was varying significantly along the coast. See Appendix D for further discussions.

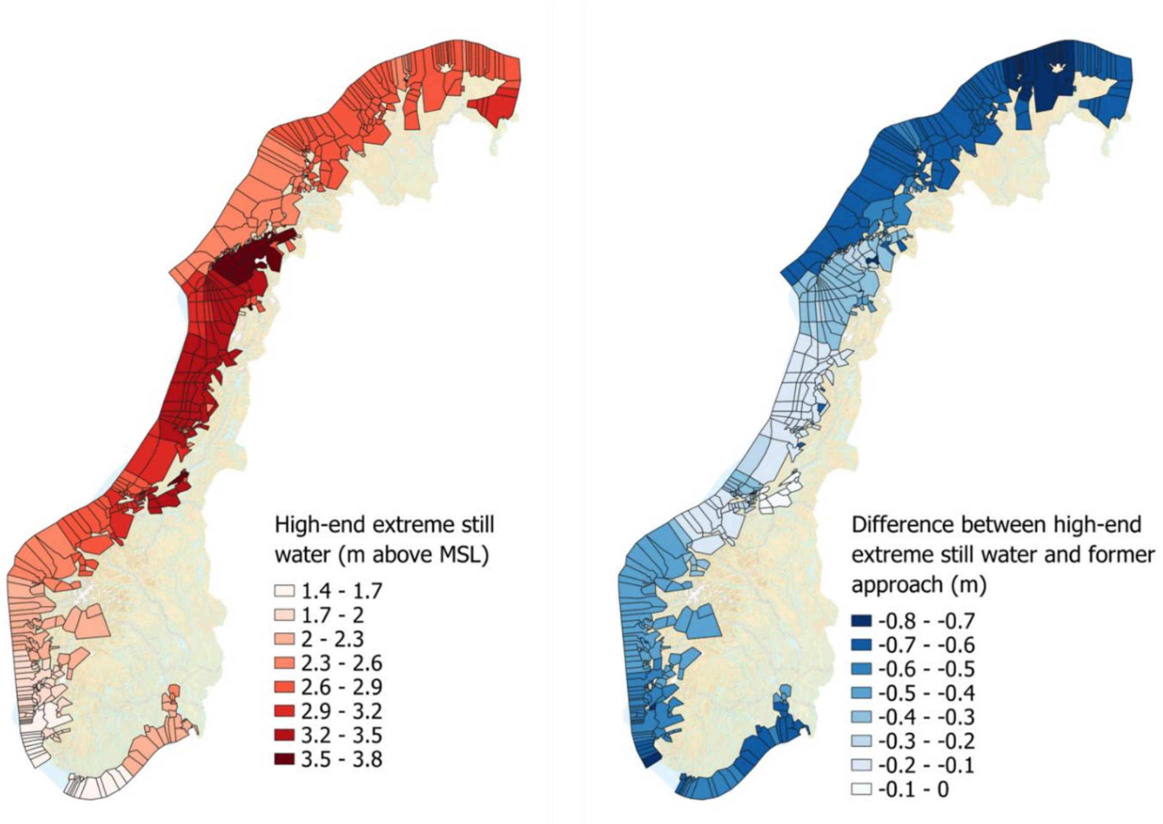

Figure 15: The new high-end extreme still water levels (left) and the difference between this and the 1000-year extreme water level where one meter has been added (former approach) (right).

3.3 Comparison against observed events

To ensure the quality of the extreme water level described in 3.1 and 3.2, we make a comparison with observed events. When making such a comparison, it is important to bear in mind that the data used are based on the preprocessing steps detailed in Chapter 2. In addition, we attempt to determine return levels with a return period far above the length of the input time series. In Figure 16 and Figure 17 we show examples from Andenes and Oslo of the observed peaks and the calculated return periods. Note that in these figures, we also show the effect of the detrending routine on the observed peaks, to make the comparison more consistent. In Figure 17 from Oslo, the effect of the land rise is clearly visible, and one can note that many of the extremes from the start of the 20th century are high above the current peaks, before detrending. On this figure, one clearly sees that 2005 was used as the reference for the detrending. Similar plots for all the tide gauges can be found in C.2.

Another aspect to bear in mind is that only observed extreme events are considered in the analysis. Particularly in tide-dominated areas, a large storm surge occurring when the astronomical tide is high could cause extremes above the calculated return levels, see also the discussion of the high-end estimate in

3.2 and Appendix D.

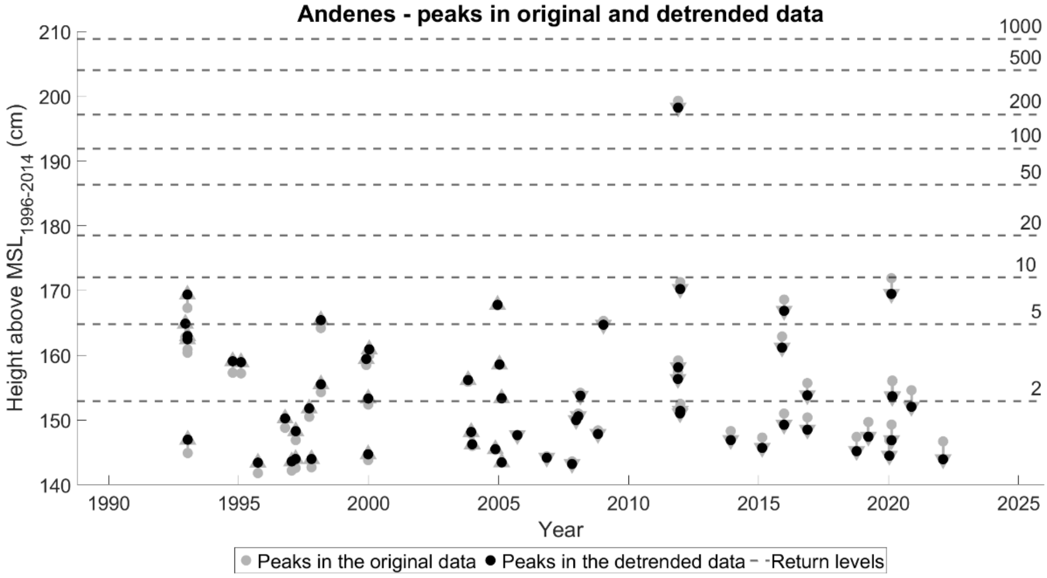

Figure 16: Illustration of peaks from the Andenes time series, before and after detrending.

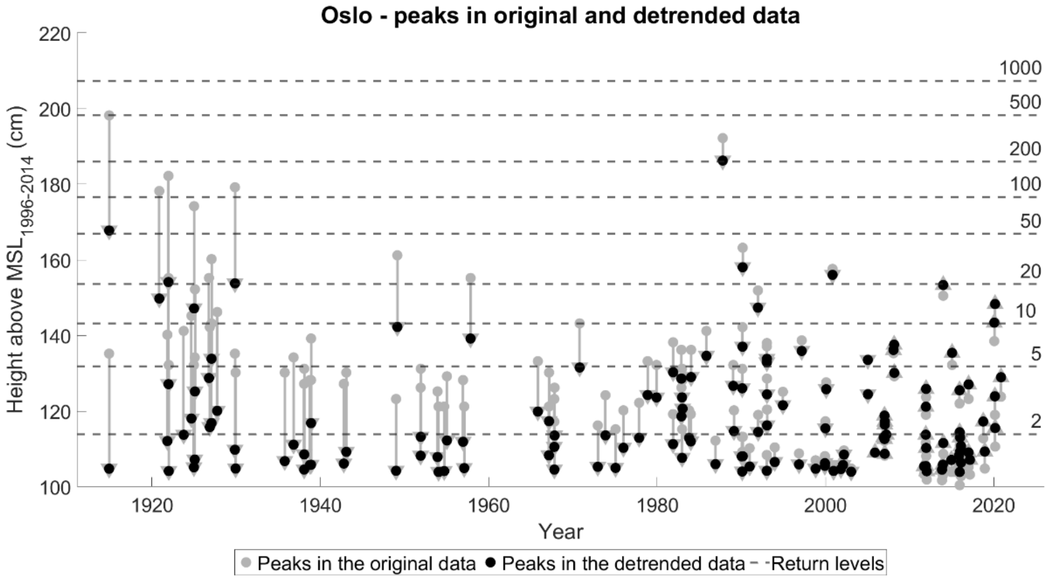

Figure 17: Illustration of peaks in the Oslo time series, before and after detrending.

4 Choices, limitations, and future work

4.1 How data and method can impact the result

Even though the baseline for this work was to use the same approach as in 2015, some further investigations have been done to consider the impact of some of the choices made in the process. This concerns which data to use and how to prepare them, as well as some of the methods involved in the work described here.

The time series from the different tide gauges have very different time spans, as shown Figure 4. This gives rise to a set of challenges when preparing for an EVA. Here we will discuss our choice to include all available data and the challenges this leads to.

When preparing a national dataset, it can be argued that the best approach is to use a common reference period and base the EVA on this. This would give a more homogeneous data set, where one could expect the uncertainty to vary less from region to region. In addition, this would allow us to use data with 10-minutes sampling instead of hourly sampling. However, using only data from 1992-2022 would be less than most recommendations (Arns et al., 2013), resulting in an unnecessary decrease in the quality of the extreme values for large parts of the county. The differences in uncertainty using all available data and using only data from 1990-2022 are shown in E.1. Furthermore, in E.2, the sensitivity tests show that there is very little difference between the results when using the different samplings for most of the tide gauges.

Not using all the available data also means that you could leave out extreme events in the past that will influence the result. However, the sensitivity test in E.1 show that the assumed best result (using all available data) for all tide gauges lies within the confidence interval of the result using only 33 years of data. There is therefore reason to believe that any extremes not included in one of the shorter time series is reflected in the uncertainty.

As noted in 3.1, it is more than just the length of the series that impacts the uncertainty. Adding 8 years of data had different impact on tide gauges with similar time span of the time series. The most surprising change was to some of the longest series, where the uncertainty increased. This leads to another choice not considered here: Is there a maximum time span that should be used when preparing data for EVA?

Another drawback to consider, as mentioned in 2.3.2, is the effect on the consistency between tide gauges when combining all available data with the same detrending approach as in 2015. The length of the series could also influence the effect of the other types of fluctuations suggested in the same chapter. Whether or how decadal variations, for instance, should be dealt with in an EVA has not been considered here. The tests done on the same length of times series with different starting years shown in E.3 do suggest that these kinds of fluctuations or variations may impact the result.

4.2 Limitations of the method and knowledge base

The EVA described in this report aims to obtain robust extreme water levels for the entire Norwegian coast. For some geographical locations the knowledge base is not sufficient to obtain accurate extreme water levels using the approach detailed here. This will be further described below.

4.2.1 Knowledge base

The analysis described here is based on the data from the permanent tide gauge network, as described in 2.1. Although we use the tide zone model described in 2.2 there are limitations to the model based on the lack of observations from parts of the Norwegian coast.

The long fjords where we currently miss long-term observations are one example of areas that may be affected more by storm surges than our model and analysis show. An example of this can be seen in Figure 18 where we observe that surges in the innermost parts of the Oslofjord (at the Oslo tide gauge) are higher compared to the tide gauges further out (Oscarsborg and Viker tide gauges). Some of the same effects can be seen in Sognefjorden (Breili et al., 2020), but our current model for water level data does not model this, thus it is not a part of the current EVA.

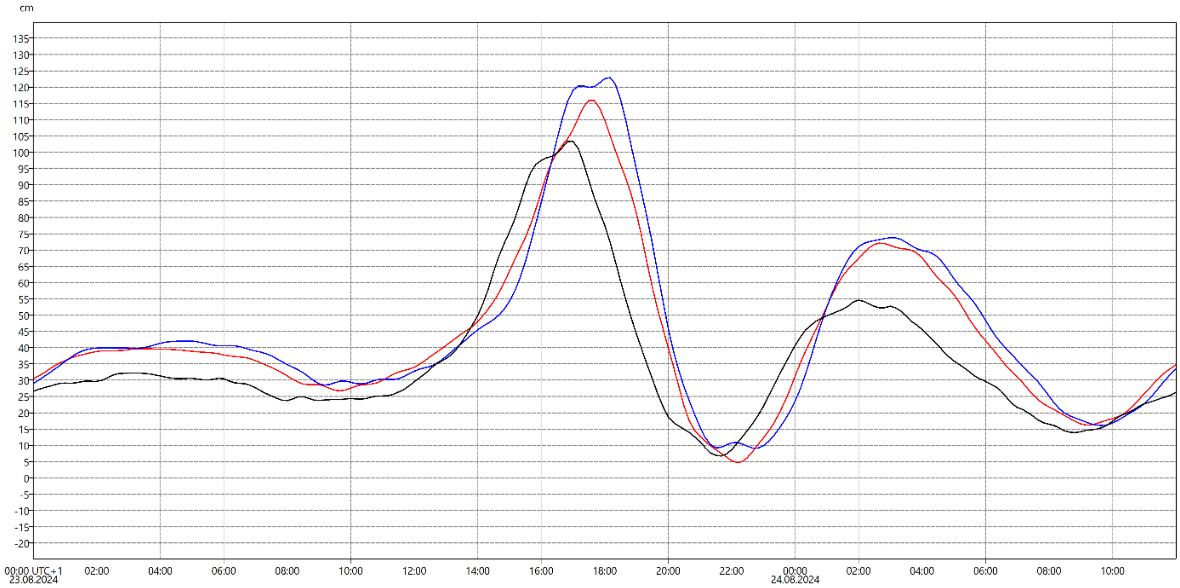

Figure 18: The effect of the size of the surge in Oslofjorden, going from the Viker tide gauge (black) on the coast, into the fjord passing Oscarsborg (red) and ending in Oslo (blue).

In 2.2.1 and A.3 we have described areas where we are currently not able to do the EVA because of the tide zone model/knowledge base.

4.2.2 The tidal zone approach

Although the tidal zone model, described in detail in 2.2.1, makes it possible to provide estimated extreme values for most of the coast, the method has some potential weaknesses in addition to those related to the knowledge base described in 4.2.1.

The tidal zone approach requires that the tidal signal is completely removed from the weather contribution. If a tidal signal persists in the weather effect, this could amplify or reduce peaks when constructing the EVA time series. In Figure 19 a severe example of this is illustrated. One can note that there is a clear tidal signal present in the calculated surge after April 5th. These types of situations are often present in the historical part of the data series and are often caused by a timing error. Nevertheless, such effects can also be present to a smaller extent in both the modern and the historic data and are then more difficult to observe than the example in Figure 19.

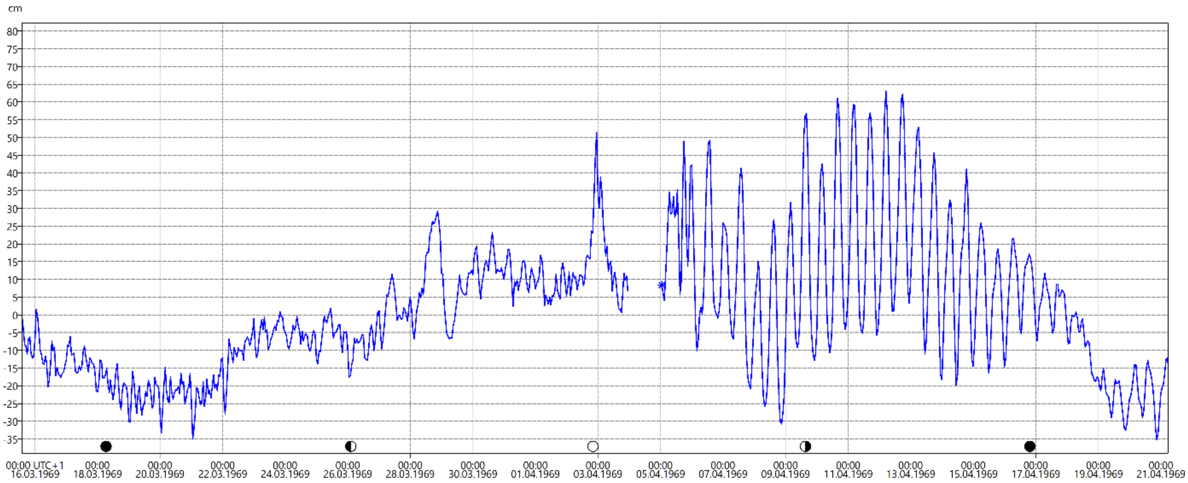

Figure 19: Illustration of the surge obtained when subtracting the predicted tide from the observed water level in Narvik in March/April 1969. Note the presence of tide in the signal, particularly after an interval with missing data on April 5th.

As the tidal zone model consists of polygons, the boundary of these polygons determines how the extreme values change along the coast. In challenging areas such as tidal streams, the rapidly changing water level pattern can lead to steps in both the tidal zones model and the extreme values. Another similar situation is when going from a zone with a long underlying water level series to a zone with a shorter series. The reduction in quality across such a boundary could lead to a change in the extreme water levels larger than suggested by the water level step across the same boundary. Both these cases could lead to unexpected differences in treatment for nearby locations, for instance when the extreme water levels are used for planning purposes or insurance claims regarding natural hazards.

Finally, the tidal zones approach only models the tide, whereas the weather contribution is derived directly from a permanent tide gauge. There are cases where one could expect that the weather effect should be modelled more precisely, either by modelling this effect from several tide gauges or including an amplitude factor or time delay on the weather effect in the same way as for the tide model. This weakness in the tidal zones model is the same as for the water level estimation, and the extreme values calculated in this manner is consistent with the estimated water level for the same position.

4.2.3 Integration of new permanent tide gauges

Integrating new permanent tide gauges in the tidal model improves both the local tides and the estimated water level in the surrounding area. However, in the EVA we can only make use of the improved tidal part, as the improved surge data are too short time series to be used for EVA for many years to come. Surge data from a nearby tide gauge have been used, not representing the physical conditions as well as the new tide gauge, but in general, over a long timeframe, most likely adequate for EVA. This means that there is little, or no reduction of quality compared to other tidal zones away from a permanent tide gauge. The limitation of this approach is that the consistency between the extreme water levels and the other products based on the tidal model is weakened.

4.2.4 Methodology computing return levels for the surge

A comparison of the confidence intervals for the return levels for the surge and for the total water levels revealed some unexpected results. As the EVA for the surge is computed based on only 31 years of data, we do expect higher confidence intervals for the return levels for the surge than for the extreme water levels for most tide gauges. However, as shown in Figure 20, the confidence intervals are also significantly larger for the tide gauges where the EVA series for total water level is of the same length as the surge series, see for instance Viker, Trondheim and Andenes. As there is no sign of a geographical pattern here, this might indicate some limitation of the method used for analysing the surge. This comparison was not part of the original tests and checks, and therefore no further analysis of this potential limitation has been conducted.

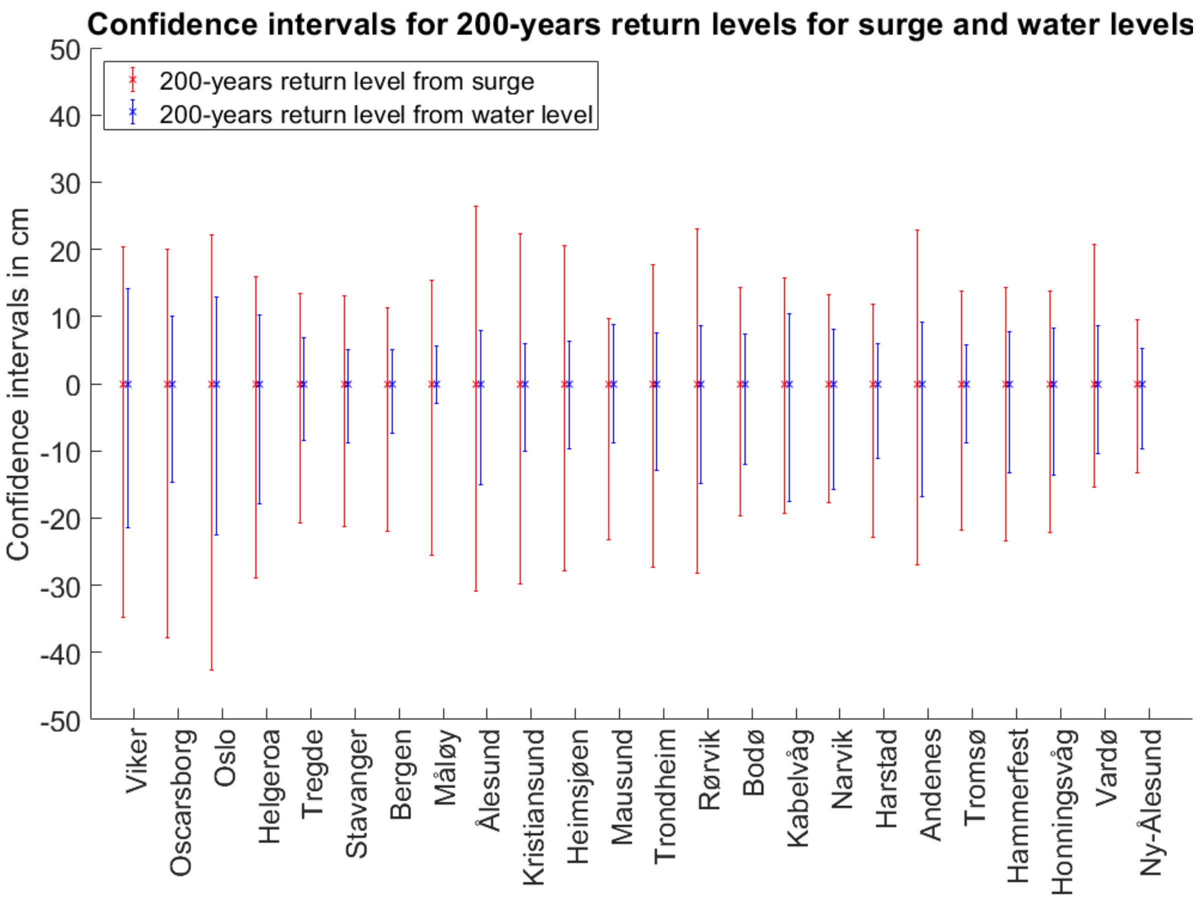

Figure 20: Comparing confidence intervals for the return levels for surge and for the total water level. Note that the figure only shows the confidence intervals, centered around zero.

4.3 Local effects not included in extreme still water levels

When using the results provided in this report it is important to be aware of effects that can cause inundation and damages to the infrastructure that are not included in the extreme still water levels. One important effect is wind waves. Wind waves will influence the instantaneous water level and cause possible inundation through the wave height itself, but also through effects such as wave setup and swash. The direction of the wave will depend on the wind direction and local topography will influence the consequences of the wave. (Simpson et al., 2024) describes how the wave climate varies along the Norwegian coast and gives some examples of wave and storm surge interactions.

In inlets and harbours, seiches can be experienced. Seiches are standing waves that occur in partially bounded water bodies. The standing waves are caused by a disturbance in the basin with the appropriate frequency compared to the size of the basin. Such a disturbance can come from different sources; meteorological phenomena, seismic and volcanic activity. In Norway, based on the observations from the tide gauge network, we have several examples of large vessels creating a disturbance that sets up a standing wave in a harbour. Although these standing waves often have small amplitudes, we could imagine situations where the effect could be noticeable on an extreme event.

Tsunamis and meteotsunamis are particular types of waves, not caused by wind but by displacement of water from other phenomena. Tsunamis are typically formed after earthquakes and volcanic eruptions while meteotsunamis are formed from large pressure differences in a fast-moving weather system. Both events can cause inundation, damage to human life, health and infrastructure, but are not a part of this analysis.

Where rivers meet the sea, there might be local effects due to the combination of river flow and the tides and surges at the coast. These effects are not considered in this report. The Norwegian Water Resources and Energy Directorate (NVE) is responsible for mapping floods in rivers, and users should refer to them for information on return levels in rivers.

4.4 Recommendations and future work

The results presented in this report is part of the Norwegian Mapping Authority's official products available through different services. As the knowledge base is in continuous development these products will be continuously improved in the coming years, even if none of the recommendations are acted upon. This includes, but is not limited to, improving the tidal zones model because of new measurements, changes to the data series because of new quality control and changes to the vertical reference levels.

In addition to the continuous updates and improvements, we recommend that some additional work is carried out or considered before the next major revision to the extreme values for Norway. These recommendations are grouped in three categories and have been outlined as bullet point lists below.

Improvements related to the knowledge base and data:

- Consider installing new permanent tide gauges in areas where the knowledge base for EVA is missing or of low quality.
- Determine the optimal length of the times series used for the statistical analysis, as discussed in 4.1.
- Improve detrending routines as discussed in 2.3.2.
- Provide "lower quality estimates" for the tidal zones where we currently do not provide data
- Research better ways to estimate the surge in general for the model and in particular for areas with the newly established permanent tide gauges.

Improvements of the statistical method

- Determine whether the statistical method (ACER) used for this revision is the optimal method for future revisions.
- Investigate how the spatial problem could be improved, consider other statistical methods or improving the models by making use of shorter time series, as investigated partly by (Røed, 2021). This could also include ways to harmonize the results, particularly if no new method is chosen.
- Improve the estimation of extreme low events and for surge data.

Improving the knowledge of the physics behind

- Improve the understanding of how extremes propagate in fjords
- Improve the understanding of extremes on the boundary between river and coast
- Improve understanding of other local effects as described in 4.3 and investigate how these could influence the extremes.

How these recommendations are prioritized depends on user needs. More knowledge of how the results is used and by whom is essential. New users and different user needs might appear in the coming years when the effect of sea level rise becomes more noticeable or if public awareness of the issue increases. Future laws and regulations might also influence the further development of the methods and products described in this report.

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Appendix

A. Data and tidal zones

This appendix includes some additional details on issues with the data and tidal zones discussed in Chapter 2.

A.1. Changes in Mean Sea Level after calibration and quality control

Mean Sea Level based on data from 1996–2014 has been the current MSL in Norway since September 2015. After the quality enhancement work done in 2019 as discussed in 2.1.2, Mean Sea level was recalculated based on the same period. As shown in Table 2 the change in $MSL_{1996\text{-}2014}$ was less than 0.5 cm for all tide gauges.

Table 2: Changes in the current Mean Sea Level after the quality enhancement work in 2019.

Tide gauge	Changes in MSL1996-2014 [cm]
Andenes	0.12
Bergen	0.11
Bodø	-0.15
Harstad	0.13
Heimsjø	0.14
Helgeroa	0.07
Honningsvåg	-0.17
Kabelvåg	-0.21
Kristiansund	0.13
Måløy	0.10
Narvik	0.34
Ny-Ålesund	-0.15
Oscarsborg	0.12
Oslo	0.19
Rørvik	0.08
Stavanger	0.02
Tregde	0.38
Tromsø	-0.05
Trondheim	0.12
Vardø	0.19
Viker	-0.12
Ålesund	0.48

A.2. Tromsø: Different location from 1961-1985

During the work with this analysis, it was discovered that the historical data series from Tromsø came from two different locations. In the period 1961 through 1985, the permanent tide gauge was placed north of the Tromsø bridge. In this location, the amplitude of the tide is approximately 6-7% higher than in the current location of the tide gauge. The amplitude difference was noted by (Hansen & Roald, 2000) and the amplitude corrected in their work but not registered in the database. Thus, in previous work on extreme values, (Haug, 2012) and (Ravndal & Borck, 2016), the Tromsø data were used directly, without any corrections. This might have led to too high extreme water levels for this location as Figure 11 indicates. To remove the effects of the tidal amplitude difference, the period in which the tide gauge was placed north of the Tromsø bridge has been removed from the data series used for the analysis.

A simple analysis of the tide gauges around Tromsø has been performed. This analysis shows similar results to the buddy check by (Breili, 2022) described above, and it is therefore difficult to make assumptions on an eventual difference in yearly means caused by the different locations of the tide gauge. It is nevertheless something one should be aware of when using the yearly means from Tromsø for analysis.

A.3. Zones where the EVA time series differs from the tidal zone model

The construction of EVA time series for each tidal zone is described in 2.3.3. Here we describe in detail the cases where the EVA time series differs from water level data from the tidal zone model.

Surge for zones based on new tide gauges (see Figure 6 showing the relevant areas):

- For Sandnes tide gauge we use Stavanger. Sandnes is only used for the zone covering the inner part of Gandsfjorden. Stavanger and Sandnes are so close to each other that there is no reduction in quality or consistency for this zone.
- For Leirvik and Bruravik tide gauges we use Bergen. These two tide gauges provide the surge for all zones in Hardangerfjorden and the nearby coast, an area where Bergen was considered the best fit before the new tide gauges were established.
- For Træna tide gauge we use Rørvik. Træna is so far only used for the zone covering the surrounding islands earlier based on Rørvik. For surrounding zones, Rørvik is still used.
- For Solumstrand tide gauge we use Viker. Solumstrand is only used for the zone covering the inner part of Drammensfjorden, a zone earlier based on Viker. For this inner part a delay in the surge (comparing Solumstrand to Viker) has been observed but this is not corrected for. Because of this, consistency is reduced between the extreme values and the other products based on the model for this innermost zone, and the quality might also be reduced.
- For Sirevåg tide gauge we use Stavanger. Sirevåg is used as surge for the zones from Sirevåg and north to Tananger, an area not covered by the tidal zone model prior to the new tide gauge. However, also for the EVA in

2015 Stavanger was used for the surge in this area, as it on average is expected to represent the area in an adequate way.

Surge for zones with no surge station in the tidal zone model:

- Bergen is used as surge for the two zones covering Lindås and Mo in Modalen where the model provides no surge. These two zones are surrounded by zones with surge from Bergen, see the two small white dots in the red area of Figure 6, and Bergen is likely to represent the surge adequate on average and therefore used for the EVA.
- No surge is applied to the two zones in the river close to Fredrikstad, hence there are no EVA done here.
- No surge is available for the two zones on Jan Mayen. Hence NMA only provides tidal data for Jan Mayen, and no extreme water levels, which is why Jan Mayen is not included in the discussions of data or EVA in this report.

Water level data for EVA for areas not covered by the tidal zone model:

- For the white zone in Figure 6 south of Sirevåg, from Egersund to Jøssingfjord, we use tidal predictions from Egersund of good quality and surge from Stavanger. As for the zones north of this area, Stavanger is likely to represent the surge on average, but the quality of the extreme water levels will be lowered here.
- For the second white zone in Figure 6 south of Sirevåg, from Jøssingfjord to Lista, we use tidal predictions from Abelnes of good quality and surge from Tregde. Surge from Tregde was also used for EVA in 2015 and is still likely to be adequate for EVA, with some reduction of quality of the resulting extreme water levels.
- The parts of the Svalbard archipelago and the other smaller spots not covered by the tidal zone model have not been included in this EVA.

B. ACER parameters and supplementary results

In this appendix we briefly include the parameters chosen for the analysis. As described earlier, the ACER-method (Skjong et al., 2013) has been used with the same approach as for the previous EVA as described in (Ravndal & Borck, 2016).

B.1. Parameters used

Number of previous non-exceedances: Based on the considerations from previous EVAs, see (Ravndal & Borck, 2016), we use 2 as the number of previous non-exceedances, that is k=3, for all analysis. It is worth noting that when extracting the peaks, every local extreme is included for the time series of water level data, while for the surge, the extreme among 12 hourly values was extracted.

Threshold: The threshold η has been established for each time series by finding the value for which 5% of the data points are above for the high return levels and below for the low return levels. In Table 3 the thresholds used for the zones with a tide gauge are listed. The thresholds for the surrounding zones will be of the same magnitude as the nearby tide gauge.

Table 3: Threshold values used for each tide gauge

Tide gauge	High water level threshold (cm)	Low water level threshold (cm)	High surge threshold (cm)	Low surge threshold (cm)
Viker	40	-35	35	-30
Oscarsborg	43	-38	38	-32
Oslo	43	-40	39	-33
Helgeroa	36	-31	31	-26
Tregde	28	-25	23	-20
Stavanger	34	-32	24	-21
Bergen	51	-52	23	-20
Måløy	75	-76	26	-23
Ålesund	81	-80	28	-24
Kristiansund	88	-86	27	-24
Heimsjøen	99	-97	27	-23
Mausund	97	-92	29	-23
Trondheim	120	-111	26	-23
Rørvik	101	-99	28	-23
Bodø	112	-108	29	-23
Kabelvåg	121	-114	29	-23
Narvik	129	-121	31	-24
Harstad	89	-88	26	-22
Andenes	85	-86	27	-22
Tromsø	105	-105	26	-22
Hammerfest	110	-110	26	-22
Honningsvåg	106	-106	26	-21
Vardø	121	-123	27	-22
Ny-Ålesund	59	-61	18	-16

B.2. Extreme low water levels

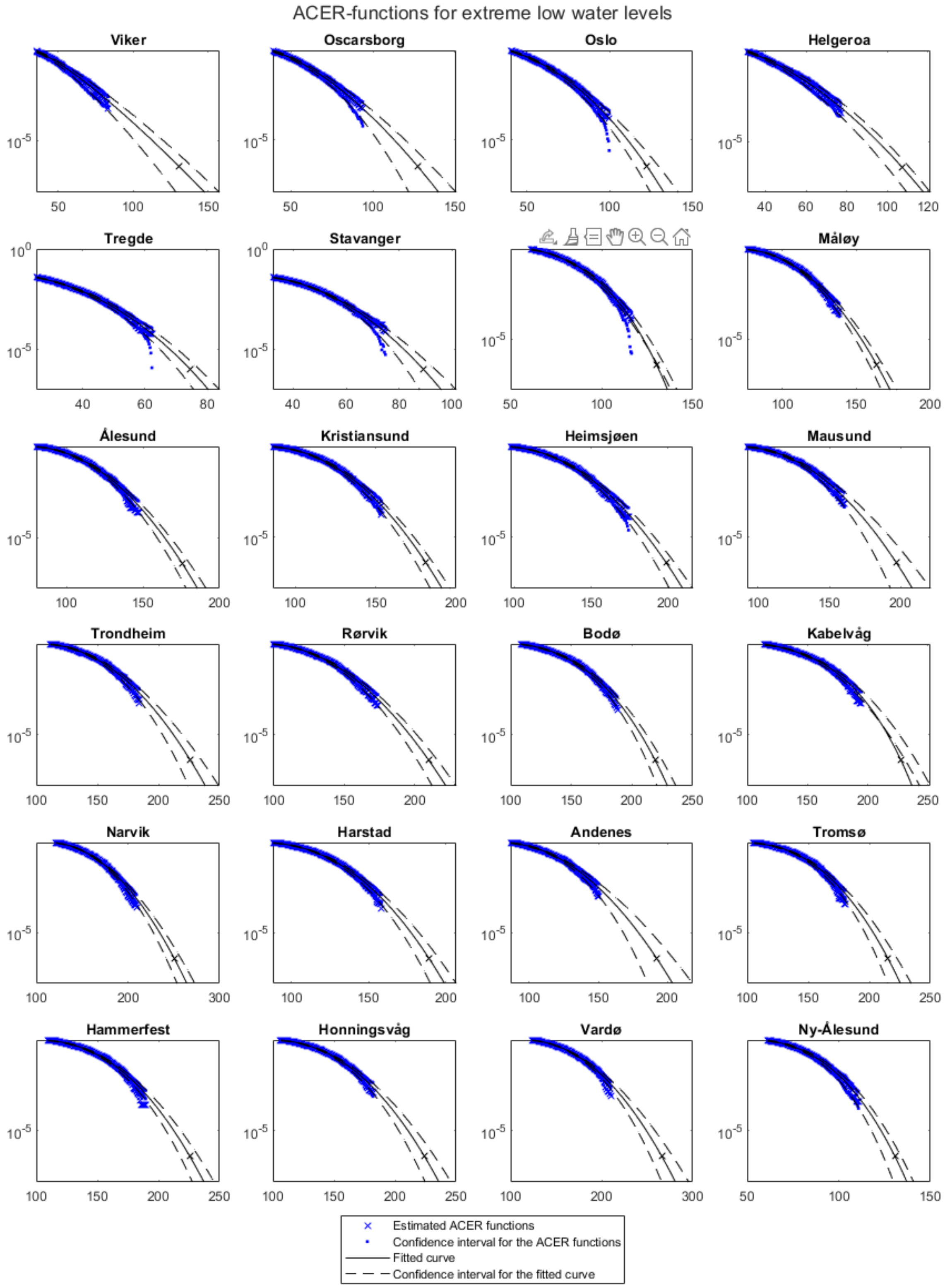

Figure 21: Estimated ACER-functions and fitted curves with confidence intervals for low extreme values for each tide gauge. The x-axis is centimeters and the y-axis is rate.

B.3. Extreme high-water levels

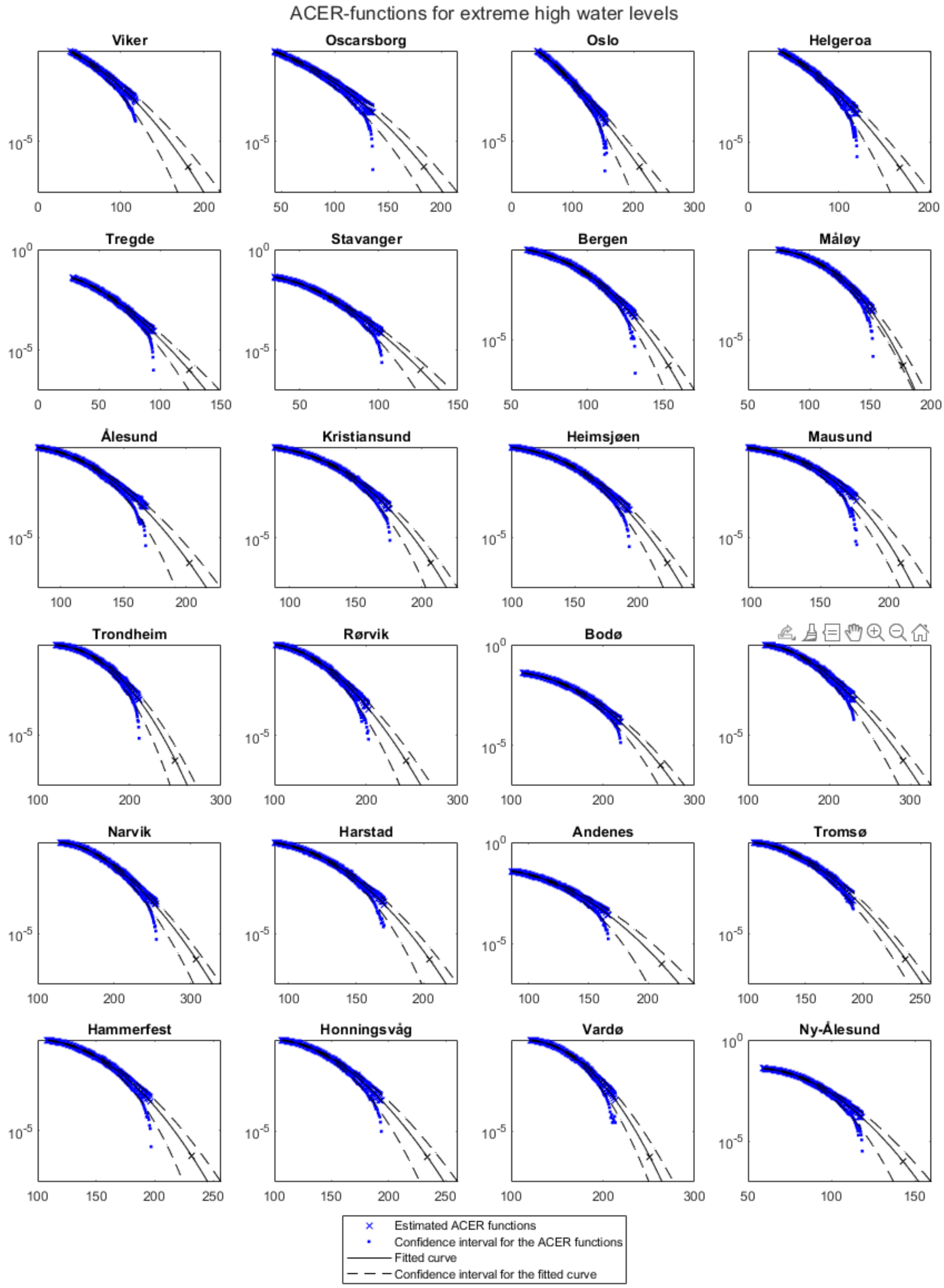

Figure 22: Estimated ACER-functions and fitted curves with confidence intervals high extreme values for each tide gauge. The x-axis is centimeters and the y-axis is rate.

B.4. Extreme surges

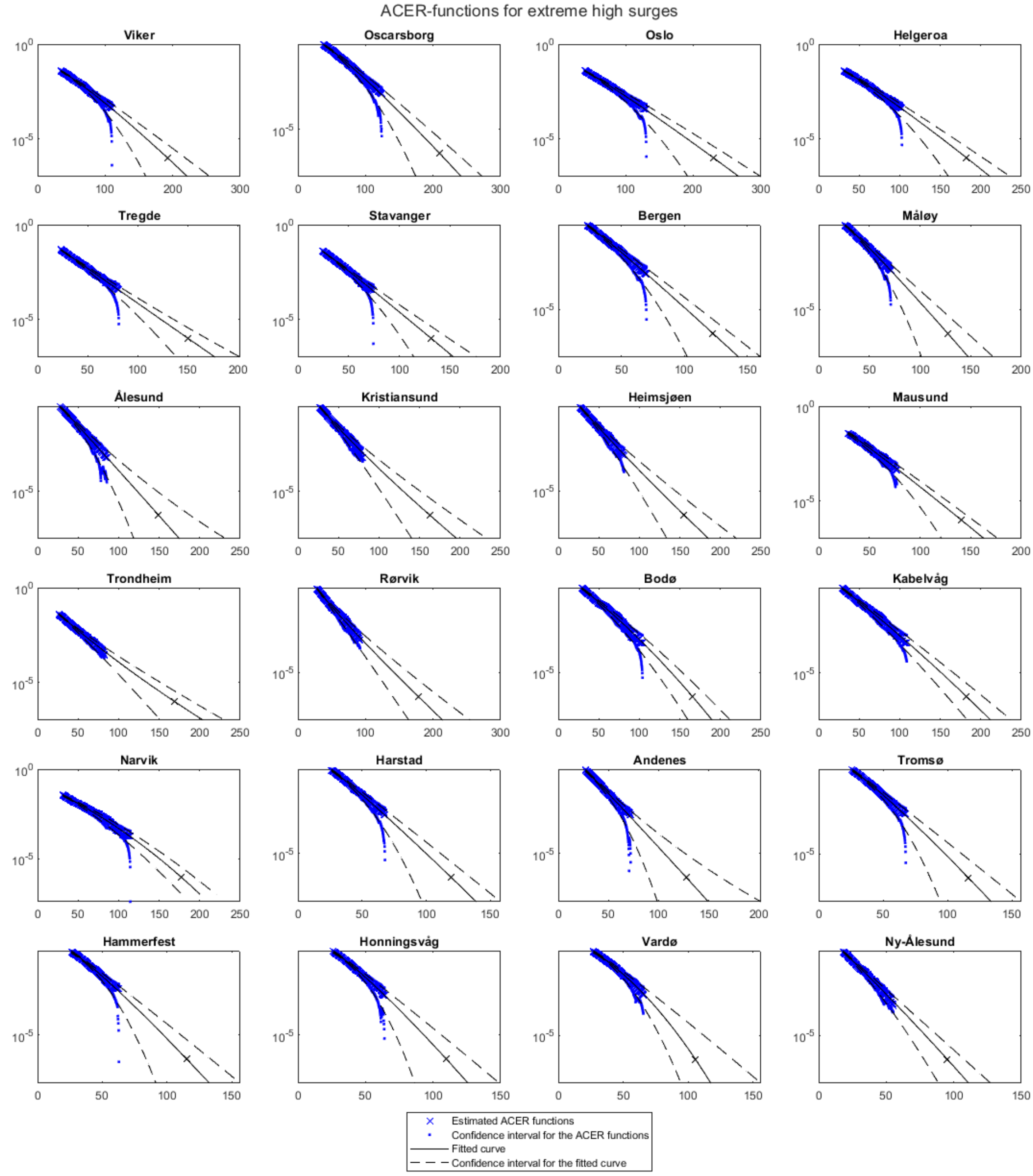

Figure 23:Estimated ACER-functions and fitted curves with confidence intervals for the high extreme surges for each tide gauge. The x-axis is centimeters and the y-axis is rate.

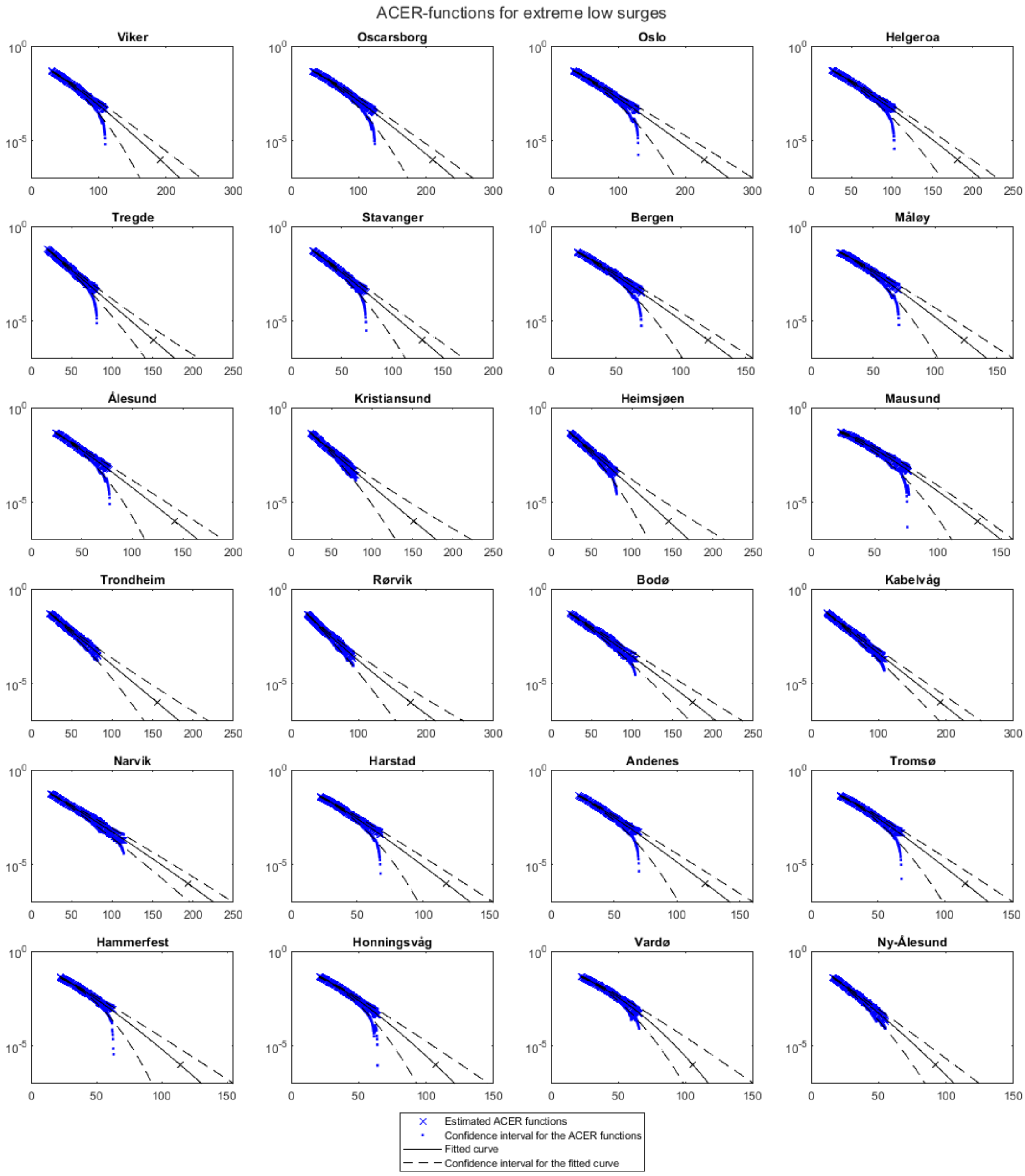

Figure 24: Estimated ACER-functions and fitted curves with confidence intervals for low extreme surges for each tide gauge. The x-axis is centimeters and the y-axis is rate.

C. Some results for the permanent tide gauges

C.1. Plot of extreme water levels with confidence intervals

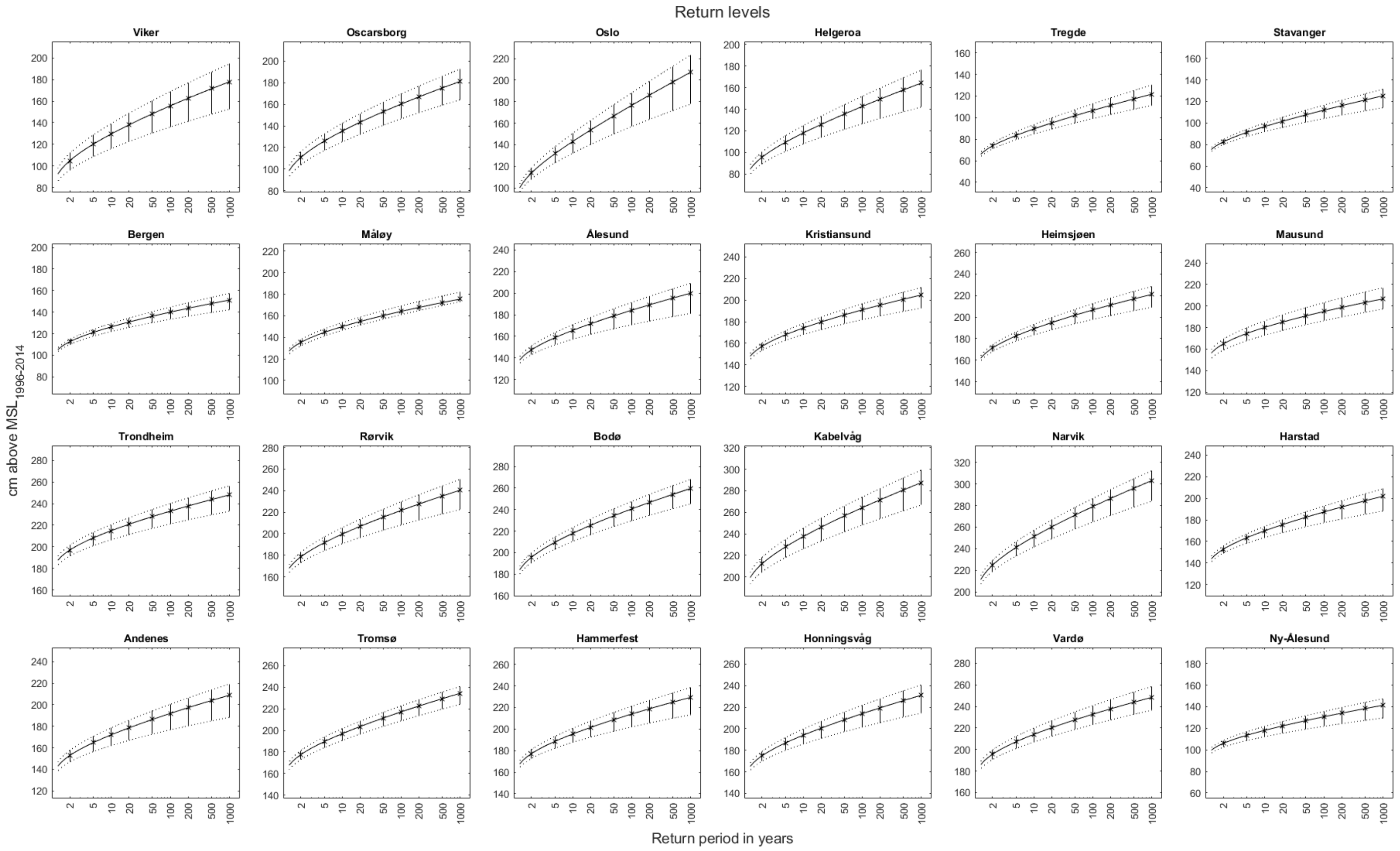

Figure 25: Return levels as functions of return periods for the high extreme water levels at the tide gauges, with confidence intervals. Note that the spacing on the y-axis is equal for each tide gauge, but the range differs between the tide gauges.

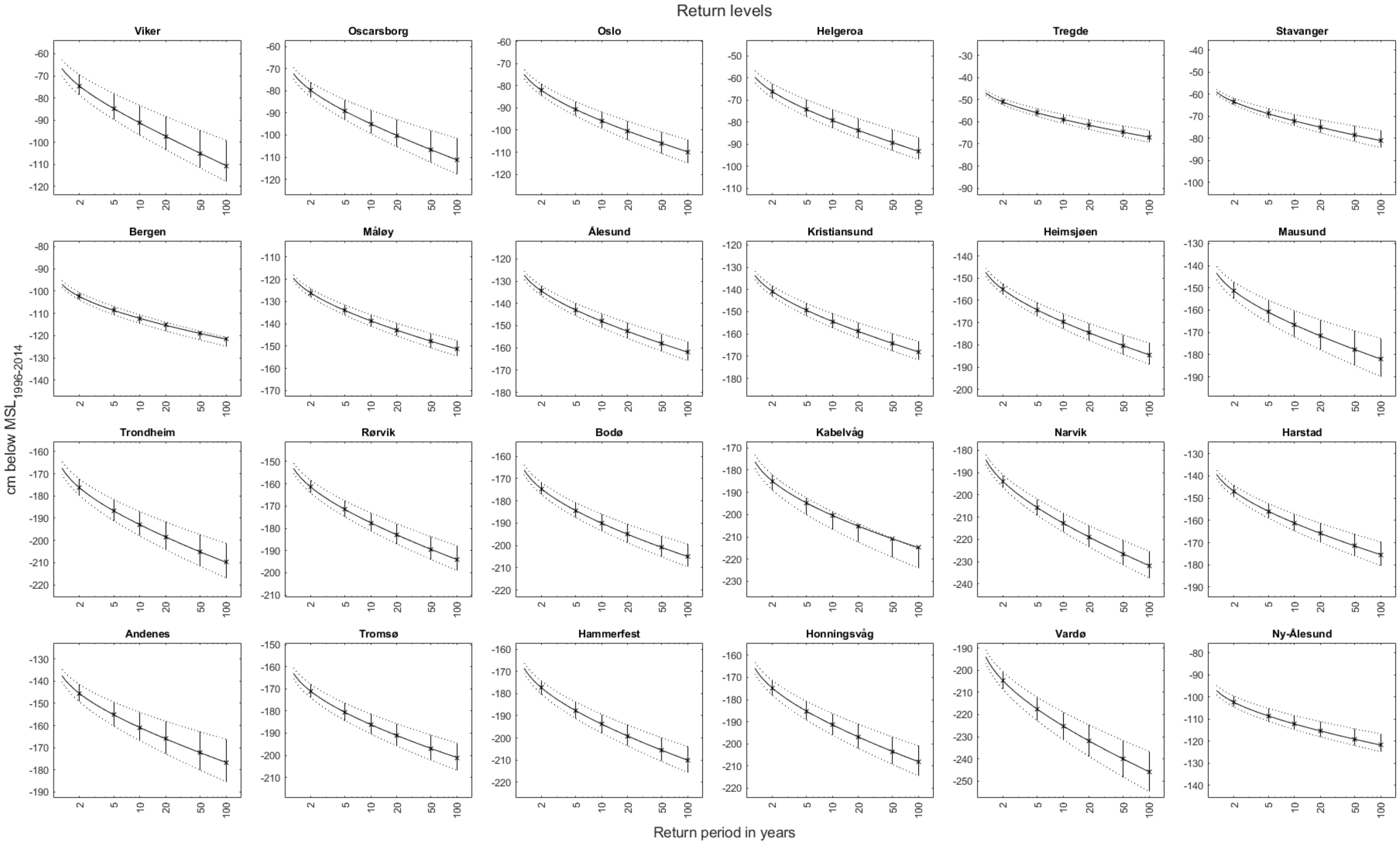

Figure 26: Return levels as a function of return periods for the low extreme water levels up to 100-years return period with confidence intervals. Note that the spacing on the y-axis are the same, but the range varies between the tide gauges.

C.2. Comparison against observed events for all tide gauges

In 3.3 we described the attempt to compare observations with the estimated return levels with a few examples. In this appendix the comparisons for all permanent tide gauges are presented. See the figure caption for any remarks for the tide gauge in question.

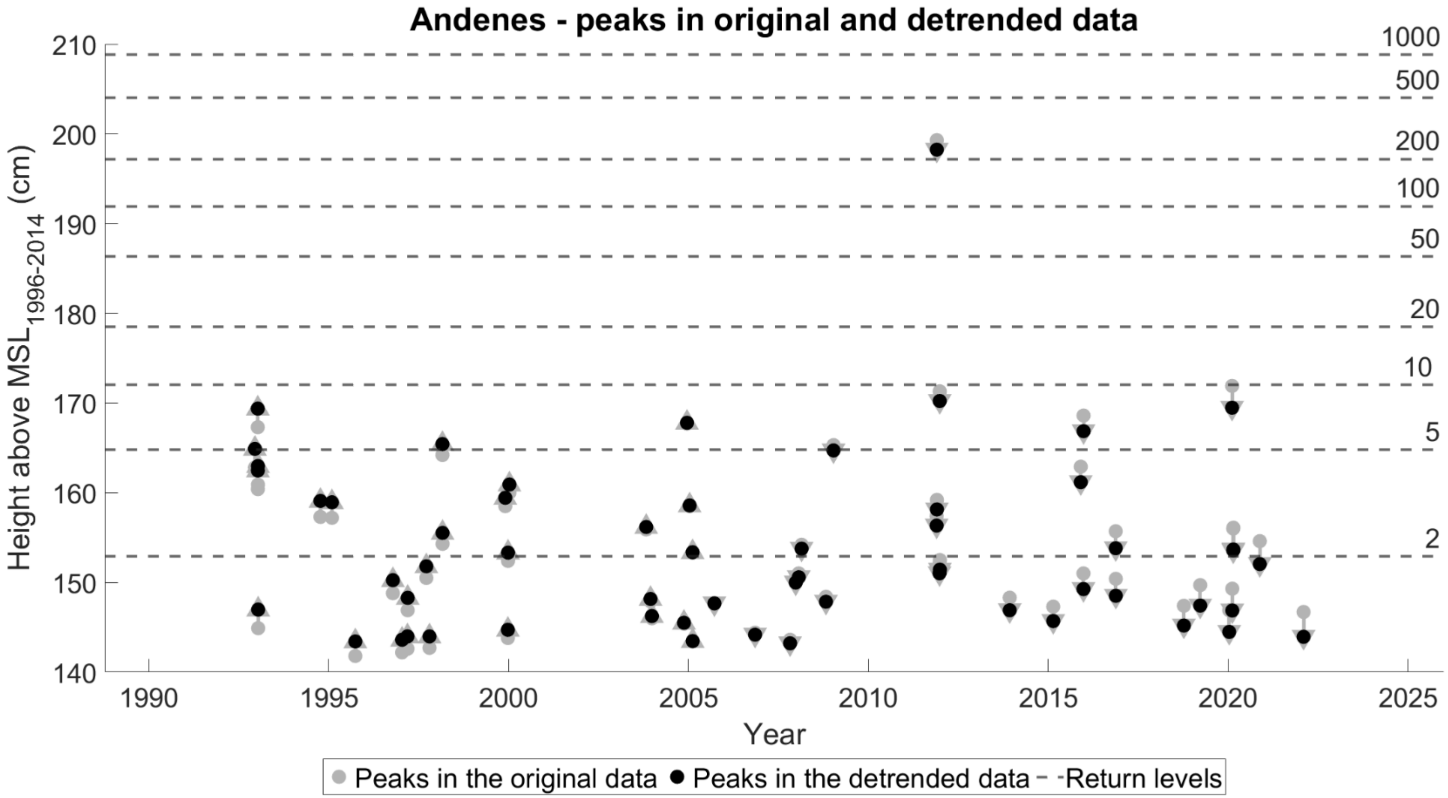

Figure 27: Andenes (also presented in 3.3)

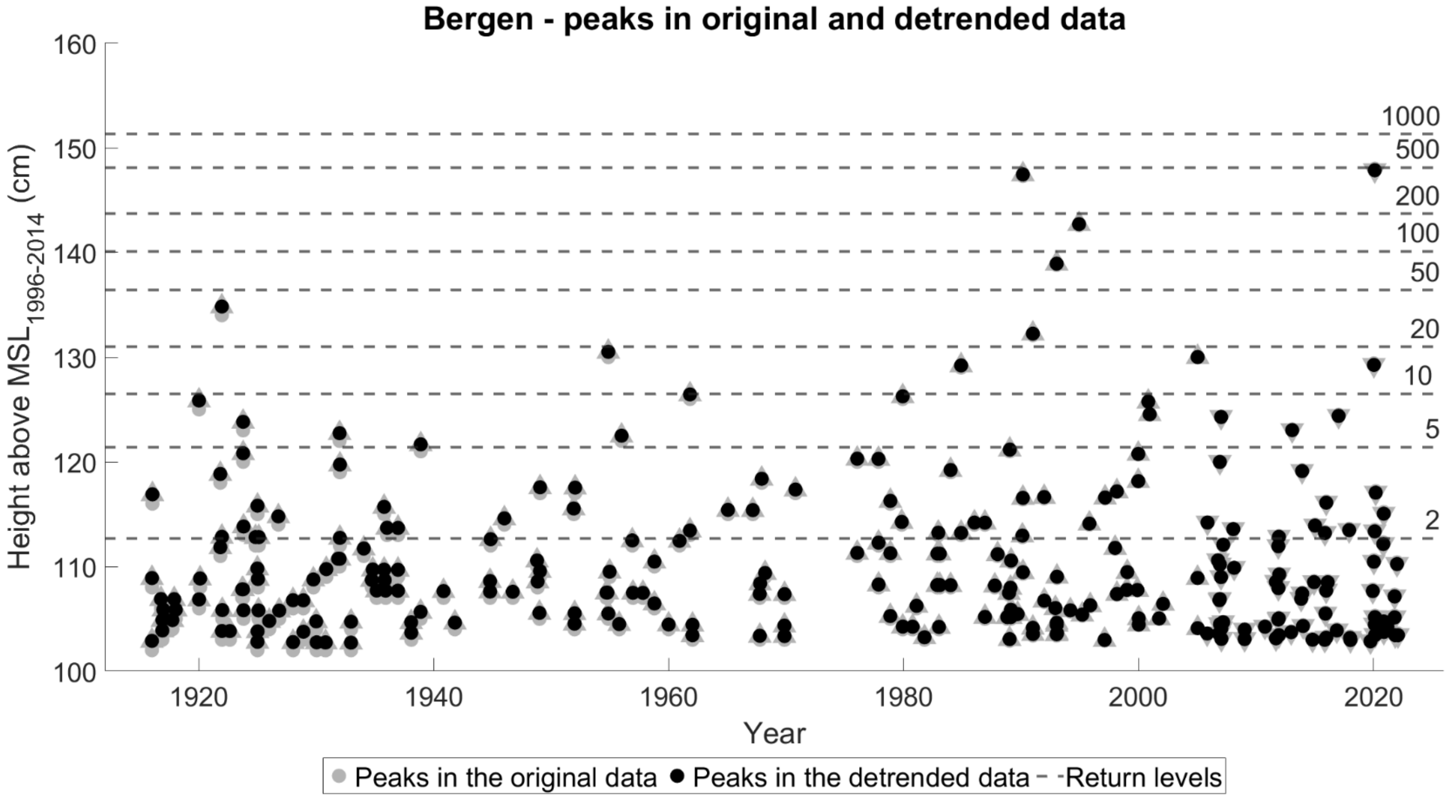

Figure 28: Bergen

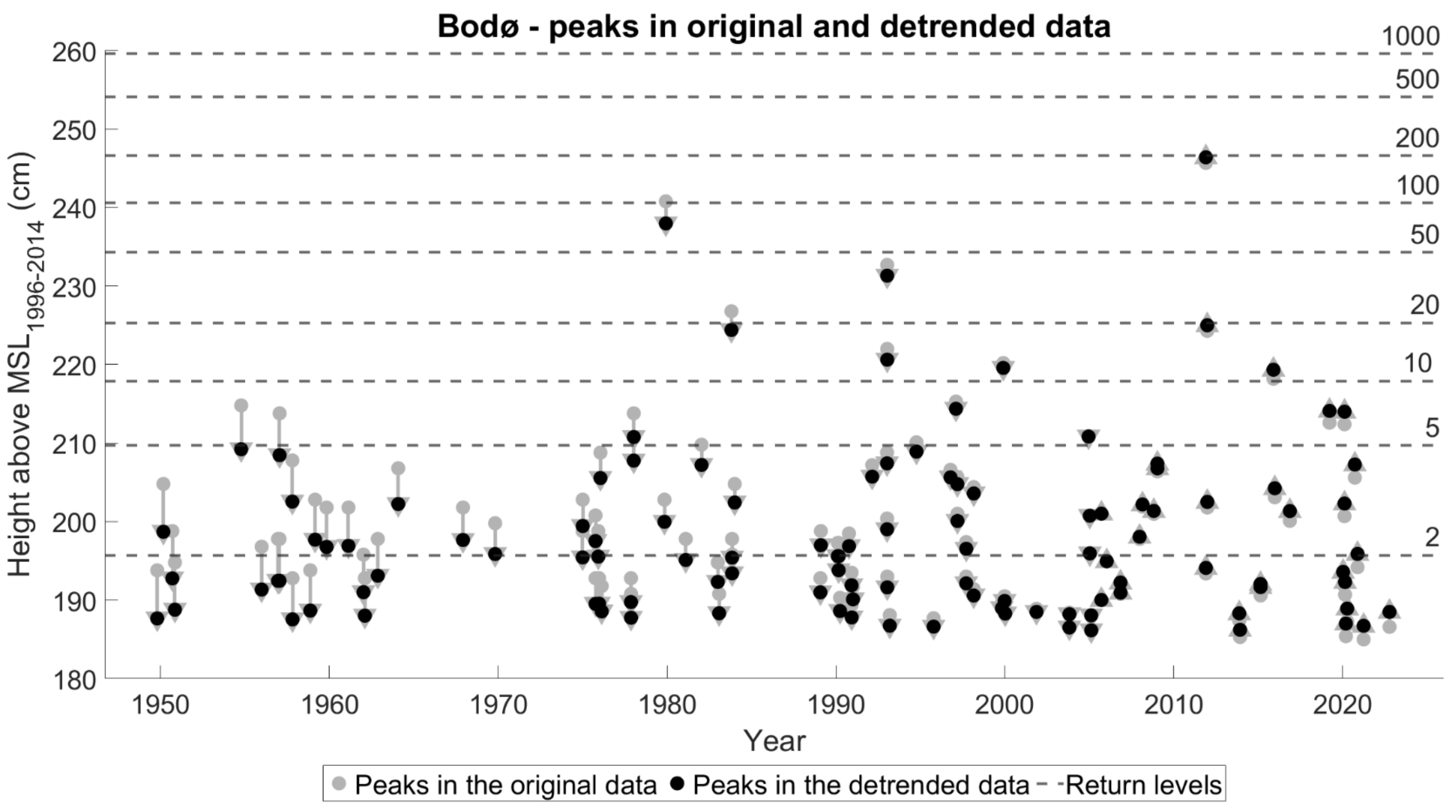

Figure 29: Bodø

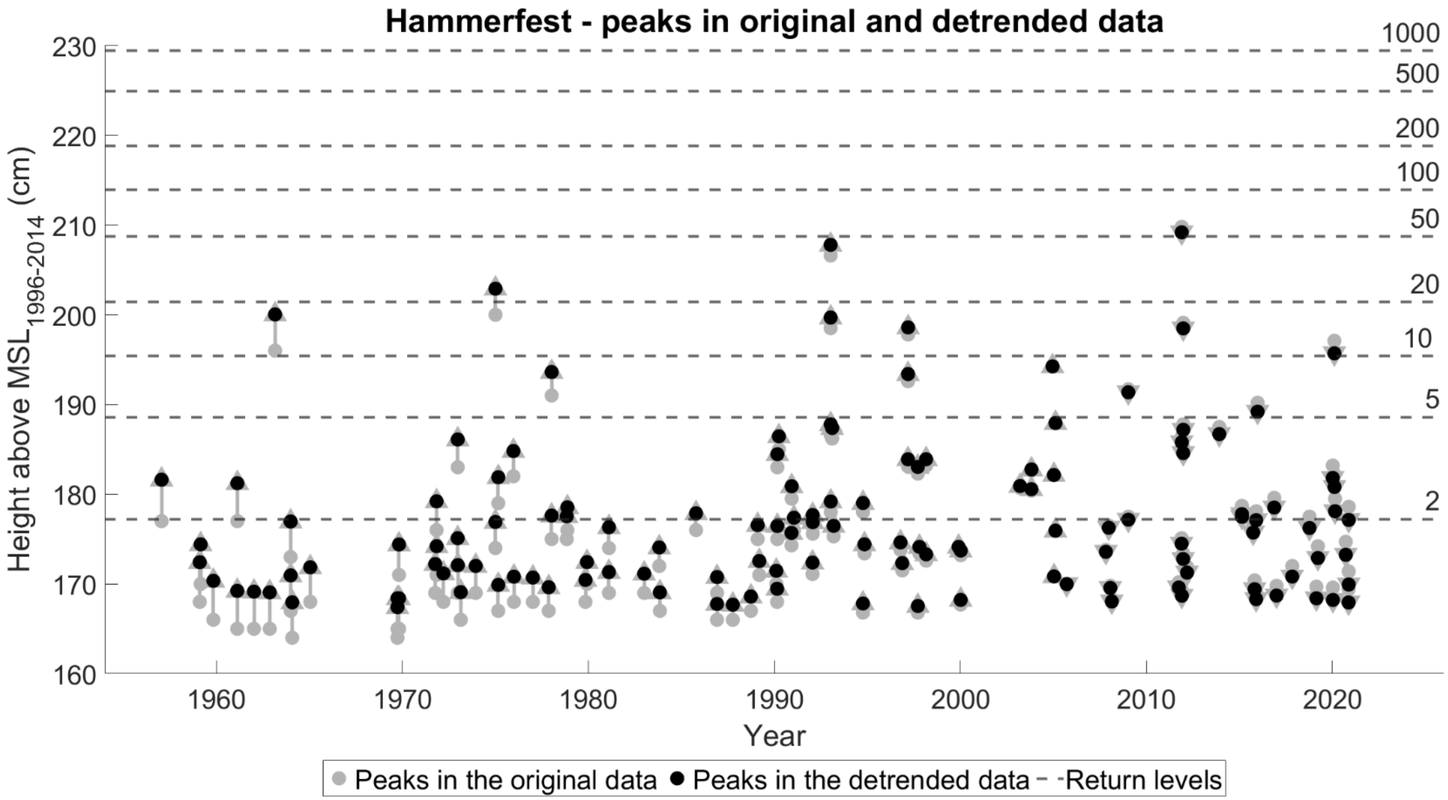

Figure 30: Hammerfest

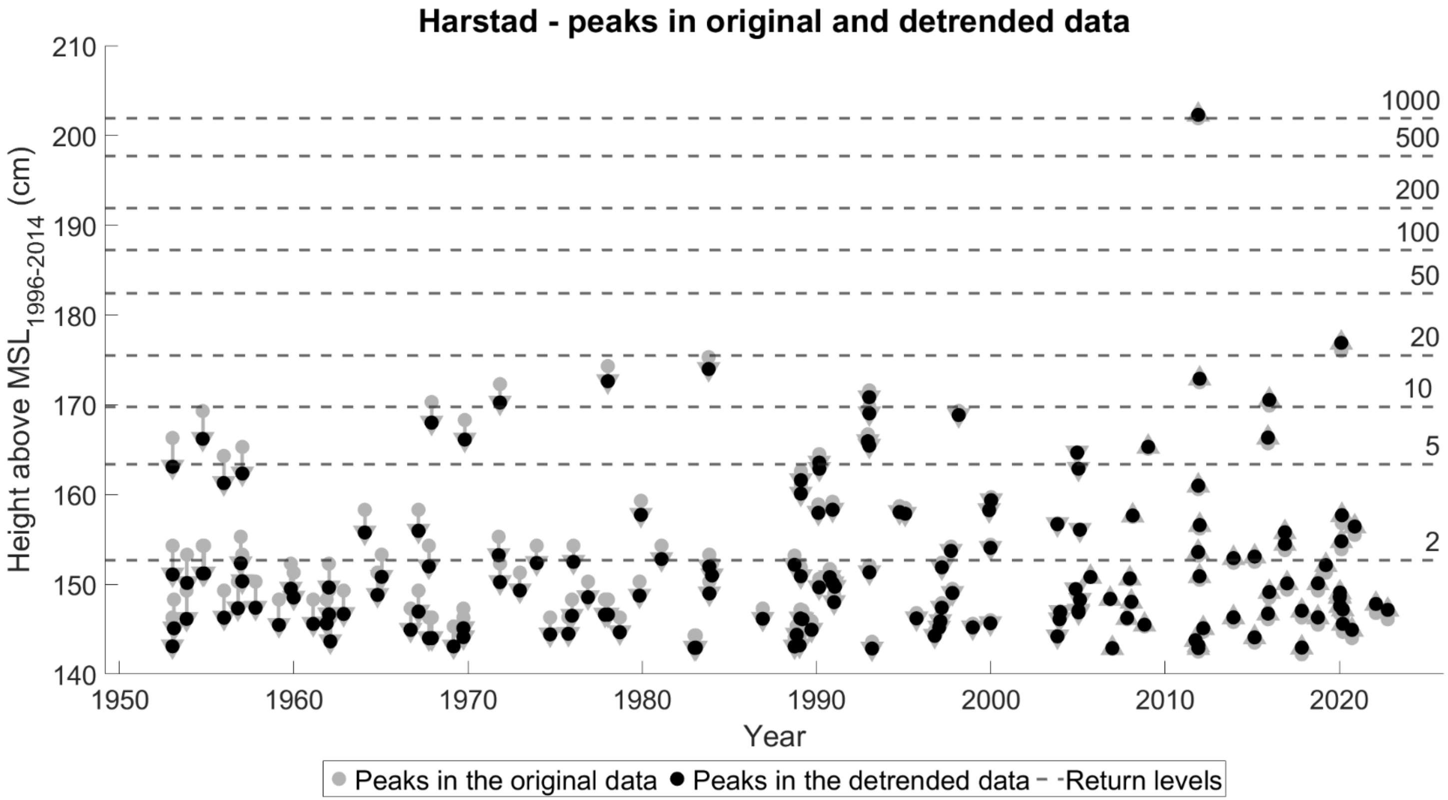

Figure 31: Harstad

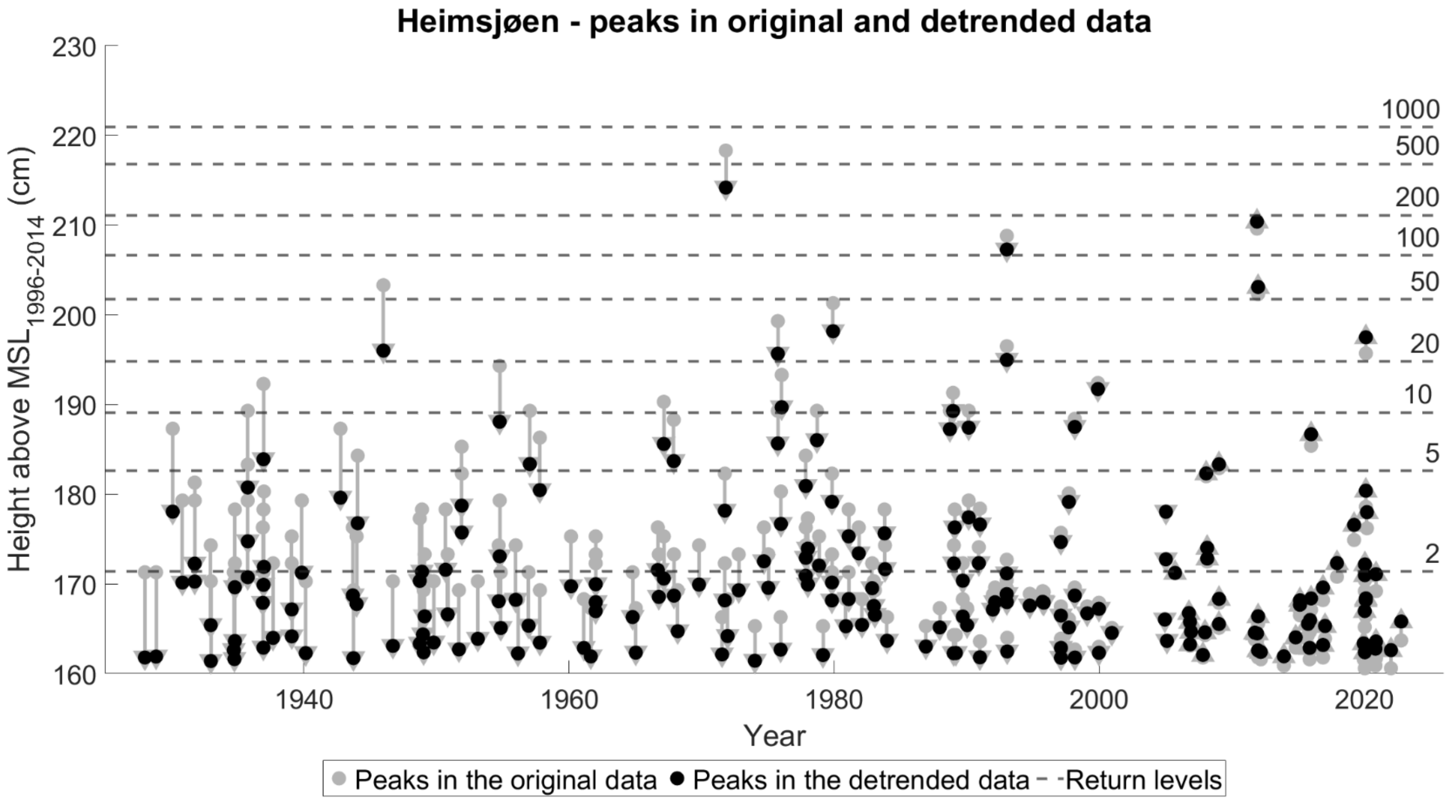

Figure 32: Heimsjøen

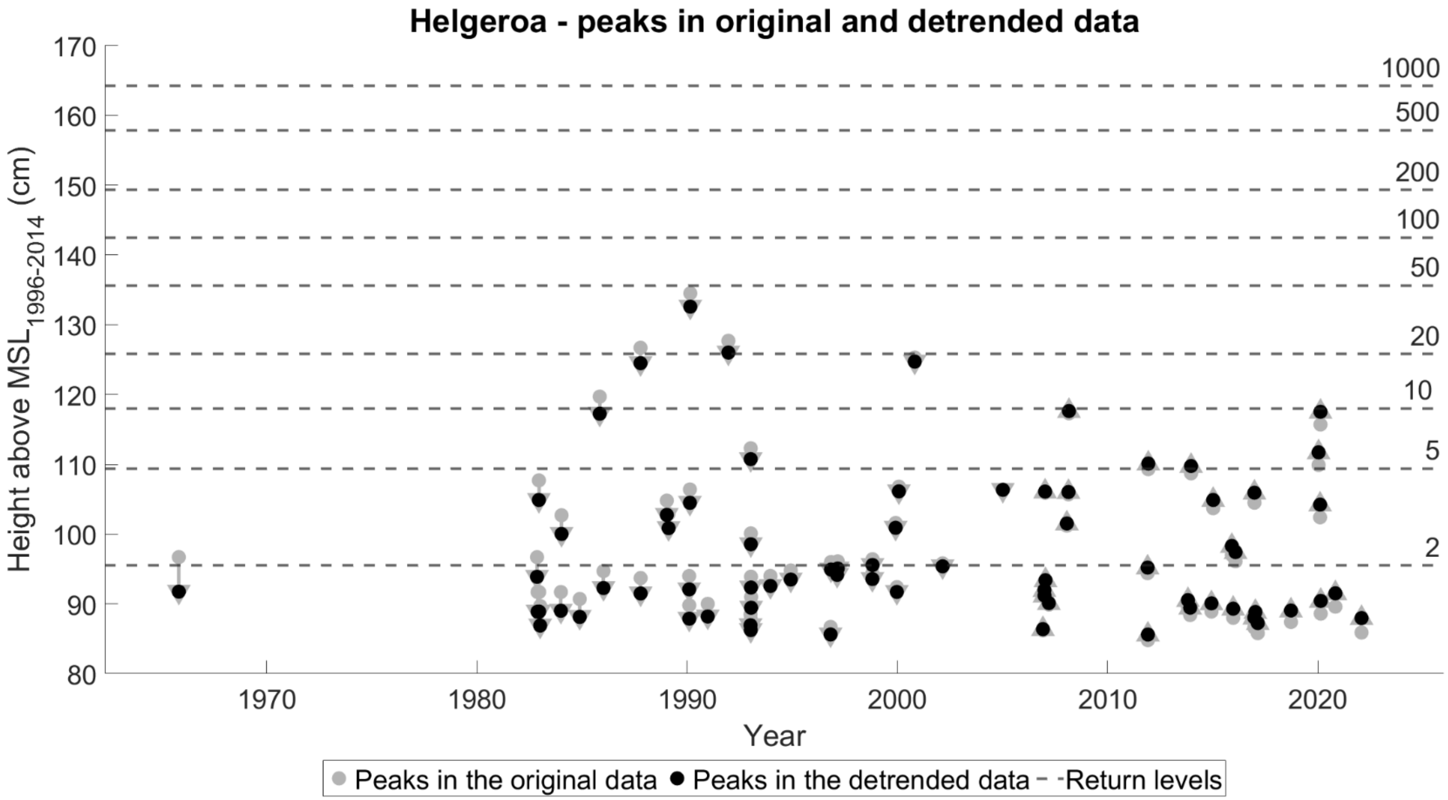

Figure 33: Helgeroa. Note that there is a large gap in the data series from 1970 to 1982, and few extremes recorded in the short data series before 1970.

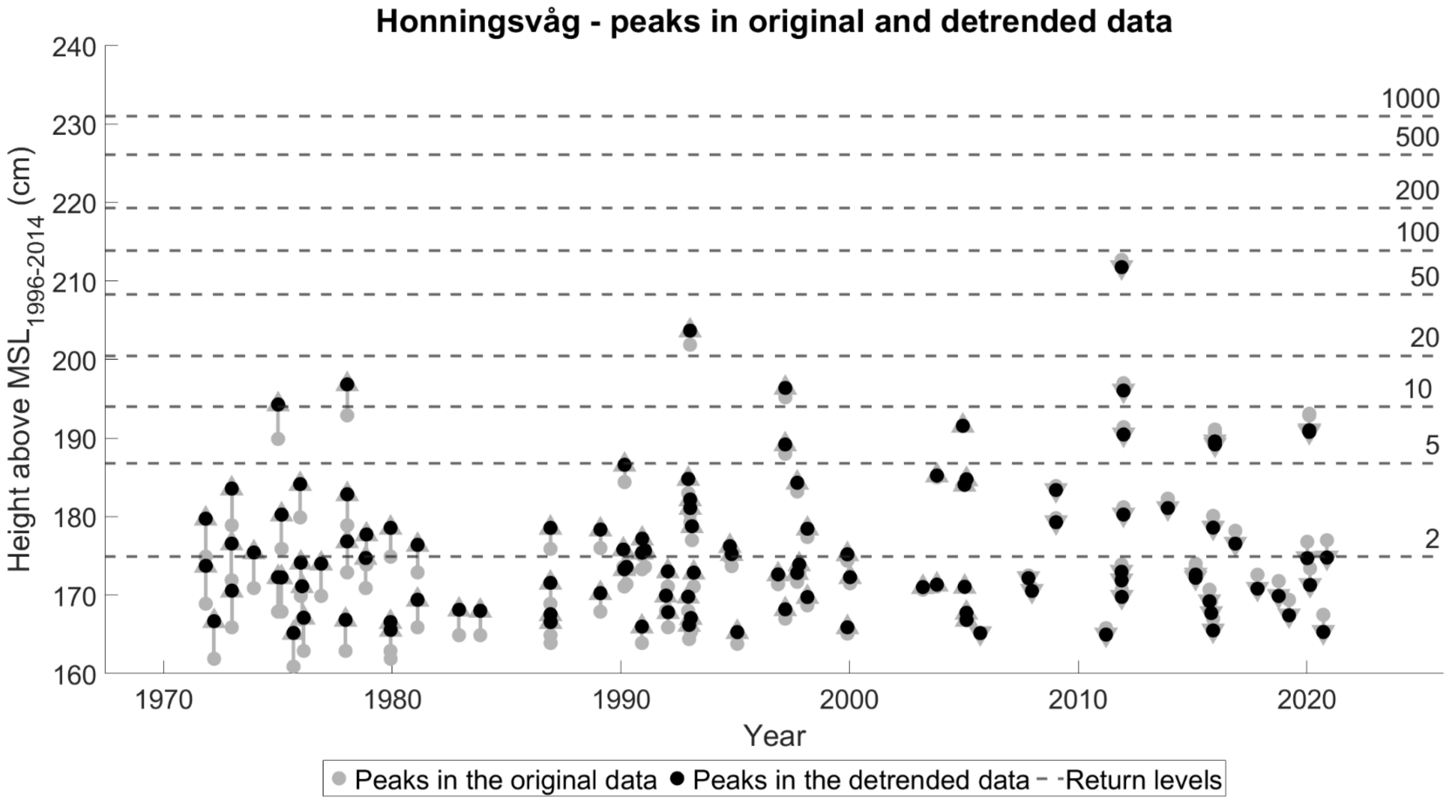

Figure 34: Honningsvåg

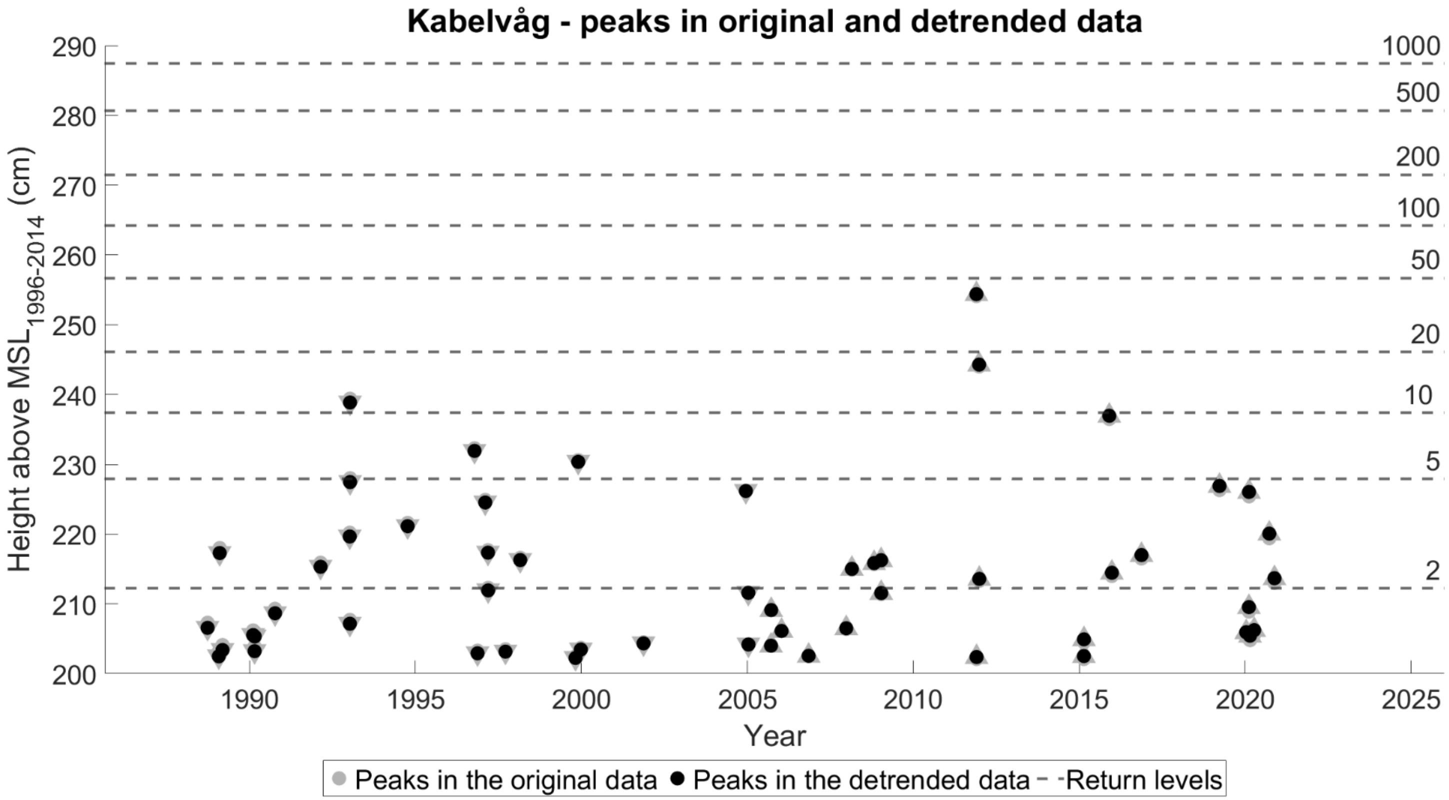

Figure 35: Kabelvåg (also presented in 3.3)

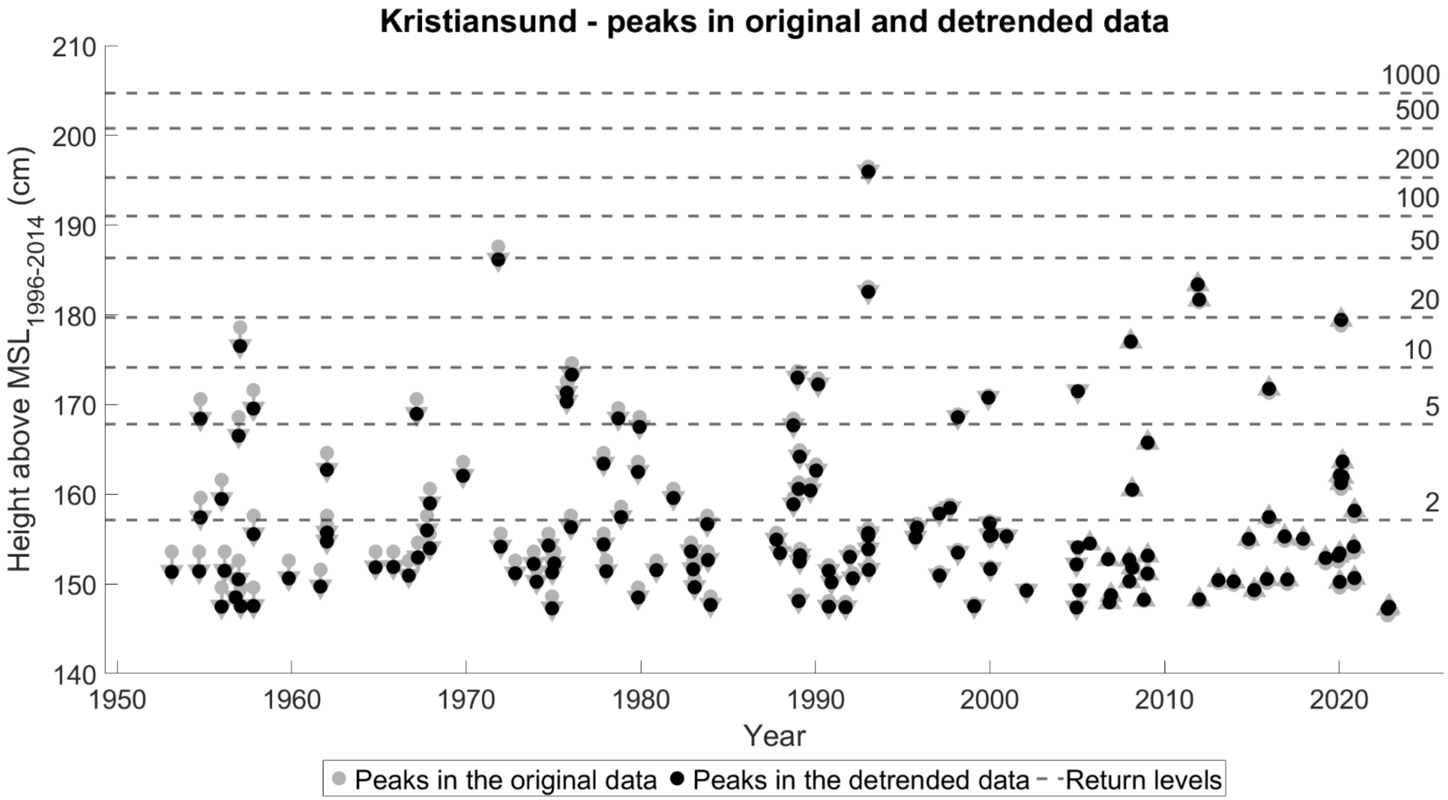

Figure 36: Kristiansund

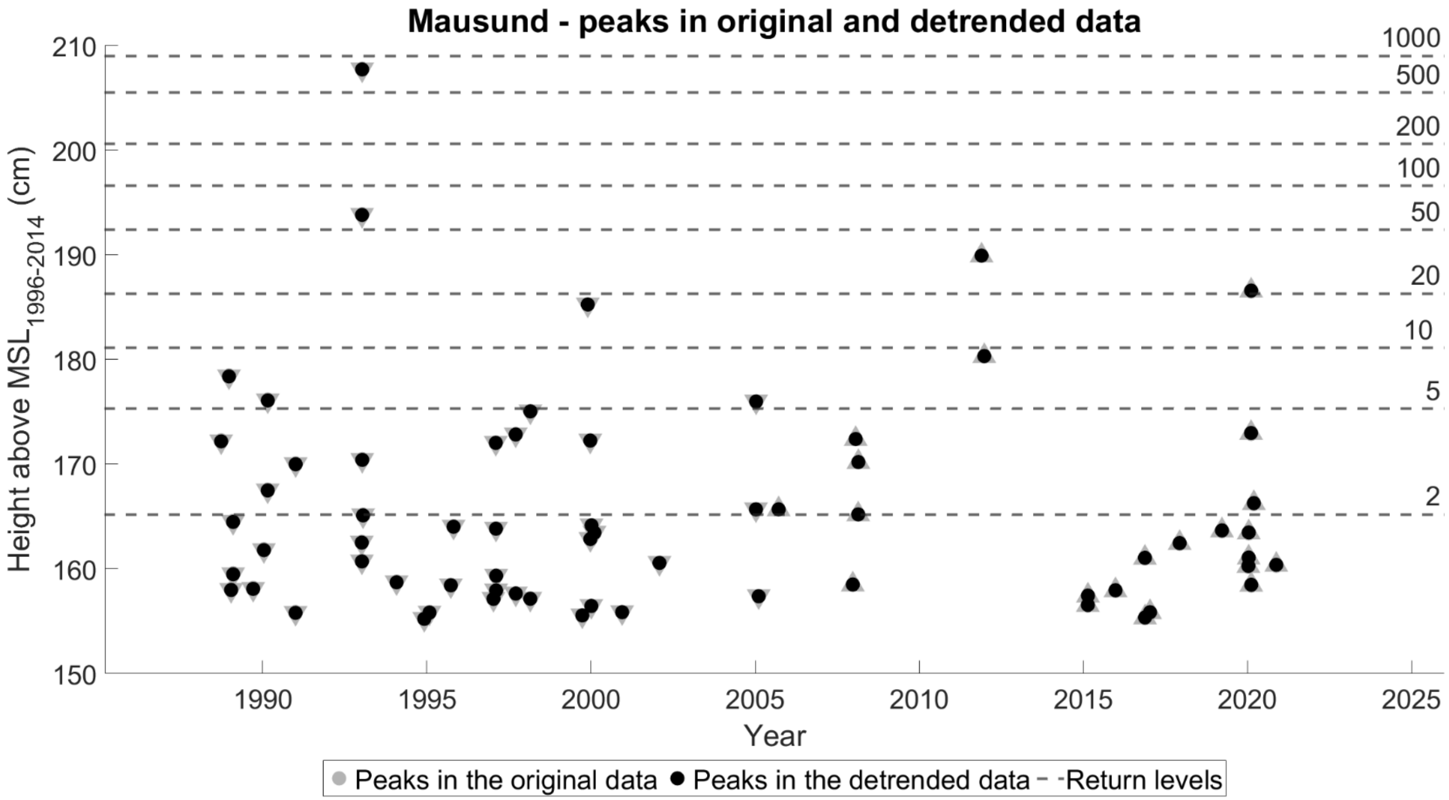

Figure 37: Mausund

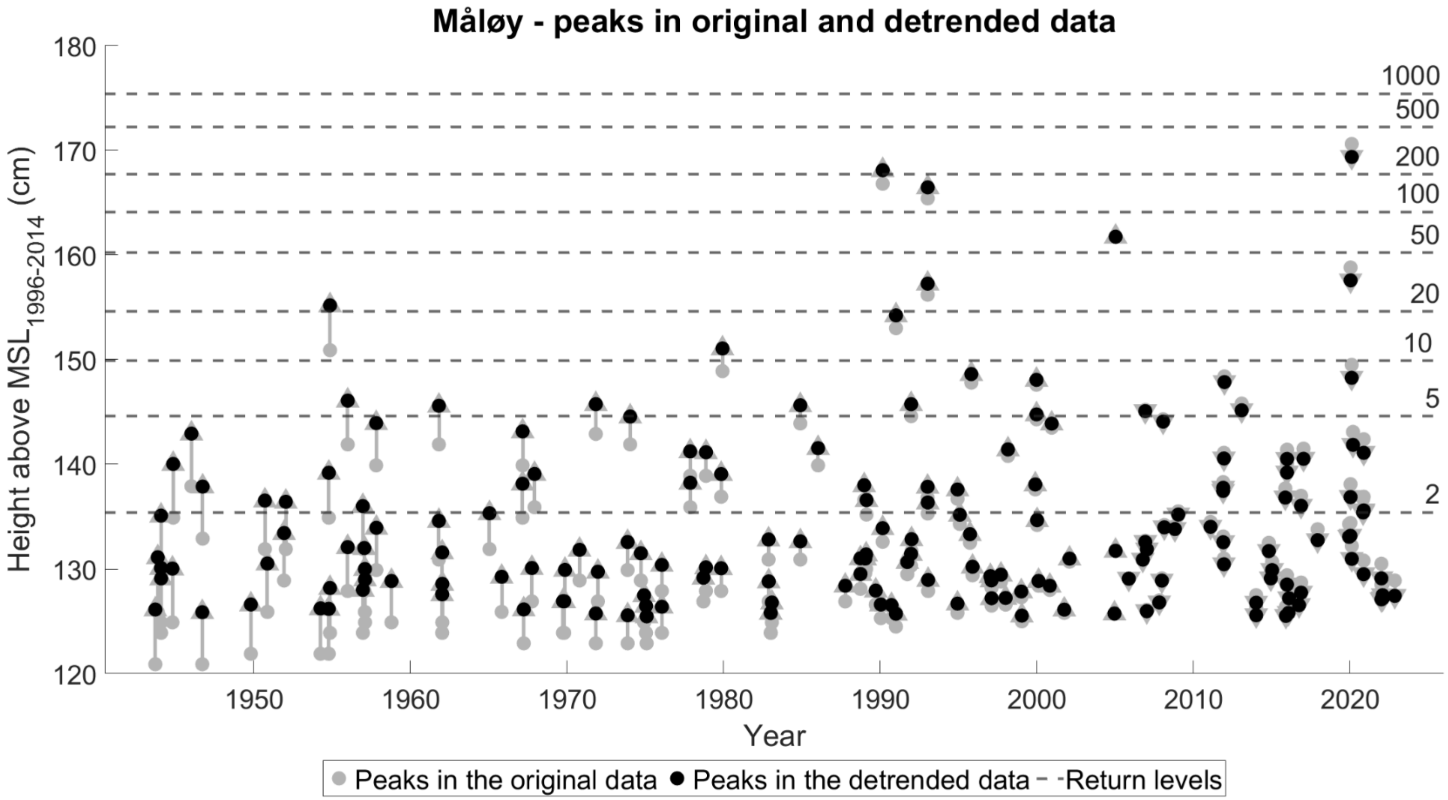

Figure 38: Måløy

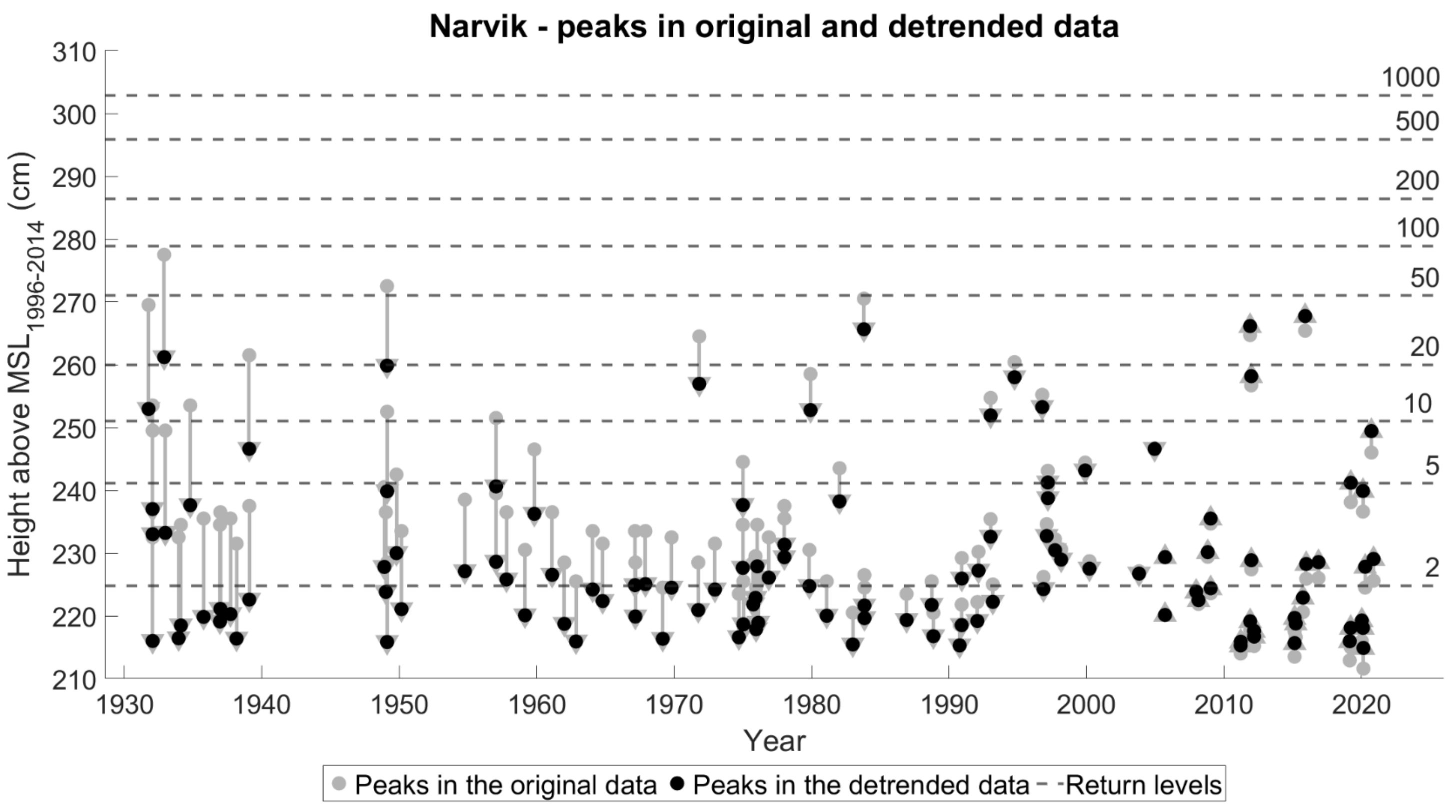

Figure 39: Narvik

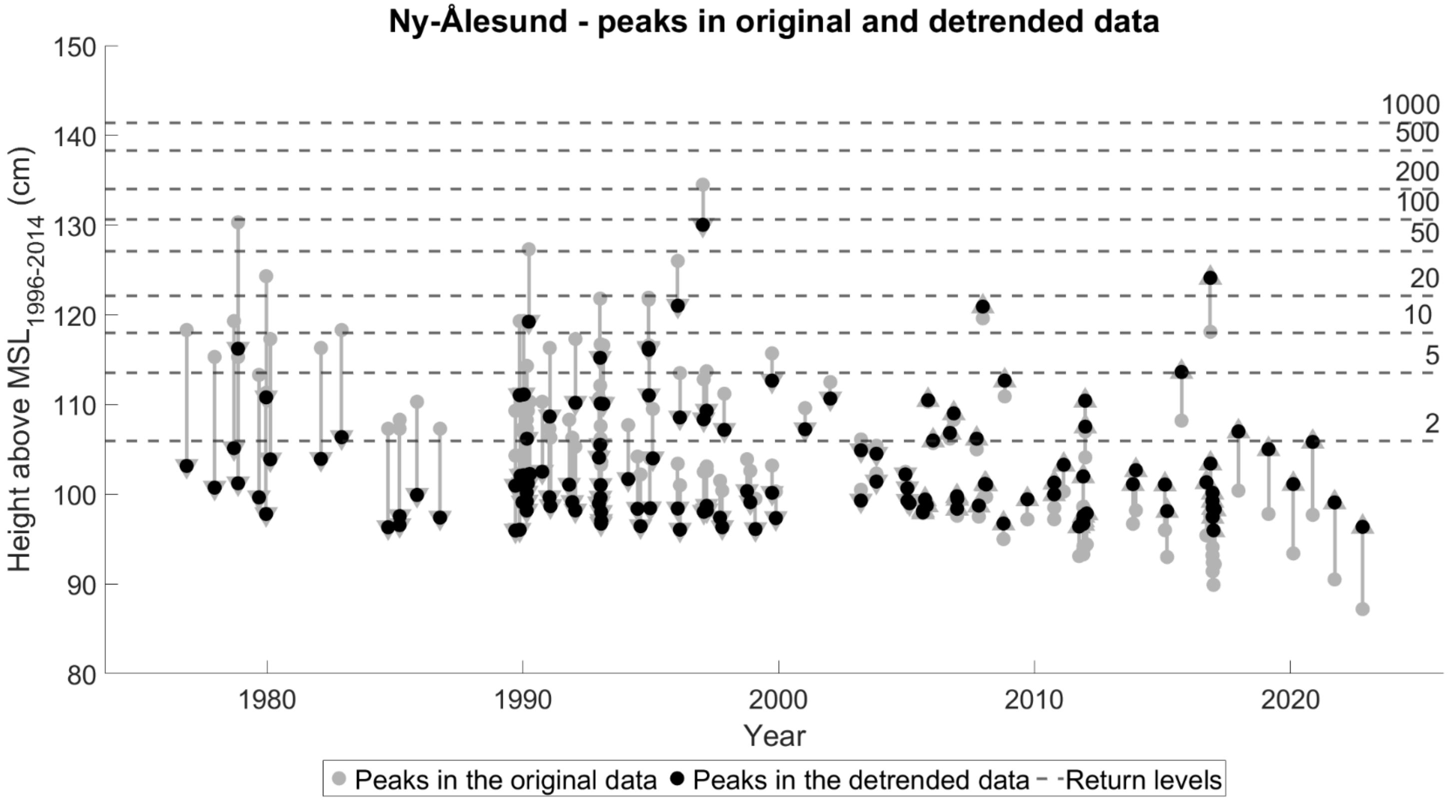

Figure 40: Ny-Ålesund. Note here the large effect of the Glacial isostatic adjustment

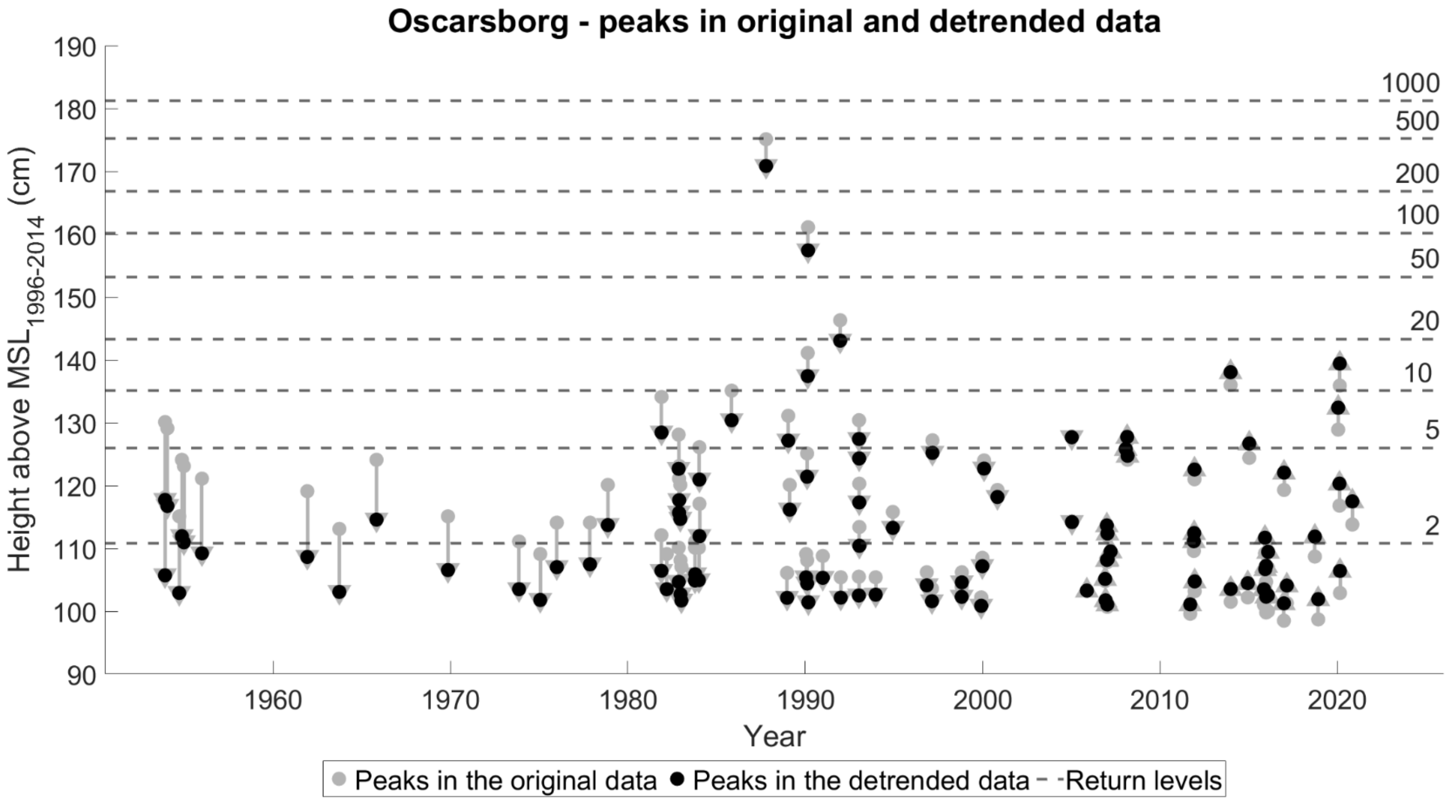

Figure 41: Oscarsborg

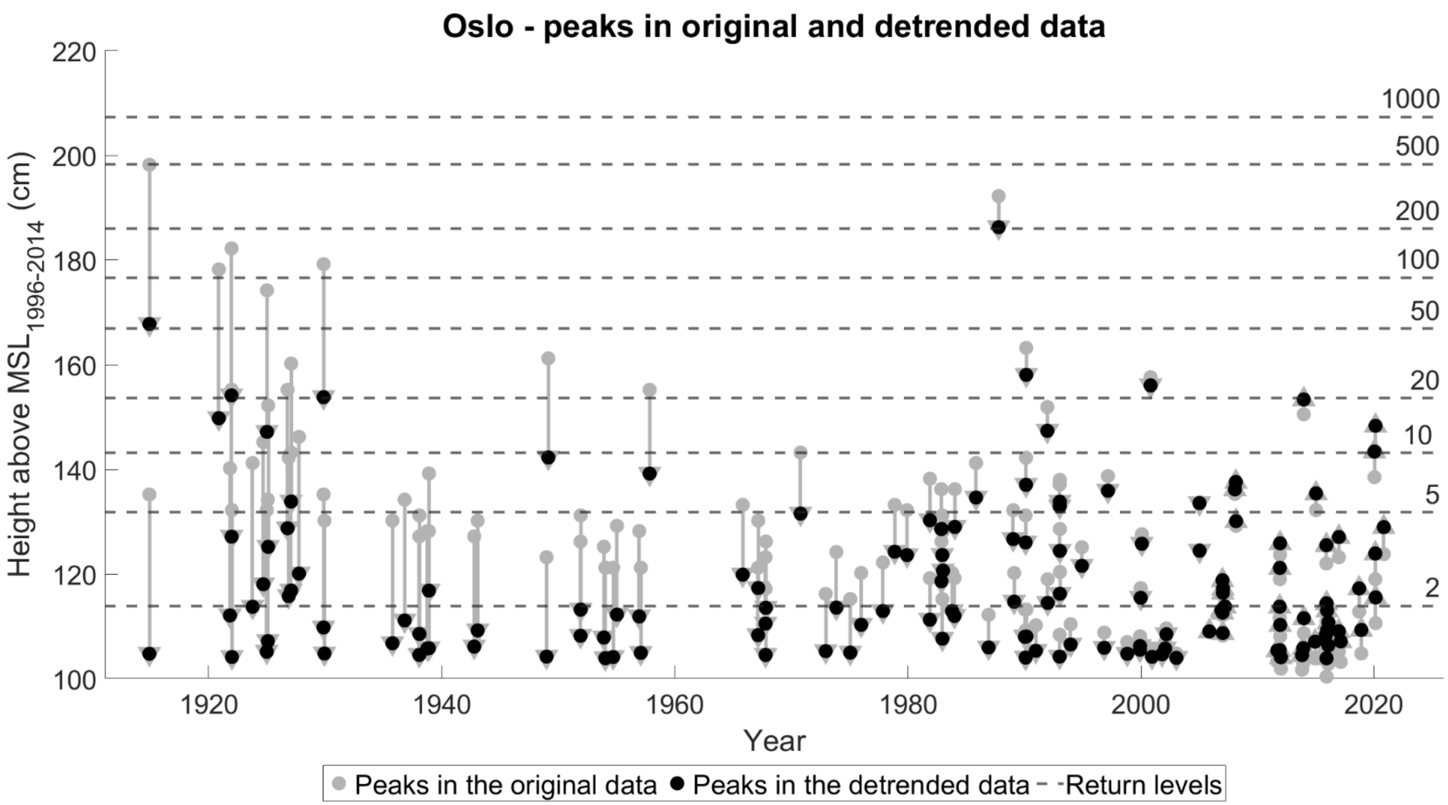

Figure 42: Oslo (also presented in 3.3)

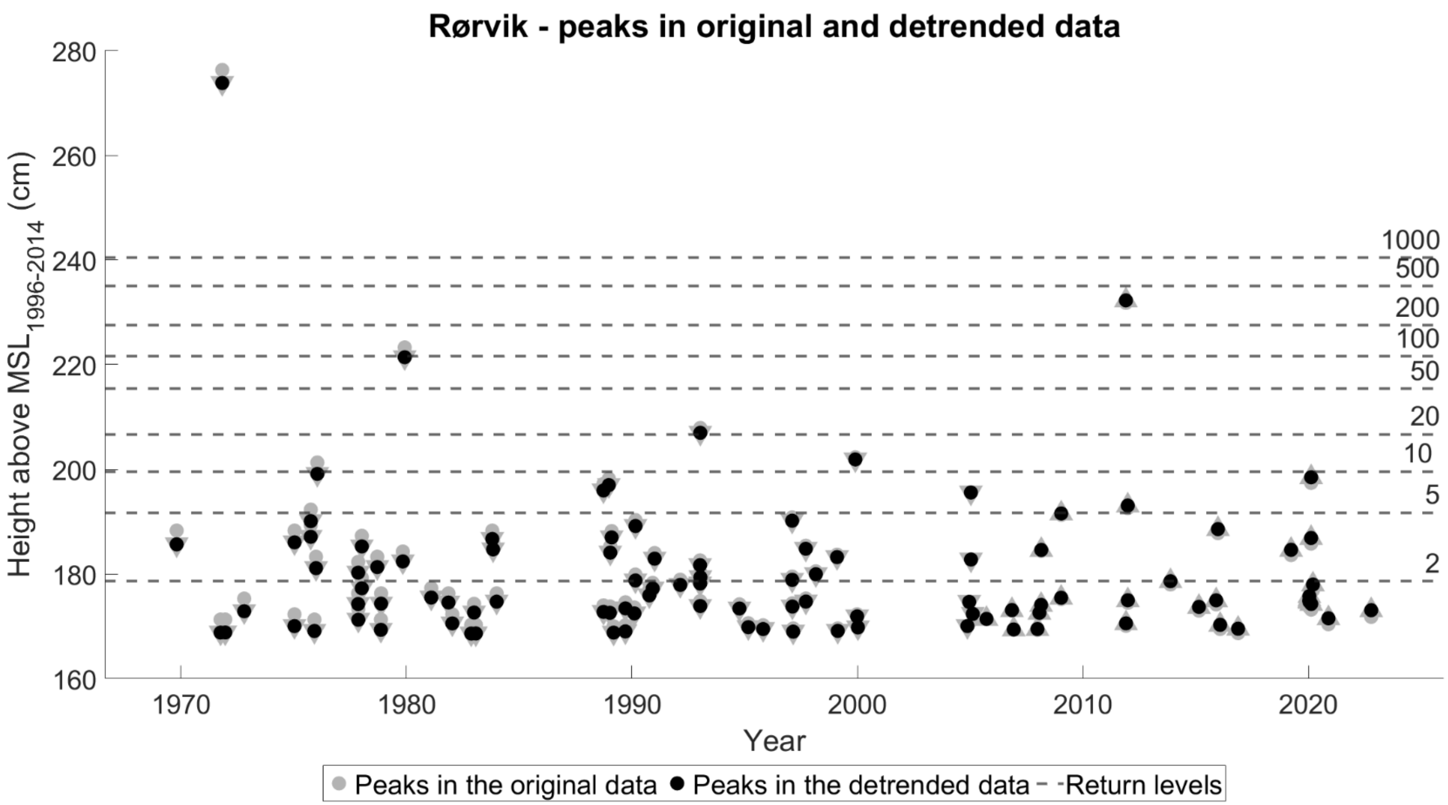

Figure 43: Rørvik. Please note that the extreme from 1972, far above the estimated return levels, is an outlier of dubious value. The recording equipment failed during a storm, and the tide curve was manually drawn on the recording paper. Analysis shows that the peak of the curve was probably too high.

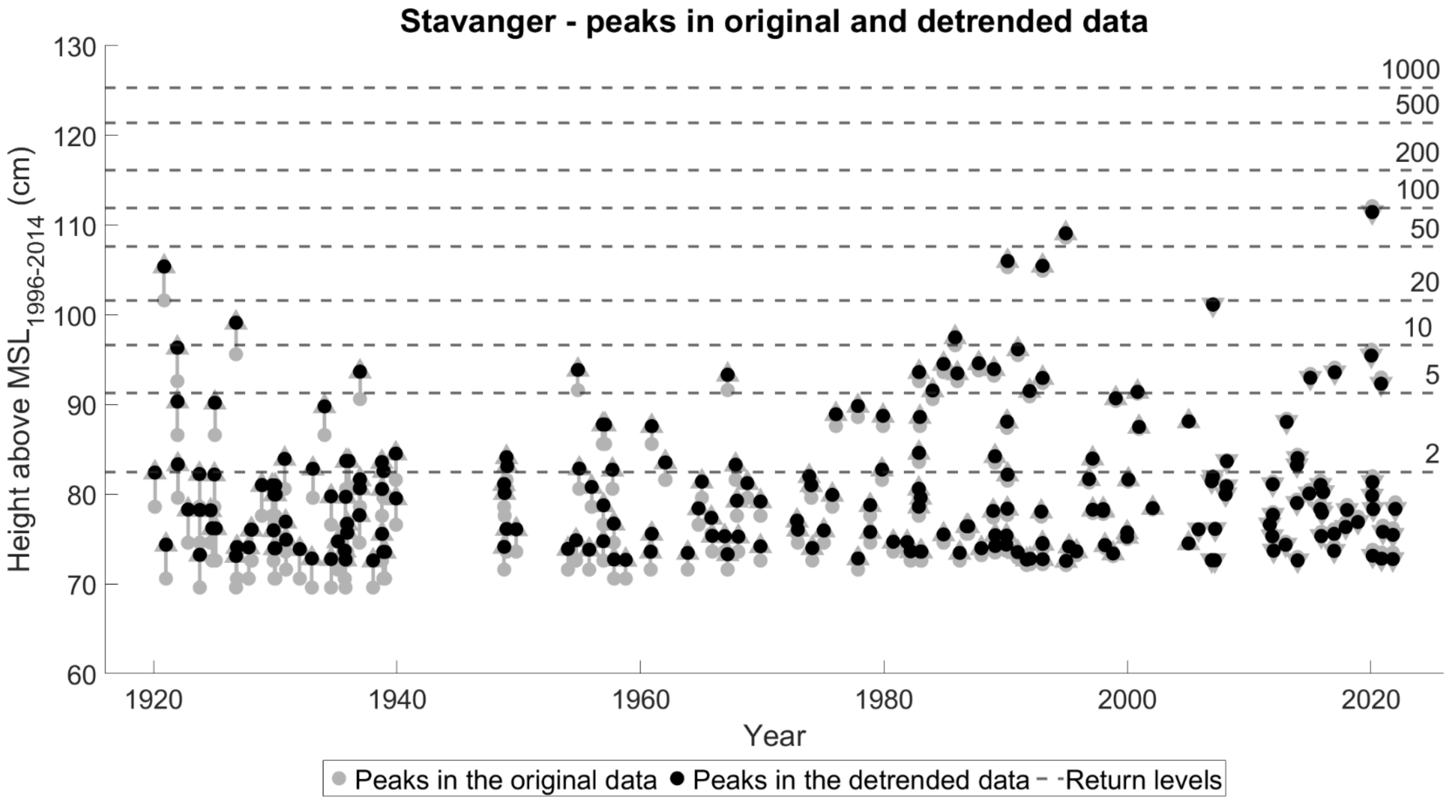

Figure 44: Stavanger

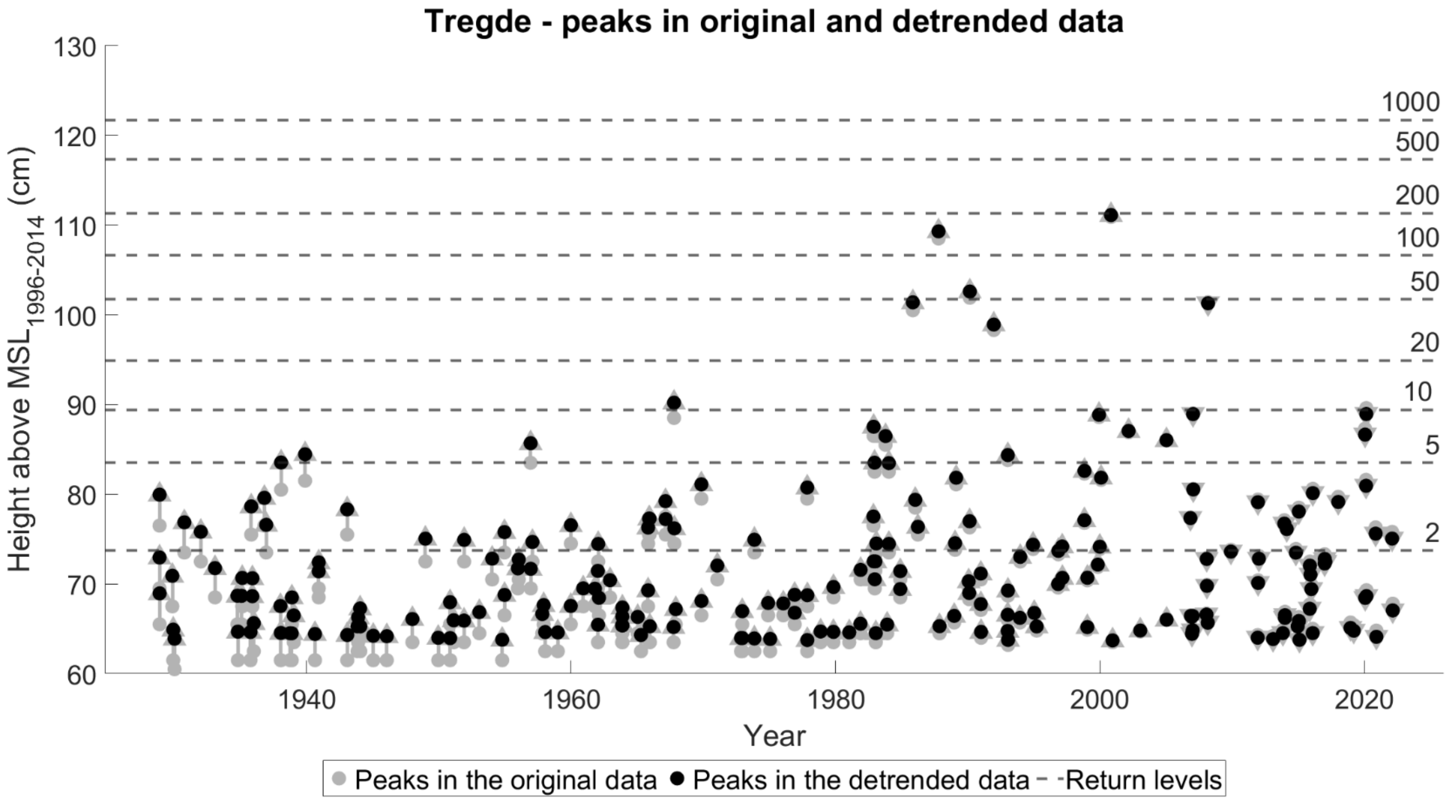

Figure 45: Tregde

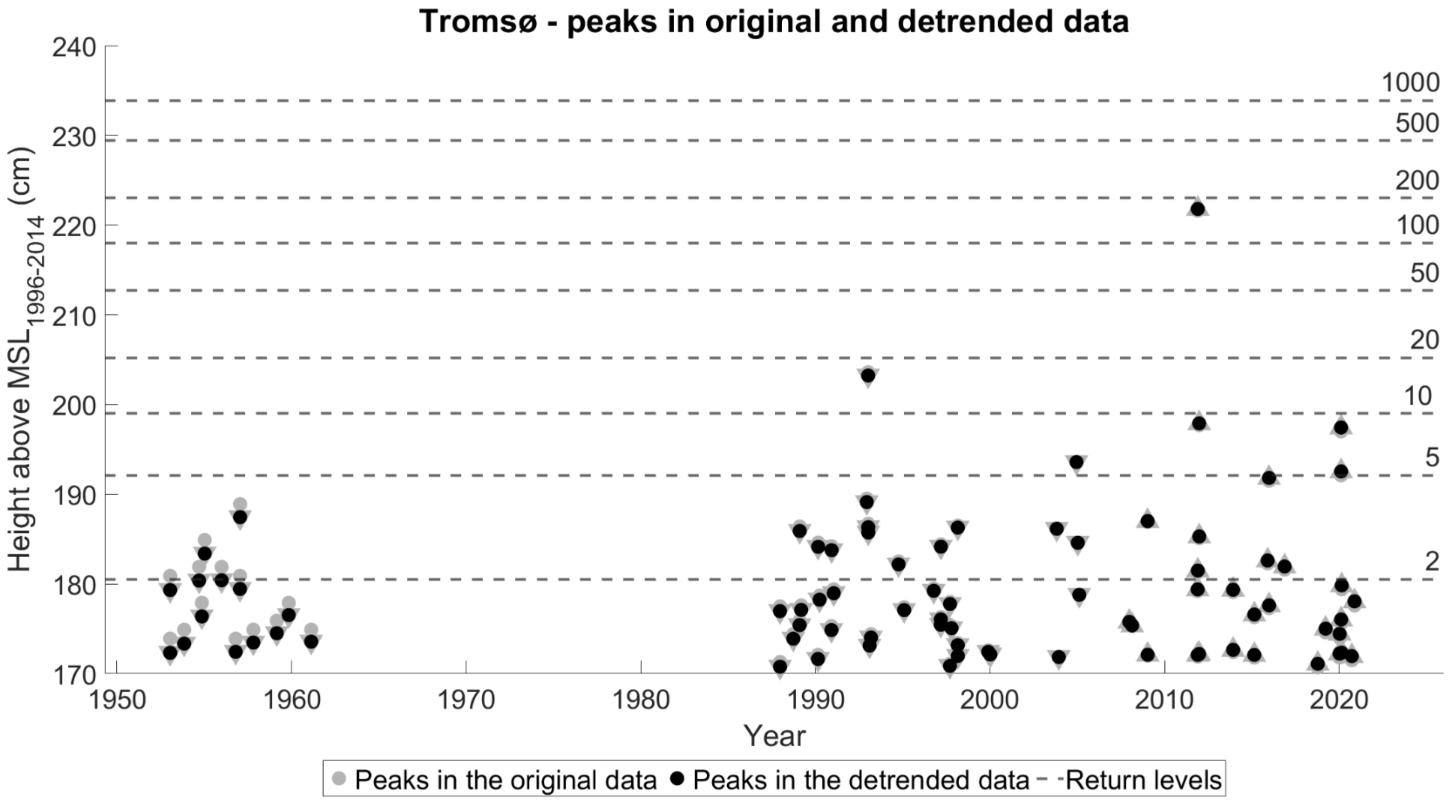

Figure 46: Tromsø

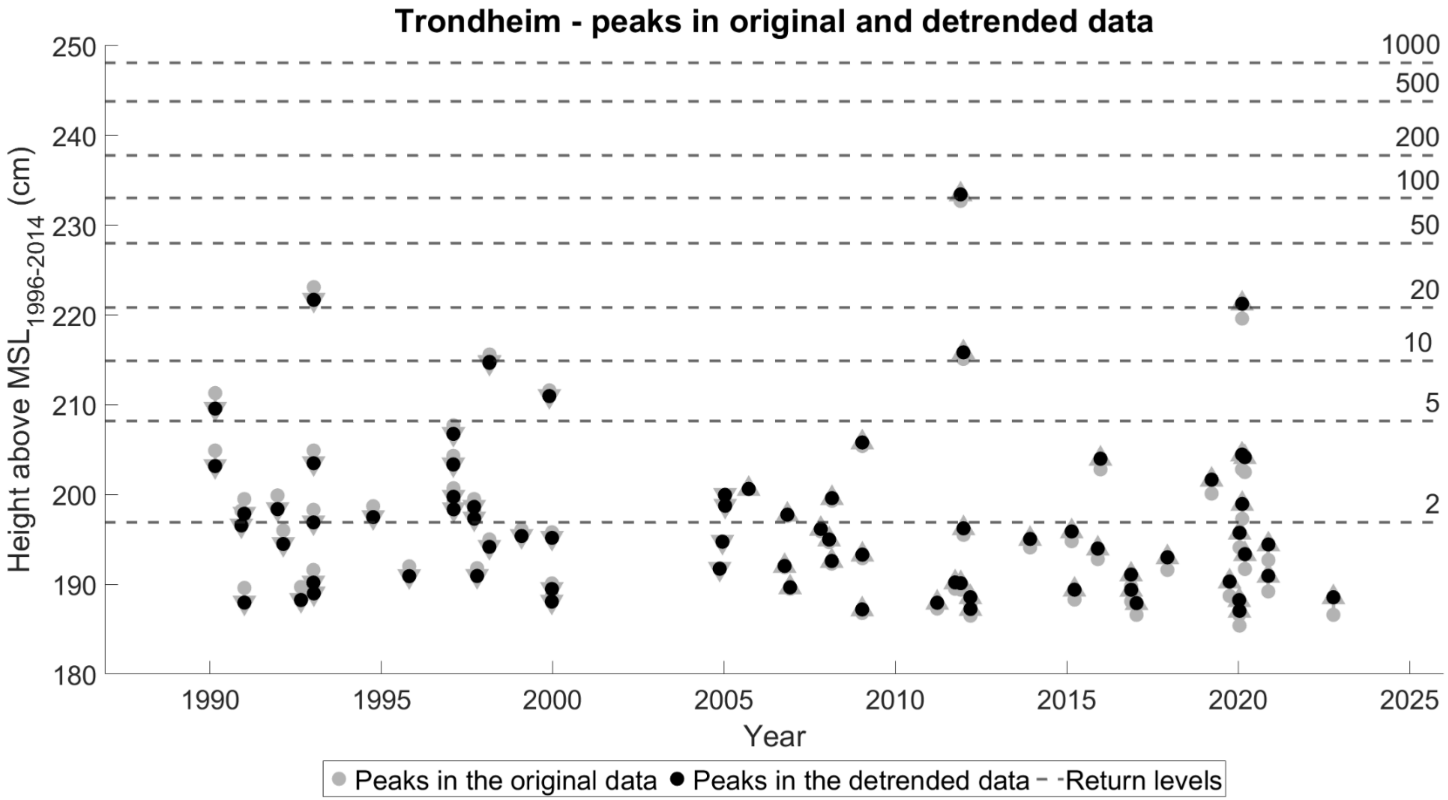

Figure 47: Trondheim

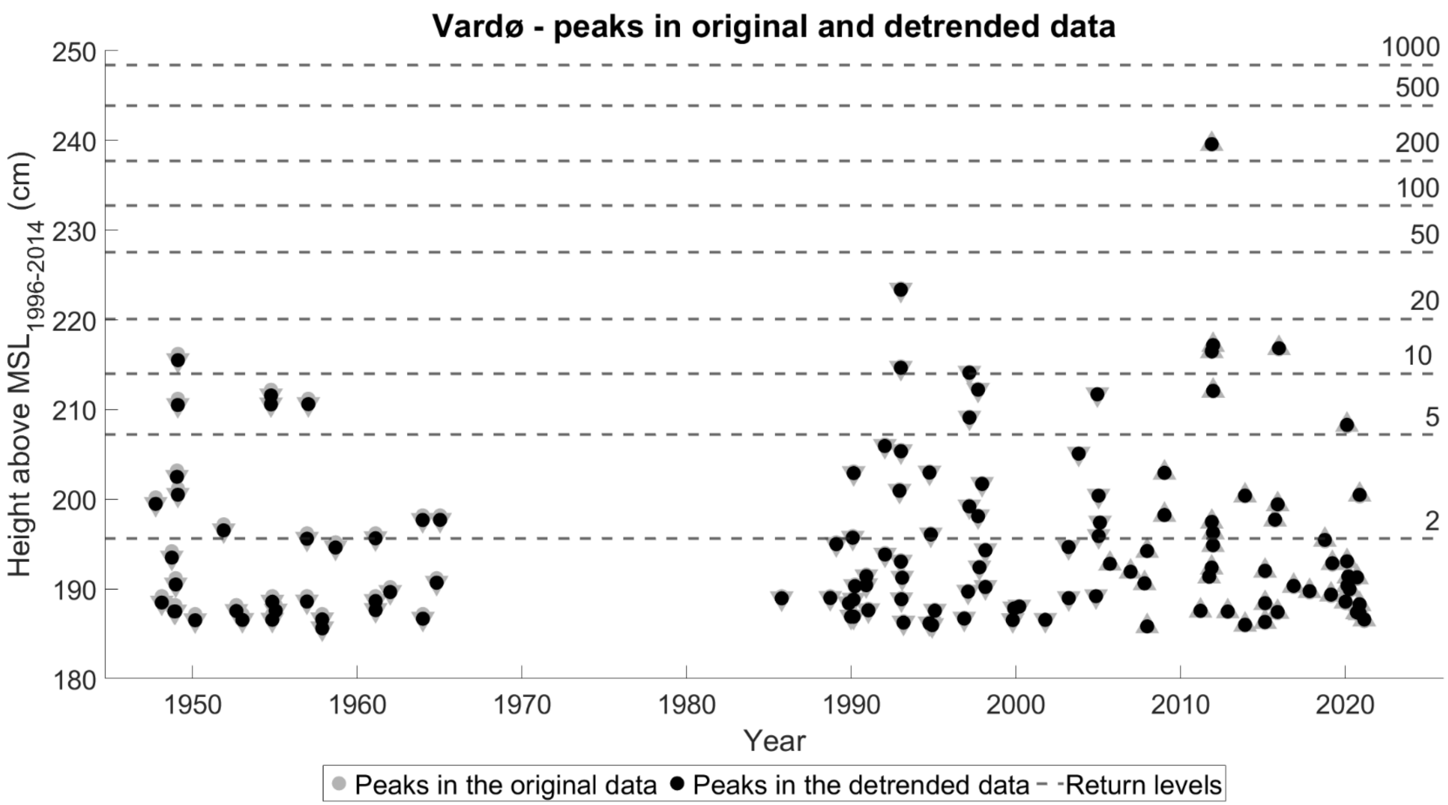

Figure 48: Vardø

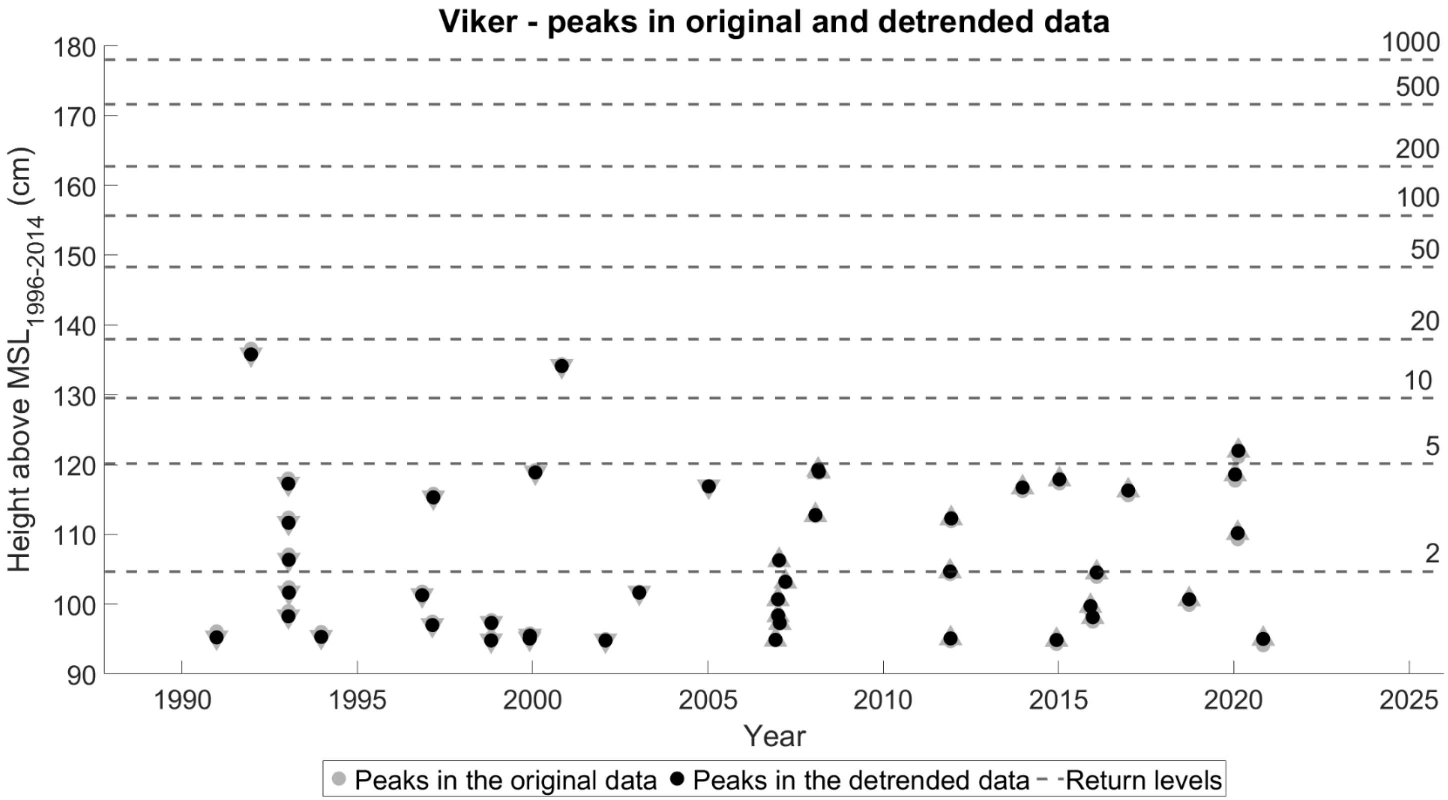

Figure 49: Viker

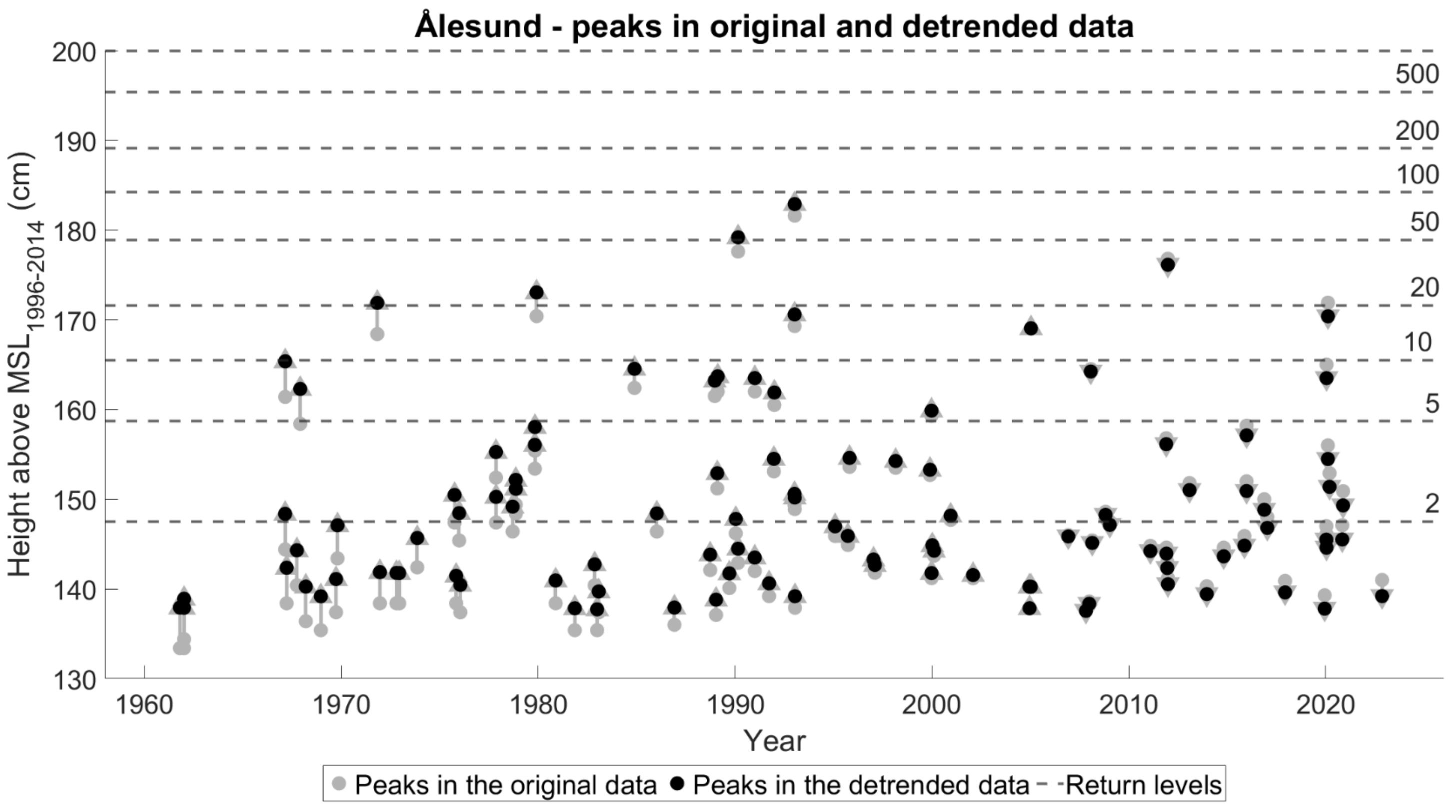

Figure 50: Ålesund

D. High-end estimate – alternative ways of estimating

The need for a high-end estimate above which you are highly unlikely to get inundation came after the SLR-report in 2015 (Simpson et. al., 2015), when the Norwegian Directorate for Civil Protections (DSB) updated their guidelines. NMA estimated the highest observed surge added to the HAT for all the permanent tide gauges as an input to DSB. Based on these numbers, the high-end scenario was chosen as the 1000-year extreme still water level from the (Simpson et. al., 2015), with an additional safety margin of 1 meter. This estimate was well above the rare event that the largest observed surge coinciding with HAT at any tide gauge but was overshooting much more for the southern regions than the western and some northern regions.

For (Simpson et. al., 2024) and corresponding guidelines (DSB, 2024) it was therefore a goal to provide better upper estimates for risk of inundation from the sea, not being more conservative for parts of the country. Using a very high return period, for instance 10 000 or 100 000 years is often suggested, but not generally recommended for an EVA where some of the time series are no more than 30 years. Furthermore, the direct methods used are known to underperform in tidal dominated areas (Arns et al., 2013), resulting in less conservative estimates for the tidal dominated areas. Based on this, an approach with a separate EVA for the surge was chosen.

There are many different ways of combining a return level for the surge with a reasonable estimate for the tidal part. In the end, we suggest using the 1000-year return period for the surge, as higher return periods can be problematic, in particular for an analysis based on only 31 years. For the tidal part, it was natural to suggest using HAT, but estimates using mean high water (MWH) or mean high water springs (MWHS) are included in Figure 51 for comparison. In addition to combining these tidal levels with 1000-years or 10000-year return period for the surge, Figure 51 also includes the 1000-year and 10000-year return period for the still water level with a 1 meter safety margin, and the highest observation with a 1 meter safety margin.

For the southern region it is clear that the new approach (the third bar) is less conservative than using the same approach as earlier (the seventh bar), while for the stretch from Ålesund to Narvik the differences are small. Figure 51 also clearly illustrates how the surge (gray part of the bars) dominates the water level estimates for the tide gauges from Viker to Stavanger.

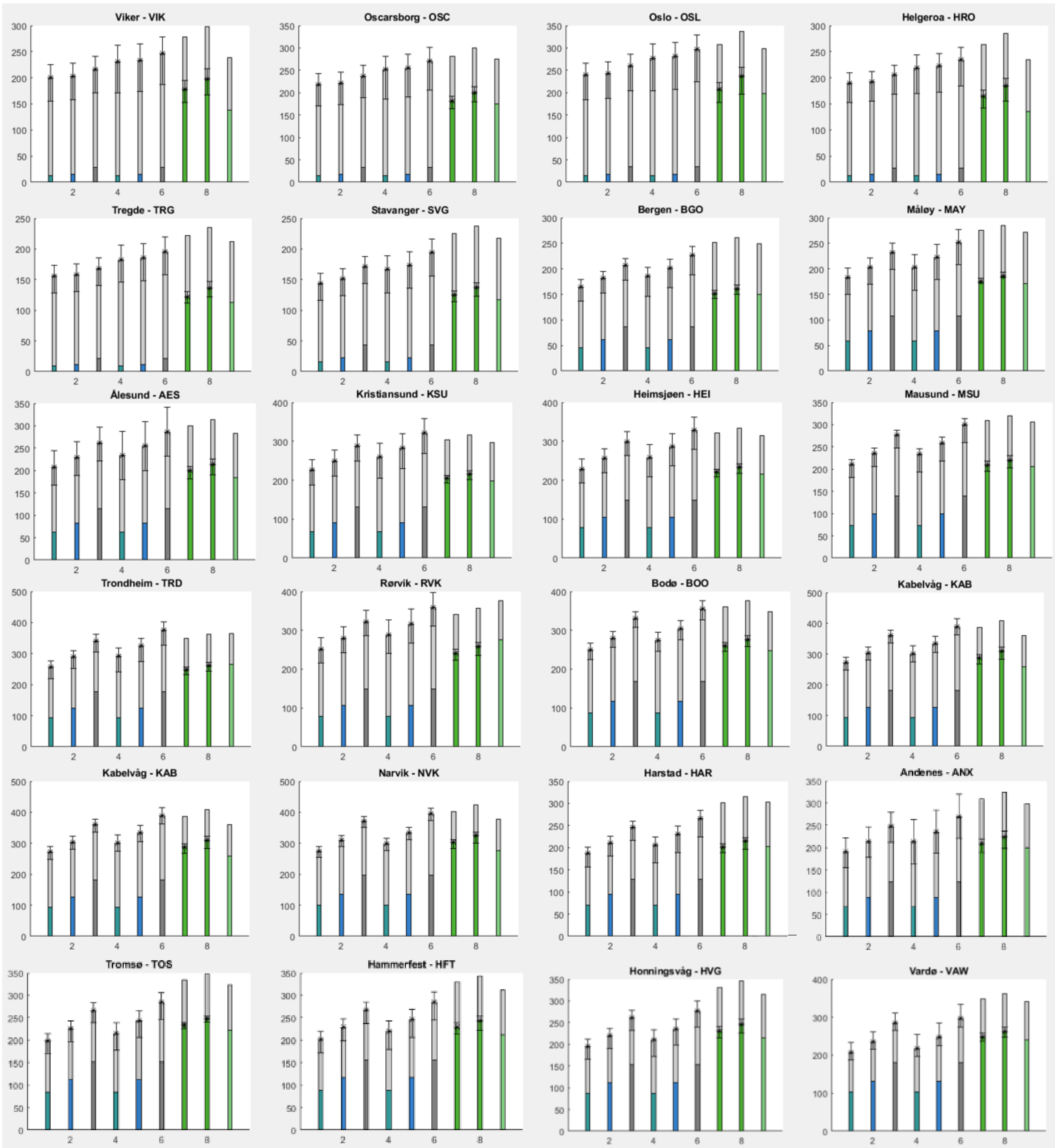

Figure 51: Different potential estimates for high-end extreme still water level in centimeters above $MSL_{1996\text{-}2014}$ for each tide gauge from south-eastern boarder with Sweden (upper left) along the coast to the north (bottom right). From left to right in each plot: 1) Mean High Water (MHW) + 1000-year surge, 2) Mean High Water Spring (MHWS) + 1000-year surge, 3) HAT + 1000-year surge, 4) MHW + 10000-year surge, 5) MHWS + 10000-year surge, 6) HAT + 10000-year surge, 7) 1000-year extreme water level + 1 m, 8) 10000-year extreme water level +1 m, 9) highest observation + 1 m.

E. EVA sensitivity tests

Even though the scope of this work was to apply the same methodology as for the last EVA major updates, some tests have been done, and we try to summarize and discuss them briefly here.

E.1. Sensitivity length of data series

Some tests have been done to get an idea of how sensitive the EVA is to the length of the series. In this section we have included tests where EVA for data series starting in 1990 have been compared to EVA of a data series starting at

- 1910 for Oslo, Bergen[1],
- 1920 for Stavanger[1],
- 1930 for Tregde, Narvik[1],
- 1940 for Måløy,
- 1950 for Oscarsborg, Kristiansund, Bodø, Harstad, Vardø,
- 1960 for Helgeroa, Ålesund, Hammerfest,
- 1970 for Rørvik, Honningsvåg,
- 1980 for Ny-Ålesund.

Viker, Trondheim and Andenes are not included, as these time series start in 1990 or later. Heimsjøen (starting from 1930) and Tromsø (starting from 1950) were part of the analysis, but due to errors found in the data files used for this analysis, they have been removed from this discussion.

Figure 52 shows the fitted ACER-curve and the confidence interval for the high extremes from this comparison, where blue is based on the data series starting in 1990 and red is the longer data series. The difference between the two does not follow a given pattern: Bergen and Oslo both have an 80-year difference in the starting points of the data series used, but where they for Bergen are quite different as expected, the two runs for Oslo are quite similar. Clearly the length of the data series is only one of several parameters impacting the results.

In general, it is fair to assume that the EVA results of the longer data series is the best result, that is, the result the EVA for gradually longer data series would converge to. Thus, the confidence interval of the EVA using only data after 1990 (blue dashed lines) should include the best fit (red line). From Figure 52 we see that this is in fact the case for all tide gauges, giving confidence to the results.

It is worth noting that this is also the case for Rørvik where the data series starting in 1970 includes a record high observation which is likely not correct as the pen went out of the paper recording the water level at the time. This shows one of the strengths of the ACER-method: using more of the data, the method is less influenced by one single extreme like this.

The results for the same test comparing different EVA runs of low extremes shown in Figure 53 do not give us the same amount of confidence. Most of the confidence intervals for the EVA run on data series starting in 1990 include the best fit from

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[1] There are some errors in the data files used for this test for these tide gauges, but they are still included as tests show that the EVA results differ with less than 2 mm compared to the analysis of the correct data set.

analysing the longer data series, but for Oslo this is not true for the longer return periods. The assumed best fit for Bergen do not seem to be a valid result for the longer return periods at all. For the shorter data series there are several tide gauges with indications of non-valid results for the higher return periods of the low extremes, see for instance Rørvik, Bodø and Narvik. This highlights the prior discussed problems related to the low extremes and the need to improve the analysis of these as recommended in 4.4.

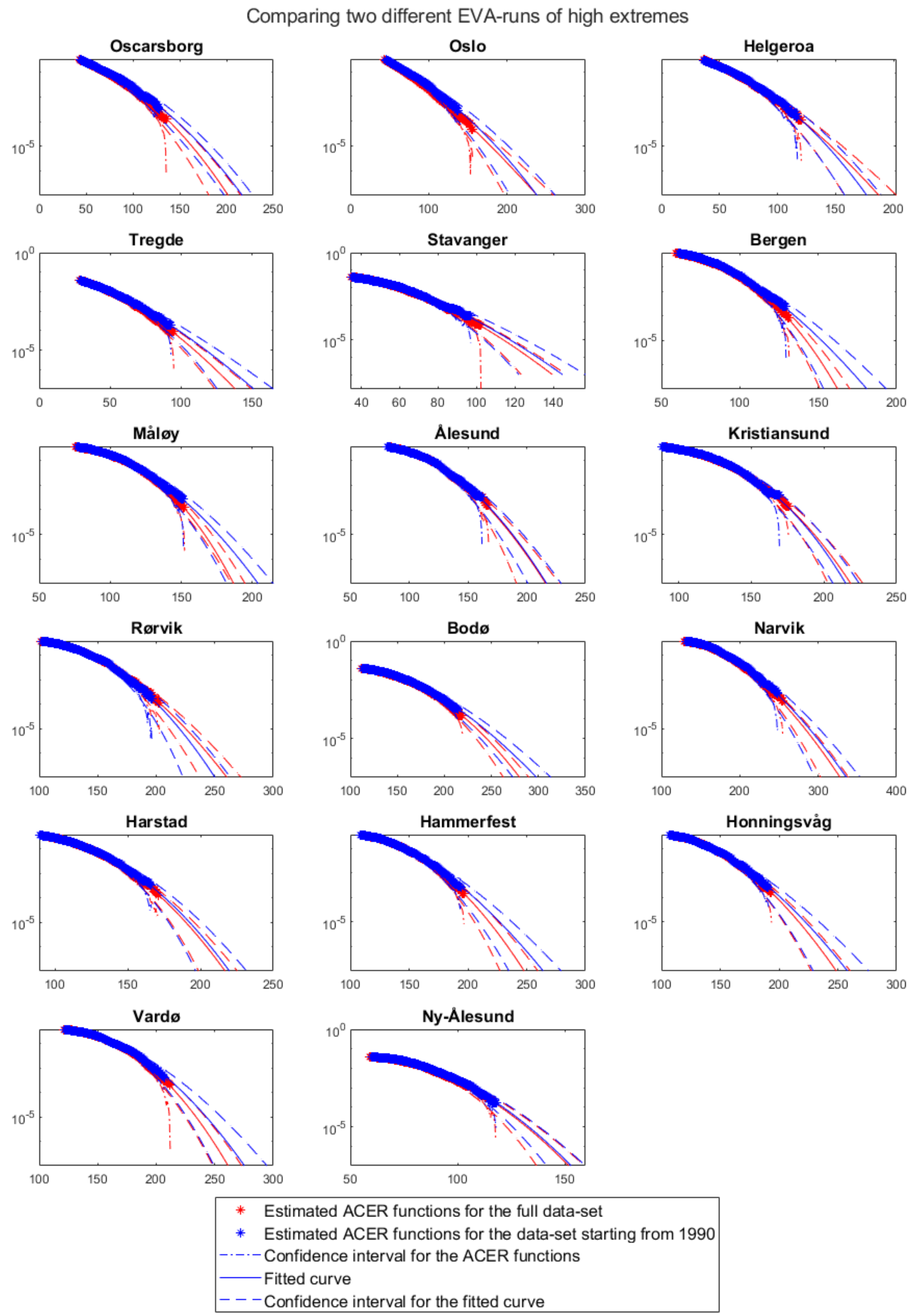

Figure 52: ACER-functions and fitted curves with confidence intervals for the extreme high water levels from the EVA-run with all data (red) and just data after 1990 (blue). The x-axis is centimeters and the y-axis is rate.

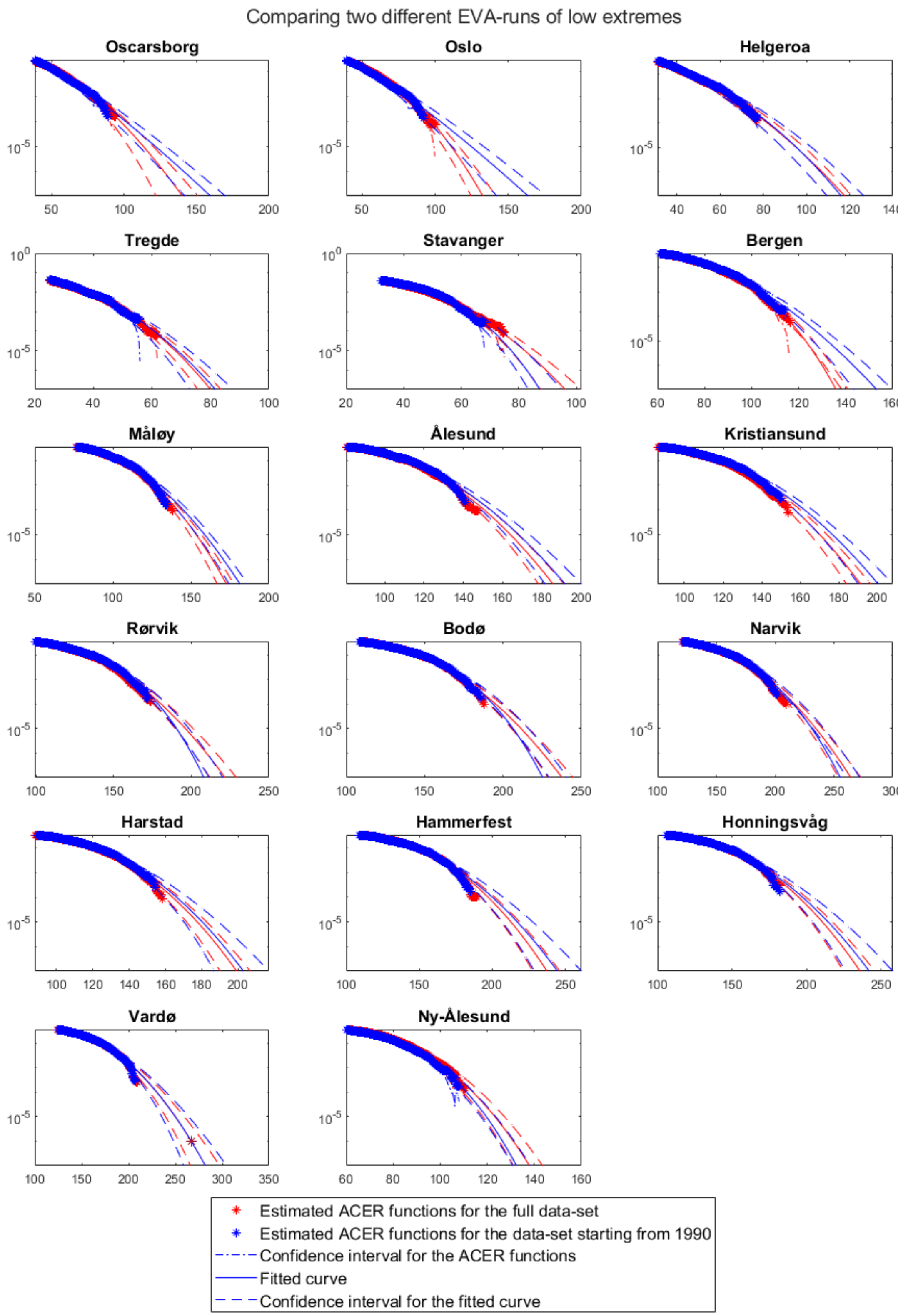

Figure 53: ACER-functions and fitted curves with confidence intervals for the extreme low water levels from the EVA-run with all data (red) and just data after 1990 (blue). The x-axis is centimeters and the y-axis is rate.

E.2. Sensitivity of data sampling

To see if the EVA is sensitive to the rate of the data sampling, we did a test also using 10-minute data to prepare the EVA surge series and compare the two runs. This test is done for the EVA of surge only because the period from 1992-2022 corresponds to a period with 10-minute data for all tide gauges and therefore we did not need to prepare new hourly data series with an extra EVA. This test did not include Ny-Ålesund as it was linked to the work for the sea level rise report (Simpson et al., 2024) focusing only on the Norwegian coast.

A comparison of the surge EVA done on 10 minutes sampling and 60 minutes sampling for the high extremes are given in Figure 54 showing almost identical results for most of the tide gauges. For a few tide gauges, the blue curve based on 10-minute data differs from the red based on hourly data for the extreme high return periods. We suspected that the 10 minutes data could give higher extreme values based on some extremes being better resolved with higher sampling, but the results show that it varies which of the two gives the highest return values.

The comparison for the low extremes shown in Figure 55 does not either show any significant difference due to the sampling of the data series used. For the low extremes there was some problems with the run using 10 minutes data for Tregde and Heimsjøen, thus, these are excluded from the plot. No further investigation has been done into this issue as there were no such problems with the main EVA run for the surge as shown in B.4 and these low extremes are not used in any further products.

Even though the peaks are handled slightly different in the analyse of the surge than for the total water level, there is no reason to suggest that the EVA of water level is sensitive to the sampling rate used. Therefore, no sensitivity tests of data samplings for water level data were conducted.

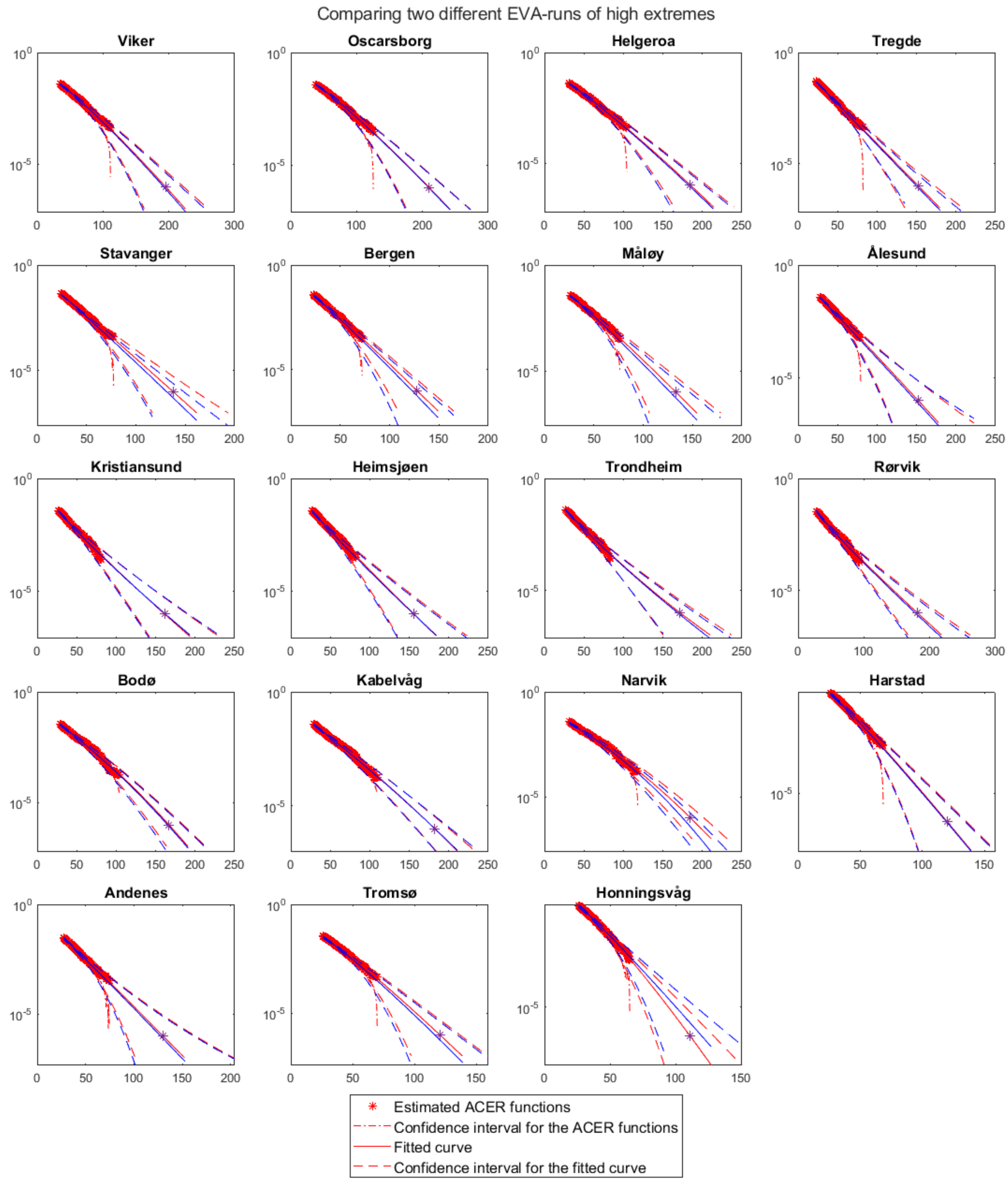

Figure 54: Comparison of ACER-functions for high extreme surges based on EVA on 60 minutes data in red and 10 minutes data in blue. The x-axis is centimeters and the y-axis is rate.

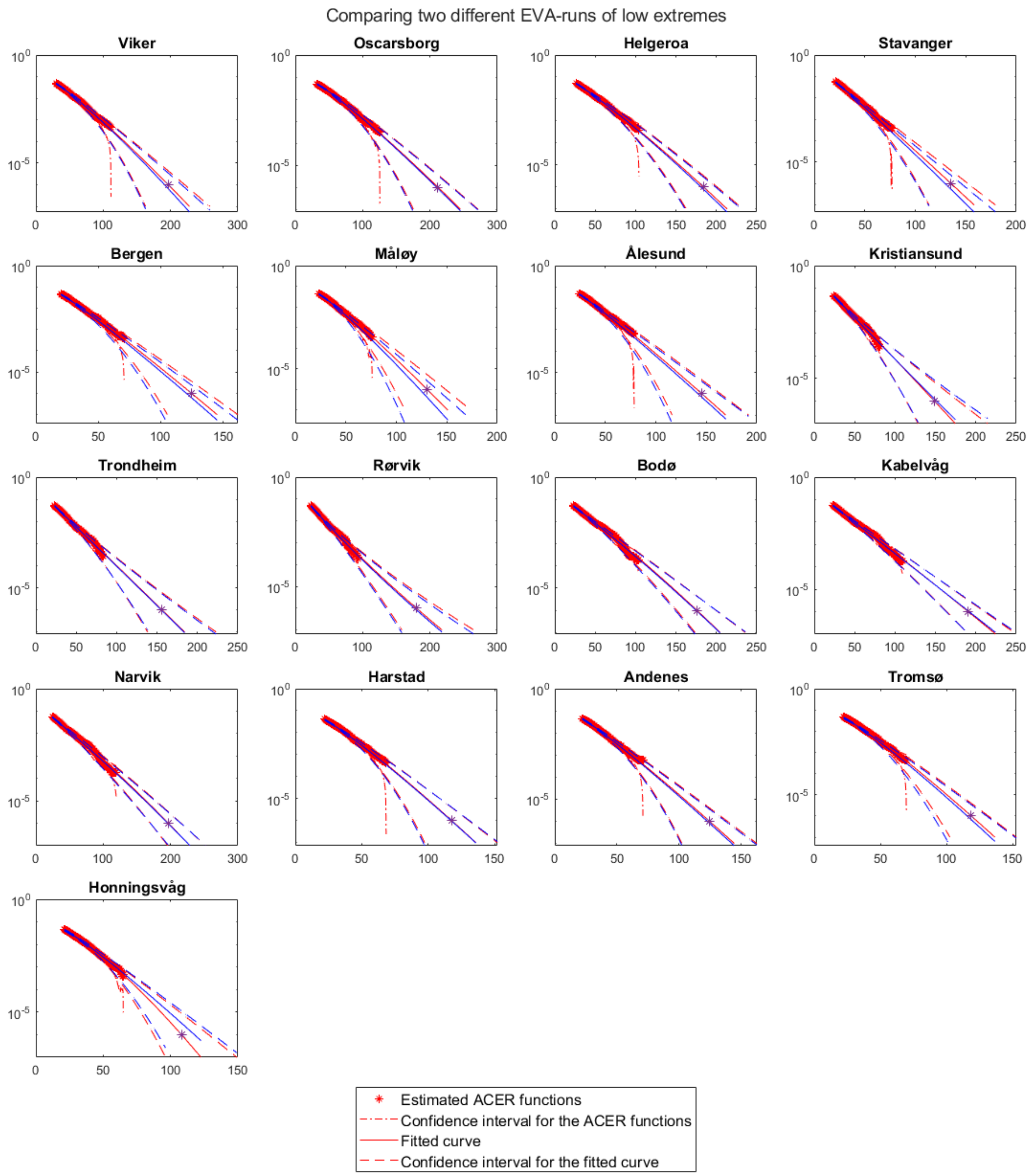

Figure 55: Comparison of ACER-functions for low extreme surges based on EVA on 60 minutes data in red and 10 minutes data in blue. The x-axis is centimeters and the y-axis is rate.

E.3. Sensitivity of data periods

A sensitivity test was done analysing different periods for a few selected few tide gauges. Each data series used was for an interval of 33 years, starting at every ten years from 1950 to 1990.

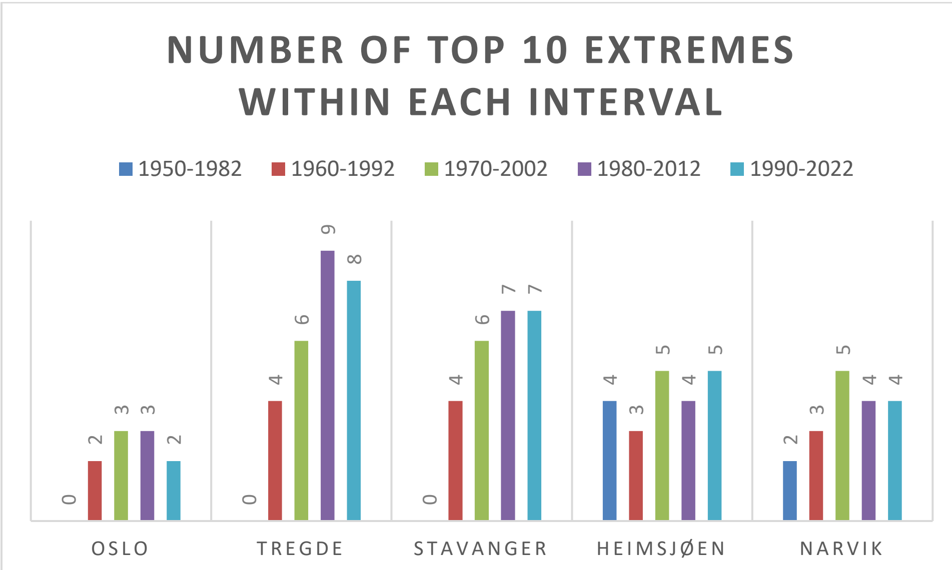

Figure 56: Number of top 10 records within each of the data series used in this test for the different tide gauges

Some of the tide gauges have one missing year in some of the periods, but all analysed series have at least 32 years of data. The standard linear detrending has been used, detrending to the current mean sea level.

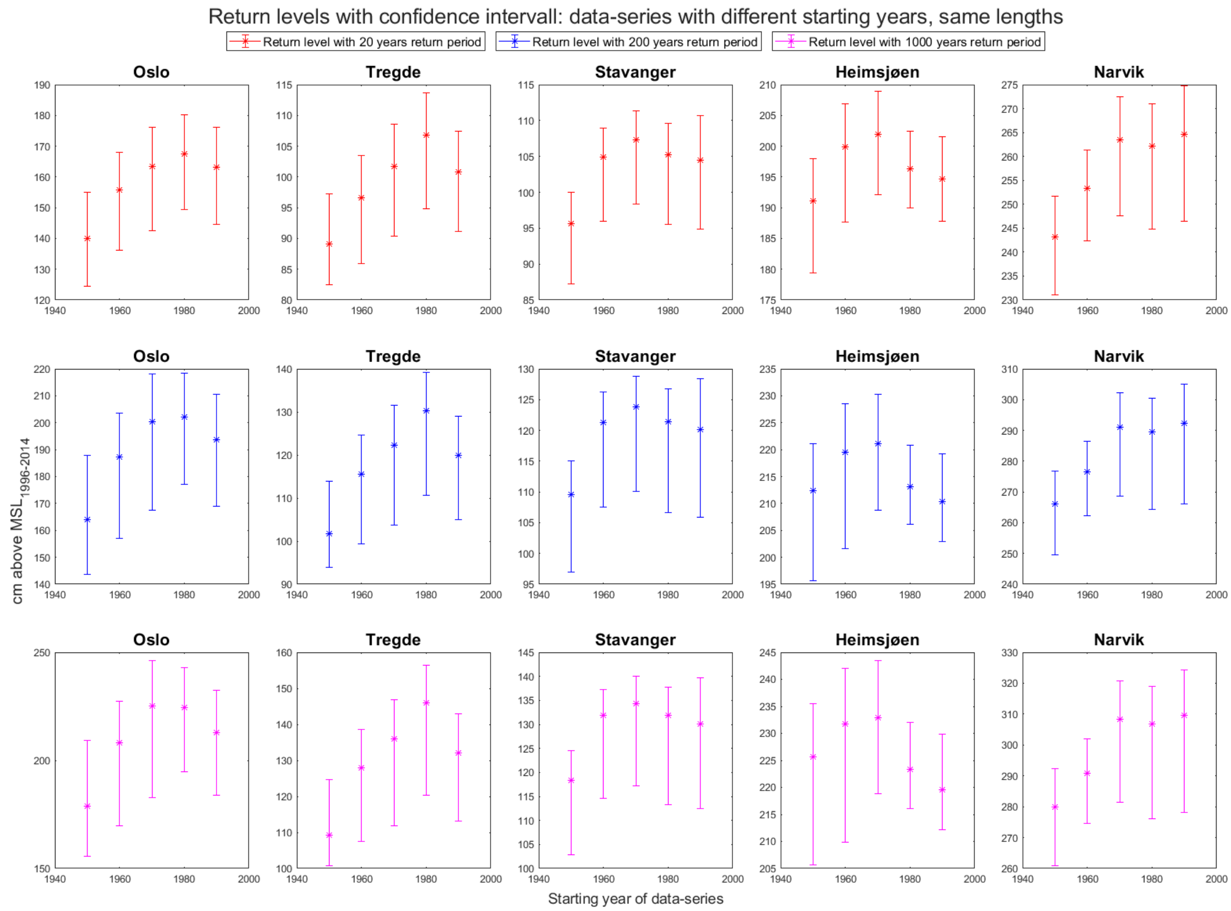

Figure 57: Selected return levels from analyzing different periods of 33 years of data

The 20-, 200- and 1000-year return levels from the tests are shown in Figure 57 according to the different starting years. As expected, the results are sensitive to the period of data chosen. For most tide gauges the pattern is strongly correlated to the pattern in Figure 56 showing how many of the top 10 extremes registered for the tide gauges are within the given period. A higher number of extremes within the 33-year period gives higher return levels, as expected. Only Heimsjøen shows a slightly different pattern, there it is a clear change from the series starting in 1970 to the one starting later. However, as can be seen in

Table 4, this corresponds to when the highest observation at Heimsjøen from 1971 is no longer part of the analysed data series. This seems also to impact the confidence intervals quite a lot, implying that a small confidence interval is highly influenced by the variation within the data series analysed.

Table 4: Year of highest observation at the different tide gauges and year of the highest observation between 1950-2022

Tide gauge	Oslo	Tregde	Stavanger	Heimsjøen	Narvik
Year of record	1914	2000	1994	1971	1932
Highest 1950-2022	1987 (2nd)	2000 (1st)	1994 (1st)	1971 (1st)	1983 (3rd)

This sensitivity test only confirms that well-known fact that the EVA is sensitive to the number of high events within the given period analysed. Thus, selecting a different period than the full series will always be sensitive to the choice of cut-off criteria.

Kartverket

www.kartverket.no

Postadresse: Postboks 600 Sentrum, 3507 Hønefoss

Telefon: 32 11 80 00

Telefaks: 32 11 81 01

E-post: post@kartverket.no

Organisasjonsnummer: 971 040 23