Sea-level rise allowances for the UK

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Abstract

We evaluate sea-level-rise allowances for UK tide-gauge locations based on the best available current description of present-day extreme still water return level curves and the United Kingdom Climate Projections 2018 (UKCP18) regionalised projections of future time-mean sea-level (MSL) change. We focus primarily on projections for 2100 under Representative Concentration Pathway 8.5. The practical benefit of an allowance is that it condenses a distribution of MSL projections into a single recommendation. Our basic allowances are founded on the probability distributions of all components of time-mean sea-level rise considered by UKCP18 except the Antarctic dynamic uncertainty. For the Antarctic dynamic contribution we include the mean projection. These basic allowances are suitable for use in situations where there is some tolerance of uncertainty. The allowance is always greater than the central estimate (50th percentile) of mean sea-level rise. Our basic allowance is found to lie below the 80th percentile in most cases, and below the 90th percentile in all cases, throughout the 21st century. We find significant sensitivity of the allowance to the uncertainty (but not the curvature) of the present-day return level plot. We find that the normal approximation is legitimate for the sum of all components of time-mean sea-level rise considered by UKCP18 except the Antarctic dynamic uncertainty. UKCP18 used a lognormal distribution to parameterise the Antarctic dynamic contribution. For a lognormal distribution of MSL rise, Hunter’s allowance is not finite. Modifying the lognormal distribution, we give an additional allowance for the Antarctic dynamic contribution uncertainty, which could be added to the basic allowance in situations where there is less tolerance of uncertainty. This additional allowance is small (less than 1 cm at any UK location before 2060) compared to the basic allowance, and, at least over the 21st century, it is virtually independent of greenhouse gas concentration pathway.

1. Nomenclature and notation

For ease of reference some terms which arise throughout this article are given in table 1.

2. Introduction

Around £150 billion of assets in the UK are at risk from coastal flooding (Howard et al 2010), and damages to the UK from coastal flooding are estimated to be of the order of £500 million per year (Edwards 2017).

Time-mean sea-level (MSL) rise is the projected dominant 21st-century contribution to change in coastal flood risk (Sterl et al 2009, Lowe et al 2009, Church et al 2013a, Garner et al 2017, Vousdoukas et al 2017). By the end of the 21st century, global mean sea level (MSL) is projected to rise by between 0.29 and 1.10 metres relative to 1986–2005 (bottom of RCP2.6 to top of RCP8.5 likely range, IPCC, in press 2019). For the UK, UKCP18-Marine found the regional MSL contribution to be typically more than five times larger than any of the other contributions they considered (Howard et al 2019).

The worst and earliest effects of MSL rise will be experienced at the coasts during extreme events, which typically involve a combination of high tide and a storm surge. In spite of the predictability of the tides, surge events are necessarily uncertain owing to their dependence on mid-latitude storms, which are not predictable.
Table 1. Nomenclature and notation.

| Name or Symbol | Description |
|----------------|-------------|
| MSL            | Time-mean sea level. |
| RCP            | Representative Concentration Pathway (van Vuuren et al 2011) |
| IPCC-AR5       | Intergovernmental Panel on Climate Change Fifth Assessment Report (Church et al 2013a) |
| UKCP18-Marine  | The United Kingdom Climate Projections 2018 Marine Report (Palmer et al 2018). |
| CFB18          | Coastal Flood Boundary Conditions for the UK: update 2018 (Environment Agency 2018). |
| H12            | Hunter (2012) (see References, section 7) |
| ‘Basic Allowance’ | Allowance for all components of MSL change including the mean Antarctic dynamic contribution but excluding the Antarctic dynamic uncertainty. |
| ‘Additional Allowance’ | Additional Allowance for the Antarctic dynamic uncertainty. |
| Course         | Projections of future mean sea-level change are uncertain. This uncertainty is typically represented by a continuous probability distribution of mean sea level rise for each future year relative to some near-present-day baseline, or by a ‘Monte Carlo’ discrete probability distribution of many possible future trajectories of mean sea level, each trajectory being a function of time. In this work we refer to such trajectories as ‘courses’. |
| $z_i'$         | MSL rise associated with course $i$, for some given future time. |
| $a$            | Allowance (see section 4.1). |
| ‘Departure’, $\delta_i'$ | If $z_i' = a + \delta_i'$ then $\delta_i'$ is the departure of course $i$ from the allowance $a$. |
| $R$            | Return period of some extreme still water level. In this work we define $R$, the return period, in the same way as the average recurrence interval in years, in contrast to the definition used by some authors as the reciprocal of the exceedance probability. These two definitions are not identical and differ significantly for small values of $R$. |
| ‘MF’ or $M$    | Multiplication Factor (some authors use the term ‘Amplification Factor (AF)’). The factor by which the expected frequency of occasional extreme sea level exceedances increases as mean sea level increases (see section 5.2). |
| $M_a$          | Multiplication factor (see above) associated with a MSL rise equal to the allowance. |
| $M (\delta_i')$ | ‘Departure-related multiplication factor’: The Multiplication factor (see above) associated with the departure of course $i$ from the allowance $a$. |
| $\lambda$      | The gradient of the local extreme still water return level curve (see equation (3) and section 4.1), plotted in the usual way with a logarithmic scale on the return-period axis. $\lambda$ is not assumed to be independent of return period. |

Beyond a few days ahead. This uncertainty is usually represented statistically, by a return level curve (see for example Coles 2001).

These, then, are two major sources of future coastal flood risk uncertainty: the unpredictability of storm surge as represented by a present-day return level curve, and the uncertain projections of 21st-century MSL rise.

A typical projection of UK regional MSL rise is 0.29 to 1.15 metres (bottom of representative concentration pathway 2.6 (RCP2.6) range to top of RCP8.5 range for 2100 for London from UKCP18–Marine, relative to a baseline period of 1981–2000). These figures vary significantly by region around the rest of the UK coastline. An obvious policy response to this threat is to raise the level of coastal defences or assets by some allowance to accommodate the projected future sea level rise. Given the uncertainty in the projections, the choice of an appropriate size for the allowance is difficult: too small, and the protection is compromised; too large, and unnecessary expense is incurred. Hunter (2012) describes a method for calculating such an allowance which is intended to preserve the expected frequency of flooding events under a given uncertain projection of sea-level rise. The allowance draws together the two major sources of coastal flood risk uncertainty described above.

The benefit of the allowance is that in situations where some uncertainty is tolerable, the allowance combines the uncertainty in projections of future MSL change with the risk which is implicit in present-day levels of protection to give a single suggested increase in those levels to maintain the same risk at some time in the future. The allowance avoids some of the subjectivity involved in selecting a suitable amount by which to raise an asset as a defence against MSL rise once the MSL rise distribution has been chosen. However, the allowance does depend on the distribution of projected MSL rise. Here we use the UKCP18 projections and thus our allowances are consistent with UKCP18. However, many other projections of MSL rise have been put forward in the literature. This is discussed further in section 6.

We give a brief outline of the physical basis for the allowance calculation here; for full details see Hunter (2012). A return level plot of still water level extremes relates each level to an expected frequency of exceedance, usually expressed as a return period, on a logarithmic scale. A typical UK return level plot is (approximately) straight, indicating a (near) exponential relationship between an increase in return level and a increase in return period, or, equivalently, a (near) exponential relationship between an increase in future MSL and an increase in future frequency of exceedance. Hunter’s (2012) method exploits this exponential relationship to associate each possible future MSL rise with a multiplication factor by which the expected frequency of extremes increases relative to the present day. Thus a distribution of possible MSL rises can be associated with a distribution of multiplication factors, and this distribution has an expected value (the mean). Similarly, raising a coastal asset
relative to its present height divides the expected frequency of exceedance. Hunter’s allowance is the amount by which a coastal asset must be raised so that this division exactly offsets the expected multiplication due to MSL rise. In other words, the allowance preserves the present-day expected frequency of exceedance in the face of uncertain future MSL.

The nature of the relationship between changes of level and changes of expected frequency of exceedance is described by the gradient (here named \( \lambda \), see section 4.1) of the (log-linear) return level plot, which characterizes the variability in the extremes: a larger value of \( \lambda \) corresponds to a longer tail on the distribution of extremes. Furthermore, a smaller variability (smaller \( \lambda \)) places greater weight on the higher sea-level projections and results in a larger allowance.

A feature of the calculated allowance is that, if the central estimate of projected MSL remains fixed, an increase in the uncertainty of the projections leads to an increase in the allowance. The reason again is the asymmetric (exponential) relationship between level and expected frequency of exceedance. In simple terms this asymmetry can be thought of as follows: building the sea wall 5 cm too high will lead to a small decrease in the frequency of flooding events, whereas building the sea wall 5 cm too low will lead to a larger increase in the frequency of flooding events.

### 2.1. Utility of the allowance approach

The utility of the allowance approach depends on the relative sizes of the two uncertainties. To see this, it is instructive to consider two limiting cases. For simplicity, suppose the distribution of a future MSL rise projection is uniform between a lower bound, \( z_L \), and an upper, \( z_U \). H12 (in his supplementary material) gives the allowance for such a distribution. (Note that this distribution is considered for illustration only; a uniform distribution is not a realistic representation of the MSL rise uncertainty). On one hand, suppose the projection uncertainty is small compared to the present-day extremes variability. As \( (z_L - z_U) \rightarrow 0 \) the allowance tends to \((z_L + z_U)/2\); the allowance is determined entirely by the central estimate of the projections. On the other hand, suppose the present-day extremes variability is small compared to the projection uncertainty. As \( \lambda \rightarrow 0 \) the allowance tends to \( z_U \); the allowance is determined entirely by the upper estimate of the projections. The allowance approach is at its most useful in between these two extreme cases, when the spread in the present-day extremes and the spread in the projections are comparable.

### 2.2. Caveats

The allowances evaluated here do not take any account of projected future changes in wave setup or runup, nor of changes in the statistics of storm surge over and above the mean sea level, nor of changes in the tidal characteristics. Although current guidance for the UK suggests that these are most likely to be small contributions compared to the MSL rise (Palmer et al 2018), some recent work has shown that such contributions and their non-linear interactions may not be small everywhere (Arns et al 2017).

The allowances pertain to long-term (century-scale) MSL rise. On shorter time-scales, small short-period internal variations which are not considered here (such as the 18.6-year nodal tidal cycle or the North Atlantic Oscillation) may be relatively more important. For this reason we present allowances from 2040 onwards.

### 3. Brief review of previous applications of Hunter’s method

To apply the method and calculate a single unique allowance at a given location, the usual procedure is to assume that the extremes follow the Gumbel probability distribution (we do not make this assumption here—see section 5.3). Furthermore one requires a complete probability distribution of local projected MSL change. It is well-recognized (Church et al 2013a) that such a complete probability distribution is not known. For the UK, this is mostly due to the difficulty in quantifying the uncertainty in the Antarctic dynamic ice-melt contribution to future MSL change. Nevertheless, the method has been widely applied, owing in part to the appeal of calculating an objective allowance after the probability distribution has been prescribed.

McInnes et al (2015) used the method to calculate allowances for the coast of Australia. They took the 5 to 95 percentile range of the IPCC AR5 process-based models (Church et al 2013a) to be the 5 to 95 percentile range of projected MSL rise, and assumed a normal probability distribution. This contrasts with the IPCC AR5 approach, where the 5 to 95 percentile range of the process-based models is taken to be the 66 percent confidence interval of projected MSL rise, and symmetry of the distribution is not assumed. However, in defence of the McInnes et al (2015) approach, we note that the review by Clark et al (2015) finds that several strands of work since the IPCC AR5 (Church et al 2013a) provide additional evidence in support of the AR5 assessment, and increase confidence in the AR5 likely range, suggesting that there is a greater than 66% probability that sea level rise by 2100 will lie in this range.
Simpson et al (2017) applied the method to generate allowances for the coast of Norway. They used the same approach as McInnes et al (2015), but also calculated an alternative (larger) allowance based on the IPCC identification of the 5 to 95 percentile range of the process-based models with the 66 percent confidence interval (the ‘likely range’, in IPCC calibrated uncertainty language) of projected MSL rise. To do so they assumed a normal distribution of projected MSL rise, mapping the 5th percentile of the model range to the 17th percentile of projected MSL rise and the 95th percentile of the model range to the 83rd percentile of projected MSL rise. The alternative (larger) allowance is typically larger by ~0.2 metres and in places as much as 0.4 metres, illustrating the sensitivity of the allowance to the spread of the projections. A similar magnitude of sensitivity for the Australian coastline is also found by McInnes et al (2015), who note that the increase in allowance would be around 0.4 metres for RCP8.5 if the model 5 to 95 percentile range were to be reinterpreted as the likely range (although, unlike Simpson et al 2017, they do not report any detailed results of such a reinterpretation).

Buchanan et al (2016) extended Hunter’s (2012) method to calculate allowances which accommodate the time-varying MSL rise, different asset lifetimes, the level of confidence in the projections, and stakeholder risk appetite. We touch on this again in section 7. Buchanan et al (2017) dropped the assumption of a Gumbel distribution and concentrated on what they call the ‘amplification factor’ (termed ‘multiplication factor’ MF here and in AR5; see appendix A): the factor by which the frequency of sea level exceedances increases in the absence of any adaptation. Based on data for the coastline of the United States, they found important sensitivities in the MF to the choice of extreme value model (EVM) for the present-day extremes, and to the uncertainties in the parameters of the EVM fit to the data. We discuss this further in section 5.3.

Goodwin et al (2017) used a hybrid approach to projecting 21st century MSL change, using a simpler modelling approach than the IPCC AR5 to estimate the thermosteric contribution, combined with a semi-empirical model estimate of the ice-melt contribution. To obtain a MF they fitted a generalized extreme value (GEV) model to annual maxima and used the scale parameter \( \lambda_{\text{GEV}} \) from the GEV fit as follows:

\[
M = \exp\left(\frac{\varepsilon}{\lambda_{\text{GEV}}}\right).
\]

They were not concerned with the calculation of an allowance, and instead report MFs as a function of the percentile of the MSL rise (their figure 4).

Some further work (Vitousek et al 2017, Rasmussen et al 2018) has concentrated on evaluating multiplication factors, which can be significant even under relatively small amounts of MSL increase.

4. Method

We calculate sea-level-rise allowances for 2100 under RCP8.5 at 46 UK class A tide-gauge locations based on the distribution of MSL rise projections reported in UKCP18-Marine and the present-day still water return level curves given by the Environment Agency’s report ‘Coastal Flood Boundary Conditions for the UK: update 2018’ Environment Agency (2018) (henceforth CFB18). Allowances based on projections of future time-mean sea-level change for other years of the 21st century under RCP2.6, RCP4.5 and RCP8.5 will be made available through the UKCP18 User Interface. CFB18 is the result of a major research and analysis project which provides the UK government’s current best estimates of still water return level for the UK coastline. For each location, CFB18 uses an empirical distribution of skew surge with a fitted generalized Pareto distribution to describe the tail. This is then combined with a complete distribution of high tides at that location to give a return level curve for extreme still water level.

UKCP18 (Lowe et al 2018) considers many physical aspects of climate change for the UK, and is the latest in a series of similar initiatives (Hulme et al 2002, Lowe et al 2009). UKCP18-Marine (Palmer et al 2018) is the part of UKCP18 which focuses on projections of sea-level change.

The projections of MSL change used here are taken directly from UKCP18-Marine. In this section, we present a brief synopsis of the UKCP18-Marine methods. Full details are available in Palmer et al (2018) and Palmer et al (2019).

The UKCP18-Marine projections build upon the sea-level-rise methods of the IPCC AR5 (Church et al 2013a), based on CMIP5 climate model simulations (Taylor et al 2012) under the RCP climate change scenarios (Meinshausen et al 2011). Assessment of CMIP5 model simulations shows their ability to reproduce the main components of global and regional sea-level rise over the historical record (Slater et al 2017b, Meyssignac et al 2017) and gives confidence in their ability to create useful projections of future change. The primary innovations to the UKCP18-Marine sea-level projections relative to IPCC AR5 are: (i) inclusion of scenario-dependent estimates of Antarctic dynamic ice input based on Levermann et al (2014); (ii) use of a regression to estimate the regional oceanographic changes, better isolating the climate change signal from CMIP5 simulations (e.g. Perrette et al 2013, Bilbao et al 2015); (iii) a more comprehensive treatment of regional uncertainties.

The regional projections accommodate the spatial patterns that come from the different ice mass and land water changes on account of the response of Earth’s gravitational field, rotation and vertical land movements (e.g. Tamisiea and Mitrovica 2011). Some account is taken of the uncertainty associated with these effects by the
use of two sets of these ‘mass fingerprints’ (Slangen et al 2014, Spada and Melini 2019). The effects of local changes in ocean circulation and seawater density are represented by using simulations from 21 CMIP5 models. This introduces substantial additional uncertainty at regional scales. Estimates of the effects of glacial isostatic adjustment (GIA) on regional MSL, which are dominated by the effects of vertical land movement, come from a 15-member ensemble created as part of the NERC BRITICE-CHRONO project (Bradley et al 2018). The uncertainties of the contributions to regional sea-level change (except for the uncertainty due to Antarctic dynamic ice melt—see below) are combined using a 100,000 member Monte Carlo simulation that preserves the covariance structure of the global and regional sea-level components.

Our allowance acknowledges all of the contributions to MSL rise considered by UKCP18-Marine. These are: thermal expansion, Antarctic dynamic ice melt, Antarctic surface mass balance, Greenland dynamic ice melt, Greenland surface mass balance, glacier melt, landwater changes, and sea-level change due to glacial isostatic adjustment. For all of these contributions except the Antarctic dynamic ice melt, our allowance accommodates a central estimate and uncertainties. For the Antarctic dynamic ice melt contribution, our allowance accommodates a central estimate (the mean) but not uncertainties. The distribution of Antarctic dynamic ice melt uncertainties used in UKCP18-Marine is incompatible with the basic allowance calculation, and so these uncertainties are addressed separately: see section 6.

4.1. Allowance calculation

Our allowance is based on the full Monte Carlo distribution of MSL rise used in UKCP18, that is to say we do not approximate the Monte Carlo distribution with a normal distribution.

In H12, 𝑧′ was defined relative to a projected mean sea level. Following Slangen et al (2017), we modify the notation of H12 so that here we use 𝑧′ as the total projected sea level rise to simplify the equations. Let 𝑁 be the Monte Carlo sample size and 𝑖 the course number (that is, a counter that counts through the courses from 1 to 𝑁). Each course represents a plausible time-series of projected MSL rise, created using a similar approach to that described in IPCC AR5 (Church et al 2013a), with some innovations which are described in Palmer et al (2018) and Palmer et al (2019). The Monte Carlo distribution of MSL rise for a given year from all contributions (including Antarctic dynamic mean but not including Antarctic dynamic uncertainties, as described above) is

\[ z_i' \text{ where } i = 1, N \]  \hspace{1cm} (1)

and our allowance (c.f H12) is evaluated as

\[ a = \lambda \log \left( \frac{1}{N} \sum_{i=1}^{N} \exp \frac{z_i'}{\lambda} \right) \]  \hspace{1cm} (2)

where \( \lambda \) is here defined as the gradient of the local extreme still water return level curve:

\[ \lambda = \frac{z_J - z_K}{L_J - L_K} \]  \hspace{1cm} (3)

where \( z_J \) is the \( J \)-year still water return level, \( z_K \) is the \( K \)-year still water return level, \( L_J = \log(J) \), \( L_K = \log(K) \) and \( J \) and \( K \) are two different return periods, in years. For our allowance we use \( J = 1 \) and \( K = 10000 \). We discuss sensitivity to this choice in subsection 5.3. If the extremes are assumed to follow a Gumbel distribution (as in H12) then \( \lambda \) (and consequently the allowance) is independent of the choice of \( J \) and \( K \). In that case \( \lambda \) is the scale parameter of the extreme still water return level curve, which is then described by

\[ z_R = \alpha + \lambda \log(R) \]

for all return periods \( R \). \( \alpha \) is the location parameter which is equal to the one-year return level. However, we do not assume a Gumbel distribution in this work. For each location, CFB18 uses an empirical distribution of skew surge with a fitted generalized Pareto distribution to describe the tail. This is then combined with a complete distribution of high tides at that location to give a return level curve for extreme still water level.

The UKCP18-Marine Monte Carlo distribution of MSL rise is measured relative to a baseline period of 1981–2000, whereas CFB18 provides return levels correct at 2017. To accommodate this difference we first calculate allowances relative to the 1981–2000 baseline period, and then adjust by subtracting the allowance for 2017, to give allowances relative to 2017. A possible alternative approach would be to subtract the 2017 value of each course from all future years of that course before making the allowance calculation. The differences between these two approaches are small (for example, at Lerwick under RCP8.5, less than 4 cm by 2100 and less than 5% of the allowance for any year). The former approach preserves the full spread of the UKCP18-Marine uncertainties for each year and gives the slightly more precautionary (i.e. slightly larger) allowance and so that is the approach that we follow.
5. Results and discussion

5.1. Basic allowance

Figure 1 shows allowances for the sea-level change to 2100 at four tide gauge locations. We selected these particular ones as follows. Sheerness: because it is on the Thames estuary. Lowestoft: because it has a particularly large \( \lambda \). Lerwick: because it has a particularly small \( \lambda \). Portrush: because it has a more typical value of \( \lambda \), and it is in the west of the UK, whereas the other three locations are in the east. In the figure, allowances and corresponding UKCP18 MSL rise distributions are shown relative to a baseline of 2017, and thus the absolute values shown for the distributions are not identical to those given in UKCP18-Marine, where a different baseline is used.

Allowances for 2100 for all three RCPs at all 46 tide gauges are tabulated in appendix F. Allowances based on projected MSL rise for 2040, 2050, 2060, 2070, 2080, 2090, and 2100 at all 46 tide gauges will be made freely available in the public domain through the UKCP18 user interface (UKCP18UI 2019).

Figure 1 has two notable features. Firstly, and importantly, the allowance is larger than the 50th percentile. The allowance is always greater than the mean (Hunter 2012) for any realistic still water return level curve; this is an example of Jensen’s (Jensen et al. 1906) inequality. Secondly, this effect is more pronounced for small values of \( \lambda \). Thus at Lerwick, where \( \lambda \) is relatively small, the allowance is considerably larger than the corresponding 50th percentile, but at Lowestoft, where \( \lambda \) is relatively large, the allowance is only slightly larger than the corresponding 50th percentile. Any positive skew in the distribution used to form the allowance exacerbates this effect, because it moves the mean above the 50th percentile, but this is not an important contribution here: recall that our basic allowance is formed without the Antarctic dynamic uncertainty, which is the main cause of the positive skew evidenced by the up/down asymmetry in the crossed ‘I’s (\( \sim \)) of figure 1. Without the Antarctic dynamic uncertainty, the skew is small.

Considering all 46 tide gauges and all three RCPs, our basic allowance lies below the 80th percentile of the UKCP18 MSL rise throughout the 21st century, except at Newlyn, St Mary’s, and Lerwick. At these three sites, our basic allowance lies below the 90th percentile of the UKCP18 MSL rise throughout the 21st century.

The allowance is rather like a weighted mean of the distribution, with more weight placed on the larger values than on the small. Either an increase in spread or a decrease in \( \lambda \) serve to exacerbate the uneven weighting.
moving the resulting allowance higher above the centre of the distribution. Figures 1 panels (e) and (f) illustrate the effect of increasing spread, showing the evolution of the allowance at Portrush from 2040 to 2100, and showing where the allowance sits as a percentile of the corresponding distribution of MSL rise projections. The effect of the spread and $\lambda$ on the allowance is discussed further in appendix G.

5.2. Multiplication factors corresponding to the basic allowance

Any MSL rise can be associated with a multiplication factor using the local value of $\lambda$. Similarly, the allowances calculated in section 5.1 can be associated with a multiplication factor, as follows

$$M_a = \exp \frac{a}{\lambda}$$

($M_a$ is the expected factor by which the frequency of a given level of flood would increase in the absence of any adaptation (see for example IPCC AR5 (Church et al 2013a), their figure 13.25 and their discussion). Values of $M_a$ for our four example locations are given in table 2. This table emphasizes the fact that the value of $\lambda$ (which is large at Sheerness; small at Lerwick) has a profound effect on the multiplication factors. A multiplication factor of $>10^4$ at a given location implies that a still water level which is currently expected to be exceeded only once every ten thousand years would in future be expected to be exceeded more often than once a year, in the absence of any adaptation. Multiplication factors for 2100 for all three RCPs at all 46 tide gauges are tabulated in appendix F.

5.3. Sensitivity tests: basic allowance

In contrast to some previous studies (Hunter 2012, McInnes et al 2015, Simpson et al 2017) we do not assume a Gumbel distribution of extreme still water levels (see section 4.1). However, our basic allowance is evaluated using a single value of $\lambda$ based on the best-guess present-day return level curve. Wahl et al (2017) found that the uncertainties in the present-day sea-level extremes can, for some locations, be comparable to the uncertainties in MSL rise projections. In a study based on the coastline of the United States, Buchanan et al (2017) found sensitivities in the multiplication factor to the choice of extreme value model and the uncertainties in its parameters. We do not assume a normal distribution in the projections of MSL rise. Slangen et al (2017) tested the dependence of the allowance on the use of three different probability distributions of MSL rise, and found strong sensitivity. In view of these results, and taking Sheerness as an example, we quantified the sensitivity of our basic allowance to three factors:

- Curvature in the return level plot (that is, departure of the extremes from a Gumbel distribution)
- Uncertainty of the return level plot
- Approximation of the MSL rise distribution by a normal distribution.

In each case we focus on the allowance at 2100 under RCP8.5, as this is the largest allowance and so will likely highlight any important sensitivities. We made the same calculation for each tide gauge and we report the largest sensitivities alongside the Sheerness result. Our results are summarized in figure 2.

5.3.1. Curvature in the return level plot

CFB18 provides return levels at each tide gauge for a set of sixteen different return periods between one and ten thousand years. By testing each combination of two different return periods $I$ and $J$ in equation (3) we can find a maximum and minimum $\lambda$ for each location. So, we recalculated the basic allowance using the maximum and minimum $\lambda$ for Sheerness. We use the difference between these two alternative allowance calculations to characterise the sensitivity, $C$, to curvature in the return level plot. For 2100 at Sheerness, under RCP8.5, $C = 2.1$ centimetres, which is only about 3% of the allowance. The largest value is 5 cm (6%) at Lerwick, so we conclude that the allowance is not very sensitive to this factor, although we note that curvature in the return level plot

| Location   | RCP2.6 | RCP4.5 | RCP8.5 |
|------------|--------|--------|--------|
| Sheerness  | 7      | 12     | 41     |
| Portrush   | 9      | 21     | 135    |
| Lerwick    | $\sim$5000 | $>10^4$ | $>10^3$ |
| Lowestoft  | 5      | 8      | 21     |

Table 2. Multiplication factors corresponding to basic allowance.
implies that the appropriate allowance may not be independent of the return period of interest (Buchanan et al 2017).

5.3.2. Uncertainty of the return level plot

CFB18 provides an indication of the uncertainty in the return level curve by giving five different percentiles of each return level. We recalculated the basic allowance for Sheerness using the 5th and 95th percentiles of the return level curve (this time maintaining \( I = 1 \) and \( J = 10000 \)). We use the difference between these two alternative allowance calculations to characterise the sensitivity, \( U \), to uncertainty in \( \lambda \). For 2100 at Sheerness, under RCP8.5, \( U = 4.2 \) centimetres, which is about 6% of the allowance there. The largest value is 10 cm (16%) at Moray Firth. This is the largest of the three sensitivities considered. This result suggests that accommodating the uncertainty of the return level plot should be the first focus of any refinement of this work. In principle this source of uncertainty could be accommodated into the calculation of the allowance (Hunter, personal communication; Tawn, personal communication, Buchanan et al 2017), but this is beyond the scope of the present work.

5.3.3. Approximation of the MSL rise distribution by a normal distribution

Some previous studies (e.g. Hunter 2012, McInnes et al 2015, Simpson et al 2017) have approximated the MSL rise distribution by a normal distribution determined by matching one low and one high percentile of the MSL rise distribution. We tested that approach, using the 5th and 95th percentile of the distribution which we used to calculate our basic allowance (remember that this does not include the Antarctic dynamic uncertainty) at Sheerness. This gives an alternative allowance \( a_N \). We use the difference \( \Delta a \) between \( a \) and \( a_N \) to characterise the sensitivity to this approximation. For 2100 at Sheerness, under RCP8.5, using the normal approximation in this way changes the allowance by \( \Delta a \) less than 0.4 centimetres. The largest value is found at Felixstowe Pier and is less than half a centimetre (less than 1%). We conclude that this is a negligible sensitivity, and the use of a normal approximation for the sum of the contributions excluding Antarctic dynamic uncertainty would be justified (although we do not use that approximation to produce results shown here). This finding is consistent with the use of a normal distribution to treat the CMIP5 model spread for some of the major components of MSL change (see section 13.SM.1.2 of Church et al 2013b).

In contrast, we find that approximating the Antarctic dynamic uncertainty distribution (which, in UKCP18-Marine, is heavily skewed even after capping at 0.5 metres, c/1’s section 6) with a normal distribution determined by matching one low (5th) and one high (95th) percentile of the Antarctic dynamic uncertainty distribution is not appropriate: it would be a mistake. For example at Sheerness, mistakenly using a normal approximation to the Antarctic dynamic uncertainty distribution would spuriously increase the additional Antarctic dynamic uncertainty allowance (described in section 6) by about 5 centimetres (which is more than 200% of the additional Antarctic dynamic uncertainty allowance there).

6. Additional Antarctic dynamic uncertainty allowance

UKCP18 used a lognormal fit to the distribution of sea level rise due to Antarctic dynamic ice melt given by Levermann et al (2014). Hunter’s allowance for a full lognormal distribution is infinite (Appendix D). Thus it is not possible to give a finite allowance which is completely consistent with the UKCP18 approach. This is one reason why our basic allowance does not accommodate the uncertainty in the Antarctic dynamic contribution. Another reason is that the uncertainty in the Antarctic dynamic contribution is qualitatively different to the uncertainty in the other components, in part because the science is not yet at the level where process-based models can fully quantify the uncertainty. Thus the Antarctic dynamic uncertainty is “deep” (Lempert 2003): in contrast to the other contributions,
there is little consensus on the type or the parameters of the probability distribution that might most appropriately be used in an attempt to describe the uncertainty. We believe that the average of the lognormal distribution is an appropriate representation of the Antarctic dynamic contribution to include in the basic allowance, although we acknowledge that this choice is somewhat arbitrary. The resulting basic allowance indicates the amount that a coastal structure needs to be raised to maintain the same expected frequency of sea-level extremes predicted on the UKCP18 distribution of sea level rise from all contributions except the Antarctic dynamic uncertainty. It is a useful guide in situations where there is some tolerance of uncertainty. In this section we evaluate an additional allowance associated with the Antarctic dynamic uncertainty. This addition is intended to serve in situations where there is a lower tolerance of uncertainty. In such situations, the additional allowance can simply be added to the basic allowance. Any finite allowance derived from the UKCP18 Antarctic dynamic contribution uncertainty will depend entirely on how the lognormal distribution is modified. Here we modified it by ‘capping’ the Antarctic dynamic contribution at 0.5 m. This cap is based on the work of Edwards et al (2019) (their figure 1(b)), who found that a parametrisation of Marine Ice Cliff Instability (MICI, Pollard et al 2015) was not required to reproduce the historical sea-level changes of three calibration periods, and that without MICI, their distribution of projections of the Antarctic contribution to 21st century MSL rise has a much shorter tail than those of DeConto and Pollard (2016). 0.5 m is not a physical upper limit to the Antarctic dynamic contribution by 2100. As discussed by Hinkel et al (2015), in the present state of knowledge the uncertainties are so large that any such upper limit that could be quoted would be of limited value to coastal engineers. Much larger Antarctic dynamic uncertainty allowances have been evaluated using other distributions, for example Slangen et al (2017), who identify a strong sensitivity of the allowance to the use of different (uncapped) probability distributions of MSL rise, and Hunter (personal communication). In situations where any level of coastal flooding—no matter how small the risk—is intolerable (an example might be a major coastal infrastructure project), a review of some of the many publications discussing ‘high-end’ sea-level rise scenarios and their application (for example Pfeffer et al 2008, Rohling et al 2008, Church et al 2013a, Ranger et al 2013, Hinkel et al 2015, DeConto and Pollard 2016, Kopp et al 2017, Le Cozannet et al 2017, Edwards et al 2019) would be an essential complement to consideration of the allowances discussed here. As discussed by Hinkel et al (2015), ‘high end’ sea-level rise scenarios have been accommodated in coastal flood management projects, notably the Thames Estuary 2100 project (Lowe et al 2009, Ranger et al 2013). We briefly investigate the relationship between the cap and the resulting additional Antarctic dynamic uncertainty allowance in appendix E.

Our method for applying the cap is to remove from the Monte Carlo samples any courses in which the Antarctic dynamic contribution exceeds 0.5 m by 2100. For RCP8.5 this means removing approximately the top 2.5% of the courses (less than 1% for the other RCPs). We then evaluate an allowance for Antarctic dynamic uncertainty as in equation (2), with $z^c$ replaced by the distribution of Antarctic dynamic uncertainty relative to the Antarctic dynamic mean (recall that the mean is already included in the basic allowance).

Figure 3 shows the Antarctic dynamic uncertainty allowance for 2100 for three example locations.

As illustrated in figure 3, the Antarctic dynamic uncertainty allowance is relatively small (once the 0.5 metre cap is applied): considering all 46 sites, the largest value is about 16 cm, found at Lerwick for 2100 under RCP8.5. The evolution of the Antarctic dynamic uncertainty allowance at Lerwick over the 21st century is shown in the bottom right panel of figure 3. Considering this panel, and bearing in mind that Lerwick is the site of the largest Antarctic dynamic uncertainty allowance, we can see firstly that before 2060, this allowance is very small (we find it is less than 1 cm at any site before about 2060) and secondly that the difference in this allowance between RCPs is pretty-much negligible (we find it is less than 7 mm at any site, anytime over the 21st century and less than 3 mm at any site before 2070).

By design, the Antarctic dynamic uncertainties and the Antarctic surface mass balance uncertainties in UKCP18-Marine have a small positive correlation. The Antarctic surface mass balance uncertainties are included in the ‘all-other’ contributions from which the basic allowance is formed. This inclusion, then, introduces a small positive correlation between the Antarctic dynamic uncertainties and the ‘all-other’ uncertainties. Positive correlation between any two contributions in general means that the allowance associated with the sum of the contributions is greater than the sum of the allowances associated with each contribution. This means that treating the Antarctic dynamic uncertainties separately (as we do here) has the potential to introduce a negative bias because we neglect the part due to correlation. However, sensitivity tests (not shown here) show that such biases are less than 0.5% of the basic allowance, so it is reasonable to neglect them.

7. Conclusions and suggestions for further work

For a set of 46 UK tide gauges, we have evaluated and discussed sea-level rise allowances that are (as far as possible) consistent with the most recent assessments of present-day still-water extremes and the most recent projections of future mean sea-level rise.
Our basic allowance is the amount by which a coastal structure needs to be elevated to maintain the present-day expected frequency of sea-level extremes under the UKCP18 distribution of projected mean sea-level rise. The allowance is greater than the central estimate (50th percentile) of mean sea-level rise. Our basic allowance lies below the 80th percentile in most cases and below the 90th in all cases throughout the 21st century.

We have also evaluated an additional allowance for the Antarctic dynamic uncertainty. This additional allowance is small. It could be added to the basic allowance in situations with a lower uncertainty tolerance. Over the 21st century, the additional allowance is virtually independent of RCP pathway.

We have investigated sensitivity of the basic allowance to various factors. We find an important sensitivity to the uncertainty in the gradient of the return level plot (this is essentially the uncertainty in the parameters of the extreme value model fit to the present-day extremes). In principle this source of uncertainty could be accommodated into the calculation of the allowance, and we recommend this be addressed in further work. However, we find relatively little sensitivity to the curvature of the return level plot at any of the UK tide gauges considered. A normal approximation to the distribution of MSL rise is appropriate provided the Antarctic dynamic uncertainty is excluded.

Results in this publication mostly focus on RCP8.5 and the year 2100. Results for other years and for RCP2.6, RCP4.5 and RCP8.5 will be made freely available in the public domain through the UKCP18 User Interface (UKCP18UI 2019).

Buchanan et al (2016) provide a framework of MSL rise allowances that accommodate both user-defined flood risk management preferences and levels of confidence in MSL rise projections. A comparable framework for the UK, again based on the UKCP18 MSL rise projections and the CFB18 extreme still water level return curves, is a desirable extension of the work presented here.

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Author contributions

TH evaluated the allowances and lead the writing. MDP produced the time-mean sea-level change projections for UKCP18 and assisted with the writing and development of the analysis.

Appendix A. Multiplication factors

The allowance (equation (2)) could be evaluated in three steps:

\[ M_i = \exp(z_i' / \lambda) \quad \text{evaluate multiplication factor for each } z_i' \]

\[ \overline{M} = \frac{\sum_{i=1}^{N} M_i}{N} \quad \text{mean multiplication factor} \]

\[ a = \lambda \log(\overline{M}) \quad \text{allowance} \]

The expression for \( \overline{M} \) can be seen as a discrete form of the integral

\[ \int_{-\infty}^{\infty} P(z') \exp \left( \frac{z'}{\lambda} \right) dz' \]

with each realization \( z_i' \) given equal probability 1/N, since each realization is regarded as equally likely.

The relationship between \( M_i \) and \( z_i' \) can be conveniently visualised on a return level plot as shown in figure 4 (for simplicity we illustrate the relationship using a straight return level curve). To see this, follow these steps: move the return level curve up by \( z_i' \) to represent the future RL plot, relabel the X-axis with ‘expected number of events in 10,000 years’, so that the labels change from (1,10,100,1000,10000) to (10000,1000,100,10,1) respectively, draw a horizontal line at the present-day 10 000-year return level i.e. the 1 event in 10,000 year level and note that it intersects the future return level line at the 100-year return period (i.e. 100 events in 10,000 years). So the multiplication factor is from 1 events to 100 events: a factor of 100. Observe that the simpler construction in figure 4 gives the same answer.

**Figure 4.** The relationship between a single multiplication factor and a single value of MSL rise as it appears on a RL plot. In this example, \( z_i' = 0.4 \text{ metres } \lambda = 0.0868 \), and \( M_i = 10000 \text{ years/100 years} = 100 \).
Appendix B. Departure-related multiplication factors in the calculation of our basic allowance

λ as defined in equation (3) essentially relates a difference in water level to a difference in the expected frequency of occurrence of an extreme event, and the allowance is the amount by which an asset must be raised to preserve the existing expected frequency of occurrence under a given distribution of MSL rise. In that framework, any change in water level may be associated with a multiplication factor M of the expected frequency of occurrence of an extreme still water level (see appendix A):

\[ M = \exp \frac{z}{\lambda} \]  

and the allowance can be recast as the amount by which an asset must be raised to give an average value of

\[ \exp \frac{z - a}{\lambda} = 1 \]

Suppose, then, that a coastal planner raises an asset today by the allowance a as a strategy to defend against the distribution of MSL rise projections given by equation (1). The uncertainty in the future MSL relative to the new asset level, a, is

\[ \delta_i = z_i' - a \quad \text{where} \quad i = 1, N \]  

and the corresponding departure-related multiplication factors are

\[ M(\delta_i') = \exp \frac{\delta_i'}{\lambda} \]  

— these average out to one. For an explanation of why the departure-related multiplication factors are calculated in this particular way see appendix C. Due to the exponential, for a course with a large departure δt from the allowance a, at a location with a small λ, M(δt) could be quite large, a value of one thousand representing, for example, a change in expected frequency from once every thousand years to once every year, or once every ten thousand years to once every ten years, etc... However, very large values of M(δt) may not be an appropriate cost (weighting) of the consequence of a large departure from a. For example suppose δt = 1.5 metres and λ = 0.1 metre, then M(δt) is around three million. This would represent an increase in expected frequency from once every ten thousand years to three hundred times per year. But the actual cost of an expected frequency of three hundred floods per year would not be three hundred times the cost of one flood per year, since in practice some other strategy would be adopted—the asset might instead be abandoned, or moved elsewhere.

Buchanan et al (2017) discuss and address this issue, pointing out that lower flood levels saturate first, yielding flooding influenced primarily by tidal events and effectively dampening the growth of the multiplication factor (they use the term ‘amplification factor’). Hunter (personal communication) has experimented with the effect of capping the departure-related multiplication factor M(δt) at one thousand for various MSL rise distributions. Thus it is appropriate to ask what is the maximum value of M(δt) in any given allowance calculation—very large values (e.g., > one thousand) might undermine the relevance of the result. For the allowances reported in section 5.1, the maximum value of M(δt) is around nine hundred. This arises at Lerwick under RCP8.5 and corresponds to λ = 0.057 metre and a departure of z_i' - a = 0.4 metre. Considering all 46 tide gauges and all three RCPs for 2100, the overall maximum is around nine hundred and thus our basic allowances would not be affected by capping M(δt) at one thousand. Maximum values of around 25 are more typical, and a value of 100 is exceeded at only 3 locations under RCP2.6, 3 locations under RCP4.5, and 11 locations under RCP8.5. Values of M(δt) in the calculation of the additional allowance for the Antarctic dynamic uncertainty are smaller. We conclude that the values of M(δt) do not undermine the relevance of our results.

Appendix C. Capping of departure-related multiplication factors

To see why we might consider putting a cap on a multiplication factor like

\[ \exp \frac{z_i' - a}{\lambda} \]

instead of

\[ \exp \frac{z_i'}{\lambda} \]

consider an unrealistic but illustrative case where the uncertainty in the MSL rise is very small compared to the central estimate of MSL rise. For example, suppose that for our location the MSL rise was a normal distribution with central estimate of 5 metres (we stress that this is for illustration only) and standard deviation σ = 0.1 metre, and suppose now that λ = 0.05 metre. The multiplication factor for the central estimate is
But we would not dismiss an allowance of (at least) 5 metres for this distribution just because this $M_{CE}$ is very large. Instead we might take a first-guess allowance of 5 metres, and then calculate the additional allowance for uncertainty, using multiplication factors $M_i$ based on $(z_i' - 5$ metres). This allowance could be calculated analytically as (Hunter 2012) $\sigma^2/2\lambda = 0.01 \text{ m}^2/0.05 \text{ m} = 0.2 \text{ m}$, so our allowance would be 5.2 metres. If we were going to apply a MF-cap, then we could take this (5.2 metres) as our guess at the allowance, then calculate values of $M_i$ based on $(z_i' - 5.2$ metres), cap them at $10^4$ or whatever value, and then calculate the corresponding next-guess allowance and repeat until converged.

Our assessment of whether a value of $M_i$ is too high (e.g. $>10^4$) is thus based on the multiplication factor of the departure of the future MSL rise from the allowance.

Viewed in this way it seems quite intuitive that the factor that we might want to cap is the departure-related multiplication factor as in subsection B.

Appendix D. Hunter’s allowance is infinite for a lognormal distribution of sea-level increase

UKCP18 uses a lognormal distribution to represent the Antarctic dynamic contribution. For a lognormal distribution with no upper limit, the uncapped Hunter’s allowance is infinite.

Here we follow a similar approach to Hunter (2012) Electronic Supplementary Material, but we consider a lognormal distribution.

Let $z'$ have a lognormal distribution with probability density function

$$P(z') = \frac{1}{z'\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\log(z') - \mu)^2}{2\sigma^2}\right\}$$

Hunter’s allowance can be expressed as

$$\lambda \log(I)$$

where

$$I = \int_{z'=0}^{z'=-\infty} P(z') \exp\left(\frac{z'}{\lambda}\right) dz'$$

Let $y = \log(z')$; then $z' = \exp(y)$, $dz'/z' = dy$ and using 11:

$$I = \int_{y=-\infty}^{y=-\infty} \frac{1}{z'\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\log(z') - \mu)^2}{2\sigma^2}\right\} \exp\left(\frac{z'}{\lambda}\right) dz'$$

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{y=-\infty}^{y=-\infty} \frac{1}{z'} \exp\left\{-\frac{(\log(z') - \mu)^2}{2\sigma^2}\right\} \exp\left(\frac{z'}{\lambda}\right) dz'$$

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{y=-\infty}^{y=-\infty} \exp\left(\frac{y - \mu}{2\sigma^2}\right) \exp\left(\frac{\exp(y)}{\lambda}\right) dy$$

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{y=-\infty}^{y=-\infty} \exp\left[\frac{\exp(y)}{\lambda} - \frac{(y - \mu)^2}{2\sigma^2}\right] dy$$

Owing to the first exponential in equation (17), the integrand of equation (17) is non-negative. $\mu$ is finite. $\lambda$ and $\sigma$ are finite and positive. Thus we can always choose a value of $y$ above which the quantity in the square brackets in equation (17) is positive and increases monotonically with $y$. Consequently $I$ is infinite, and so is the resulting allowance, expression 12.

This argument can be constructed using a notation which is more similar to that of Hunter (2012), but the algebra is then more long-winded.
Appendix E. Relationship between cap and Antarctic dynamic uncertainty additional allowance

As discussed in section 6, Hunter’s allowance for a full lognormal distribution is infinite (Appendix D), and any finite allowance derived from the UKCP18 Antarctic dynamic contribution uncertainty will depend entirely on how the lognormal distribution is modified. We modified it by ‘capping’ the Antarctic dynamic contribution at 0.5 m. We consider this to be a sensible choice of cap value, but as noted in section 6, larger Antarctic dynamic uncertainty allowances have been evaluated by other studies. In view of this, we show here some results of adjusting the cap value.

Figure 5 shows the relationship between the cap value and the resulting Antarctic dynamic uncertainty additional allowance for five sites which are chosen to span the range of relationships over all of the sites considered. Values of $\lambda$ at each site are also shown. The figure is consistent with the remarks of section 2.1: as the spread in the present-day extremes ($\lambda$) decreases, the additional allowance moves closer to the upper limit of the distribution. For very large values of cap/small values of $\lambda$, the allowance approach adds little value to the approach of simply choosing an upper limit. Furthermore, figure 5 shows that the departure-related multiplication factor corresponding to the cap is greater than 1000 for large values of the cap. In other words at least one of the courses could be just below the cap and still have a multiplication factor greater than 1000, potentially undermining the practical relevance of the additional allowance (see appendix B) for these large cap values.

At small cap values, the additional allowance is slightly negative. This does not conflict with the rule that the allowance is always greater than the mean of the projection distribution; it simply reflects the fact that the Antarctic dynamic mean contribution has been evaluated based on the full lognormal distribution, whereas the additional allowance is based on a capped distribution.

Appendix F. Tabulated allowance data for 2100

These tables show the allowance and related information at 2100 for each of the 46 sites and each of the three RCPs. The column heading abbreviations are as follows.

- **BA**: Basic Allowance (see section 5.1), in metres.
- **AA**: Additional Antarctic Dynamic Uncertainty Allowance (section 6), in metres.
- **$M_a(BA)$**: The multiplication factor, $M_a$ (equation (4)) in the context of the basic allowance at that site, rounded to a whole number.
- **$M_a(AA)$**: The multiplication factor as above in the context of the Additional Antarctic Dynamic Uncertainty Allowance at that site, rounded to a whole number.
- **Lam**: $\lambda$ (equation (3)), in metres.
- **ADM**: The mean of the Antarctic Dynamic projections (see section 4), in metres.
- **Max UMF(BA)**: The maximum departure-related multiplication factor in the context of the basic allowance at that site for any year and any RCP (section B and appendix C), rounded to a whole number.
- Max UMF(AA): The maximum departure-related multiplication factor in the context of the Additional Antarctic Dynamic Uncertainty Allowance at that site for any year and any RCP, rounded to a whole number.

***** indicates a multiplication factor that is greater than ten thousand.

### RCP2.6

| Site         | BA   | AA   | Ma(BA) | Ma(AA) | ADM | Lam | Max UMF(BA) | Max UMF(AA) |
|--------------|------|------|--------|--------|-----|-----|-------------|-------------|
| Newlyn       | 0.461| 0.098| 243    | 3      | 0.102 | 0.084| 104         | 92          |
| StMarys      | 0.473| 0.117| 503    | 4      | 0.102 | 0.076| 163         | 119         |
| Padstow      | 0.442| 0.081| 115    | 2      | 0.101 | 0.093| 68          | 69          |
| Ilfracombe   | 0.415| 0.058| 42     | 1      | 0.100 | 0.111| 36          | 41          |
| Hinkley      | 0.403| 0.029| 12     | 1      | 0.099 | 0.162| 12          | 14          |
| Avonmouth    | 0.392| 0.018| 6      | 1      | 0.099 | 0.211| 7           | 8           |
| Newport      | 0.393| 0.021| 7      | 1      | 0.099 | 0.195| 8           | 9           |
| Mumbles      | 0.393| 0.030| 11     | 1      | 0.100 | 0.160| 12          | 15          |
| MilfordHaven | 0.398| 0.050| 25     | 1      | 0.101 | 0.122| 27          | 32          |
| Fishguard    | 0.391| 0.073| 35     | 2      | 0.101 | 0.097| 56          | 60          |
| Barmouth     | 0.351| 0.026| 7      | 1      | 0.100 | 0.177| 10          | 12          |
| Holyhead     | 0.337| 0.064| 23     | 1      | 0.101 | 0.107| 39          | 46          |
| Llandudno    | 0.339| 0.050| 16     | 1      | 0.100 | 0.121| 26          | 32          |
| Pembrokeshire| 0.343| 0.040| 12     | 1      | 0.100 | 0.136| 18          | 23          |
| PortErin     | 0.294| 0.046| 10     | 1      | 0.101 | 0.127| 22          | 28          |
| Heysham      | 0.314| 0.022| 5      | 1      | 0.099 | 0.192| 8           | 10          |
| Workington   | 0.282| 0.029| 5      | 1      | 0.100 | 0.165| 11          | 14          |
| Portpatrick  | 0.258| 0.041| 7      | 1      | 0.101 | 0.138| 17          | 23          |
| Millport     | 0.240| 0.022| 3      | 1      | 0.101 | 0.192| 8           | 10          |
| PortEllen    | 0.266| 0.037| 6      | 1      | 0.102 | 0.147| 14          | 19          |
| Tobermory    | 0.279| 0.033| 5      | 1      | 0.102 | 0.158| 12          | 16          |
| Ullapool     | 0.312| 0.051| 13     | 1      | 0.101 | 0.121| 24          | 32          |
| Stornoway    | 0.358| 0.078| 40     | 2      | 0.102 | 0.097| 52          | 62          |
| Kinlochbervie| 0.339| 0.040| 11     | 1      | 0.102 | 0.140| 16          | 22          |
| Lerwick      | 0.485| 0.166| 4783   | 18     | 0.101 | 0.057| 459         | 265         |
| Wick         | 0.334| 0.089| 44     | 2      | 0.101 | 0.088| 73          | 77          |
| MorarFirth   | 0.288| 0.078| 21     | 2      | 0.100 | 0.094| 55          | 64          |
| Aberdeen     | 0.290| 0.075| 20     | 2      | 0.100 | 0.096| 52          | 60          |
| Leith        | 0.255| 0.055| 9      | 1      | 0.100 | 0.113| 29          | 38          |
| NorthShields | 0.328| 0.042| 12     | 1      | 0.099 | 0.131| 19          | 25          |
| Whitby       | 0.367| 0.031| 10     | 1      | 0.099 | 0.156| 12          | 15          |
| Immingham    | 0.390| 0.021| 7      | 1      | 0.098 | 0.191| 8           | 10          |
| Cromer       | 0.415| 0.017| 7      | 1      | 0.098 | 0.213| 6           | 8           |
| Lowestoft    | 0.413| 0.013| 5      | 1      | 0.097 | 0.249| 5           | 5           |
| FelixstowePier| 0.407| 0.015| 6     | 1      | 0.097 | 0.227| 5           | 7           |
| Sheerness    | 0.404| 0.018| 7      | 1      | 0.097 | 0.206| 7           | 8           |
| Dover        | 0.406| 0.024| 10     | 1      | 0.097 | 0.173| 9           | 12          |
| Newhaven     | 0.417| 0.048| 33     | 1      | 0.098 | 0.119| 26          | 32          |
| Portsmouth   | 0.425| 0.065| 67     | 1      | 0.098 | 0.101| 45          | 50          |
| Bournemouth  | 0.432| 0.074| 95     | 2      | 0.099 | 0.095| 58          | 62          |
| Weymouth     | 0.429| 0.065| 66     | 1      | 0.099 | 0.102| 45          | 50          |
| Exmouth      | 0.434| 0.072| 83     | 2      | 0.100 | 0.098| 54          | 58          |
| Devonport    | 0.443| 0.074| 94     | 2      | 0.101 | 0.097| 57          | 60          |
| Portrush     | 0.283| 0.048| 9      | 1      | 0.102 | 0.127| 22          | 29          |
| Belfast      | 0.269| 0.030| 5      | 1      | 0.101 | 0.166| 11          | 14          |
| Jersey       | 0.426| 0.060| 53     | 1      | 0.099 | 0.107| 38          | 43          |

### RCP4.5

| Site         | BA   | AA   | Ma(BA) | Ma(AA) | ADM | Lam | Max UMF(BA) | Max UMF(AA) |
|--------------|------|------|--------|--------|-----|-----|-------------|-------------|
| Newlyn       | 0.584| 0.096| 1040   | 3      | 0.117 | 0.084| 119         | 78          |
| StMarys      | 0.597| 0.114| 2569   | 4      | 0.118 | 0.076| 175         | 101         |
| Padstow      | 0.561| 0.081| 416    | 2      | 0.116 | 0.093| 79          | 59          |
(Continued.)

| Site       | BA  | AA  | Ma(BA) | Ma(AA) | ADM | Lam | Max UMF(BA) | Max UMF(AA) |
|------------|-----|-----|--------|--------|-----|-----|-------------|-------------|
| Ilfracombe | 0.530 | 0.039 | 120 | 1 | 0.115 | 0.111 | 42 | 36 |
| Hinkley    | 0.514 | 0.030 | 23 | 1 | 0.114 | 0.162 | 14 | 13 |
| Avonmouth  | 0.500 | 0.019 | 10 | 1 | 0.113 | 0.211 | 8 | 7 |
| Newport    | 0.502 | 0.022 | 13 | 1 | 0.114 | 0.195 | 9 | 8 |
| Mumbles    | 0.504 | 0.031 | 23 | 1 | 0.115 | 0.160 | 14 | 14 |
| MilfordHaven | 0.512 | 0.051 | 65 | 1 | 0.116 | 0.122 | 30 | 28 |
| Fishguard  | 0.507 | 0.074 | 185 | 2 | 0.116 | 0.097 | 61 | 52 |
| Barmouth   | 0.459 | 0.027 | 13 | 1 | 0.115 | 0.177 | 11 | 11 |
| Holyhead   | 0.451 | 0.064 | 68 | 1 | 0.116 | 0.107 | 41 | 40 |
| Llanddno   | 0.451 | 0.050 | 41 | 1 | 0.115 | 0.121 | 28 | 28 |
| HilbreIsland | 0.453 | 0.041 | 27 | 1 | 0.114 | 0.136 | 20 | 20 |
| PortErin   | 0.404 | 0.047 | 23 | 1 | 0.116 | 0.127 | 22 | 25 |
| Heysham    | 0.419 | 0.023 | 8 | 1 | 0.114 | 0.192 | 8 | 9 |
| Workington | 0.388 | 0.030 | 10 | 1 | 0.115 | 0.165 | 11 | 12 |
| Portpatrick| 0.375 | 0.042 | 15 | 1 | 0.116 | 0.138 | 17 | 20 |
| Millport   | 0.342 | 0.023 | 5 | 1 | 0.115 | 0.192 | 7 | 9 |
| PortEllen  | 0.370 | 0.038 | 12 | 1 | 0.117 | 0.147 | 13 | 17 |
| Tobermory  | 0.381 | 0.034 | 11 | 1 | 0.117 | 0.158 | 11 | 15 |
| Ullapool   | 0.415 | 0.052 | 30 | 1 | 0.116 | 0.121 | 19 | 28 |
| Stornoway  | 0.464 | 0.078 | 121 | 2 | 0.117 | 0.097 | 39 | 53 |
| Kinlochbervie | 0.439 | 0.041 | 22 | 1 | 0.117 | 0.140 | 13 | 19 |
| Lerwick    | 0.598 | 0.159 | ***** | 16 | 0.116 | 0.057 | 240 | 178 |
| Wick       | 0.442 | 0.087 | 153 | 2 | 0.116 | 0.088 | 52 | 66 |
| MorayFirth | 0.395 | 0.078 | 67 | 2 | 0.115 | 0.094 | 40 | 55 |
| Aberdeen   | 0.400 | 0.074 | 64 | 2 | 0.115 | 0.096 | 41 | 52 |
| Leith      | 0.364 | 0.056 | 25 | 1 | 0.114 | 0.113 | 27 | 33 |
| NorthShields | 0.436 | 0.043 | 28 | 1 | 0.114 | 0.131 | 21 | 22 |
| Whitby     | 0.475 | 0.032 | 20 | 1 | 0.113 | 0.156 | 14 | 14 |
| Immingham  | 0.497 | 0.022 | 13 | 1 | 0.113 | 0.191 | 9 | 9 |
| Cromer     | 0.523 | 0.018 | 11 | 1 | 0.112 | 0.213 | 7 | 7 |
| Lowestoft  | 0.520 | 0.014 | 8 | 1 | 0.112 | 0.249 | 6 | 5 |
| FelixstowePier | 0.515 | 0.016 | 9 | 1 | 0.112 | 0.227 | 7 | 6 |
| Sheerness  | 0.513 | 0.019 | 12 | 1 | 0.111 | 0.206 | 8 | 7 |
| Dover      | 0.517 | 0.025 | 19 | 1 | 0.111 | 0.173 | 12 | 11 |
| Newhaven   | 0.533 | 0.049 | 89 | 1 | 0.112 | 0.119 | 36 | 28 |
| Portsmouth | 0.544 | 0.065 | 216 | 1 | 0.113 | 0.101 | 60 | 44 |
| Bournemouth| 0.551 | 0.074 | 336 | 2 | 0.114 | 0.095 | 77 | 53 |
| Weymouth   | 0.547 | 0.065 | 210 | 1 | 0.114 | 0.102 | 58 | 44 |
| Exmouth    | 0.533 | 0.071 | 279 | 2 | 0.115 | 0.098 | 67 | 50 |
| Devonport  | 0.562 | 0.074 | 323 | 2 | 0.116 | 0.097 | 70 | 52 |
| Portrush   | 0.390 | 0.049 | 21 | 1 | 0.117 | 0.127 | 20 | 25 |
| Belfast    | 0.374 | 0.030 | 9 | 1 | 0.116 | 0.166 | 11 | 13 |
| Jersey     | 0.546 | 0.060 | 163 | 1 | 0.113 | 0.107 | 52 | 38 |

| Site       | BA  | AA  | Ma(BA) | Ma(AA) | ADM | Lam | Max UMF(BA) | Max UMF(AA) |
|------------|-----|-----|--------|--------|-----|-----|-------------|-------------|
| Newlyn     | 0.859 | 0.101 | ***** | 3 | 0.154 | 0.084 | 202 | 47 |
| StMarys    | 0.876 | 0.118 | ***** | 4 | 0.155 | 0.076 | 306 | 58 |
| Padstow    | 0.831 | 0.086 | 7517 | 2 | 0.154 | 0.095 | 129 | 37 |
| Ilfracombe | 0.792 | 0.063 | 1272 | 1 | 0.152 | 0.111 | 65 | 24 |
| Hinkley    | 0.766 | 0.031 | 114 | 1 | 0.151 | 0.162 | 20 | 10 |
| Avonmouth  | 0.748 | 0.017 | 34 | 1 | 0.150 | 0.211 | 10 | 6 |
| Newport    | 0.751 | 0.021 | 47 | 1 | 0.150 | 0.195 | 12 | 7 |
| Mumbles    | 0.754 | 0.032 | 111 | 1 | 0.152 | 0.160 | 20 | 11 |
| MilfordHaven | 0.767 | 0.035 | 530 | 1 | 0.153 | 0.122 | 46 | 20 |
| Fishguard  | 0.768 | 0.080 | 2709 | 2 | 0.153 | 0.097 | 98 | 34 |
| Barmouth   | 0.703 | 0.027 | 53 | 1 | 0.152 | 0.177 | 15 | 9 |
| Holyhead   | 0.703 | 0.069 | 722 | 1 | 0.153 | 0.107 | 69 | 27 |
Appendix G. Illustration of factors influencing the allowance

Following the discussion in section 5.1, figure 6 further illustrates the factors affecting the allowance. The basic allowance for 2100 under RCP8.5 is plotted against the value of $\lambda$ in panel (a) for each of our tide gauge locations. In this panel, each symbol size is a monotonic increasing function of the central estimate of MSL rise for the site. It is clear that the central estimate—which varies substantially around the UK (Howard et al 2019, Palmer et al 2019)—has a dominant effect on the allowance. To see the effect of the other factors more clearly, we show in panel (b) the basic allowance minus the central estimate, again plotted against $\lambda$ (note the change of Y-axis scale). In both panels the range of the 2100 RCP8.5 MSL projections at each site (quantified by the 90% confidence interval) is shown by the color of the symbol. Panel (b) shows that a decrease in $\lambda$ increases the allowance (the obvious relationship in the plot). Panel (b) also shows that an increase in the range increases the allowance (the curve of the yellow-ish dots lies to the right of/above the curve of the blue-ish dots).
Figure 6. Factors influencing the allowance under RCP8.5 for 2100. (a) Scatter plot showing basic allowance against $\lambda$ for all 46 sites. Symbol size is a monotonic increasing function of the central estimate of MSL rise for site. (b) Scatter plot showing basic allowance minus central estimate of MSL rise against $\lambda$ for all 46 sites. In both (a) and (b), symbol colour indicates the range (90% confidence interval) of MSL rise projection for site, following the colour bar shown.

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