# CONTRACTOR DOCUMENT FRONT SHEET

## UK PROTECT

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# Update to estimation of extreme high-water levels at SZC

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# Executive Summary

EDF Nuclear New Build (NNB) needs to consider the likely occurrence of extreme high-water levels at the Sizewell C (SZC) site to ensure that the nuclear power plant (NPP) is adequately protected against coastal flooding. This report provides an update to the previous 2020 study into extreme high-water levels at Sizewell [1]. We provide return level estimates for additionally requested return periods for the present-day climate and additional return periods and uncertainty percentiles based on future climate change projections. In addition, we provide a small update to the methodology that was used in [1] to adjust the return levels between the Lowestoft tide gauge and the Sizewell site. The sea level estimates include combinations from the astronomical tide cycle and storm surge, but not ocean waves.

Following the same methodology as [1], the return level estimates for the current climate are based on tide gauge data at Lowestoft between 1964 and 2019 and are derived using the skew surge joint probability method (SSJPM). The Lowestoft estimates are then adjusted to estimates for Sizewell by comparison with local hydrodynamic model outputs from the Environment Agency's (EA) Coastal Flooding Boundary model [2]. Table 5 details the sea level estimates for the present climate for the requested return periods and uncertainty percentiles in units of metres above Ordnance datum (mOD). The shaded cells are where the return period is too long compared to the data time range to provide reliable uncertainty estimates.

Climate change adjustment factors have been estimated using the latest UKCP18 data from the Met Office [3] and are based on the most severe emissions scenario, RCP8.5, giving the most conservative estimates available for sea level rise. In the UKCP18 projections, the grid point closest to Sizewell is at Lowestoft, so we use a site adjustment factor to convert to estimates for Sizewell. Table 6 details the adjustment factor that must be added to the present-day sea level return levels to incorporate future climate change projections. The asterisked values are not provided directly from UKCP18 and have instead been interpolated from the other uncertainty percentiles. Therefore, they have an additional element of uncertainty that can be bounded above and below by the higher and lower percentiles, respectively.

The adjustment in return levels between Lowestoft tide gauge, where the observations from the present-day climate are taken, and the nuclear power station site at Sizewell, has been updated in this report compared to [1] to make the site comparison more in line with local climate projections from the EA Coastal Flooding Boundary model [2]. The updated site adjustment factor gives a larger update to the return levels for shorter return periods. For example, the 10-year return levels are 31 cm higher. Return levels for longer return periods, are not changed as much by the update of the site adjustment factor.

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# 1 Introduction

In 2020, EDF R&D UK Centre delivered a report that provided the sea level projections for Sizewell, 2020-NNB-D40 “Estimation of extreme high-water levels at SZC” [1]. To match Office for Nuclear Regulation (ONR) requirements, the present report provides an update to this previous report to include extreme high still water at Sizewell at additional return periods, years, and uncertainty percentiles.

EDF Nuclear New Build (NNB) needs to consider the likely occurrence of extreme high-water levels at the Sizewell C (SZC) site to ensure that the nuclear power plant (NPP) is adequately protected against coastal flooding. This deliverable will primarily assist NNB on providing the most accurate and defensible design basis for extreme high-water levels, as the regulatory framework requires a flood defence to be built to withstand an event that occurs with an annual exceedance probability (AEP) of $10^{-4}$ (i.e. the 10,000-year return level). This includes an assessment using the latest climate model data released in through the UK Climate Projections project released by the Met Office (UKCP18), to consider the potential impact that climate change may have on extreme high-water levels at SZC.

The initial 2020 report for Sizewell sea level rise investigated the differences between the different sea level rise values provided in these various reports and gave an expert judgement on the most statistically appropriate methodology to be used for determining the extreme still high-water level [1]. In this report, we will use, where appropriate, the same methodology as [1], and will explicitly state and defend where methodological changes are made. For completeness, in this report we include a description of all the definitions, data, and methodology used for the analysis. Waves are not considered in the analysis in line with standard practice for estimating sea level rise and previous EDF R&D reports on the subject.

In the rest of Section 1 we outline some important definitions used within the report and briefly summarise the physical science behind sea level rises due to climate change.

## 1.1 Important definitions

Extreme sea levels around the UK are experienced as a combination of tidal high water with a further contribution from storm surges. The surge is defined as the instantaneous difference between the recorded observed sea level and the predicted (astronomical) level (an example at Cromer is provided in Figure 1). High surges arise as a result of low atmospheric pressure and increasing strength of surface winds, which can lead to an increase in sea levels.

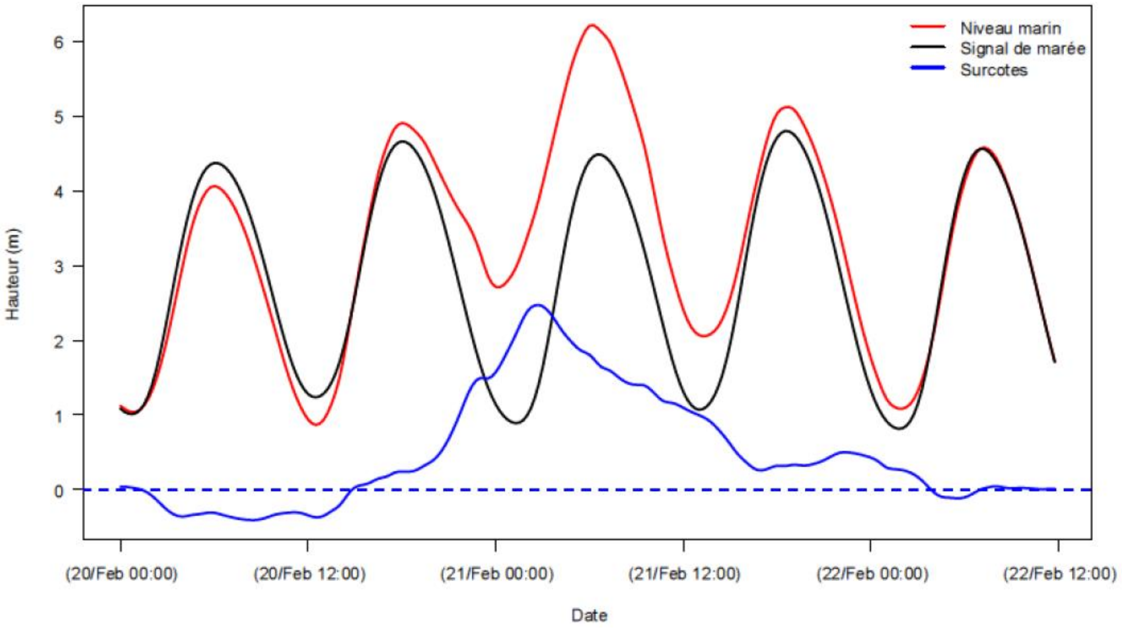


Figure 1: Decomposition of the sea level at Cromer (England) around 21/02/1993 into observed sea level (red), tide signal (black) and surge (blue). Figure taken directly from [4].

Skew surge, the difference between the maximum water level and predicted astronomical high tide, is a more reliable indicator of meteorological impacts on sea level than the non-tidal residual, which may contain errors due to timing or harmonic prediction. Figure 2 provides a schematic of how the skew surge is extracted from the sea level and tidal time-series. In practice, to extract the skew surge we pick out the peak tide and look at the sea level values within a four-hour window of this peak tide (Figure 3); the maximum sea level within this window is extracted and the difference between this maximum sea level and the peak tide provides the skew surge value.

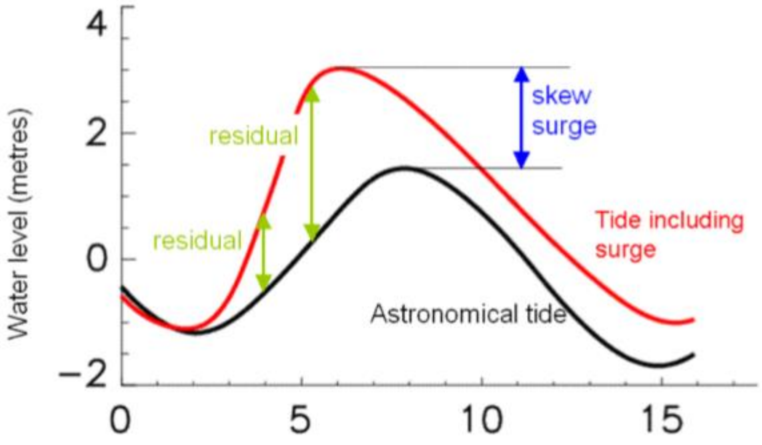


Figure 2: Schematic of how the skew surge is calculated from the sea level and tide values. Image taken directly from [5].

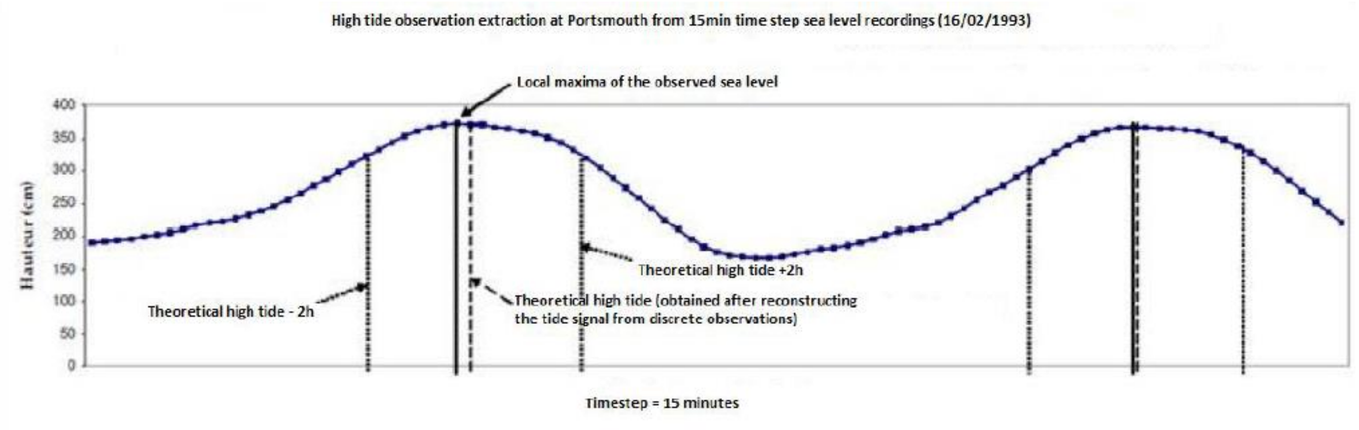


Figure 3: Practical approach for deriving the skew surge from the sea level and tide values. Image taken directly from [4].

## 1.2 Physical drivers of sea level rise due to climate change

It is important to assess the changing risks posed by climate change, and in particular the impacts of anticipated future sea level rise. Changes in global and regional sea level arise from a wide variety of geophysical processes that operate on different time and space scales; for more information on the components of sea level refer to [6] (Figure 4 provides a readable schematic of all the processes affecting local and global climate change).

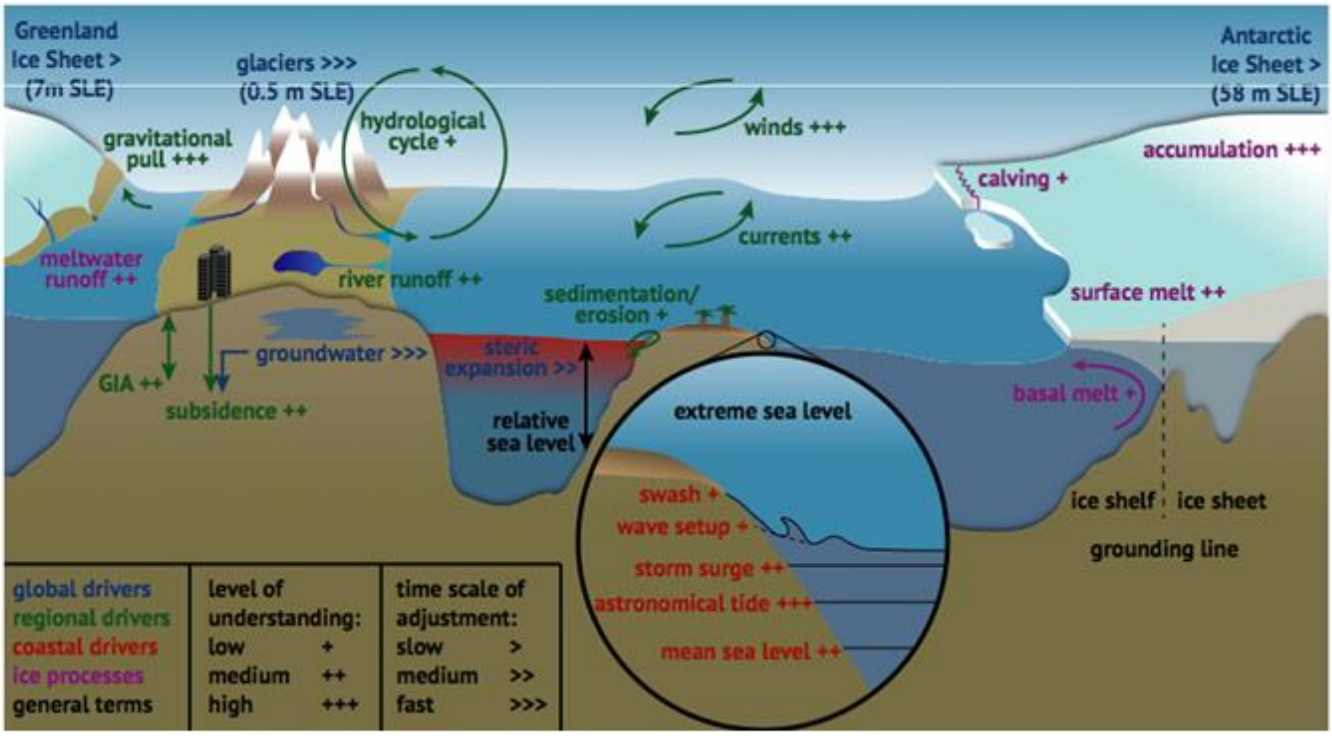


Figure 4: Schematic of climate and non-climate driven processes that can influence global, regional, relative and extreme sea level events along coasts. SLE stands for Sea Level Equivalent and reflect the increase in Global Mean Sea Level (GMSL) if the mentioned ice mass melted completely [7].

Global mean sea level (GMSL) rise occurs from thermal expansion of seawater and the addition of water to the ocean from the loss of land-based ice and water. Changes in land-based ice and water storage result in spatial patterns of regional sea level change through the associated impact on Earth’s gravity field and other effects. Local changes in seawater density and ocean circulation also give rise to a spatial pattern of change, which varies markedly among climate models, and is therefore highly uncertain. In addition, the ongoing response of the Earth system to the last deglaciation brings about a spatial pattern of regional sea level change across the UK that is dominated by the effect of vertical land motion.

As we move to the local scale, it is important to consider the potential for changes in the drivers of sea level extremes. It is well known that many of the worst and earliest effects of sea level rise will be experienced during extreme high-water events, which are usually associated with high tides combined with storm surges and may involve overtopping due to extreme wave heights. While previous studies have emphasised the dominance of changes in time-mean sea level in driving changes in future coastal sea level extremes, it is important to also consider changes in the extremes themselves that may arise through, for example, changes in atmospheric storminess. It should also be noted that there is potential for interaction between the changes in local time-mean sea level and tide and surge characteristics, due to the influence of water depth on the tide and surge. For a more detailed discussion on the topic of sea level rise see [6].

# 2 Data

In this section, two different types of data are introduced which are used for the different parts of the analysis: (i) tide gauge data for the observational period (Section 2.1); (ii) climate model data for the future period to take into account climate change (Section 2.2).

## 2.1 Observational Data

At the Sizewell B site, there is a tide gauge that has intermittent data available from 1995 to 2019. However, there are several years with no data or very sparse data. Additionally, even for the years where data is available, the quality of the data is unknown. Therefore, for the extreme value analysis for the present climate in this report, we choose not to use this data and instead analyse data that we can have more confidence in, namely, the tide gauge at Lowestoft.

The main source of tide gauge data used for the determination and validation of extreme sea levels in the UK is provided from the UK National Tidal and Sea Level Facility, owned and operated by the Environment Agency, and obtained from the British Oceanographic Data Centre (BODC) which is part of the National Oceanography Centre (NOC).

Figure 5: Map of the different class A tide gauges (black triangles) in the vicinity of SZC for which sea level data are available. Cropped version of map from [5].

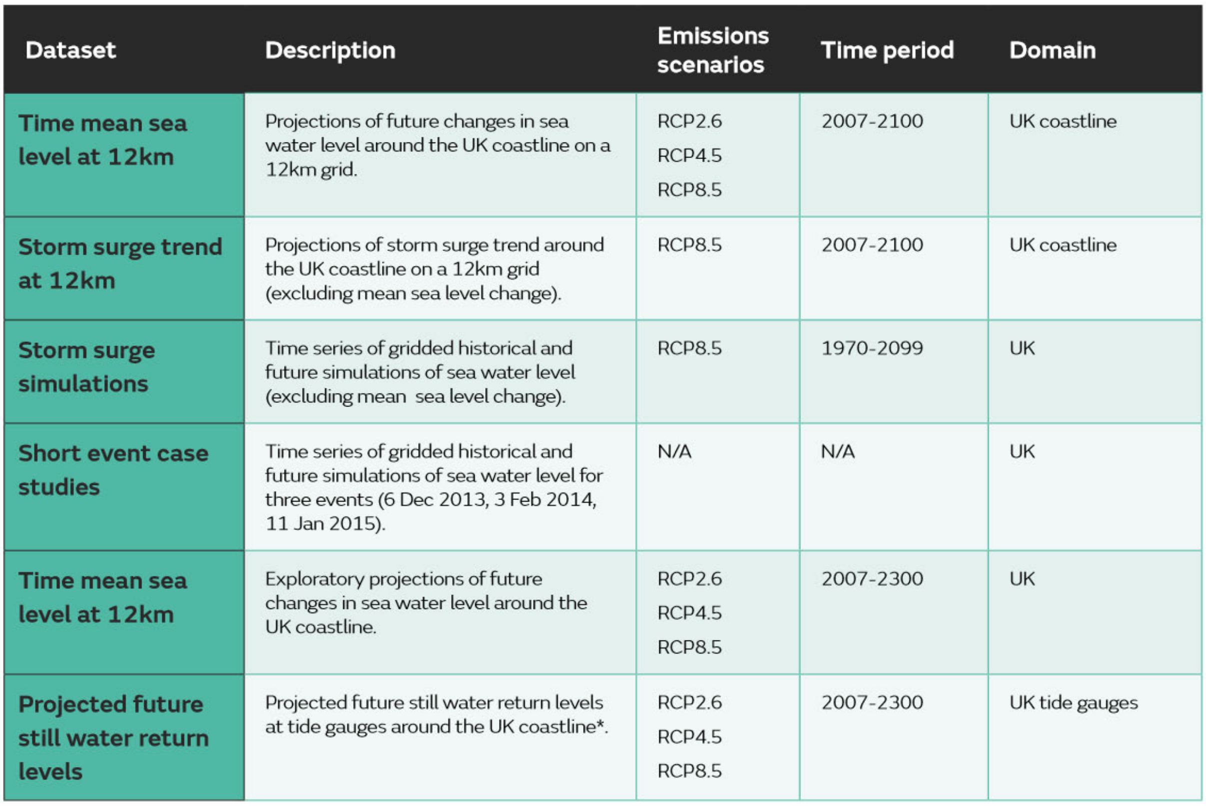
The closest available long-term data are those for Lowestoft, located 30 km to the north of Sizewell. This tide gauge forms part of the UK National Tide Gauge Network and is maintained to the highest standards. It would therefore be expected to provide a reliable long-term record of sea levels at these locations. Each of the previous studies [5], [8], [9] have used the tide gauge data from the Lowestoft tide gauge as the reference gauge for SZC and, for consistency, the same tide gauge record is used in this study. Data are available over the period from January 1964 to the present day (for this analysis December 2019). The tide gauge data have different temporal resolution throughout the time-series.

From 1964 to 1992 the observations are available every hour and from 1993 to the present day the data are available on a 15-minute resolution. The BODC data is quality checked by the Permanent Service for Mean Sea Level and the relevant adjustments made (see [10] for more information).

There is a small amount of non-stationarity in the time-series due to mean sea level rise that has already been observed over the observational period; within [2] this value is given as 2.27 mm/year. This is added/subtracted from the tide gauge data series around a control year of 2017 (i.e. 2.27 mm is added to all observations from the year 2016, 4.54 mm is added for 2015 and so on; in the same way 2.27 mm is subtracted for 2018 and so on).

## 2.2 Model Data

A climate change adjustment factor will be estimated using model data extracted from UKCP18. There are UKCP18 marine data available of the following types (up to 2100): (i) regional time-mean sea level; (ii) changes in surge extremes; (iii) potential changes in tide and surge characteristics; (iv) changes in local wave climate. In addition, UKCP18 presents exploratory projections of regional time-mean sea level change out to 2300. All projections are rooted in, or traceable to, CMIP5 climate model simulations under the RCP climate change scenarios. Figure 6 shows the data available in UKCP18 marine projections and their spatial and temporal resolution.



| Dataset | Description | Emissions scenarios | Time period | Domain |
|---|---|---|---|---|
| **Time mean sea level at 12km** | Projections of future changes in sea water level around the UK coastline on a 12km grid. | RCP2.6<br>RCP4.5<br>RCP8.5 | 2007-2100 | UK coastline |
| **Storm surge trend at 12km** | Projections of storm surge trend around the UK coastline on a 12km grid (excluding mean sea level change). | RCP8.5 | 2007-2100 | UK coastline |
| **Storm surge simulations** | Time series of gridded historical and future simulations of sea water level (excluding mean sea level change). | RCP8.5 | 1970-2099 | UK |
| **Short event case studies** | Time series of gridded historical and future simulations of sea water level for three events (6 Dec 2013, 3 Feb 2014, 11 Jan 2015). | N/A | N/A | UK |
| **Time mean sea level at 12km** | Exploratory projections of future changes in sea water level around the UK coastline. | RCP2.6<br>RCP4.5<br>RCP8.5 | 2007-2300 | UK |
| **Projected future still water return levels** | Projected future still water return levels at tide gauges around the UK coastline*. | RCP2.6<br>RCP4.5<br>RCP8.5 | 2007-2300 | UK tide gauges |

Figure 6: Summary of data available from UKCP18 marine projections. The annual time-mean sea level here is the average height of the sea over a year, with the shorter-term variations of tides and storms averaged out. *Based on the latest EA Coastal Flood Boundary Conditions. Table taken from [11].

The UKCP18 regional time-mean sea level projections are produced using the projections of global mean sea level presented in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). These global changes are regionalised for the UK by considering the spatial patterns associated with each of the components of global sea level and assessing the contribution to local sea level changes associated with ongoing glacial isostatic adjustment.

### 2.2.1 Construction of model data in UKCP18

In this section we present the materials and methods used to produce the regional time-mean sea level projections for UKCP18. The general approach is to take a subset of global climate models, downscale them to provide regional information and then use the regional surface wind speed and sea level pressure data to force a storm surge model. A schematic illustrating this experimental design is shown in Figure 7.

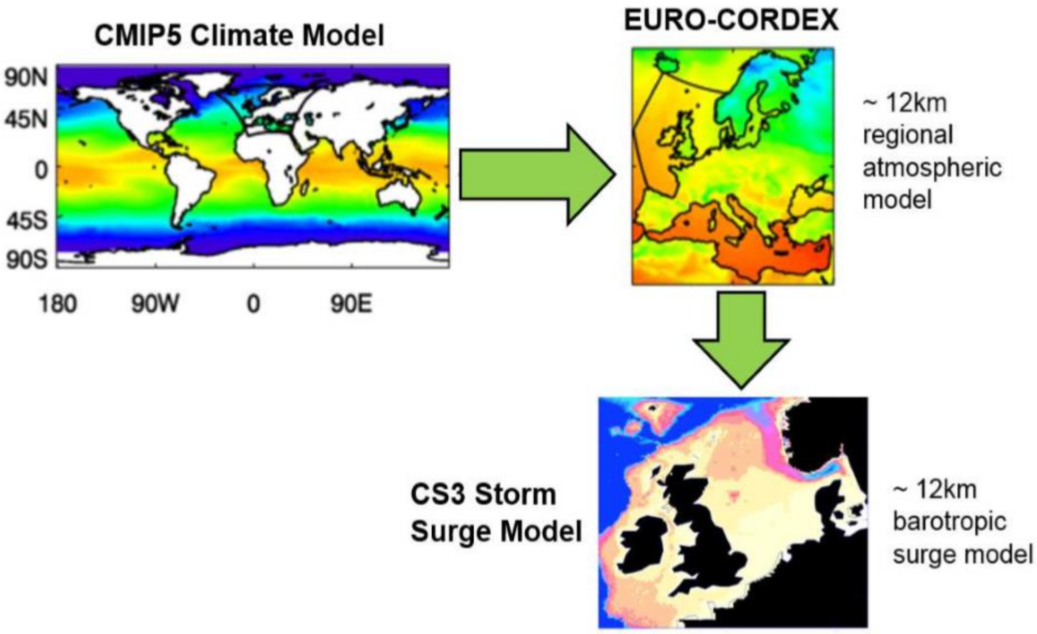


Figure 7: Schematic diagram showing the experimental design of the UKCP18 surge simulations [3].

#### 2.2.1.1 Climate models chosen

To produce projections of the likely component of change in sea level extremes due to 21st century atmospheric storminess change, five models contributing to the CMIP5 database were selected and downscaled using the Swedish Meteorological and Hydrological Institute Rossby Centre regional atmospheric model (RCA4) as part of the EURO-CORDEX initiative. The five climate models selected are: CNRM-CM5, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES and MPI-ESM-LR. UKCP18 refer to surge model projections based on these five models downscaled by RCA4 as CNRM-CM5-RCA4, EC-EARTH-RCA4, IPSL-CM5A-MR-RCA4, HadGEM2-ES-RCA4 and MPI-ESM-LR-RCA4 respectively.

The five global models were selected for downscaling by the EURO-CORDEX project from the CMIP5 models based on their ability to simulate a realistic climatology, particularly for the European region, but they do not necessarily exhibit a large 21st century change in the atmospheric drivers of extreme surge. UKCP18 did not have any say in which models were downscaled by the EURO-CORDEX project; the project simply chose the most appropriate available data.

Whilst there are good reasons for using regional model data for the 21st century projections, there are global model simulations which exhibit a larger century-scale change in the storm track around the UK than the five global models underlying the RCA4-downscaled simulations. In particular, the GFDL-ESM2M global simulation exhibits a large increase in storm track intensity in winter and a substantial northward shift in the maximum storm track intensity. Thus, to capture a wider spread of century-scale response, UKCP18 additionally analyses the response of the surge model when driven directly by data from the global GFDL-ESM2M 21st century RCP8.5 simulation, which is expected to see a greater change in storminess, so is used as a worst-case scenario. This differs from the RCA simulations which are regional models, like the ones used in the CMIP5 ensemble.

It should be noted that UKCP18 selected the representative concentration pathway RCP8.5 as this is expected to give the largest signal of change and is the primary scenario used in the atmospheric UKCP18 simulations. The results show there is little future trend evident in storm surges for this scenario. Since lower emission scenarios are expected to give a lower response, there is little reason to expect a significant forced change from lower emission scenarios if it is not found in RCP8.5. Thus, for storm surge UKCP18 does not run simulations using other emission scenarios.

#### 2.2.1.2 CS3 storm surge model

The simulated winds and surface pressure from the climate models described in Section 2.2.1.1 are used to drive the National Oceanography Centre’s ~12km resolution barotropic storm surge model (CS3). The model produces a numerical simulation of the North Sea tides and surges, for further detail see [12], [13].

### 2.2.2 Evaluation of model data in UKCP18

To make a comprehensive comparison of simulated extremes with observations for the historical period, the UKCP18 Marine Report compares return level curves of skew surge from Lowestoft tide gauge with the corresponding data from the nearest-grid point in the surge model. Figure 8 (taken from [3]) shows a comparison of model data for the historical simulations (1971-2005 inclusive) by each of the RCA4-downscaled models, model data for a simulation driven by the reanalysed data (ERA-interim, 1981-2009 inclusive) and the observation tide gauge data.

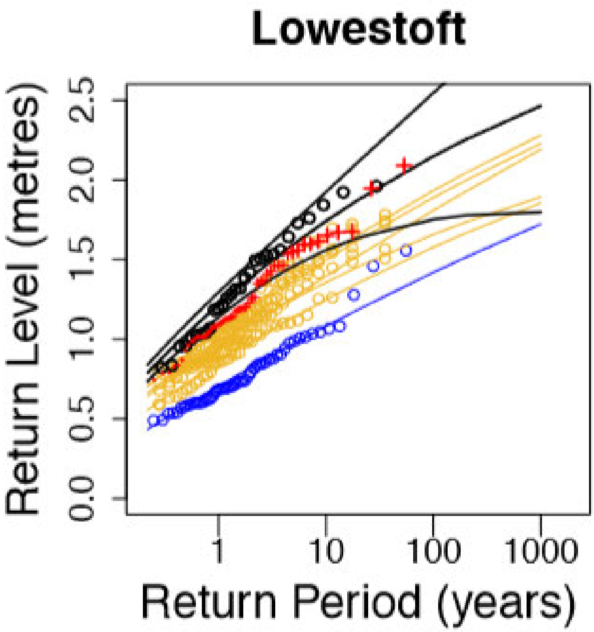


Figure 8: Skew surge return level plots with: model data for the historical simulations (1971-2005 inclusive) by each of the RCA4-downscaled models (yellow); model data for a simulation driven by the reanalysed data (ERA-interim, 1981-2009 inclusive) (black); observation tide gauge data (red) [3].

Figure 8 shows that the skew surge extremes from the RCA4-downscaled simulations do differ from the observed surges. This size of bias is not unusual in surge modelling and may be associated with the more complex coastline around the tide gauge, which will not be well-represented in the model. The bias is generally larger in the GFDL-ESM2M simulation (which does not include the regional downscaling step).

It should be noted that the 21st century surge and wave projections are based upon relatively small CMIP5 model ensembles. It is unlikely that these simulations span the full range of CMIP5 model responses under climate change. These projections should be viewed as indicative of the overall magnitude of changes one might see over the 21st century. For both these sets of simulations, one cannot be sure of the relative influence of the climate change signal versus natural variability.

The simulations of changes in tide and surge characteristics make the simple assumption of a fixed coastline under all levels of future sea level rise. However, several global tide model studies find that tidal changes are very sensitive to coastal management practices. Thus, the findings should be interpreted as illustrative of potential changes. Further work is needed under more realistic model configurations to make progress in this research avenue.

# 3 Statistical methodology

The regulatory framework which guides EDF standards, dictates that coastal defences need to be built to withstand an event with a $10^{-4}$ annual occurrence probability, i.e. an event that occurs on average once every 10,000 years. It is of primary importance that we can accurately and reliably estimate the occurrence and severity of such events, so we can adapt accordingly.

Modelling extreme sea level requires us to sum up the contributions of the astronomical tide and the meteorological surge. A common approach in the UK is the joint probability method (JPM). Alongside this, multiple companies (EDF R&D UK Centre, Environment Agency, HR Wallingford, Atkins, and Centre of Environment, Fisheries and Aquaculture Science (CEFAS) have previously undertaken extreme sea level studies with varying methods and inputs. In France, the French nuclear regulatory body (ASN) state that the simple sum of extreme surges and extreme tides should be used to characterise extreme sea levels.

Sea level can be decomposed into two different contributions named tide and surge (as discussed in Section 1.1). Tide is an astronomical contribution with a pre-defined cycle that is deterministic. Surge is a meteorological contribution that is a function of atmospheric pressure and the wind and is therefore stochastic. To model sea level, we need an approach that sums up the tide and surge contributions. A summary of different methods that can be used to estimate extreme high-water levels is provided in Section 3.2.

## 3.1 Primer on extreme value analysis (EVA)

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## 3.2 Methods for characterising extreme high-water level

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### 3.2.1 Joint probability method (JPM)

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### 3.2.2 Skew surge joint probability method (SSJPM)

[redacted]

### 3.2.3 Additive method

[redacted]

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### 3.2.4 Summary of method to be used within this study for the observational period

[redacted]

## 3.3 Climate change adjustment factors in UKCP18

To estimate the climate change adjustment factor for extreme high-water level we use the estimates already provided from the UKCP18 project for different return levels and percentiles that are available. This is to match the methodology used in the previous report on sea level at Sizewell [1]. The rest of this section outlines the methodology used to estimate the future return levels and thus the necessary climate change adjustment factors for SZC.

### 3.3.1 Statistical model for analysis of storm surge changes

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### 3.3.2 Projected future return levels

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# 4 Results

In this section, we present the results of statistical analysis on sea level data for both the present climate (Section 4.1) and the projected future climate (Section 4.3) for a variety of return periods, years, and uncertainty percentiles derived from model variation. In Section 4.2 we discuss how we convert between return levels at Lowestoft, where the observational data is measured, and Sizewell, the site of nuclear interest.

## 4.1 Present climate return levels

As discussed in Section 2.1, data are extracted from the Lowestoft tide gauge and adjusted to take into account the observed sea level rise trend over the observational period from 1964 to the present day (end of December 2019 as of this report). The skew surges are extracted from the sea level and tide values using the approach outlined in Section 1.1. Using the same methodology as the previous report on Sizewell sea level [1], a GPD is fitted to the skew surges using a threshold value of 0.5 m which corresponds to the 97th quantile estimated from the observational data at Lowestoft. The fitted model parameters can be used to estimate the return level for the skew surge at a variety of return levels, as shown in Table 1.

| Return period (years) | 50th percentile (mOD) | 84th percentile (mOD) | 95th percentile (mOD) |
|---|---|---|---|
| 10 | 1.64 | 1.71 | 1.76 |
| 100 | 2.19 | 2.35 | 2.46 |
| 200 | 2.36 | 2.56 | 2.70 |
| 500 | 2.59 | 2.85 | 3.03 |
| 1,000 | 2.77 | 3.08 | 3.29 |
| 10,000 | 3.40 | 3.91 | 4.24 |
| 100,000 | 4.06 | | |

Table 1: Estimates of extreme return levels for skew surge at Lowestoft tide gauge. The dark grey shaded cells are values in which we do not have sufficient confidence due to the extremely long return period.

Following the skew surge joint probability method, the skew surge distribution is mathematically convolved with the tide distribution to provide probability estimates of the sea level. The extreme sea level return levels at the Lowestoft tide gauge are provided in Table 2. The percentiles that have been requested by our clients for this report are not provided at the Sizewell site in the EA model in [2] so we use a site adjustment factor in the following section to calculate present climate return levels for the site of interest.

| Return period (years) | 50th percentile (mOD) | 84th percentile (mOD) | 95th percentile (mOD) |
|---|---|---|---|
| 10 | 2.55 | 2.61 | 2.66 |
| 100 | 3.09 | 3.23 | 3.32 |
| 200 | 3.27 | 3.44 | 3.55 |
| 500 | 3.50 | 3.72 | 3.88 |
| 1,000 | 3.67 | 3.94 | 4.13 |
| 10,000 | 4.30 | 4.76 | 5.07 |
| 100,000 | 4.96 | | |

Table 2: Return levels for still sea level rise above mOD at Lowestoft tide gauge using the SSJPM method with confidence intervals obtained via bootstrapping. The units for the return levels and upper percentiles are in units of metres above ordinance data. The dark grey shaded cells are uncertainty values for which we do not have sufficient confidence in due to the extremely long return period.

## 4.2 Conversion between Lowestoft and Sizewell

The results provided in Section 4.1 are for the Lowestoft tide gauge which is located approximately 30 km north of the Sizewell site. To convert from the Lowestoft sea level to that of Sizewell, we compare the return levels derived using Lowestoft tide gauge data in Table 2 with those derived by the EA in their Coastal Flood Boundary report at several points close to Sizewell [2]. The EA report uses a 12 km CS3X model that was forced by the European Centre for Medium-range Weather Forecasting (ECMWF) ERA40 meteorological re-analysis dataset (at 1° resolution) [2]. Return levels, with associated confidence intervals, derived using this model are given in Table 3. The location of the three points in the EA model that are closest to Sizewell are illustrated in Figure 11. The latitude and longitude coordinates of the Lowestoft model data point are (52.4729°N, 1.7499°E) and those of the Sizewell points 1, 2, and 3 are (52.22129°N, 1.654454°E), (52.20345°N, 1.652568°E), and (52.18550°N, 1.652234°E), respectively.

| Return period (years) | Return level for given location (95% CI) | | | |
|---|---|---|---|---|
| | **Lowestoft** | **Sizewell Point 1** | **Sizewell Point 2** | **Sizewell Point 3** |
| 10 | 2.56<br>(2.45, 2.77) | 2.51<br>(2.39, 2.72) | 2.51<br>(2.40, 2.72) | 2.51<br>(2.40, 2.72) |
| 100 | 3.10<br>(2.85, 3.59) | 2.99<br>(2.74, 3.48) | 2.98<br>(2.73, 3.47) | 2.98<br>(2.73, 3.47) |
| 200 | 3.28<br>(2.96, 3.89) | 3.12<br>(2.80, 3.73) | 3.12<br>(2.80, 3.73) | 3.11<br>(2.79, 3.72) |
| 500 | 3.51<br>(3.11, 4.29) | 3.31<br>(2.90, 4.09) | 3.30<br>(2.89, 4.08) | 3.29<br>(2.88, 4.07) |
| 1,000 | 3.69<br>(3.21, 4.63) | 3.44<br>(2.96, 4.38) | 3.43<br>(2.95, 4.37) | 3.42<br>(2.94, 4.36) |
| 10,000 | 4.32<br>(3.58, 5.97) | 3.90<br>(3.14, 5.54) | 3.87<br>(3.11, 5.51) | 3.85<br>(3.09, 5.49) |

Table 3: Best estimates (mOD) and 95% confidence intervals (in parentheses, representing the 2.5th and 97.5th quantiles) for various return periods at the model data point closest to Lowestoft and the three data points closest to the Sizewell site.

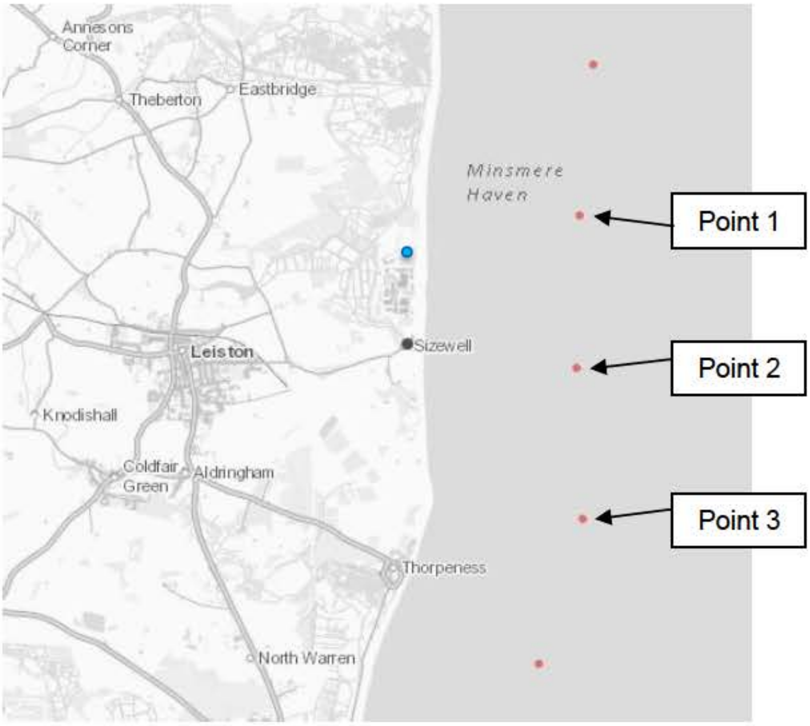

Figure 11: Map of points where downscaled data are available (red dots) in the vicinity of Sizewell C Nuclear Power Station (blue dot) and Sizewell village (black dot). Three points referenced within Table 3 are highlighted.

The previous report from the EDF R&D UKC on Sizewell sea level rise used the same site adjustment factor for all return periods [1]. They used the adjustment factor derived from difference between the 10,000-year return levels for all the other return periods. However, comparing the 50th percentiles from Table 2 with that of point 1, the closest point to Sizewell C NPP, from Table 3 motivates the use of a different site adjustment factor for each return period. This aligns our results more with the EA model outputs and, in turn, produces more conservative return levels at Sizewell for return periods shorter than 10,000 years. The previous and updated site adjustment factors between Lowestoft and Sizewell are given in Table 4. The uncertainty percentiles for any given return period have the same site adjustment factor.

| Return period (year) | Lowestoft → Sizewell<br>Previous site adjustment factor used in [1] (m) | Lowestoft → Sizewell<br>Updated site adjustment factor (m) |
|---|---|---|
| 10 | -0.41 | -0.04 |
| 100 | -0.41 | -0.11 |
| 200 | N/A | -0.16 |
| 500 | N/A | -0.20 |
| 1,000 | -0.41 | -0.25 |
| 10,000 | -0.41 | -0.42 |
| 100,000 | N/A | -0.42* |

Table 4: Adjustment factor added to the sea level return levels at the Lowestoft tide gauge to give an estimate of the sea level at Sizewell. Updated values are calculated by taking the difference between the sea level return levels at the point closest to Sizewell C power station (column 2 in Table 3) and the return levels derived from the Lowestoft tide gauge data (column 2 in Table 2). Due to the lack of information for the 100,000-year return level in the EA model data to estimate a site adjustment factor directly, the asterisked value is taken to be equal to the site adjustment factor for the next longest return period, which provides a conservative estimate of the site adjustment factor for this return period.

The reason that the observational data is used with a site adjustment derived from the climate model, rather than using purely the climate model data for the whole analysis is because the Lowestoft tide gauge data is of very high quality due to a rigorous quality control process run by the EA so more trustworthy results can be gained by using the observational data as far as possible. Using the updated site adjustment factors in Table 4, we derive the updated return levels, with various uncertainty percentiles, for the requested return periods. These are listed in Table 5.

| Return period (years) | 50th percentile (mOD) | 84th percentile (mOD) | 95th percentile (mOD) |
|---|---|---|---|
| 10 | 2.51 | 2.57 | 2.62 |
| 100 | 2.98 | 3.12 | 3.21 |
| 200 | 3.11 | 3.28 | 3.39 |
| 500 | 3.30 | 3.52 | 3.68 |
| 1,000 | 3.42 | 3.69 | 3.88 |
| 10,000 | 3.88 | 4.34 | 4.65 |
| 100,000 | 4.54 | | |

Table 5: Return levels and associated uncertainty percentiles of sea level at Sizewell based on the present climate. The values are calculated by SSJPM analysis of data from Lowestoft tide gauge and adjusted to the Sizewell site using comparison with data from the EA model.

The comparison of the sea level values for Lowestoft derived using the SSJPM method on the tide gauge dataset and those using the EA model shows that they both are very similar. In particular, the 50th percentile 10,000-year return level derived from the observations is 4.30 mOD (Table 2) and the value derived from the EA model is 4.32 mOD (Table 3). To be within 0.02 m at such a long return period shows that the extreme values in the observations and model are in very strong alignment. This adds validation to the use of the EA model to calculate the site adjustment factor. The higher percentiles are less comparable as different percentiles are given, calculated using different methods.

## 4.3 Future climate return levels

We now estimate the extreme high sea level return levels using the UKCP18 data at the Lowestoft tide gauge and convert to the Sizewell site using the site adjustment factors in Table 4. We directly use the return level estimates provided in the UKCP18 data obtained using the approach described Section 3.3. In this section, we report the return level results for a selection of future years and uncertainty percentiles from these data. All the results for the future climate are based on the most extreme emissions scenario in the UKCP18 projections, RCP8.5, to provide conservative sea level rise estimates.

In the scope for this report, the 50th, 84th, and 95th uncertainty percentiles were requested for a variety of return levels and future years. The 50th and 95th percentiles are available directly from the extreme value analysis that was conducted to produce the UKCP18 data outputs and can be found in the projected future still water return levels dataset listed in Figure 6. However, the 84th percentile is not available. We have taken two approaches to provide an estimate of the 84th percentile: (i) bounding the 84th percentile above and below by the 70th and 90th percentiles that are available in UKCP18, and (ii) extrapolating the 84th percentile using polynomial regression of the available percentiles.

The 70th and 90th percentiles of future return levels are not directly available from the UKCP18 datasets listen in Figure 6, however, a comparison between the dataset of *time-mean sea level at 12 km*, which details the future sea level anomalies at the 5th, 10th, 30th, 33rd, 50th, 67th, 70th, 90th, and 95th percentiles, and the *projected future still water return levels*, which detail only the 5th , 50th, and 95th percentiles of the future return levels, for a given future year allows the 70th and 90th percentiles of the future return levels to be calculated exactly as if it had been available directly through UKCP18. Derived in this way, the 70th and 90th percentiles of the climate change adjustment factors are given in Table 6. These values give an upper and lower bound to the 84th percentile.

To get a closer estimate to compliment the bounds, we fit a cubic polynomial to the available percentiles (5, 10, 30, 33, 50, 67, 70, 90, 95) using least squares regression. This order polynomial provided the closest fit to the available percentiles, providing a suitable trade-off between overfitting and underfitting. For the 100-year return levels at 2050, we show the available percentiles in UKCP18, the fitted curve, and the interpolated 84th percentile of the return period uncertainty in Figure 12.

There are only nine different percentiles provided by UKCP18, so the fitted polynomial model has significant uncertainty. The choice of interpolation function has been chosen to fit the data rather than based on fundamental properties of the model variability on which the percentiles are derived. This means that there is an additional uncertainty associated with the estimated 84th percentile compared to the other percentiles in Table 6.

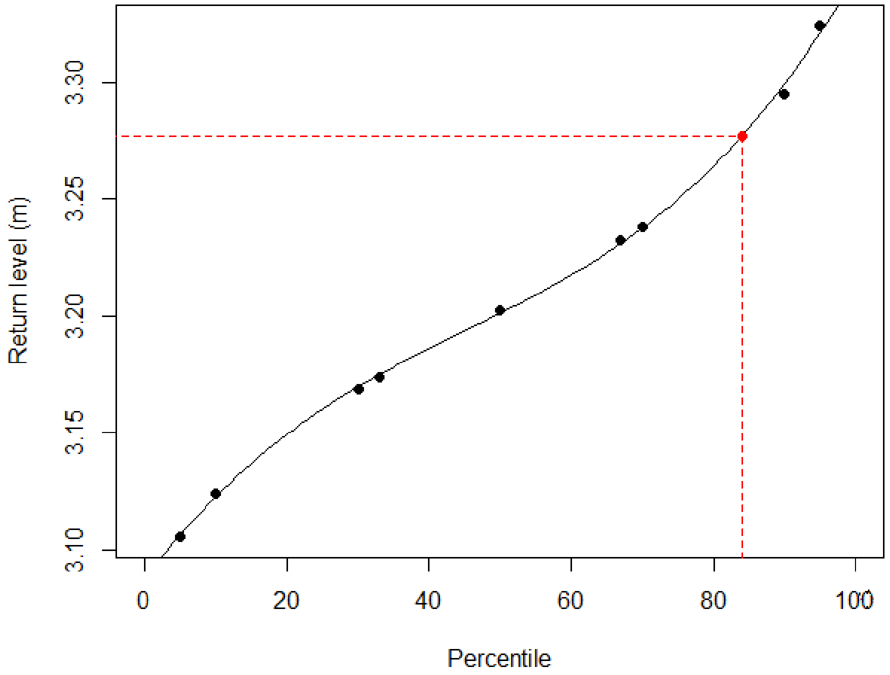

Figure 12: Interpolation of percentiles of return levels provided by UKCP18. This example is for the 100-year return level in 2050. The black points are the percentiles provided by UKCP18, the black line is the interpolation curve, and the red point and dashed lines indicate the interpolated 84th percentile.

Using the methods described in Section 3.3 and the interpolation methods described earlier in the present section, the adjustment factors that can be added to the present-day return levels (Table 5) to calculate climate change adjusted return levels for a variety of years are given in Table 6. When the climate change adjustment factors are added to the median estimate (i.e. 50th percentile) of the present-day sea level return level for a given return period, then they can be interpreted in a statistically meaningful way. For example, by adding the 95th percentile 100-year return level climate change adjustment factor for the year 2140 (+1.75 m) to the 50th percentile 100-year return level for the present-day climate at Sizewell (2.98 mOD) we can say with 95% confidence that the maximum sea level at Sizewell over 100 years of 2140 climate will be less than 4.73 mOD. Equivalently, we can say with 95% confidence that the maximum sea level expected with $10^{-4}$ probability in 2140 is 4.72 mOD.

It is also possible to add a climate change adjustment factor to the higher percentile estimates of the present-day return levels to derive a more conservative sea level value. The downside to this approach is that its meaning is no longer succinctly explained in a statement of the percentage of confidence in the given value because the uncertainty percentiles for the present day were calculated using a different method to those for the future climate and are therefore not easily comparable. On the other hand, a value calculated in this way can be used as a conservative upper bound. For example, by adding the 95th percentile 100-year return level climate change adjustment factor for the year 2140 (+1.75 m) to the 84th percentile (rather than the 50th percentile) 100-year return level for the present-day climate at Sizewell (3.12 mOD) we calculate a sea level of 4.87 mOD. This can be interpreted as meaning that, with 95% confidence, the maximum sea level at Sizewell over 100 years of 2140 climate will be less than 4.73 mOD. Due to the incomparable uncertainty percentiles, it is difficult to quantify how much less the true value would be. However, if a more conservative estimate than is given using the future climate uncertainty percentiles only is required, then a calculation like that above is valid.

| Return period (years) | Percentile | 2030 | 2050 | 2080 | 2090 | 2100 | 2110 | 2140 | 2190 |
|---|---|---|---|---|---|---|---|---|---|
| 100 | 50th | - | +0.21 | +0.48 | - | +0.68 | +0.80 | +1.12 | - |
| | 70th | - | +0.25 | +0.54 | - | - | +0.90 | +1.27 | - |
| | *84th | - | +0.29 | +0.62 | - | - | +1.04 | +1.47 | - |
| | 90th | - | +0.30 | +0.65 | - | - | +1.10 | +1.56 | - |
| | 95th | - | +0.33 | +0.72 | - | +1.04 | +1.22 | +1.75 | - |
| 200 | 50th | - | +0.20 | +0.47 | - | - | +0.79 | +1.11 | - |
| | 70th | - | +0.24 | +0.53 | - | - | +0.89 | +1.26 | - |
| | *84th | - | +0.28 | +0.61 | - | - | +1.03 | +1.46 | - |
| | 90th | - | +0.29 | +0.64 | - | - | +1.09 | +1.54 | - |
| | 95th | - | +0.32 | +0.71 | - | - | +1.21 | +1.74 | - |
| 10,000 | 50th | +0.08 | +0.22 | +0.48 | +0.59 | +0.69 | +0.80 | +1.13 | +1.62 |
| | 70th | - | +0.26 | +0.55 | - | - | +0.91 | +1.28 | - |
| | *84th | - | +0.29 | +0.63 | - | - | +1.05 | +1.48 | - |
| | 90th | - | +0.31 | +0.66 | - | - | +1.10 | +1.56 | - |
| | 95th | +0.16 | +0.34 | +0.73 | +0.89 | +1.05 | +1.23 | +1.75 | +2.58 |

Table 6: Climate change adjustment factors to be added to the present-day still water return levels to calculate the return levels based on climate change projections up to selected future years, derived using UKCP18 data. The second column gives uncertainty percentiles based on variability between model runs in UKCP18. The asterisked percentile is not available directly from UKCP18 so has been interpolated from the percentiles available (5, 10, 30, 33, 50, 67, 70, 90, 95). Where available, results from future years (2030, 2090, 2100, 2190) that were derived in the previous report [1] have been included for completion.

Table 7 synthesises the results from the present-day and future climate sea level projections. It gives the present-day return levels for Lowestoft, the site adjustment factor to convert to Sizewell, the climate change adjustment factor associated with the projected climate change up to 2050, and the projected sea level at Sizewell. The values for other years can be calculated in a similar way by referring directly to Table 6 for the respective climate change adjustment factors. The return levels for various future years and uncertainty percentiles in the final column have been calculated by adding the climate change adjustment factor of the respective uncertainty percentile to the 50th percentile of the present-day value.

| Return period (years) | Percentile | Lowestoft present-day sea level (mOD) | Lowestoft → Sizewell site adjustment factor (m) | Climate change adjustment factor for 2050 (m) | Sizewell expected sea level in 2050 (mOD) |
|---|---|---|---|---|---|
| 10 | **50th** | **2.55** | -0.04 | - | - |
| | 84th | 2.61 | | - | - |
| | 95th | 2.66 | | - | - |
| 100 | **50th** | **3.09** | -0.11 | +0.21 | 3.19 |
| | 84th | 3.23 | | +0.29 | 3.27 |
| | 95th | 3.32 | | +0.33 | 3.31 |
| 200 | **50th** | **3.27** | -0.16 | +0.20 | 3.31 |
| | 84th | 3.44 | | +0.28 | 3.39 |
| | 95th | 3.55 | | +0.32 | 3.43 |
| 500 | **50th** | **3.50** | -0.20 | - | - |
| | 84th | 3.72 | | - | - |
| | 95th | 3.88 | | - | - |
| 1,000 | **50th** | **3.67** | -0.25 | - | - |
| | 84th | 3.94 | | - | - |
| | 95th | 4.13 | | - | - |
| 10,000 | **50th** | **4.30** | -0.42 | +0.22 | 4.10 |
| | 84th | 4.76 | | +0.29 | 4.17 |
| | 95th | 5.07 | | +0.34 | 4.22 |
| 100,000 | **50th** | **4.96** | -0.42* | - | - |

Table 7: Present and future sea level return levels for various return periods and uncertainty percentiles for Lowestoft and Sizewell. The rightmost column is calculated by adding the site and climate change adjustment factors from columns 4 and 5 to the 50th percentile value from column 3. The climate change adjustments for this table are for the year 2050. For climate change adjustment factors for other future years, see Table 6.

# 5 Conclusions and recommendations

In this report, we provide return level estimates of still sea level at Sizewell for additional return periods, future climate projections, and uncertainty percentiles in addition to the previous report [1]. The sea level values are still water values that include the astronomical tide cycle and storm surges but do not include the influence of ocean waves. The future climate return levels also do not take into account uncertainty due to coastal erosion or changes in storminess due to climate change.

Following the same methodology as [1], the return level estimates for the current climate are based on tide gauge data at Lowestoft between 1964 and 2019 and are derived using the skew surge joint probability method (SSJPM). The Lowestoft estimates are then adjusted to estimates for Sizewell by comparison with local hydrodynamic model outputs from the Environment Agency's (EA) Coastal Flooding Boundary model [2]. The current study provides present-day climate return levels at Lowestoft (Table 2) and at Sizewell (Table 5) for the requested return periods and percentiles.

The methodology used in this study is the same as in the previous report [1] apart from two updates: (i) the site adjustment factor has been updated, and (ii) interpolation was used to provide an estimate for the requested percentiles not provided by UKCP18.

The site adjustment factor has been updated to be more in line with EA's Coastal Flooding Boundary model for return periods shorter than 10,000 years. The most significant impact of this update is to increase the shortest return levels by 31 cm for the 10-year return level. For example, the 50th percentile of the 10-year return period of sea level based on the projected 2100 climate at Sizewell has been updated from 2.82 mOD in [1] to 3.19 mOD in this report. Return level estimates for longer return periods are updated by a smaller amount as the discrepancy between the tide gauge data at Lowestoft and the model output data from EA's Coast Flooding Boundary model is smaller. We recommend that, where there are differences between the previous report and this report, the values in the present report are taken as more trustworthy.

Climate change adjustment factors have been estimated using the latest UKCP18 data from the Met Office [3] and are based on the most severe emissions scenario RCP8.5, giving the most conservative estimates available for sea level rise. In the UKCP18 projections, the grid point closest to Sizewell is at Lowestoft, so we also use a site adjustment factor to convert to estimates for Sizewell for the future climate. For example, the 50th percentile estimate of the 10,000-year return levels at Sizewell in the years 2050, 2080, 2110, and 2140 are 4.10, 4.36, 4.68, and 5.01 mOD, respectively. The climate change adjustment factors for sea level at Sizewell for the remainder of the requested return periods, years, and percentiles, are given in Table 6.

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