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Climate Adaptation by Managed Realignment

Future mean and extreme sea levels

Summary

This report is part of the research project CAMEL (Climate Adaptation by Managed Realignment), which aims to investigate managed retreat and adaptation of society to a changed coast- and shoreline, due to climate change, as a possible strategy for climate adaptation. Visualization is a tool in overcoming existing obstacles and facilitating long-term sustainable decisions in community planning.

CAMEL is led by the Swedish Geotechnical Institute (SGI) and based on a collaboration between RISE, Linköping University and SMHI. The County Administrative Boards of Västra Götaland, Skåne and Halland as well as the Municipalities of Karlstad, Öckerö, Trelleborg and Umeå are partners. CAMEL is a three-year research project that began in 2018 and will be completed by 2021. The project is funded by the FORMAS Research Council.

Within CAMEL, a prototype of an interactive visualization tool has been developed. Visualization of future mean and extreme sea levels is a potential tool for policy-makers in designing well-founded strategies aiming at long-term sustainable land use. Using the visualization tool, land areas can be identified that will be either permanently flooded due to a rise of mean sea level or temporarily flooded due to extreme sea level events.

For the visualization tool SMHI has estimated future mean and extreme sea levels with return periods of 5- to 200-years based on today’s (2020) and future perspectives (2050, 2100 and 2200) at four different locations. Three of these sites are located in the southern or western part of Sweden (Halmstad, Trelleborg, Öckerö). In addition, Umeå was chosen as a reference located in the northern part of the country.

High sea level events, such as storm surges, cause flooding in exposed areas. Due to a rising mean sea level, caused by climate change, storm surge events that historically occurred once per century can recur more frequently in the future.

For Trelleborg and Halmstad, estimated future mean sea levels (median values) are higher than today’s values under all RCP-scenarios. For Öckerö, estimated future mean sea levels (median values) are similar to today’s level under RCP2.6 and RCP4.5 in a short-term perspective, while future mean sea levels are higher under RCP4.5 and RCP8.5 for longer time spans. Due to relatively large local land uplift, estimated future mean sea levels for Umeå are lower than today’s under RCP2.6 and RCP4.5. Under RCP8.5 the estimated future mean sea level is lower than today’s prior to 2100 and higher subsequent to 2100.

Due to mean sea level rise, estimated extreme values in future climate are higher than today’s under all RCP-scenarios for Trelleborg, Halmstad and Öckerö. As an example, for Trelleborg today’s 100-year event corresponds to a 5-year event under RCP4.5 by the end of the 21st century, or a 5-year event under RCP2.6 by the end of the 22nd century. For Halmstad, today’s 100-year event corresponds to a 10-year event under RCP8.5 by the end of the 21st century, or a 10-year event under RCP4.5 by the end of the 22nd century. For Öckerö, today’s 100- and 200-year event corresponds to a 5-year event under RCP4.5 by the end of the 22nd century, or a 5-year event under RCP8.5 prior to the end of the 21st century.

As future mean sea levels for Umeå are lower than today’s under RCP2.6 and RCP4.5, estimated extreme values in future climate are also lower than today’s under the same RCP-scenarios. This implies that extreme sea level events historically occurring once per century, will occur less frequently under these two RCP-scenarios. Under RCP8.5 future mean sea levels are lower than today’s prior to 2100 and higher beyond. Hence, estimated extreme values will follow a similar pattern.

Contents

1 Background

This report is a part of the research project CAMEL (Climate Adaptation by Managed Realignment), which aims to investigate managed retreat and adaptation of society to a changed coast- and shoreline (due to climate change) as a possible strategy for climate adaptation. Visualization is a tool in overcoming existing obstacles and facilitating long-term sustainable decisions in community planning.

1.1 CAMEL project

High sea level events, such as storm surges, cause flooding in exposed areas. Due to a rising mean sea level, caused by climate change, storm surge events that historically occurred once per century can recur more frequently in the future.

The aim of the CAMEL project is to investigate managed retreat as a possible alternative for climate adaptation. The goal is to increase society's adaptability to climate change by allowing a more flexible, dynamic and natural shift of coast- and shorelines, which will benefit both the environment as well as socio-economic development.

CAMEL is led by the Swedish Geotechnical Institute (SGI) and based on a collaboration between RISE, Linköping University and SMHI. The County Administrative Boards of Västra Götaland, Skåne and Halland as well as the Municipalities of Karlstad, Öckerö, Trelleborg and Umeå are partners. CAMEL is a three-year research project that began in 2018 and will be completed in 2021. The project is funded by the FORMAS Research Council.

Within CAMEL, a prototype of an interactive visualization tool has been developed. Visualization of extreme and future mean sea levels is a potential tool for policy-makers in designing well-founded strategies aiming at long-term sustainable land use. With the visualization tool land areas can be identified that will be either permanently flooded due to a rise of mean sea level or temporarily flooded due to extreme sea level events.

For the visualization tool, SMHI has calculated future mean sea levels and extreme sea levels with return periods from 5- to 200-years as of today’s (2020) and future perspectives (2050, 2100 and 2200) at four locations. Three of these are located in the southern or western part of Sweden (Halmstad, Trelleborg, Öckerö). In addition, Umeå was chosen as a reference located in the northern part of Sweden. In this report, methods and results of estimated future mean and extreme sea levels for the locations of interest are presented. Extreme sea level events with return periods of less than 100-years were estimated to illustrate the shift of frequency, i.e. extreme sea level events that historically were relatively rare can recur more frequently in the future.

1.2 IPCC and Global Sea Level Rise

The United Nation’s Intergovernmental Panel on Climate Change (IPCC) is the UN body for assessing the science related to climate change. It was set up in 1988 by the World Meteorological Organization and United Nations Environment Programme to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. IPCC does not conduct its own research. It identifies agreement in the scientific community, differences of opinion and need for further research. It is a partnership between scientists and policymakers. Since 1988, the IPCC has produced five comprehensive Assessment Reports and several Special Reports on specific topics. The Fifth Assessment Report (AR5) was finalized in 2013/2014. The Sixth Assessment Report (AR6) is underway, and three Special Reports and a Methodology Report have already been produced (https://www.ipcc.ch/ n.d.). The Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was published in September 2019, IPCC (2019). Information on sea level rise and implications for low-lying islands, coasts and communities is provided in Chapter 4 of the Special Report SROCC (Oppenheimer et al., 2019). Chapter 4 of SROCC also assesses past and future contributions of various processes to global, regional and extreme sea level changes, associated risks as well as response options and pathways to resilience and sustainable development.

Some of the key conclusions from IPCC (2019) regarding sea levels are described below.

Global mean sea level is rising and accelerating. The sum of glacier and ice sheet contributions is now the dominant source to these changes. Tide gauges and altimetry observations show that the global mean sea level has increased from 1.4 mm/year over the period 1901–1990 to 3.6 mm/year over the period 2006–2015. The dominant cause of global mean sea level rise since 1970 is anthropogenic forcing.

Future rise in the global mean sea level caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes is strongly dependent on the Representative Concentration Pathway (RCP) emission scenario that is considered, see Figure 1. Sea level rise at the end of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement.

IPCC provides projections of global mean sea levels as median values and “likely range”, where the “likely range” indicates the assessed likelihood that the outcome has a 66 % probability to lie within the given range. Thus, the “likely range” indicates that the assessed likelihood of the outcome lies within the 17-83% probability range.

Up to 2050, uncertainty in climate change-driven future sea levels is relatively small, which provides a robust basis for short-term (30 years) adaptation planning. The global mean sea level will rise between 0.22 m (0.15 to 0.28 m, likely range) under RCP2.6 and 0.27 m (0.20–0.34 m, likely range) under RCP8.5 by 2050.

Beyond 2050, uncertainty in climate change-induced sea level rise increases substantially due to uncertainties in emission scenarios and associated climate changes and the response of the Antarctic ice sheet in a warmer world. Combining process-model based studies, it is found that the global mean sea level is projected to rise between 0.43 m (0.29–0.59 m, likely range) under RCP 2.6 and 0.84 m (0.61–1.10 m, likely range) under RCP 8.5 by 2100 relative to the reference period 1986-2005.

Beyond 2100, sea levels will continue to rise for centuries and will remain elevated for thousands of years. Only few modelling studies are available for sea level rise beyond 2100, but all agree that the difference in global mean sea levels between RCP2.6 and RCP8.5 increases substantially on multi-centennial and millennial time scales. On a millennial time scale, this difference is about 10 meters in some model simulations, whereas it is only several decimeters at the end of 21st century. The larger the emissions the larger the risks associated with sea level rise. Under RCP8.5, the few available studies indicate a likely range of 2.3–5.4 m (low confidence) in 2300. With strong mitigation efforts (RCP2.6), sea level rise will be limited to a likely range of 0.6–1.1 m (Figure 1).

There is a 17% chance that the global mean sea level will exceed 0.59 m under RCP2.6 and 1.10 m under RCP8.5 in 2100. Process-model based studies cannot yet provide information above this range, but expert elicitation studies show that a global mean sea level of 2 m in 2100 cannot be ruled out.

Sea level rise has accelerated due to the combined increased ice loss from the Greenland and Antarctic ice sheets. Mass loss from the Antarctic ice sheet during the period 2007–2016 tripled relative to 1997–2006. For Greenland, mass loss doubled over the same period.

Acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea level rise of several meters within a few centuries, is observed in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica. These changes may be the onset of an irreversible ice sheet instability. Uncertainty related to the onset of ice sheet instability arises from limited observations, inadequate model representation of ice sheet processes, and limited understanding of the complex interactions between the atmosphere, ocean and the ice sheet.

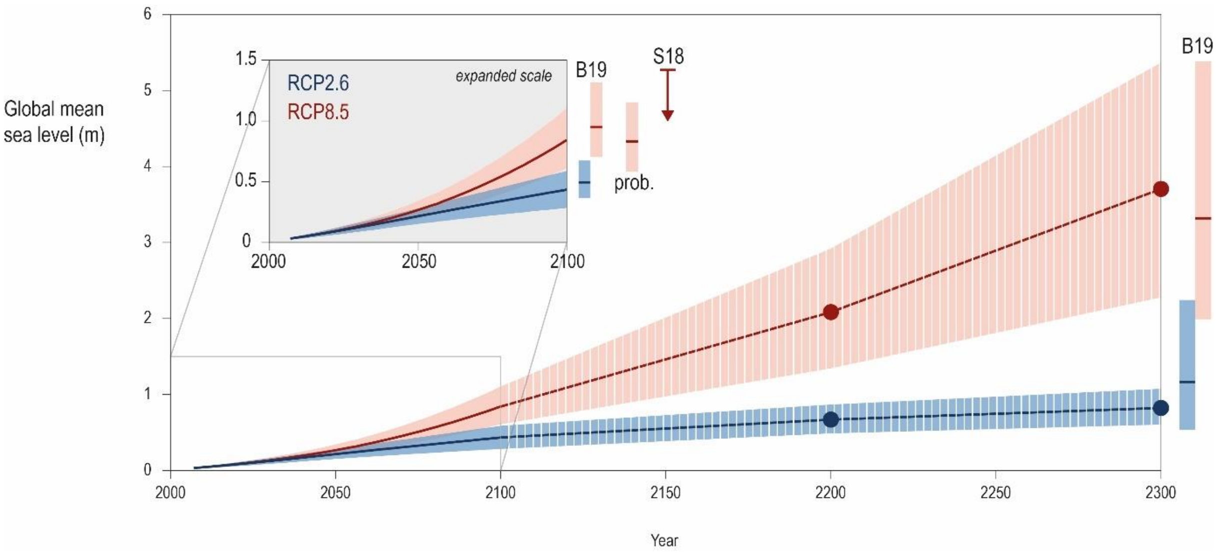

Figure 1. Projected sea level rise (SLR) until 2300. The inset shows an assessment of the likely range of the projections for RCP2.6 and RCP8.5 up to 2100 (medium confidence). Projections for longer time scales are highly uncertain but a range is provided (low confidence). For context, results are shown from other estimation approaches in 2100 and 2300. The two sets of two bars labelled B19 are from an expert elicitation for the Antarctic component (Bamber et al., 2019), and reflect the likely range for a 2ºC and 5ºC temperature warming (low confidence). The bar labelled "prob." indicates the likely range of a set of probabilistic projections. The arrow indicated by S18 shows the result of an extensive sensitivity experiment with a numerical model for the Antarctic Ice Sheet (AIS) (Schlegel et al., 2018) combined, like the results from B19 and "prob.", with results from Church et al. (2013) for the other components of SLR. S18 also shows the likely range. Source: IPCC Figure 4.2.

In Table 1, median values and likely ranges for projections of global mean sea level rise are provided for three scenarios: RCP2.6, RCP4.5 and RCP8.5. Projections are given in meters for the years 2050, 2100 and 2200 relative to the reference period 1986-2005. Data were retrieved from IPCC and are illustrated for RCP2.6 and RCP8.5 in Figure 1 .

Table 1. Median values and likely ranges for projections of global mean sea level rise in meters by 2050, 2100 and 2200 relative to 1986-2005 for the scenarios RCP2.6, RCP4.5 and RCP8.5.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	0.22 (0.15 to 0.28)	0.23 (0.17 to 0.29)	0.27 (0.20 to 0.34)
2100	0.43 (0.29 to 0.59)	0.55 (0.39 to 0.72)	0.84 (0.61 to 1.10)
2200	0.67 (0.49 to 0.87)	1.03 (0.71 to 1.38)	2.08 (1.34 to 2.92)

Sea level rise is not globally uniform and varies regionally. Regional differences of about ±30% of the global mean sea level rise are expected as a result from thermal expansion, ocean dynamics and land ice loss. Differences from the global mean may be even greater (than ±30%) in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction.

Due to projected global mean sea level rise, extreme sea level events that historically occurred once per century (today's hundred-year events/historical centennial events) are projected to become common by 2100 under all RCP-scenarios. Many low-lying cities and small islands at most latitudes will experience such events annually by 2050. The height of a historical centennial sea level event varies widely and, depending on the level of exposure, may have severe impacts. Impacts may increase with rising frequency of historical centennial events. Greenhouse gas mitigation envisioned in low-emission scenarios (e.g., RCP2.6) is expected to sharply reduce but not eliminate risk to low-lying coasts and islands from sea level rise and extreme sea level events. For the first half of the 21st century, differences in extreme sea level events among the different scenarios are small. A schematic illustration of extreme sea level events and their average recurrence in the recent past (1986–2005) and future is shown in Figure 2. As a consequence of mean sea level rise, historical centennial events are projected to recur more frequently in the future.

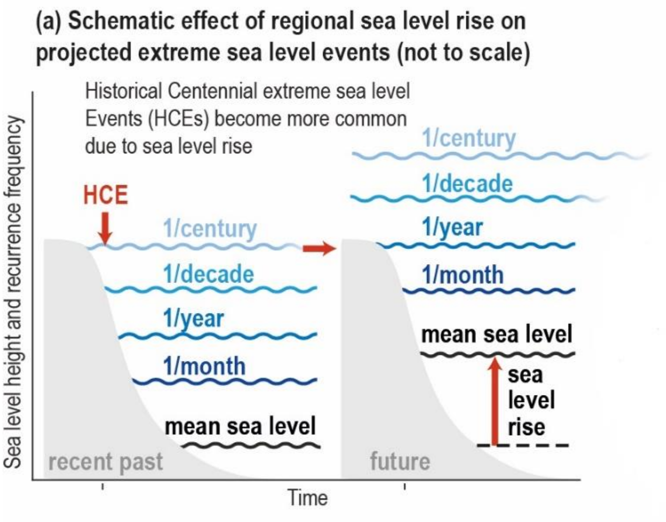

Figure 2. The effect of regional sea level rise on extreme sea level events at coastal locations. Schematic illustration of extreme sea level events and their average recurrence in the recent past (1986–2005) and future. As a consequence of mean sea level rise, local sea levels that historically occurred once per century are projected to recur more frequently in the future. Source: Summary for Policymakers (IPCC, 2019), Figure SPM.4 (a).

2 Methodology

2.1 Land uplift

The postglacial land uplift in Scandinavia reduces the effect of sea level rise. The postglacial land uplift is explained by the return of the earth crust to its state of equilibrium after being heavily loaded by kilometer-thick ice during the last ice age. When the ice started to melt approximately 20 000 years ago, the pressure on the earth crust was relieved and land started to rise. The last ice disappeared from Scandinavia about 10 000 years ago. Due to the viscous interior of the Earth a complete return to the original state of equilibrium is still far away. Until now, land has risen by several hundred meters and it is estimated that there are several tens of meters still to rise (Lantmäteriet). Land uplift varies over the country; it is largest in the north along the coast of the Baltic Bay, around 10 mm/year, and smallest in the south, around 1 mm/year, (Vestøl et al., 2019).

When estimating future mean sea levels, the levelled land uplift is used. Levelled land uplift refers to land uplift relative to the sea surface (geoid) unaffected by climate effects. Information on the land uplift has been obtained from the land uplift model NKG2016LU. The model was launched in 2016 by the Nordic Commission for Geodesy (NKG) and is the official land uplift model in Sweden as well as in other Nordic and Baltic countries, see Figure 3. Data from NKG2016LU has been delivered by Lantmäteriet.

The levelled land uplift used in this study is 0.07 cm/year on average for Trelleborg municipality, 0.20 cm/year for Halmstad, 0.29 cm/year for Öckerö and 0.96 cm/year for Umeå (SMHI Climatology 41, 2017). The rate of land uplift is assumed to be unchanged until 2200.

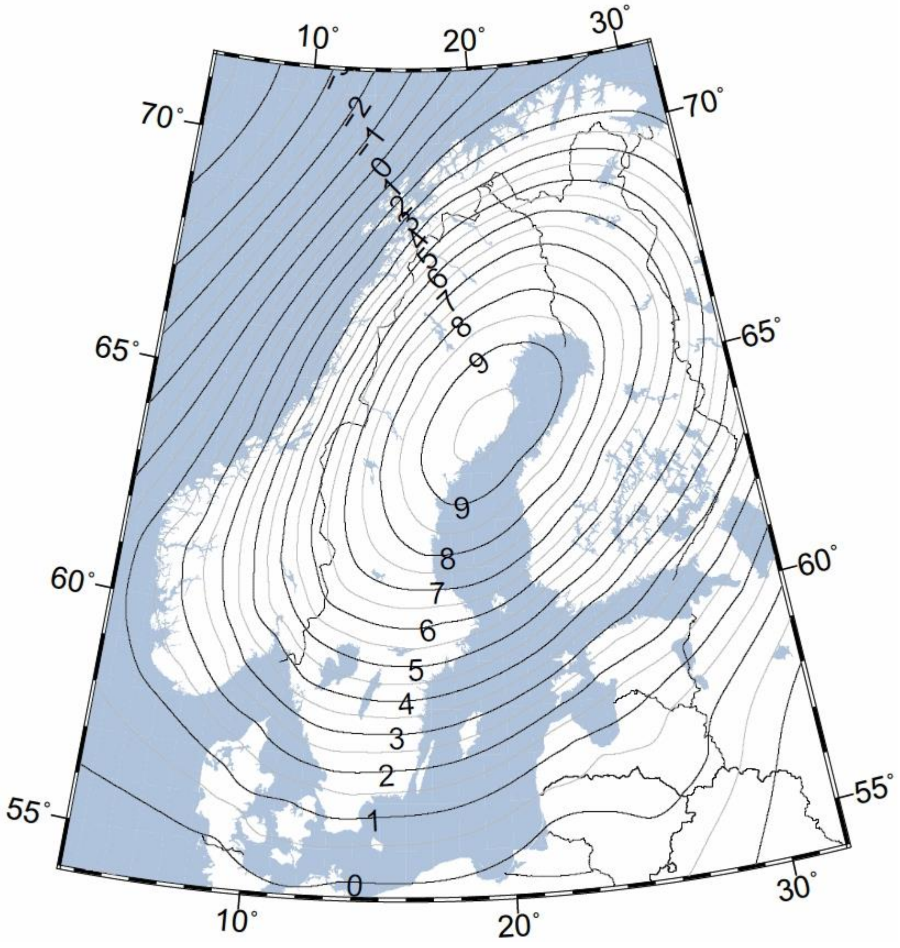

Figure 3. Levelled land uplift (mm/year) according to the land uplift model NKG2016LU. Levelled land uplift refers to land uplift relative to the sea surface (geoid) unaffected by climate effects. Source: Lantmäteriet.

2.2 Mean sea levels

Future mean sea levels for the selected places are estimated according to the following equation:

$$MSL_{year} = MSL_{reference} + SLR_{RCP,year} - LU \times (year - 1995)$$

where MSL_{year} is the mean sea level at a certain future year, $MSL_{reference}$ is the mean sea level during the reference period 1986-2005, $SLR_{RCP,year}$ is the sea level rise for a certain RCP-scenario and year, and LU is the levelled land uplift for the period specified from 1995 to a certain year. 1995 represents the mid-point of the reference period, therefore the land uplift is estimated from that year.

To estimate sea levels in a future climate the following assumptions were made:

- The future mean sea level at a given year is a normally distributed stochastic variable with a probability of 66% to lie within the likely ranges specified in the IPCC (2019).
- Median values of global mean sea level rise for each RCP-scenario stated in IPCC (2019) are the expected values.
- Based on likely ranges for each RCP-scenario, standard deviations were estimated for the years of interest. Standard deviations were used as a measure of uncertainty in future mean sea levels and were combined with other uncertainties to form a total uncertainty for return values.

Further, we assume that future mean sea levels along the coast of Sweden will follow the global mean sea level rise. At present, IPCC does not provide data for regional sea level rise beyond 2100, but projections of global mean sea level rise to 2300, median values along with likely ranges, are provided. As we are interested in the future also beyond 2100, global mean sea level rise was chosen as a basis for estimates of mean sea levels at locations of interest taking local land uplift into account. Regional variations occur, but differences between global and regional mean sea levels in a future climate are relatively small in Sweden (approximately 10 cm difference considering median value RCP8.5, 2100). The primary source of spatial inhomogeneities in sea level rise for Sweden is glacial isostatic adjustment (GIA) or the post-glacial rebound (Hieronymus and Kalén, 2020).

Estimates of expected values and uncertainties are based on current information provided by the IPCC (2019).

2.3 Extreme sea levels

Extreme value analysis is performed to estimate extreme sea levels with return periods of up to 200 years for the locations of interest. In Figure 4 to Figure 7, estimated return values at different return periods for Trelleborg, Halmstad, Öckerö and Umeå are shown. All calculations are based on yearly maximum values representative of each location and considering the time period from July to June. The time frame was chosen to avoid inclusion of interdependent events.

For Trelleborg, observations from Ystad from the period 1887 to 1986 have been used. The well-known storm surge event called *Backafloden* occurring in November 1872 was also included in the analysis. For more details about the observations included in the analysis, see Nerheim, 2018.

For Halmstad, no suitable long time series of observed sea levels is available. However, the Swedish Maritime Administration (SMA) has performed measurements of sea levels in Halmstad from 2009 and onwards. This time series is too short for direct use in the present analysis. Estimates of return values with a return period of up to 200 years would not be reliable. Therefore, sea level observations from Viken station in combination with wind speed observations from Nidingen station have been used to obtain a longer data series describing conditions representative for Halmstad. For more details on observations included in the analysis, see Johansson, 2018.

Observations of sea levels from the station located at Göteborg-Torshamnen have been used to estimate return values for Öckerö. Observations from Göteborg-Torshamnen are assumed to be representative of Öckerö. Observations from 1967 to 2019 have been used in the analysis.

Sea level observations from the station located at Ratan, covering the period from 1891 to 2019, have been used to estimate extreme sea levels with return periods of up to 200 years valid for Umeå. To ensure that sea level observations from Ratan represent the conditions in Umeå, observations from Holmsund station, where sea levels have been measured by SMA since 2009, were used to compare with observations from Ratan. The comparison showed that sea level observations from Ratan represent the conditions in Umeå well.

The choice of function of distribution is to some extent arbitrary. Usually, the distribution that is considered to be best suited to the underlying data series is used, but it is rarely an unambiguous choice.

As an example, the extreme sea level with a 100-year return period for Trelleborg was estimated to 1.57 meters relative to mean sea level, with a 95 % confidence interval ranging from 1.28 to 1.83 meters.

For Halmstad, the extreme sea level with a 100-year return period was estimated to 2.52 meters relative to mean sea level, with a corresponding confidence interval of 95 % from 2.07 to 2.98 meters.

The extreme sea level with a 100-year return period for Öckerö is estimated to 1.62 meters relative to mean sea level, with a 95 % confidence interval ranging from 1.35 to 1.89 meters.

For Umeå, the extreme sea level with a 100-year return period was estimated to 1.31 meters relative to mean sea level, with a corresponding 95 % confidence interval ranging from 1.18 to 1.43 meters.

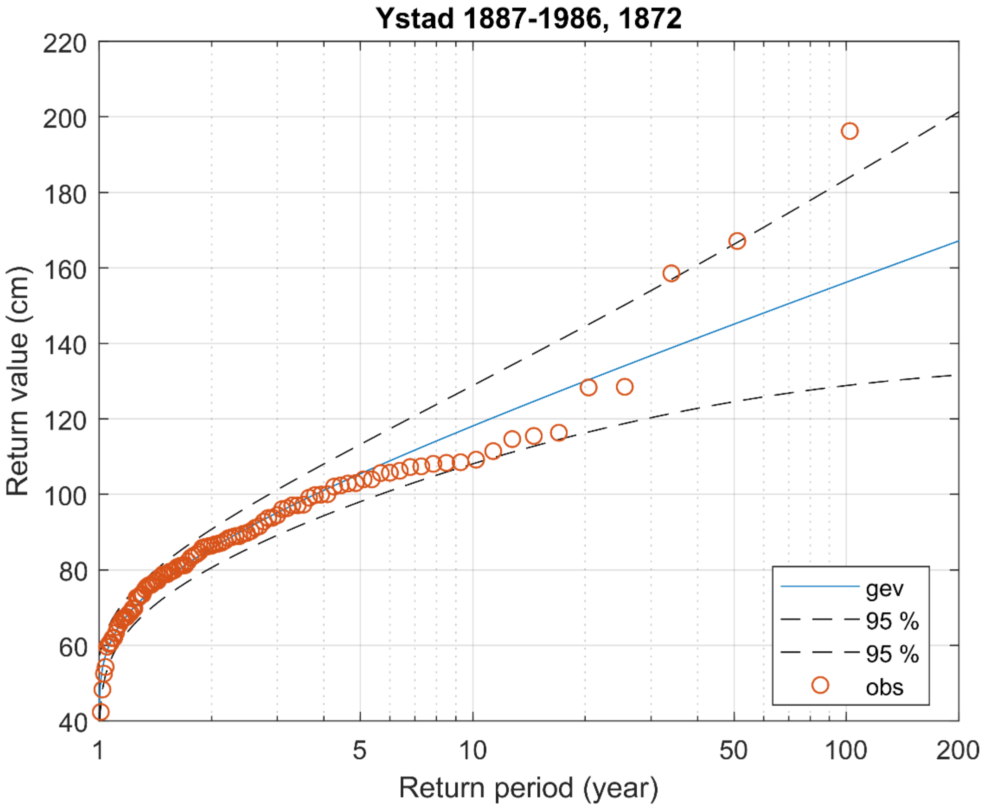

Figure 4. Estimated return values at different return periods, blue curve. Dashed curves indicate a 95% confidence interval. The rings show observed annual max. The values are given in centimeter relative to mean sea level.

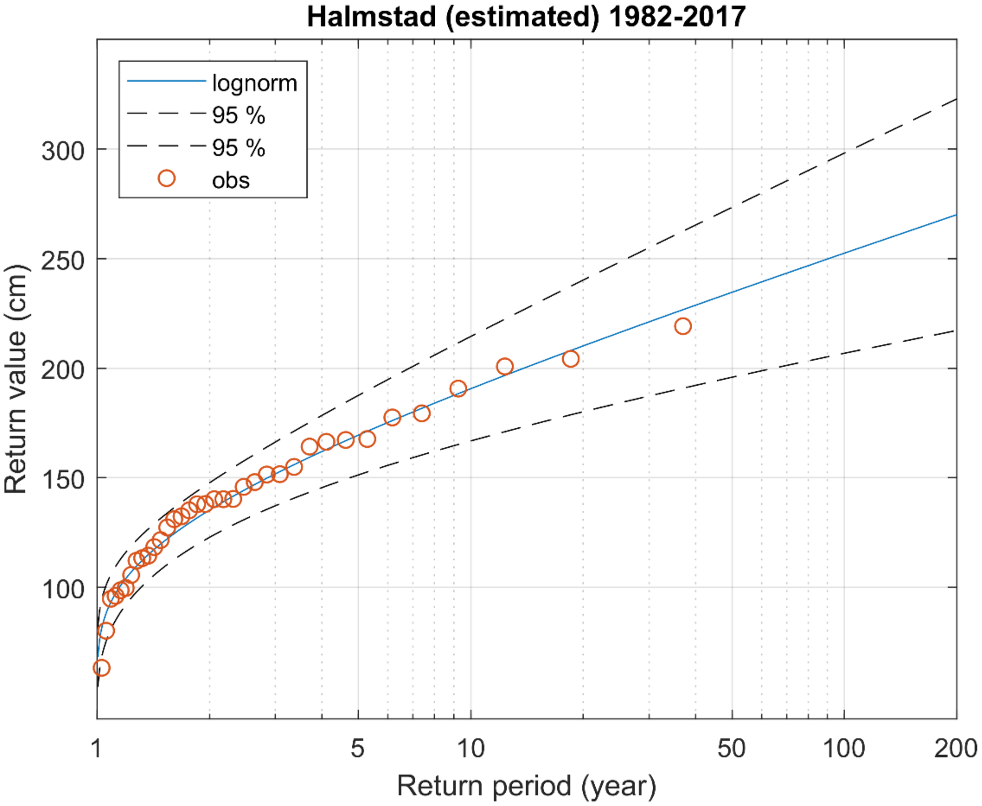

Figure 5. Estimated return values at different return periods, blue curve. Dashed curves indicate a 95% confidence interval. The rings show observed annual max. The values are given in centimeter relative to mean sea level.

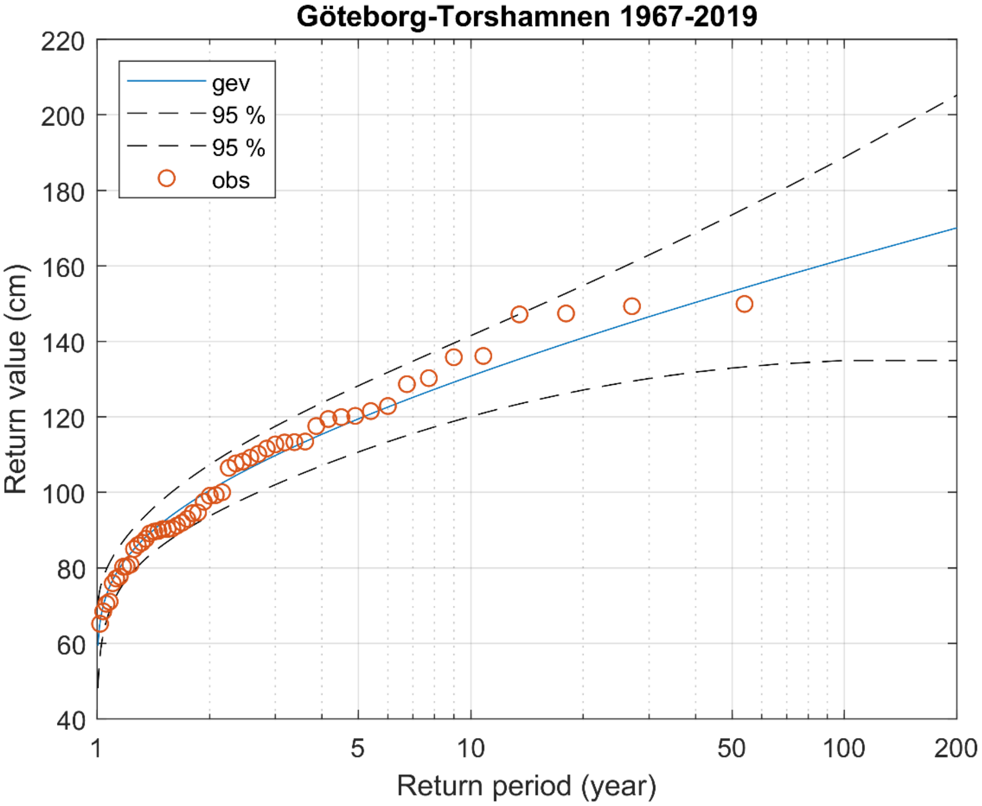

Figure 6. Estimated return values at different return periods, blue curve. Dashed curves indicate a 95% confidence interval. The rings show observed annual max. The values are given in centimeter relative to mean sea level.

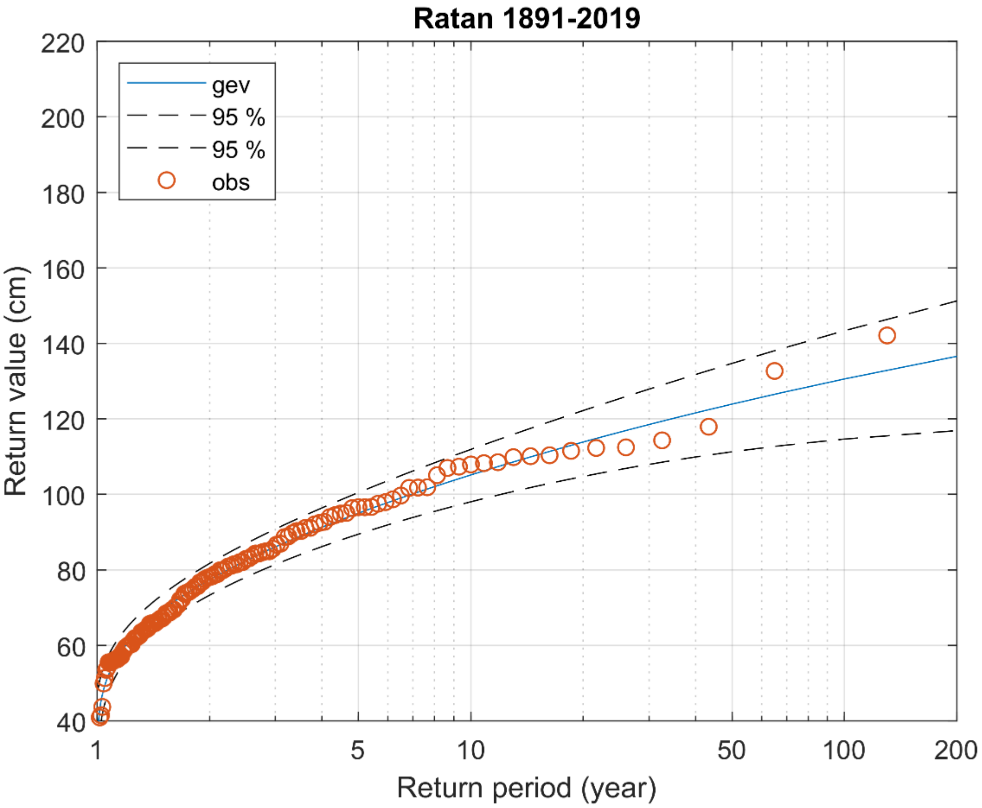

Figure 7. Estimated return values at different return periods, blue curve. Dashed curves indicate a 95% confidence interval. The rings show observed annual max. The values are given in centimeter relative to mean sea level.

2.4 Combined uncertainties

Estimated extreme sea levels with return periods of up to 200 years are provided along with a confidence interval of 95 %. The confidence intervals are estimated from a combined uncertainty, which consists of the uncertainty in the climate projection for each RCP-scenario, the uncertainty in the extreme value calculation and the uncertainty in the measurement. A geographical uncertainty is considered for Umeå and Öckerö. The same applies for confidence intervals for extreme values valid for year 2020, but without the uncertainty in the climate projection.

3 Results

3.1 Mean sea levels

Estimated future mean sea levels, median values and 95 % confidence intervals, for Trelleborg, Halmstad, Öckerö and Umeå are listed in Table 3 to Table 6 respectively. Values are given for the climate scenarios RCP2.6, RCP4.5 and RCP8.5 for the years 2050, 2100 and 2200. The estimated mean sea levels are based on information on global mean sea level rise according to IPCC 2019 and local land uplift from the model NKG2016LU. Values are presented in meters (rounded to nearest decimeter) in the chart datum RH 2000.

Mean sea levels in 1995 and 2020 are presented in Table 2. The values are given in centimeter in the chart datum RH 2000. Mean sea levels in 1995 were obtained from SMHI Climatology 41, 2017. In Trelleborg, the mean sea level in 1995 was lower than in 2020, which suggests that sea level rise exceeded local land uplift during this period. In Halmstad, Öckerö and particularly in Umeå, the opposite was the case, i.e. local land uplift exceeded sea level rise.

Estimated future mean sea levels (median values) for Trelleborg and Halmstad are higher than today's values under all RCP-scenarios. For Öckerö, estimated future mean sea levels (median values) are similar to today's level under the lower RCP-scenarios and shorter time span, while future mean sea levels are higher under RCP4.5 and RCP8.5 for longer time spans. Estimated future mean sea levels for Umeå are lower than today's under RCP2.6 and RCP4.5. Under RCP8.5 the estimated future mean sea level is lower than today's prior to 2100 and higher subsequent to 2100, i.e. sea level rise will most likely exceed land uplift in Umeå some time between 2050 and 2100. However, estimated future mean sea levels are associated with great uncertainties, particularly beyond 2100.

Table 2. Mean sea levels in Trelleborg, Halmstad, Öckerö and Umeå in 1995 and 2020. Values are given in centimeter in the chart datum RH 2000.

	Trelleborg	**Halmstad**	**Öckerö**	**Umeå**
1995	12.9	6.4	6.9	23.3
2020	15.8	5.8	2.6	2.2

Table 3. Estimated future mean sea levels in Trelleborg, median values and 95 % confidence intervals. Values are based on information on global mean sea level rise according to IPCC (2019) and local land uplift from NKG2016LU. Values are given in meters in the chart datum RH 2000.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	0.3 (0.2 to 0.4)	0.3 (0.2 to 0.4)	0.4 (0.2 to 0.5)
2100	0.5 (0.2 to 0.8)	0.6 (0.3 to 0.9)	0.9 (0.4 to 1.4)
2200	0.7 (0.3 to 1.0)	1.0 (0.4 to 1.6)	2.1 (0.6 to 3.5)

Table 4. Estimated future mean sea levels in Halmstad, median values and 95 % confidence intervals. Values are based on information on global mean sea level rise according to IPCC (2019) and local land uplift from NKG2016LU. Values are given in meters in the chart datum RH 2000.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	0.2 (0.1 to 0.3)	0.2 (0.1 to 0.3)	0.2 (0.1 to 0.4)
2100	0.3 (0.0 to 0.6)	0.4 (0.1 to 0.7)	0.7 (0.2 to 1.2)
2200	0.3 (0.0 to 0.7)	0.7 (0.1 to 1.3)	1.7 (0.3 to 3.2)

Table 5. Estimated future mean sea levels in Öckerö, median values and 95 % confidence intervals. Values are based on information on global mean sea level rise according to IPCC (2019) and local land uplift from NKG2016LU. Values are given in meters in the chart datum RH 2000.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	0.1 (0.0 to 0.3)	0.1 (0.0 to 0.3)	0.2 (0.0 to 0.3)
2100	0.2 (-0.1 to 0.5)	0.3 (0.0 to 0.6)	0.6 (0.1 to 1.1)
2200	0.1 (-0.2 to 0.5)	0.5 (-0.1 to 1.1)	1.6 (0.1 to 3.0)

Table 6. Estimated future mean sea levels in Umeå, median values and 95 % confidence intervals. Values are based on information on global mean sea level rise according to IPCC (2019) and local land uplift from NKG2016LU. Values are given in meters in the chart datum RH 2000.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	-0.1 (-0.2 to 0.0)	-0.1 (-0.2 to 0.1)	0.0 (-0.2 to 0.1)
2100	-0.3 (-0.6 to 0.0)	-0.2 (-0.5 to 0.1)	0.1 (-0.4 to 0.5)
2200	-1.1 (-1.4 to -0.7)	-0.7 (-1.3 to -0.1)	0.4 (-1.1 to 1.8)

3.2 Extreme sea levels

3.2.1 Trelleborg

Estimated extreme values with up to 200-years return periods for Trelleborg are given in Table 7 for the year 2020 and in Table 8 to Table 12 for future climate (years 2050, 2100 and 2200). Values are given in meters in the chart datum RH 2000 along with 95 % confidence intervals. The estimated values have been rounded to nearest decimeter as this is the appropriate accuracy in the context.

Due to mean sea level rise, estimated extreme values in future climate are greater than today's under all RCP-scenarios. It is also shown that extreme sea level events that historically occurred once per century, for example, can occur more frequently in the future. As an example, today's 100-year event corresponds to a 5-year event under RCP4.5 by the end of the 21st century, or a 5-year event under RCP2.6 by the end of the 22nd century. Equivalently, today's 200-year event corresponds to a 10-year event under RCP4.5 by the end of the 21st century, or a 10-year event under RCP2.6 by the end of the 22nd century.

Table 7. Estimated extreme values with 5-, 10-. 50-, 100-, 200-year return periods for Trelleborg year 2020. Values are given in meters in chart datum RH 2000 with 95 % confidence intervals.

	5-year	**10-year**	**50-year**	**100-year**	**200-year**
2020	1.2 (1.0 to 1.4)	1.3 (1.2 to 1.5)	1.6 (1.4 to 1.9)	1.7 (1.4 to 2.0)	1.8 (1.5 to 2.2)

Table 8. Estimated extreme values with a 5-year return period in future climate for Trelleborg. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.4 (1.2 to 1.6)	1.4 (1.2 to 1.6)	1.4 (1.2 to 1.7)
2100	1.6 (1.2 to 1.9)	1.7 (1.3 to 2.0)	2.0 (1.5 to 2.5)
2200	1.7 (1.3 to 2.1)	2.1 (1.4 to 2.7)	3.1 (1.7 to 4.6)

Table 9. Estimated extreme values with a 10-year return period in future climate for Trelleborg. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.5 (1.3 to 1.7)	1.5 (1.3 to 1.7)	1.5 (1.3 to 1.8)
2100	1.7 (1.3 to 2.0)	1.8 (1.4 to 2.2)	2.1 (1.6 to 2.6)
2200	1.8 (1.4 to 2.2)	2.2 (1.5 to 2.9)	3.3 (1.8 to 4.7)

Table 10. Estimated extreme values with a 50-year return period in future climate for Trelleborg. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.8 (1.5 to 2.0)	1.8 (1.5 to 2.1)	1.8 (1.5 to 2.1)
2100	2.0 (1.6 to 2.3)	2.1 (1.7 to 2.5)	2.4 (1.8 to 2.4)
2200	2.1 (1.7 to 2.6)	2.5 (1.8 to 3.2)	3.5 (2.0 to 5.0)

Table 11. Estimated extreme values with 100-year return period in future climate for Trelleborg. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.9 (1.6 to 2.2)	1.9 (1.6 to 2.2)	1.9 (1.6 to 2.3)
2100	2.1 (1.7 to 2.5)	2.2 (1.8 to 2.6)	2.5 (1.9 to 3.0)
2200	2.2 (1.8 to 2.7)	2.6 (1.9 to 3.3)	3.6 (2.1 to 5.1)

Table 12. Estimated extreme values with 200-year return period in future climate for Trelleborg. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	2.0 (1.6 to 2.4)	2.0 (1.6 to 2.4)	2.0 (1.6 to 2.4)
2100	2.2 (1.7 to 2.7)	2.3 (1.8 to 2.8)	2.6 (2.0 to 3.2)
2200	2.3 (1.8 to 2.9)	2.7 (2.0 to 3.4)	3.8 (2.2 to 5.3)

3.2.2 Halmstad

Estimated extreme values with up to 200-years return periods for Halmstad are given in Table 13 for the year 2020 and in Table 14 to Table 18 for future climate (years 2050, 2100 and 2200). Values are given in meters in the chart datum RH 2000 along with 95 % confidence intervals. The estimated values have been rounded to nearest decimeter as this is the appropriate accuracy in the context.

Due to mean sea level rise, estimated extreme values in future climate are greater than today's under all RCP-scenarios. It is also shown that extreme sea level events that historically occurred once per century, for example, can occur more frequently in the future. As an example, today's 100-year event corresponds to a 10-year event under RCP8.5 by the end of the 21st century, or a 10-year event under RCP4.5 by the end of the 22nd century. Equivalently, today's 200-year event corresponds to a 50-year event under RCP4.5 by the end of the 21st century, or a 10-year event under RCP8.5 between 2100 and 2200.

Table 13. Estimated extreme values with 5-, 10-. 50-, 100-, 200-year return periods for Halmstad year 2020. Values are given in meters in chart datum RH 2000 with 95 % confidence intervals.

	5-year	**10-year**	**50-year**	**100-year**	**200-year**
2020	1.8 (1.5 to 2.0)	2.0 (1.7 to 2.3)	2.4 (2.0 to 2.8)	2.6 (2.1 to 3.0)	2.8 (2.3 to 3.3)

Table 14. Estimated extreme values with 5-year return period in future climate for Halmstad. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.9 (1.6 to 2.2)	1.9 (1.6 to 2.2)	1.9 (1.6 to 2.2)
2100	2.0 (1.6 to 2.4)	2.1 (1.7 to 2.5)	2.4 (1.9 to 2.9)
2200	2.0 (1.6 to 2.5)	2.4 (1.7 to 3.1)	3.4 (1.9 to 4.9)

Table 15. Estimated extreme values with 10-year return period in future climate for Halmstad. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	2.1 (1.8 to 2.4)	2.1 (1.8 to 2.4)	2.1 (1.8 to 2.5)
2100	2.2 (1.8 to 2.6)	2.3 (1.9 to 2.7)	2.6 (2.1 to 3.2)
2200	2.2 (1.8 to 2.7)	2.6 (1.9 to 3.3)	3.6 (2.2 to 5.1)

Table 16. Estimated extreme values with 50-year return period in future climate for Halmstad. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	2.5 (2.1 to 2.9)	2.5 (2.1 to 2.9)	2.6 (2.2 to 3.0)
2100	2.6 (2.2 to 3.1)	2.8 (2.3 to 3.3)	3.0 (2.4 to 3.7)
2200	2.7 (2.2 to 3.2)	3.0 (2.3 to 3.8)	4.1 (2.6 to 5.6)

Table 17. Estimated extreme values with 100-year return period in future climate for Halmstad. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	2.7 (2.2 to 3.2)	2.7 (2.3 to 3.2)	2.7 (2.3 to 3.2)
2100	2.8 (2.3 to 3.3)	2.9 (2.4 to 3.5)	3.2 (2.6 to 3.9)
2200	2.8 (2.3 to 3.4)	3.2 (2.4 to 4.0)	4.3 (2.7 to 5.8)

Table 18. Estimated extreme values with 200-year return period in future climate for Halmstad. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	2.9 (2.4 to 3.4)	2.9 (2.4 to 3.4)	2.9 (2.4 to 3.4)
2100	3.0 (2.4 to 3.6)	3.1 (2.5 to 3.7)	3.4 (2.7 to 4.1)
2200	3.0 (2.4 to 3.6)	3.4 (2.6 to 4.2)	4.4 (2.9 to 6.0)

3.2.3 Öckerö

Estimated extreme values with up to 200-years return periods for Öckerö are given in Table 19 for the year 2020 and in Table 20 to Table 24 for future climate (years 2050, 2100 and 2200). Values are given in meters in the chart datum RH 2000 along with 95 % confidence intervals. The estimated values have been rounded to nearest decimeter as this is the appropriate accuracy in the context. Note, due to rounding, estimated values with 100- and 200-year return period are the same, however, the confidence interval is greater for the latter return period.

Due to mean sea level rise, estimated extreme values in future climate are greater than today's under all RCP-scenarios. It is also shown that extreme sea level events that historically occurred once per century, for example, can occur more frequently in the future. As an example, today's 100- and 200-year event corresponds to a 5-year event under RCP4.5 by the end of the 22nd century, or a 5-year event under RCP8.5 prior to the end of the 21st century.

Table 19. Estimated extreme values with 5-, 10-. 50-, 100-, 200-year return period for Öckerö year 2020. The values are given in meters in chart datum RH 2000 with 95 % confidence intervals.

	5-year	**10-year**	**50-year**	**100-year**	**200-year**
2020	1.2 (1.1 to 1.3)	1.3 (1.2 to 1.5)	1.6 (1.4 to 1.8)	1.7 (1.4 to 1.9)	1.7 (1.4 to 2.1)

Table 20. Estimated extreme values with 5-year return period in future climate for Öckerö. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.3 (1.2 to 1.5)	1.3 (1.2 to 1.5)	1.4 (1.2 to 1.5)
2100	1.4 (1.1 to 1.7)	1.5 (1.2 to 1.8)	1.8 (1.3 to 2.3)
2200	1.3 (1.0 to 1.7)	1.7 (1.1 to 2.3)	2.7 (1.3 to 4.2)

Table 21. Estimated extreme values with 10-year return period in future climate for Öckerö. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.4 (1.3 to 1.6)	1.5 (1.3 to 1.6)	1.5 (1.3 to 1.7)
2100	1.5 (1.2 to 1.8)	1.6 (1.3 to 2.0)	1.9 (1.4 to 2.4)
2200	1.5 (1.1 to 1.8)	1.8 (1.2 to 2.5)	2.9 (1.4 to 4.3)

Table 22. Estimated extreme values with 50-year return period in future climate for Öckerö. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.7 (1.4 to 1.9)	1.7 (1.4 to 1.9)	1.7 (1.5 to 2.0)
2100	1.7 (1.4 to 2.1)	1.9 (1.5 to 2.2)	2.1 (1.6 to 2.7)
2200	1.7 (1.3 to 2.1)	2.0 (1.4 to 2.7)	3.1 (1.6 to 4.6)

Table 23. Estimated extreme values with 100-year return period in future climate for Öckerö. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.8 (1.5 to 2.0)	1.8 (1.5 to 2.1)	1.8 (1.5 to 2.1)
2100	1.8 (1.4 to 2.2)	1.9 (1.5 to 2.3)	2.2 (1.7 to 2.8)
2200	1.8 (1.3 to 2.2)	2.1 (1.4 to 2.8)	3.2 (1.7 to 4.7)

Table 24. Estimated extreme values with 200-year return period in future climate for Öckerö. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.8 (1.5 to 2.2)	1.9 (1.5 to 2.2)	1.9 (1.5 to 2.3)
2100	1.9 (1.5 to 2.4)	2.0 (1.6 to 2.5)	2.3 (1.7 to 2.9)
2200	1.9 (1.4 to 2.3)	2.2 (1.5 to 2.9)	3.3 (1.8 to 4.8)

3.2.4 Umeå

Estimated extreme values with up to 200-years return periods for Umeå are given in Table 25 for the year 2020 and in Table 26 to Table 30 for future climate (years 2050, 2100 and 2200). Values are given in meters in the chart datum RH 2000 along with 95 % confidence intervals. The estimated values have been rounded to nearest decimeter as this is the appropriate accuracy in the context.

Due to large local land uplift in Umeå, future mean sea levels are lower than today's under RCP2.6 and RCP4.5, therefore estimated extreme values in future climate are lower than today's under the same RCP-scenarios. This implies that extreme sea level events that historically occurred once per century for example, can occur less frequently in the future under these two RCP-scenarios.

Under RCP8.5 future mean sea levels are lower than today's prior to 2100 and higher beyond, hence estimated extreme values follows the same pattern approximately.

Table 25. Estimated extreme values with 5-, 10-. 50-, 100-, 200-year return periods for Umeå year 2020. The values are given in meters in chart datum RH 2000 with 95 % confidence intervals.

	5-year	**10-year**	**50-year**	**100-year**	**200-year**
2020	1.0 (0.9 to 1.1)	1.1 (1.0 to 1.2)	1.3 (1.1 to 1.4)	1.3 (1.1 to 1.5)	1.4 (1.2 to 1.6)

Table 26. Estimated extreme values with 5-year return period in future climate for Umeå. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	0.9 (0.7 to 1.0)	0.9 (0.7 to 1.0)	0.9 (0.8 to 1.1)
2100	0.6 (0.3 to 0.9)	0.7 (0.4 to 1.1)	1.0 (0.5 to 1.5)
2200	-0.1 (-0.5 to 0.3)	0.3 (-0.4 to 0.9)	1.3 (-0.2 to 2.8)

Table 27. Estimated extreme values with 10-year return period in future climate for Umeå. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	**RCP4.5**	**RCP8.5**
2050	1.0 (0.8 to 1.1)	1.0 (0.8 to 1.2)	1.0 (0.9 to 1.2)
2100	0.7 (0.4 to 1.0)	0.8 (0.5 to 1.2)	1.1 (0.6 to 1.6)
2200	0.0 (-0.4 to 0.4)	0.4 (-0.3 to 1.0)	1.4 (-0.1 to 2.9)

Table 28. Estimated extreme values with 50-year return period in future climate for Umeå. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	RCP4.5	RCP8.5
2050	1.2 (1.0 to 1.4)	1.2 (1.0 to 1.4)	1.2 (1.0 to 1.4)
2100	0.9 (0.6 to 1.2)	1.0 (0.7 to 1.4)	1.3 (0.8 to 1.8)
2200	0.2 (-0.2 to 0.6)	0.5 (-0.1 to 1.2)	1.6 (0.1 to 3.1)

Table 29. Estimated extreme values with 100-year return period in future climate for Umeå. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	RCP4.5	RCP8.5
2050	1.2 (1.0 to 1.4)	1.3 (1.1 to 1.4)	1.3 (1.1 to 1.5)
2100	1.0 (0.6 to 1.3)	1.1 (0.7 to 1.4)	1.4 (0.9 to 1.9)
2200	0.3 (-0.1 to 0.6)	0.6 (0.0 to 1.3)	1.7 (0.2 to 3.1)

Table 30. Estimated extreme values with 200-year return period in future climate for Umeå. Values are given in meters in chart datum RH 2000 along with 95 % confidence intervals.

	RCP2.6	RCP4.5	RCP8.5
2050	1.3 (1.1 to 1.5)	1.3 (1.1 to 1.5)	1.4 (1.1 to 1.6)
2100	1.0 (0.7 to 1.4)	1.2 (0.8 to 1.5)	1.4 (0.9 to 1.9)
2200	0.3 (-0.1 to 0.7)	0.7 (0.0 to 1.3)	1.7 (0.2 to 3.2)

4 Discussion

Future mean sea levels along the Swedish coastline were calculated based on IPCC SROCC 2019 scenarios combined with information on land uplift. Other regional processes, however, were not included.

The development of knowledge in this area is rapid. New information is gathered, made available and used to improve estimates. The global political development makes certain, previous scenarios, less likely, while others become more likely. Completely new scenarios may also have to be developed and considered in order to capture greenhouse gas emissions that actually occur. The sixth assessment report by IPCC is underway, which is expected to present new and improved estimates. As a consequence, the values presented in this report may then need to be revised.

Sea level rise beyond the year 2100 will mainly depend on the response of the ice sheets in Greenland and especially Antarctica. Loss of ice from the Greenland ice sheet is predominantly controlled by melting at surface levels caused by rising air temperatures. In Antarctica, floating ice shelfs melt from below, a process controlled by heat from the ocean. A lack of understanding as to how the Antarctic ice sheet reacts to ocean warming is the greatest source of uncertainty in forecasts for future sea level rise. Critically important research on the processes related to melting of the Antarctic ice sheet is ongoing.

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