APPENDIX C: **CLIMATE CHANGE PROJECTIONS**

Contents

C.1 Coastal climate futures

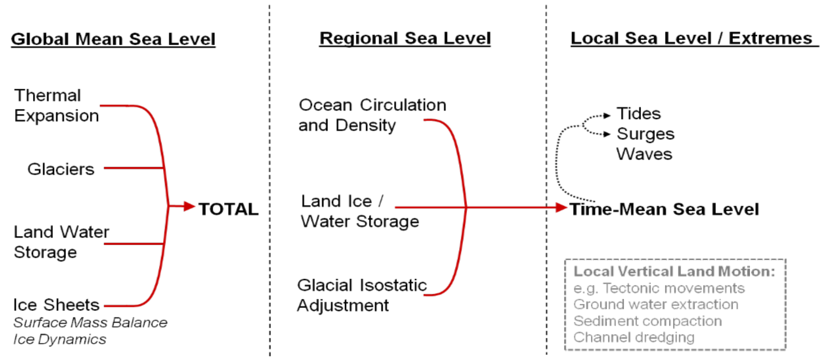
C.1.1 Climate change variable of interest: Relative sea level rise

Wave conditions around much of the UK coast are depth limited (Burgess & Townend, 2001). Relative Sea Level Rise (rSLR) therefore has a dominant influence on coastal flooding (increasing both wave-driven overtopping, the chance of a breach and tidal overflow). Coupled with the lack of evidence of climate driven changes in other aspects of coastal storms (see Box 1) rSLR is considered here as the only driver of climate related change at the coast (an assumption also made in CCRA2, Sayers *et al.*, 2015).

Box 1 Exclusion of other influences of climate change on coastal extremes

UKCP18 finds no evidence for significant changes in future storm surges or offshore wave conditions (Palmer et al., 2018). There is some indication in UKCP18 that the relative contribution of swell waves (i.e. longer period waves) may be increasing. There is little confidence in this indicator, and it is assumed here that it can be ignored. Future analysis should revisit this assumption as a change could influence the nearshore processes and overtopping (including increasing the ensemble size for the wave simulations; an ensemble that is small in UKCP18). UKCP18 also suggests that offshore wave heights are changing (moderately) and makes no suggestion of a change in direction. Given the process of refraction and depth-limitation the influence of such changes in the offshore conditions are likely to be limited at the coast. Changes to storm sequence, surge, wave direction, wetting and drying of embankments and other changes in climate that may be important to the performance of coastal defences (Sayers *et al.,* 2015) are out of scope. Palmer et al, 2018 also suggests there may be changes in low and high tide in response to mean sea level change, these are excluded here. These exclusions are considered reasonable in the context of this study and the accepted dominance of sea level rise. However, it is noted that the methods established here have the capability to include these subtle changes if evidence exists to do so in the future.

The UKCP18 sea level projections are used here. The SLR values are consistently larger than in the previous set of UK climate projections (i.e. UKCP09, Lowe *et al.,* 2009) for similar emissions scenarios (see Section 5 of Palmer *et al.,* 2018). In part this reflects an improved representation of ice sheets and the inclusion of a wider range on influences on sea level (Figure 1).



Source: Reproduced from the UKCP18 Marine Report (Palmer *et al.,* 2018b, originally drawn by Lowe)

Figure 1 The major contributors to changes in mean sea level

Due to the inertia within the response of sea level to changed climate forcing, the sea level anomaly for a given temperature change varies depending upon the evolution in temperature to that point (hence it is not possible to trade time and temperature). As such, this analysis takes the lower, central and higher rSLR values that relate to the three RCP-percentile combinations representing a rise of 2 and 4°C in GMST. The RCP-percentiles are interpolated from analysis of rebased GMST anomaly data introduced in Chapter 5 of the main report - summarised in Table 1. The resulting central estimates are presented in Table 2 for selected locations. To illustrate uncertainty in the response of sea level to different warming pathways, Figure 2 shows the lower, central and higher estimate rSLR for the 2 and 4°C rise in GMST for Wick, Cromer and Mumbles. The central estimates at 2100 are mapped around the UK coast in Figure 3.

Table 1 Relationship between RCP percentile and GMST increase by 2100

GMST increase by 2100 from pre industrial times (1860-1900)

	Percentile																				
	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.98
RCP26	0.94	1.10	1.27	1.38	1.48	1.57	1.64	1.72	1.79	1.85	1.92	1.99	2.07	2.14	2.22	2.30	2.41	2.52	2.68	2.89	3.10
RCP45	2.01	2.18	2.36	2.50	2.62	2.72	2.81	2.90	2.98	3.08	3.16	3.23	3.33	3.42	3.52	3.61	3.74	3.89	4.08	4.38	4.62
RCP60	2.44	2.61	2.85	3.03	3.16	3.27	3.37	3.47	3.56	3.64	3.74	3.83	3.93	4.03	4.15	4.26	4.40	4.55	4.76	5.10	5.34
RCP85	3.41	3.68	3.94	4.15	4.32	4.47	4.61	4.75	4.86	4.99	5.14	5.25	5.39	5.54	5.68	5.86	6.05	6.24	6.55	6.93	7.24

Source: Sayers – based on GMST anomaly data corresponding to the UKCP18 probabilistic projection data given a baseline of 1860-1900 - Met Office, 2019 pre-release prior to upload to CEDA Data Archive

Note:

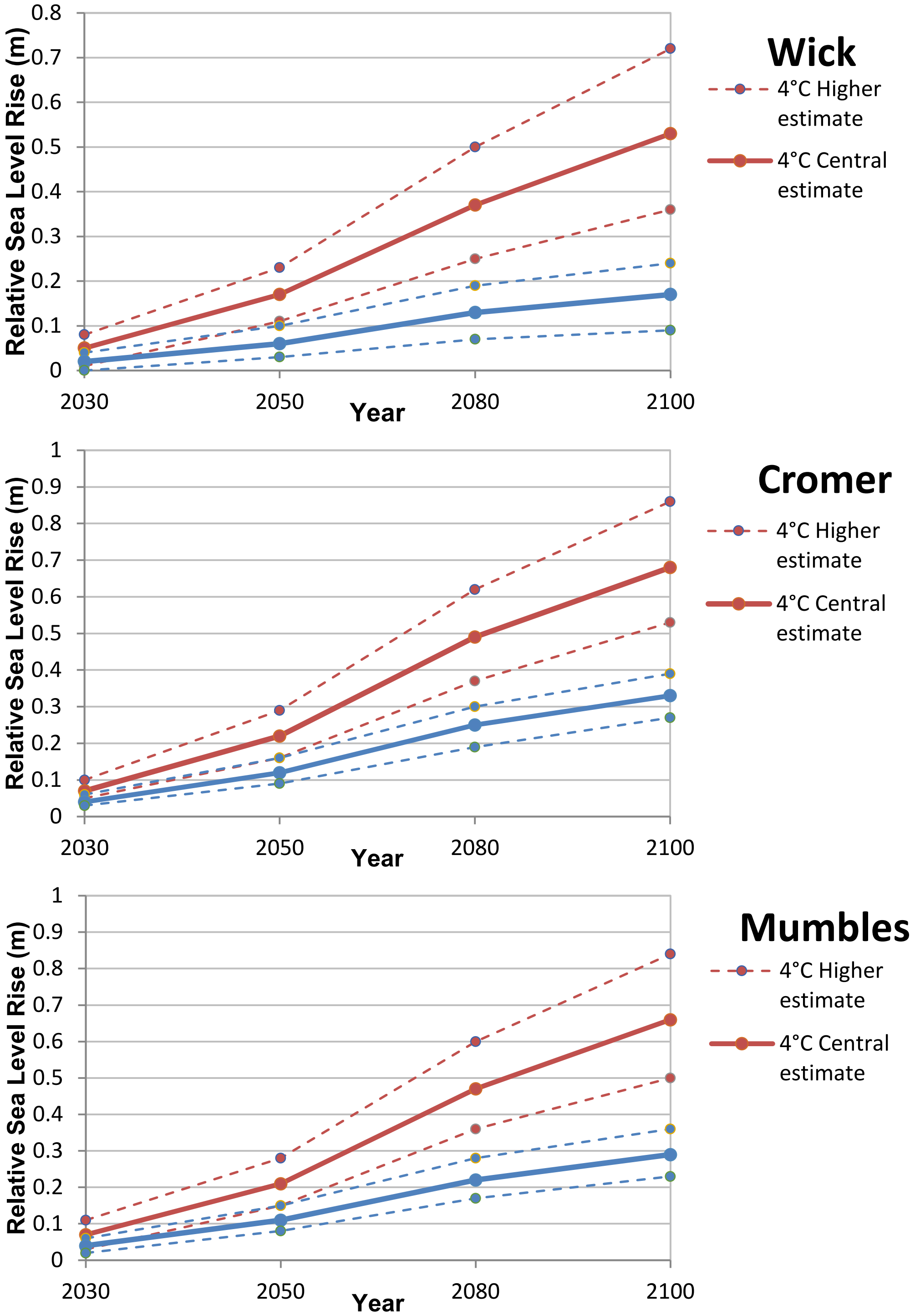
The sea level anomalies from UKCP18 are given for RCPC 2.6, 4.5 and 8.5 and the 5th, 50th and 95th percentiles only. Individual ensemble member projections are not available. It has therefore been necessary to interpolate the anomaly to either a 2 or 4°C future. This has been done by fitting a separate normal distribution to each half of the distribution. All rSLR values from UKCP18 have been re-based to show change from 2018.

Table 2 Coastal hazard: Relative sea level rise projections (m) for selected locations

	2oC		4oC	
	2050s	**2080s**	**2050s**	**2080s**
England				
Avonmouth	0.06	0.13	0.17	0.37
Cromer	0.12	0.25	0.22	0.49
Dover	0.14	0.28	0.22	0.49
Harwich	0.12	0.24	0.22	0.49
Ilfracombe	0.11	0.23	0.22	0.48
Immingham	0.11	0.23	0.22	0.47
Liverpool	0.09	0.18	0.19	0.43
Newhaven	0.12	0.24	0.22	0.48
Newlyn	0.13	0.25	0.23	0.51
North shields	0.07	0.14	0.17	0.39
Plymouth	0.12	0.25	0.23	0.50
Portsmouth	0.12	0.24	0.22	0.48
Weymouth	0.12	0.24	0.22	0.48
Whitby	0.10	0.20	0.20	0.45
Workington	0.07	0.14	0.17	0.39
Wales				
Fishguard	0.10	0.21	0.21	0.46
Holyhead	0.08	0.17	0.19	0.42
Mumbles	0.11	0.22	0.21	0.47
Scotland				
Aberdeen	0.06	0.13	0.17	0.37
Leith	0.06	0.13	0.17	0.37
Lerwick	0.13	0.26	0.23	0.50
Millport	0.06	0.12	0.16	0.37
Stornoway	0.09	0.18	0.19	0.42
Ullapool	0.09	0.18	0.19	0.42
Wick	0.06	0.13	0.17	0.37
Northern Ireland				
Bangor	0.06	0.13	0.17	0.38

Note: Central estimate of relative sea level anomaly (metres) from a 2018 baseline for increases in Global Mean Surface Temperature of 2° and 4° from pre-industrial to 2100. 2050 refers to central estimate in 2055 and 2080s refers to a central estimate in 2085.

Source: Sea level anomalies derived from UKCP18 21st Century Time-mean Sea Level Projections around the UK for 2007-2100. Re-based to show anomaly



from 2018 and sampled from all three RCP (2.6, 4.5 and 8.5). https://catalogue.ceda.ac.uk/uuid/0f8d27b1192f41088cd6983e98faa46e Accessed August 2019

Note: Lower (10th percentile) , central (50th percentile) and higher (90th percentile) estimate of relative sea level anomaly (metres) from a 2018 baseline for increases in Global Mean Surface Temperature of 2°C and 4°C from pre-industrial to 2100.

Figure 2 Uncertainty in the estimate of relative sea level rise due to the variation in rate of warming

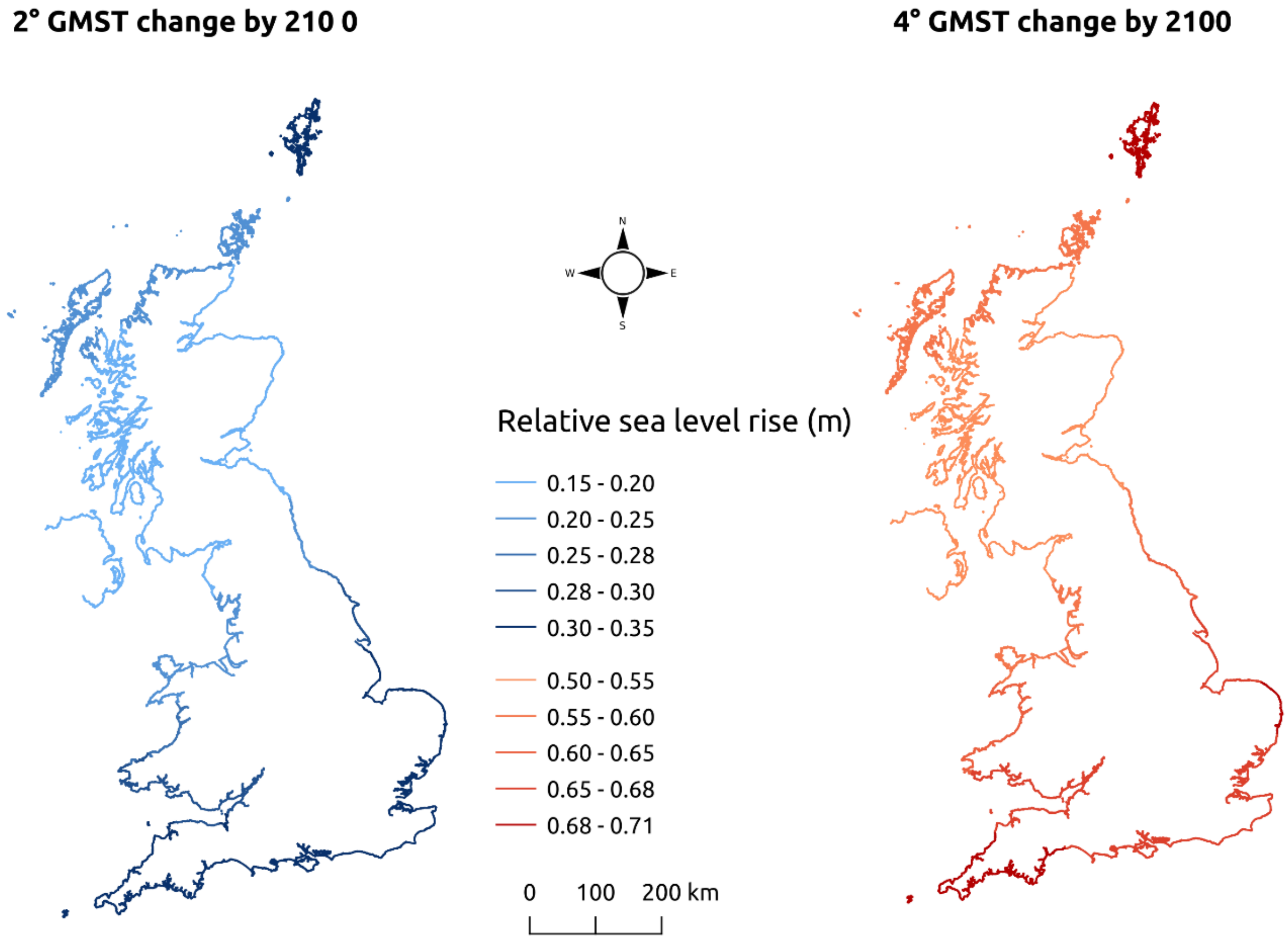


Figure 3 Central estimate of relative sea level rise around UK coast from 2018 to 2100 based on GMST increase of 2° and 4° by 2100

C.1.2 Assessing changes in relative sea levels and associated changes in coastal overtopping

The relationship between changes in rSLR and changes in Standard of Protection (SOP) afforded by a given coastal defence is established through a detailed analysis of change in overtopping rates as sea level is varied; a process summarised in Figure 4. The nearshore boundary comprises a 10,000 year synthetic dataset of waves (Gouldby *et al*., 2017) which is propagated to the coastal defences assuming Goda wave breaking (Goda, 2010) at which point overtopping rates are estimated using methods outlined in the EurOtop Manual (Pullen *et al*., 2007). The wave propagation and overtopping are repeated for a range of increases in sea level and the response of the defences to this change is analysed. This work extends research carried out by HR Wallingford (in review) covering a range of defence types and exposure to different wave climates.

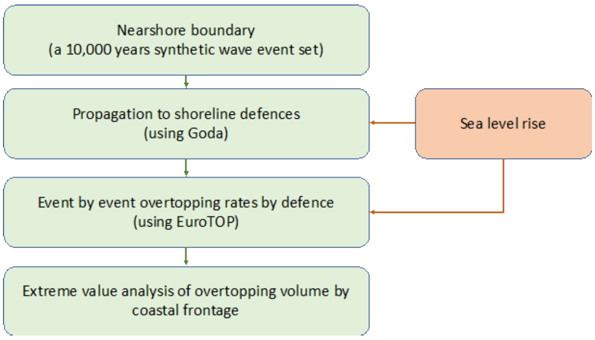


Figure 4 Assessing the impact of rSLR on coastal defence standards

The analysis of defence response is presented at the scale of Shoreline Management Plan (SMP) Policy Units (illustrated in Figure 5). In the absence of the underlying models for Wales, Scotland and Northern Ireland it has been necessary to use more aggregated frontage lengths that reflect areas exposed to similar wave climates and rSLR projections (see note below). An example set of results, drawn from the high-resolution analysis, is provided in Table 3.

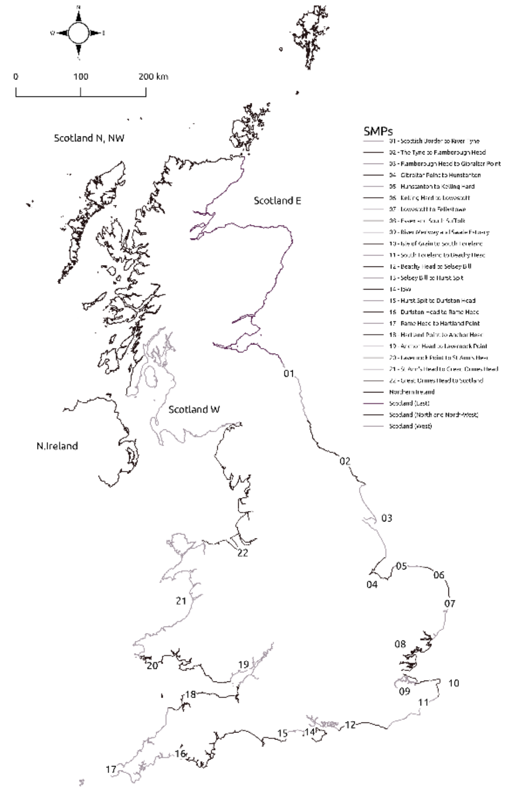
Note: ***Extrapolation to Wales, Scotland and Northern Ireland using analogues from England:*** To complete this analysis across the whole of the UK it has been necessary to use analogues from England to infill data gaps elsewhere. For example, to estimate the impact of climate change on coastal defence standards it is assumed that the west coast of Scotland responds similarly to rSLR as the south west England. Although necessary given the lack of quantified analysis data, this assumption is recognized as a weakness. The significance of this assumption is difficult to gauge in the context of this study, but adds additional uncertainty to the coastal results in Wales, Scotland and Northern Ireland.

Source: Shoreline Management Plan Policy Units for England and Wales (December 2018)

Figure 5 Example frontages for coastal hazard projections as used in England

Table 3 Future Standard of Protection: Example assuming rSLR increase of 0.35 metres

	Present Day SoP (Return Period - Years)								
	2	5	10	20	50	100	200	500	1000
England - SMP									
01 - Scottish Border to River Tyne	0	1	3	5	12	23	44	107	202
02 - The Tyne to Flamborough Head	1	3	5	10	24	47	91	256	567
03 - Flamborough Head to Gibraltar Point	1	2	3	7	17	35	70	198	370
04 - Gibraltar Point to Hunstanton	1	3	5	8	18	32	60	145	288
05 - Hunstanton to Kelling Hard	0	2	3	7	15	28	53	128	243
06 - Kelling Hard to Lowestoft	1	2	4	9	23	42	84	232	420
07 - Lowestoft to Felixstowe	0	2	3	6	18	38	78	231	449
08 - Essex and South Suffolk	0	1	3	5	14	30	64	186	435
09 - River Medway and Swale Estuary	0	2	4	7	18	37	73	229	622
10 - Isle of Grain to South Foreland	0	1	3	6	15	31	63	162	360
11 - South Foreland to Beachy Head	1	3	5	8	17	33	64	145	288
12 - Beachy Head to Selsey Bill	1	1	2	4	11	21	40	105	215
13 - Selsey Bill to Hurst Spit	0	0	1	3	7	13	25	62	119
14 - Isle of White	0	1	2	5	10	20	40	95	185
15 - Hurst Spit to Durlston Head	1	2	3	7	18	36	70	171	331
16 - Durlston Head to Rame Head	1	2	5	9	22	41	79	197	379
17 - Rame Head to Hartland Point	1	2	4	8	19	37	72	176	351
18 - Hartland Point to Anchor Head	1	2	3	6	14	26	50	123	265
19 - Anchor Head to Lavernock Point	0	2	4	7	17	33	70	190	369
22 - Great Ormes Head to Scotland	0	1	3	6	15	30	55	135	249
Wales - Region									
19 - Anchor Head to Lavernock Point	0	1	3	5	12	23	47	129	278
20 - Lavernock Point to St Ann's Head	0	1	2	4	9	18	35	86	175
21 - St Ann's Head to Gread Ormes Head	0	1	2	5	13	24	46	111	212
22 - Great Ormes Head to Scotland	0	1	3	5	14	28	51	126	225
Scotland - Region									
East	0	1	1	3	8	16	32	79	158
North and North-West	1	1	2	5	12	23	44	105	207
South-West	0	1	3	5	14	27	51	126	225
Northern Ireland - All									
Northern Ireland	0	1	3	5	14	28	51	126	225



Example: In this case the SoP afforded by a defence in SMP 22) with a current SoP of 1:100 would reduce to 1:14 years.

C.2 Fluvial climate futures

This section provides an in-depth summary – further detail is provided in the project Technical Note Kay et al, 2020.

C.2.1 Climate change variables of interest: Changes in peak flow

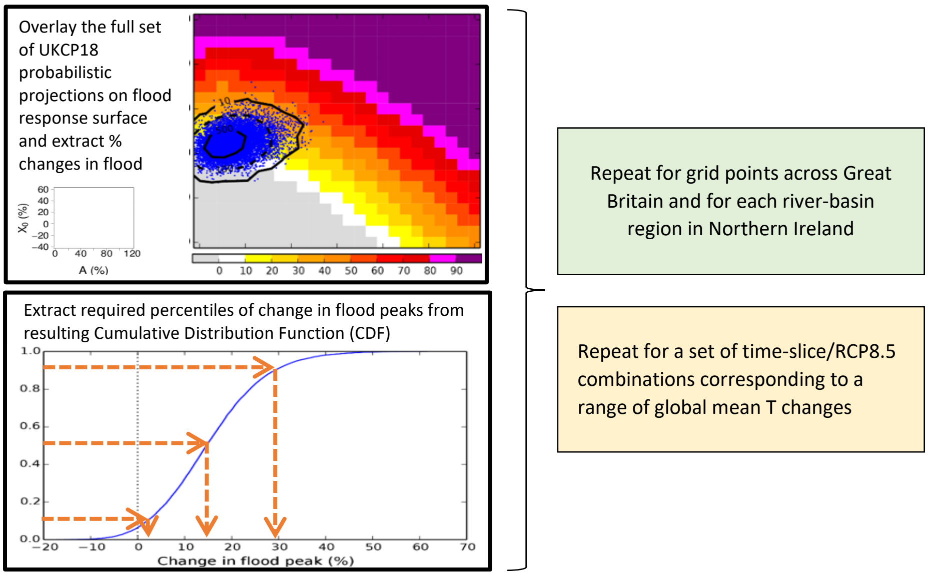
Fluvial flooding is assumed to respond to changes in peak river flows. Changes in peak flows reflect the change in the climatic variables (such as the spatial and temporal variation in rainfall and temperature) as well as the characteristics of the catchment.

C.2.2 Assessing changes in peak fluvial flows

To provide percentage changes in flood peaks the UKCP18 probabilistic projections for river-basin regions (Met Office Hadley Centre 2018) are applied to modelled 'response surfaces', enabling the potential change in peak flows to be assessed on a 1km grid. This is based on the sensitivity approach to impacts of climate change on flood peaks set out in Kay et al. (2020), which uses a national-scale grid-based hydrological model, Grid-to-Grid (Bell et al., 2009).

To provide changes in peak flows corresponding to a range of GMST changes (that may occur *en route* to a 2 or 4°C future in 2100) a 'time-sampling' approach (James et al., 2017) is used. This entails the selection of 20-year time slices (1971-1990, 1972-1991, … , 2080-2099) for each ensemble member within the UKCP18 probabilistic projections (rebased to pre-industrial times) that represent different increases in GMST (of 0.5°C intervals between 1 to 4.5°C within a maximum deviation of +/-0.04999°C – Table 4). Not all RCPs (or all ensemble members for a given RCP – see later), reach the required GMST changes. Data from RCP8.5 covers the greatest range of GMST changes and has been used to drive the fluvial flow analysis (the importance of this assumption is discussed below).

To estimate changes in fluvial flows, the changes in rainfall that relate to the selected combinations of ensemble member and time-slice are first calculated from the time-series of rainfall anomalies provided by the UKCP18 probabilistic projections. These sets of projections are then overlaid on the response surfaces, as illustrated in Figure 6 and the 50th percentile impact is selected. In this way, 1km grids of 50th percentile changes in 50-year return period flood peaks were produced for each required GMST change (Figure 7).



Top left axes: monthly precipitation changes applied *y* mean (X) and *x* seasonal amplitude (A). **For further detail see supporting Technical Note by Kay et al, 2020.**

Figure 6 Schematic showing method for estimating peak flow changes from UKCP18 precipitation changes

Note: This approach is a significant improvement on CCRA2. The analysis here is much higher resolution using 12,421 1km river cells across GB, compared to 19 regional values in CCRA2. The analysis has been applied to catchment area ≥ 100km^2. Grid points with smaller upstream catchment areas have been assigned the same climate change as the nearest downstream point with a catchment area ≥ 100km2. Where this does not exist the response of the nearest point has been assigned.

Table 4 Example 20-year time-slices corresponding to a 1°C GMST change (highlighted in yellow)

20-year	Ensemble member						
time-slice	0	1	2	3	4	5	6
1991-2010	0.420407	0.681923	0.559854	0.990239	0.696034	0.808617	0.625549
1992-2011	0.441583	0.721366	0.579787	1.006666	0.724914	0.826765	0.646448
1993-2012	0.473947	0.773227	0.610988	1.042548	0.770370	0.857946	0.683297
1994-2013	0.528367	0.810408	0.650120	1.080593	0.807845	0.889507	0.721842
1995-2014	0.576238	0.834748	0.697879	1.116436	0.838915	0.910153	0.757813
1996-2015	0.590215	0.867254	0.765643	1.146458	0.865153	0.925586	0.785264
1997-2016	0.607134	0.917737	0.813881	1.180373	0.885877	0.945359	0.816865
1998-2017	0.633826	0.942636	0.832498	1.216115	0.927343	0.960772	0.830383
1999-2018	0.651828	0.959198	0.843917	1.238400	0.970619	0.960479	0.847786
2000-2019	0.675728	0.991259	0.890801	1.259634	0.996480	0.956632	0.862788
2001-2020	0.711533	1.020891	0.919701	1.280825	1.026111	0.962611	0.880883
2002-2021	0.742032	1.036525	0.931712	1.294694	1.056997	0.965877	0.890215
2003-2022	0.775667	1.045098	0.952902	1.321351	1.079954	0.974753	0.905321
2004-2023	0.796867	1.052701	0.985476	1.371402	1.117991	0.984458	0.926620
2005-2024	0.793126	1.071300	1.026638	1.410740	1.154461	0.991544	0.953048
2006-2025	0.805018	1.094451	1.065712	1.446901	1.184837	1.005349	0.969315
2007-2026	0.829458	1.102751	1.089889	1.482153	1.204426	1.030607	0.980268
2008-2027	0.851369	1.124305	1.116933	1.517999	1.233243	1.047958	1.001052
2009-2028	0.878194	1.165945	1.141099	1.561671	1.256323	1.067268	1.006868
2010-2029	0.907850	1.193680	1.174338	1.604863	1.274413	1.094007	1.007159
2011-2030	0.920608	1.197095	1.208536	1.647793	1.311962	1.114079	1.009983
2012-2031	0.938091	1.203983	1.256200	1.689770	1.349701	1.134575	1.028743
2013-2032	0.972313	1.229781	1.297763	1.711150	1.363646	1.151188	1.041233
2014-2033	0.985339	1.264282	1.326705	1.746743	1.393176	1.162837	1.044680
2015-2034	0.992159	1.291048	1.357726	1.782475	1.436793	1.187407	1.051620
2016-2035	1.019948	1.313105	1.388891	1.820207	1.469664	1.216574	1.067582

Note: Shown for a subset of 7 ensemble members (RCP 8.5). Not all 20-year time-slices are shown; there are both earlier and later time-slices available.

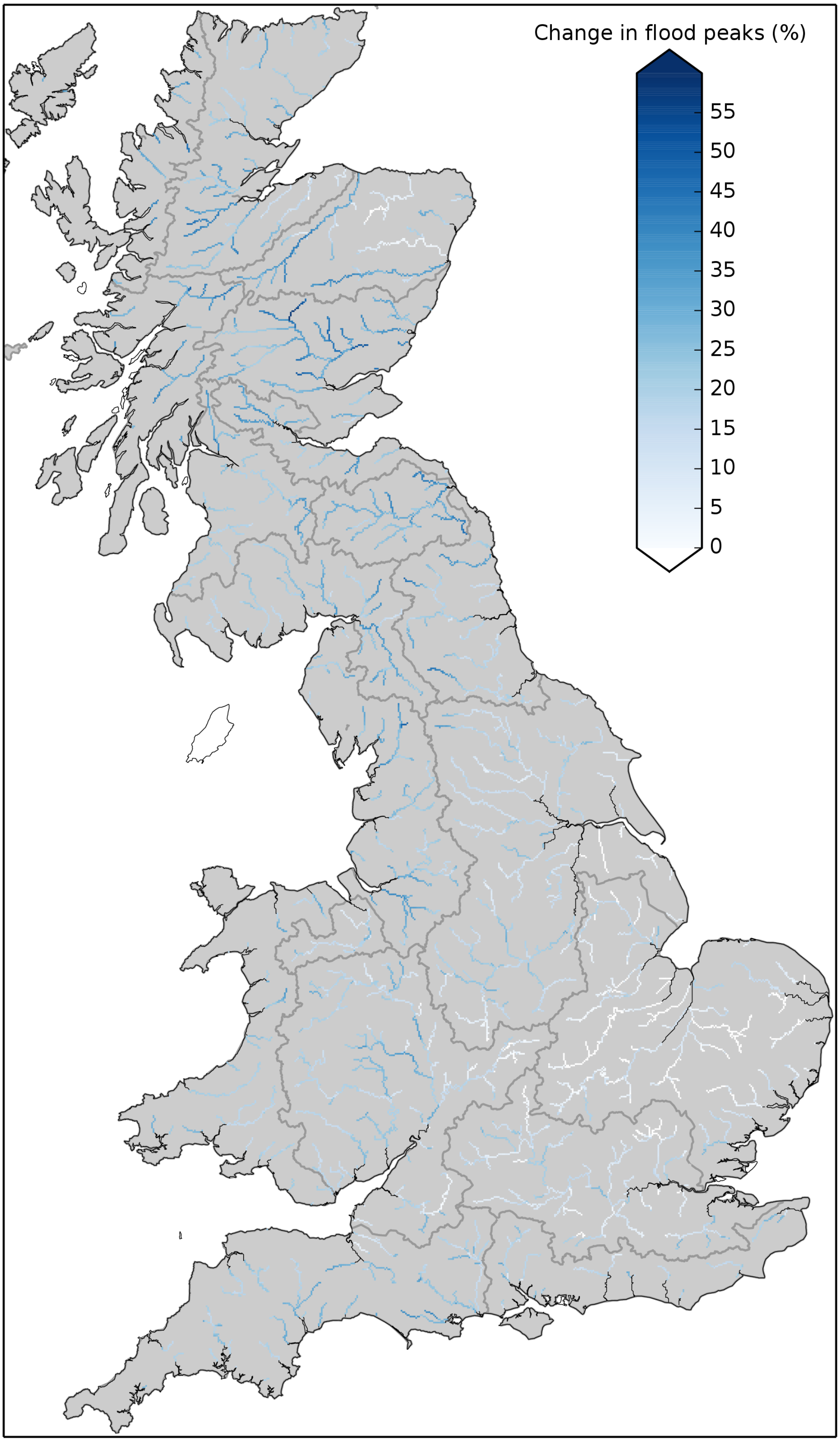
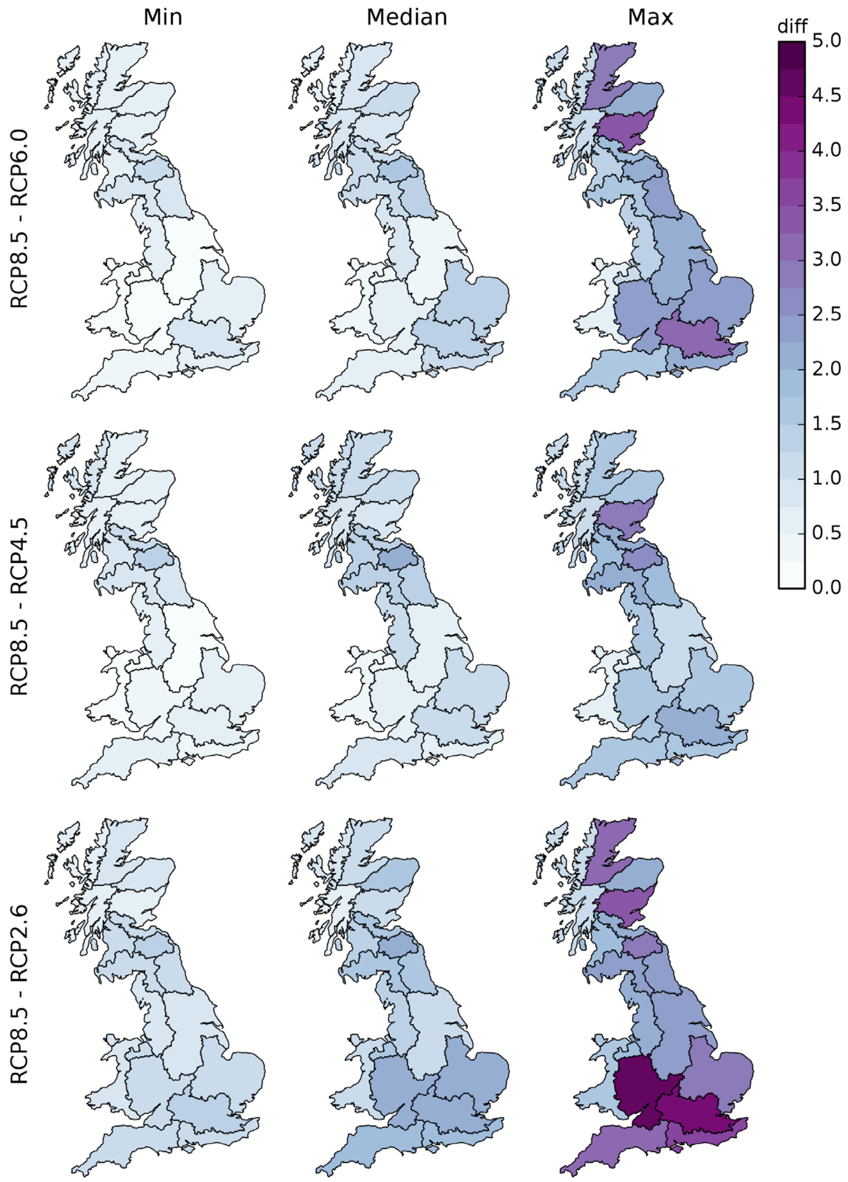


Figure 7 Gridded changes in peak fluvial flows: Example 2.5°C GMST change using RCP8.5 emissions precipitation changes

Uncertainty arising from using a single emissions trajectory (RCP 8.5)

Other RCPs (RCP2.6, RCP4.5 and RCP6.0) also project changes in GMST that might be of interest here at some stage before 2100. To test the effect of the emissions trajectory, the 50th percentile changes in 50-year return period flood peaks are compared for each RCP for a 1.5°C increase in GMST (an increase that all 3000 ensemble members in each RCP project at some time before 2100). The results (Figure 8) show that the choice of RCP does influence the projected change in peak flow (most notably between the RCP8.5 and 2.6 as expected), but differences are relatively small (around 2% or less of the RCP 8.5 based result for most 1km pixels in most regions, with differences going up to about 5% for some 1km pixels in some regions).



Note: Minimum, median, maximum differences between the 50th percentile changes in flood peaks (%) for RCP8.5 compared to RCP6.0, RCP4.5 and RCP2.6 shown for a GMST change of 1.5°C (full ensemble membership).

Figure 8 Uncertainty in changes in peak flood flows arising from emissions trajectory

Bias arising from incomplete ensemble membership

For GMST changes of 2.5°C and below, all 3000 ensemble members within the UKCP18 probabilistic projections for RCP8.5 can be used, but for higher GMST changes some ensemble members cannot be used; they do not reach the required increase in GMST by 2100 (Table 5). This introduces structural bias into the precipitation changes, and thus in the derived flood peak changes, for higher GMST changes. To investigate the bias in the 50th percentile peak flow, the percentage of the ensemble members applied is systematically reduced (for GMST changes with full ensembles; 1.5, 2.0 and 2.5°C), to see how this affects the estimate of peak flow change (when compared to use of the whole ensemble). The percentage reductions in ensemble size applied are those corresponding to each of the required higher GMST changes (3.0, 3.5, 4.0, 4.5°C; Table 5), and ensemble members are preferentially removed according to their time-slice and their position on the response surfaces (i.e. they are ordered first by time-slice, earlier to later, then by precipitation harmonic amplitude, low to high, and ensemble members are systematically removed from the end of the ordered list). The biases derived for each percentage reduction in ensemble size for the lower GMST changes are then extrapolated, to estimate the biases for each of the required higher GMST changes[1]. Using these results a 'bias correction' has been derived for each increase in GMST >2.5^{o}C. The correction is then applied to each 1km river cell (Figure 9).

Table 5 Number of ensemble members for each increase in GMST

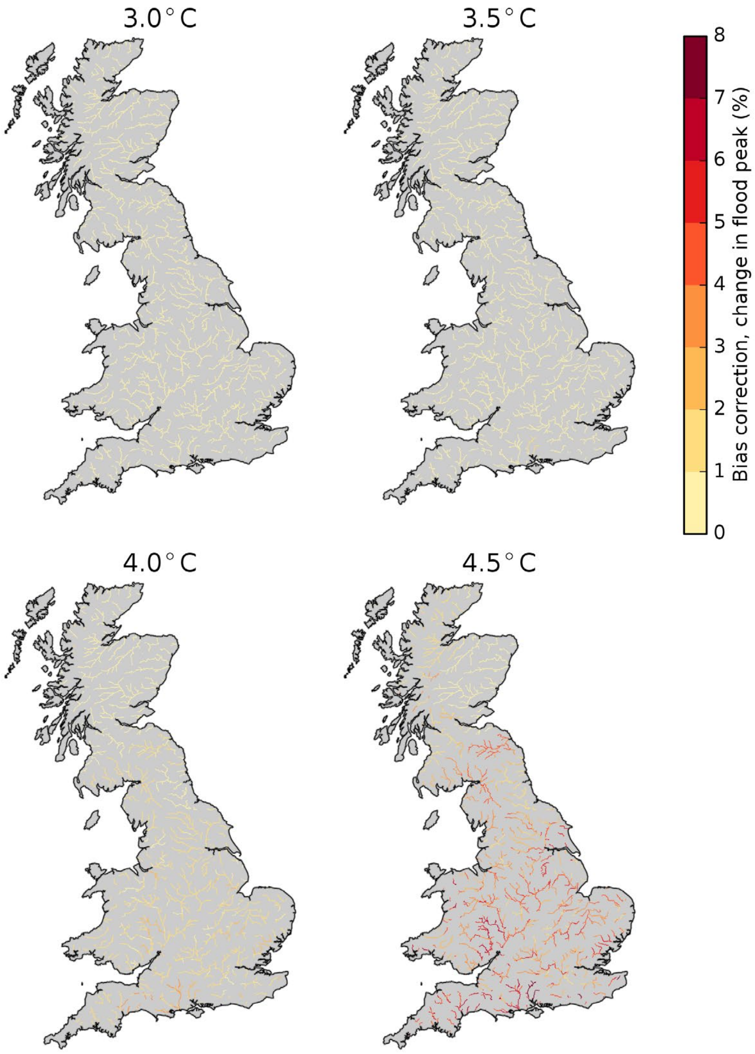
GMST change (°C from pre-industrial)	# ensemble members (RCP8.5)	% of missing ensemble members
1.0	3000	0.0
1.5	3000	0.0
2.0	3000	0.0
2.5	2997	0.1
3.0	2919	**2.7**
3.5	2700	**10.0**
4.0	2213	**26.2**
4.5	1578	**47.4**
5.0	989	**67.0**
5.5	515	**82.8**
6.0	213	**92.9**

Note: The table includes those higher than 4.5°C for completeness – these are not used here.

Extending the analysis to Northern Ireland

To extend the GB sensitivity framework to Northern Ireland (NI) the precipitation changes derived from the UKCP18 probabilistic projections are overlaid on a representative flood response surface based on a 'Neutral' response type (one of the most prevalent in the north/west of GB, Kay et al. 2014a, and assumed here to represent the response type for catchments in Northern Ireland).

[1] The ensemble corresponding to a 1.0°C GMST change is not used as part of the extrapolation, despite being a complete ensemble, as its strong concentration to the left-hand side of the sensitivity domain, regardless of time-slice, when combined with the response surfaces, introduces 'noise' into the extrapolation

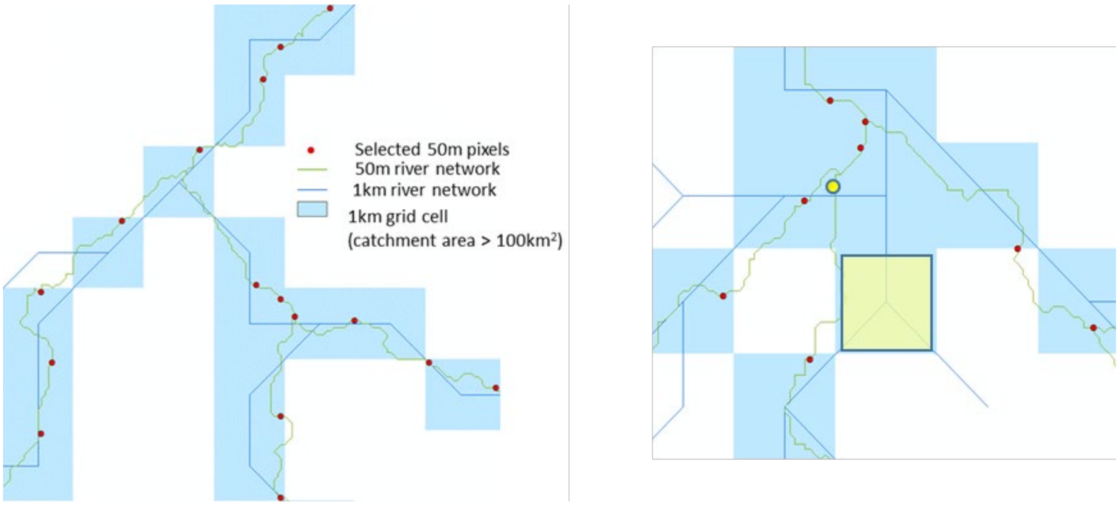


Note: Bias correction grids for 50th percentile changes in 50-year return period flood peaks, for each GMST change with an incomplete ensemble.

Figure 9 Bias corrections for changes in peak flood flows

C.2.3 Assessing the impact on river water levels

To assess future flood risk, changes in peak fluvial flow must first be translated to a change in in-river water levels (the effective storm loading on a defence where it exists). To do this an appropriate 50m pixel from the Flood Estimation Handbook (FEH) statistical method (Kjeldsen *et al.,* 2008) is assigned to each 1km river cell (from above). For GB, this was done by first choosing the FEH pixel within the 1km river cell that has the closet match in terms of upstream catchment (within a 10% tolerance) and, if this was not possible, the surrounding eight 1km cells are considered - Figure 10. For NI, the 50m pixel with the maximum catchment area within a 1km cell is used to represent the 1km cell, as is it not necessary for 50m pixels to match specific 1km flow changes.



Left: Example showing 50m pixels (red dots) selected within 1km river cells (blue boxes) based on catchment area.
Right: Example where a selected 50m pixel (yellow circle) is outside the corresponding 1km river cell (yellow box).

Figure 10 Selecting appropriate highly localised growth curves

Once the appropriate pixel was selected the FEH statistical method is applied at each of the 1km cells (i.e. at 12,282 points in Great Britain and 1,433 points in NI). To do so, eight catchment descriptors (Centroid Easting, Centroid Northing, *AREA, SAAR, FARL, BFIHOST,* $URBEXT_{2000}$ and *FPEXT*) were extracted from the Oracle grid tables held at CEH, which allowed *QMED* to be estimated at each 1km grid point. Next, pooled growth curves were derived at each grid point by fitting the Generalised Logistic distribution to pooling-groups[2]. The pooled growth curves, when combined with the QMED estimates, provided FEH peak flow estimates for a set of return periods ranging from 2 to 1000 years at each grid point. The FEH flood frequency curve for each grid point was used to estimate the change in the return period of the current T-year flood corresponding to a set of percentage changes in flow, as illustrated in Figure 11 and for an example pixel in Table 6.

Note:

In the CCRA2 this was done using regional growth curves taken from the Flood Studies Report (NERC, 1975). CCRA3 significantly improves upon this by using the latest analytical methods set out in the FEH and applied at each 1km grid point in Great Britain where percentage changes in peak flows are estimated. This enables a change in return period of the water level to be associated with a range of percentage changes in peak flows at a very high spatial resolution (capturing local response features simply missed in CCRA2).

Extreme storms - It should be recognized however that FEH Vol. 1 (Reed 1999) states that the statistical method is intended principally for use for return periods between 2 and 200 years, and thus the higher return period estimates should be used with caution, especially as the average length of record of the NRFA Peak Flow data is 42 years. However, the FEH statistical method has previously been used for return periods of up to 1000 years in flood mapping studies (EA 2015) and the use of a single estimation procedure across the full range of frequencies was considered to provide consistency.

[2] formed from the NRFA Peak Flow dataset version 7 (https://nrfa.ceh.ac.uk/peak-flow-dataset)

Use FEH statistical method enables a change in peak flow to be related to a change in water level.

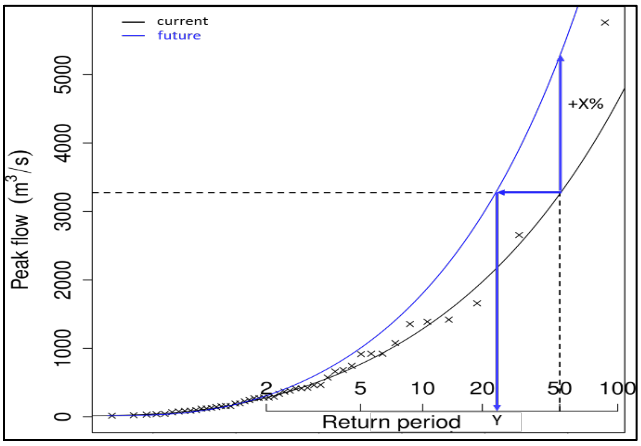


Figure 11 Schematic showing method for estimating change in return period from change in peak flow

Table 6 Fluvial flooding: Relating percentage changes in peak flow to changes in return period

ID: 30243 E: 231500, N: 717500	Current Return Period (years)									
% change in peak flow	2	5	10	25	50	75	100	200	500	1000
	Revised return period (years) given a change in peak flow									
-20%	4.8	16	33	86	173	260	346	690	1717	3419
-10%	2.9	8.4	18	45	90	135	180	359	896	1788
-5%	2.4	6.4	13	33	67	100	133	266	664	1327
+0%	2.0	5.0	10	25	50	75	100	200	500	1000
+5%	1.7	4.0	7.8	19	38	57	76	152	381	764
+10%	1.6	3.3	6.2	15	30	44	59	118	295	590
+15%	1.4	2.8	5.0	12	23	35	46	92	230	461
+20%	1.3	2.4	4.1	9.4	18	27	36	72	182	364
+25%	1.3	2.1	3.4	7.6	15	22	29	58	145	290
+30%	1.2	1.8	2.9	6.3	12	18	23	46	116	233
+40%	1.1	1.5	2.2	4.4	8.1	12	16	31	77	154
+50%	1.1	1.4	1.8	3.3	5.8	8.3	11	21	52	105
+60%	1.1	1.2	1.6	2.6	4.3	6.0	7.8	15	37	73
+80%	1.0	1.1	1.3	1.8	2.6	3.5	4.4	8.0	19	38
+100%	1.0	1.1	1.1	1.4	1.9	2.3	2.8	4.8	11	21
+150%	1.0	1.0	1.0	1.1	1.2	1.3	1.5	2.0	3.7	6.6
+200%	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.3	1.9	2.9

Example: For one point within the dataset (ID 30243, Easting 231500, Northing 717500t: A 10% increase in peak flow (+10%) would reduce the return period of a flow from 1:100 to 1:59 years.

C.3 Surface water climate futures

C.3.1 Climate change variable of interest: Intense rainfall (<6 hours duration)

Surface water flooding primarily responds to intense short duration rainfall. Here, this is represented through a change in sub-daily rainfall of less than 6 hours duration. It has long been known that climate models are relatively poor at simulating short duration precipitation extremes (Flato et al., 2013), and regional climate models have been noted to have limited skill in the simulation of UK summer rainfall extremes on both daily and sub-daily timescales (Chan et al., 2014a; Fowler and Ekström, 2009, Kendon et al, 2014). This is primarily due to their relatively coarse resolution and the associated inadequate representation of important processes, such as convection. The recent development of kilometre-scale climate models is allowing an improved representation of convection and for the first-time credible projections of changes in sub-daily rainfall (Kendon et al 2014, Kendon et al 2019). These estimates continue to support the underlying principle of the Clausius–Clapeyron relationship (that predicts an increase in the water holding capacity of air of approximately 7% per degree Celsius rise in temperature) and associated empirical evidence that demonstrates temperature change is a significant driver of changes in rainfall intensity (Dale et al., 2015). These fine-grid models remind in their infancy and data from the Met Office UKCP 2.2km climate model (Kendon et al, 2019) is yet to be fully mined from spatial changes in rainfall extreme (although studies are progressing – see note below).

It is necessary therefore to use non-UKCP18 existing estimates of changes to intense rainfall here. Unfortunately, there is limited consensus in existing data sources. For example, the Environment Agency guidance on climate allowances (Environment Agency, 2016 based on UKCP09 that had a well-known inability to represent convective storms) and allowances within Dale et al., 2017 (based on 1.5km a pre-cursor to the 2.2km UKCP18 short duration rainfall projections, Kendon et al, 2014) are notably different; with the latter significantly greater. These two sources of evidence are used here to develop estimates of future increases in intense rainfall (Table 7). In establishing these values the generally lower estimates within the Environment Agency guidance have been used to moderate the generally higher projections of change in Dale et al, 2017. This process has been based on discussion and review of initial suggestions that the UKCP18 2.2km outputs show a marked increase in rainfall intensity (although some questions remain) and hence the values used here are biased towards Dale et al, 2017.

Note:

Further analysis: The Met Office / NERC have recently supported an extremes analysis of the UKCP18 2.2km outputs (FutureDrainage studies). The results from this analysis should improve the estimates of changes in intense rainfall used here and should be readily updated in the FFE.

Level of confidence: Uncertainty in these estimates is considered significantly higher than the uncertainty in changes for peak river flows or sea level rise.

Comparison with CCRA2: CCRA2 was largely based on UKWIR (UKWIR, 2015a&b). This in turn was based on UKCP09 (and its well-recognised inability to capture convective storms) together with very early insights from CONVEX (a research programme focused on understanding convective extremes) and international analogues. CCRA3 uses an update to the same analysis used in CCRA2 based on additional detail from the previous Met Office 1.5km model as published in Dale et al., 2017.

Table 7 Surface water flooding: Percentage changes in intense rainfall of < 6 hours duration

duration < 6 hours	2030s		2050s		2080s	
GMST by 2100	2	4	2	4	2	4
Water company						
Scottish Water (west)	20	25	30	40	40	60
United Utilities	20	25	30	40	40	60
Northern Ireland	20	25	30	40	40	60
Water Northumbrian Water	10	18	20	30	35	53
Anglian Water (north)	10	18	20	30	35	53
Severn Trent (north east)	10	18	20	30	35	53
Scottish Water (east	10	18	20	30	35	53
Yorkshire Water	10	18	20	30	35	53
Dwr Cymru	10	15	15	23	25	43
South West Water	10	15	15	23	25	43
Wessex Water	10	15	15	23	25	43
Severn Trent (south west)	10	15	15	23	25	43
Thames Water	10	15	15	23	25	43
Southern Water	10	15	15	23	25	43
Anglian Water (south)	10	15	15	23	25	43

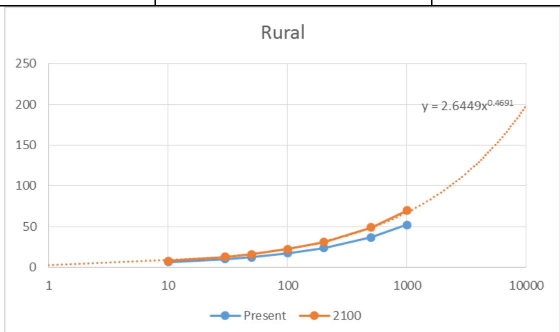
Source: Sayers - developed here (including discussions with Dale, Fowler and Kendon but this does not imply agreement).

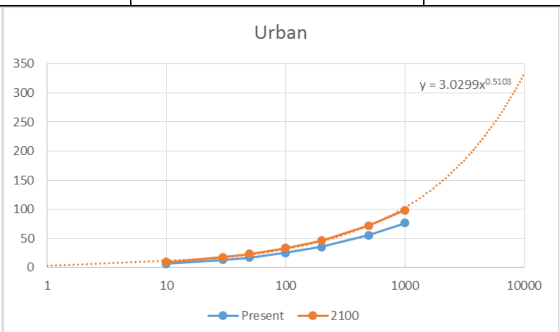
C.3.2 Assessing changes in short duration rainfall and their impact on surface water run-off

Surface water flooding does not, however, respond directly to changes in rainfall but is also influenced by drainage. The climate change influence on short-duration rainfall (from Dale et al., 2017) is therefore included with a simplified rainfall-runoff relationship (Sayers et al., 2015) to produce a change in the runoff-frequency curve (in rural and urban settings) after taking account of the assumed capacity of the conventional piped drainage network within the area (assumed to be 12mm/hr today but varies according to future adaptation). Example results are shown in Table 8.

Table 8 The influence of a 20% increase in intense short duration rainfall (≤6 hours) on run-off

Present Day Run-off (Return period in years)	Rural		Urban	
	Example present day runoff (mm)	Future Return Period (years)	Example present day runoff (mm)	Future Return Period (years)
30	10	18	13	17
100	17	56	25	63
1000	52	580	76	560





**The example results are based on the runoff-frequency curves shown in the bottom row for rural and urban areas.*

C.4 Groundwater climate futures

C.4.1 Climate change variables of interest: A combination of rainfall and evapotranspiration

Groundwater levels are governed by the amount and timing of groundwater use and recharge. Assuming no change in use (outside the focus of this study), groundwater levels are considered to respond to changes in recharge which is in turn a function of rainfall and evapotranspiration. The relationship between rainfall and groundwater recharge is non-linear because soil moisture deficits need to be satisfied before recharge can take place, and the properties of soil and rock constrain the volume of water that can recharge in each period. These relationships drive a seasonal groundwater response, with recharge typically greatest in the winter months when evapotranspiration is low.

C.4.2 Assessing changes in groundwater levels and their impact of groundwater flooding

The projections of groundwater levels used here are based on the existing classification of areas susceptibility to groundwater flooding (Macdonald *et al.,* 2008), observations of the frequency of groundwater flooding at a number of reference sites and the results of the BGS Groundwater Susceptibility Mapping undertaken as part of the Future Flows project (Jackson *et al.,* 2011). Therefore, the projection of groundwater is the same as CCRA2. This analysis enables the impacts of climate change on three forms of groundwater flooding to be considered, including: (i) *Clearwater flooding* (from Chalk or Limestone aquifers); (ii) *Clearwater flooding* (from other aquifers), and (iii) flooding from *Permeable Superficial Deposits (PSD)* (where groundwater and fluvial systems are well linked). The areas susceptible to these different types of groundwater flooding are presented in Sayers et al., 2015. In areas subject to clearwater flooding the influence of climate change on susceptibility to groundwater flooding is taken from the Future Flows as reported in CCRA2 (Table 9).

Table 9 Groundwater: Influence of climate change the frequency of clearwater flooding

		Change factors					
		2020		2050		2080	
Region	**Baseline recurrence (years)**	**2ºC**	**4 ºC**	**2 ºC**	**4 ºC**	**2 ºC**	**4 ºC**
Chalk North Downs + Kent	30	1	1	1.2	0.3	1.3	0.5
Chalk South Downs	20	0.8	1.1	1.8	1	2	1.9
Chalk Wessex	15	1	1	1.5	0.9	1.6	1.5
Chalk Berks/Bucks	25	0.9	0.8	1.2	0.6	1.2	0.7
Chalk East Anglia	50	0.5	0.6	0.6	0.2	1.3	0.3
Jurassic Yorkshire	25	0.7	1	0.8	0.8	1	0.4
Jurassic South	25	0.7	0.7	1.2	1	1.5	1.1
Chalk Yorkshire	30	0.6	0.9	0.7	0.5	1	0.5
Chalk Lincolnshire	40	0.6	0.9	0.7	0.6	1.2	0.5
Chalk Hampshire	20	0.8	0.7	1.2	0.7	1.5	1.2
Non Chalk/Lst CWF	50	1.2	0.8	1.2	1	1.5	0.9

Source: CCRA2 Sayers et al., 2015 Appendix D, Table D3

Note:

No change has been made to the underlying groundwater analysis between CCRA2 and CCRA3. It should be recognised however that as in CCRA2, the change in the susceptibility to groundwater flooding in PSD areas is assumed to be linked to the influence of climate change on fluvial flows; a response that is updated here (see earlier).

No change in the locations susceptible to groundwater flooding: It is assumed that climate change will affect the frequency of groundwater flooding, rather than its spatial extent. In the context of a national study this is reasonable because groundwater discharges are generally constrained by geological and hydrological factors, for instance the presence of fractures enhancing local permeability, or lithological variation constraining the location of a spring.

Future groundwater flood frequencies are unaffected by land use change or changes in use: Groundwater recharge is significantly affected by land use and hence by changes in land use. In urban areas impermeable pavements and buildings reduce recharge, whereas sustainable urban drainage systems and utility leakage can increase recharge. In rural settings evapotranspiration can vary significantly between woodland, grassland and different crops. Equally, change in use (for example increased or decreased industrial use) can influence groundwater levels and hence the susceptibility of flooding. These may well be additional drivers of change. These interactions are excluded here.

C.5 References

See Main Report