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Research

In search of lost storms:

or can one infer the magnitudes of extremely rare flood events from short observational records?

2024:06

Author: Magnus Hieronymus, SMHI, Norrköping
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SSM perspektiv

Bakgrund
Kärnkraftverken, övriga kärntekniska anläggningar och andra verksamheter som acceleratorerna ESS och MAX IV ska kunna motstå yttre händelser, såsom väderfenomen, i sådan omfattning att säkerhetssystemens förmåga att utföra sina uppgifter inte äventyras. Fukushima-olyckan i Japan 2011 är ett exempel på konsekvenserna av yttre händelser med magnituder överstigande vad som förutsatts i säkerhetsanalyserna. Efter olyckan i Japan initierades omfattandet arbete, både nationellt och internationellt.

Att uppskatta magnituder för osannolika yttre händelser med frekvens på 10^{-6}/år är svårt, eftersom tillräckligt med empiriska data saknas för att kunna skatta dessa låga frekvenser med klassiska statistiska metoder. Framtagning av extremvärdesmetoder som till sin natur har stora osäkerheter krävs. En ytterligare försvårande faktor är att när dessa extremvärden ska beräknas används tillgängliga och i sammanhanget korta mätserier som oftast inte sträcker sig längre tillbaka i tiden än 100-årsskala för att extrapolera till 10^{-6}/år-värden. Dessa extrapolationer bygger oftast på antagandet att klimatet är konstant vilket utelämnar klimatförändringars potentiella inverkan på genomförda analyser. Ytterligare forskning är därför viktig för att utveckla metoder för att bättre kunna skatta magnituder för osannolika väderfenomen med frekvenser till och med 10^{-6}/år.

Resultat
Rapporten visar att för korta planeringshorisonter (några decennium) är det primärt kortvariga havsnivåextremer som driver översvämningsrisken medan medelvattenståndsförändringar driver risken på längre planeringshorisonter (mot slutet av seklet och längre). Ett resultat som enligt SMHI tidigare visats hålla också på andra Svenska platser. Planeringshorisonter, och deras sannolikheter används primärt i rapporten istället för årliga sannolikheter. Detta beror på att de årliga sannolikheterna inte är stationära utan förändras kraftigt med förändringar i medelvattenståndet. Detta gäller särskilt händelser med mycket låg sannolikhet, där den årliga sannolikheten kan ändras med många storleksordningar redan under det nuvarande seklet, särskilt i scenarier med höga utsläpp och som konsekvens stora medelvattenståndshöjningar.

Angående olika scenarier visas det att översvämningsrisken på de tidsskalorna som diskuteras i denna rapport inte främst styrs av om uppvärmningen kan begränsas till Parisavtalets 2 oC, utan av om de två allra högsta utsläppsscenarierna SSP3-7.0 och SSP5-8.5 kan undvikas. Vidare diskuteras det att även om medelvattenståndsförändringar och kortvariga högvattenhändelser båda bidrar till översvämningsrisk, så är tidsskalorna de verkar på och längden på förvarningen man kan få innan de sker väldigt olika. Detta betyder förstås att metoderna man kan välja för att anpassa sig till dessa två faror är väldigt olika, deras liknande verkan till trots.

Relevans
Denna forskningsrapport är en del i SSM:s arbete att bygga upp kunskap om hur osannolika yttre händelser kan påverka kärntekniska anläggningar. Resultatet är till nytta för förståelse av hur höga vattenstånd kan uppstå vid Ringhals kärnkraftverk nu och i framtiden beroende på hur klimatförändringarnas påverkan på vattenståndet.

Behov av vidare forskning
Det är av vikt att SSM även fortsättningsvis följer forskning inom området för klimatförändringar för att förstå hur dessa kan påverka kärnkraftverk som är placerade vid den svenska kusten.

Projektinformation
Kontaktperson SSM: Henrik Hellberg
Referens: SSM2022-4868 / 4530526

In search of lost storms: or can one infer the magnitudes of extremely rare flood events from short observational records?

Magnus Hieronymus, SMHI

April 18, 2024

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1 Sammanfattning

Rapporten som här presenteras summerar arbetet som gjorts inom projektet Nuclear pOwer And long tail flood risK (NOAK), för att estimera havsnivåer med mycket låga sannolikheter i dagens och möjliga framtida klimat vid Ringhals. Nivåerna som presenteras är beräknade med ett nytt innovativt verktyg kallat en havsnivåsimulator. Verktyget inkorporerar medelvattenståndsförändringar och kortvariga havsnivåextremer i ett gemensamt sannolikhetsramverk, något som inte var möjligt med tidigare planeringsmetoder. Fördelningar som beskriver kortvariga havsnivåextremer beräknas både från en lång observationsserie och från en mycket lång vattenståndserie från en numerisk oceanmodell, som korrigerats med hjälp av en maskinlärningsmetod. Dessa två datakällor är på många sätt ett unikt stort material både i en nationell och internationell kontext. Medelvattenståndsprojektionerna kommer från IPCC:s senaste syntesrapport.

Simuleringarna visar att på korta planeringshorisonter (några decennium) är det primärt kortvariga havsnivåextremer som driver översvämmningsrisken medan medelvattenståndsförändringar driver risken på längre planeringshorisonter (mot slutet av seklet och längre). Ett resultat som tidigare visats hålla också på andra Svenska platser. Planeringshorisonter, eller planning periods som de kallas på engelska och deras sannolikheter (planning period probabilities) används primärt i rapporten istället för årliga sannolikheter. Detta beror på att de årliga sannolikheterna inte är stationära utan förändras kraftigt med förändringar i medelvattenståndet. Detta gäller särskilt händelser med mycket låg sannolikhet, där den årliga sannolikheten kan ändras med många storleksordningar redan under det nuvarande seklet, särskilt i scenarier med höga utsläpp och som konsekvens stora medelvattenståndshöjningar.

Angående olika scenarier visas det att översvämningsrisken på de tidsskalorna som diskuteras här inte främst styrs av om uppvärmningen kan begränsas till Parisavtalets 2 $^\circ\mathrm{C}$, utan av om de två allra högsta utsläppsscenarierna SSP3-7.0 och SSP5-8.5 kan undvikas. Vidare diskuteras det att även om medelvattenståndsförändringar och kortvariga högvattenhändelser båda bidrar till översvämningsrisk, så är tidsskalorna de verkar på och längden på förvarningen man kan få innan de sker väldigt olika. Detta betyder förstås att metoderna man kan välja för att anpassa sig till dessa två faror är väldigt olika, deras liknande verkan till trots.

Allt material, modell såväl som data, som behövs för att göra vidare simuleringar finns öppet att ladda ner för alla intresserade. För den hågade finns sålunda utmärkta möjligheter att utöka materialet.

2 Introduction

Infrastructure planning in coastal areas must account for both weather related sea level extremes (Arns et al., 2013) and mean sea level change (Oppenheimer et al., 2019; Hieronymus and Kalén, 2020). In a global context, warming induced sea level rise is the predominant cause of mean sea level change. However, in large parts of Sweden a considerable post glacial rebound is still ongoing, yielding sea level fall or slower than average rise. The land uplift has considerable spatial inhomogeneity, which causes Swedish mean sea level projections for the current century to be similarly spatially inhomogeneous. Typically, they are showing sea level fall in the northern parts, and sea level rise almost on par with the global average in the southernmost part of the country.

The data-types used to assess mean sea level change and sea level extremes are of different kinds, but somewhat standardized for both types of data. Estimates of sea level extremes used for planning purposes are most often given in terms of return period (yearly probability) -return level plots. Mean sea level change projections used for planning, meanwhile, are typically given in terms of time and emission-scenario dependent probability density functions. Merging these two different data-types has proven to be a challenging endeavour. Current coastal spatial planning typically uses arbitrary constructs such as adding a high mean sea level projection to a high return level to find safe locations to place new infrastructures. This is, of course, problematic since the relation to a yearly probability is lost in such constructs and consequently that the risk that locations deemed safe could get flooded cannot be quantified.

At the heart of this problem lies the fact that mean sea level change affects the yearly probabilities of sea level extremes. In many locations in Sweden the difference between a sea level with a yearly probability of 1/100 and one with a yearly probability of 1/10000 is only a few decimetres (Hieronymus, 2021). The difference is even smaller if one compares a 1/10000 sea level to a 1/1000000 sea level. These differences are therefore often dwarfed by the range of projected mean sea levels for the current century. This means that a sea level that has a yearly probability of 1/10000 today, may have a yearly probability 1/10 in the year 2100 under a high emission-scenario, where the mean sea level rises considerably (Oppenheimer et al., 2019; Hieronymus and Kalén, 2020; Fox-Kemper et al., 2021).

A solution to the problem of non-stationary flooding probabilities was recently devised by Hieronymus (2021) who introduced a sea level simulator that integrates mean sea level change and sea level extremes into a joint probabilistic framework. The simulator was further developed in Hieronymus and Kalén (2022) and Hieronymus (2023b). The simulator solves the problem of having time-dependent yearly probabilities by instead introducing stationary planning period probabilities. That is, instead of calculating a yearly flood probability that may change by orders of magnitude over some decades, one instead calculates a flood probability for the whole planning period which is time-independent. The planning period is a user-defined period that can be, for example, the expected life time of a structure or the time it takes for a building to depreciate to some suitable low amount.

Having accurate probabilistic estimates of the risk of flooding is important for many types of infrastructures, but it is particularly important for critical infrastructure. The site discussed here is the nuclear power station Ringhals, for which there is an extremely small risk tolerance. Regulations require that a 1/1000000 yearly probability of flooding is considered. The object of this report is to quantify the risk of flooding at the site using state-of-the-art estimates for both sea level extremes and mean sea level rise. Joint probabilities of flooding (i.e. from both mean sea level rise and sea level extremes) are therefore derived using the sea level simulator for a number of different emission-scenario probabilities, planning period lengths and high water durations. The fact that emission-scenarios are given probabilities of coming to pass in the simulator, instead of just assuming one scenario, typically the highest, to be realized, is another great innovation encompassed in the simulator framework. This turns the risk of flooding into a self-contained probabilistic estimate dependent on emission-scenario probabilities, planning period lengths and the distributions used for mean sea level change and sea level extremes. Moreover, it makes it possible to quantify how the risk of flooding depends on, for example, emission-scenario probabilities or the distributions used to model sea level extremes in a straightforward manner.

A frequent problem with sea level planning is that the very low yearly probabilities for sea level extremes wanted by planners, especially for critical infrastructures, are far beyond what can be determined directly from empirical distribution functions derived from time series of observed sea levels. This problem is what is alluded to by “lost storms” in the title. However, lost storms in the sense that the amplitude of long past sea level extremes is unknown, is not the only problem. In fact, climate variability, in particular the presence of ice ages, ensures that statistically stationary million years long extreme sea level records cannot exist. Yearly probabilities are therefore derived not from empirical distributions but from continuous distribution functions, whose governing parameters have been estimated using observed data. The confidence one can put on the exactness of these parameters and thus the derived yearly probabilities is essentially a function of the length of the observed data record (Hieronymus and Hieronymus, 2021).

The exactness of mean sea level projections is even trickier to judge than those for sea level extremes, as these projections depend on many subjective design choices (Hieronymus, 2020). This inherit ambiguity lead the authors of the sixth assessment report of the Intergovernmental Panel on Climate Change (AR6 IPCC, Fox-Kemper et al. (2021) to present two different mean sea level projections for two of the emission-scenarios considered in the report. The probabilities for different future mean sea levels in these projections should thus be interpreted as subjective (Bayesian) probabilities representing a state of knowledge or a degree of belief rather than a frequency. The same is true about the probabilities of different emission scenarios coming to pass. A fundamental consequence of this is that even though arbitrary low probabilities requested by planners can be calculated, for example, using the sea level simulator by Hieronymus (2023b), the results will never be absolute. New knowledge, new data and differing personal beliefs can give rise to differing estimates. A useful feature of the simulator is, however, that the effect that different design choices have on the estimated probabilities can quantified (Hieronymus, 2021).

Apart from the novelty of supplying a joint probability of flooding dependent on both sea level extremes and mean sea level change, the report also provides updated estimates of the distributions governing both extremes and mean sea level change. For mean sea level rise we use distributions from IPCC’s AR6 (Fox-Kemper et al., 2021). For extremes we use both an observationally based estimates derived from a long merged time series of data from the tide gauge in Ringhals and a discontinued neighbouring and highly covariant tide gauge in Varberg, the municipality where Ringhals is situated. A secondary data source for extremes is data from a numerical ocean model that has been run forced with atmospheric states from wide range of future emission-scenarios. In total over 2600 years of data has been integrated using this model, and the model data has also been bias corrected using a novel machine learning technique (Hieronymus and Hieronymus, 2023).

The overall aim of the report is to provide state-of-the-art estimates of very low probability extreme sea levels at Ringhals, including the effects of mean sea level change for future periods. A number of different emission-scenario probabilities are considered as well as different extreme sea level distributions and different models for uncertainty quantification. However as noted earlier, the derived probabilities are subjective and they depend on many different design choices. The report therefore spends considerable effort to discuss the effects that such choices have on the estimated probabilities, and also to contextualize some of the different choices and outline some of the authors own beliefs in what may constitute sound choices. For anyone wanting to test other design choices, the model and all files needed to run these simulations are available free of charge through Hieronymus (2023b,a). Moreover, all simulations used in the report and the scripts used to produce the plots are available through Hieronymus (2023c). In other words, it is easy to extend the results shown in this report with simulations using different emission-scenario probabilities, mean sea level projections and extreme sea level distributions for anyone wanting to do so.

3 Data, models & methods

In this section we will briefly discuss the data, models and methods used to produce the flood risk estimates for Ringhals. The reason for keeping the discussion somewhat brief is that in-depth technical descriptions of the more innovative methodologies and models used here has already been published openly in the scientific literature (Hieronymus, 2023b; Hieronymus and Hieronymus, 2023), while the remainder of the data and methods are more or less standard practice.

3.1 Sea level extremes

Two main methodologies are used in scientific and engineering practices to derive distributions for sea level extremes. Either one fits a generalized extreme value (GEV) distribution to a series of sea level block maxima, or a generalized Pareto (GP) distribution to a series of sea level peaks that are higher than a pre defined threshold. We have chosen the first option here and the reason for this is that it does not require us to pre define a threshold, a choice that is hard to optimize. For the joint Varberg-Ringhals time-series, and for the Swedish west coast in general, the GEV gives higher values than the GP distribution, for the thresholds used by SMHI (2023). The choice of GEV could thus be considered a conservative estimate. The block maxima approach requires that one defines the length of the block used. However, a length of one year is almost always used, as it is the smallest block where one can reasonable expect maxima in sequential blocks to be independent, and also get enough blocks that a distribution can be fitted with some confidence. In practise, the block maxima approach is therefore an annual maxima approach in most applications. Hieronymus and Hieronymus (2023) tested the influence on return levels of using longer than annual blocks with some very long model based sea level time-series. For six out of seven stations that were modelled, it was found that annual blocks gave similar results to longer blocks, while for the seventh station annual blocks gave a large overestimate of the return levels. For the current data we found no signs of such overestimates and therefore judged annual blocks to be sufficient.

All extreme sea level data used here has hourly resolution. That is, regardless of whether the data is modelled or observed it represents sea levels sampled ones every hour. Apart from in the specific case of the bias corrected modelled sea level data, very little pre-processing is done on the original data. Before computing the annual maxima the whole time-series of hourly sea levels are linearly detrended to remove signals of land uplift and sea level rise. The annual maxima are then computed for a year starting July 1 and ending June 30. In total we have 120 such years in the joint Varberg-Ringhals time-series, which means that the joint time series is one of the longest high resolution tide gauge time series in the world. The redefinition of the calendar year is used to keep each storm season in the same block and is thus an effort to keep sequential blocks independent, as sea level maxima nearly never occur in summer at our location (Männikus et al., 2020).

As a complement to the observed time series there is also a very long modelled time series from a regional climate model that downscales global climate model data. The long time series is made by concatenating modelled time-series from runs forced with atmospheric condition from many different emission-scenarios and global climate models. A list of those scenarios and models is shown i Tab. 1. The modelled time series is 2604 years long, and it has also been bias corrected using a novel neural network based machine learning approach (Hieronymus and Hieronymus, 2023). The data in this series thus come from a wide range of emission scenarios ranging from very low emissions under RCP2.6 to very high under RCP8.5 and they are also produced using forcing from many different global climate models. A reasonable expectation is therefore that the atmospheric conditions used to make these downscalings are both such that are more and less prone to create extreme sea levels than those seen today. Yet, Hieronymus and Hieronymus (2023) found that sea level extremes modelled under these widely varying conditions had very similar distributions and could be concatenated to make very long time series of sea level extremes. In this report we view this modelled time series as a complement to the observed one. The much greater length of the modelled compared to the observed time-series ensures that many more sea level extremes and typically more rare events are present. This makes the uncertainty in the GEV distribution fitted to the modelled data much smaller than that for its observationally based counterpart.

Table 1: Downscaled global coupled models and emission scenarios. Here RCP stands for representative concentration pathway and the number after give the radiative forcing in Watts per square meter. The downscaled historical simulations start in the year 1961 and in some cases as late as 1976 owing to missing data. All historical simulations, however, end in the year 2005. The RCP scenarios all start in 2006 and end in 2100.

	Historical	RCP2.6	RCP4.5	RCP8.5
MPI-ESM-LR	X	X	X	X
EC-EARTH	X	X	X	X
GFDL-ESM2M	X	X	X	X
HadGEM2-ES	X	X	X	X
IPSL-CM5A-MR	X		X	X
CanESM2	X		X	X
CNRM-CM5	X		X	X
NorESM1-M	X	X	X	X
MIROC5	X	X	X	X

3.2 Mean sea level projections

The mean sea level projections used in this report are based on those in the IPCC's sixth assessment report, but the land uplift estimates used by the IPCC have been replaced with more accurate uplift data from Lantmäteriet (Vestøl et al., 2019). The new projections are based to a large degree on model data from the Coupled Model Intercomparison Project phase 6 (CMIP6). They are therefore following the same scenario convention with shared socio-economic pathways (SSPs) as CMIP6. In Fig. 1 it is shown in more detail how the different SSPs relate to different radiative forcing and global mean surface temperatures. Radiative forcing is the change in net radiation at the top of the atmosphere that the emissions in the respective scenarios impose in the year 2100, compared to a pre-industrial background. Higher radiative forcing implies greater warming.

Not all of the SSP-radiative forcing combos shown in Fig. 1 have corresponding mean sea level projections, SSP4-3.4, SSP4-6.0 and SSP5-3.4 are therefore not included here. However, some SSP-radiative forcing combos have more than one mean sea level projection. Here we have dual projections for SSP1-2.6 and SSP5-8.5. The "extra" projections (called *low confidence*) have their estimates of sea level rise owing to melt from Antarctica and Greenland taken from some of the highest estimates in the published scientific literature (Bamber et al., 2019; DeConto et al., 2021), instead of being based on data from the large ice sheet model intercomparison projects, as in the standard projections. The *low confidence* badge is IPCC parlance. Basically, the confidence statement is an assessment of the robustness of the evidence behind the projection. As a comparison the standard projections have *medium confidence*, and no *high confidence* projections exist. In total we have seven different mean sea level projection for five different SSP-radiative forcing combos represented in our simulations. That is, we use the complete set of AR6 projections released by (NASA, 2022; Fox-Kemper et al., 2021).

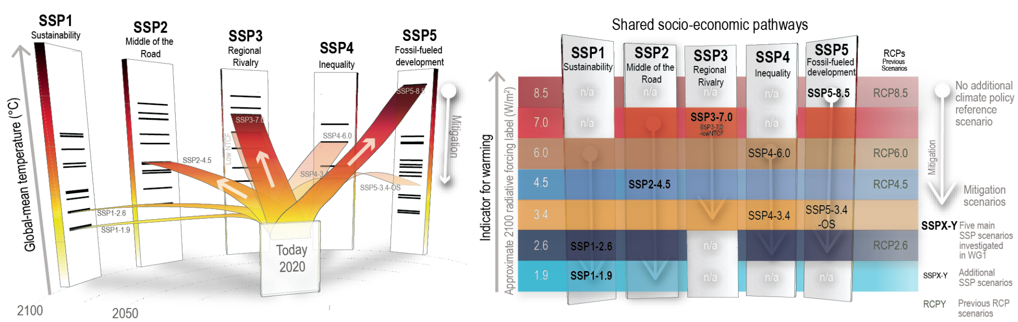

Figure 1: Explainer of the SSPs and their relations to radiative forcing and mean surface temperature at the end of the century. This figure is the Cross-Chapter Box 1.4, Figure 1 in IPCC, 2021: Chapter 1. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

The mean sea level projections are given in terms of discreet probability density functions for every ten years from 2020 until 2150. The horizontal resolution of these projections is one degree in latitude and longitude. The different SSP-radiative forcing combos have not had their probability of occurrence assessed by their makers. Planners are therefore largely left to their own devices in assessing the likelihood of different emission scenarios coming to pass. The SSP framework shown in Fig. 1 does, however, offers at least some guidance. In particular, getting a radiative forcing as low as 1.9 Wm^{-2} is only deemed possible under sustainable and middle of the road assumptions (SSP 1 and 2), while getting as high as 8.5 Wm^{-2} is only deemed possible under fossil-fueled development (SSP 5). The integrated assessment model (IAM) community has provided some much more detailed quantifications. Capellán-Pérez et al. (2016) and Huard et al. (2022) are two examples that use economic modelling and assessments of fossil fuel availability to constrain the probability of having different emission scenarios. Generally speaking most probed IAMs in these studies show similar outcomes having emissions in the range of the scenario SSP2-4.5 as the most probable outcome for this century. However, there is a strong time dependence in the emission probabilities. Many scenarios have similar probabilities up until about the year 2040, while after that the probability of having as high emissions as SSP5-8.5 declines quickly and reaches zero in three out of five IAMs probed by Huard et al. (2022). To summarize, there is a considerable uncertainty in the probability of the different emission scenarios coming to pass. The very low emissions under SSP1-1.9 and SSP1-2.6 are, however, very unlikely unless very strong mitigation policies are put in place. The very high emissions under SSP5-8.5 are very unlikely in the long term under most assumptions.

3.3 The sea level simulator

The purpose of the sea level simulator is to combine mean sea level projections and distributions of sea level extremes into a joint probabilistic framework. Here we use the sea level simulator v1.0 (Hieronymus, 2023b), which was released to the public in the beginning of the year. A schematic illustrating how the simulator operates is shown in Fig. 2. Essentially, the sea level simulator uses a Monte Carlo method to model yearly sea level maxima over a given planning period. Here we model planning periods starting in 2020 and ending in 2150, which also gives us the statistics for all shorter planning periods in ten year increments.

The loop depicted in Fig. 2 starts with a tide gauge, whose high temporal resolution data is used to derive a distribution for the annual sea level maxima at the site. Note that not only tide gauge data, but any sea level series with high temporal resolution can be used. Here we also use a much longer time series from a numerical ocean model (Hordoir et al., 2018) that has been bias corrected using a machine learning approach, as a second option (Hieronymus and Hieronymus, 2023). The fitted distribution (illustrated by the thick line in panel b) is then used to draw random yearly maxima, for each year in the planning period, from. However, there is also an option to include uncertainty in the yearly maximum distribution, which is illustrated by the dashed confidence intervals in the same panel. When this option is used a random yearly maximum distribution based on the confidence intervals on the fit is first drawn randomly for each planning period (Hieronymus, 2023b). Then the yearly maxima for the planning period is drawn from that distribution. The range of the uncertainty in the underlying distribution depends on the length of the time series used to fit the distribution, meaning that there is considerable uncertainty in the distribution fitted to the short observed time series and a much less uncertainty in that fitted to the much longer modelled time series.

In module three a SSP-radiative forcing combo is chosen randomly, through the use of user defined probabilities given to each scenarios. In this report, we have tested both to give each SSP-radiative forcing combo a probability of one, and also to give all scenarios non-zero probabilities simultaneously. The first option is included to illustrate what difference a SSP-radiative forcing trajectory makes and the latter aims to model a more realistic scenario when future emissions are unknown. Details are given in the results section.

Module four randomly selects the mean sea level projection from the already chosen SSP-radiative forcing combo. This module is therefore only active for SSP1-2.6 and SSP5-8.5, where we also have the *low confidence* projections, for all other SSP-radiative forcing combos there is only one mean sea level projection available.

The fifth module selects a random quantile of the already selected mean sea level projection. The same quantile is used at all times throughout the planning period to keep the mean sea level change projection physically plausible. That is if the 0.78 quantile is drawn, then this quantile is extracted from the mean sea level distributions for 2020, 2030,...,2150. A mean sea level projection for the 0.78 quantile for the planing period with yearly resolution is then created using linear interpolation between the years where distributions are available.

In the last module the planing periods sea level extremes and mean sea level projection is added together. This gives a long projection of yearly sea level maxima relative to the current mean sea level. The large left arrow below the modules in Fig. 2 indicates that the loop between the modules is repeated. For the simulations shown we repeat the loop 10^7 times (i.e. we model 10^7 planing periods). From this data we then calculate statistics, for example, the planning period probability for sea level extremes, mean sea levels and joint sea levels (mean + extreme). Many more details about the sea level simulator as well as it's source code is available through (Hieronymus, 2021; Hieronymus and Kalén, 2022; Hieronymus, 2023b).

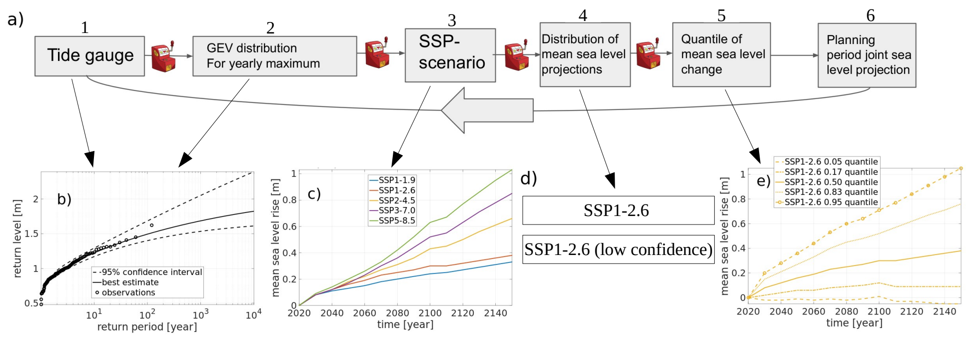

Figure 2: A schematic of the sea level simulator showing the model's different modules. A slot machine indicates that a stochastic process is activated when going from one module to the next. The large left arrow indicates that the simulations are run very many times (10^7 planning periods are modelled in each experiment). The figure is taken from Hieronymus (2023b)

4 Results

In this section results from many different simulations are shown, detailing differences owing to future emission scenario, extreme sea level distributions, planning period lengths and much more. For comparison with older work using yearly probabilities instead of planning period probabilities, the section starts with a subsection showing classical yearly probabilities for sea level extremes relative to the mean sea level.

4.1 Yearly probabilities for sea level extremes relative to the mean sea level

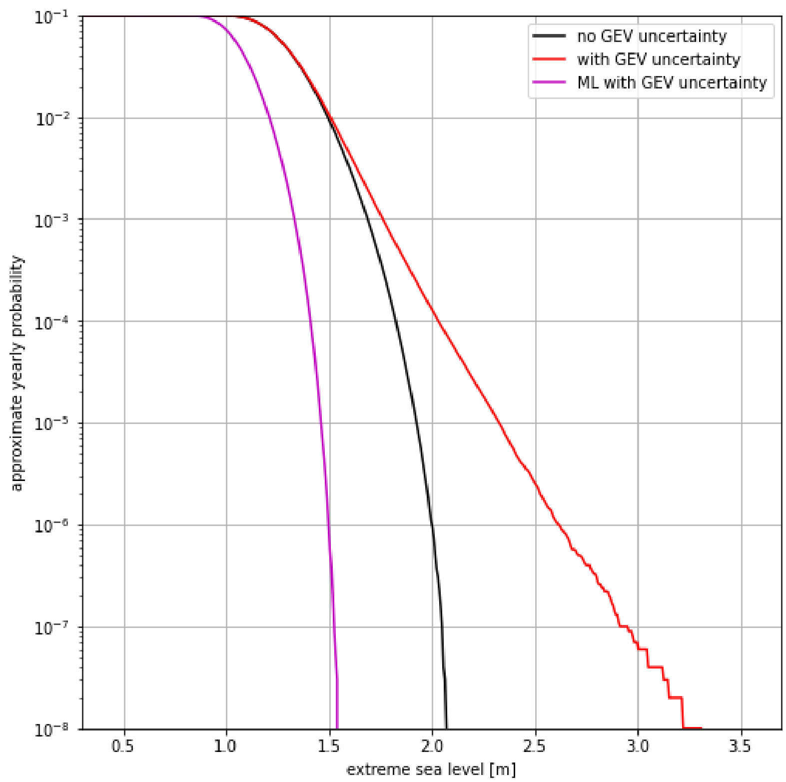

Figure 3: Return period (yearly probability) return level plot. The yearly probability is approximated from the planning period probability, using the 2020-2030 planning period. The red and black curves are for the observationally based extreme sea level with and without uncertainty in the GEV parameters. The magenta line based on the data from a bias corrected numerical model (Hieronymus and Hieronymus, 2023) and includes GEV parameter uncertainty.

Fig. 3 shows approximate yearly probabilities for different sea levels. The yearly probabilities are derived from the planning period probabilities for the period 2020-2030, assuming that the probability of the extremes is unchanged throughout the period. This is a very fair approximation as the mean sea level change in this short period is pretty much negligible. All curves are thus derived by randomly sampling from the respective GEV distributions, while modelling 10^7 ten year long planning periods. The red and black lines are both based on the observational Varberg-Ringhals series. The difference between them is that the black is the best estimate of the extreme sea level distribution (i.e. the typical return level-return period plot), while the red is derived using a distribution of plausible extreme sea level distributions based on the confidence intervals for the GEV parameters, following Hieronymus (2023b).

The magenta curve is based on a 2604 year long time series from a numerical ocean model running multiple different emission scenarios (see Tab. 1). The data is also corrected using a neural network based bias correction method (Hieronymus and Hieronymus, 2023). The magenta curve used the same uncertainty modelling as the red curve, but being based on a much longer time series this uncertainty does not affect the result very much.

The authors personal judgement is that the black curve is likely the best approximation of the return levels we have at the site. The magenta curve appears in spite of being bias corrected to still have a bias, as the highest observed sea level at the site is 1.62 m above the mean and would thus have an extremely low probability of occurrence if the curve was correct. The red curve is very likely overly pessimistic. This conclusions rest upon multiple lines of evidence. Firstly, we find the shape of the best estimate curve to be very similar to the shape of the modelled curve (this is true also without the bias corrections). Moreover, this shape suggest that the extremes are Weibull distributed. The Weibull distribution is one of three distributions contained within in the GEV distribution family. Weibull distributed extremes are found when the GEV distribution's shape parameter has a value smaller than zero. All other Swedish tide gauges have earlier been found to have Weibull distributed yearly maxima as the best estimate (Hieronymus and Kalén, 2020). Thus, it seems very likely that the correct shape is that of the black and magenta lines, while the magnitude of the highest recorded sea level suggests that the true line is closer to the black than the magenta one.

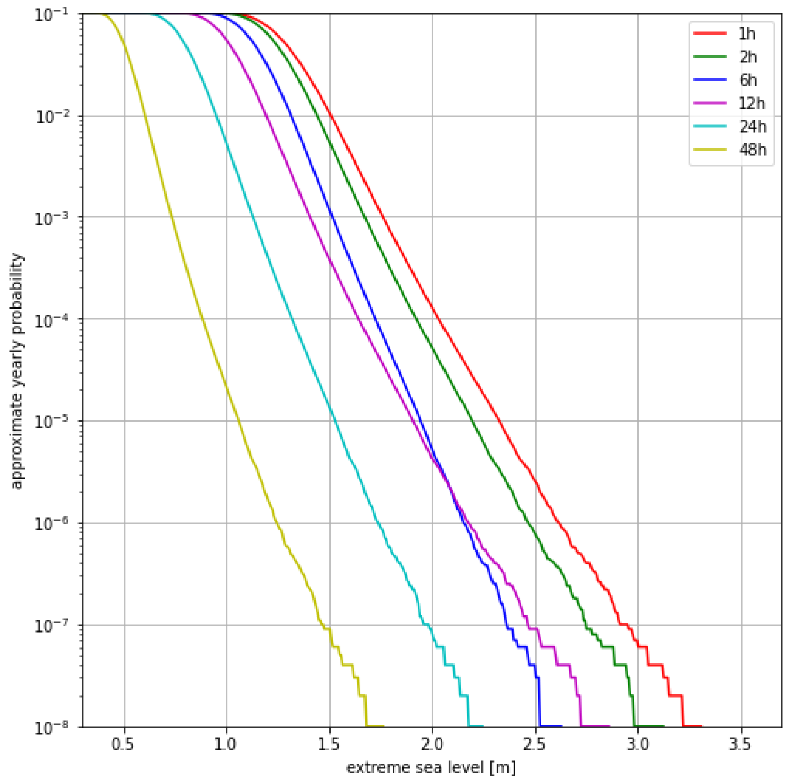

Figure 4: Return period (yearly probability) return level plot. The yearly probability is approximated from the planning period probability, using the 2020-2030 planning period. The different lines show yearly probabilities for different high water durations. The 1h line is the same as in Fig. 3.

Figure 4 shows yearly probabilities for different high water durations. The red line is the same as that in Fig. 3 and is the only one that does not properly show duration as 1 h is the sampling frequency of the sea level measurements. That is, we cannot say that the sea level remains above these levels for at least one hour. The other curves are produced by filtering the 1 h sea level time series with a min-filter of length equal to the number of hours in the sought after duration. That is, taking the six hour duration as an example, we loop over and take the min of the sea level over all possible six hour periods. Then we calculate the yearly maxima from the filtered series the same way as was done for the 1 h values.

The aim of this figure is to show the typical temporal extent of sea level extremes. Several things are worthy of note. Firstly, if one is looking for the absolute highest sea level one might expect even in an instant, then the difference between the 1 h and 2 h lines suggest that one might want to add a few decimetres to the 1 h value at the lowest probabilities. However, if one is not very worried about sea levels with very short durations it is perhaps good to note that the difference between the 24 h and the 1 h can exceeds 1 m at the lowest yearly probabilities. In any case, the figure contains information that might be relevant both for dimensioning purposes and perhaps also for planning protection. For example, a protection system that can keep water away, but not forever, like say sand bags may or may not be a useful safety precaution dependent on its expected length of protection.

Note also that short duration sea levels may not be able to flood structures even if they are situated at a level above the current mean sea level that is reached by a temporary extreme. This is because it takes time for water to spread on land, and the speed of spreading depends strongly on local topography. Detailed simulations with high resolution topography are therefore needed to estimate the durations and magnitudes of sea level extremes that a certain structure can withstand.

4.2 SSPs and their influence on mean and joint sea levels

Earlier work has shown that for Swedish conditions the risk of seeing high joint (i.e. mean + extreme) sea levels goes from being dominated by the sea level extreme component in short planning periods to being dominated by mean sea level change in long planning periods (Hieronymus, 2021; Hieronymus and Kalén, 2022; Hieronymus, 2023b). When the transition from extreme to mean sea level risk domination occurs differs depending on the mean sea level rise projection. Mean sea level rise risk becomes dominant earlier in high emission scenarios, but regardless of scenario the transition typically occurs within this century for Swedish locations and the commonly used CMIP6 scenarios.

A more in depth view of how the planning period probabilities for high joint sea levels are affected by different lengths of the planning period and SSP probabilities are shown in Figs. 6-9. The different lines represent simulations where a single SSP and corresponding mean sea level projection has been given a probability of occurrence equal to one. It is clear from the figures that in the shortest planning period 2020-2050, all SSPs give rise to very similar joint sea levels. That is, all these high joint sea levels are a consequence of high sea level extremes and modest mean sea level change.

As the planning periods grow longer it is, however, evident that the mean sea level projection becomes the deciding factor. In particular, the scenario SSP5-8.5 *low confidence* diverges from the others with its very extreme mean sea level rise, giving rise to extreme joint sea levels. Clearly, property values of astronomical proportions would be lost around the world in the very unlikely circumstance that sea level rise as extreme as that in SSP5-8.5 *low confidence* would come to pass. On the other end of the spectra, the difference between SSP1-1.9 and SSP1-2.6 is negligible in this time frame. The best estimate end of the century global mean surface temperature increase in these two scenarios relative to 1850-1900 is 1.4 $^{\circ}\mathrm{C}$ for SSP1-1.9 and 1.8 $^{\circ}\mathrm{C}$ for SSP1-2.6. Even the much warmer SSP2-4.5 with an end of the century warming of 2.7 $^{\circ}\mathrm{C}$ is relatively close to the lower emission scenarios in the terms of planning period probabilities all the way up to the year 2150. This suggests that the warming target of well under 2 $^{\circ}\mathrm{C}$ of the Paris agreement is quite far from the most relevant threshold values for this particular problem. In fact, the difference in joint sea level planning period probability for 2020-2150 is considerably larger between SSP2-4.5 (warming of 2.7 $^{\circ}\mathrm{C}$) and SSP3-7.0 (warming of 3.6 $^{\circ}\mathrm{C}$) than between SSP2-4.5 and SSP1-1.9 even though the difference in global mean surface temperature is larger between SSP2-4.5 and SSP1-1.9.

Thus, avoiding very high mean sea level rise at Ringhals in the long run is primarily a question of avoiding the two highest emission pathways. Getting down all the way to SSP1-1.9 is certainly safer than only getting to SSP2-4.5, but going over SSP2-4.5 implies much more sea level rise than is saved by going under the same emission pathway by a similar amount. In the shorter time frames ending in 2050 and 2070, sea level extremes dominate the contribution to the joint sea levels for most SSP-radiative forcing combos and the scenario difference is practically negligible except for SSP5-8.5 *low confidence* in the 2020-2070 planning period. Note also that the extreme sea levels that are part of the joint sea levels in these figures are those that use the GEV parameter uncertainty (i.e. they follow the red line in Fig. 3), while the authors best estimate for the extremes is the black line in Fig. 3, so for the shorter periods these should be considered conservative estimates. Examples, of shorter periods with extremes following the black line in Fig. 3 is given later on for a scenarios where all mean sea level projections have been given a non-zero probability of occurrence. A further note is that a more quantitative analysis of the contributions of extremes and mean sea level change to joint sea levels in Ringhals is given in Hieronymus (2023b) for the same scenario where all mean sea level projections have a non-zero probability of occurrence.

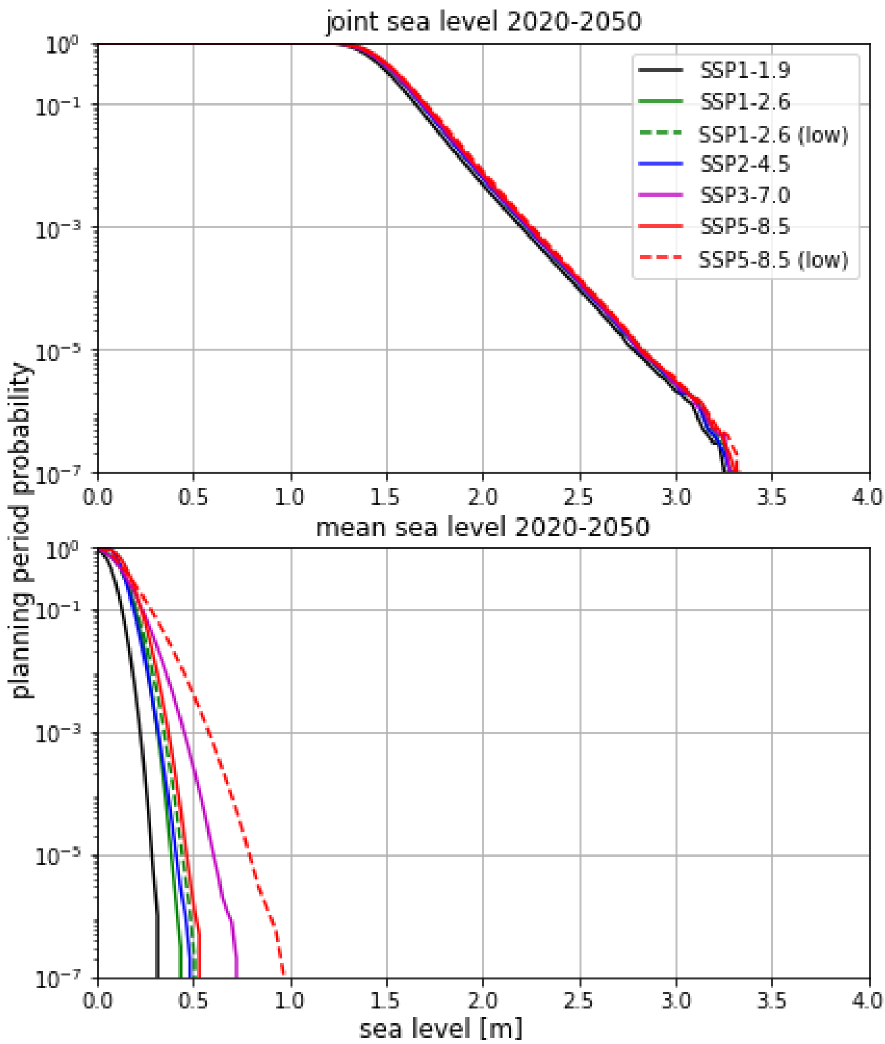

Figure 5: Joint and mean sea level planning period probabilities for the period 2020-2050. The different lines show different mean sea level projections. Sea level extremes are modelled using the GEV parameter uncertainty (i.e. they follow the red line in Fig. 3). (low) indicates that the *low confidence* version of the scenario is used.

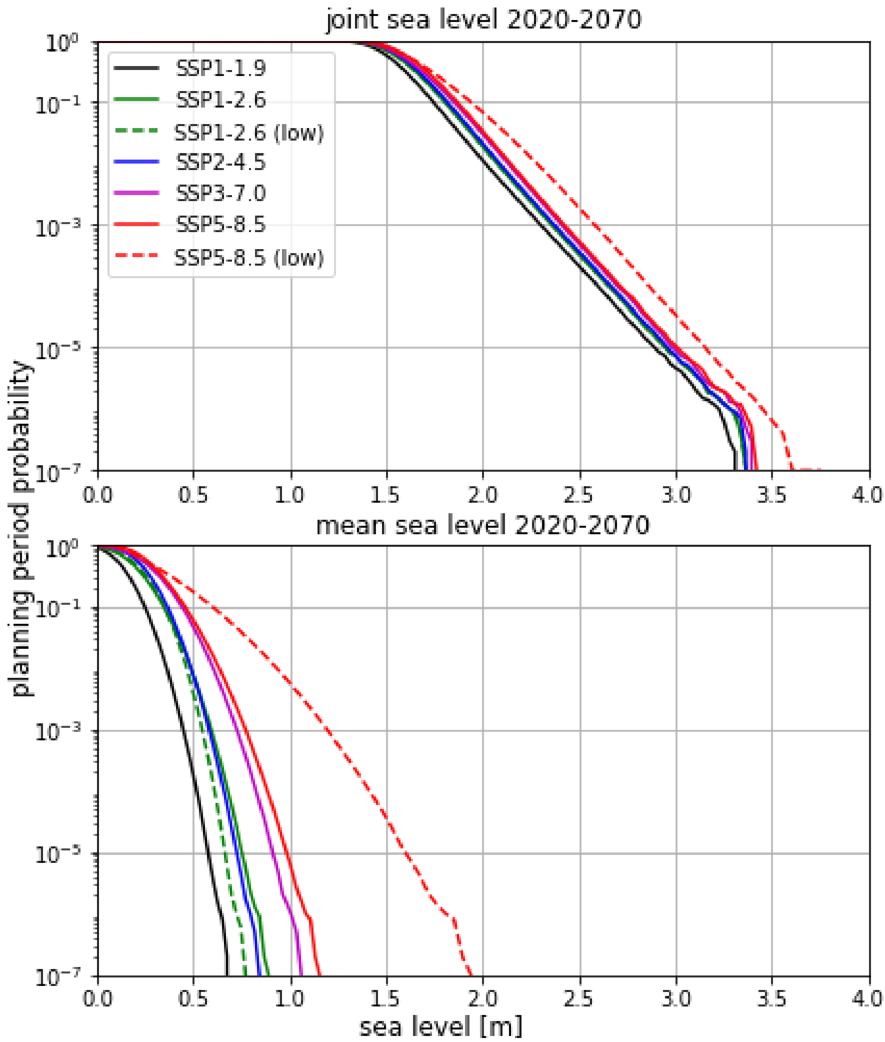

Figure 6: Same as Fig. 5, but for the 2020-2070 planning period.

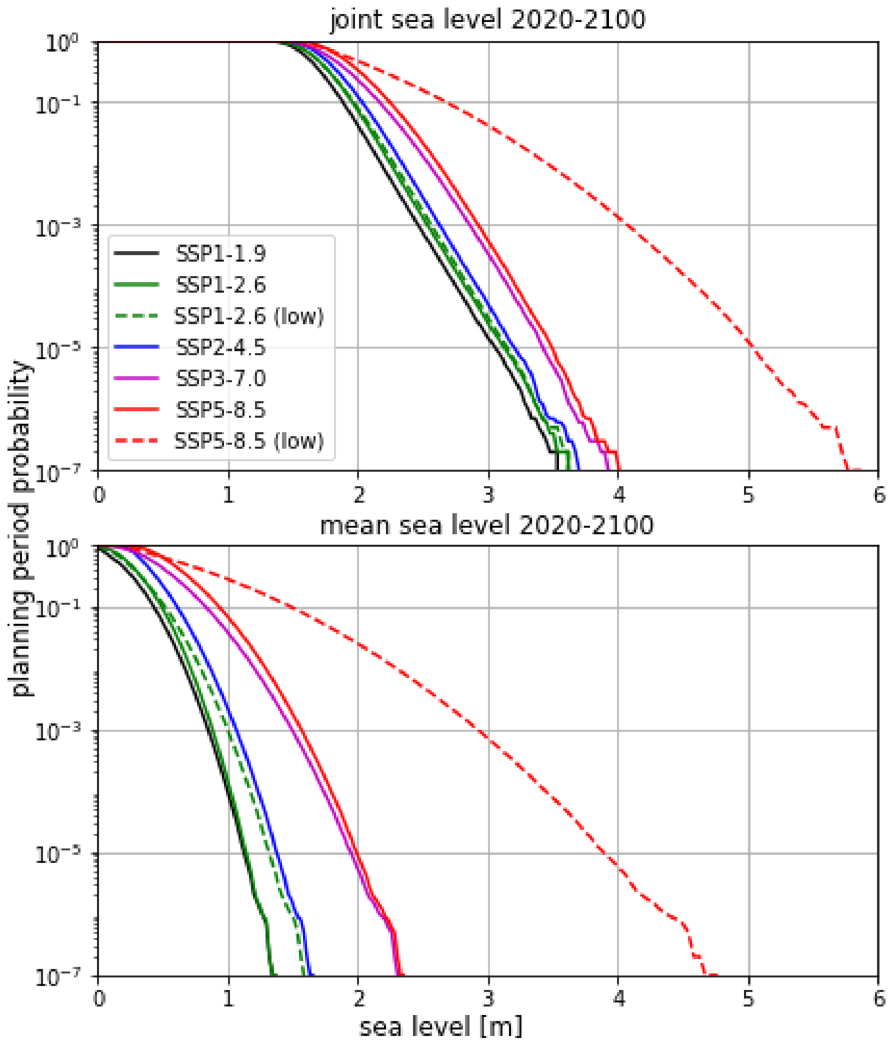

Figure 7: Same as Fig. 5, but for the 2020-2100 planning period.

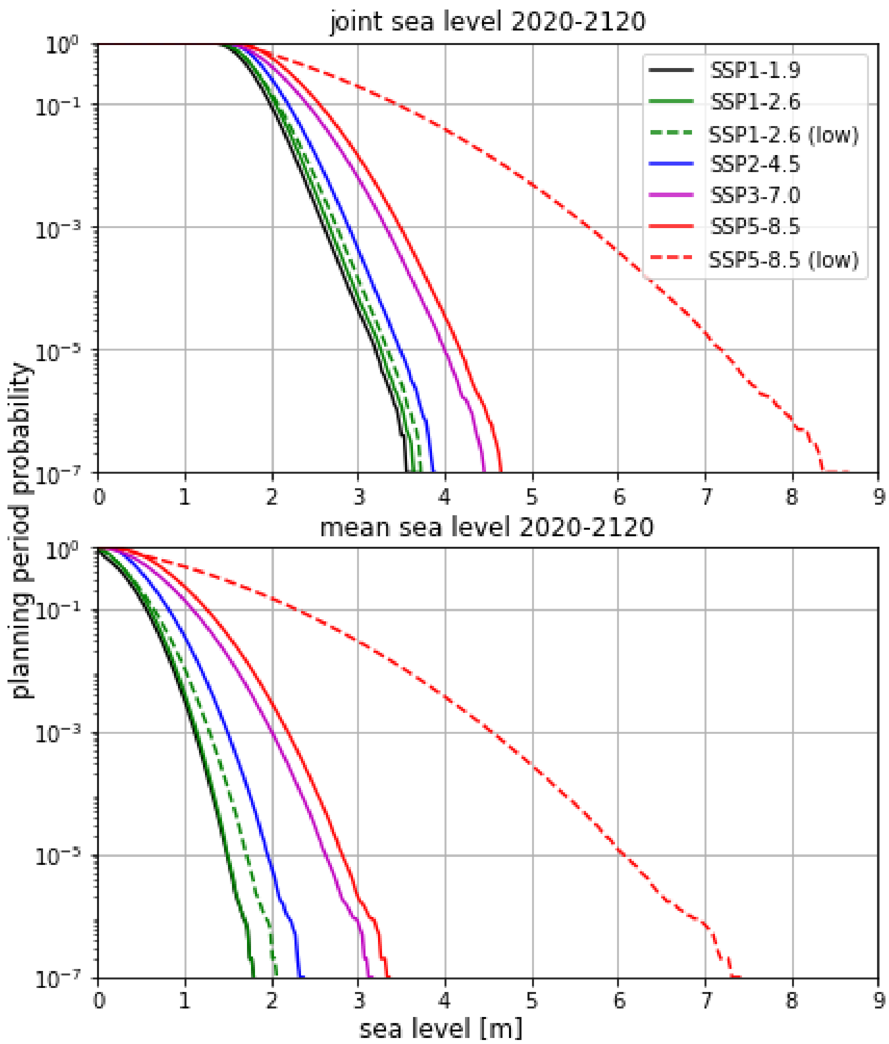

Figure 8: Same as Fig. 5, but for the 2020-2120 planning period.

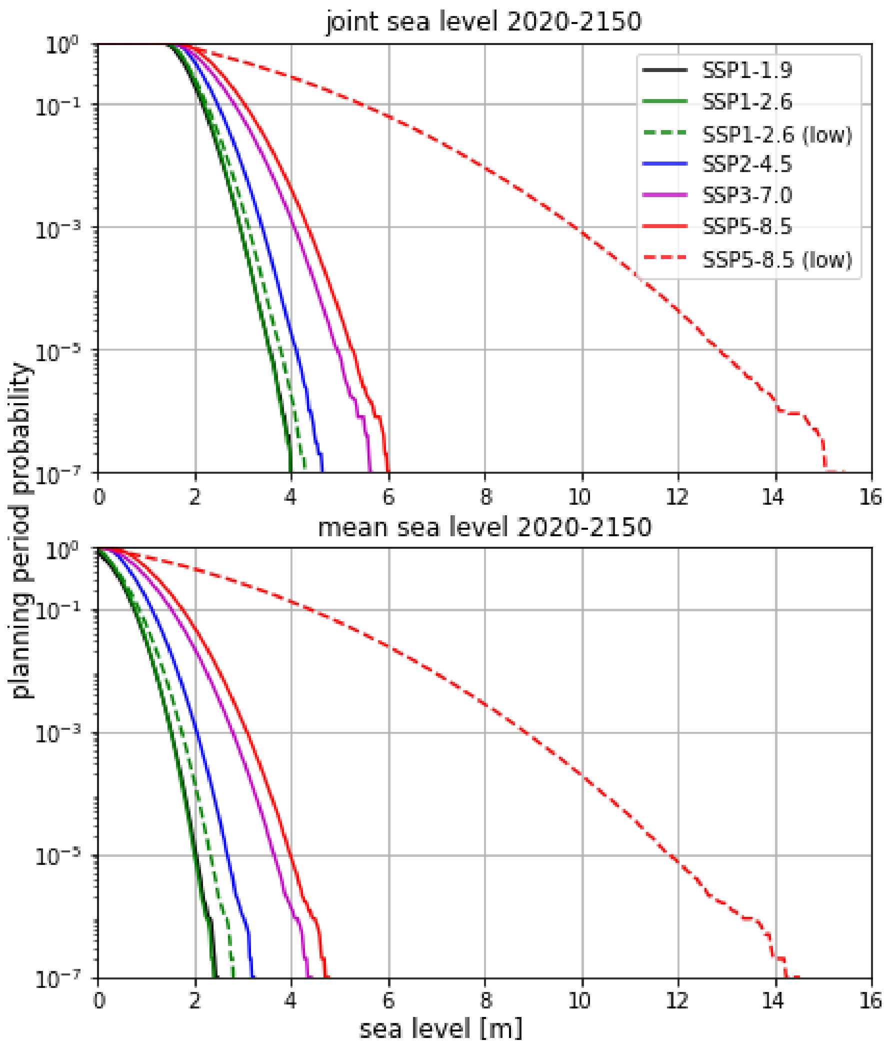

Figure 9: Same as Fig. 5, but for the 2020-2150 planning period.

4.3 A scenario where all mean sea level projections are given non-zero probabilities

In the former subsection we looked at the effect different mean sea level projections have on the risk of flooding. In reality we do not know neither our future emissions, nor their effects on global mean sea level change with even a semblance of certainty. It is therefore instructive to ascribe non-zero probabilities to multiple emission scenarios to model a more probable range of future sea levels than can be modelled using only one sea level projection. Here we have settled for scenario probabilities according to Tab. 2. A uniformly distributed random number between zero and one is drawn for each planing period, and a projection is chosen based on where the number fits in the probability range given in the table. Note that we do not claim that these probabilities are in any way best estimates of our uncertain future emissions. The numbers are inspired to a degree by the results of Huard et al. (2022). In particular, SSP2-4.5 is given the highest probability, and the very high and very low emission scenarios are given lower probabilities. However, we note that in the longer planning periods the probabilities of having very high emissions is much higher in the mixed scenario used here than in most projections by Huard et al. (2022). I therefore view our mixed scenario as somewhat overly positive in the short term and overly negative in the long run. More than anything I urge planners to make their own judgements of these probabilities, and to revisit them at regular intervals as the probabilities will undoubtedly change as our society evolves, and as our transition away from fossil fuels continue.

Table 2: Probabilities given to the different mean sea level projections and the probability range in which the different projection are applied. The same probabilities were used by Hieronymus (2023b).

mean sea level distribution	probability	probability range
SSP1-1.9	0.05	[0, 0.05]
SSP1-2.6	0.155	(0.05, 0.2050]
SSP1-2.6 (low confidence)	0.01	(0.2050, 0.2150]
SSP2-4.5	0.5	(0.2150, 0.7150]
SSP3-7.0	0.22	(0.7150, 0.9350]
SSP5-8.5	0.064	(0.9350, 0.999]
SSP5-8.5 (low confidence)	0.001	(0.999, 1]

Fig. 10 shows the planning period probabilities for joint, mean and extreme sea levels under the probabilities given in Tab. 2. The results are similar to the earlier ones in that extremes dominate joint sea levels up to about 2070. Another similarity is that the planning period probabilities up until about 2070 are similar to those for shorter planning periods. A noteworthy observation is how influential the probability of occurrence given to the SSP5-8.5 *low confidence* projection is on the planning period probabilities in longer planning periods. Here it was given a probability of occurrence of 1/1000 and it is plain to see that in the longer planning periods it dominates the joint sea levels for probabilities smaller than about 10^{-3}.

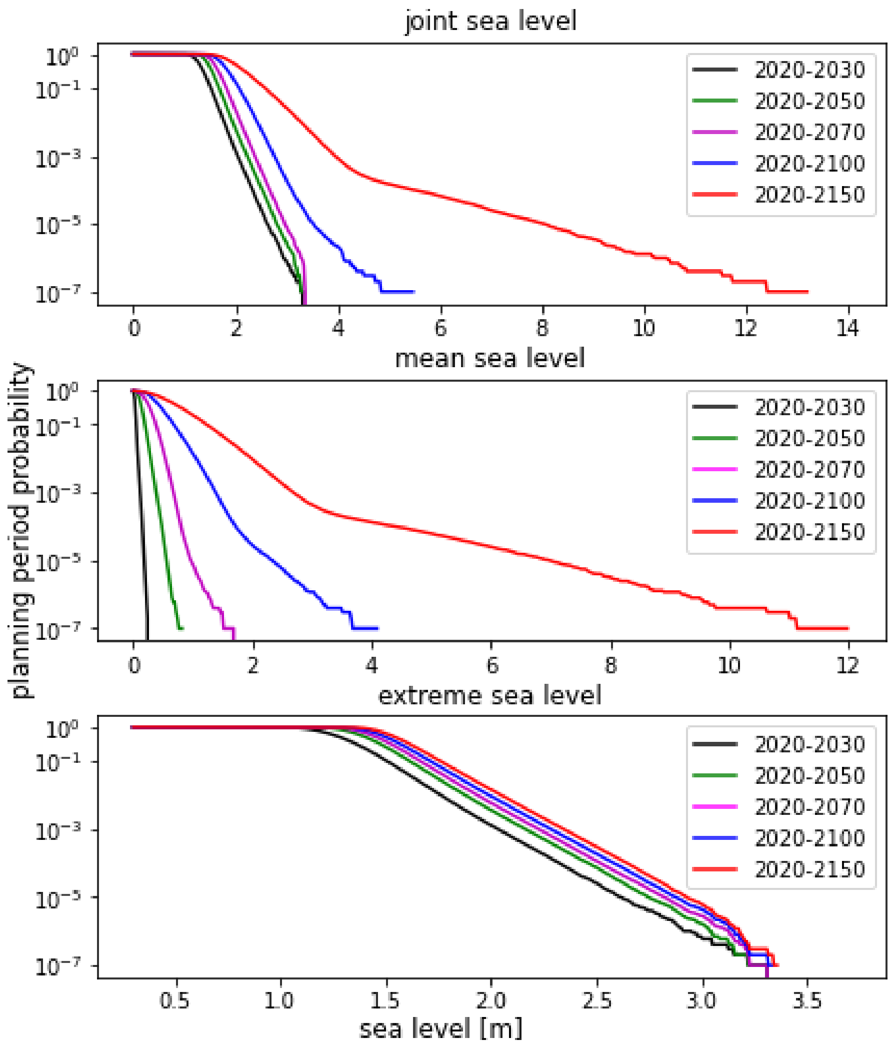

Figure 10: Joint, mean and extreme sea level planning period probabilities for a number of lengths of the planning period. The mean sea level projections have been given probabilities according to Tab. 2

Getting rid of the *low confidence* projections changes the picture significantly for longer planning periods, as is evident from Fig. 11. There we can see that when these scenarios are given zero probability of occurrence the very low probabilities are more of a natural continuation of the higher ones (i.e. there is no regime shift). In this case both *low confidence* projections were excluded, but the difference is pretty much entirely down to not having SSP5-8.5 *low confidence*, as SSP1-2.6 *low confidence* is much less of an outlier, see Fig. 9.

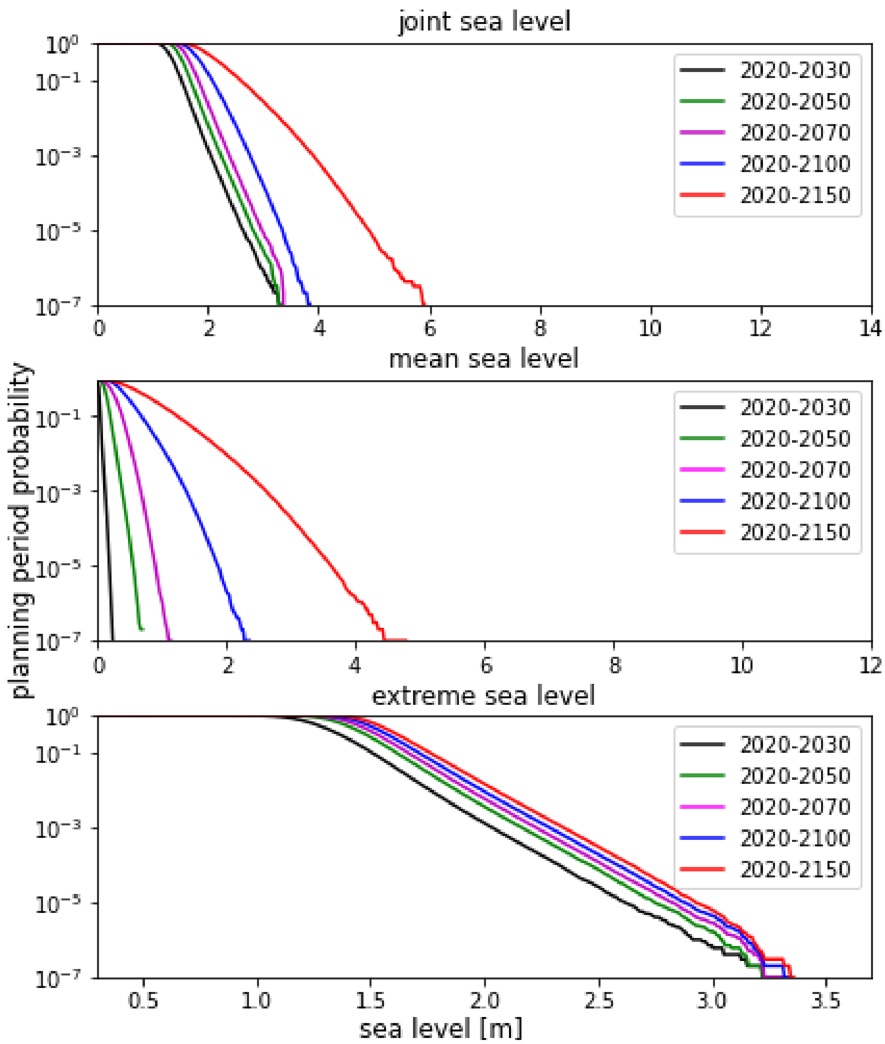

Figure 11: Same as Fig. 10, but with zero probability given to the *low confidence* projections

Figures 10 and 11 both use the red line in Fig. 3 to model their sea level extremes, while the author of this report believe the black line to be the best available model for the sea level extremes at the site. A version of Fig. 10 where the extremes are instead modelled using the black line in Fig. 3 is therefore given in Fig. 12. Here we find important differences particularly in the shorter planning periods as would be expected given the dominance of sea level extremes in the joint sea level probabilities in these periods. Conversely, in a century long perspective we find that the nature of the distribution controlling the yearly sea level maxima is not particularly important as the joint sea levels are determined much more by mean sea level change.

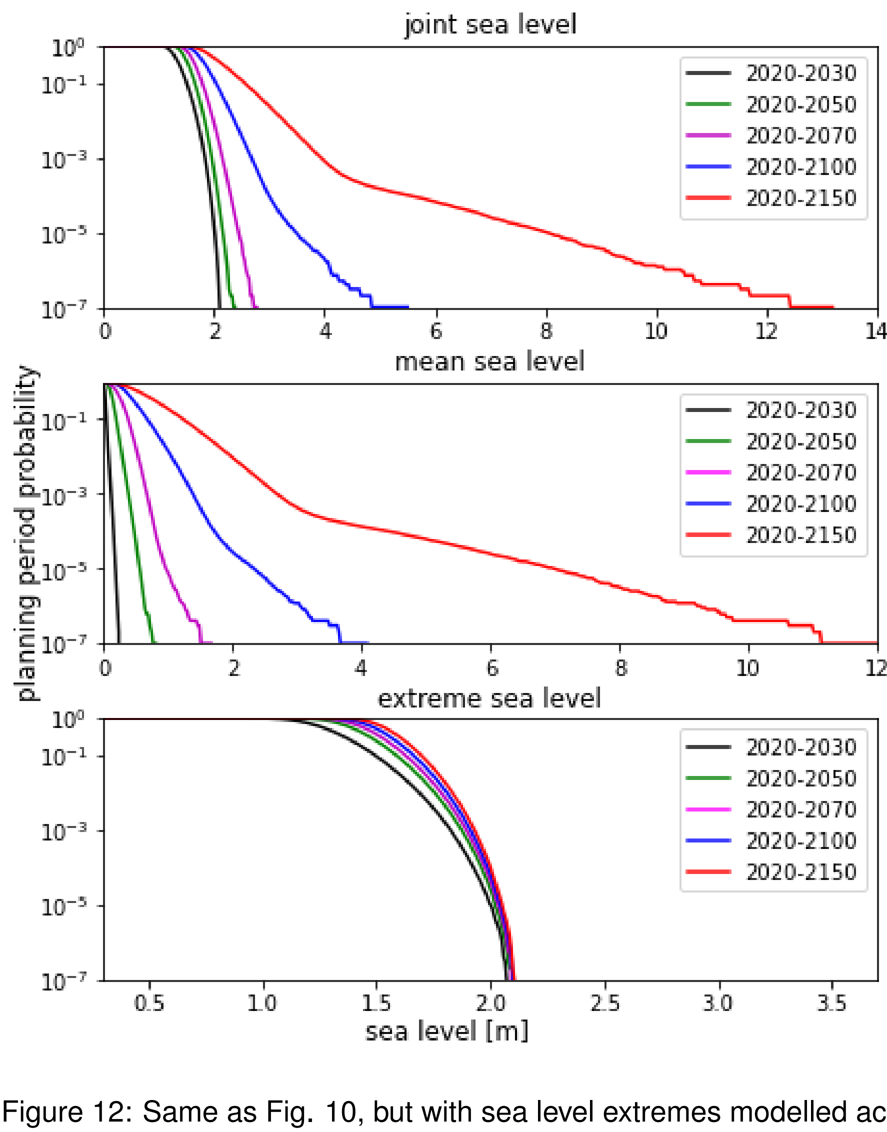

Figure 12: Same as Fig. 10, but with sea level extremes modelled according to the black line in Fig. 3

One last figure detailing the same mean sea level projection probabilities, but for different high water durations is shown in Fig. 13. Here focus is put on shorter planning periods as the magnitude of the extremes is much less important in longer periods. A conclusion that can be drawn is that regardless of which duration one chooses to plan for, it makes little difference if ones planning period ends in 2040 or 2060 as the probabilities are similar. The dominance of the contribution to the joint sea levels from the extreme component over the mean component in short planning periods, is thus robust to a significant range of high water durations.

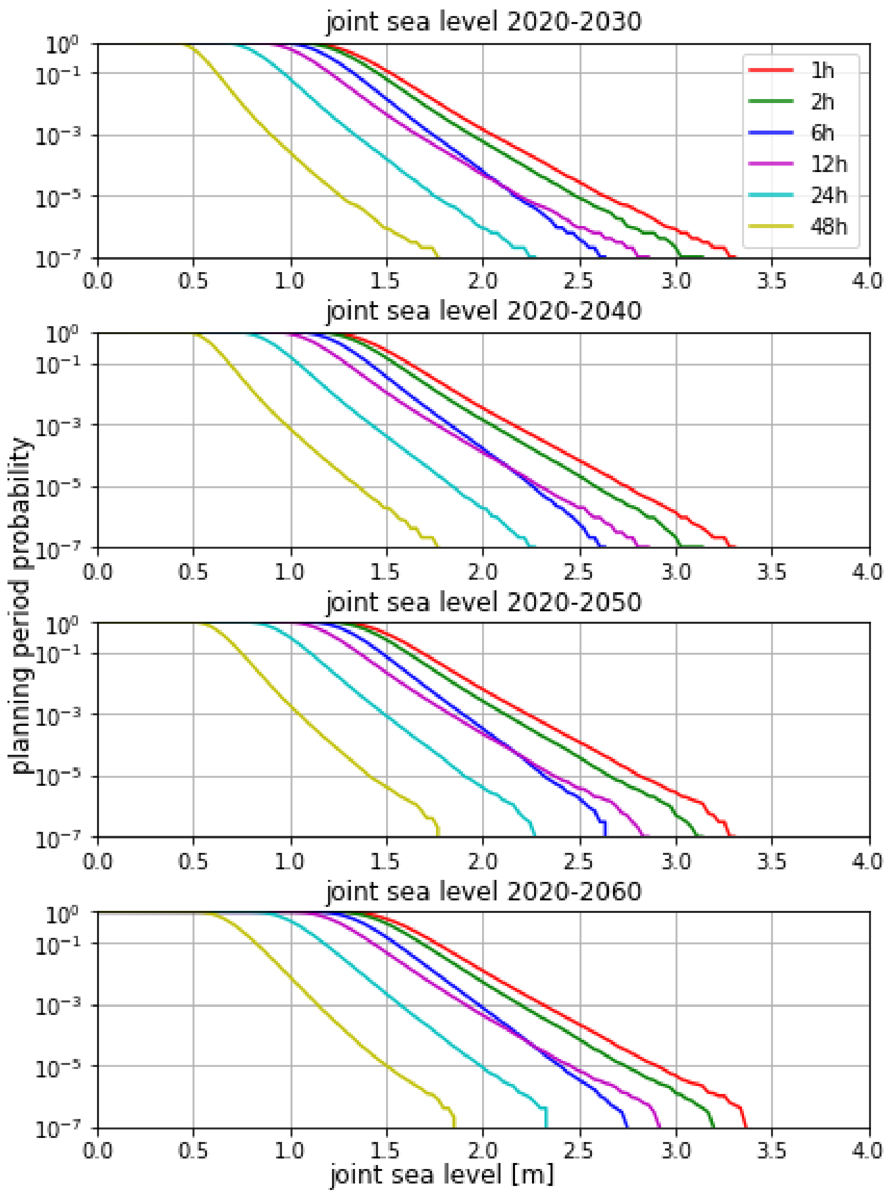

Figure 13: Joint sea levels for different high water durations and lengths of the planning period. Mean sea level projection probabilities are according to Tab. 2. Sea level extremes modelled according to the red line in Fig. 3 for the high water durations shown in Fig. 4

5 Discussion

The author of this report has no knowledge about the height above the current mean sea level where the nuclear station is situated, nor about its ability to handle flooding. It is therefore impossible to give meaningful advice about possible actions that could be taken to mitigate the risk of flooding. The objective of the report is therefore restricted to give a characterisation of the physical risk of coastal flooding as a function of height about the current mean sea level, both currently and long into the future.

Overall, the characteristics of the flood risk at the site are similar to other Swedish locations. We find flood risk to be dominated by the risk of seeing very high extremes in the short term (several decades) and by mean sea level rise in the longer perspective (later part of the century and longer). Similar findings have been reported for other Swedish locations (Hieronymus and Kalén, 2022) and for Ringhals specifically by Hieronymus (2023b). The exact timing of when mean sea level rise becomes the primary driver of flood risk depends on the assumed probabilities given to each SSP and mean sea level projection.

It is important to note, that even though both mean sea level change and sea level extremes contribute to joint sea levels, they are from a planning perspective two very different beasts. Sea level extremes are typically picked up, or predicted, by weather forecasting systems, perhaps a few days before they occur. Mean sea level rise meanwhile, will typically be apparent decades ahead of its occurrence. This is evidenced by the small separation between mean sea level projections from 2020 to 2040 in Fig. 2 c). An obvious consequence of the different time scales is that the set of actions that can be implemented to mitigate flooding caused by these two hazards is very different.

Another important point to bring out regarding the risk being dominated by one or the other of these two hazards, is that the short term dominance of sea level extremes over mean sea level rise will very likely be a consistent feature even if the starting time is moved forward in time. That is, a hypothetical investigation of the same kind as this one, but stating in 2120 and ending in 2250 is also likely to find a short term dominance of extreme sea level risk, as their current mean sea level will be known and their mean sea level projections are also likely to be rather scenario independent for some decades and their yearly sea level rise will also be much smaller than the amplitude of typical yearly sea level maxima. In other words, it is the much more rapid growth in time of mean sea level than extreme sea level uncertainty that leads to the dominance of the former, and not specific changes in mean sea level projections for certain time periods.

This also means, that if a seawall is built in the future to compensate for the mean sea level rise the planning period probabilities are essentially reduced back to those today for short planning periods. In fact, Hieronymus (2021) found that conditioning adaptation on mean sea level rise was a very good risk reducing strategy for Stockholm. Adaptation in form of seawalls does not necessarily have to be done locally either. Groeskamp and Kjellsson (2020) suggested that a massive enclosure dam in the North Sea stretching from France to England and from Scotland to Norway could be built to protect the area from sea level rise. Such a dam would in time transform the whole Baltic North Sea area into a fresh water lake. A much more cost efficient and easily constructed solution would be a sea wall between Sweden and Denmark. Such ideas may seem unrealistic in our world, but in the context of a future like that portrayed in the SSP5-8.5 *low confidence* projection, massive scale geo-engineering seem much more believable.

Uncertainties are still very large in long term mean sea level projections, especially for high emission scenarios as is evidenced by the presence of two projections for SSP5-8.5. Efforts are being done to better constrain sea level rise also under very high emissions. van de Wal et al. (2022) is a notable community effort that aim to give physically plausible high-end projections for two different warming levels. The high-end projection for 2100 by van de Wal et al. (2022), gives 1.6 m of globally average sea level rise for a global warming of 5 $^{\circ}\mathrm{C}$ (best estimate for SSP5-8.5 is 4.4 $^{\circ}\mathrm{C}$). Although extremely high, this magnitude of sea level rise occurs already under the main projection for SSP5-8.5 at high percentiles. One could thus argue that the high-end, or at least the physically plausible high-end is already included in the main SSP5-8.5 projection. That is, even without the separate *low confidence* projections. From a more human perspective one might also question the likelihood that something as bad as the SSP5-8.5 *low confidence* projection could be allowed occur. The only SSP leading to such high emissions describes a world with very strong fossil fuel based economic growth. In essence, a very rich world with considerable resources. At least to the author it seems much more likely that the citizens of this world would be willing to reach its extremely high emissions if their consequences were modest, than if multimeter sea level rise, permanent land loss and flooding occurred on a massive scale. Therefore, it seems reasonable, and not just on physical grounds, to put a much lower probability of occurrence on the SSP5-8.5 *low confidence* projection than on the standard SSP5-8.5 projection. In any case, it is extremely difficult to pin down a sensible probability of occurrence for the SSP5-8.5 *low confidence* projection, both from a physical and more human perspective. The authors best guess is that this projection should have significantly lower probability of occurrence than 1/1000, which was used in Fig. 10. I therefore believe that Fig. 11 shows a more plausible future than Fig. 10.

Uncertainties in sea level extremes are also very large. However, Sweden probably has more long high resolution observational data series than any other country in the world, meaning that in an international context we have an abundance of evidence to base our assessments on. Even so, the about 10^2 years of data are clearly, as alluded to in the title of the report, insufficient to infer 10^{-6} yearly probabilities from. Meaning that, estimates of very low probability extremes are very uncertain. Here, two paths have been taken to improve the representation of extremes. The first takes into account parameter uncertainty of the underlying GEV distribution, giving rise to much larger sea levels for low probabilities, see Fig. 3. The second path is to extend the yearly maxima dataset using 2604 year of data from a numerical ocean model bias-corrected using a machine learning approach (Hieronymus and Hieronymus, 2023). Which of these representations that is the most accurate is hard to judge (a subjective call). The author sees the tail behaviour of the distribution fitted to the much longer numerical ocean model, as well as the fact that similar tail behaviour is seen in all other Swedish tide-gauge fits (Hieronymus and Kalén, 2020) as strong evidence that the red line in Fig. 3 gives too high extremes. Meanwhile the observations suggest that the magenta lines gives to low extremes. The author therefore believes that the most accurate curve in Fig. 3 is the black one, and thus that Fig 12 gives the best representation of short term planning period probabilities.

Some unaccounted for small scale processes may also contribute to joint sea levels. Particularly, surface waves and some bay effects can raise the sea level appreciably albeit momentarily. If these processes are very short lived like, for example, wave swash they are unlikely to affect the water levels inside the well where the sea level observations are made (the well works like a filter) and may thus be unaccounted for in the distributions used here to model extremes. Longer lived surface wave processes like wave set-up will likely be able to affect the water level in the well and is thus likely accounted for. However, for very small scale processes the placement of the well can also be important. For example, the sea level maxima deep inside a bay is likely to be somewhat higher than outside of the bay, as water can pile up more efficiently in bays than outside. Local knowledge from people working at the site may be able inform planners on whether any small scale effects are likely to be problematic. The fact that the tide gauge at Ringhals and that in Varberg shows very similar sea levels, however, suggests that local effects are unlikely to be very sizeable at Ringhals. Another caveat is that the GEV distributions used to model the sea level extremes are taken here to be independent of climate change. In reality, it is likely that also extremes would be somewhat different in a world with a perturbed climate. However, (Hieronymus and Hieronymus, 2023) looked at trends in yearly sea level maxima in a large ensemble of climate projection and found no clear signal. Therefore, our current best guess is that extremes are unchanged, or at least that the changes are negligible. One last caveat worth mentioning is that the one hour sampling frequency will undoubtedly miss the very highest sea level peaks, and thus that the extreme sea level at the site should be expected to, albeit only briefly, surpass those estimated here.

Lastly in this discussion section and also earlier, I have shared a number of personal judgements, for example about the likelihood of different projection. I do so because I believe planners could benefit from knowing an expert's view on such matters. All flood risk projections are dependent to a considerable degree on subjective judgements. In this case not just the author's judgements, but also those of the IPCC authors, who constructed the mean sea level projections and in that process made a number of subjective judgements. I do not claim that my judgements are superior to those of others. Most often only time can tell which projections are most accurate. Therefore, I believe it is important that it is made clear that the probabilities estimated here are not objective, and that there is no way that objective probabilities of future flood risk can be produced. The process through which the probabilities are estimated is, however, tractable and all material needed to make different judgements and assumptions are distributed freely. I strongly believe that in the absence of objectivity tractability should be a primary aim for producers of flood risk assessments and similar data.

6 Conclusions

A set of flood risk projections for Ringhals has been computed for a wide range of emission scenario probabilities, planning period lengths and different distributions of extreme and mean sea levels. A general conclusion is that the risk of flooding goes from being dominated by the risk of high extremes to being dominated by the risk of high mean sea level rise as the planing periods grow longer. Exactly when this transmission occurs depends on the assumed emission scenario probabilities. However, generally speaking the risk is dominated by mean sea level rise if the planning period stretches toward the end of the current century or longer.

Regarding emission scenario probability and flood risk it was found that in the time frame until 2150, it is not keeping well below the 2 $^{\circ}\mathrm{C}$ (aim for below 1.5 $^{\circ}\mathrm{C}$) goal of the Paris agreement that makes the biggest difference. Instead it is keeping well away from the SSP3-7.0 and SSP5-8.5 scenarios that is most important in the respect. However, lower is of course better from a flood risk perspective.

A number of refinements were done to the representation of sea level extremes in the simulations resulting in three different yearly maxima distributions, shown in Fig. 3. For reasons elaborated on in the discussion and results sections the author has most confidence in the observationally based estimate (i.e. the black line in Fig. 3). Sea level extremes is the only quantity for which we show both yearly and planning period probabilities, given that it is the only stationary distribution. For both mean and joint sea levels the distributions are very strongly time dependent, and the yearly probability of a sea level X could hence vary by many orders of magnitude between 2020 and 2150. A problem that becomes exacerbated if the sea level X corresponds to a very low probability event.

The discussion section highlighted that even though mean sea level rise and sea level extremes both contribute to joint sea level events, the range of actions one can implement to adapt to them is very different, given that the heads-up is much longer for mean sea level rise. It was also discussed how building a wall was essentially a way of nullifying mean sea level rise and transform back to extreme sea level dominated risk for some time.

It is also worth noting that the whole scheme of using the simulator to calculate flood risk is fundamentally different and in many ways superior to the more classical approach of simply picking a high percentile mean sea level rise from a high emission scenario for a given year and add a high return level to that. Most notably perhaps, because the classical version is not probabilistic. This is because the mean sea level used in those calculations is essentially given the probability of one. However, one perhaps just as important difference is the time dependence. Say you want your infrastructure to have a certain level of safety until 2060. Then because of the time dependence of the mean sea level projections one cannot infer that number from one or a few individual years within that planning period. The simulator based planing period probabilities presented here are thus a fundamental improvement on the more arbitrary levels in use today.

Lastly, the use of emission scenario probabilities generalizes the implementation of mean sea level change into flood risk projections. Of course, we should note carefully that the probabilities that should be given to different scenarios are extremely hard to pin down, although some guidance has been given by the IAM community (Capellán-Pérez et al., 2016; Huard et al., 2022). Here we have ran simulations both with each SSP given the probability of one, and also in a more realistic scenario where all SSPs are given non-zero probabilities. We find that, the probability given to the SSP5-8.5 *low confidence* projection essentially determines the joint sea levels for planning period probabilities smaller than its given probability of occurrence (in our scenario 10^{-3}). The author of this report believes this probability to be much smaller than 10^{-3} and favours therefore the scenario depicted in Fig. 11. However, that is just an opinion, other experts may have other opinions. The tractability of these projections back to different design choices such as emission scenario probabilities, and the free software and data that makes it possible to replicate and perform complementing experiments are therefore of paramount importance for well informed decision making.

7 Acknowledgements

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