Department for Environment Food & Rural Affairs

Llywodraeth Cymru
Welsh Government

SEPA
Scottish Environment Protection Agency
Buidheann Dìon Àrainneachd na h-Alba

Cyfoeth Naturiol Cymru
Natural Resources Wales

Environment Agency

delivering benefits through evidence

Exploratory sea level projections for the UK to 2300

SC150009

Flood and Coastal Erosion Risk Management Research and Development Programme

We are the Environment Agency. We protect and improve the environment.

Acting to reduce the impacts of a changing climate on people and wildlife is at the heart of everything we do.

We reduce the risks to people, properties and businesses from flooding and coastal erosion.

We protect and improve the quality of water, making sure there is enough for people, businesses, agriculture and the environment. Our work helps to ensure people can enjoy the water environment through angling and navigation.

We look after land quality, promote sustainable land management and help protect and enhance wildlife habitats. And we work closely with businesses to help them comply with environmental regulations.

We can't do this alone. We work with government, local councils, businesses, civil society groups and communities to make our environment a better place for people and wildlife.

Published by:
Environment Agency, Horizon House, Deanery Road,
Bristol, BS1 5AH

http://www.gov.uk/government/organisations/environment-agency

ISBN: 978-1-84911-428-8

Email: fcerm.evidence@environment-agency.gov.uk

Further copies of this report are available from our publications catalogue:
http://www.gov.uk/government/publications

or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk

Authors:
Tom Howard, Matt Palmer, Galina Guentchev and Justin Krijnen

Dissemination status:
Publicly available

Keywords:
Sea level rise, climate change, UKCP18, 2300, mean sea levels, extreme sea levels, waves

Research contractor:
Met Office, FitzRoy Road, Exeter, Devon EX1 3PB
Tel: 0370 900 0100.

Environment Agency's Project Manager:
Stuart Allen, Research, Analysis and Evaluation

Theme Manager:
Susan Manson, Incident Management and Modelling

Project number:
SC150009

Evidence at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. The Joint Programme is jointly overseen by Defra, the Environment Agency, Natural Resources Wales and the Welsh Government on behalf of all Risk Management Authorities in England and Wales:
http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM.aspx.

You can find out more about our current science programmes at:
https://www.gov.uk/government/organisations/environment-agency/about/research.

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Background

This project has developed new projections of mean and extreme sea levels to the year 2300. This information is critical for long-term planning and the UK's adaptation response to increasing sea levels. Flood and coastal erosion risk management authorities, developers and infrastructure operators all need information about the likely impacts of climate change on sea levels so they can incorporate appropriate levels of protection into their designs. Some assets and developments have expected life spans that go beyond the end of the 21st century. These schemes need information about how extreme sea levels and waves may change over longer timescales.

In 2016 the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales, the Welsh Government and the Department for Food, Environment and Rural Affairs commissioned the Met Office to develop new projections of sea level rise for the UK out to the year 2300. The work complements the updated projections of mean and extreme sea level rise to 2100 developed under the UK Climate Projections 2018 (UKCP18) project.[1] The data associated with this work are available through the UKCP18 data portal and the results are incorporated in associated UKCP18 project publications. The project also carried out a literature review of past and future expected impacts of climate change on waves.

Approach

The Met Office extended the sea level rise projections to 2300 by constructing a simpler version of the model used in the UKCP18 projections. The model was based on phase 5 of the coupled model inter-comparison project (CMIP5) projections to ensure consistency between the 2100 and exploratory 2300 marine projections. Future extreme sea levels for 46 UK tidal gauges were produced, derived from time series of mean sea level rise to 2300 and current best estimates of the return periods for observed sea levels. The research assessed low, medium–low and high emissions of greenhouse gas concentration trajectories or 'representative concentration pathways' (RCPs) as adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report.

Key findings

- Sea level will continue to rise to 2300 under all climate change projections. The global average sea level ranges at 2300, relative to a 1981-2000 baseline period, are:
  - 0.6–2.2m (low emissions scenario, RCP 2.5)
  - 0.9–2.6m (medium–low emissions scenario, RCP 4.5)
  - 1.7–4.5m (high emissions scenario, RCP 8.5)

  The UK land surface is tilting, with Scotland rising and southern England sinking, such that greater rates of sea level rise will be experienced in the south of England.
- By 2300, sea water levels with a current probability of only 0.01% of occurring in any one year, could be experienced every year.

---

[1] www.metoffice.gov.uk/research/collaboration/ukcp

- There is limited consensus on how waves will be affected by climate change. The research indicates there may be a reduction in average offshore wave height, but extreme offshore wave heights may increase. The sea level rise element of climate change is expected to be a greater threat to coastal defences than changes in offshore waves.
- Higher sea levels will cause waves to carry greater energy to the shore, which will have an impact on sea defences. Nearshore waves will be higher and break later, increasing flood water volumes in areas already affected by coastal flooding. This will have implications for the expected lifetime and continued performance of coastal defences, likely requiring greater investment in flood and coastal erosion risk management to maintain current defence lines and standards of protection.
- There is a large degree of unquantified uncertainty with these projections, which must be recognised by anyone using the research's findings. The uncertainty is associated mostly with the potential for accelerated ice loss from the West Antarctic ice sheet.

How will the research be used?

This research will be useful for infrastructure operators and those managing the risks of our changing climate. A detailed assessment of the results is presented both in this project and in the UKCP18 Marine Report published by the Met Office in 2018. The underlying dataset is publically available from the UKCP18 data portal (www.metoffice.gov.uk/research/collaboration/ukcp/download-data).

Contents

1 Introduction 1
1.1 Background 1
1.2 Drivers of sea level change 1
1.3 Approach used in this project 3
1.4 Structure of the report 4

2 Data and methods 5
2.1 Extended RCP scenarios 5
2.2 Two-layer model 6
2.3 Global mean sea level projections to 2300 9
2.4 From global to regional projections 11
2.5 Environment Agency coastal flood boundary conditions 12
2.6 Note on percentiles 13
2.7 Definition of return period 13

3 Projections of coastal extreme water levels 15
3.1 Projections of time-mean sea level change out to 2300 15
3.2 Changes in future return levels 17

4 Past and future wave climate in the North Atlantic including the UK 21
4.1 Overview of waves and wave generation 21
4.2 Review of 20th century wave climate in the North Atlantic 22
4.3 Review of possible causes of 20th century changes in wave climate 23
4.4 Review of 21st century wave projections for the North Atlantic 24
4.5 Uncertainty sources and considerations 30
4.6 Review of possible causes of 21st century changes in wave climate 32
4.7 Gaps in understanding 32
4.8 Conclusions from the waves literature review 33

References 35

List of abbreviations 42

Glossary 43

Appendix A: Projections of future extreme coastal still water levels at UK tide gauges 44

Appendix B: Wave literature review summary tables and results by focus area 50

Appendix C: Datum and interpretation of the extreme sea level projections, or ‘Why don’t you call the results ‘ODN’?’ 84

Appendix D: Coastal flood boundary data 86

List of tables and figures

Table 2.1 A summary of methods used for each mass component time series 10
Table 2.2 Comparison of the UKCP18 21st century global time-mean sea level projections and the extended projections presented in this section 11
Table A.1 RCP2.6: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300) 45
Table A.2 RCP4.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300) 46
Table A.3 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300) 47
Table A.4 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for all sites (central estimate only) and 3 future times (2100, 2200, 2300) 48
Table B.1 Summary table of the GCMs used in the simulations for studies focused on north-east Atlantic and around the British Isles 56
Table B.2 Summary table of the GCMs used in the simulations for North Sea studies 60
Table B.3 North-east Atlantic and areas around the British Isles: positive changes 62
Table B.4 North-east Atlantic and areas around the British Isles: negative changes 69
Table B.5 North Sea: positive and negative changes 77
Table D.1 Return levels (in mODN) 87

Figure 1.1 Summary of the major contributors to changes in: global mean sea level, regional sea level, and local sea level and extremes 2
Figure 2.1 Left: Carbon dioxide concentrations for the coming centuries under 3 extended RCPs. Right: Associated global mean surface temperature change for the two-layer model ensemble used in the extended sea level projections 6
Figure 2.2 Schematic representation of the two-layer energy balance model 7
Figure 2.3 Ensemble projections of global mean surface temperature change relative to a baseline period of 1986 to 2005 8
Figure 2.4 Ensemble projections of the global mean sea level change associated with global thermal expansion relative to a baseline period of 1986 to 2005 9
Figure 2.5 Time series of global time-mean sea level change to 2300 with a baseline period of 1981 to 2000 11
Figure 3.1 Left panel: Time series of time-mean sea level change based on the average of 49 UK ports. Right panel: The spatial pattern of change at 2300 associated with the central estimate of each RCP scenario 16
Figure 3.2 Time series of the time-mean relative sea level change for UK capital cities based on the nearest Class A tide gauge location (indicated in brackets) 17
Figure 3.3 Projected future return level curves for 4 example sites. 18
Figure 4.1 Coastal strip plots of historical wave climate and projected future changes for UK mainland 25
Figure 4.2 Change in mean SWH between present day (1970 to 1999) and future projections: RCP4.5 (left column) and RCP8.5 (right column). Top row: mid-century (2030 to 2059). Bottom row: end-century (2070 to 2099) 28
Figure C.1 Schematic diagram showing the interpretation of results: specifically why the results are not, strictly speaking, 'ODN' 85

1 Introduction

1.1 Background

In 2016, the Met Office was commissioned by the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales, the Welsh Government and the Department for Food, Environment and Rural Affairs (Defra) to develop new projections of sea level rise for the UK out to the year 2300. The work described in this report complements the updated projections of mean and extreme sea level rise to 2100 developed under the UK Climate Projections 2018 (UKCP18) project. The data associated with this work are available through the UKCP18 data portal[2] and the results incorporated in associated UKCP18 project publications. The project also carried out a literature review of past and future expected impacts of climate change on waves.

Information on projections of mean and extreme sea levels to the year 2300 is critical for long-term planning and the UK's adaptation response to increasing sea levels. Flood and coastal erosion risk management authorities, developers and infrastructure operators all need information about the likely impacts of climate change on sea levels so they can incorporate appropriate levels of protection into their designs. Some assets and developments have expected life spans that go beyond the end of the 21st century. These schemes need information about how extreme sea levels and waves may change over longer timescales.

1.2 Drivers of sea level change

This section presents background information on the various drivers of sea level change and how these can interact with each other. Much of the information is taken from the UKCP18 Marine Report (Palmer et al. 2018b), which includes additional discussion. Changes in sea level occur due to a broad range of geophysical processes that operate on different spatial scales and time scales. A schematic of the different sea level components that can contribute to sea level change, including sea level extremes, and how these fit together, is presented in Figure 1.1.

---

[2] www.metoffice.gov.uk/research/collaboration/ukcp/download-data

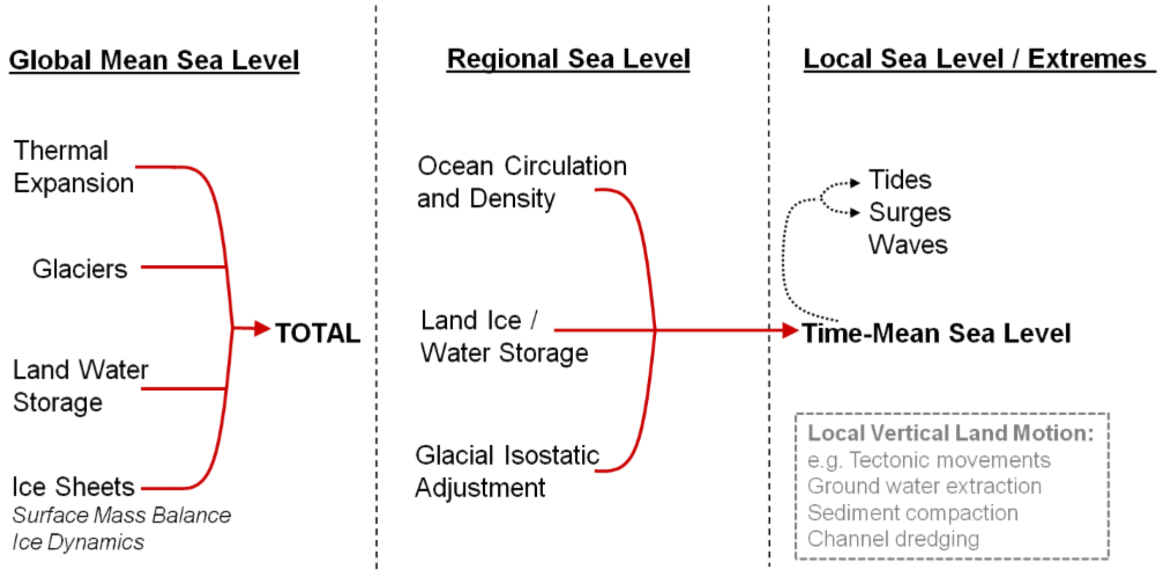

Figure 1.1 Summary of the major contributors to changes in: global mean sea level, regional sea level, and local sea level and extremes

Notes: The black dashed lines indicate the potential interaction between local time-mean sea level and tide and surge characteristics.
The grey text highlights some of the non-climatic processes that can give rise to sea level change through vertical land motion.
Source: Palmer et al. (2018b, Figure 2.1.1).

1.2.1 Drivers of changes in global mean sea level

Changes in global mean sea level (Figure 1.1, left column) arise due to either a change in the average ocean density (for example, if the ocean becomes less dense, the volume increases and the global mean sea level rises) or a change in global ocean mass through the input or removal of water.

For global mean sea level, changes in density are overwhelmingly dominated by thermal expansion (that is, the tendency for seawater to become less dense as temperature increases). Under anthropogenic climate change, freshwater input to the ocean arises from the loss of land-based ice from mountain glaciers and the Greenland and Antarctic ice sheets.

Following the methods described in Chapter 13 of the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) AR5 (Church et al. 2013), the sea level projections presented here include both surface mass balance (that is, the balance between accumulated snowfall and ice melt) and ice dynamics (that is, changes in rate of discharge in active ice flows) for each of the ice sheets.

Finally, changes in land water storage – through processes such as groundwater extraction and reservoir impoundment – make a substantial contribution to the change in global mean sea level. The full list of mass (or freshwater) inputs to the ocean considered in the projections presented here is:

- glaciers
- Greenland ice sheet surface mass balance
- Greenland ice sheet ice dynamics
- Antarctic ice sheet surface mass balance

- Antarctic ice sheet ice dynamics
- changes in land water storage

1.2.2 Drivers of changes in regional sea levels

On regional scales, a number of additional processes come into play (Figure 1.1, middle column).

Firstly, changes in local seawater density and/or ocean circulation leave their imprint in the shape of the sea surface. While temperature effects dominate density changes for global mean sea level, locally both changes in temperature and salinity are important factors. Due to the differing responses among climate models the spatial pattern of change associated with this term in climate change projections is highly uncertain (which is accounted for in our sea level projections).

Secondly, changes in land-based ice and land water storage are also associated with spatial patterns of regional sea level change. These spatial patterns depend on the geographic distribution of the mass changes and arise from:

(i) the solid Earth response to changes in local mass loading

(ii) the effect of the mass redistribution on the Earth's gravity field

(iii) the combined effect of (i) and (ii) on the Earth's rotation (see, for example, Tamisiea and Mitrovica 2011)

This report refers to the combined effect of these 3 processes as 'mass fingerprints'.

Thirdly, the ongoing response of the Earth system to the last deglaciation (which terminated approximately 10,000 years ago) – referred to as glacial isostatic adjustment (GIA) – gives rise to a spatial pattern of relative sea level change across the UK with peak magnitudes of approximately ±1mm per year. This pattern is characterised by a relative sea level fall that is centred on western Scotland and a relative sea level rise to the south of the mainland UK, with maximum values in the south-east and south-west. While vertical land movement is the dominant contribution to this pattern, gravitational and rotational effects also make a substantial contribution. Due to the long adjustment timescales associated with GIA, the rates of change are time-invariant for the sea level projections presented in this report.

The superposition of these 3 different spatial elements determines the relative sea level change for a given location in the time-mean sea level projections presented in Section 3.1).

Changes in sea level extremes (Figure 1.1, right column) are discussed in Section 3.2.

1.3 Approach used in this project

The method for exploratory extended sea level projections is described in Palmer et al. (2018a) and the UKCP18 Marine Report (Palmer et al. 2018b). An important aspect of these extended projections is that they can be used seamlessly with the UKCP18 21st century sea level projections. However, the extended projections are exploratory and there is a greater degree of unquantified uncertainty than there is with the UKCP18 21st century projections. In particular, there is deep uncertainty associated with potential changes in the dynamic ice input to the ocean from the West Antarctic ice sheet on these extended time horizons (see, for example, DeConto and Pollard 2016), which could lead to substantially larger sea level rise.

The extended projections presented in this report therefore provide illustrative example projections against which vulnerabilities can be assessed. Note that work to develop updated ‘high end/H++’ scenarios for sea level rise over the coming centuries is being explored at the Met Office in collaboration with the wider research community.

The assessment of potential changes in extreme coastal water levels makes use of the updated coastal flood boundary conditions for UK mainland and islands (Environment Agency 2019). The coastal flood boundary conditions represent our best understanding of current coastal water level extremes and the updated dataset includes the severe winter storms of 2013 to 2014. This project combined the return level curves from 46 tide gauge locations with the extended sea level projections to illustrate how coastal extreme water levels may change under future sea level rise over the coming centuries. The report focuses on a few example locations that span a range of behaviour around the UK and the plan is to release a full dataset for users as part of the UKCP18 data portal.

The final element of this report is a review of the literature on projected wave changes for the North Atlantic and North Sea with results pertinent to the UK coastline. This work includes a synthesis of the recent wave modelling results presented in Bricheno and Wolf (2018) and the related work presented in the UKCP18 Marine Report (Palmer et al. 2018b).

1.4 Structure of the report

Section 2 presents an overview of the extended sea level projections to 2300.

Section 3 illustrates and discusses future return levels of extreme water for example sites around the UK.

Section 4 summarises results of past and projected 21st century wave climate in the North Atlantic and North Sea.

2 Data and methods

One of the main limitations to exploring climate change projections beyond 2100 is the availability of climate model simulations from phase 5 of the Coordinated Modelling Intercomparison Project (CMIP5) beyond this time horizon. Although climate change scenarios based on representative concentration pathways (RCP) were specified out to 2300 (see Section 2.1), few modelling centres carried out these extended simulations due to the computational expense. The method presented here makes use of a simple two-layer climate model (Section 2.2) to extend individual CMIP5 model simulations of global surface temperature and global thermal expansion to 2300. These projections of global surface temperature and thermal expansion are then combined with additional assumptions to provide global and regional sea level projections to 2300 that are traceable to the CMIP5 model ensemble. This report presents a brief overview of the data and methods used. Full details of the two-layer model simulations are available in Palmer et al (2018a). The methods used to translate these simulations into global and regional sea level projections are described in the UKCP18 Marine Report (Palmer et al. 2018b).

2.1 Extended RCP scenarios

The extended sea level projections are based on 3 of the 4 extended RCP climate change scenarios described by Meinshausen et al. (2011). These extended scenarios were devised by making simple assumptions based on either smoothly stabilising concentrations or constant emissions for the period post 2100. The 3 scenarios are the same as used in the UKCP18 21st century sea level projections and can be thought of as:

- a ‘low’ emissions scenario (RCP2.6)
- a ‘medium–low’ emissions scenario (RCP4.5)
- a ‘high’ emissions scenario (RCP8.5)

Figure 2.1 presents time series of the atmospheric greenhouse gas concentrations and global surface temperature response (based on the two-layer model simulations).

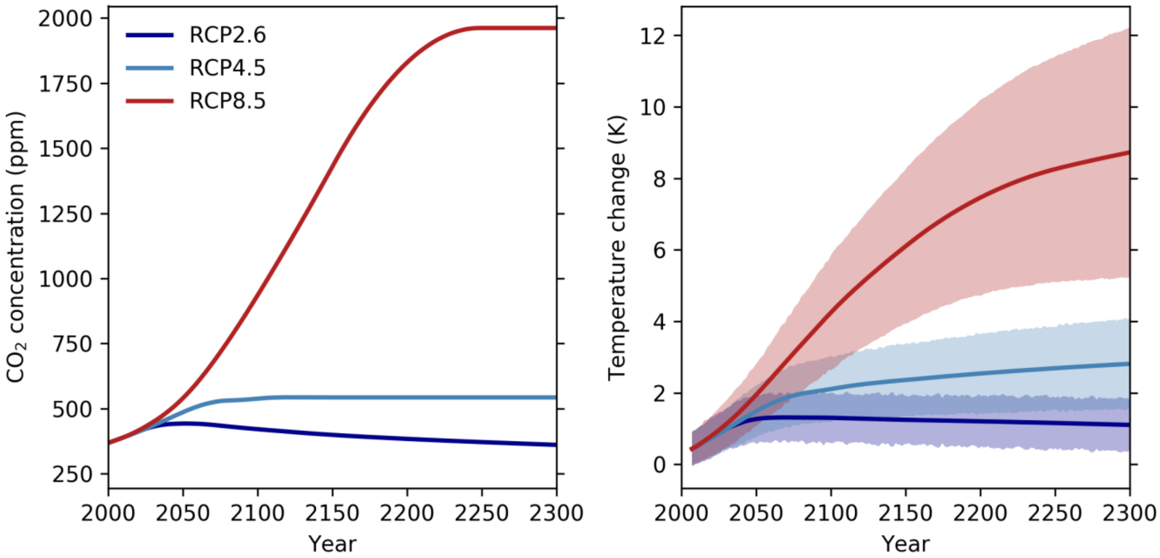

Figure 2.1 Left: Carbon dioxide concentrations for the coming centuries under 3 extended RCPs. Right: Associated global mean surface temperature change for the two-layer model ensemble used in the extended sea level projections

Notes: Temperature change is shown relative to the 1981 to 2000 average.
The shaded regions represent the 5th to 95th percentile range, assuming a normal distribution.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 4.1).

2.2 Two-layer model

The time-mean sea level projections presented in this report make use of a simple two-layer energy balance model (Figure 2.2) to emulate the response of the more complex CMIP5 climate models. Essentially, this means using a much simpler and computationally efficient model to estimate what each CMIP5 model would have done if it had run on to 2300.

The two-layer model is a well-established modelling framework and has been used in numerous previous studies as an aid to understanding the climate change response in complex global climate models (for example, CMIP5). The two-layer model projections make use of parameter settings developed for individual CMIP5 models by Geoffroy et al (2013a, 2013b). These are used to produce an ensemble of two-layer model simulations, factoring in the limitations in the two-layer model performance using a subset of CMIP5 model simulations that were run to 2300 (see Palmer et al. 2018a for details).

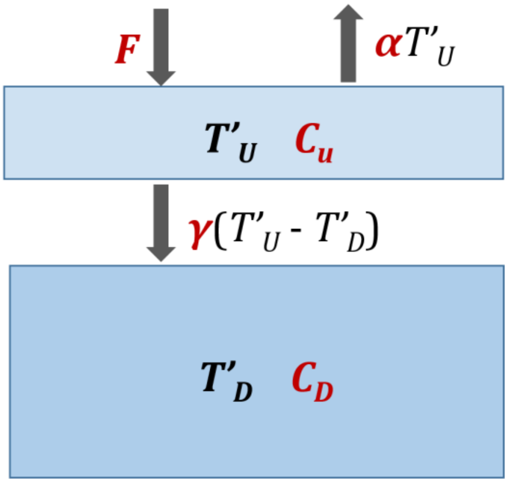

Figure 2.2 Schematic representation of the two-layer energy balance model

Notes: The model consists of an upper ocean layer, which represents surface temperature and the atmosphere and a deep ocean layer.
F is the radiative forcing at top-of-atmosphere, α is the climate feedback parameter, γ is the heat exchange coefficient.
T'_U and T'_D represent temperature perturbations from a pre-industrial equilibrium state.
Prognostic variables are indicated in black and tuneable parameters are indicated in red.
Source: Palmer et al (2018b, Figure A1.2.1)

Global surface temperature is a prognostic variable in the two-layer model and is therefore directly output from the model. Time series of global ocean heat content change (informed by the layer temperatures and heat capacities) are converted to the sea level rise due to global thermal expansion using the CMIP5 model-specific coefficients documented by Lorbacher et al. (2015).

Overall, the two-layer model ensemble projections of global surface temperature and thermal expansion compare favourably with CMIP5 climate model ensemble projections over the 21st century and also individual CMIP5 model simulations that are available to 2300 (Figures 2.3 and 2.4).

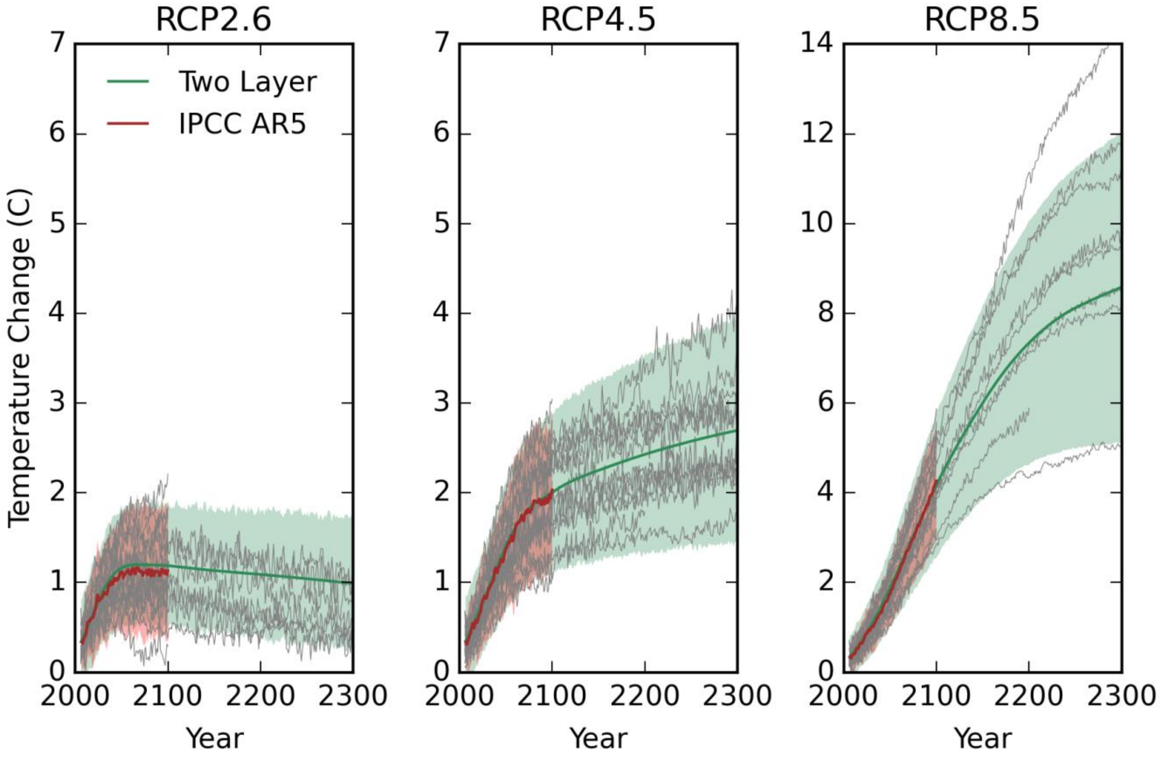

Figure 2.3 **Ensemble projections of global mean surface temperature change relative to a baseline period of 1986 to 2005**

Notes: Time series include:

- the 21 member IPCC AR5 ensemble (red, shaded regions indicate 5th to 95th percentile range)
- the 14 member two-layer model ensemble (green, shaded regions indicate 5th to 95th percentile range)
- individual CMIP5 model projections (grey lines)

Source: Palmer et al (2018b, Figure A1.2.2)

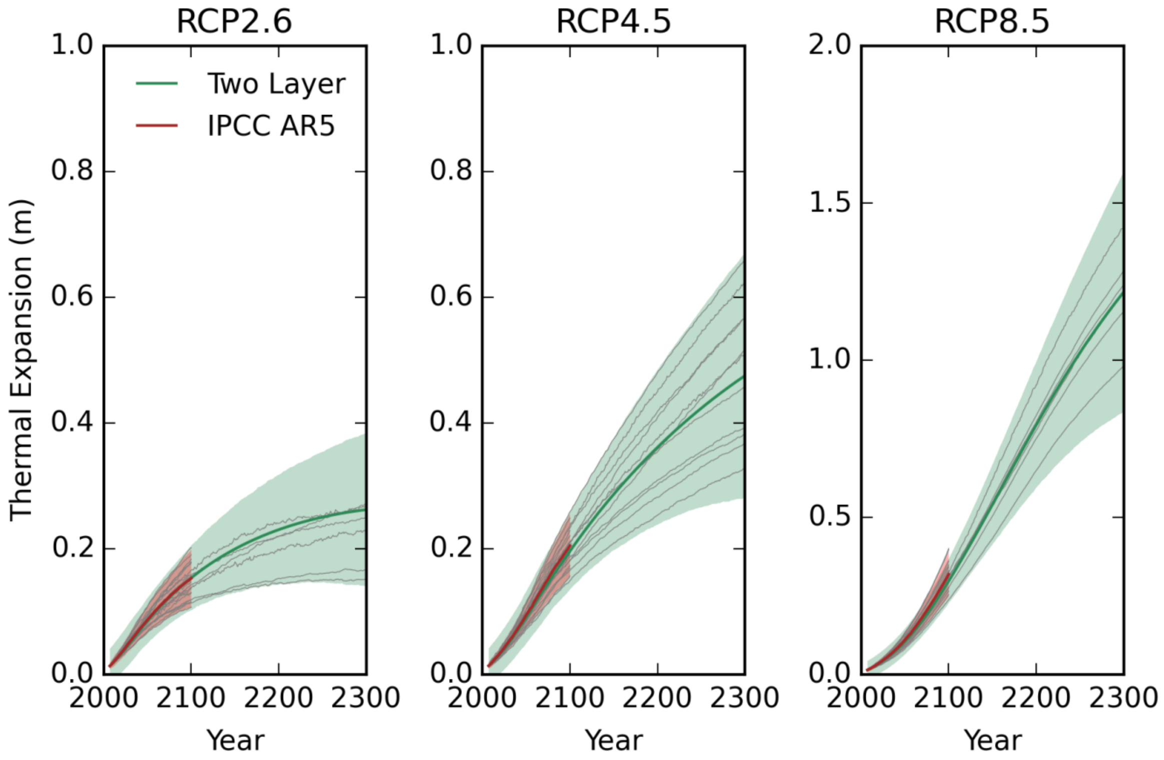

Figure 2.4 Ensemble projections of the global mean sea level change associated with global thermal expansion relative to a baseline period of 1986 to 2005

Notes: Time series include:

- the 21 member IPCC AR5 ensemble (red, shaded regions indicate 5th to 95th percentile range)
- the 14 member two-layer model ensemble (green, shaded regions indicate 5th to 95th percentile range)
- individual CMIP5 model projections (grey lines)

Source: Palmer et al (2018b, Figure A1.2.3)

2.3 Global mean sea level projections to 2300

The two-layer model ensemble projections of global mean surface temperature (Figure 2.3) and thermal expansion (Figure 2.4) are combined with additional assumptions to generate projections of global mean sea level that extend to 2300.

- The rise in global mean sea level due to thermal expansion is taken directly from the two-layer model ensemble.
- The projections of global surface temperature are used as the basis for determining future changes in glacier ice melt and changes in surface mass balance for the Greenland and Antarctic ice sheets using the same relationships as described in IPCC AR5 (Church et al. 2013).
- A statistical fit to the scenario-dependent projections of Levermann et al. (2014) is used to provide an estimate of contribution from Antarctic ice dynamics using the same approach as for the UKCP18 21st century sea level projections.
- The rates of ice dynamic loss for Greenland and changes in land water are assumed to remain constant after 2100.

The methods are summarised in Table 2.1 with further details available in the UKCP18 Marine Report (Palmer et al. 2018b).

Table 2.1 A summary of methods used for each mass component time series

Mass component	Method
Antarctica: surface mass balance	The same relationship with global surface temperature used in the IPCC AR5 21st century projections is applied out to 2300 (Church et al. 2013).
Antarctica: ice dynamics	A statistical fit to the Levermann et al. (2014) results is used up to 2100, with rates held constant between 2100 and 2300.
Greenland: surface mass balance	The same relationship with global surface temperature used in the IPCC AR5 (Church et al. 2013) is used up to 2100, with rates held constant between 2100 and 2300.
Greenland: ice dynamics	The mass loss rates at 2100 from the IPCC AR5 21st century projections are held constant between 2100 and 2300 (Church et al. 2013).
Glaciers	The same relationship with global surface temperature used in the IPCC AR5 21st century projections is applied out to 2300 (Church et al. 2013), with a cap on the total sea level equivalent of 0.32m to reflect current estimates of global glacier volume (Grinsted 2013).
Land water storage	The rates at 2100 from the IPCC AR5 21st century projections are held constant between 2100 and 2300 (Church et al. 2013).

Source: UKCP18 Marine Report (Palmer et al. 2018b, Table A.1.2.1)

The resulting global mean sea level projections show that sea level will continue to rise throughout the 22nd and 23rd centuries under all scenarios (Figure 2.5). This behaviour is in contrast to global surface temperature, which post-2100 shows a marked reduction in the rate of rise under RCP4.5 and a decrease under RCP2.6. The 5th to 95th percentile ranges for global mean sea level rise at 2300 are much larger that the corresponding ranges at 2100 (Table 2.2). In particular, the large range for RCP8.5 is dominated by uncertainty in the dynamic ice input from Antarctica. These illustrative projections suggest that the total glacier mass could be exhausted (from glacial melt) by the middle of the 22nd century under RCP8.5 (or the 23rd century under RCP4.5).

The extended sea level projections presented in this report show a high degree of consistency with the 21st century projections presented in UKCP18, promoting their seamless use across timescales (Table 2.2). At 2100, the extended projections (based on the two-layer model ensemble) are typically in agreement with the UKCP18 21st century projections (based on the CMIP5 model ensemble used in IPCC AR5) to within a centimetre or so.

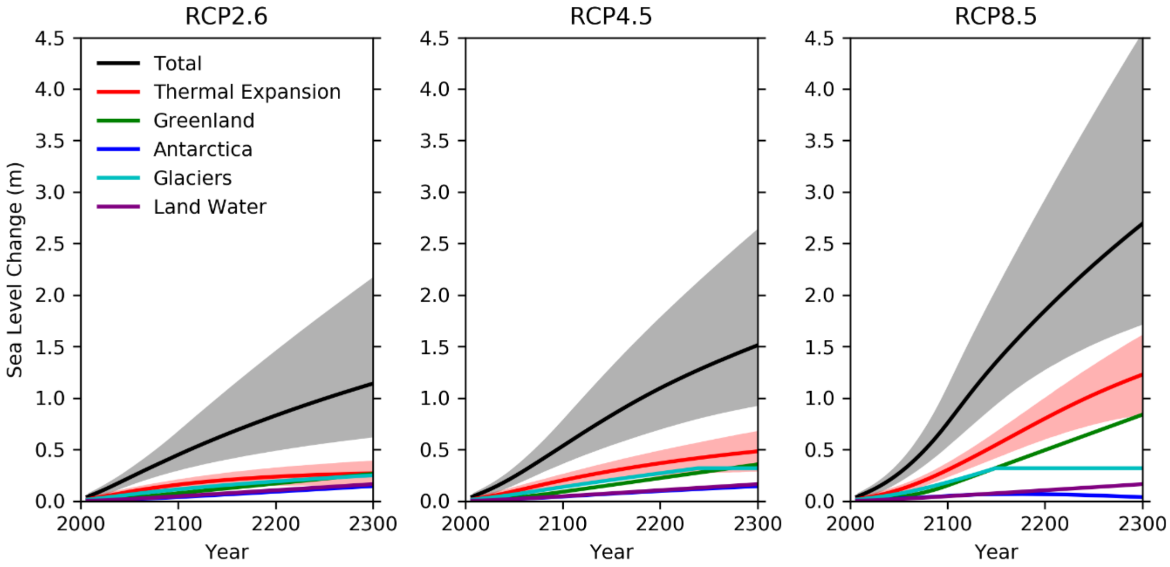

Figure 2.5 Time series of global time-mean sea level change to 2300 with a baseline period of 1981 to 2000

Notes: Individual components are indicated by the coloured lines.
The 5th to 95th percentile range from the model ensemble is indicated by the shaded regions for total and thermal expansion.
Note that the surface mass balance and ice dynamics terms for Greenland and Antarctica have been combined.
Source: UKCP18 Marine Report (Palmer et al. 2018b)

Table 2.2 Comparison of the UKCP18 21st century global time-mean sea level projections and the extended projections presented in this section

	Year	RCP2.6	RCP4.5	RCP8.5
UKCP18 21st century projections	2100	0.44 (0.29–0.67)	0.54 (0.38–0.79)	0.78 (0.56–1.12)
Extended projections (this report)	2100	0.45 (0.30–0.68)	0.54 (0.36–0.79)	0.76 (0.53–1.12)
	2200	0.8 (0.5–1.5)	1.1 (0.7–1.8)	1.8 (1.3–2.9)
	2300	1.1 (0.6–2.2)	1.5 (0.9–2.6)	2.7 (1.7–4.5)

Notes: The numbers given are the central estimates for the year indicated, with the 5th to 95th percentile range given in brackets.
Numbers beyond 2100 are quoted to the nearest 0.1m, given the lower confidence associated with projections on these extended time horizons.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Table 4.2.1)

2.4 From global to regional projections

A number of additional processes need to be accounted for to provide regional projections for the UK.

Each of the global mean sea level components (Figure 2.5) is associated with a non-uniform spatial pattern of change (see Section 1.1). Essentially, each of the mass and freshwater input time series is combined with a corresponding ‘mass fingerprint’ to determine the local effect of each individual component.

Potential changes in local ocean circulation and density are accounted for by establishing regression relationships between global thermal expansion and the local ‘oceanographic’ sea level. These regression relationships vary by climate model and hence additional regional uncertainty is introduced for this term.

Finally, an estimate of the ongoing effects of GIA is included in the regional sea level projections.

The various mass fingerprints and example regression relationships are presented in the UKCP18 Marine Report (Palmer et al. 2018b).

The combined uncertainty in regional sea level projections is computed using a 100,000 member Monte Carlo simulation. For each member of the Monte Carlo, a set of global mean sea level time series is drawn at random from the underlying distributions. Uncertainties in the mass fingerprints, the oceanographic sea level regressions and GIA are factored in by also making random draws from several estimates of each.

Statistics for the full Monte Carlo set are then used to compute the overall uncertainty, following the approach presented in IPCC AR5 (Church et al. 2013). That is, the 5th and 95th percentiles of the 100,000 members provide the basis for the uncertainties in total regional sea level change.

However, there may be a greater than 10% chance that the real world response lies outside these ranges. This likelihood cannot be accurately quantified. In particular, it is not possible to rule out substantial additional sea level rise associated primarily with dynamic ice discharge from the West Antarctic ice sheet (see Section 3.2.1 of Palmer et al. 2018b for further discussion).

2.5 Environment Agency coastal flood boundary conditions

In 2008, the Environment Agency set up the R&D project, ‘Coastal Flood Boundary Conditions for UK Mainland and Islands’ (SC060064) to provide a consistent set of still water return level curves around the coasts of England, Wales and Scotland (Environment Agency 2011).

In 2017, the project was reviewed and the return level curves were updated in 2018 with additional data and improved science methods (Environment Agency 2019). Since the original study was commissioned in 2008, nearly 10 years of additional observational data have been recorded at Class A gauge sites. The review also identified additional secondary channel data available at Class A gauge sites. Many of the statistical methods applied during the 2018 update were the same as detailed in the 2011 report. However, a number of significant improvements were made including (Environment Agency 2019):

- improved tidal analysis and determination of skew surges with explicit calculation of the 18.6 year nodal cycle
- improved determination and removal of the long-term mean sea level trend at each tide gauge

- improved statistical treatment of the shape parameter in the skew surge distribution
- more complete determination of uncertainty (confidence intervals) in the statistical method including the choice of threshold
- a physically based approach to the determination of the extremal index parameter, used to generate the final probabilities of extremes

For most tide gauge locations, the changes in 200-year return level associated with the update are less than 0.1m. At a small number of locations the changes exceed 0.1m; for example, there is an increase of around 0.19m at the Mumbles in south Wales and a decrease of around 0.16m at Felixstowe on the east coast of England.

The update also increased the geographical extent of the analysis. The original report considered all open coastline around England, Scotland and Wales (Environment Agency 2011). The 2018 update also analysed data from the following island tide gauges:

- St Mary’s (Scilly Isles)
- Holyhead (Anglesey)
- Port Erin (Isle of Man)
- Stornoway (Hebrides)
- Lerwick (Shetland)
- Belfast (Northern Ireland)
- Portrush (Northern Ireland)
- Jersey

Data on these tide gauges from Environment Agency (2019) are tabulated for ease of reference in Appendix D.

2.6 Note on percentiles

In simplified terms, a percentile refers to the percentage of different projections falling below that level. For example, when we say that the 5th percentile of the RCP8.5 projections of mean sea level change for 2300 is 1.7m, the implication is that 5% of model projections fall below 1.7m and the other 95% are above 1.7m. Where the number of model projections is insufficient to clearly identify this level, a normal probability distribution is fitted to the model projections and the 5th percentile of the fitted distribution is used. The ‘central estimate’ usually refers to the 50th percentile projection (that is, the median value).

2.7 Definition of return period

Two conflicting definitions of return period are in common use. This report calls them the correct definition and the intuitive definition.

- **Correct definition.** The return period is defined as the expected average amount of time between exceedances. In other words, it is the reciprocal of the average rate of exceedance.

- **Intuitive definition**. The return period is defined as the reciprocal of the exceedance probability.

For long return periods (for example, 200 years), these definitions are very similar. To see the difference between them, it is necessary to look at short return periods.

Consider the one-year return level. Using the correct definition, the one-year return level is the level that is expected to be exceeded once per year on average. Even in an unchanging climate, such exceedances would not be distributed uniformly in time. There would be some years with no exceedances of the one-year return level, some with just one and some with more than one. In the long run, however, an average of one exceedance of the one-year return level per year would be expected.

Using the intuitive definition produces an absurdity. If the return period is the reciprocal of the exceedance probability, then the probability of exceeding the one-year return level must be one; it would be the level that can be guaranteed to be exceeded every year without fail. This is not meaningful in the context of the probabilistic model used here, which allows for random variations in the surge component of sea level.

This report therefore uses the correct definition. The correct definition is also used in Environment Agency (2019).

Under the correct definition, the relationship between the return period and annual exceedance probability is not a simple reciprocal. Instead it is:

$$1 - AEP = \exp\left(\frac{-1}{RP}\right) \tag{2.1}$$

where RP is return period and AEP is annual exceedance probability.

Users who wish to work in terms of annual exceedance probability can use this relationship to convert from return period to annual exceedance probability. This is an expression of the Poisson relationship, which is more familiar as:

$$\mathrm{Prob(no\ events)} = \exp(-\gamma) \tag{2.2}$$

where γ is the average rate of occurrence.

This relationship is well-approximated for large return periods by:

$$AEP \approx \frac{1}{RP}\ , (RP \gg 1) \tag{2.3}$$

For ease of reference, the best estimates of present day return levels from Environment Agency (2019) are reproduced in Appendix D.

3 Projections of coastal extreme water levels

Century-timescale changes in coastal sea level extremes are expected to be overwhelmingly dominated by the steady increase in coastal water level associated with anthropogenic sea level rise (see Section 1.1). UKCP18 reports a ‘best estimate’ projection of no change for the future characteristics of storm surges around the UK (Palmer et al. 2018b). In addition, UKCP18 analysis of historical case studies showed essentially no interaction between potential future time-mean sea level change and the characteristics of surge events. However, stakeholders should be aware of the potential for substantial changes in tidal characteristics (including tidal amplitude) under a sea level rise of the order of 1m and higher (see, for example, Pickering et al. 2012, Palmer et al 2018b).

Projections of time-mean sea level change for the UK coastline are presented in Section 3.1. These projections are then combined with the current best estimate of present day return levels in Section 3.2.

3.1 Projections of time-mean sea level change out to 2300

As part of the UKCP18 data delivery, the regional projections presented here are made available on a ~12.5km grid around the UK coastline (Figure 3.1). The time series shown are based on the average of 49 UK ports and are illustrative of the time evolution of sea level rise for the UK as a whole and the dependence on RCP climate change scenario (Figure 3.1, left panel).

As with the UKCP18 21st century projections, the UK is broadly characterised by the largest sea level rise in the south of the UK (and also Shetland) and the smallest sea level rise in southern Scotland and Northern Ireland (Figure 3.1, right panel). These spatial variations are primarily the result of the spatial pattern of GIA and the mass fingerprint associated with the Greenland ice sheet.

This spatial pattern of sea level rise is also illustrated by the projections presented for the UK’s capital cities, which illustrate the geographical representations around the UK (Figure 3.2).

Larger rises are seen for London and Cardiff, with central estimates that exceed 2m and 95th percentiles that exceed 4m for the RCP8.5 scenario. For London and Cardiff, the projection ranges at 2300 are approximately 0.5m to 2.2m, 0.8m to 2.6m and 1.4m to 4.3m for low (RCP2.6), medium–low (RCP4.5) and high (RCP8.5) emissions respectively.

Edinburgh and Belfast show smaller values, with central estimates less than 2m and 95th percentiles of approximately 3.5m for RCP8.5. The values for Edinburgh and Belfast are substantially lower than those for London and Cardiff, with corresponding ranges at 2300 of approximately 0.0m to 1.7m, 0.2m to 2.1m and 0.7m to 3.6m. Edinburgh and Cardiff also show the potential for a decrease in local sea level over the coming centuries under the RCP2.6 and RCP4.5 scenarios. This decrease arises primarily from the vertical land uplift associated with GIA in these locations; this is because the regional projections are projections of relative sea level (that is, sea level relative to the local land level).

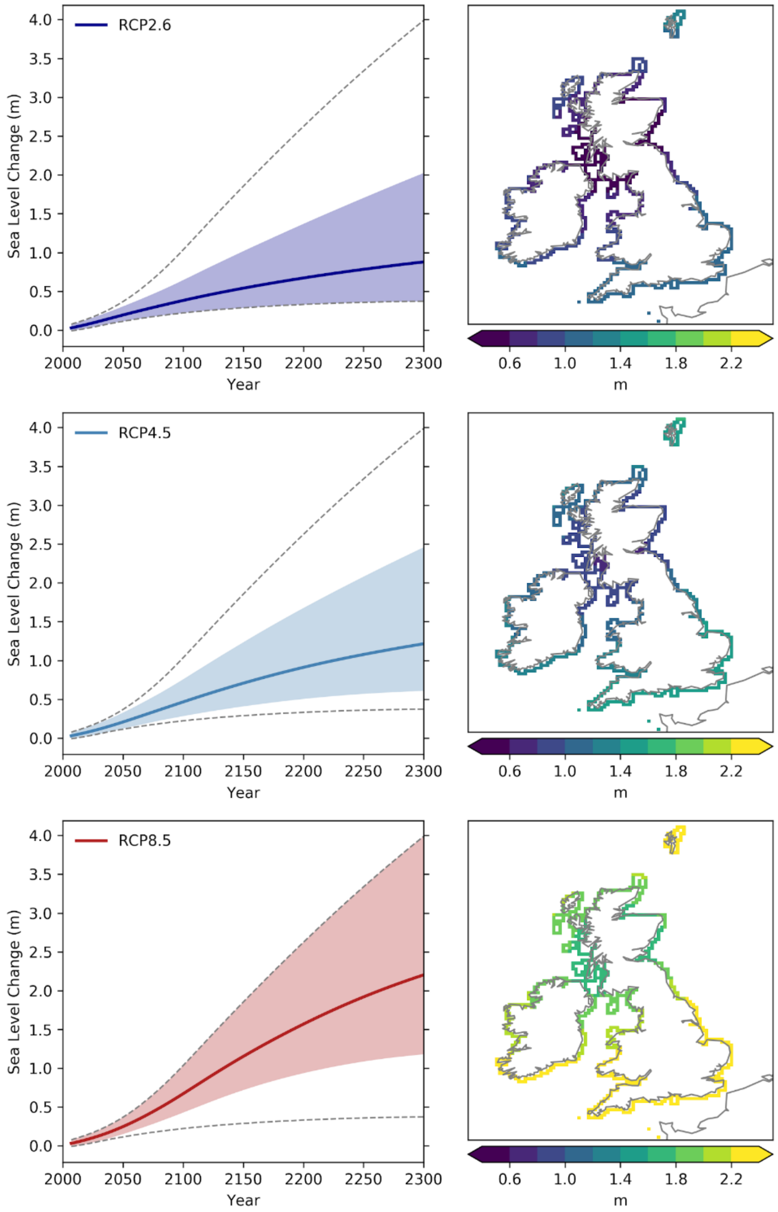

Figure 3.1 Left panel: Time series of time-mean sea level change based on the average of 49 UK ports. Right panel: The spatial pattern of change at 2300 associated with the central estimate of each RCP scenario

Notes: In the left panel, the solid line and shaded regions represent the central estimate and 5th to 95th percentile confidence range for each RCP scenario as indicated in the legend. The dashed lines indicate the overall range across RCP scenarios. All projections are presented relative to a baseline period of 1981 to 2000. Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.1.3).

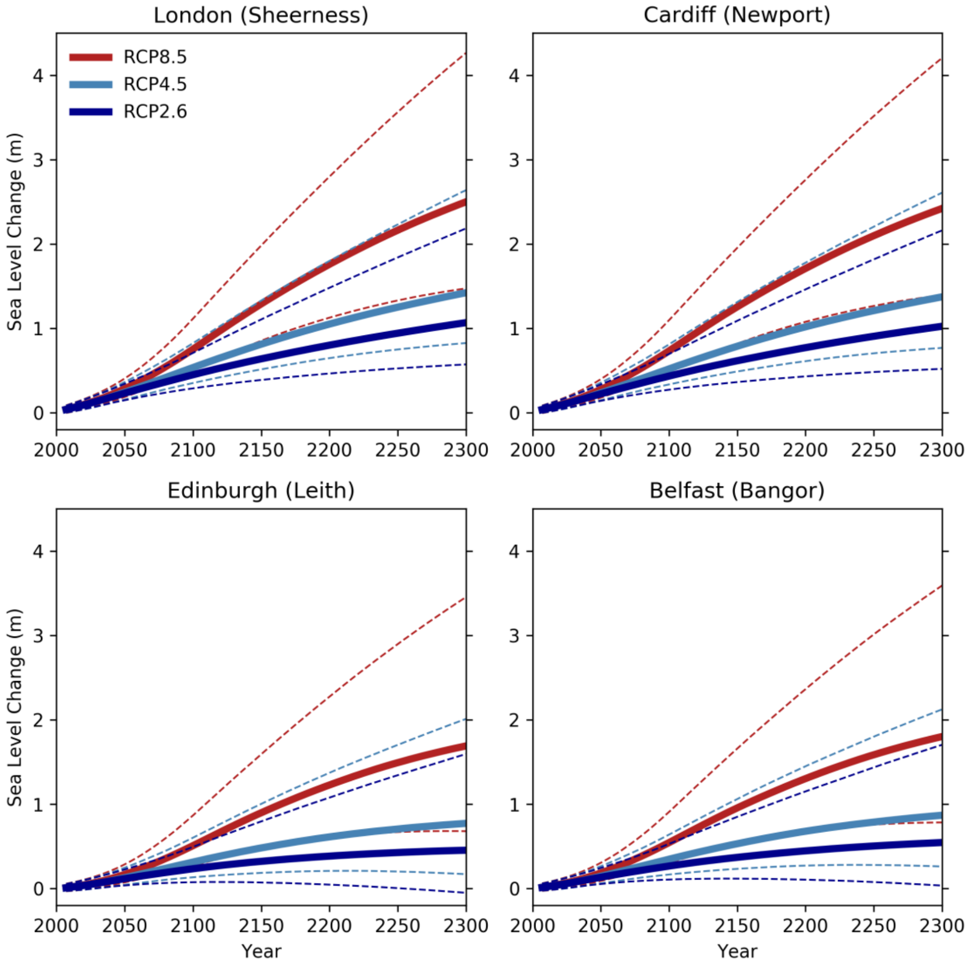

Figure 3.2 Time series of the time-mean relative sea level change for UK capital cities based on the nearest Class A tide gauge location (indicated in brackets)

Notes: Solid lines indicate the central estimate and dashed lines indicate the 5th to 95th percentile range for each RCP scenario as indicated in the legend (top left panel). All projections are presented relative to a baseline period of 1981 to 2000.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.1.4)

3.2 Changes in future return levels

The 2018 update of coastal flood boundary conditions for UK mainland and islands (Environment Agency 2019) documents the current best estimate of present day extreme still water levels (tide plus surge, but not including waves). In this report, future extreme water levels at UK tide gauges are projected by adding the 5th, 50th and 95th percentiles of projected regional relative time-mean sea level change to the present day extreme still water levels.

Figure 3.3 illustrates the projection of future return levels at 4 example tide gauge sites; tabulated data for all the 46 studied sites are provided in Appendix A. All of the data produced by this project will be made available through the UKCP18 user interface.

The uncertainty within the projection for each RCP is treated as follows in Figure 3.3. The shaded red band shows the 5th to 95th percentile range of the RCP8.5 projection. For any given panel, this band has the same vertical extent at every return period, because it shows uncertainty in the mean sea level projection only. Uncertainty in the present day return levels (which varies by return period) is not included. Combining uncertainty in present day return levels and projections of future change in a meaningful way is not straightforward and it is expected that this combination will form the basis of further work.

To avoid cluttering the plot, the uncertainty in the RCP2.6 projection is shown as a single vertical line at the 1,000-year return period, instead of a band of shading. Similarly, the uncertainty in the RCP4.5 projection is shown as a single vertical line at the 10-year return period.

Full details of the locations of the tide gauges can be found on the UK National Tide Gauge Network website (www.ntslf.org/data/uk-network-real-time) and/or the Permanent Service for Mean Sea Level website (www.psmsl.org). Nominal tide gauge locations are also given in the tables in Appendices A and D.

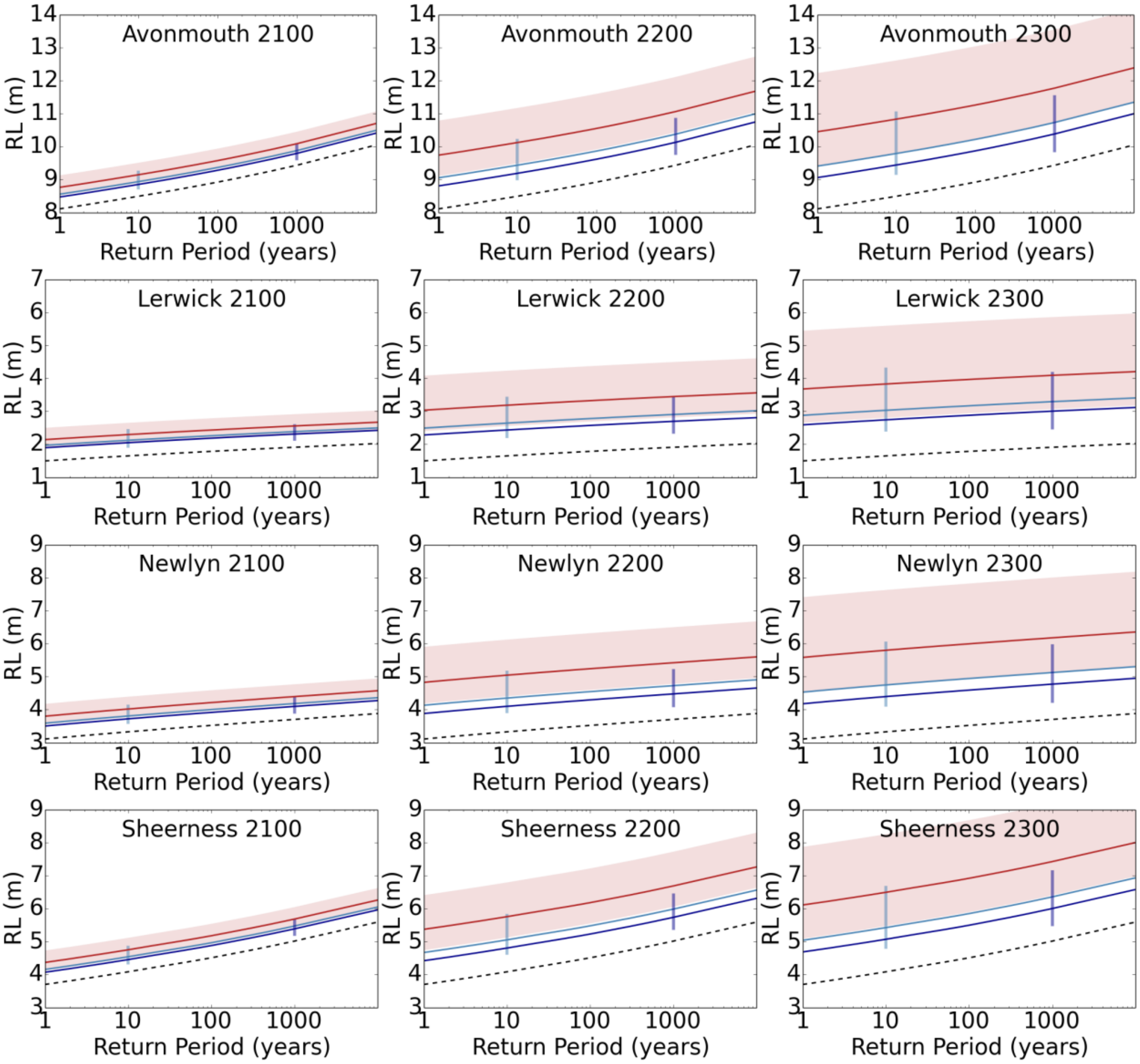

Figure 3.3 Projected future return level curves for 4 example sites.

Notes: The present day return level curve is shown by the dashed line.
The lowest (dark blue) continuous line shows the central estimate of the RCP2.6 projection.
The next (light blue) continuous line shows the central estimate of the RCP4.5 projection.
The upper (red) continuous line shows the central estimate of the RCP8.5 projection.
For details of the representation of uncertainty see the main text.

3.2.1 Discussion

The projected future extreme still water levels are not, strictly speaking, above Ordnance Datum Newlyn (ODN) because the projections include relative mean sea level change whereas ODN is an absolute datum. For full details see Appendix C.

At those coastal sites that currently experience low variability in sea level extremes (that is, they have a shallow return level curve), projected future still water[3] return levels for 2100 may be outside the envelope of present day return levels (Figure 3.3). For example, the 2100 projected one-year return level for Lerwick under RCP8.5 (high emissions) is a level that would not be expected to occur there under sustained present day mean sea levels even once in 10,000 years.

Similarly, at coastal sites that currently experience high variability in sea level extremes (that is, they have a steep return level curve), projected future still water return levels for 2100 may be inside the envelope of present day return levels. For example, the 2100 projected one-year return level for Avonmouth under RCP8.5 is a level that would be expected to occur there about every 40 years under sustained present day mean sea levels.

The return level curve at Avonmouth is steeper than the other return level curves (Figure 3.3). This is associated with the large variability in sea level at Avonmouth. One reason for this large variability at Avonmouth is that the Bristol Channel is close to resonance with the dominant mode of tidal variability, the M2 lunar mode with time period of 12 hours 25 minutes. This brings a caveat to the projections: they do not include possible changes in tidal characteristics with increased water depth.

The UKCP18 Marine Report (Palmer et al. 2018b) presents the results of a simple model experiment to investigate this effect. Comparison of their Figure 4.3.2 with Figure 4 in Pickering et al. (2012) depicting a sea level rise of 2m shows a strikingly similar spatial pattern of increase and decrease except for the region which spreads out from the Bristol Channel, where signs of change disagree between the 2 models. Flather and Williams (2000) also reported an increase in tidal range in this region with a 0.5m mean sea level rise. Flather and Williams (2000) used the same model as Palmer et al. (2018b), whereas Pickering et al. (2012, 2017) identified a decrease using 2 quite different independent global and regional models. Pelling et al. (2013) again using a different model also reported a decrease in the Bristol Channel with a 2m sea level rise and a fixed coastline. Idier et al. (2017) used a substantially higher resolution model (~2km rather than ~12.5km) and found spatially variable increases and decreases in the Bristol Channel.

Therefore, there is disagreement between models about the sign of the change in and around the Bristol Channel. More generally, Pickering et al. (2017) noted that the tidal response is strongly influenced by the treatment of the coastline: a more realistic treatment of coastal recession assuming no hard coastal engineering (in contrast to the use of simple vertical walls) is capable even of reversing the sign of the tidal response at some sites.

Although projections of change in the tidal range, particularly for the Bristol Channel, appear to be model-dependent, changes in tidal range at the coast of up to 10% (under a mean sea level increase of 3m) are seen at some locations. This is of scientific interest, but it is stressed that it is a secondary effect, with the change in time-mean sea level being the dominant effect.

---

[3] Still water level refers to water level averaged over a period (say ~15 minutes) much longer than the period of a surface wave. It accounts for tide and surge but not intermittent overtopping by waves.

Another caveat is that this report does not consider changes in extreme sea level arising as a result of changes in atmospheric storminess. Palmer et al. (2018b) in the UKCP18 Marine Report considered such changes and concluded that a central estimate of no change during the 21st century was representative of the 5 different simulations they considered. The central estimate in this report is consistent with UKCP18. It is reasonable to neglect this inflation because it is a small uncertainty compared with the much larger uncertainties in time-mean sea level change.

4 Past and future wave climate in the North Atlantic including the UK

This section presents an overview of the past (20th century) and future wave climate (21st century), with a focus on the eastern North Atlantic and surrounding UK seas (for example, the North Sea).

4.1 Overview of waves and wave generation

Waves are generated by winds acting on the sea surface. When local wind within an area of interest blows across the sea surface, it creates ‘wind waves’. Over time, waves formed in remote regions may travel long distances until they reach a location. These waves are self-sustaining and are not formed by the local winds. These are known as ‘swell waves’ or simply ‘swell’.

The parameters of wave climate[4] that are often considered for various applications are:

- the significant wave heights (SWHs)
- wave direction
- wave period

SWH is traditionally defined as the mean wave height (trough to crest) of the highest third of the waves (Holthuijsen 2007, p. 70). The wave direction is defined as the direction from where the waves are coming (for example, a westerly wave direction is one where waves are coming from the west and travelling east). The wave direction is measured in degrees from true North (which is 0 degrees). The wave period is known as the duration of one cycle to the next from the crest of one wave to the crest of another. It is measured in seconds.

The wave heights depend not only on the speed of the predominant winds but also on the wind direction and its variation (Wolf and Woolf 2006, Debernard and Røed 2008). These determine the length of the fetch[5] and the duration for which waves are forced (grown) by the wind. The frequency, intensity and passage of strong tropical or extra-tropical storms contribute to wave generation or changes in wave characteristics, and swell is especially dependent on the frequency of occurrence and the intensity of such storms in remote areas (Young et al. 2011).

For the UK therefore, the wave climate in coastal areas that are more exposed to the North Atlantic (that is, the western areas) is likely to be affected by swell, whereas the wave climate in more enclosed coastal areas (that is, along the North Sea) is likely be dominated by local wave characteristics (Bricheno and Wolf 2018).

---

[4] Wave climate is the distribution of wave characteristics averaged over a period of time for a particular location.

[5] Fetch is the area of ocean over which the wind blows in a constant direction.

4.2 Review of 20th century wave climate in the North Atlantic

This section describes the results of wave climate studies of changes in wave characteristics during the 20th century in the North Atlantic. For the purposes of this study, the North Atlantic is subdivided here further into 2 separate geographical areas:

- the north-east Atlantic (Section 4.2.1)
- the North Sea (Section 4.2.2)

4.2.1 North-east Atlantic

The majority of the existing research agrees on the direction of change in wave heights in the past several decades in the north-east Atlantic.

During the second half of the 20th century, SWHs increased in the north-east Atlantic; this finding is valid for almost all metrics (mean or extreme wave heights) used in the various analyses performed on annual, seasonal or a monthly scale. For example, Draper (1986), Sterl et al. (1998) and Cox and Swail (2001) found increases in the winter season wave heights, which is often reflected in the increases in annual mean and extreme SWH over the north-east Atlantic. Such increases in annual mean and extremes were also established by Wang et al. (2012). Some authors found that the increases were larger for the extremes compared with the mean SWHs (Cox and Swail 2001, Young et al. 2011).

Although these studies found a robust change in wave heights, the large wave climate variability in the wider North Atlantic, which is in part driven by large-scale climate modes such as the North Atlantic Oscillation (NAO) (see Section 4.3), sometimes results in very weak wave climate changes being identified in this larger region. For instance, Woolf et al. (2002) did not find any significant trends in either annual mean or winter mean SWH when considering the North Atlantic as a whole. However, they did focus on a very large area and a relatively short time period (1991 to 2000). A short time period of this kind reduces the likelihood of obtaining a robust change signal when superimposed on high wave climate variability.

4.2.2 North Sea

During the 20th century, the direction of change was also positive for both mean and extreme SWHs in the North Sea. This finding applies to the northern North Sea (see, for example, Vikebo et al. 2003), the central North Sea (Rye 1976, Pfizenmayer and von Storch 2001) and the southern North Sea (Caires et al. 2008).

As with the north-east Atlantic, the wave climate exhibits large interannual variability in the North Sea, with some authors correspondingly obtaining no significant trends in wave heights or highlighting the large interannual variability by identifying years with increases or decreases in wave activity (see, for example, Bacon 1989, Bacon and Carter 1991, Weisse and Günther 2007). For example, Weisse and Günther (2007) pointed out that severe wave conditions decreased off the UK North Sea coast between 1958 and 2002.

4.3 Review of possible causes of 20th century changes in wave climate

The relationship between wind, storminess and wave climate is complex as shown in the following studies.

- Neu (1984) commented that the low and medium sea states resulted from the influence of the prevailing westerlies, while the high and extreme sea states were generated mostly by cyclonic disturbances and mid-Atlantic storms.
- Harrison and Wallace (2005) performed a sensitivity study on the changes in wave heights and wave period in relation to changes in wind speed. They concluded that the wave heights depended on the increases in wind speed rather than being directly proportional to the wind speed itself. In contrast, the wave period depended directly on the wind speed values.
- Wolf and Woolf (2006) found that, for a location west of the Hebrides, the strength of the westerly winds contributed the most to the increase in the mean and maximum monthly wave heights, and the frequency, intensity, track and speed of storms did not significantly affect the mean wave heights. The maximum wave heights, however, were influenced greatly by the intensity, track location and speed of movement of the storms.

Many authors found a significant increase in wind speeds over the North Atlantic and especially over the north-east Atlantic since the 1950s after analysing various sources of data and using analysis periods of different lengths (Rodewald 1972, Neu 1984, Cox and Swail 2001, Bertin et al. 2013). This is consistent with the earlier noted increase in SWHs in the North-east Atlantic.

Many studies identified an overall link between wave climate and the NAO[6] in the North Atlantic, or specifically in the north-east Atlantic and the European shelf seas (see, for example, Kushnir et al.1997, The WASA Group 1998, Günther et al. 1997, Wang and Swail 2001, Bauer 2001, Woolf et al. 2002, Wang and Swail 2002, Gulev and Grigorieva 2004, Sterl and Caires 2005, Dupuis et al. 2006, Dodet et al. 2010, Mackay et al. 2010, Le Cozannet et al. 2011, Bertin et al. 2013, Bromirski and Cayan 2015, Martinez-Asensio et al. 2015).

When the NAO index is in its positive phase, the mid-latitude westerly winds are stronger than normal. A decrease in westerly wind strength occurs during a negative NAO index phase. Consequently during episodes of stronger westerly winds (during a positive NAO phase), it would be expected that the SWHs would increase as well (Jevrejeva et al. 2014). Correlations between wave heights and the NAO were positive in the north-east Atlantic (Shimura et al. 2013), while the correlations were negative in the south-west of the North Atlantic (Bertin et al. 2013) and in the subtropics south of 40°N (Kushnir et al. 1997, Wang and Swail 2001, Shimura et al. 2013). For the North Sea, Bauer (2001) established that the wave variability (the dominant modes of

---

[6] The NAO is a hemispheric meridional oscillation in atmospheric mass between a centre of action near Iceland and another over the subtropical North Atlantic (Visbeck et al. 2001). It mainly dominates the northern hemisphere winter (December, January, February) season. There are 2 phases. During a positive NAO phase, the strength of the mid-latitude westerlies increases, leading to warmer than normal and wetter than normal conditions in north-western Europe. A negative phase of the NAO results in a weaker pressure gradient between the Icelandic Low and Azores High, weakening the westerly winds and resulting in colder than normal and drier than normal conditions in north-western Europe.

synoptic scale wave variability were estimated using wavelet spectrum analysis) of the North Sea was lower when the NAO index was higher and vice versa.

Finally, studies have also focused on changes in cyclonic activity over the second half of the 20th century. Research to date indicates that storm frequency increased in the north-east Atlantic and the shelf seas (The WASA Group 1998, Gulev and Grigorieva 2004). Weisse et al. (2005) identified that the number of storms increased between 1958 and 1990, but decreased between 1990 and 1995 in the north-east Atlantic and southern North Sea; Paciorek et al. (2002) found an increase in the number of intense cyclones in the North Atlantic. As stated in Jevrejeva et al. (2014), during episodes of increased storminess, it would be expected that SWHs would increase.

4.4 Review of 21st century wave projections for the North Atlantic

There is a considerable interest in potential future changes in the wind and wave climate in light of the increased vulnerability of coastal areas. This interest is due to more people settling there and to the expanding exploration and economic development of oil and gas fields in the ocean.

The IPCC AR5 concluded that:

> '… in general, there is *low confidence* in wave model projections because of uncertainties regarding future wind states, particularly storm geography, the limited number of model simulations used in the ensemble averages, and the different methodologies used to downscale climate model results to regional scales' (Church et al. 2013, Chapter 13, p. 1204).

The most important message from the section in the UKCP18 Marine Report (Palmer et al. 2018b) on waves is that, around the UK coastline:

- the annual mean SWHs are projected to decrease by 10–20% at the end of the 21st century (2070 to 2099) compared with the historic wave climate under the highest emissions scenario (RCP8.5)
- changes in extreme waves are also of the order 10–20%, but there is no agreement in the sign of change among the model projections

For further details of each study included in the summary text below, such as the atmospheric models used to derive relevant wave climate variables and the magnitude of change and particular metric associated with a given study and emissions scenario used, see Tables B.1 to B.5 in Appendix B.

4.4.1 North-east Atlantic

At the end of the 21st century, several studies (Wang et al. 2004, Wang and Swail 2006, Leake et al. 2008, Lowe et al. 2009, Fan et al. 2013, Fan et al. 2014) projected an increase in mean SWHs during the winter season or across all seasons. The magnitude of this change is generally of the order of 5cm to 35cm. However, one study (Fan et al. 2013) projected an increase of over 50 cm within the north-east Atlantic during the winter months under the A1B emissions scenario (see Table B.3 in Appendix B).

In terms of more extreme metrics (that is, the 90th or 99th percentile of SWHs, seasonal or annual maxima or period mean of seasonal or annual maxima), many studies have again projected increases in these wave metrics. For the 90th or 99th percentile of SWHs, Wang et al. (2004) and Wang and Swail (2006) reported an up to

50cm increase in the winter or summer extremes in the north-east Atlantic (or 11% and 9% respectively compared with the relevant baseline climate values). Even greater increases in the period mean winter maximum SWHs have been projected (up to 130cm under the A2 scenario) for the period 2070 to 2100 by Leake et al. (2008), while Bricheno and Wolf (2018) indicated that the period mean annual maximum along west-facing coasts will increase by about 10–20% under RCP4.5 and 8.5 (see Table B.3 in Appendix B).

In contrast to these studies listed above, 2 studies that focused on the north-east Atlantic or the North Atlantic as a whole indicated decreases (Hemer et al. 2013b, Bricheno and Wolf 2018). The former found reductions in the monthly or seasonal mean (for example, winter monthly means will decrease by about 1m, while seasonal summer mean will decrease by about 0.2m) and 99th percentile of SWHs in the North Atlantic as a whole. The latter found that compared to historic (top panel, Figure 4.1), annual mean SWHs will decrease by about 0–5% (middle panel in Figure 4.1). Bricheno and Wolf also looked at changes in annual maximum SWH (see bottom panel, Figure 4.1)

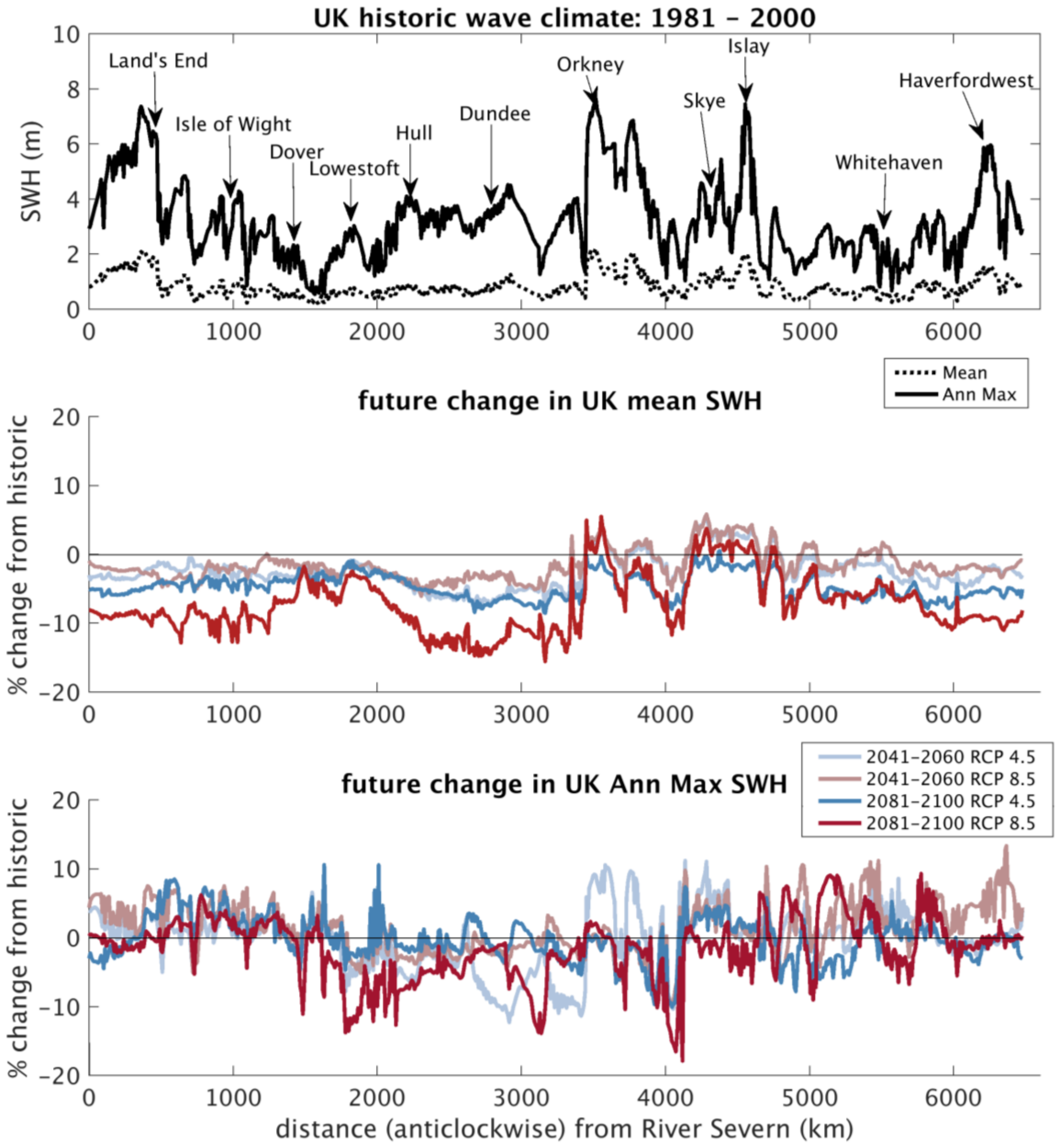

Figure 4.1 Coastal strip plots of historical wave climate and projected future changes for UK mainland

Notes: The modelled coastline of the British mainland is ‘unwrapped’ anticlockwise, starting and ending in the Bristol Channel.
The top panel shows the mean SWH (dotted line) and mean annual maximum wave height (AnnMax) (solid line) from the historical simulation.
The middle and bottom panels show percentage changes in mean SWH and AnnMax respectively relative to a 1981 to 2000 baseline period.
The 4 coloured lines represent ‘mid-21st century’ (2041 to 2060) and ‘end-21st century’ (2081 to 2100) change signals for RCP4.5 and RCP8.5.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.3.3)

Quite a few studies can be grouped together according to the geographical regions they established results for. Below the results are summarised for:

- areas to the north and north-west of the UK
- areas to the west of the British Isles
- areas to the south-west of the British Isles
- areas around the UK and Ireland
- the Liverpool Bay area

The studies that produced numerical results are summarised in more detail below. The detailed list of study results is given in Appendix B (Section B.1 and Tables B.3 and B.4.)

Areas to the north and north-west of the UK

The studies do not agree on the direction of change in wave climate. While Kaas et al. (2001) reported an increase in winter, spring and autumn mean SWHs in these areas, Mitchell et al. (2016) indicated a statistically significant decrease in the ensemble mean of the annual mean SWHs near the Bernera site (north-west of the UK) by the mid-century. Lowe et al. (2009) and Wolf et al. (2015) provided mixed results.

In contrast to Kaas et al. (2001), the study by Lowe et al. (2009) indicated that the winter (changes by up to -0.4m) and spring mean, and the annual extreme (changes by -0.3cm per year) SWHs would decrease north of the UK. However, they indicated that the summer and autumn SWHs would increase around the UK and north-west of Scotland respectively.

The study by Wolf et al. (2015) established an increase for the annual mean SWHs by mid-century contrary to that of Mitchell et al. (2016), but a decrease in this parameter by the end of the century to the north-west of Scotland contrary to Kaas et al. (2001). At the same time, Wolf et al. (2015) found that the 30-year period mean annual maxima would increase by between 10 and 20% in the north-west approaches, which is at odds with the results found by Lowe et al. (2009).

Areas to the west of the British Isles

Three of the studies agree that, in these areas, the wave climate will experience decreases.

Reductions were identified in the spring, summer and autumn mean and 99th percentile of SWHs in the West European shelf seas (Zacharioudaki et al. 2011); Gallagher et al. (2016a, 2016b) cited a decrease as large as -10% for the winter mean, and up to -5% for the spring and autumn mean SWHs off the west coast of Ireland for RCP8.5. They also found a decrease in the annual mean SWHs of about 5–10% off the Atlantic coast of Ireland for both scenarios.

Both Gallagher et al. (2016a, 2016b) and Aarnes et al. (2017) identified decreases in the 95th or 99th percentile of the SWHs. In the winter, the extremes would decrease by about 5%, while in summer the reductions would be largest at more than 10% (Gallagher et al. 2016a, 2016b). The annual 99th percentile and maximum would decrease by about 2–6% to the west of UK and Ireland (Aarnes et al. 2017).

Only one study indicated increases in these areas: Debernard and Røed (2008) found an increase in the winter 99th percentile of SWHs by 2–4% west of the British Isles and up to a 6% increase in the 99th percentile of the annual SWH west of the British Isles.

Areas to the south-west of the British Isles

Several studies agreed that the annual mean SWHs would decrease (Zacharioudaki et al. 2011, Reeve et al. 2011, Wolf et al. 2015, Perez et al. 2015).

Zacharioudaki et al. (2011) estimated a 3-5% reduction, while Reeve et al. (2011) indicated a decrease in annual mean wave power of -2.27% under the B1 scenario at the Wave Hub test site off the north coast of Cornwall; however, they found an increase of similar magnitude under the A1B scenario. Perez et al. (2015) established a decrease varying between 0.04m and 0.08m, depending on the emissions scenario. A decrease in the summer seasonal mean (up to 15%) and 95th percentile of SWHs was also indicated by Gallagher et al. (2016a, 2016b) off the south coast of Ireland.

In contrast and further enhancing the picture of the changes to the south-west of the UK and Ireland, several studies established an increase in seasonal means, and seasonal and annual extremes in these areas (Leake et al. 2008, Lowe et al. 2009, Zacharioudaki et al. 2011, Wolf et al. 2015). Numerical results include:

- an increase in winter mean around 0.1m in the English Channel (Lowe et al 2009)
- >0.14m south-west of the UK (Leake et al. 2008)
- 4–8% (Zacharioudaki et al. 2011)
- changes in the extremes varying around >0.4m for the winter maximum (Leake et al. 2008)
- 10–20% by the end of the century for the period mean of annual maximum SWHs. (Wolf et al. 2015)

Figure 4.2 shows the change in SWH between the present day and future projections as established by Wolf et al. (2015) in a report for the RISES-AM EU FP7 Collaborative Research Project (Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation).

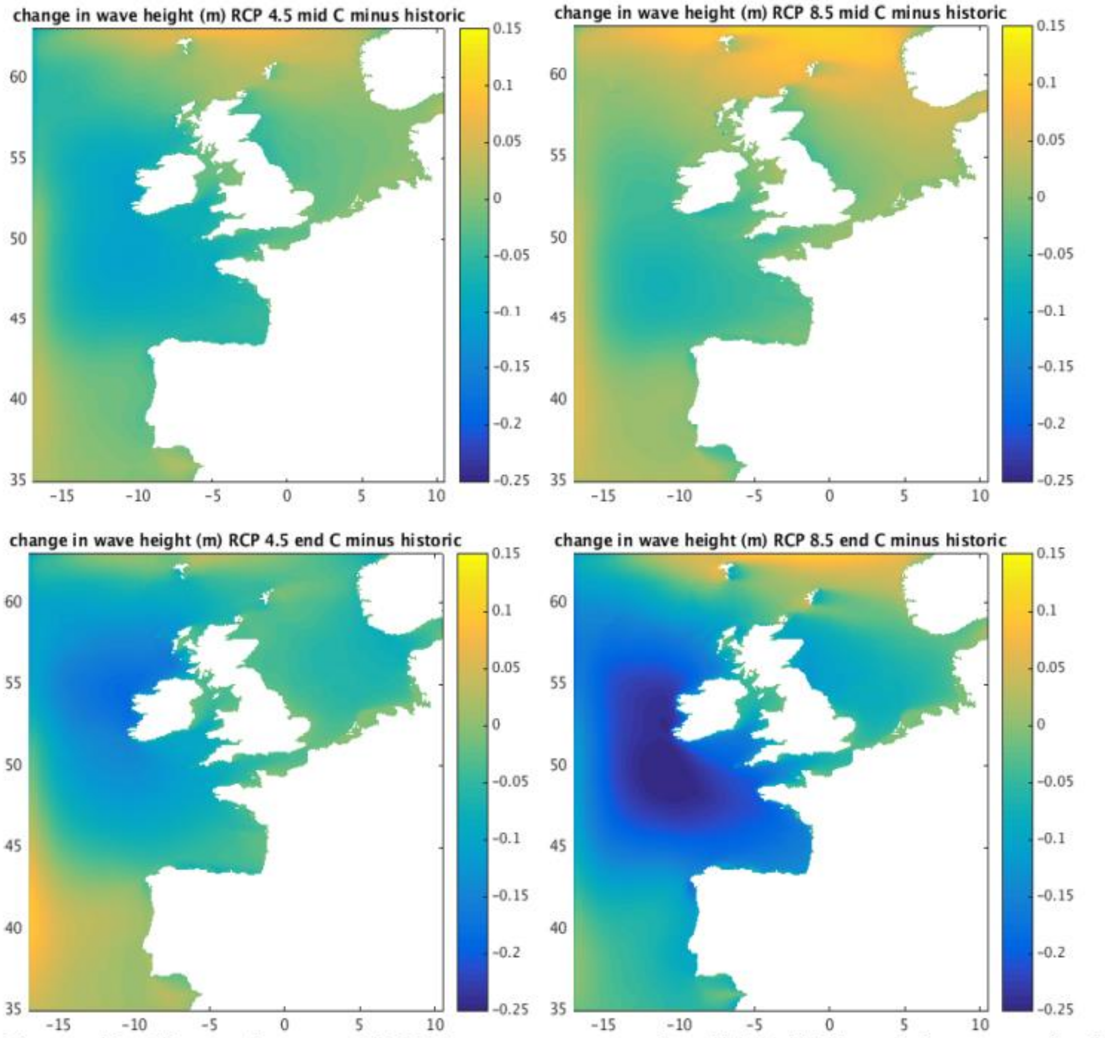

Figure 4.2 Change in mean SWH between present day (1970 to 1999) and future projections: RCP4.5 (left column) and RCP8.5 (right column). Top row: mid-century (2030 to 2059). Bottom row: end-century (2070 to 2099)

Source: Wolf et al. (2015, Figure 13)

Areas around Ireland or UK as a whole

Three studies agreed that the annual mean SWHs would decrease:

- Perez et al. (2015) (see above)
- Aarnes et al. (2017): reductions of 2–6% and up to 8% around Great Britain and Ireland
- Bricheno and Wolf (2018): decreases of 0–5% around the UK coast

However, 2 studies provide conflicting results about the annual maximum SWHs

- Wolf et al. (2015) found increases varying between 10% and 30% around Ireland, except for the areas to the east of Ireland in the 30-year period mean of annual maximum SWHs.
- Aarnes et al. (2017) indicated a decrease in the annual 90th percentile of 2–4% around the UK and 4–6% around Ireland.

Liverpool Bay area:

Brown et al. (2012) found differing patterns of change depending on the month or season of the year in the Liverpool Bay area including:

- increases in mean monthly SWHs in December, November and June (largest, about 16% in June)
- increases in large and extreme wave events[7] varying between 0.31% and 9.5% during the winter months
- decreases in the rest of the months (largest in September, -20%)
- decreases in seasonal mean SWHs (for example, about -8.8% for spring and -5.5% for summer)

4.4.2 North Sea

Two studies that consider the North Sea as a whole agreed that seasonal mean SWHs and/or annual extreme waves will increase in the future (Kaas et al. 2001, Caires et al. 2008).

The rest of this section follows a similar structure to that in the previous section. The projected changes are presented in order according to the geographical focus of the reviewed studies and projected results; the southern and eastern North Sea, and the western North Sea are presented separately.

The studies that established numerical results are summarised in more detail here. The detailed list of study results is given in Appendix B (Section B.2 and Table B.5).

Southern and eastern sections of the North Sea

The majority of the research agrees that annual median or extremes – or winter mean and extremes – will increase in the future (Debernard and Røed 2008, Grabemann and Weisse 2008, Lowe et al. 2009, Groll et al. 2014, Wang et al. 2014, Grabemann et al. 2015, Wolf et al. 2015). Wolf et al. (2015) found increases for the eastern North Sea only; they found decreases for the southern North Sea.

The identified increases in the seasonal or annual extremes vary between 5% and 8% (Debernard and Røed 2008, Wolf et al. 2015) or from 5% to 8% up to 18% for the annual 99th percentile (or 0.25–0.35m, Grabemann and Weisse 2008). Wang et al. (2014) also established that the 1 in 10 years SWH event would double or triple in frequency along the Danish coast under RCP8.5.

For the southern North Sea, however, Leake et al. (2008) obtained somewhat conflicting results depending on the emissions scenario. They identified increases near East Anglia in the winter mean and winter maximum SWH of 0.1m and 0.2m respectively, and an increase in the annual maximum SWH of 0.2m under the A2 scenario. Under the B2 emissions scenario, they identified decreases of -0.04m (-0.19m) in the winter mean (extremes) and a -0.56m reduction in the annual maximum.

Western and north-western sections of the North Sea

Existing research agrees on the projected decreases in the annual mean/median and extreme SWHs (Debernard and Røed 2008, Grabemann and Weisse 2008, De Winter

---

[7] See Section B.1.5 in Appendix B for definitions of the ‘large’ and ‘extreme’ wave events.

et al. 2012, Groll et al. 2014, Grabemann et al. 2015, Wolf et al. 2015, Aarnes et al. 2017). For example the annual mean SWH is projected to decrease by 2–4% (Debernard and Røed 2008) and up to 6% (Aarnes et al. 2017) by the end of the century. Aarnes et al. (2017) identified the same percentage reductions for the annual maximum, 90th and 99th percentile SWHs. Grabemann and Weisse (2008), Groll et al. (2014) and Grabemann et al. (2015) also all pointed to decreases;, Grabemann and Weisse (2008), Groll et al. (2014) established decreases of between 0.02m and 0.05m in the median SWH in the western and north-western parts of the North Sea, while Grabemann et al. (2015) projected reduction of between 0.25m and 0.75m in the annual median off the northern British coast.

Finally, some authors did not identify significant changes either when considering the North Sea as a whole or when studying a small area close to the UK or Dutch coasts: De Winter et al. (2012) indicated that the annual mean wave climate would not differ in the future in a small area in front of the Dutch coast or a small decrease would be seen in the annual maximum. Wolf et al. (2015) found that the future wave climate off the north Norfolk coast will not change compared with the current wave climate.

4.5 Uncertainty sources and considerations

Projections of 21st century wave climate are inherently uncertain. This has to some degree already been noted through the differing sign and/or magnitude of the wave heights projections in the literature. Some key sources of uncertainty are discussed below.

4.5.1 Climate model uncertainty

Uncertainty in the climate model is important to consider. The number of climate models and which specific models are being used varies (see Tables B.1 and B.2 in Appendix B). Each individual study has its own set of atmospheric climate models that are used to drive a (set of) wave model(s). This gives rise to ‘structural’ uncertainty because the ways in which the mathematical equations are solved within each model and the used parameterisations differ.

4.5.2 Emissions scenario uncertainty

Different emissions scenarios will give rise to different wave climate projections, particularly at the end of the 21st century. For instance, RCP8.5, being the highest concentration pathway, will give rise to the largest changes in wave heights in general. This would mainly be attributed to the large climate change effects on atmospheric circulation, which would then have an impact on the wave climate. On the other hand, RCP2.5, which would include strong greenhouse gas mitigation measures, would result in the least change in wave climate relative to the present since there would be less external climate forcing that could change the atmospheric circulation and hence ultimately the wave climate.

4.5.3 Experimental method

Another source of uncertainty is the experimental method used to produce the wave climate projections.

Some studies (for example, Wang and Swail 2006) used statistical methods where a statistical relationship between a large-scale driving variable such as mean sea level pressure from a global climate model (GCM) and the parameter of interest (waves in this case) is first established. The statistical relationship is formed from observed wave data compared with the historical mean sea level pressure fields from re-analysis data. The projections of changes in mean sea level pressure fields are then inputted into the statistical model to give projections of wave climate for the period of interest.

Some studies use wave models to obtain the wave climate simulations, with GCMs providing boundary input information. To obtain local-scale results, these studies use a technique called dynamical downscaling where the output of GCMs is used as input to regional climate models, which then provide higher resolution boundary information for a regional wave model representing the area of interest. These methodological differences will lead to different projections of the local wave climate.

4.5.4 Natural climate variability

The variability in the natural climate should also be considered when talking about the uncertainty in the wave climate projections. As mentioned previously, inherently large wave variability has been observed in the 20th century and hence some authors have commented that the changes by the end of this century may be partly related to internal variability rather than to external forcing (Grabemann et al. 2015). Mitchell et al. (2016) also indicated that the changes in wave climate by 2050 were smaller than the interannual variability of the wave climate in the Bernera and Wave Hub sites, as well as being smaller than the uncertainty in the climate projections. Hence the characterisation of the interannual variability of the wave climate would remain important for the years up to the middle of this century.

4.5.5 Locally driven waves versus swell waves

Those areas that are less exposed around the UK, such as the Irish Sea and the east coast of the UK may be dominated by high internal wave variability well into the 21st century. This is because these regions are far less influenced by swell waves that originate from remote locations than they are from locally generated waves from storm systems. Extracting a robust climate change signal in these regions as a result of the high variability associated with the generation of wind waves from storm systems (especially from a single model) can be difficult.

Studies have found that, when only one GCM was used under a few emissions scenarios, the results depended on the emissions scenario (Wang et al. 2004, Reeve et al. 2011). However, when a larger GCM ensemble was used in addition to the various emissions scenarios, all the studies agreed that the modelling uncertainty was greater than the emissions scenario uncertainty (Wang and Swail 2006, Debernard and Røed 2008, Grabemann and Weisse 2008, Charles et al. 2012, Wang et al. 2015).

4.5.6 Additional sources of uncertainty

Two studies explored additional sources:

- natural variability (Grabemann et al. 2015)
- wave climate generation methodology (Hemer et al. 2013a)

Grabemann et al. (2015) concluded that emissions scenarios had the least importance as a source of uncertainty. Hemer et al. (2013a) who studied the ensemble of opportunity in the COWCLIP project,[8] concluded that the uncertainty due to study methodology was greater than the modelling or emissions scenario uncertainty.

Finally, the geographical scope of the study and the time periods used are also important. Some authors have focused on larger areas in the North Atlantic and others on smaller regions. In terms of the time period, this consideration includes both the baseline period and the future time period in the 21st century against which the historic or baseline values are compared. For example, some authors have used a 1961 to 1990 baseline, whereas others have employed a 1971 to 2000 reference period. Similar time offsets are evident at the end of the 21st century.

4.6 Review of possible causes of 21st century changes in wave climate

Many authors have indicated that the changes in the projected wave climate are significantly related to the expected changes in wind characteristics (Kaas et al. 2001, Debernard and Røed 2008, Grabemann and Weisse 2008, Mori et al. 2010, Brown et al. 2012, Charles et al. 2012, De Winter et al. 2012, Hemer et al. 2013a, Gallagher et al. 2016a, Gallagher et al. 2016b).

Some authors have found that, in a warming climate, the intensity of the westerlies will increase in winter, leading to enhanced wind speeds and ultimately higher winter seasonal mean SWHs in the North-east Atlantic (Wang et al. 2004, Fan et al. 2013, Fan et al. 2014). These authors suggested that this would be due to an increased frequency of the positive phase of the NAO.

Research has also linked changes in wave climate to changes in the cyclonic activity in the future (Wang and Swail 2006). Lowe et al. (2009) indicated that, in winter and autumn, the changes in total SWH were closely linked to the changing storms in the North Atlantic. More frequent occurrence of strong cyclones expected in a warmer climate (Wang et al. 2004) was projected to affect wave development and lead to increases in wave heights in the north-east Atlantic.

4.7 Gaps in understanding

An important caveat to have in mind for all of the discussed studies is the realism of the storminess characteristics in the GCM simulations. Since the swell waves are generated remotely, the hypothesis is that the climate projections may be more robust – in that they may be less sensitive to the precise details of how weather systems change in the future. But if extreme wave climate conditions are of interest, the representation of storms and the atmospheric resolution of the model will still be important, because very strong winds or very large storms create long period swell (Andrew Saulter, personal communication).

Another specific gap in the existing research is the consideration of the retreat of Arctic sea ice and how it can affect the wave climate on northward facing coasts (especially in the north north-east parts of the North Atlantic) through the potential for a larger fetch for northerly winds and a systematic increase of the wave maxima. It is also worth considering whether and how the changes in ice coverage may affect the storm track (Andrew Saulter, personal communication).

---

[8] Coordinated Ocean–Wave Climate Projections project

Finally, although some of the models do include wave generation processes in shallow waters, wave climate changes closer to coasts are not directly inferable from the existing research and merit focused investigation.

4.8 Conclusions from the waves literature review

During the second half of the 20th century, SWHs have increased in the north-east Atlantic, consistent with the identified increases in wind speed and storm frequency, and in the number of intense cyclones passing through the area. In the North Sea, the mean and extreme SWHs have increased as well. The wave climate in both regions was characterised by high interannual and decadal variability.

The UKCP18 21st century projections of offshore average wave height suggest changes of the order of 10–20% and a general tendency towards lower wave heights (Palmer et al. 2018b). Changes in extreme offshore waves are also of the order of 10–20%, but there is no agreement on the sign of the change among the model projections. High resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be determined by the global response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability over the 21st century.

In terms of the established changes in the offshore wave climate in the north-east Atlantic and various smaller areas around the UK, the rest of the studies indicate the following.

- For the north-east Atlantic, existing research agrees on the projected increases in seasonal mean SWHs, or seasonal and annual extremes of SWHs. The changes vary between 5cm and 35cm or up to 50cm for the seasonal means, around 50cm for seasonal extremes, and up to 130cm or by about 10–20% for the period mean of the annual maxima for west-facing coasts.
- For the areas north or north-west of the UK, the existing studies do not agree on the sign of the change in annual and seasonal mean and extreme SWHs.
- For the areas to the west of the British Isles, most studies indicate a decrease in the seasonal mean and extreme SWHs (the changes vary between -5 and -10%). In agreement with the UKCP18 findings, the annual mean of the SWHs is also projected to decrease (by 5–10% off the west coast of Ireland). The annual maxima or 99th percentile are found to decrease by about 2–6% west of the UK and Ireland. Only one study indicated increases in the annual extremes west of the British Isles by 2–6% (Debernard and Røed 2008).
- For the areas to the south-west of the British Isles, in accordance with the UKCP18 results the annual mean SWHs were projected to decrease by several studies (the changes were between 3% and 5% or 0.04–0.08m). The annual extremes were projected to increase by 10–20% for the period mean of the annual maxima. The results on the changes in the summer mean SWHs are conflicting; several studies projected increases in seasonal means and extremes especially for winter (increases of winter means are between 4% and 8%, or around 0.1m, while the extremes would rise by about 0.4m).
- For the areas around Ireland and the UK, in general, the studies indicated that the annual mean SWHs would decrease (by between 2 and 8%) in

agreement with the UKCP18 results and the above mentioned results about the areas to the west of UK; The results regarding the changes in the annual extreme SWHs are conflicting.

- For the Liverpool Bay area, the research has indicated decreases in seasonal and most monthly means (up to -20% in September and up to -8.8% in spring), but increases in extreme wave events of between 0.31% and 9.5%. The findings on the changes in the average SWHs are in parallel with the UKCP18 results.

For the North Sea, the results from the reviewed studies indicate an increase in the projected seasonal means or extremes of the wave climate, and of the annual extremes in the basin as a whole. Considering regional changes in the wave climate, the research indicates an increase in annual median or extremes, or winter mean and extreme SWHs within the southern and eastern North Sea. The projected changes vary between 5% and 8%, or up to 18% for seasonal and annual extremes, or also between 0.25 and 0.35m for the annual 99th percentile. The studies agree that the western and north-western sections of the North Sea will be characterised by reductions in the annual mean and extreme SWHs varying around 2–6%, or between 0.02–0.05m and 0.25–0.75m.

Despite the uncertainties in the wider literature, for decision-making purposes, it is recommended that the headlines within the UKCP18 wave study that translate to pertinent wave climate projections at coastal locations around the UK are followed.

Finally, in coastal flood risk assessment any change in offshore wave climate due to climate change does not have as great an impact as the increased water depths due to sea level rise, which allow a bigger wave to reach the flood defences. Waves are depth limited in the UK shallow water coastline (controlling features are water depth, wavelength and seabed slope) and any changes to offshore wave height without a commensurate increase in water depth are not transformed to the defence. Wave height and period are critical features for consideration in coastal defence and 2 important points are highlighted with wave height (assuming no changes predicted to wave period).

- With increasing wave height, breaking later, flood water volumes will increase in the flood zones.
- With increasing wave height, breaking later, the energy of the waves increases by the square (that is, a wave that is twice as high will have 4 times the energy). This has huge implications for the infrastructure vulnerability on the coast in the UK.

In summary, the sea level rise element of climate change is expected to have a greater impact on coastal defences than changes in offshore wave magnitudes due to changes in weather patterns (Tim Hunt, personal communication).

References

AARNES, O.J., REISTAD, M., BREIVIK, Ø., BITNER-GREGERSEN, E., INGOLF EIDE, L., GRAMSTAD, O., MAGNUSSON, A.K., NATVIG, B. AND VANEM, E., 2017. Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic. *Journal of Geophysical Research: Oceans*, 122 (4), 3394-3403.

BACON, S., 1989. *Waves recorded at Dowsing Light Vessel 1970-1985*. Report No. 262. Godalming, Surrey: Institute of Oceanographic Sciences, Deacon Laboratory, National Environmental Research Council.

BACON, S. AND CARTER, D.J.T., 1991. Wave climate changes in the North Atlantic and North Sea. *International Journal of Climatology*, 11 (5), 545-558.

BAUER, E., 2001. Interannual changes of the ocean wave variability in the North Atlantic and in the North Sea. *Climate Research*, 18 (1-2), 63-69.

BERTIN, X., PROUTEAU, E. AND LETETREL, C., 2013. A significant increase in wave height in the North Atlantic Ocean over the 20th century. *Global and Planetary Change*, 106, 77-83.

BRICHENO, L.M. AND WOLF, J., 2018. Future wave conditions of Europe, in response to high-end climate change scenarios. *Journal of Geophysical Research: Oceans*, 123, https://doi.org/10.1029/2018JC013866.

BROMIRSKI, P.D. AND CAYAN, D.R., 2015. Wave power variability and trends across the North Atlantic influenced by decadal climate patterns. *Journal of Geophysical Research: Oceans*, 120 (5), 3419-3443.

BROWN, J.M., WOLF, J. AND SOUZA, A.J., 2012. Past to future extreme events in Liverpool Bay: model projections from 1960–2100. *Climatic Change*, 111 (2), 365-391.

CAIRES, S., GROENEWEG, J. AND STERL, A., 2008. Past and future changes in the North Sea extreme waves. In *Coastal Engineering 2008*, Proceedings of the 31st International Conference on Coastal Engineering (Hamburg, 2008), edited by J. McKee Smith). Singapore: World Scientific

CHARLES, E.D., IDIER, D., DELECLUSE, P., DÉQUÉ, M. AND LE COZANNET, G., 2012. Climate change impact on waves in the Bay of Biscay, France. *Ocean Dynamics*, 62 (6), 831-848.

CHURCH, J.A., CLARK, P.U., CAZENAVE, A., GREGORY, J.M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M.A., MILNE, G.A., NEREM, R.S., NUNN, P.D., PAYNE, A.J., PFEFFER, W.T., STAMMER, D. AND UNNIKRISHNAN, A.S., 2013. Sea level change. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley), Chapter 13, pp. 1137-1216. Cambridge and New York: Cambridge University Press.

COX, A.T. AND SWAIL, V.R., 2001. A global wave hindcast over the period 1958–1997: validation and climate assessment. *Journal of Geophysical Research: Oceans*, 106 (C2), 2313-2329.

DEBERNARD, J.B. AND RØED, L.P., 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus A*, 60 (3), 427-438.

DECONTO, R.M. AND POLLARD, D., 2016. Contribution of Antarctica to past and future sea-level rise. *Nature*, 531, 591-597.

DE WINTER, R.C., STERL, A., DE VRIES, J.W., WEBER, S.E. AND RUESSINK, G., 2012. The effect of climate change on extreme waves in front of the Dutch coast. *Ocean Dynamics*, 62 (8), 1139-1152.

DODET, G., BERTIN, X. AND TABORDA, R., 2010. Wave climate variability in the North-East Atlantic Ocean over the last six decades. *Ocean Modelling*, 31 (3) 120-131.

DRAPER, L., 1986. *Wave measurements at North Atlantic weather stations 'India' and 'Juliett' in the 1970s (India 2 and Juliett 2).* Report No. 222. Prenton, Merseyside: Institute of Oceanographic Sciences, Bidston Laboratory, National Environmental Research Council.

DUPUIS, H., MICHEL, D. AND SOTTOLICHIO, A., 2006. Wave climate evolution in the Bay of Biscay over two decades. *Journal of Marine Systems*, 63 (3), 105-114.

ENVIRONMENT AGENCY, 2011. *Coastal flood boundary conditions for UK mainland and islands – Design sea levels*. Report SC060064/TR2. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2019. *Coastal flood boundary conditions for UK mainland and islands – update 2018*. *Technical summary report.* Bristol: Environment Agency.

FAN, Y., HELD, I.M., LIN, S.J. AND WANG, X.L., 2013. Ocean warming effect on surface gravity wave climate change for the end of the twenty-first century. *Journal of Climate,* 26 (16), 6046-6066.

FAN, Y., LIN, S.J., GRIFFIES, S.M. AND HEMER, M.A., 2014. Simulated global swell and wind-sea climate and their responses to anthropogenic climate change at the end of the twenty-first century. *Journal of Climate*, 27 (10), 3516-3536.

FLATHER, R.A. AND WILLIAMS, J., 2000. Climate change effects on storm surges: methodologies and results. In *Climate Scenarios for Water-Related and Coastal Impacts,* ECLAT-2 KNMI Workshop Report No. 3 (De Bilt, The Netherlands, 2000), edited by J. Beersma, M. Agnew, D. Viner and M. Hulme, pp. 66-78. Norwich: Climatic Research Unit, University of East Anglia.

GALLAGHER, S., GLEESON, E., TIRON, R., MCGRATH, R. AND DIAS, F., 2016a. Wave climate projections for Ireland for the end of the 21st century including analysis of EC-Earth winds over the North Atlantic Ocean. *International Journal of Climatology*, 36 (14), 4592-4607.

GALLAGHER, S., GLEESON, E., TIRON, R., MCGRATH, R. AND DIAS, F., 2016b. Twenty-first century wave climate projections for Ireland and surface winds in the North Atlantic Ocean. *Advances in Science and Research*, 13, 75-80.

GEOFFROY, O., SAINT-MARTIN, D., OLIVIÉ, D.J., VOLDOIRE, A., BELLON, G. AND TYTÉCA, S., 2013a. Transient climate response in a two-layer energy-balance model. Part I: analytical solution and parameter calibration using CMIP5 AOGCM experiments. *Journal of Climate*, 26, 1841-1857.

GEOFFROY, O., SAINT-MARTIN, D., BELLON, G., VOLDOIRE, A., OLIVIÉ, D.J., & TYTÉCA, S., 2013b. Transient climate response in a two-layer energy-balance model. Part II: Representation of the efficacy of deep-ocean heat uptake and validation for CMIP5 AOGCMs. *Journal of Climate*, 26, 1859-1876.

GRABEMANN, I. AND WEISSE, R., 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. *Ocean Dynamics*, 58, 199-212.

GRABEMANN, I., GROLL, N., MÖLLER, J. AND WEISSE, R., 2015. Climate change impact on North Sea wave conditions: a consistent analysis of ten projections. *Ocean Dynamics*, 65 (2), 255-267.

GRINSTED, A., 2013. An estimate of global glacier volume. *The Cryosphere*, 7, 141-151.

GROLL, N., GRABEMANN, I. AND GASLIKOVA, L., 2014. North Sea wave conditions: an analysis of four transient future climate realizations. *Ocean Dynamics*, 64 (1), 1-12.

GULEV, S.K. AND HASSE, L., 1999. Changes of wind waves in the North Atlantic over the last 30 years. *International Journal of Climatology*, 19 (10), 1091-1117.

GULEV, S.K. AND GRIGORIEVA, V., 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research Letters*, 31 (24), L24302.

GÜNTHER, H., ROSENTHAL, W., STAWARZ, M., CARRETERO, J.C., GOMEZ, M., LOZANO, L., SERRANO, O. AND REISTAD, M., 1997. *The wave climate of the Northeast Atlantic over the period 1955-1994: the WASA wave hindcast.* GKSS97/E/73. Geesthacht, Germany: GKSS Forschungszentrum Geesthacht GmbH-Publications-E.

HARRISON, G. AND WALLACE, R., 2005. Sensitivity of wave energy to climate change. *IEEE Transactions on Energy Conversion*, 20 (4), 870-877.

HEMER, M.A., FAN, Y., MORI, N., SEMEDO, A. AND WANG, X.L., 2013a. Projected changes in wave climate from a multi-model ensemble. *Nature Climate Change*, 3 (5), 471-476.

HEMER, M.A., KATZFEY, J. AND TRENHAM, C.E., 2013b. Global dynamical projections of surface ocean wave climate for a future high greenhouse gas emission scenario. *Ocean Modelling*, 70, 221-245.

HOLTHUIJSEN, H., 2007. *Waves in Oceanic and Coastal Waters*. Cambridge and New York: Cambridge University Press.

IDIER, D., PARIS, F., LE COZANNET, G., BOULAHYA, F. AND DUMAS, F., 2017. Sea-level rise impacts on the tides of the European Shelf. *Continental Shelf Research*, 137, 56-71.

JEVREJEVA, S., WOLF, J., HARLE, J., BRICHENO, L., BROWN, J., CANNABY, H., JACKSON, L., LIONELLO, P., SCARASCIA, L., DINU, I., PAU SIERRA, J., AND A. SANCHEZ ARCILLA., 2014. *Physical projections at global scale for sea level rise, storminess, surge and wave distributions under RCP scenarios.* RISES-AM EU FP7 Collaborative Research Project (Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation). Work Package D2.4 report.

WOLF, J., BRICHENO, L., LIONELLO, P., CONTE, D., GASLIKOVA, L. AND JEVREJEVA, S., 2015. *Results from NW European wave modelling.* RISES-AM EU FP7 Collaborative Research Project (Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation). Work Package D2.5 report, Annex 1.

KAAS, E., ANDERSEN, U., FLATHER, R., WILLIAMS, J.A., BLACKMAN, D., LIONELLO, P., DALAN, F., ELVINI, E., NIZZERO, A., MALGUZZI, P., PFIZENMAYER, A., VON STORCH, H., DILLINGH, D., PHILIPPART, M., DE RONDE, J., REISTAD, M., MIDTBØ, K., VIGNES, O., HAAKENSTAD, H., HACKETT, B., FOSSUM, I. AND SIDSELRUD, L., 2001. *Synthesis of the STOWASUS-2100 project: regional storm, wave and surge scenarios for the 2100 century*. Copenhagen: Danish Meteorological Institute.

KUSHNIR, Y., CARDONE, V.J., GREENWOOD, J.G. AND CANE, M.A., 1997. The recent increase in North Atlantic wave heights. *Journal of Climate*, 10 (8), 2107-2113.

LEAKE, J., WOLF, J., LOWE, J., STANSBY, P., JACOUB, G., NICHOLLS, R., MOKRECH, M., NICHOLSON-COLE, S., WALKDEN, M., WATKINSON, A. AND HANSON, S., 2008. Predicted wave climate for the UK: towards an integrated model of coastal impacts of climate change. In *Estuarine and Coastal Modelling*, Proceedings of 10th International Conference on Estuarine and Coastal Modelling (Newport, Rhode Island 2007), edited by M/L/ Spaulding, pp. 393-406. Reston, VA: American Society of Civil Engineers.

LE COZANNET, G., LECACHEUX, S., DELVALLEE, E., DESRAMAUT, N., OLIVEROS, C. AND PEDREROS, R., 2011. Teleconnection pattern influence on sea-wave climate in the Bay of Biscay. *Journal of Climate*, 24 (3), 641-652.

LEVERMANN, A., WINKELMANN, R., NOWICKI, S., FASTOOK, J.L., FRIELER, K., GREVE, R., HELLMER, H.H., MARTIN, M.A., MEINSHAUSEN, M., MENGEL, M., PAYNE, A.J., POLLARD, D., SATO, T., TIMMERMANN, R., WANG, W.L. AND BINDSCHADLER, R.A., 2014. Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models. *Earth System Dynamics*, 5, 271-293.

LORBACHER, K., NAUELS, A. AND MEINHAUSEN, M., 2015. Complementing thermosteric sea level rise estimates. *Geoscientific Model Development*, 8 (9), 2723-2734.

LOWE, J., HOWARD, T., PARDAENS, A., TINKER, J., HOLT, J., WAKELIN, S., MILNE, G., LEAKE, J., WOLF, J., HORSBURGH, K., REEDER, T., JENKINS, G., RIDLEY, J., DYE, S. AND BRADLEY, S., 2009. *UK Climate Projections science report: marine and coastal projections.* Exeter: Met Office Hadley Centre.

MACKAY, E.B.L., BAHAJ, A.S. AND CHALLENOR, P.G., 2010. Uncertainty in wave energy resource assessment. Part 2: Variability and predictability. *Renewable Energy*, 35 (8), 1809-1819.

MARTÍNEZ-ASENSIO, A., TSIMPLIS, M.N., MARCOS, M., FENG, X., GOMIS, D., JORDÀ, G. AND JOSEY, S.A., 2015. Response of the North Atlantic wave climate to atmospheric modes of variability. *International Journal of Climatology*, 36 (3), 1210-1225.

MEINSHAUSEN, M., SMITH, S.J., CALVIN, K.V., DANIEL, J.S., KAINUMA, M.L.T., LAMARQUE, J.-F., MATSUMOTO, K., MONTZKA, S.A., RAPER, S.C.B., RIAHI, K., THOMSON, A.M., VELDERS. G.J.M. AND VAN VUUREN, D., 2011. The RCP greenhouse gas concentrations and their extension from 1765 to 2300. *Climatic Change*, 109, 213.

MITCHELL, J.A., BETT, P.E., HANLON, H.M. AND SAULTER, A., 2016. Investigating the impact of climate change on the UK wave power climate. *Meteorologische Zeitschrift*, 26 (3), 291-306.

MORI, N., YASUDA, T., MASE, H., TOM, T. AND OKU, Y., 2010. Projection of extreme wave climate change under global warming. *Hydrological Research Letters*, 4, 15-19.

NEU, H.J.A., 1984. Interannual variations and longer-term changes in the sea state of the North Atlantic from 1970 to 1982. *Journal of Geophysical Research: Oceans*, 89 (C4), 6397-6402.

PACIOREK, C.J., RISBEY, J.S., VENTURA, V. AND ROSEN, R.D., 2002. Multiple indices of Northern Hemisphere cyclone activity, winters 1949–99. *Journal of Climate*, 15 (13), 1573-1590.

PALMER, M.D., HARRIS, G.R. AND GREGORY, J.M., 2018a. Extending CMIP5 projections of global mean temperature change and sea level rise due to thermal expansion using a physically-based emulator. *Environmental Research Letters*, 13 (8), 084003.

PALMER, M.D., HOWARD, T., TINKER, J., LOWE, J.A., BRICHENO, L., CALVERT, D., EDWARDS, T., GREGORY, J., HARRIS, G., KRIJNEN, J. AND ROBERTS, C., 2018b. *UKCP18 marine report*. Exeter: Met Office.

PELLING, H.E., MATTIAS GREEN, J.A. AND WARD, S.L., 2013. Modelling tides and sea level rise: to flood or not to flood. *Ocean Modelling*, 63, 21-29.

PEREZ, J., MENENDEZ, M., CAMUS, P., MENDEZ, F.J. AND LOSADA, I.J., 2015. Statistical multi-model climate projections of surface ocean waves in Europe. *Ocean Modelling*, 96 (1), 161-170.

PFIZENMAYER, A. AND VON STORCH, H., 2001. Anthropogenic climate change shown by local wave conditions in the North Sea. *Climate Research*, 19 (1), 15-23.

PICKERING, M.D., WELLS, N.C., HORSBURGH, K.J. AND GREEN, J.A.M., 2012. The impact of future sea-level rise on the European Shelf tides. *Continental Shelf Research*, 35, 1-15.

PICKERING, M.D., HORSBURGH, K.J., BLUNDELL, J.R., HIRSCHI, J.J.-M., NICHOLLS, R.J., VERLAANE, M. AND WELLS, N.C., 2017. The impact of future sea-level rise on the global tides. *Continental Shelf Research*, 142, 50-68.

REEVE, D.E., CHEN, Y., PAN., S., MAGAR, V., SIMMONDS, D.J. AND ZACHARIOUDAKI, A., 2011. An investigation of the impacts of climate change on wave energy generation: the Wave Hub, Cornwall, UK. *Renewable Energy*, 36 (9), 2404-2413.

RODEWALD, M., 1972. Long-term variations of the sea temperature in the area of the nine North Atlantic Ocean Weather Stations during the period 1951–1968. *Rapports et Proces-verbaux des Réunions. Conseil International pour l'Éxploration de la Mer*, 162, 139-153.

RYE, H., 1976. Long-term changes in the North Sea wave climate and their importance for the extreme wave predictions. *Marine Science Communications*, 2 (6), 420-448.

SEMEDO, A., WEISSE, R., BEHRENS, A., STERL, A., BENGTSSON, L. AND GÜNTHER, H., 2013. Projection of global wave climate change toward the end of the twenty-first century. *Journal of Climate*, 26 (21), 8269-8288.

SHIMURA, T., MORI, N. AND MASE, H., 2013. Ocean waves and teleconnection patterns in the Northern Hemisphere. *Journal of Climate*, 26 (21), 8654-8670.

STERL, A., KOMEN, G.J. AND COTTON, P.D., 1998. Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather Forecasts reanalysis: validating the reanalyzed winds and assessing the wave climate. *Journal of Geophysical Research: Oceans*, 103 (C3), 5477-5492.

STERL, A. AND CAIRES, S., 2005. Climatology, variability and extrema of ocean waves: the web-based KNMI/ERA-40 wave atlas. *International Journal of Climatology*, 25, 963-977.

TAMISIEA, M.E. AND MITROVICA, J.X., 2011. The moving boundaries of sea level change: understanding the origins of geographic variability. *Oceanography*, 24 (2), 24-39.

THE WASA GROUP, 1998. Changing waves and storms in the Northeast Atlantic? *Bulletin of the American Meteorological Society*, 79 (5), 741-760.

VIKEBO, F., FUREVIK, T., FURNES, G., KVANSTO, N.G. AND REISTAD, M., 2003. Wave height variations in the North Sea and on the Norwegian Continental Shelf, 1881-1999. *Continental Shelf Research*, 23 (3-4), 251-263.

VISBECK, M.H., HURRELL, J.W., POLVANI, L. AND CULLEN, H.M., 2001. The North Atlantic Oscillation: past, present, and future. *Proceedings of the National Academy of Sciences of the United States of America*, 98 (23), 12876-12877.

WANG, X.L. AND SWAIL, V.R., 2001. Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *Journal of Climate*, 14 (10), 2204-2221.

WANG, X.L. AND SWAIL, V.R., 2002. Trends of Atlantic wave extremes as simulated in a 40-year wave hindcast using kinematically reanalyzed wind fields. *Journal of Climate*, 15 (9), 1020-1035.

WANG, X.L., AND SWAIL, V.R., 2006. Climate change signal and uncertainty in projections of ocean wave heights. *Climate Dynamics,* 26 (2-3), 109-126.

WANG, X.L., ZWIERS, F.W. AND SWAIL, V.R., 2004. North Atlantic Ocean wave climate change scenarios for the twenty-first century. *Journal of Climate*, 17 (12), 2368-2383.

WANG, X.L., FENG, Y. AND SWAIL, V.R., 2012. North Atlantic wave height trends as reconstructed from the 20th century reanalysis. *Geophysical Research Letters*, 39 (18), L18705.

WANG, X.L., FENG, Y. AND SWAIL, V.R., 2014. Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophysical Research Letters*, 41 (3), 1026-1034.

WANG, X.L., FENG, Y. AND SWAIL, V.R., 2015. Climate change signal and uncertainty in CMIP5-based projections of global ocean surface wave heights. *Journal of Geophysical Research: Oceans*, 120 (5), 3859-3871.

WEISSE, R. AND GÜNTHER, H., 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, 57 (3), 161-172.

WEISSE, R., VON STORCH, H. AND FESER, F., 2005. Northeast Atlantic and North Sea storminess as simulated by a regional climate model during 1958–2001 and comparison with observations. *Journal of Climate*, 18 (3), 465-479.

WOLF, J., AND WOOLF, D.K., 2006. Waves and climate change in the north-east Atlantic. *Geophysical Research Letters*, 33 (6), L06604.

WOLF, J., LOWE, J. AND HOWARD, T., 2015. Climate downscaling: local mean sea level, surge and wave modelling. In *Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium* (ed. R.J. Nicholls, R.J. Dawson and S.A. Day), pp. 79-102. Dordrecht, The Netherlands: Springer.

WOOLF, D.K., CHALLENOR, P.G. AND COTTON, P.D., 2002. Variability and predictability of the North Atlantic wave climate. *Journal of Geophysical Research: Oceans,* 107 (C10), 9.1-9.14

YOUNG, I.R., ZIEGER, S. AND BABANIN, A.V., 2011. Global trends in wind speed and wave height. *Science*, 332 (6028), 451-455.

ZACHARIOUDAKI, A., PAN, S., SIMMONDS, D., MAGAR, V. AND REEVE, D.E., 2011. Future wave climate over the west-European shelf seas. *Ocean Dynamics*, 61 (6), 807.

List of abbreviations

AnnMax	mean annual maximum wave height
AR5	Fifth Assessment Report
CMIP5	Coordinated Modelling Intercomparison Project Phase 5
GCM	global climate model
GIA	glacial isostatic adjustment
IPPC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
ODN	Ordnance Datum Newlyn
RCP	representative concentration pathway
RCM	regional climate model
SWH	significant weave height
UKCIP18	UK Climate Projections 2018

Glossary

Fingerprint	The characteristic pattern of global mean sea level change associated with a specific land-based mass source.
Glacial isostatic adjustment (GIA)	The ongoing movement of the lithosphere in response to the removal of ice mass at the end of the last Ice Age.
Representative concentration pathway (RCP)	These replace the emissions scenarios (of climate change). See the glossary entry in IPPC AR5 (Church et al. 2013, Glossary, p. 1461).
Return level	The level that is expected to be exceeded on average once per return period.
Return period	See definition and discussion in Section 2.7.
Still water level	Still water level refers to the water level averaged over a period (say ~15 minutes) much longer than the period of a surface wave. It accounts for tide and surge but not intermittent overtopping by waves.
Time-mean sea level	Sea level at a given location averaged over a period long enough to remove the influence of the tides and short-term climatic variability. Typically an averaging period of at least one year is used.

Appendix A: Projections of future extreme coastal still water levels at UK tide gauges

Projections of future extreme still water levels at selected UK tide gauge locations and different RCPs are shown in Tables A.1 to A.4. This information is also available via the UKCP18 user interface (https://ukclimateprojections-ui.metoffice.gov.uk/). Please note the following.

- Nominal latitude (Nom. Lat.) and nominal longitude (Nom. Long.) may be slightly different to the exact latitude and longitude of the gauge because the location of the nearest Continental Shelf 3 (CS3) coastal shelf model grid box is used.
- 'Chain' is the coastal chainage defined in Environment Agency (2011).
- The results are given under the lower, central and upper estimates of mean relative sea level change for each RCP.
- Even though the uncertainty in the Environment Agency (2019) estimates of present day return levels is not included, the range (upper minus lower) is not zero at 2017. This is because the projections of mean sea level change are provided relative to a baseline period of 1981 to 2000 and therefore there is some uncertainty in the projected sea level rise prior to 2017.
- Full details of the locations of the tide gauges can be found on the UK National Tide Gauge Network website (www.ntslf.org/data/uk-network-real-time) and/or the Permanent Service for Mean Sea Level website (www.psmsl.org).

Table A.1 RCP2.6: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp26 (lower) **central** (upper)															
Site	**Chain (km)**	**Nom.Lat.**	**Nom. Long.**	**1 year return level (m)**				**200 year return level (m)**				**10,000 year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	(3.06) **3.11** (3.17)	(3.34) **3.5** (3.77)	(3.53) **3.88** (4.59)	(3.66) **4.18** (5.35)	(3.53) **3.58** (3.64)	(3.81) **3.97** (4.24)	(4.0) **4.35** (5.06)	(4.13) **4.65** (5.82)	(3.83) **3.88** (3.94)	(4.11) **4.28** (4.54)	(4.31) **4.66** (5.37)	(4.43) **4.95** (6.12)
Avonmouth	380.0	51.5	-2.75	(8.06) **8.11** (8.17)	(8.31) **8.47** (8.73)	(8.46) **8.8** (9.49)	(8.55) **9.06** (10.19)	(9.02) **9.07** (9.12)	(9.26) **9.43** (9.69)	(9.42) **9.76** (10.45)	(9.51) **10.02** (11.15)	(10.0) **10.05** (10.11)	(10.25) **10.41** (10.67)	(10.4) **10.74** (11.43)	(10.49) **11.0** (12.13)
Tobermory	2320.0	56.61	-6.25	(2.94) **2.98** (3.04)	(3.06) **3.22** (3.48)	(3.07) **3.41** (4.12)	(3.02) **3.53** (4.69)	(3.76) **3.8** (3.86)	(3.88) **4.04** (4.3)	(3.89) **4.23** (4.94)	(3.84) **4.35** (5.51)	(4.39) **4.43** (4.49)	(4.51) **4.67** (4.94)	(4.53) **4.87** (5.57)	(4.47) **4.98** (6.14)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.74) **1.9** (2.16)	(1.95) **2.28** (2.98)	(2.09) **2.59** (3.74)	(1.78) **1.83** (1.88)	(2.07) **2.23** (2.48)	(2.28) **2.61** (3.31)	(2.42) **2.92** (4.07)	(1.98) **2.02** (2.08)	(2.27) **2.42** (2.68)	(2.48) **2.81** (3.51)	(2.62) **3.12** (4.27)
Sheerness	4314.0	51.5	0.75	(3.65) **3.7** (3.75)	(3.91) **4.07** (4.33)	(4.08) **4.42** (5.1)	(4.19) **4.69** (5.8)	(4.61) **4.65** (4.71)	(4.86) **5.02** (5.28)	(5.04) **5.37** (6.05)	(5.15) **5.64** (6.76)	(5.54) **5.59** (5.65)	(5.8) **5.96** (6.22)	(5.98) **6.31** (6.99)	(6.09) **6.58** (7.7)
Dover	4410.0	51.17	1.42	(3.75) **3.8** (3.86)	(4.01) **4.17** (4.43)	(4.18) **4.52** (5.19)	(4.29) **4.78** (5.89)	(4.63) **4.68** (4.74)	(4.89) **5.05** (5.31)	(5.06) **5.4** (6.07)	(5.17) **5.66** (6.77)	(5.34) **5.39** (5.45)	(5.6) **5.76** (6.02)	(5.77) **6.11** (6.79)	(5.88) **6.38** (7.49)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP2.6 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.2 RCP4.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp45 (lower) **central** (upper)															
Site	**Chain (km)**	**Nom. Lat.**	**Nom. Long.**	**1 year return level (m)**				**200 year return level (m)**				**10,000 year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	(3.06) **3.11** (3.17)	(3.4) **3.59** (3.89)	(3.72) **4.13** (4.91)	(3.91) **4.53** (5.8)	(3.53) **3.58** (3.64)	(3.87) **4.06** (4.36)	(4.19) **4.6** (5.38)	(4.38) **5.0** (6.27)	(3.83) **3.88** (3.94)	(4.18) **4.36** (4.66)	(4.49) **4.91** (5.69)	(4.69) **5.31** (6.57)
Avonmouth	380.0	51.5	-2.75	(8.06) **8.11** (8.17)	(8.37) **8.55** (8.84)	(8.65) **9.05** (9.81)	(8.8) **9.41** (10.64)	(9.02) **9.07** (9.13)	(9.33) **9.51** (9.8)	(9.6) **10.01** (10.77)	(9.76) **10.37** (11.6)	(10.0) **10.05** (10.11)	(10.31) **10.49** (10.78)	(10.58) **10.99** (11.75)	(10.74) **11.35** (12.58)
Tobermory	2320.0	56.61	-6.25	(2.94) **2.98** (3.04)	(3.12) **3.3** (3.59)	(3.23) **3.64** (4.41)	(3.22) **3.83** (5.09)	(3.75) **3.8** (3.86)	(3.94) **4.12** (4.41)	(4.05) **4.45** (5.23)	(4.04) **4.65** (5.91)	(4.39) **4.43** (4.49)	(4.57) **4.75** (5.04)	(4.68) **5.09** (5.86)	(4.68) **5.28** (6.54)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.79) **1.97** (2.26)	(2.09) **2.49** (3.25)	(2.28) **2.88** (4.13)	(1.78) **1.83** (1.88)	(2.12) **2.3** (2.59)	(2.42) **2.82** (3.58)	(2.6) **3.21** (4.46)	(1.98) **2.02** (2.08)	(2.32) **2.5** (2.78)	(2.62) **3.02** (3.78)	(2.8) **3.41** (4.66)
Sheerness	4314.0	51.5	0.75	(3.65) **3.7** (3.76)	(3.97) **4.15** (4.44)	(4.26) **4.67** (5.42)	(4.44) **5.04** (6.25)	(4.6) **4.65** (4.71)	(4.93) **5.11** (5.4)	(5.22) **5.62** (6.37)	(5.4) **6.0** (7.21)	(5.54) **5.59** (5.65)	(5.87) **6.05** (6.34)	(6.16) **6.56** (7.31)	(6.34) **6.93** (8.15)
Dover	4410.0	51.17	1.42	(3.75) **3.8** (3.86)	(4.07) **4.25** (4.54)	(4.36) **4.77** (5.51)	(4.54) **5.14** (6.35)	(4.63) **4.68** (4.74)	(4.95) **5.13** (5.42)	(5.24) **5.65** (6.39)	(5.42) **6.02** (7.23)	(5.34) **5.39** (5.45)	(5.66) **5.85** (6.14)	(5.96) **6.36** (7.11)	(6.14) **6.73** (7.95)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP4.5 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.3 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp85 (lower) **central** (upper)															
Site	**Chain (km)**	**Nom. Lat.**	**Nom. Long.**	**1 year return level (m)**				**200 year return level (m)**				**10,000 year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	(3.05) **3.11** (3.17)	(3.55) **3.8** (4.17)	(4.19) **4.83** (5.91)	(4.55) **5.59** (7.42)	(3.52) **3.58** (3.64)	(4.02) **4.27** (4.64)	(4.66) **5.3** (6.38)	(5.02) **6.06** (7.89)	(3.83) **3.88** (3.94)	(4.33) **4.58** (4.95)	(4.96) **5.6** (6.68)	(5.32) **6.36** (8.19)
Avonmouth	380.0	51.5	-2.75	(8.05) **8.11** (8.17)	(8.52) **8.76** (9.13)	(9.11) **9.74** (10.79)	(9.43) **10.45** (12.23)	(9.01) **9.07** (9.12)	(9.48) **9.72** (10.08)	(10.07) **10.7** (11.75)	(10.39) **11.41** (13.19)	(9.99) **10.05** (10.11)	(10.46) **10.7** (11.06)	(11.05) **11.68** (12.73)	(11.37) **12.39** (14.17)
Tobermory	2320.0	56.61	-6.25	(2.93) **2.98** (3.04)	(3.25) **3.48** (3.84)	(3.58) **4.21** (5.28)	(3.67) **4.69** (6.48)	(3.75) **3.8** (3.86)	(4.07) **4.3** (4.66)	(4.4) **5.03** (6.1)	(4.49) **5.51** (7.3)	(4.38) **4.43** (4.49)	(4.7) **4.93** (5.29)	(5.03) **5.67** (6.73)	(5.12) **6.14** (7.94)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.91) **2.14** (2.5)	(2.4) **3.04** (4.08)	(2.65) **3.68** (5.45)	(1.77) **1.83** (1.88)	(2.24) **2.47** (2.83)	(2.73) **3.37** (4.41)	(2.98) **4.01** (5.78)	(1.97) **2.02** (2.08)	(2.44) **2.67** (3.03)	(2.93) **3.56** (4.61)	(3.18) **4.21** (5.98)
Sheerness	4314.0	51.5	0.75	(3.64) **3.7** (3.76)	(4.12) **4.37** (4.73)	(4.74) **5.37** (6.41)	(5.09) **6.11** (7.88)	(4.6) **4.65** (4.71)	(5.08) **5.32** (5.68)	(5.7) **6.33** (7.37)	(6.04) **7.07** (8.83)	(5.54) **5.59** (5.65)	(6.02) **6.26** (6.62)	(6.63) **7.27** (8.31)	(6.98) **8.01** (9.77)
Dover	4410.0	51.17	1.42	(3.74) **3.8** (3.86)	(4.22) **4.47** (4.83)	(4.84) **5.48** (6.52)	(5.2) **6.22** (7.99)	(4.62) **4.68** (4.74)	(5.1) **5.35** (5.71)	(5.72) **6.36** (7.4)	(6.08) **7.1** (8.87)	(5.34) **5.39** (5.45)	(5.82) **6.06** (6.42)	(6.44) **7.07** (8.11)	(6.79) **7.82** (9.58)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP8.5 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.4 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for all sites (central estimate only) and 3 future times (2100, 2200, 2300)

rcp85 50th percentile															
Site	**Chain (km)**	**Nom.Lat.**	**Nom. Long.**	**1-year return level (m)**				**200-year return level (m)**				**10,000-year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	3.11	3.8	4.83	5.59	3.58	4.27	5.3	6.06	3.88	4.58	5.6	6.36
St Mary’s	nan	49.94	-6.25	3.41	4.11	5.14	5.9	3.84	4.54	5.57	6.33	4.11	4.81	5.84	6.6
Padstow	128.0	50.61	-4.92	4.56	5.24	6.25	6.98	5.05	5.72	6.73	7.47	5.42	6.1	7.1	7.84
Ilfracombe	250.0	51.28	-4.08	5.43	6.09	7.07	7.78	5.99	6.65	7.62	8.34	6.45	7.11	8.09	8.8
Hinkley	326.0	51.28	-3.08	7.05	7.7	8.69	9.41	7.78	8.44	9.42	10.14	8.54	9.19	10.18	10.89
Avonmouth	380.0	51.5	-2.75	8.11	8.76	9.74	10.45	9.07	9.72	10.7	11.41	10.05	10.7	11.68	12.39
Newport	398.0	51.5	-2.92	7.45	8.1	9.08	9.79	8.33	8.98	9.96	10.67	9.25	9.9	10.88	11.59
Mumbles	492.0	51.61	-3.92	5.51	6.16	7.12	7.82	6.34	6.99	7.95	8.65	6.99	7.63	8.6	9.29
Milford Haven	622.0	51.61	-5.08	4.2	4.84	5.8	6.48	4.84	5.48	6.44	7.12	5.33	5.97	6.92	7.61
Fishguard	712.0	52.06	-4.92	3.1	3.72	4.65	5.31	3.62	4.24	5.17	5.83	3.99	4.61	5.54	6.2
Barmouth	832.0	52.72	-4.08	3.46	4.06	4.96	5.59	4.38	4.98	5.88	6.52	5.09	5.69	6.59	7.22
Holyhead	1012.0	53.28	-4.75	3.37	3.93	4.79	5.37	3.94	4.51	5.36	5.95	4.35	4.92	5.77	6.36
Llandudno	1110.0	53.39	-3.75	4.7	5.27	6.14	6.74	5.33	5.91	6.77	7.37	5.81	6.39	7.25	7.85
Hilbre Island	1154.0	53.39	-3.25	5.24	5.83	6.7	7.32	5.96	6.54	7.42	8.03	6.5	7.08	7.96	8.57
Port Erin	nan	54.17	-4.75	3.27	3.79	4.59	5.12	3.95	4.48	5.27	5.81	4.44	4.97	5.76	6.3
Heysham	1254.0	54.06	-2.92	5.86	6.42	7.27	7.85	6.86	7.42	8.26	8.84	7.63	8.19	9.03	9.62
Workington	1390.0	54.61	-3.58	5.09	5.61	6.4	6.93	5.95	6.47	7.26	7.79	6.62	7.14	7.93	8.46
Portpatrick	1648.0	54.83	-5.25	2.82	3.32	4.07	4.57	3.56	4.06	4.81	5.3	4.09	4.59	5.34	5.84
Millport	1782.0	55.72	-4.92	2.67	3.14	3.86	4.31	3.65	4.12	4.84	5.3	4.44	4.91	5.63	6.08
Port Ellen	nan	55.61	-6.08	1.45	1.94	2.67	3.15	2.24	2.73	3.47	3.94	2.81	3.3	4.03	4.51
Tobermory	2320.0	56.61	-6.25	2.98	3.48	4.21	4.69	3.8	4.3	5.03	5.51	4.43	4.93	5.67	6.14
Ullapool	2564.0	57.94	-5.25	3.22	3.74	4.48	4.97	3.9	4.42	5.16	5.65	4.34	4.85	5.6	6.09
Stornoway	nan	58.17	-6.25	2.89	3.44	4.22	4.75	3.44	3.99	4.77	5.3	3.78	4.33	5.11	5.64
Kinlochbervie	2670.0	58.5	-5.08	3.17	3.72	4.49	5.01	3.94	4.48	5.25	5.78	4.46	5.01	5.78	6.3
Lerwick	nan	60.17	-1.08	1.5	2.14	3.04	3.68	1.83	2.47	3.37	4.01	2.02	2.67	3.56	4.21
Wick	2870.0	58.39	-3.08	2.4	2.93	3.69	4.2	2.91	3.44	4.2	4.71	3.21	3.74	4.5	5.01
Moray Firth	3012.0	57.61	-4.08	2.85	3.33	4.05	4.52	3.35	3.84	4.56	5.02	3.71	4.2	4.92	5.38

rcp85 50th percentile															
Site	**Chain (km)**	**Nom.Lat.**	**Nom. Long.**	**1-year return level (m)**				**200-year return level (m)**				**10,000-year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Aberdeen	3226.0	57.17	-2.08	2.69	3.19	3.93	4.42	3.22	3.72	4.46	4.94	3.58	4.07	4.82	5.3
Leith	3420.0	56.06	-3.25	3.37	3.85	4.57	5.03	3.96	4.43	5.15	5.62	4.41	4.89	5.61	6.07
North Shields	3630.0	55.06	-1.42	3.21	3.77	4.61	5.19	3.85	4.42	5.26	5.84	4.42	4.98	5.82	6.4
Whitby	3720.0	54.5	-0.58	3.36	3.98	4.88	5.53	4.11	4.72	5.63	6.28	4.81	5.42	6.32	6.97
Immingham	3888.0	53.61	-0.25	4.17	4.81	5.77	6.46	5.06	5.7	6.66	7.35	5.92	6.57	7.52	8.21
Cromer	4096.0	52.94	1.25	3.07	3.75	4.75	5.49	4.08	4.76	5.76	6.5	5.03	5.7	6.71	7.45
Lowestoft	4162.0	52.5	1.75	2.02	2.7	3.71	4.46	3.27	3.95	4.96	5.71	4.31	4.99	6.01	6.76
Felixstowe Pier	4232.0	51.94	1.42	2.68	3.36	4.37	5.11	3.74	4.41	5.42	6.16	4.77	5.45	6.46	7.2
Sheerness	4314.0	51.5	0.75	3.7	4.37	5.37	6.11	4.65	5.32	6.33	7.07	5.59	6.26	7.27	8.01
Dover	4410.0	51.17	1.42	3.8	4.47	5.48	6.22	4.68	5.35	6.36	7.1	5.39	6.06	7.07	7.82
Newhaven	4526.0	50.72	0.08	3.87	4.54	5.55	6.29	4.46	5.13	6.14	6.88	4.96	5.63	6.64	7.38
Portsmouth	4616.0	50.83	-1.08	2.55	3.22	4.23	4.97	3.1	3.77	4.77	5.51	3.49	4.15	5.16	5.9
Bournemouth	4682.0	50.61	-1.92	1.4	2.08	3.08	3.83	1.9	2.58	3.59	4.33	2.28	2.95	3.96	4.7
Weymouth	4736.0	50.61	-2.42	1.82	2.49	3.5	4.24	2.35	3.02	4.03	4.77	2.76	3.43	4.44	5.18
Exmouth	4836.0	50.61	-3.42	2.76	3.43	4.44	5.18	3.34	4.01	5.02	5.75	3.66	4.34	5.34	6.08
Devonport	4950.0	50.28	-4.08	2.95	3.63	4.65	5.4	3.47	4.15	5.17	5.92	3.84	4.53	5.54	6.29
Portrush	nan	55.28	-6.58	1.61	2.12	2.87	3.36	2.29	2.8	3.55	4.04	2.78	3.29	4.04	4.53
Belfast	nan	54.72	-5.75	2.16	2.67	3.43	3.92	2.96	3.46	4.22	4.72	3.69	4.2	4.96	5.45
Jersey	nan	49.17	-2.08	6.21	6.89	7.92	8.67	6.75	7.43	8.46	9.21	7.2	7.88	8.9	9.66

Appendix B: Wave literature review summary tables and results by focus area

B.1 North-east Atlantic

The majority of the studies indicate an **increase** in the mean and extreme SWHs in the north-east Atlantic.

- Wang et al. 2004:
  - increase in winter and autumn means of 5–35cm and 5–20cm respectively
  - increase in winter 90th percentile of up to 50cm (11% of baseline)
- Wang and Swail 2006:
  - increase in winter, spring and summer mean SWHs (for winter the increase is up to 12cm, about 6%, for A2 emissions scenario)
  - increase in winter, spring, summer and autumn extreme SWHs under A2 scenario (for summer the increase is largest up to 50cm or 9%)
- Leake et al 2008:
  - increase of >14cm of the winter mean SWHs for A2 and B2
  - increase of up to 130cm for A2 and up to 100cm for B2 in period mean of winter maximum for 2070 to 2100
- Lowe et al. 2009:
  - increase in winter, spring and summer mean SWHs
- Fan et al. 2013:
  - increase of 7–8% and up to 15% or >0.5m increase in winter mean SWHs
- Fan et al. 2014:
  - winter mean wind waves energy increases in the future
- Bricheno and Wolf 2018:
- increase up to about 10–20% in the period mean annual maximum along west-facing coasts under RCP4.5/8.5

However, 2 studies indicated a **decrease** in SWHs in the North-east Atlantic or the North Atlantic as a whole.

- Hemer et al. 2013b focused on the North Atlantic as whole. They indicated that:
  - reductions in monthly mean and 99th percentile of SWHs were projected for the future

  - the monthly means in winter would decrease by about 1m and the seasonal summer mean would decrease by about 0.2m

- Bricheno and Wolf 2018:
- a decrease in the annual mean SWHs varying between 0% and 5% (see middle panel of Figure 4.1)

B.1.1 Areas to the north and north-west of the UK

One study indicates an **increase** in mean or extreme SWHs: Kaas et al. (2001) projected an increase in winter, spring and autumn mean SHWs;

Two studies indicated **mixed results**:

- Lowe et al. (2009) projected a decrease in winter and spring mean SWHs (up to -0.4m for winter) to the north of UK, but an increase in the summer mean SWHs around the UK and in the autumn mean SWHs north-west of Scotland. They also found a statistically significant trend in annual extremes of -0.3cm per year north of Scotland.
- Wolf et al. (2015) showed that, while an increase in annual mean SWHs can be expected mid-century north of the British Isles (see Figure 4.2), by the end of the century this parameter will decrease north-west of Scotland (Figure 4.2). They also indicated that the 30-year period means of annual maxima would increase in the north-west approaches (Western Isles of Scotland) by between 10% and 20%.

Mitchell et al. (2016) found a statistically significant **decrease** in the ensemble mean of the annual mean SWH near the Bernera site by the mid-century.

B.1.2 Changes to the west of the British Isles

Three studies indicate that **decreases** are to be expected in these areas:

- Zacharioudaki et al. (2011) indicated a decrease in spring, summer and autumn mean and 99th percentile SWHs in the West European shelf seas.
- Gallagher et al. (2016a, 2016b) found decreases in the winter (summer) seasonal mean of up to -10% (up to -15%) off the west (south) coast of Ireland for RCP8.5. For spring (autumn), they found a small decrease in the seasonal mean SWHs of less than 5% for both scenarios. The annual mean SWHs were projected to decrease by 5–10% off the Atlantic coast of Ireland in both scenarios. They also found robust decreases in the 95th percentile of SWHs varying by about -5% for the winter and summer seasons and for the annual extremes off the west and southern coasts. The largest changes were seen for RCP8.5 in summer when reductions in the 95th percentile were projected to be > 10%.
- Aarnes et al. (2017) established that the annual 99th percentile (annual maximum) would decrease by 2–4% and up to 6% (no change or up to 2–4% under RCP4.5 or up to 4–% under RCP8.5) to the north and west of the UK and Ireland.

One study indicated an **increase**: Debernard and Røed (2008) found an increase in the winter 99the percentile of SWHs of 2–4% west of the British Isles, and an increase of up to 6% in the 99the percentile of the annual SWH west of British Isles.

B.1.3 Changes to the south-west of the British Isles

Several studies agree that the annual mean SWHs will **decrease**:

- Zacharioudaki et al. 2011:
    - decrease of -3% to -5% in annual mean SWHs (their Figure 5) south-west of the UK
- Wolf et al. 2015:
    - decrease in annual mean wave heights south-west of the UK in mid-century (see Figure 4.2)
- Perez et al. 2015:
    - period mean SWHs decreasing in all RCPs, varying between 0.04m for RCP2.6 and up to about 0.08m for RCP8.5 in mid- and late century periods to the south-west of the UK
- Reeve et al 2011 obtained conflicting results at the Wave Hub under the 2 emissions scenarios they used:
    - an increase in annual mean wave power by 2.95% under A1B
    - a decrease by 2.27% under the B1 scenario
- Gallagher et al. 2016a and 2016b:
    - a decrease in the summer mean and 95th percentile SWHs
    - a decrease in seasonal mean of up to 15% off the south coast of Ireland for RCP8.5
    - robust decrease in the 95th percentile off the south coast

Several studies are in accord that some seasonal means, extremes or the annual extremes will **increase**:

- Leake et al. 2008:
    - an increase in winter mean of >0.14m for A2 and B2 scenarios south-west of the UK (their Figure 7)
    - >0.4m increase in winter maximum SWH for January, February and March (their Figure 8)
- Lowe et al. 2009:
    - increase in winter mean SWHs in the south-west approaches and an increase of around 0.1m in the English Channel
    - increase in the spring mean SWHs in the south-west approaches to the UK
    - increase in the summer mean SWHs in the waters around the UK
    - increase in the maximum annual wave heights in the English Channel
- Zacharioudaki et al. 2011:
    - agreed with the findings of Lowe et al. (2009) and Leake et al. (2008) and also indicated that the winter mean SWHs would increase by 4–8% south-west of the UK

  - in accordance with Leake et al. (2008) they found that the winter 99th percentile would also increase to the south-west of the UK

- Wolf et al. 2015:
  - agreed with Lowe et al. (2008) and indicated that the 30-year period means of annual maxima would increase in the south-west (English Channel) between 10% and 20% by the end of the century

B.1.4 Around Ireland or UK

Three studies agreed that **decreases** in the annual mean SWHs would be evident around the UK or Ireland.

- Perez et al. 2015:
  - period mean annual SWHs would decrease around Great Britain and Ireland in all RCPs
- Aarnes et al. 2017:
  - decreases around the UK and Ireland varying between 2–4% and 6–8% respectively for 2071 to 2100
  - decreases in annual 9th percentile around the UK and Ireland varying between 2–4% and 4–6% respectively for 2071 to 2100
- Bricheno and Wolf 2018:
  - decreases in annual mean in sites around the UK coast varying between 0% and 5% for the future (see middle panel of Figure 4.1)

One study does not agree with these findings: Wolf et al. (2015) found **increases** in 30-year period mean of annual maximum SWHs varying between 10% and 30% around Ireland by the end of the century except for the eastern coast.

B.1.5 About the Liverpool Bay area

Brown et al. (2012) found differences in the SWH change patterns depending on the month or season of the year.

- They found **increases** in mean monthly SWHs in December and November (between 2.5 and 3%), and also in June of about 16%. Positive trends in large wave events (waves >3m) and extreme (waves >5m) varying between 0.31% and 9.5% respectively were found during the winter months, with a largest increases in January.
- **Decreases** were found for the rest of the months (lowest reductions in May about 2%, largest decreases for September -20%). All seasonal means were decreasing (more specifically by 8.8% in spring and 5.5% in summer).

B.2 North Sea changes

Two studies that considered the North Sea as a whole agreed that seasonal mean SHWs and annual extreme waves would **increase** in the future.

- Kaas et al. 2001:

  - winter, spring and autumn mean SWHs will increase, with the increase being largest in autumn
  - there is a tendency for an increase of the annual 99.9th percentile for waves
- Caires et al. 2008:
  - the annual exceedances above a threshold will increase by 0.001m per year in the future

B.2.1 Southern and eastern sections

The majority of the research agreed that annual median or extremes, or winter mean and extremes will **increase** in the future:

- Debernard and Røed 2008 – 6-8% increase is expected for the winter, summer and annual extremes along the North Sea east coast.
- Grabemann and Weisse 2008 – increase in the annual median SWHs in the Eastern North Sea, as well as an Increase by 0.25-0.35m (5-8%, up to 18%) of 99p in eastern and southern North Sea.
- Lowe et al. 2009 – an increase in winter means in southern North Sea, and in summer means in southern and eastern North Sea; they also found an increase in winter and the annual maximum in the southern North Sea.
- Groll et al. 2014 – Also found an increase in the annual median of the SWHs in eastern North Sea by the end of the century, and rise in the 99p of SWHs in the southern and eastern North Sea by the end of the century.
- Wang et al. 2014 showed that the 1 in 10 years SWHs will double or triple in frequency along Danish coast under RCP8.5.
- Grabemann et al. 2015 – also found an increase in the annual median SWHs in the south and eastern North Sea, as well as a rise in the annual maximum and 99p extreme waves in the same areas.
- Wolf et al. 2015 – Increase of annual mean SWHs in the eastern North Sea by the mid-century for RCP8.5, and an increase of 5% along the eastern North Sea for the period mean of annual maximum SWHs.

Finally, Leake et al. had somewhat conflicting results depending on the emissions scenario: An increase in winter mean (extremes) of 0.1m (0.2m) near East Anglia, and an increase in annual maximum of SWHs of 0.2m in southern North Sea was projected under the A2 scenario, while a decrease of -0.04m (-0.19m) in the winter mean (extremes), and of -0.56m for the annual maximum was identified for southern North Sea under the B2 emissions scenario.

B.2.2 Western sections

Existing research agreed on projected **decreases** in the annual mean and extreme SWHs in the western sections of the North Sea:

- Debernard and Røed 2008: a decrease of 2–4% in annual mean SWHs and a reduction in the 99th percentile of annual SWHs along the UK east coast

- Aarnes et al 2017: similar changes of 2–4% and up to a 6% decrease in annual mean SWHs, together with a 2–4% reduction in the annual 90th percentile, 99th percentile and maximum in the western North Sea

The rest of the studies indicated the changes in metres and not as a relative change.

- Grabemann and Weisse (2008) found a decrease in annual median SWHs by ranging between 0.02m and 0.05m off the UK coast.
- De Winter et al. (2012) indicated a projected decrease in the annual maximum in western North Sea.
- Groll et al. (2014) indicated a decrease of 0.04m in the annual median in the north-west North Sea extending towards south and central North Sea.
- Grabemann et al. (2015) found a reduction of -0.25m to -0.75m off the northern British coast in the annual median wave heights. They also indicated a decrease in the annual maximum and the 99th percentile in the west and north-western North Sea.
- Wolf et al. (2015) found a slight decrease in the annual mean SWHs, especially in the southern and western North Sea, in both periods for RCP4.5 and in late period for RCP8.5. They also identified a decrease in southern North Sea of the period mean of the annual maximum.

No projected changes or very small changes were established by 2 studies that either considered the North Sea as a whole or focused on relatively small areas close to the UK or Dutch coasts.

- De Winter et al. 2012 focused on a small area in front of the Dutch coast. They found that the annual mean wave climate is not projected to differ, but projected a small decrease in the annual maximum.
- Wolf et al. (2015) found that the future wave climate off the north Norfolk coast would not change compared with today.

Table B.1 Summary table of the GCMs used in the simulations for studies focused on north-east Atlantic and around the British Isles

(A)

Study\ model	**CGCM2**	**ECHAM4**	**MRI-CGCM2**	**HadCM3**	**HadAM3H**	**GFDL CM2.1**	**CSIRO Mk3.5**	**ECHAM 5**	**BCCR BCM**	**Complete CMIP3 18 model ensemble**	**8 GCMs from COWCLIP**	**GFDL HiRAM**	**EC-Earth ESM**	**Set of CMIP5 models**
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
Kaas et al. 2001		X												
Wang et al. 2004	X													
Wang and Swail 2006	X	X		X										
Leake et al. 2008				X	X HadRM3H									
Debernard and Røed 2008		X			X				X					
Lowe et al. 2009				X HadRM3 PPE										
Zacharioudaki et al. 2011								X						

Study\ model	**CGCM2**	**ECHAM4**	**MRI-CGCM2**	**HadCM3**	**HadAM3H**	**GFDL CM2.1**	**CSIRO Mk3.5**	**ECHAM 5**	**BCCR BCM**	**Complete CMIP3 18 model ensemble**	**8 GCMs from COWCLIP**	**GFDL HiRAM**	**EC-Earth ESM**	**Set of CMIP5 models**
								CLM RCM						
Reeve et al. 2011[1]														
Brown et al 2012				X HadRM3 PPE										
Hemer et al. 2013b							X Cubic Conformal atm RCM	X Cubic Conformal atm RCM						

Notes: [1] Used MPI GCM and RCM without explicitly specifying the names of the models.
RCM = regional climate model

(B)

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM5	BCCR BCM	CMIP3 18 model ensemble mean	8 GCMS from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
Hemer et al. 2013a COWCLIP	X Wang and Swail 2006	X Wang and Swail 2006	X Atm only model at 20km resolution Mori et al. 2010	X Wang and Swail 2006			X Hemer et al. 2013b	X Hemer et al. 2013b X Semedo et al. 2013				X Fan et al. 2013		
Fan et al. 2013												X		
Fan et al. 2014				Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X				
Perez et al. 2015														X^2 17 models
Wolf et al. 2015													X	

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM5	BCCR BCM	CMIP3 18 model ensemble mean	8 GCMS from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
													RCA4 RCM	
Mitchell et al. 2016				X HadRM3 PPE										
Gallagher et al. 2016a, 2016b													X	
Aarnes et al. 2017													X	X[3] Plus 5 more models
Bricheno and Wolf 2018											X		X RCA4 RCM	

Notes:

[2] Used the following 17 CMIP5 models: CMCC-CMS, MPI-ESM-LR, ACCESS1.3, EC-EARTH, CMCC-CM, MPI-ESM-MR, HadGEM2-CC, ACCESS1.0, CNRM-CM5, HadGEM2-ES, GISS-E2-R, BNU-ESM, HadCM3, CanESM2, MIROC4h, GFDL-ESM2G, CanCM4

[3] Additional 5 CMIP5 models: HadGEM2-ES, IPSL-CM5A-MR, GFDL-CM3, MIROC5, MRI-CGCM3

Table B.2 Summary table of the GCMs used in the simulations for North Sea studies

Study\ model	**ECHAM4**	**HadCM3**	**HadAM3H**	**ECHAM5**	**BCCR BCM**	**EC-Earth ESM**	**HadGEM2 ESM**	**Set of CMIP5 models**
	CMIP2 model	CMIP3 models				CMIP5 models		
Kaas et al. 2001	X							
Leake et al. 2008		X	X HadRM3H					
Caires et al. 2008				X 17 runs ESSENCE project				
Debernard and Røed 2008	X		X		X			
Grabemann and Weisse 2008	X RCAO RCM		X RCAO RCM					
Lowe et al. 2009		X HadRM3 PPE						
De Winter et al. 2012				X 17 runs ESSENCE project				
Groll et al. 2014				X COSMO CLM RCM				

Study\ model	**ECHAM4**	**HadCM3**	**HadAM3H**	**ECHAM5**	**BCCR BCM**	**EC-Earth ESM**	**HadGEM2 ESM**	**Set of CMIP5 models**
	CMIP2 model	CMIP3 models				CMIP5 models		
Wang et al. 2014						X	X	X[1] Plus 18 more models
Grabemann et al. 2015	X RCAO RCM		X RCAO RCM	X COSMO CLM, REMO, HIRHAM RCMs				
Wolf et al. 2015		X HadRM3 PPE						
Wolf et al. 2015						X RCA4 RCM		
Aarnes et al. 2017						X		X[2] Plus 5 more models

Notes:

[1] Additional 18 CMIP models: ACCESS1.0, BCC-CSM1-1, BCC-CSM1-1(m), CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-s2, GFDL-ESM2M, INMCM4, IPSL-CM5A-MR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M

[2] Additional 5 CMIP5 models: HadGEM2-ES, IPSL-CM5A-MR, GFDL-CM3, MIROC5, MRI-CGCM3

Table B.3 North-east Atlantic and areas around the British Isles: positive changes

(A) NORTH-EAST ATLANTIC

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Wang et al. 2004 – statistical relationship between cold season sea level pressure and SWH, 2070 to 2099	CGCM2	IS92a, A2, B2	Increase of 5–35cm			Increase of 5–20cm		Increase of up to 55cm in 90th percentile over 1990 to 2080 (11% of baseline value)				
Wang and Swail 2006 – statistical relationship between seasonal sea level pressure and SWH, 2080 to 2099	CGCM2, HadCM3 and ECHAM4	IS92a, A2, B2	Increase of up to 12cm for 1990 to 2080 (about 6% of the climate value for 1990) A2 scenario	Increase	Increase			Increase under A2	Increase under A2	Increase of up to 50cm or 9% (Jul, Aug, Sep)	Increase under A2	
Leake et al. 2008 – wave modelling, 2070 to 2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	>14cm for A2 and B2 scenarios in north-east Atlantic					Increase of up to 130cm for A2 and up to 100cm for B2 in period mean of				

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
								winter maximum for 2070 to 2100 for north-east Atlantic				
Lowe et al. 2009 –wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B	Increase in north-east Atlantic	Increase in north-east Atlantic	Increase in north-east Atlantic							
Fan et al. 2013 – wave modelling; 2081 to 2100	GFDL HiRAM	A1B	7–8% and up to 15% or >0.5m									
Fan et al. 2014 – wave modelling, 2081 to 2100	HadCM3, GFDL CM2.1, ECHAM5, CMIP3 18 model ensemble mean	A1B	Wind waves energy increase in north-east Atlantic									
Bricheno and Wolf 2018 – wave modelling; 1970 to 1999, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5										Increase up to ~10–20% in period mean annual maximum

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
												along west-facing coasts under RCP4.5/8.5

(B) NORTH, NORTH-WEST OF THE UK

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Kaas et al. 2001 – wave modelling, 2060 to 2089	ECHAM4	IS92a	Increase	Increase		Increase						
Lowe et al. 2009 – wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B			Increase in waters around UK	Increases to the north-west of Scotland						
Wolf et al. 2015 – wave modelling; 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Increase in mid-century (see Figure 4.2, their					30 year period means of annual maxima increase

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							Figure 13), north of the British Isles					in north-west approaches (western isles of Scotland) varying between 10% and 20%

(C) WEST OF THE BRITISH ISLES

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Debernard and Røed 2008 – wave and surge modelling, 1961 to 1990, 2071 to 2100	HadAM3H, ECHAM4, BCCR BCM	A2, B2, A1B						2–4% in 99th percentile west of British Isles				Up to 6% increase in 99th percentile of annual SWH west of British Isles

(D) SOUTH-WEST OF THE BRITISH ISLES

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Leake et al. 2008 – wave modelling, 2070-2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	>0.14m for A2 and B2 scenarios south-west of UK (their Figure 7)					>0.4m increase in maximum SWH for Jan, Feb, Mar (their Figure 8)				
Lowe et al. 2009 – wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B	Increase in south-west approaches Increase ~0.1m in English Channel	Increase in south-west approaches to UK	Increase in waters around UK							Maximum increase in wave heights in English Channel
Reeve et al. 2011 – wave modelling, 2061 to 2100; Wave Hub site	MPI GCM and RCM	A1B and B1					Mean wave power will increase by 2.95% under A1B and will decrease by 2.27% under B1 scenario					
Zacharioudaki et al. 2011 –	ECHAM5 GCM and CLM RCM	B1, A1B and A2	4–8% increase to south-					Increase in 99th percentile south-				

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
wave modelling, 2061 to 2100			west of UK					west of UK				
Wolf et al. 2015 – wave modelling; 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5										30 year period means of annual maxima increase in south-west (English Channel) varying between 10% and 20% by the end of the century

(E) IN THE LIVERPOOL BAY AREA OR AROUND IRELAND

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Brown et al. 2012 – wave modelling 2050 to -2060, 2060-2070, 2070-2080 (focus on Liverpool Bay area)	1 member of the HadCM3/ HadRM3 PPE	A1B	For Dec, increase of 2.5–3% in mean monthly SWH		For June, increase of ~ 16% of mean monthly SWH	For Nov, increase of 2.5–3% in mean monthly SWH		Positive trends in large[1] and extreme[2]wave events varying between 0.31% and 9.5% respectively – largest increase in Jan				
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099 (notes about areas around Ireland)	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5										Increases in 30 year period mean of annual maximum of 10–30% around Ireland except for eastern coast by the end of the century

Notes:

[1] Large wave events are >3m.

[2] Extreme wave events are >5m.

Table B.4 North-east Atlantic and areas around the British Isles: negative changes

(A) NORTH-EAST ATLANTIC

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Hemer et al. 2013b – wave modelling, 2070 to 2099 (focus on North Atlantic as a whole)	ECHAM5 and CSIRO Mk3.5 GCMs and Cubic Conformal atm RCM	A2	Monthly mean decrease of ~1m	Monthly mean decrease	Monthly mean decrease of ~0.2m	Monthly mean decrease		Decrease in monthly 99th percentile				
Bricheno and Wolf 2018 – wave modelling, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5					Decrease in north-east North Atlantic varying between 0% and 5% (see middle panel in Figure 4.1)					

(B) NORTH AND NORTHWEST OF UK

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Lowe et al. 2009 – wave modelling, 2080 to 2099	HadCM3 GCM/HadRM3 RCM PPE	A1B	Decrease of up to -0.4m to the north of UK	Decrease to the north of UK								Statistically significant trend of -0.3cm per year north of Scotland
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Decrease in annual mean wave heights north-west of Scotland by the end of century (see Figure 4.2)					
Mitchell et al. 2016 – wave modelling, 2040 to 2069 (focus on Wave Hub and Bernera locations to the south-west and north-west of the UK respectively)	5 members of the HadCM3/ HadRM3 PPE	A1B					Statistically significant decrease in ensemble mean near the Bernera site (north-west of UK) by mid-century					

(C) WEST OF UK AND IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Zacharioudaki et al. 2011 – wave modelling, 2061 to 2100	ECHAM5 GCM and CLM RCM	B1, A1B and A2		Decrease in West European shelf seas					Decrease in 99th percentile SWH in West European shelf seas			
Gallagher et al. 2016a, 2016b – wave modelling, 2070 to 2099 (focus on areas around Ireland)	EC-Earth ESM	RCP4.5, RCP8.5	Decrease in seasonal mean of up to 10% off the west coast of Ireland for RCP8.5	Small decreases of <5% for both scenarios	Decrease off the west coast	Small decreases of <5% for both scenarios	Decrease in ensemble mean of 5–10% off the Atlantic coast of Ireland in both scenarios	Robust decrease in 95th percentile off the west coast under RCP8.5; decrease > 5% in 90th percentile off the west coast in RCP4.5		Robust decrease in 95th percentile off the west coast Largest changes in 95th percentile for RCP8.5 >10% reduction		Robust decrease in 95th percentile off the west coast of less than 5% under RCP8.5 Decrease of over 5% in 90th percentile off the west coast in RCP4.5
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs (see Table B.1)	RCP4.5, RCP8.5										Annual 99th percentile (annual maximum) decreases

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
												of 2–4% and up to 6% (no change or up to 2–4% under RCP4.5 or up to 4–6% under RCP8.5) to north and west of UK and Ireland

(D) TO THE SOUTHWEST OF UK, IN ENGLISH CHANNEL, AND SOUTH OF IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Zacharioudaki et al. 2011 – wave modelling, 2061 to 2100	ECHAM5 GCM and CLM RCM	B1, A1B and A2					Decrease -3% to -5% in annual mean SWH (their Figure 5) south-west of UK					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Decrease in annual mean wave heights south-west of UK in mid-century, (see Figure 4.2)					
Perez et al. 2015 – statistical relationship between sea level pressure and waves; several periods – 2010 to 2039, 2040 to 2069 and 2070 to 2099 – compared with 1975 to 2004	Set of CMIP5 GCMs (see Appendix B Table 1A)	RCP2.6, RCP4.5, RCP8.5					Period mean SWH decreasing in all RCPs, varying between 0.04m for RCP2.6 and up to ~0.08m for RCP8.5 in mid- and late century periods to the south-west of UK					
Gallagher et al. 2016a, 2016b – wave modelling, 2070 to 2099 (focus on areas around Ireland)	EC-Earth ESM	RCP4.5, RCP8.5			Decrease in seasonal mean of up to 15% off the south coast of					Robust decrease in 95th percentile off the south coast		

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
					Ireland for RCP8.5							

(E) AROUND UK AND IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Perez et al. 2015 – statistical relationship between sea level pressure and waves; several periods – 2010 to 2039, 2040 to 2069 and 2070 to 2099 – compared with 1975 to 2004	Set of CMIP5 GCMs (see Appendix B Table 1A)	RCP2.6, RCP4.5, RCP8.5					Period mean SWH decreasing around Great Britain and Ireland in all RCPs					
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs (see Appendix B Table 1A)	RCP4.5, RCP8.5					Decreases around UK and Ireland varying between 2–4% and 6–8%					Decreases in annual 90th percentile around UK and Ireland varying between 2–4% and 4–6%

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							respectively for 2071 to 2100					respectively for 2071 to 2100
Bricheno and Wolf 2018 – wave modelling, 1970 to 1999, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5					Decrease in sites around UK coast varying between 0% and 5% (see middle panel in Figure 4.1)					

(F) LIVERPOOL BAY AREA

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Brown et al. 2012 – wave modelling, 2050 to 2060, 2060 to 2070, 2070 to 2080 (focus on Liverpool Bay area)	1 member of HadCM3/HadRM3 PPE	A1B	Decrease for Jan and Feb monthly means Seasonal mean decreasing	Decrease for spring season monthly means lowest in May (~2%) Seasonal mean decreasing by 8.8% in spring	Decrease for the summer season monthly means Seasonal mean decreasing by 5.5% in summer	Decrease for the autumn season monthly means – largest in Sep (-20%) Seasonal mean decreasing						

Table B.5 North Sea: positive and negative changes

(A) NORTH SEA AS A WHOLE

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Kaas et al. 2001 – wave modelling, 2060 to 2089	ECHAM4	IS92a	Increase	Increase		Largest increase						Tendency of increasing 99.9th percentile
Caires et al. 2008 – wave and extreme value analysis modelling, 1950 to 2100	ESSENCE 17 member ensemble	A1B										0.001m per year Annual extremes (exceedances above a threshold)

(B) SOUTHERN AND EASTERN SECTIONS OF NORTH SEA

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Leake et al. 2008 – wave modelling, 2070 to 2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	0.1m, near East Anglia, A2 But -0.04m for B2 in southern North Sea					0.2m, winter maximum near East Anglia, A2) But -0.19m for B2 in southern North Sea				0.2m in annual maximum, southern N Sea, A2 But -0.56m for B2 for southern North Sea
Debernard and Røed 2008 – wave and surge modelling, 2071 to 2100	HadAM3, ECHAM4, BCCR BCM	A2, B2, A1B						6–8%, 99th percentile, North Sea east coast		6–8%, 99th percentile on North Sea east coast		6–8% in 99th percentile, North Sea east coast
Grabemann and Weisse 2008 – wave modelling, 2071 to 2100	HadAM3H and ECHAM4/ OPYC GCMs and RCAO RCM	A2 and B2					Increase in 50th percentile in eastern North Sea					Increase by 0.25–0.35m (5–8%, up to 18%) of 99th percentile in eastern and southern North Sea

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Lowe et al. 2009 – wave modelling, 2070 to 2100	HadCM3 GCM/ HadRM3 RCM PPE	A1B	Increase in winter mean in southern North Sea		Summer means increasing in southern and eastern North Sea			Increase in winter maximum in southern North Sea				Increase in annual maximum in southern North Sea
Groll et al. 2014 – wave modelling, 2011 to 2040, 2041 to 2070, 2071 to 2100	ECHAM5/ MPI-OM GCM, COSMO CLM RCM	A1B and B1					Increase in 50th percentile in eastern North Sea by the end of century					Increase in 99th percentile in southern and eastern North Sea by end of century
Wang et al. 2014 – statistical relationships between sea level pressure and wave characteristics, 2070 to 2099	20 CMIP5 GCMs (see Table B.2)	RCP4.5 and RCP8.5										1 in 10 years SWHs will double or triple in frequency along Danish coast under RCP8.5
Grabemann et al. 2015 – wave	ECHAM4, ECHAM5, HadAM3H GCMs and	A2, B2, A1B and B1					Increase in median in south and					Increase in annual maximum and 99th percentile

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
modelling, 2071 to 2100	REMO, HIRHAM, RCAO and COSMO CLM RCMs						east North Sea					in south and east North Sea
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Increase, in eastern North Sea by mid-century for RCP8.5, But a slight decrease, especially in southern North Sea, in both periods RCP4.5 and in late period RCP8.5 (see below)					5% along the eastern North Sea in period mean of annual maximum But a decrease in southern North Sea

(C) WESTERN SECTIONS OF NORTH SEA

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Debernard and Røed 2008 – wave and surge modelling, 1961 to 1990, 2071 to 2100	HadAM3, ECHAM4, BCCR BCM	A2, B2, A1B					-2 to -4% reduction					Decreasing, 99th percentile, along UK east coast
Grabemann and Weisse, 2008 – wave modelling, 2071 to 2100	HadAM3H and ECHAM4/ OPYC GCMs and RCAO RCM	A2 and B2					-0.02 to -0.05m off UK coast of median of wave heights					
De Winter et al. 2012 – wave modelling, 2071 to 2100	ESSENCE project 17 member ensemble	A1B										Decrease of annual maximum
Groll et al. 2014 – wave modelling, 2011 to 2040, 2041 to 2070, 2071 to 2100	ECHAM5/ MPI-OM GCM, COSMO CLM RCM	A1B and B1					-0.04m in median in north-west North Sea, extending					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							towards south and central North Sea					
Grabemann et al. 2015 – wave modelling, 2071 to 2100	ECHAM4, ECHAM5, HadAM3H GCMs and REMO, HIRHAM, RCAO and COSMO CLM RCMs	A2, B2, A1B and B1					-0.25m to -0.75m off north British coast in median annual wave heights					Decrease, annual maximum, 99th percentile in west and north-west North Sea
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099 (annual mean notes based on their Figure 13)	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Slight decrease, especially in southern and western North Sea, in both periods RCP4.5 and in late period RCP8.5					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs	RCP4.5, RCP8.5					-2 to -4% and up to -6% in western North Sea					-2 to -4%, in western North Sea in annual 90th percentile, 99th percentile and maximum

(D) NO PROJECTED CHANGES OR SMALL CHANGES

Authors and method	GCMs (and RCMs)	Emissions scenarios	Comments
De Winter et al. 2012 – wave modelling, 2071 to 2100	ESSENCE project 17 member ensemble	A1B	Annual mean wave climate is not projected to differ in a small area in front of the Dutch coast. A small decrease in annual maximum in that area.
Wolf et al. 2015 – wave modelling; 2070 to 2100	Members of the HadCM3 GCM/ HadRM3 RCM PPE	A1B	Future wave climate off the north Norfolk coast will not change compared with today.

Appendix C: Datum and interpretation of the extreme sea level projections, or ‘Why don’t you call the results ‘ODN’?’

Ordnance Datum Newlyn (ODN) is an absolute datum. In simplified terms, this means that the zero of ODN is a fixed distance above the unmoving centre of the Earth. The present day extreme sea levels given in Environment Agency (2019) use ODN as their datum.

Coastal planners need to know about sea level relative to coastal assets. The results presented here therefore combine present day extreme sea levels with projections of local relative sea level change (that is, change relative to the local land, which undergoes vertical land movement and so is not fixed relative to ODN). So while the extreme sea levels quoted in tables such as those in Appendix A are the levels that coastal planners need to know, they are not, strictly speaking, in ODN.

This is illustrated with an example.

The central estimate of the 20-year return level of still water at Tobermory in the Inner Hebrides at the present day is 3.45m above ODN (Environment Agency 2019). The projected Tobermory 20-year return level for 2100 under RCP8.5 determined by this project is 3.95m. A simple conceptual interpretation of this projection for Tobermory (sidestepping practical issues[9]) is as follows.

Make a mark in 2017 on the harbour wall at Tobermory at zero ODN. The projected Tobermory 20-year return level for 2100 (3.95m) will be 3.95m above where that Tobermory mark will be in 2100. But due to vertical land movement at Tobermory over the period (2017 to 2100), this is **not** exactly 3.95m above the zero of ODN. This is why the projected future results in this report are not reported as ‘ODN’. This is illustrated in Figure C.1.

---

[9] As an example of a practical issue, access to that level of the harbour wall might be extremely inconvenient. But we can *imagine* making the mark.

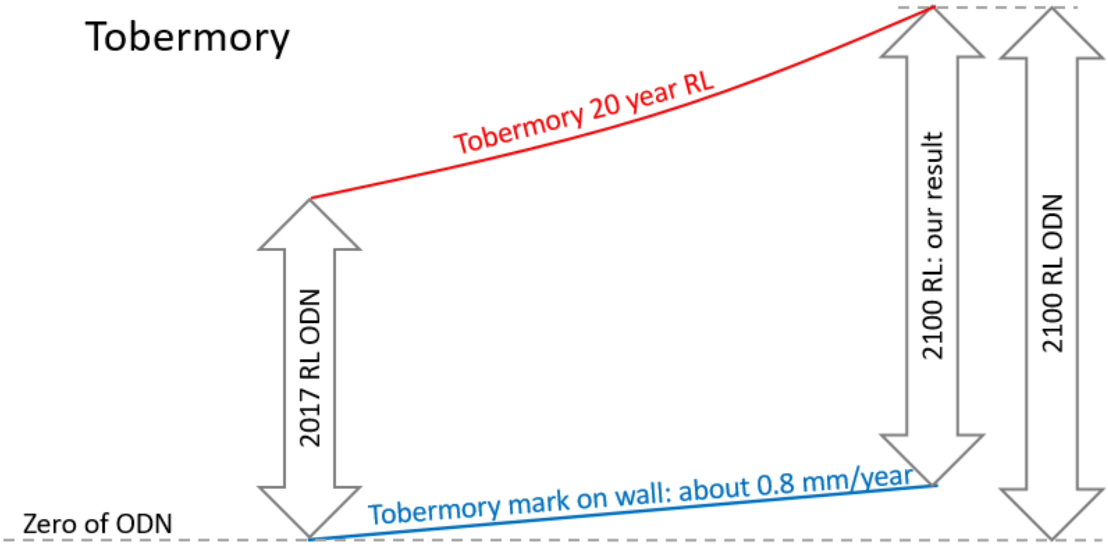

Figure C.1 Schematic diagram showing the interpretation of results: specifically why the results are not, strictly speaking, 'ODN'

Notes: Figures in this diagram are approximate and are for illustration only. For details see text.
For actual Tobermory data, see Appendix A.
RL = return level

Appendix D: Coastal flood boundary data

For ease of reference, the present day still water level return periods from the 2018 update of ‘Coastal flood boundary conditions for UK mainland and islands’ (Environment Agency 2019) are given in Table D.1.

‘Chain’ is the chainage as given by Environment Agency (2011).

‘Nom. Lat.’ and ‘Nom. Long.’ are the nominal latitude and longitude of the site. These may not be identical to the latitude and longitude of the physical tidal gauge. Rather, they are the centre of the active grid box in the surge tide model nearest to the physical tide gauge. The return levels are given in metres ODN.

Table D.1 Return levels (in mODN)

Site	Chain (km)	Nom. Lat.	Nom. Long.	Return period (years)															
				1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Newlyn	0.0	50.06	-5.42	3.11	3.18	3.26	3.33	3.39	3.41	3.47	3.5	3.52	3.56	3.58	3.6	3.61	3.65	3.7	3.88
St Mary’s*	nan	49.94	-6.25	3.41	3.48	3.56	3.61	3.67	3.69	3.74	3.77	3.79	3.82	3.84	3.86	3.87	3.9	3.96	4.11
Padstow	128.0	50.61	-4.92	4.56	4.63	4.73	4.79	4.85	4.87	4.93	4.96	4.99	5.02	5.05	5.07	5.08	5.13	5.19	5.42
Ilfracombe	250.0	51.28	-4.08	5.43	5.51	5.61	5.68	5.75	5.77	5.85	5.89	5.92	5.96	5.99	6.01	6.03	6.09	6.17	6.45
Hinkley	326.0	51.28	-3.08	7.05	7.14	7.25	7.34	7.44	7.47	7.57	7.63	7.67	7.73	7.78	7.82	7.85	7.93	8.06	8.54
Avonmouth	380.0	51.5	-2.75	8.11	8.22	8.37	8.49	8.61	8.65	8.79	8.86	8.92	9.01	9.07	9.12	9.16	9.27	9.43	10.05
Newport	398.0	51.5	-2.92	7.45	7.56	7.7	7.81	7.92	7.96	8.07	8.14	8.2	8.27	8.33	8.37	8.41	8.52	8.67	9.25
Mumbles	492.0	51.61	-3.92	5.51	5.62	5.77	5.88	5.98	6.02	6.13	6.19	6.23	6.3	6.34	6.38	6.4	6.48	6.59	6.99
Milford Haven	622.0	51.61	-5.08	4.2	4.29	4.4	4.49	4.57	4.6	4.68	4.73	4.76	4.81	4.84	4.87	4.89	4.95	5.04	5.33
Fishguard	712.0	52.06	-4.92	3.1	3.17	3.26	3.33	3.4	3.42	3.49	3.52	3.55	3.59	3.62	3.64	3.65	3.7	3.77	3.99
Barmouth	832.0	52.72	-4.08	3.46	3.59	3.75	3.87	3.99	4.03	4.14	4.21	4.26	4.33	4.38	4.42	4.45	4.54	4.67	5.09
Holyhead	1012.0	53.28	-4.75	3.37	3.44	3.55	3.62	3.7	3.72	3.79	3.84	3.87	3.91	3.94	3.96	3.98	4.03	4.1	4.35
Llandudno	1110.0	53.39	-3.75	4.7	4.78	4.9	4.98	5.06	5.09	5.17	5.22	5.25	5.3	5.33	5.36	5.38	5.44	5.53	5.81
Hilbre Island	1154.0	53.39	-3.25	5.24	5.34	5.47	5.57	5.66	5.69	5.78	5.84	5.87	5.92	5.96	5.99	6.01	6.08	6.17	6.5
Port Erin*	nan	54.17	-4.75	3.27	3.36	3.48	3.57	3.66	3.69	3.78	3.83	3.87	3.92	3.95	3.98	4.0	4.07	4.15	4.44
Heysham	1254.0	54.06	-2.92	5.86	5.99	6.16	6.29	6.42	6.46	6.59	6.67	6.72	6.8	6.86	6.9	6.93	7.03	7.17	7.63
Workington	1390.0	54.61	-3.58	5.09	5.21	5.35	5.47	5.58	5.61	5.73	5.79	5.84	5.91	5.95	5.99	6.02	6.11	6.22	6.62

Site	**Chain (km)**	**Nom. Lat.**	**Nom. Long.**	**Return period (years)**															
				1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Port Patrick	1648.0	54.83	-5.25	2.82	2.92	3.06	3.15	3.25	3.28	3.37	3.43	3.47	3.52	3.56	3.59	3.61	3.68	3.78	4.09
Millport	1782.0	55.72	-4.92	2.67	2.79	2.96	3.09	3.22	3.26	3.39	3.47	3.52	3.6	3.65	3.69	3.73	3.83	3.97	4.44
Port Ellen	nan	55.61	-6.08	1.45	1.56	1.7	1.81	1.91	1.94	2.04	2.1	2.14	2.2	2.24	2.27	2.3	2.37	2.47	2.81
Tobermory	2320.0	56.61	-6.25	2.98	3.09	3.23	3.34	3.45	3.48	3.59	3.65	3.69	3.76	3.8	3.84	3.87	3.95	4.06	4.43
Ullapool	2564.0	57.94	-5.25	3.22	3.32	3.44	3.53	3.62	3.65	3.74	3.78	3.82	3.87	3.9	3.92	3.94	4.0	4.08	4.34
Stornoway *	nan	58.17	-6.25	2.89	2.97	3.07	3.14	3.22	3.24	3.31	3.35	3.37	3.41	3.44	3.46	3.47	3.52	3.58	3.78
Kinlochbervie	2670.0	58.5	-5.08	3.17	3.28	3.42	3.52	3.62	3.65	3.74	3.8	3.84	3.9	3.94	3.97	3.99	4.06	4.16	4.46
Lerwick*	nan	60.17	-1.08	1.5	1.54	1.6	1.65	1.69	1.71	1.75	1.77	1.79	1.81	1.83	1.84	1.85	1.88	1.91	2.02
Wick	2870.0	58.39	-3.08	2.4	2.48	2.57	2.64	2.71	2.73	2.79	2.83	2.85	2.88	2.91	2.93	2.94	2.98	3.04	3.21
Moray Firth	3012.0	57.61	-4.08	2.85	2.92	3.01	3.08	3.14	3.16	3.22	3.26	3.29	3.32	3.35	3.37	3.39	3.43	3.5	3.71
Aberdeen	3226.0	57.17	-2.08	2.69	2.77	2.86	2.93	3.0	3.02	3.09	3.13	3.15	3.19	3.22	3.24	3.25	3.3	3.36	3.58
Leith	3420.0	56.06	-3.25	3.37	3.45	3.56	3.63	3.71	3.73	3.81	3.85	3.88	3.93	3.96	3.98	4.0	4.06	4.14	4.41
North Shields	3630.0	55.06	-1.42	3.21	3.29	3.4	3.48	3.56	3.59	3.68	3.73	3.77	3.82	3.85	3.89	3.91	3.99	4.08	4.42
Whitby	3720.0	54.5	-0.58	3.36	3.45	3.57	3.67	3.77	3.8	3.9	3.96	4.0	4.07	4.11	4.15	4.18	4.26	4.37	4.81
Immingham	3888.0	53.61	-0.25	4.17	4.27	4.42	4.53	4.65	4.68	4.8	4.88	4.93	5.0	5.06	5.1	5.14	5.24	5.38	5.92
Cromer	4096.0	52.94	1.25	3.07	3.19	3.35	3.48	3.61	3.65	3.79	3.88	3.93	4.02	4.08	4.13	4.17	4.29	4.45	5.03
Lowestoft	4162.0	52.5	1.75	2.02	2.17	2.38	2.55	2.72	2.77	2.93	3.03	3.1	3.2	3.27	3.32	3.37	3.5	3.69	4.31
Felixstowe Pier	4232.0	51.94	1.42	2.68	2.81	2.97	3.11	3.24	3.29	3.43	3.52	3.58	3.68	3.74	3.79	3.82	3.95	4.12	4.77

Site	**Chain (km)**	**Nom. Lat.**	**Nom. Long.**	**Return period (years)**															
				1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Sheerness	4314.0	51.5	0.75	3.7	3.81	3.96	4.08	4.21	4.25	4.37	4.45	4.51	4.59	4.65	4.7	4.74	4.85	5.01	5.59
Dover	4410.0	51.17	1.42	3.8	3.91	4.06	4.17	4.29	4.33	4.44	4.51	4.56	4.63	4.68	4.72	4.75	4.84	4.97	5.39
Newhaven	4526.0	50.72	0.08	3.87	3.94	4.04	4.12	4.2	4.22	4.3	4.35	4.38	4.43	4.46	4.49	4.51	4.57	4.66	4.96
Portsmouth	4616.0	50.83	-1.08	2.55	2.63	2.73	2.8	2.87	2.89	2.96	3.0	3.03	3.07	3.1	3.12	3.14	3.19	3.25	3.49
Bournemouth	4682.0	50.61	-1.92	1.4	1.47	1.56	1.63	1.69	1.71	1.78	1.81	1.84	1.88	1.9	1.93	1.94	1.99	2.06	2.28
Weymouth	4736.0	50.61	-2.42	1.82	1.89	1.99	2.05	2.12	2.15	2.22	2.26	2.28	2.32	2.35	2.37	2.39	2.44	2.51	2.76
Exmouth	4836.0	50.61	-3.42	2.76	2.84	2.95	3.03	3.1	3.13	3.2	3.24	3.27	3.31	3.34	3.36	3.37	3.42	3.48	3.66
Devonport	4950.0	50.28	-4.08	2.95	3.02	3.11	3.18	3.25	3.27	3.34	3.38	3.4	3.44	3.47	3.49	3.51	3.55	3.62	3.84
Portrush	nan	55.28	-6.58	1.61	1.71	1.83	1.92	2.0	2.03	2.12	2.17	2.21	2.26	2.29	2.32	2.35	2.41	2.5	2.78
Belfast	nan	54.72	-5.75	2.16	2.26	2.39	2.49	2.6	2.64	2.74	2.8	2.85	2.91	2.96	2.99	3.02	3.11	3.23	3.69
St Helier (Jersey)*	nan	49.17	-2.08	6.21	6.29	6.38	6.45	6.52	6.54	6.61	6.65	6.68	6.72	6.75	6.78	6.8	6.85	6.93	7.2

Notes: Levels are given in mODN unless otherwise stated and are correct to base year 2017.
Sites marked with * are referenced to a local datum.

Would you like to find out more about us or about your environment?

Then call us on
03708 506 506 (Monday to Friday, 8am to 6pm)

email
enquiries@environment-agency.gov.uk

or visit our website
www.gov.uk/environment-agency

incident hotline **0800 807060** (24 hours)
floodline **0345 988 1188 / 0845 988 1188** (24 hours)

Find out about call charges (www.gov.uk/call-charges)

Environment first: Are you viewing this on screen? Please consider the environment and only print if absolutely recessary. If you are reading a paper copy, please don’t forget to reuse and recycle if possible.