Technical Report

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Expected extreme sea levels at Forsmark and Laxemar–Simpevarp up until year 2100

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Summary (R-09-06)

Literature data on factors that can affect the highest expected shoreline during the operational lifetime of a final repository up until ca 2100 AD have been compiled for Forsmark and Laxemar/Simpevarp. The study takes into consideration eustasy (global sea level), isostasy (isostatic rebound) and their trends, as well as regional (North Sea) and local (Baltic Sea) annual extremes of today's sea levels and those in year 2100. The most uncertain factor of these is the future global sea level change. For this factor, three possible scenarios have been included from the literature, forming an rough uncertainty interval around a case with an "intermediate" global sea level described by /Rahmstorf 2007/. To this end, the study thus makes use of information on global sea level change that has been published since the IPCC's (UN Intergovernmental Panel on Climate Change) most recent report /IPCC 2007/.

The local cumulative impact on the shoreline of the eustatic and isostatic components for both the Forsmark and Laxemar/Simpevarp coastal areas is that the maximum sea level occurs at the end of the investigation period, by year 2100. The interaction of these estimates is discussed in terms of coastal oceanographic aspects and estimated return periods for local extreme sea level-impacting events, including estimated storm surge.

Maximum sea levels in year 2100 based on the sea level rise estimates by /Rahmstorf 2007/ are + 254 cm for Forsmark and + 297 cm for Laxemar/Simpevarp, both of these levels with an uncertainty interval of about ± 70 cm. The numbers apply for the *worst possible case* in regard to future sea level rise, and for occasions of short duration during heavy storms. In this context it is important to note that the data on which these estimates are based are the subject of intense research, and that revisions are therefore to be expected.

Contents

1 Introduction

In conjunction with the preparatory work for siting and design of a final repository in Forsmark or Laxemar-Simpevarp, information is evaluated to serve as a basis for the repository's design premises. This report presents the highest expected shoreline during the final repository's operational lifetime (until ca 2100 AD). Information from the site descriptions (SDM-Site) and other scientific literature on the subject has been used as background material for this evaluation. This background material is listed in the list of references. Decisive factors in determining the shoreline are the global sea level and the processes that influence how it changes in the future. Global warming is currently considered to be by far the dominant process.

A large portion of the scientific community consider that global warming is currently taking place, and that increasing concentrations of greenhouse gases in the atmosphere play a key role in this process /e.g. IPCC 2007/. Other researchers cite other causes, such as variations in solar activity, as being important. Regardless of the cause of global warming, it has two primary consequences as far as sea levels are concerned: i) the melting of land-based ice, and ii) thermal expansion of ocean water. Both of these processes lead to a rise in the level of the world's oceans. This sea level rise does not, however, take place evenly everywhere, due in part to simultaneous changes in the gravitational field over the Earth's surface. Furthermore, a regional impact on sea level is expected to be caused by increased precipitation, changes in wind patterns and isostatic rebound/subsidence. An overview of how the different processes interact on a global, regional and local level to determine the local sea water level is shown in Figure 1-2.

A previous draft of this report has been reviewed by Markus Meier, SMHI, who has contributed valuable viewpoints on the factual content.

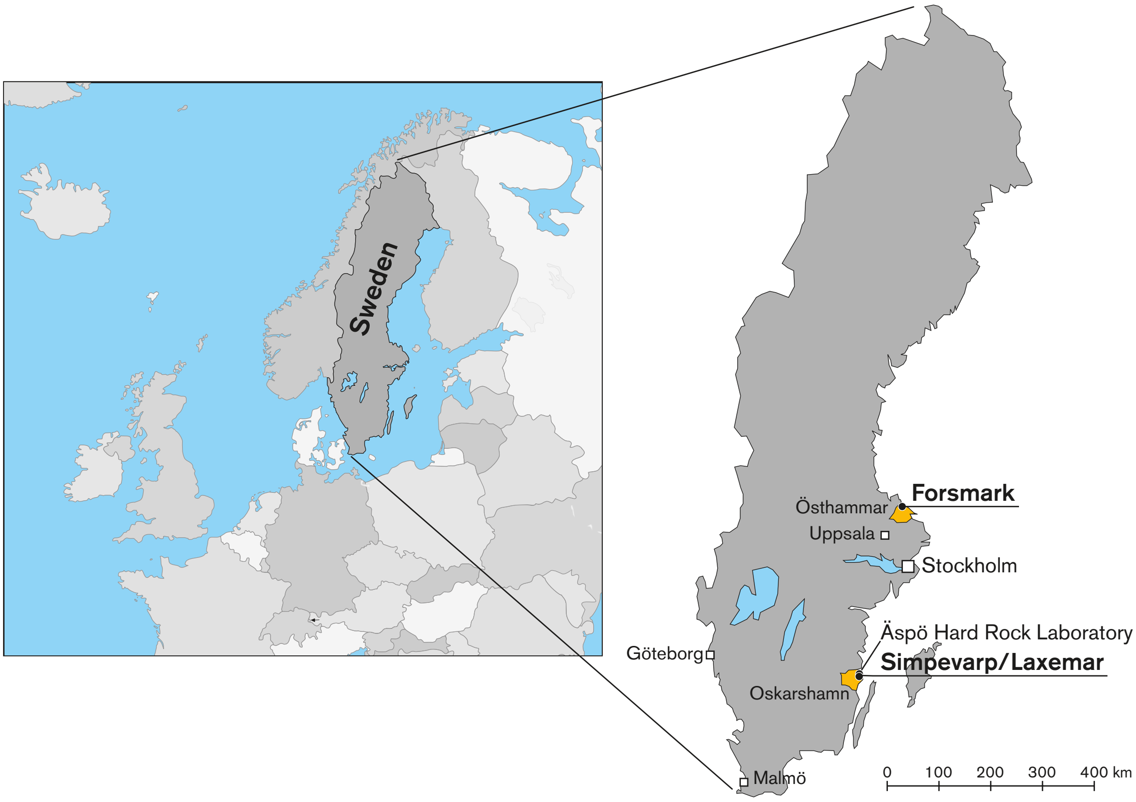

Figure 1-1. *Map of the two study sites, Forsmark and Simpevarp/Laxemar.*

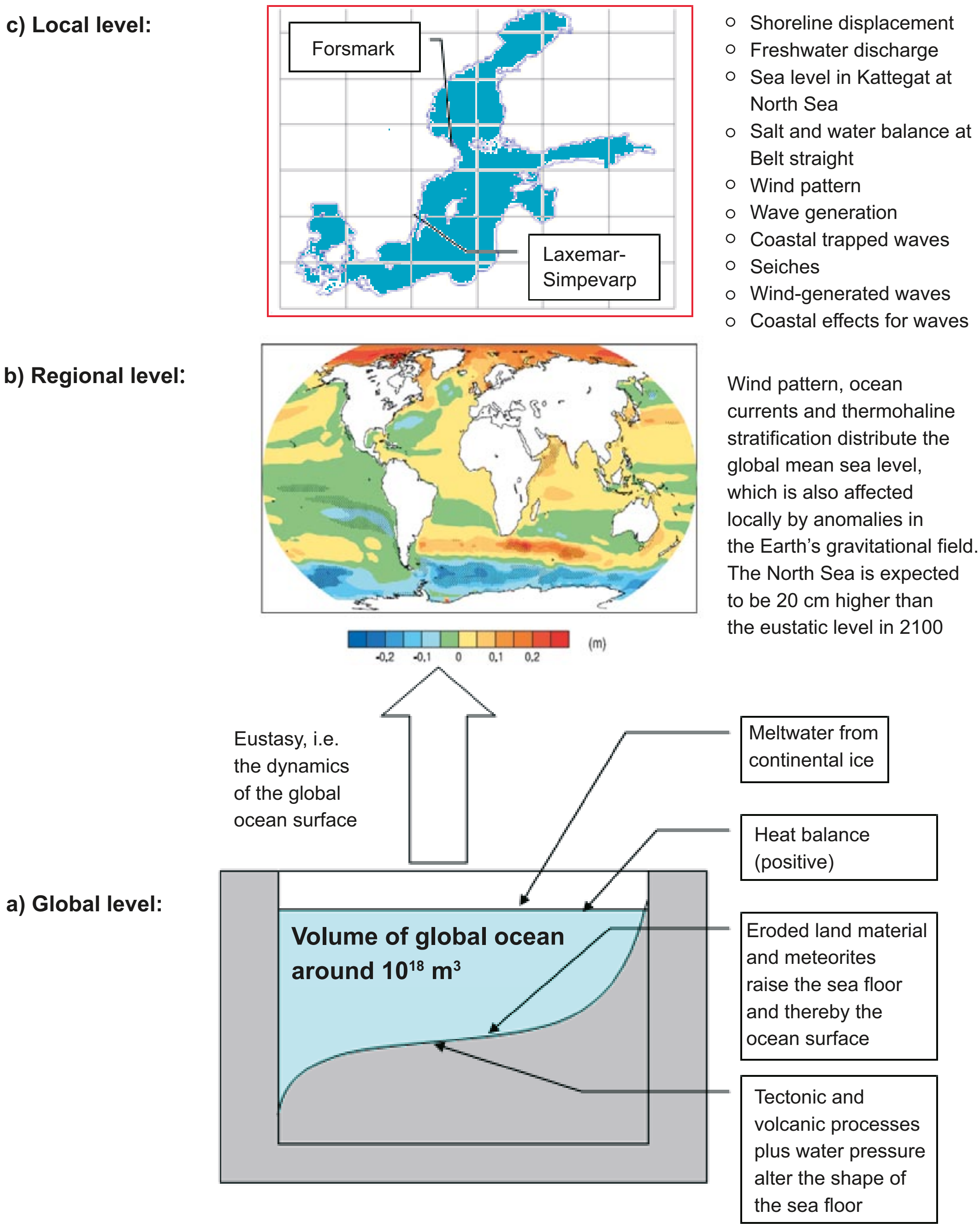

***Figure 1-2.** Schematic subdivision of processes on different spatial scales with impact on local sea level. On the global level the water volume of the world's oceans is affected. The resultant pressure, together with other processes, influences the geometry of the global ocean basin (isostasy). This results in a eustatic global sea level in quasi-steady-state equilibrium. **1-2b.** This sea level is distributed differently between different regions due to variations in the Earth's gravitational field and in atmospheric and ocean currents. Figure 1-2b is taken from /IPCC 2007/ "Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e. positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0." **1-2c.** A number of additional processes occur on the local level that have a distributing effect on the sea level of the Baltic Sea on the smaller geographic scale.*

2 Materials and methods

2.1 Input data

The following sources have been used to provide input data to the present study:

- Digital elevation models, SKB DEM 10x10 metres /Wiklund 2002/.
- Shoreline displacement models for Forsmark and Laxemar /Söderbäck (ed) 2008/.
- Cadastral map, SKB GIS, Central Office of the National Land Survey /SKB GIS/.
- Wave heights during extreme storms /Brydsten 2009/.
- Literature data on the future expected global sea level have been taken from /Church 2001/, /Rahmstorf 2007/ and /Pfeffer et al. 2008/. Data from /IPCC 2007/ have been used with regard to interregional distribution of the global sea level to the Baltic Sea's nearest marginal sea, i.e. the North Sea.
- Data from /Meier 2006/ have been used with regard to impact on the sea level in the Baltic Sea. These data have been processed statistically and related to height system RH70 by /Nerheim 2008/, who has also contributed an estimate of the local wind setup effect which the coupled atmosphere-Baltic Sea model is not able to resolve in the case of Forsmark.

2.2 Methodology review

2.2.1 Global sea level and trends

The fastest increasing scenario described by /Rahmstorf 2007/ has been used to estimate the local sea level at Forsmark and Laxemar/Simpevarp in accordance with the "worst case principle". These calculations are based on correlation analysis (annual rate of sea level change *vs.* measured warming relative to the period 1951–1980), see Figure 2-1. For a discussion on uncertainties in estimates of future sea level rise, including /Rahmstorf 2007/, see the Discussion chapter.

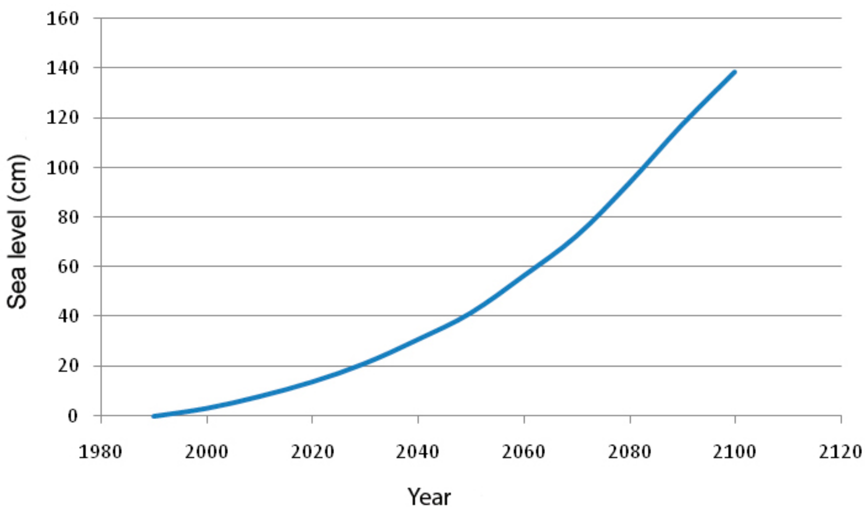

Figure 2-1. *Expected global sea level rise 1990–2100 according to the fastest increasing scenario described by /Rahmstorf 2007/.*

According to model calculations reported by /IPCC 2007/, the North Sea is expected to have a + 20 cm higher level than the global mean on a permanent basis, which is termed *interregional* distribution. The *intraregional* distribution within the North Sea area has been modelled by /Woth et al. 2006/ and amounts at most to + 7 cm in the Skagerrak. In order to consistently estimate the worst case, this episodic contribution is also included, even though it must be deemed unlikely that it would occur with sufficient duration and at times that could accentuate extreme sea levels in the Baltic Sea.

/Meier 2006/ has calculated the local impact on the water level along the Baltic Sea coast based on the maximum value given by /Church et al. 2001/ and other expected climate factors. These results have subsequently been treated statistically by /Nerheim 2008/ to eliminate the assumptions made concerning global sea level and isostatic rebound. What is left is impact on sea level with respect to expected atmospheric and hydrologic forcing in the future. The nearest grid points in /Meier 2006/ Baltic Sea model for Forsmark and Laxemar/Simpevarp have been analyzed with this method, and statistics for the extreme sea levels for the two 30-year periods 1960–1990 and 2071–2100 have been determined for comparison. These figures have been recalculated to 100-year return values relative to the mean value of the sea level for the two repository sites. In the present estimates, these statistics have been shifted in time to represent the mean value for the sea level in 2100, which means that the 100-year return values apply to a period ± 50 years centred around the year 2100. The probability that the local extreme levels obtained for the Baltic Sea will be equalled or exceeded sometime during this 100-year period with this approach is 63%, and the probability that they will occur before 2101 is then 40%.

2.2.2 Isostasy

The global sea level rise is locally compensated for by the glacial isostatic rebound (land uplift) that occurs at Forsmark and Laxemar /Simpevarp. With the shoreline displacement equations for the two sites /Söderbäck ed. 2008/, the future course of the isostasy can be calculated by subtracting the eustasy from the shoreline displacement. In this site way Rahmstorf's prediction can be adjusted for local isostasy at the site in question (Figure 2-2).

The difference in sea level change between the two sites is due to the faster rate of isostatic rebound at Forsmark. Figure 2-2 also shows that the most extreme sea level will occur at the end of the investigation period, which means it is then only of interest to calculate the sea level for 2100. For the most extreme scenario according to /Rahmstorf 2007/ corrected for local isostasy, the maximum sea level in 2100 is + 56 cm in Forsmark and + 115 cm in Laxemar.

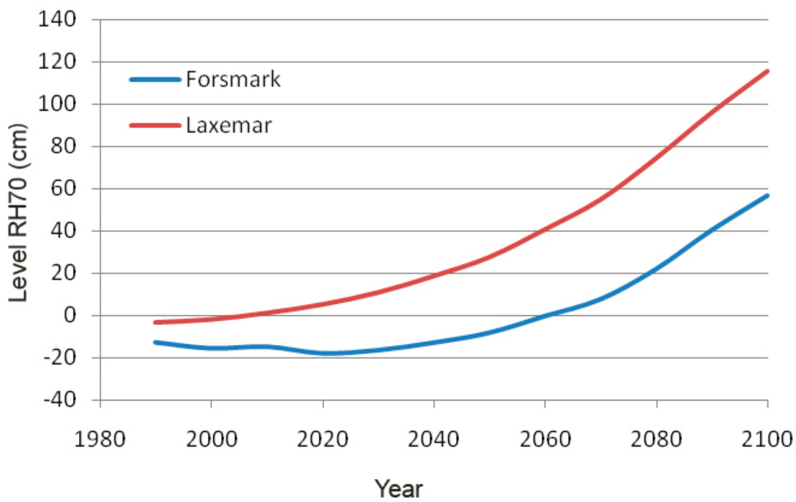

Figure 2-2. *Prediction of sea level according to /Rahmstorf 2007/ adjusted for isostasy and corrected to the height system RH70.*

2.2.3 Annual extremes today and in the future

Besides the slowly changing global eustasy and local isostasy, sea level variations of short duration also occur due to the temporary weather system (atmospheric pressure, winds etc.), Figure 1-2c. The highest sea level measured in Forsmark occurred in 2004 and amounted to + 144 cm above mean sea level, equivalent to + 141 in the height system RH70. The equivalent value for Laxemar (Oskarshamn) is + 100 cm in RH70. These values can be added to the above values, yielding extreme values amounting to + 200 cm for Forsmark and + 215 cm for Laxemar.

Besides rising sea levels, future climate change is also expected to lead to increasing wind speeds. This means that the local sea level rises generated by weather systems in the future may be higher than the values measured so far. /Nerheim 2008/ has compiled these effects for the two sites (Table 2-1).

The values given in Table 2-1 for "Today's climate" should thus be compared with the highest measured levels. The value for Oskarshamn is slightly higher than the highest measured value, which is reasonable; the value for Forsmark (+ 115 cm), on the other hand, is substantially lower than the highest measured value (+ 144 cm). The reason is that the model results which /Nerheim 2008/ analyzed are not of the resolution required to correctly illustrate the conditions in Öregrundsgrepen (Forsmark); the value given applies to the open coast north of there. The approximate calculation given for Forsmark amounts to about 20–30 cm above the value at the open coast, i.e. in the interval + 135 to + 145 cm for today's climate, values that agree well with measured extreme values.

These calculations of the extreme values for the two sites in 2100 are summarized in Table 2-2. In addition to /Rahmstorf's 2007/ prediction of the global eustasy, there are two other estimates that can be included to shed light on the uncertainties in future sea level rise. The first is from /IPCC 2007/ and predicts a 79 cm lower sea level compared with /Rahmstorf 2007/; the second is from /Pfeffer et al. 2008/ and entails a global sea level rise of 62 cm by 2100 AD. With these values, the resultant total sea level in 2100 with unchanged values for the other constituent processes is compiled in table 2-3.

Table 2-1. Calculated return levels (cm in RH70) with a return period of 100 years for high water levels at the open coast. By "today's climate" is meant the meteorological reference period 1961–1990 /Nerheim 2008/. The future scenario for Forsmark must be corrected upward by + 30 cm due to a local wind setup effect, see text and Table 2-2.

	Forsmark	Laxemar
Today's climate	115	109
Future scenario	141	137
Increase	26	28

Table 2-2. Calculation of the maximum sea levels (cm in RH70) at Forsmark and Laxemar/Simpevarp in 2007 based on /Rahmstorf 2007/.

Process	Forsmark	Laxemar	Source
Global eustasy	138	138	/Rahmstorf 2007/
Local isostasy	–82	–23	/Söderbäck ed. 2008/
Global variation in North Sea	20	20	/IPCC 2007/
Local variation in North Sea	7	7	/Woth et al. 2006/
Local variation in Baltic Sea	171	137	/Meier 2006 and Nerheim 2008/
Total 2100	254	279	

Table 2-3. Resultant maximum sea levels (cm in RH70) at Forsmark and Laxemar/Simpevarp in 2100 based on three independent predictions.

Source	Forsmark	Laxemar
IPPC 2007	175	200
Rahmstorf 2007	254	279
Pfeffer et al. 2008	316	341

2.2.4 Oceanographic viewpoints

Sea levels in the North Sea are affected by weather systems in the same way as those in the Baltic Sea. A systematic interregional sea level rise in the North Sea affects the sea level in the Baltic Sea with an equally great rise in the first approximation, provided that the density of the North Sea water is not simultaneously altered. The intraregional sea level rise in the North Sea has been modelled by /Woth et al. 2006/ and amounts to a maximum of + 7 cm. The highest rise is expected to occur on the west coast of Denmark. The rise is 5–7 cm at Skagen but declines further towards Öresund and the Danish Belts. A local sea level rise in the North Sea will presumably have a reduced amplitude in the Baltic Sea, since such a rise is expected to be of a limited duration. As a result, its propagation through the narrow and shallow straits between the Baltic Sea and the Kattegat will have a dampening effect. Furthermore, the extreme levels in Forsmark and Laxemar must occur simultaneously (within a time margin equivalent to the propagation delay from the North Sea) in order for these extreme values to interact. In an attempt to illustrate the worst case, this minor contribution has nevertheless been included in Table 2-2.

During the seasonal variations of an annual cycle, the local water level along the shores of the Baltic Sea varies with the freshwater runoff and its densimetric impact on the density stratification of the water, which is in turn determined by density conditions in the Kattegat. Water level and salinity in sea west of Sweden (Skagerrak and Kattegat) are further determined to a high degree by forcing of its boundary areas, i.e. the North Sea bordering on the Atlantic. Trying to quantify such external forcings lies beyond the scope of this report. Instead it is of interest to be able to relate these projected future extreme water levels to oceanographic processes that can cause them and that are represented in the model on which the cited statistical data /Meier 2006/ are based. It is then possible to disregard tides, which are estimated at up to a maximum of + 4 cm at the sites in question /Dietrich et al. 1975/. Nor do the water oscillations (seiches) caused by long standing waves that may be excited by the passage of low pressure regions appear to be of any great importance. A well known seiche with a period of nearly 24 hours is the one with St. Petersburg and the southern Baltic Sea as its end points (antinodes). Forsmark and Laxemar/Simpevarp are nearer its node, however, and are therefore not affected to any appreciable degree. Such seiches are first excited by the wind and subsequently decay due to friction within a couple of periods unless an extremely improbable new wind forcing in exactly the right phase supplies additional energy.

Direct wind action causes a setup, i.e. a vertical slope of the sea level against the lee coast. Provided that the wind fetch has enough time to act, a saturation phase will set in during which the setup is directly proportional to the fetch length and the square of the wind force and inversely proportional to the mean depth along the fetch. Figure 2-3 shows the type of local setup calculation cited by /Nerheim 2008/. The fetch lengths and mean depths on the Baltic Sea scale that coincide with extreme water levels do not differ appreciably between Forsmark and Laxemar-Simpevarp. With the 30% expected elevated winds which occur in the Baltic Sea in the extreme case (RCO-E/A2) /Meier 2006/, the calculated extreme cases can be largely explained by such wind setup effects. While other impacts on the water level such as those caused by atmospheric pressure variations within the Baltic Sea, Ekman dynamics, Kelvin waves etc can interact to contribute to incidents with extremely elevated coastal water levels, the single most important factor is the wind setup. The recoil if the wind shear abruptly ceases then goes radically faster with the velocity of a long surface wave, about 25 m/s, which can excite seiches as described above.

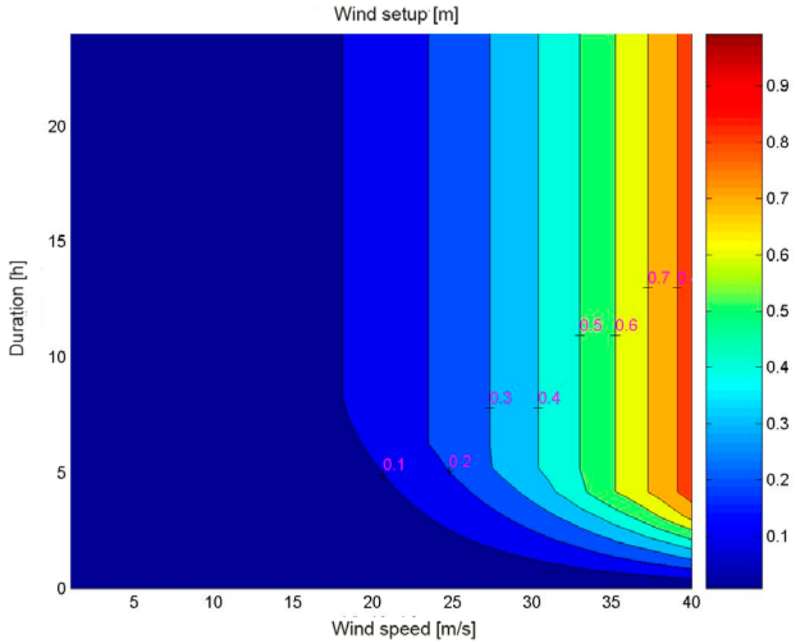

Figure 2-3. *Estimate of vertical wind setup with respect to wind speed and duration. In other words, in order to cause on its own the setup of + 20 cm for Forsmark calculated by /Nerheim 2008/, a storm wind force of 24 m/s with a duration of at least 5 hours would be required. The additional 10 cm given by /Nerheim 2008/ corresponds to an initial wave effect (Sture Lindahl (SMHI) pers. comm.).*

2.2.5 Return periods

The data calculated by /Meier 2006/ correspond to return periods of 100 years, i.e. the probability that this level will be reached or exceeded in a randomly selected year during the 100-year period is *a priori* 1%. The probability that this will happen at some time during this 100-year period is thus 63%. This is often considered to be an insufficient safety level.

If, based on the theory of the statistical distribution of extreme values /e.g. Gumbel 2004/, the 100-year return level is doubled, a 10,000-year return level is obtained. This corresponds to a 99% probability that this value will *not* be exceeded during the 100 years for which the distribution applies, i.e. in our case 2051–2150. This increased safety level has not been included in our account of expected water levels in 2100; we have instead chosen to report the uncertainty as differences in 2100 between three independent estimates of the global sea level.

2.2.6 Storm surge

Short-duration sea level rises caused by wind-generated waves must be added on top of various sea level rises caused by eustatic and isostatic processes. During storms, the water surface is raised by an accumulation of water along the shore that is exposed to the waves (wind setup) and by the surge, i.e. the portion of the beach that is only temporarily wet (Figure 2-4). The wind shear is included in the level values given in 2.2.3, but not the surge.

The surge is dependent on a large number of factors such as the height of the wave at the beach, the slope of the beach, the angle of the wave against the beach, the properties of the shore material, etc. /Silvester 1974/. In lieu of other data than wave height, it is possible to figure roughly that the surge on a natural shore very rarely exceeds the height of the breaking wave, but can nevertheless amount to a height of several metres and should therefore be included in an assessment of the probability of flooding.

Figure 2-5 shows the modelled wave height in Forsmark for a northerly storm with a wind force of 25 m s^{-1}. The wave height in the northern part of Öregrundsgrepen amounts to more than 7 metres, but declines rapidly down towards Forsmark. The pier built adjacent to SFR shelters the shores south of there, so the wave heights here are moderate (< 0.4 m). The highest wave height near the shore (1.15 m) is at the cape directly south of SFR.

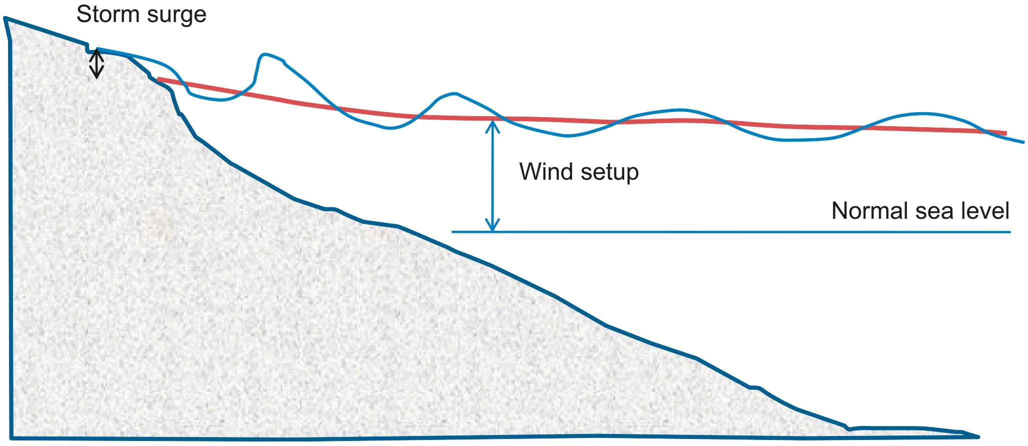

Figure 2-4. Sea level changes caused by wind-generated waves.

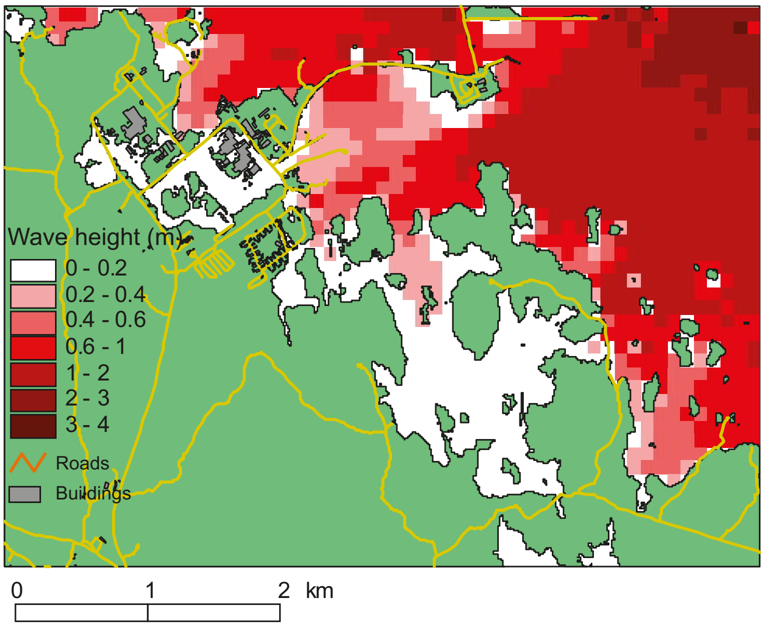

Figure 2-5. Calculated wave heights during storm-force winds in 2100 at Forsmark.

3 Extreme local impact levels

3.1 Forsmark

Figures 3-1 to 3-3 show which areas will be flooded if the sea level reaches + 175, 254 and 316 cm above the reference level in the height system RH70 (Table 2-3). The consequences are relatively small at a level of + 175 cm, while both roads and the power plant are affected at + 254 cm. There are very serious consequences at a sea level of + 316 cm.

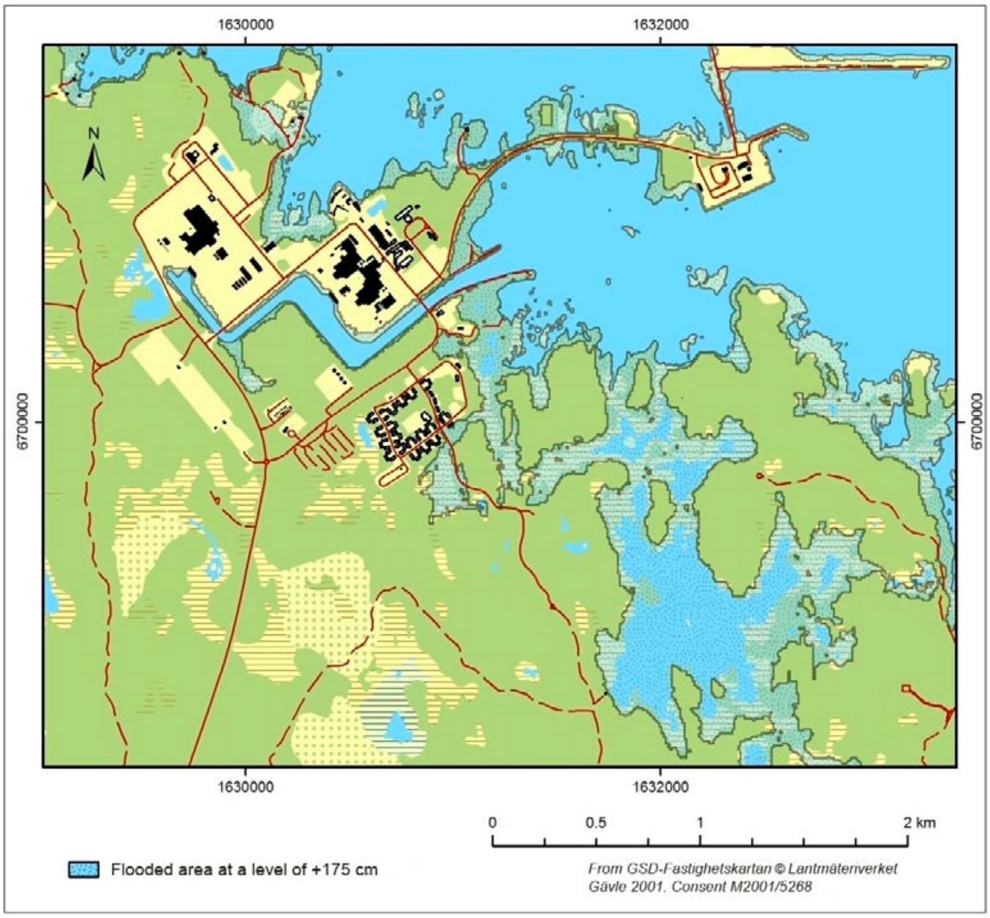

Figure 3-1. *Area at risk of flooding at an extreme level of + 175 cm in Forsmark in 2100.*

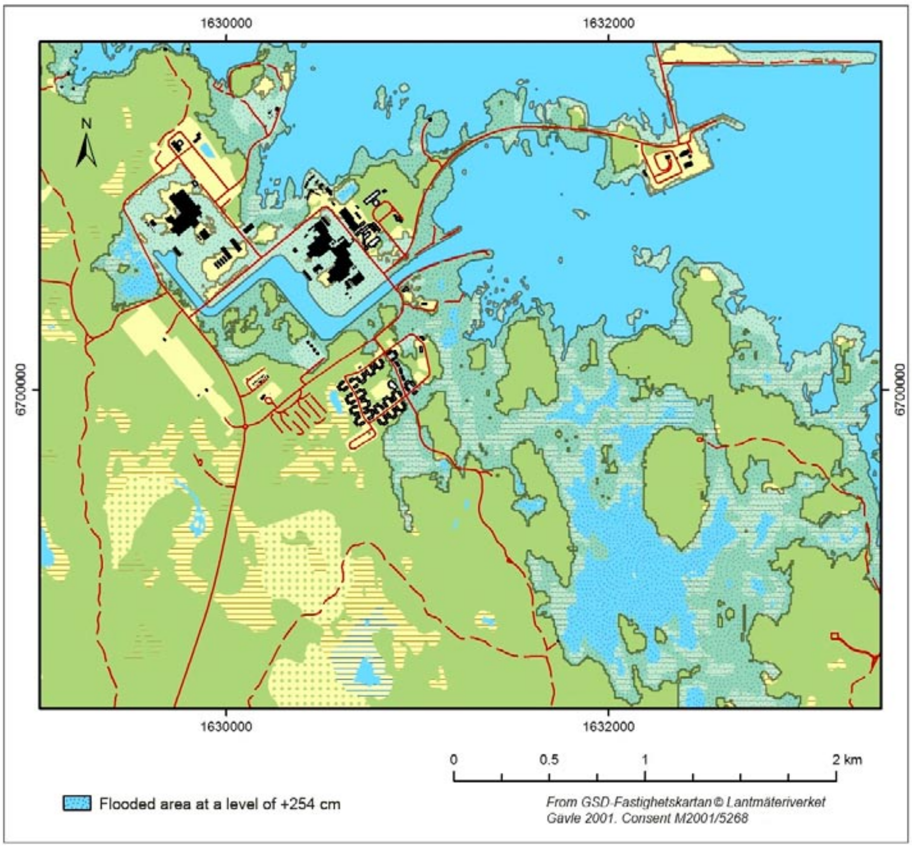

Figure 3-2. *Area at risk of flooding at an extreme level of + 254 cm in Forsmark in 2100.*

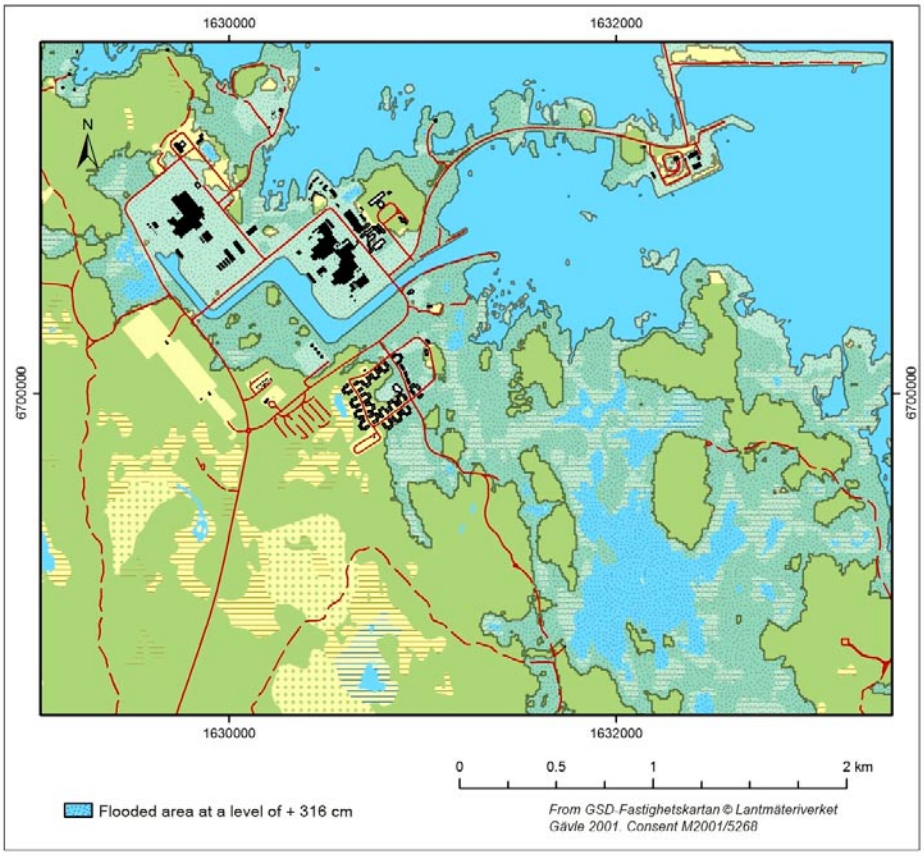

Figure 3-3. *Area at risk of flooding at an extreme level of + 316 cm in Forsmark in 2100.*

3.2 Laxemar-Simpevarp

The area in Laxemar-Simpevarp is characterized by relatively steep shores, which means that even a large sea level rise will result in relatively small flooded areas. Figure 3-4 shows flooded areas at a water level rise of 341 cm (Table 2-3) and that the consequences for the infrastructure would be moderate even for this most extreme case.

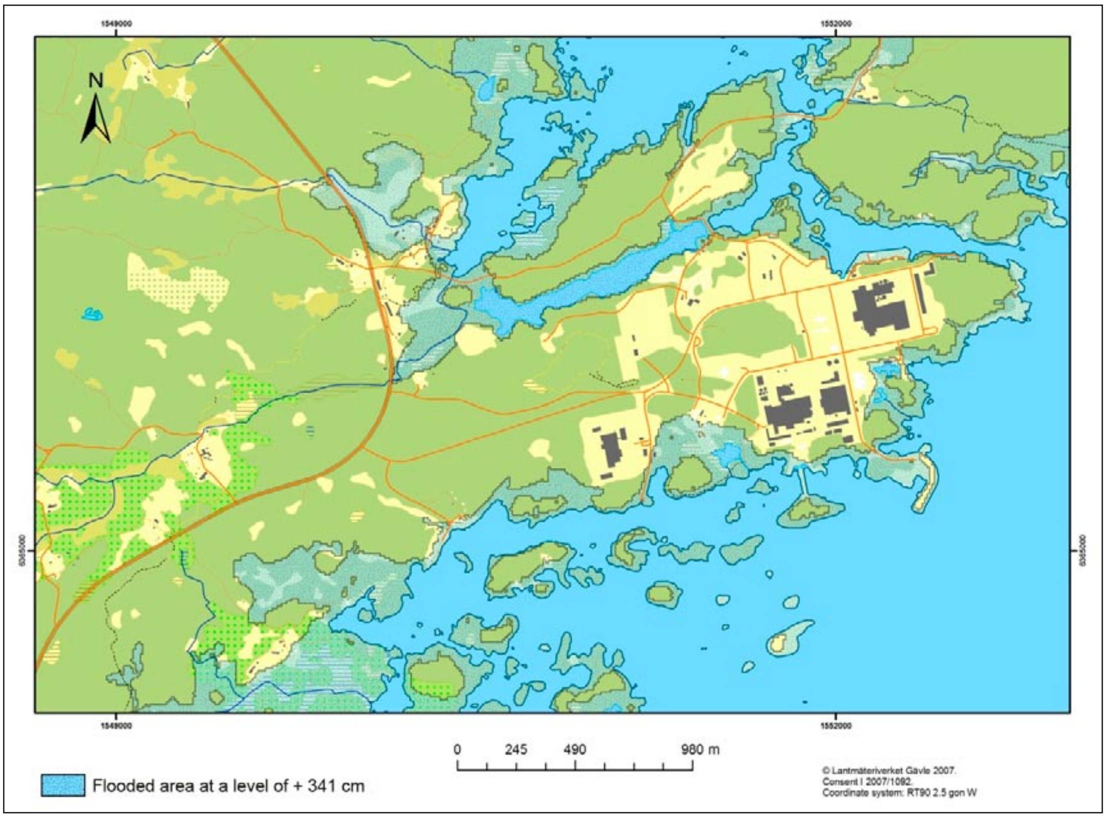

Figure 3-4. *Area at risk of flooding at an extreme level of + 341 cm in Forsmark in 2100.*

4 Discussion

At present, there are major uncertainties in the estimates of future sea-level rise due to the inferred global warming. Nevertheless, these uncertainties need to be included and considered when building near the present day coast-line. The maximum global sea level rise reported by IPCC in 2001 amounted to + 88 cm for year 2100 AD, relative to a reference year in the early 1950s /Church et al. 2001/. In the IPCC 2007 report, the maximum global sea level rise by year 2100 was reported to + 59 cm /IPCC 2007/. The difference between these two estimates is dependent on how the risks of global sea level changes are evaluated and how they are presented statistically. Primarily, in the 2007 IPCC sea level rise estimate, the contribution from a dynamic ice sheet response to global warming was deliberately excluded because of its large uncertainty /IPCC 2007/.

/Rahmstorf 2007/predicted a maximum global sea level rise by year 2100 of + 138 cm (relative to the level year 1990). This is considerably higher than the value reported by /IPCC 2007/, a difference that is mainly due to the different methodological approach taken by /Rahmstorf 2007/. In a study by /Pfeffer et al. 2008/ the Greenland and Antarctic ice sheet response to global warming is estimated and included. Also in this study the large uncertainty in sea level rise is emphasised. /Pfeffer et al. 2008/ points to two probable cases of global sea level rises by year 2100 (relative to the level year 2000) amounting to + 79 and + 83 cm, respectively. /Pfeffer et al. 2008/ also describe a less probable, but still possible, worst case where a calculated *maximum* ice discharge from the Greenland and West Antarctic ice sheets result in a global sea level rise of + 200 cm by year 2100, i.e. + 141 cm above the /IPCC 2007/ estimate (that excluded this process). It is not meaningful or possible to here assign probabilities to these different predictions of future global sea level change.

In relation to /Rahmstorf's 2007/ maximum value for year 2100 (+ 138 cm), the difference relative to the /IPCC's 2007/ estimate (59–138 = –79 cm) is almost the same as the difference relative to the extreme value given by /Pfeffer et al. 2007/ (200–138 = + 62 cm). These differences can therefore serve as a measure of the present-day uncertainty of future global sea level rise (see Figure 4-1).

The estimates on maximum sea levels presented in Table 2-3 and Figure 3-1 to 3-4 describe what might happen due to the cumulative worst-case effects of possible future processes spanning over the global, regional and local scales. The numbers apply for occasions of short duration during heavy storms. The selected processes are characterized by the fact that they are unfavourable as regards a possible raised water level at the two sites, but they can at present not be dismissed as unrealistic. However, it should again be emphasised that research on the possible future global sea level rise is in a very intensive phase, and that major uncertainties still exist in this field.

We would also like to point out that storm surge is not included in the reported figures. Storm surge is only reported as wave height at the shore, and this effect must be judged from case to case based on site-related characteristics. The models show that large areas may be affected during one or more brief periods. Different results are obtained depending on which calculation cases are assumed. No attempt has been made in this account to compensate for the non-linearly increasing effect on the extreme levels noted by /Meier 2006/ when the mean water level rises. If this is done, it becomes more probable that further elevated levels will be realized by 2100.

Critical viewpoints by /Rahmstorf 2007/ are presented in Appendix 1. Our judgement is that these objections have been satisfactorily answered by Stefan Rahmstorf in the form of comments in the Internet reference found in the same appendix. The further accentuated sea level rise cited by /Pfeffer et al. 2008/ as the most extreme case – based on calculated maximum ice fluxes – constitutes an extreme scenario that will probably be limited by other processes.

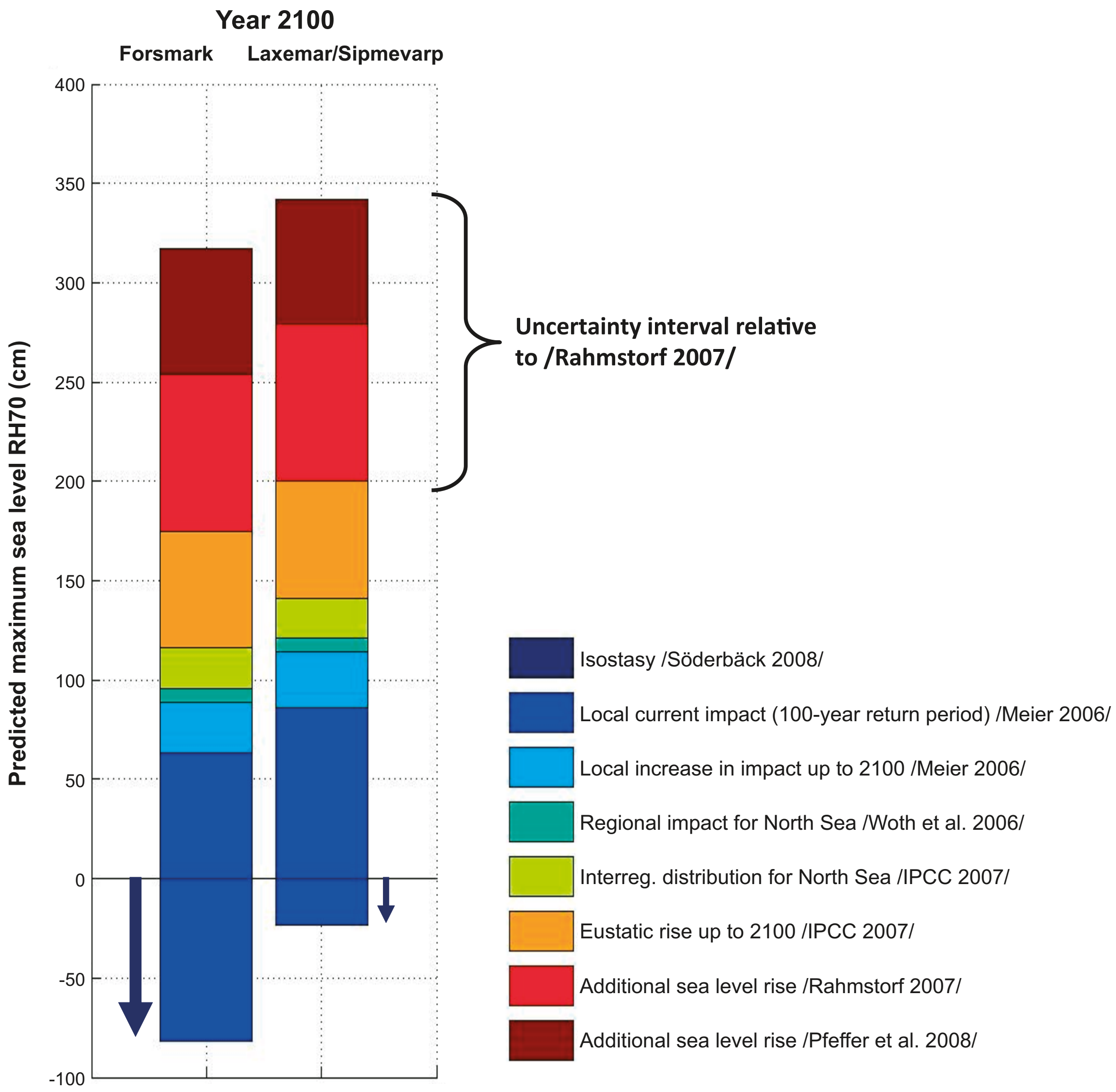

Figure 4-1. *Graphic presentation of the compilation of predicted contributions that result in the possible extreme sea level for Forsmark and Laxemar/Simpevarp in 2100 relative to the height system RH70. The isostasy is indicated by downward arrows according to the colour scale. As a primary measure of the uncertainty concerning the three eustatic contributions, this uncertainty has been indicated by a bracket centred on /Rahmstorf's 2007/ prediction, which corresponds to the top edge of the red bar.*

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Appendix 1

Viewpoints on /Rahmstorf 2007/ and responses to these viewpoints

COMMENT ON “A Semi-Empirical Approach to Projecting Future Sea-Level Rise” Simon Holgate, Svetlana Jevrejeva, Philip Woodworth, Simon Brewer: Rahmstorf (Reports, 19 January 2007, p. 368) presented an approach for predicting sea-level rise based on a proposed linear relation between global mean surface temperature and the rate of global mean sea-level change. We find no such linear relation. Although we agree that there is considerable uncertainty in the prediction of future sea level rise, this approach does not meaningfully contribute to quantifying that uncertainty. Full text at: www.sciencemag.org/cgi/content/full/317/5846/1866b.

COMMENT ON “A Semi-Empirical Approach to Projecting Future Sea-Level Rise” Torben Schmith, Søren Johansen, Peter Thejll: Rahmstorf (Reports, 19 January 2007, p. 368) used the observed relation between rates of change of global surface temperature and sea level to predict future sea-level rise. We revisit the application of the statistical methods used and show that estimation of the regression coefficient is not robust. Methods commonly used within econometrics may be more appropriate for the problem of projected sea-level rise. Full text at: www.sciencemag.org/cgi/content/full/317/5846/1866c.

RESPONSE TO COMMENTS ON “A Semi- Empirical Approach to Projecting Future Sea-Level Rise” Stefan Rahmstorf: Additional analysis performed in response to Holgate et al. and Schmith et al. shows that the semi-empirical method for projecting future sea-level rise passes the test of predicting one half of the data set based on the other half. It further shows that the conclusions are robust with respect to choices of data binning, smoothing, and de-trending. Full text at: www.sciencemag.org/cgi/content/full/317/5846/1866d 1866.

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