A framework for physically consistent storylines of UK future mean sea level rise

Climatic Change (2024) 177:106
https://doi.org/10.1007/s10584-024-03734-1

A framework for physically consistent storylines of UK future mean sea level rise

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Received: 22 June 2023 / Accepted: 25 April 2024

Abstract
We present a framework for developing storylines of UK sea level rise to aid risk communication and coastal adaptation planning. Our approach builds on the UK national climate projections (UKCP18) and maintains the same physically consistent methods that preserve component correlations and traceability between global mean sea level (GMSL) and local relative sea level (RSL). Five example storylines are presented that represent singular trajectories of future sea level rise drawn from the underlying large Monte Carlo simulations. The first three storylines span the total range of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) *likely* range GMSL projections across the SSP1-2.6 and SSP5-8.5 scenarios. The final two storylines are based upon recent high-end storylines of GMSL presented in AR6 and the recent literature. Our results suggest that even the most optimistic sea level rise outcomes for the UK will require adaptation of up to 1 m of sea level rise for large sections of coastline by 2300. For the storyline most consistent with current international greenhouse gas emissions pledges and a moderate sea level rise response, UK capital cities will experience between about 1 and 2 m of sea level rise by 2300, with continued rise beyond 2300. The storyline based on the upper end of the AR6 *likely* range sea level projections yields much larger values for UK capital cities that range between about 3 and 4 m at 2300. The two high-end scenarios, which are based on a recent study that showed accelerated sea level rise associated with ice sheet instability feedbacks, lead to sea level rise for UK capital cities at 2300 that range between about 8 m and 17 m. These magnitudes of rise would pose enormous challenges for UK coastal communities and are likely to be beyond the limits of adaptation at some locations.

Keywords Climate change · Sea level rise · Climate projections · United Kingdom · Storyline

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1 Introduction

Sea level rise represents an existential threat to coastal communities around the world. The Integovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) states that coastal cities and settlements will face severe disruption to coastal ecosystems and livelihoods caused by compound and cascading risks by the end of the 21st century. Furthermore, the risks from changes in climate impact drivers will be exacerbated by socioeconomic factors such as increased vulnerability associated with inequity and increased exposure due to urban growth in at-risk locations (Glavovic et al. 2022). However, Le Cozannet et al. (2017) noted that probabilistic frameworks lead to a conservative set of sea level projections and identified the need to consider a wider range of possible outcomes. Fox-Kemper et al (2021) adopted the "probability box" (or "p-box") approach of Le Cozannet et al to facilitate a more comprehensive risk-based assessment, including high-end storylines of future sea level rise to complement the *likely* range probabilistic projections (that characterise the central two-thirds of the probability distribution). Information on sea level rise "tail risk", such as provided by high-end storylines, is essential for coastal planners with low uncertainty tolerance (Hinkel et al. 2019). Advances in ice sheet modelling and appreciation of stakeholder needs have motivated several recent publications to develop new sea level rise high-end estimates and/or frameworks (e.g., Stammer et al, 2019; DeConto et al, 2021; Dayan et al. 2021; van de Wal et al. 2022).

Inspired by the works of Le Cozannet et al. (2017), Shepherd et al. (2018) and Fox-Kemper et al (2021), we outline a flexible storyline framework to span a comprehensive range of sea level rise outcomes based on the current scientific literature. While this study builds on existing sea level projection science, it represents a fundamentally different approach to the presentation of sea level rise information compared to the probabilistic methods emphasised by IPCC (e.g., Church et al, 2013; Fox-Kemper et al, 2021) and the UKCP18 national sea level projections (Palmer et al. 2018b, 2020). We follow the definition of Shepherd et al. (2018) of storyline as "a physically self-consistent unfolding of … plausible future events or pathways". In this framework, no a-priori likelihood information is required: the emphasis is instead placed on understanding of driving factors and their plausibility, i.e., they should be considered physically possible even if their probability is very small (see also Le Cozannet et al. 2017). As discussed by Shepherd (2019), there are several motivations for our storylines framework: (i) an event-oriented framing as a more intuitive way of perceiving and responding to risk; (ii) to enable working backwards from a particular vulnerability or decision point, to include other relevant factors to address compound risk, and to develop appropriate stress tests (iii) to explore a wider range of potential outcomes and guard against false precision and surprises. In addition, storylines can represent an effective tool for communicating and exploring risks (Betts and Brown 2021; Kopp et al. 2023a, 2023b) and a convenient way to distil a wide range of scientific evidence into a manageable number of "what if" scenarios to aid decision-making (Climate Change Committee 2021). The IPCC AR6 included a definition of climate storylines (IPCC 2021a, 2021b), with the following elements being most relevant to the work presented here: "A self-consistent and plausible unfolding of a physical trajectory of the climate system … [to] explore, illustrate and communicate uncertainties in the climate system response to forcing …."

In this paper we develop and present five storylines of future mean sea level rise that extend to 2300 and span a wide range of outcomes discussed in the scientific literature. Each storyline represents a single trajectory of future global mean sea level (GMSL) rise, including individual component timeseries for: (i) the Antarctic ice sheet; (ii) the Greenland ice sheet; (iii) glaciers; (iv) thermosteric sea level; (v) land water storage. The first three storylines span the AR6 *likely* range projections for GMSL at 2150. In addition, two high-end storylines are included that relate to uncertainty in the future ice sheet contribution to GMSL rise based on the AR6 high-end storyline (Fox-Kemper et al, 2021) and the more recent estimate of van de Wal et al. (2022). Each storyline is also regionalised for the UK using the same methods as presented in the UKCP18 Marine Report (Palmer et al. 2018a, 2018b; Palmer et al. 2020). While the regionalisation of the storylines focuses on the United Kingdom, the framework is generic and can be readily applied to other parts of the world. To our knowledge, this study is the first of its kind to develop a physically consistent set of global and local sea level storylines that provide continuous information to 2300. Compared to the UKCP18 projections (Palmer et al. 2018b, 2020), this work presents a more comprehensive set of possible outcomes by exploiting a wider range of outcomes from our Monte Carlo simulations and incorporating the results of DeConto et al (2021). Other novel aspects include provision of information on local rates and timing of sea level rise milestones, exploring the spatial patterns of change across storylines, and providing a framework for co-development of user-tailored information on future sea level rise.

The outline of the paper is as follows. In section 2, we present the data and methods used to define the storylines, including recent literature estimates of high-end sea level rise. In section 3 we present the storyline results for both GMSL and sea level changes across the United Kingdom. In section 4 we present a discussion of the results and concluding remarks.

2 Data and methods

2.1 Monte Carlo simulations of global mean sea level (GMSL) change

The storylines presented here make use of the Monte Carlo framework for GMSL projections used for the UKCP18 sea level projections (Lowe et al, 2018; Palmer et al. 2018b). These methods represent an evolution of the framework reported in the IPCC Fifth Assessment Report of Working Group I (IPCC AR5; Church et al, 2013), as described by Palmer et al. (2020). In terms of GMSL, Palmer et al. (2018a, 2020) introduced two innovations relative to AR5. The first was the inclusion of scenario dependent projections of sea level contribution from dynamic ice processes in Antarctica, based on a parameterisation of Levermann et al. (2014). The second was the extension of the projection time-horizon to 2300 based on applying a physically based emulator to individual CMIP5 (Taylor et al, 2012) climate model simulations of global surface temperature rise and global thermosteric sea level change (Palmer et al. 2018b), which are the input variables needed to seed the Monte Carlo projections Hermans et al. 2020 provide a useful schematic of the GMSL Monte Carlo in their supplementary materials. Further details are available in Palmer et al. (2018a) and Palmer et al. (2020).

We adopt this Monte Carlo framework for several reasons: (i) it provides consistency with the UKCP18 probabilistic projections, which are the current basis of UK planning guidance; (ii) it provides the multi-century information needed for exceptionally long asset lifetimes (such as nuclear power installations or new settlement building; Weeks et al. 2023); (iii) the methods provide smoothly evolving projections that are needed for adaptive

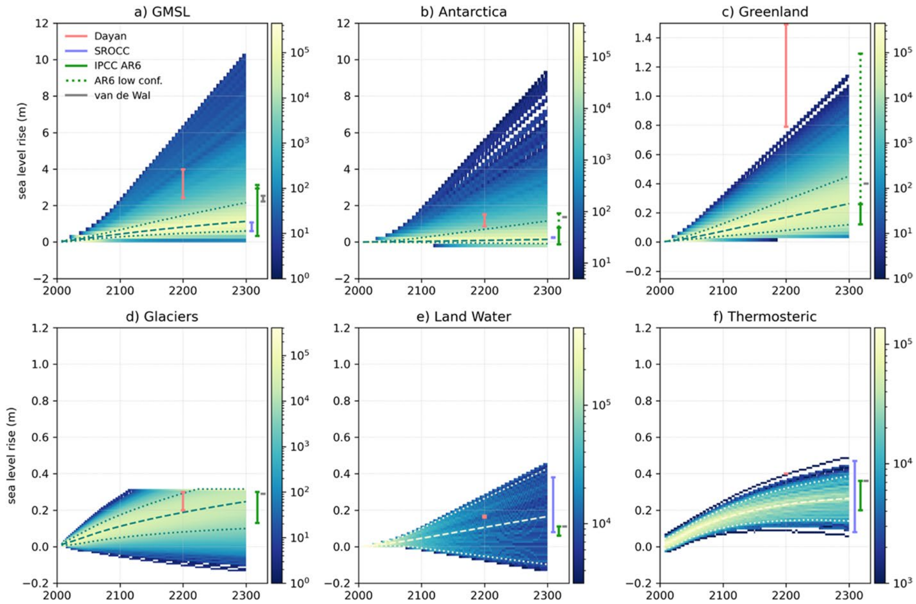

Fig. 1 Two-dimensional histograms of our standard Monte Carlo simulations for the low emissions RCP2.6 scenario with selected projection ranges from Dayan et al (2021, their Table 1 HESs-A and HESs-B), IPCC SROCC (Oppenheimer et al. 2019), IPCC AR6 (Fox-Kemper et al, 2021) and van de Wal et al. (2022). The dotted and dashed lines indicate the 5th, 50th and 95th percentiles of the Monte Carlo simulation, and correspond to the *likely* range projections in IPCC AR5 for the period up to 2100. All projections are expressed relative to the 1986-2005 average. Note that the histogram colour scale is logarithmic

planning approaches (e.g. Ranger et al. 2013). These requirements are not fulfilled by the latest IPCC AR6 sea level projections because local projections are only available to 2150 and the methods introduce discontinuities in the rates of change post-2100, which arise due to the use of the p-box approach and the transition between different lines of evidence (Fox-Kemper et al, 2021; Kopp et al. 2023a, 2023b). However, we note that our methods yield similar results to the AR6 sea level projections both globally and for UK tide gauge locations (Weeks et al. 2023).

Our Monte Carlo simulations of GMSL rise consist of 450,000 individual members designed to span both the uncertainty in the magnitude of climate change and the modelling uncertainties used to parameterise the glacier and ice sheet response to global warming (Figure S1; Church et al, 2013; Palmer et al. 2018b, 2020). The standard Monte Carlo (Figs. 1, 2, 3) represents the same Monte Carlo simulations as used in Palmer et al. (2018b, 2020) that include a scenario-dependent contributions from Antarctic ice dynamics based on the linear response framework of Levermann et al. (2014) under the RCP2.6, RCP4.5 and RCP8.5 climate change scenarios (Meinshausen et al. 2011). The fundamental basis for the Monte Carlo simulations is timeseries of global thermal expansion (GTE) and global surface air temperature (GSAT) from 14 CMIP5 climate models (Taylor et al. 2012) that have been extended to 2300 following the physically-based emulator approach described by Palmer et al. (2018a). These are used to fit a normal distribution that is sampled from to generate the different Monte Carlo members. The barystatic terms that relate to glaciers surface mass balance of ice sheets are parameterised based on GSAT and the Monte Carlo

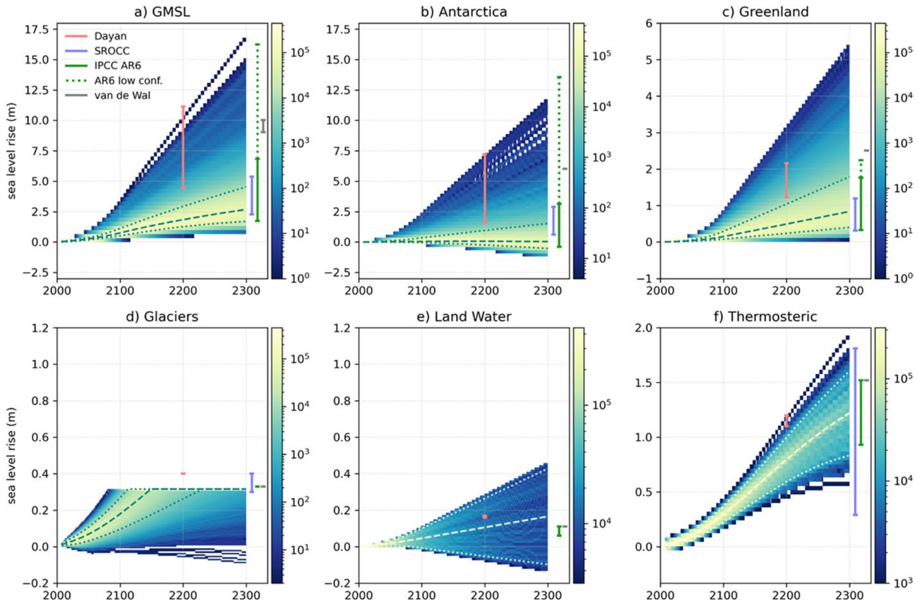

Fig. 2 Two-dimensional histograms of our standard Monte Carlo simulations for the high emissions RCP8.5 scenario with selected projection ranges from Dayan et al (2021, their Table 1 HESs-A and HESs-B), IPCC SROCC (Oppenheimer et al. 2019), IPCC AR6 (Fox-Kemper et al, 2021) and van de Wal et al. (2022). The dotted and dashed lines indicate the 5th, 50th and 95th percentiles of the Monte Carlo simulation, and correspond to the *likely* range projections in IPCC AR5 for the period up to 2100. All projections are expressed relative to the 1986-2005 average. Note that the histogram colour scale is logarithmic

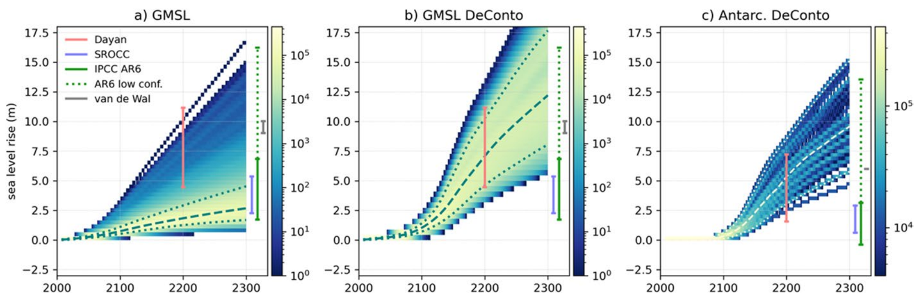

Fig. 3 Two-dimensional histograms of the standard and "DeConto" Monte Carlo simulations for the high emissions RCP8.5 scenario with selected projection ranges from Dayan et al (2021, their Table 1 HESs-A and HESs-B), IPCC SROCC (Oppenheimer et al. 2019), IPCC AR6 (Fox-Kemper et al, 2021) and van de Wal et al. (2022). The DeConto Monte Carlo replaces the sea level rise contribution from Antarctica with the DeConto et al (2021) simulations. The dotted and dashed lines indicate the 5th, 50th and 95th percentiles of the Monte Carlo simulations, and correspond to the *likely* range projections in IPCC AR5 for the period up to 2100. All projections are expressed relative to the 1986-2005 average. Note that the histogram colour scale is logarithmic

samples the uncertainty in these relationships. We retain the scenario-independent distributions used by AR5 for Greenland ice dynamics and future changes in land water storage. The assumption of perfect correlation between GSAT and GTE results in a correlation structure among components that is discussed in Palmer et al (2020, see their Fig. 9). The main element of this structure is that Greenland surface mass balance, glaciers and GTE are strongly positively correlated and anti-correlated with Antarctic surface mass balance. There is a small positive correlation between Antarctic surface mass balance and Antarctic ice dynamics. For Antarctic ice dynamics, Greenland surface mass balance, Greenland ice dynamics and land water storage the rates at 2100 are held constant to 2300 (see Palmer et al. 2020 for details). We refer the reader to Lambert et al. (2021) for a more comprehensive discussion of correlations among the different components of sea level rise.

For the “DeConto” Monte Carlo (Fig. 3), the net contribution from Antarctica is replaced by the scenario-dependent simulations of DeConto et al (2021) that include explicit representation of self-sustaining ice feedbacks, including Marine Ice Cliff Instability (MICI;) and exhibit much larger rates of sea level rise post-2100. Rather than fitting a distribution we simply randomly draw upon the 109 simulations provided by the authors as part of their supporting data files. The use of the DeConto et al (2021) simulations in the DeConto Monte Carlo retains any correlations between Antarctic surface mass balance and ice dynamics in the underlying simulations but breaks any correlation between the net Antarctica contribution and other GMSL components. However, the GMSL DeConto Monte Carlo is only used under the RCP8.5 scenario where Antarctic ice mass loss is dominated by ice dynamic processes. The implicit assumption of no correlation between Antarctic ice dynamics and other GMSL components is consistent with the standard Monte Carlo, as illustrated in Palmer et al. (2020). Furthermore, triggering positive feedback processes (such as MICI) in any single component would be expected to break the correlation structure between the components as further contributions are sustained by the feedback process rather than external climate forcing. Therefore, the inclusion of the DeConto et al (2021) simulations does not fundamentally compromise the physical consistency of our Monte Carlo framework.

A key question is whether the Monte Carlo captures the range of possible future sea level rise described in the current literature, since this potentially places practical limitations on its application. To answer it, in the remainder of this section we carry out a comparison between the full-range of Monte Carlo GMSL outcomes with the assessed ranges presented in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Oppenheimer et al. 2019) and AR6 (Fox-Kemper et al, 2021). In addition, we include comparisons with high-end estimates of GMSL rise that have been developed by Dayan et al. (2021) and van de Wal et al. (2022). In the discussion that follows, we note that the 5th to 95th percentile range of the Monte Carlo simulations are equivalent to the *likely*[1] range of the 21st century projections presented in AR5 and SROCC.

The SROCC and AR6 assessed ranges of sea level rise at 2300 presented here are based on Table 9.11 of Fox-Kemper et al (2021). The SROCC ranges use the RCP scenarios (Meinshausen et al. 2011) RCP2.6 and RCP8.5, and AR6 uses the broadly equivalent SSP scenarios (Riahi et al. 2017) SSP1-2.6 and SSP5-8.5. For AR6, we include two sets of ranges that exclude or include much larger rates of sea level rise from one study that included MICI processes (dotted lines, Figs. 1, 2, 3). Since there was no assessment of 2300 GMSL rise under RCP4.5 or equivalent scenarios for SROCC and AR6 the comparison presented here includes only our RCP2.6 and RCP8.5 Monte Carlo simulations.

[1] In the calibrated uncertainty language used by IPCC, the *likely* range represents the central two-thirds of the probability distribution.

Dayan et al. (2021) constructed two high-end estimates of future sea level rise based on the 83rd ("HESs-A") and 95th ("HESs-B") percentiles from the available literature. Since we are interested in post-2100 timescales our focus is on their high-end estimates at 2200. We present the Dayan et al. (2021) high-end estimates at 2200 as a range that spans the range of values between their HESs-A and HESs-B high-end sea level scenarios (Figs. 1, 2, 3). We briefly summarise the literature basis for these estimates as follows. The sterodynamic and glacier components were based on Kopp et al. (2014). The land water component was based on the study of Nauels et al. (2017). The estimates for Greenland and Antarctica were based on the structured expert judgement study of Bamber et al. (2019).

One of the limitations of structured expert judgement studies is the lack of traceability and transparency. The results represent a "snapshot" of the current scientific understanding based on a specific set of experts, are not reproducible, and it is usually not possible to understand the physical reasoning or processes that are behind the expert estimates. van de Wal et al. (2022) took a different expert judgement approach with a clear decision to use model distributions where the scientific confidence was judged to be high enough. For those aspects with lower scientific confidence (e.g., aspects of lower process understanding) expert judgement of a range of evidence was used by first identifying plausible process chains and then using expert judgement on the chain components, similar to Katsman et al. (2011). By making different assumptions about the correlations among the uncertainty in different sea level components (e.g., Palmer et al. 2020), they provided a range of values for their high-end estimates. For the comparisons presented here, we focus on their low and high warming estimates at 2300, which we associate with the RCP2.6 and RCP8.5 scenarios, respectively (Figs. 1, 2, 3).

Two-dimensional histograms of our Monte Carlo sea level projections under the RCP2.6 scenario illustrate that the full range of outcomes far exceeds the 5th to 95th percentile range (indicated by the dotted lines) for GMSL, Antarctica, Greenland and glaciers (Fig. 1). Conversely, the full range of outcomes for land water storage changes and global thermosteric sea level rise are relatively close to the 5th to 95th percentiles. The sea level rise ranges from SROCC, AR6, Dayan et al. (2021) and van de Wal et al. (2022) all sit within the Monte Carlo spread except for the Greenland component. The upper bound of the AR6 assessed range for Greenland at 2300 exceeds the Monte Carlo range by about 15 cm, but with a large degree of overlap between the two. Conversely, the Dayan et al range for Greenland at 2200 sits entirely outside the Monte Carlo results. This result could be reflective of expert caution in the structure expert judgement study of Bamber et al. (2019) that informed the Dayan et al range, such as acknowledgement of "unknown unknowns" for ice sheet mass loss processes. A more complete discussion of projections of Greenland ice mass loss is presented in van de Wal et al. (2022). Nevertheless, the total GMSL results of both Dayan et al and AR6 sit well within the Monte Carlo range for total GMSL, primarily due to the wide range of outcomes for Antarctica seen in our Monte Carlo simulations (Fig. 1a, b). Although it is not used in this study, the results for the GMSL DeConto Monte Carlo simulations under RCP2.6 are available as part of the supplemental material (Figure S2).

For RCP8.5, our standard Monte Carlo range for GMSL and Antarctica spans the majority of published ranges considered here (Fig. 2a, b). The AR6 Antarctica ranges at 2300 that include *low confidence* processes (e.g., MICI) have upper values that are larger than seen in our standard Monte Carlo simulations (Fig. 2b). However, the inclusion of DeConto et al (2021) simulations systematically shifts the probability distribution function to higher values post-2100 following a substantial acceleration of sea level rise with peak rates around 2150 and encapsulates the Dayan et al ranges and the upper part of the AR6 ranges for GMSL and Antarctica (Fig. 3b, c). The total range of outcomes for GMSL and Antarctica across our standard Monte Carlo and DeConto Monte Carlo simulations under RCP8.5 span all the ranges presented from SROCC, AR6, Dayan et al. (2021) and van de Wal et al. (2022). For the glaciers component the published ranges slightly exceed our Monte Carlo simulations (Fig. 2d). However, this is related to assumptions about the total ice mass, with our Monte Carlo constrained by the 0.32 m of GMSL equivalent estimated by Farinotti et al. (2019). This constraint could be relaxed in future iterations of our Monte Carlo framework to include representation of the uncertainty in the total glacier mass estimate. For global thermosteric sea level rise, all the published ranges are spanned by our Monte Carlo except for the lower end of the SROCC range (Fig. 2f).

The RCP8.5 Monte Carlo simulations for Greenland show values substantially larger than any of the published ranges presented here (Fig. 2c). The Monte Carlo projections are based on Greenland surface mass balance as cubic function of global mean surface temperature (GMST) change according to Equation (2) of Fettweis et al. (2013), following Church et al (2013). The GMST projections are based on CMIP5 climate model simulations (Palmer et al. 2018a) with surface mass balance rates held constant post-2100 (see Palmer et al. 2020 for details). It is hard to give an objective assessment of the realism of the uppermost Monte Carlo values, but the methods are consistent with the approach taken in IPCC AR5 (Church et al, 2013). We note that none of the storylines presented in this paper make use of Monte Carlo simulations beyond the published literature values considered (Figs. 1, 2, 3).

In summary, our Monte Carlo simulations span the range of potential total GMSL rise outcomes informed by the recent literature. This gives us confidence that they are a suitably flexible basis for generating a range of sea level rise storylines for informing adaptation planning and coastal decision-making.

2.2 Generation of GMSL rise storylines

The storylines for global mean sea level rise outlined in this section are intended to be examples that reduce the future uncertainty space into a small number of discrete trajectories that can be used to explore stakeholder vulnerabilities and adaptation options. The selection of storylines is based on the IPCC AR6 sea level projections and high-end estimates recently documented in the scientific literature. Three of the storylines are informed by the AR6 *likely* range projections that only include processes in which there is at least *medium confidence*: "Story A", "Story B" and "Story C" (Table 1). The final two storylines are high-end estimates that include representation of Marine Ice Cliff Instability (MICI; DeConto and Pollard, 2016), which AR6 assessed as having *low confidence*: "Story H1" and "Story H2" (Table 1).

The methods for generating storylines below are necessary for one or more of the following reasons: (i) to provide a plausible time-continuous trajectory of sea level rise from literature-based estimates that correspond to a single year (e.g. van de Wal et al. 2022); (ii) to preserve the underlying correlation structure among sea level components that is based on current scientific understanding; (iii) to perform the downscaling of GMSL change in order to provide a local expression of the storyline in terms of relative sea level (RSL) change.

The underlying concept for storylines A, B and C is to define a set that encompasses the range of outcomes from the AR6 *medium confidence likely* range projections for the year 2150 (the latest year for which the *medium confidence* projections are available). We first

Table 1 Summary of storylines presented in this paper. All target values are expressed relative to a baseline period of 1986-2005, following van de Wal et al. (2022). Note that maximum target values for glaciers are capped at 0.32 m for consistency with our Monte Carlo simulations

Name	Scenario	Storyline elements	Target GMSL rise
Story A	RCP2.6	Strong emissions reductions over the 21st century and low warming scenario. Low climate sensitivity and low sensitivity of the cryosphere and ocean to temperature rise. Plausible "best case scenario" for informing minimum adaptation requirements.	IPCC AR6 SSP1-2.6 *medium confidence* projections 17th percentile value for GMSL and its components at 2150 (i.e., bottom of the *likely* range). Sea level target values: Total GMSL = 0.49 m Antarctica = -0.01 m Greenland = 0.11 m Glaciers = 0.09 m Land water = 0.04 m Thermosteric = 0.15 m
Story B	RCP4.5	Moderate warming scenario with moderate emissions reductions (approximately in-line with current pledges). Climate sensitivity close to AR6 best estimate. Moderate response of the cryosphere and ocean to future warming.	IPCC AR6 SSP2-4.5 *medium confidence* projections 50th percentile value for GMSL and its components at 2150 (i.e., centre of the *likely* range). Sea level target values: Total GMSL = 0.95 m Antarctica = 0.18 m Greenland = 0.20 m Glaciers = 0.19 m Land water = 0.06 m Thermosteric = 0.31 m
Story C	RCP8.5	High warming scenario - policy "back-tracking" and/or carbon cycle feedbacks result in high greenhouse gas emissions throughout the 21st century and beyond. High climate sensitivity and response of the cryosphere and ocean to future warming.	IPCC AR6 SSP5-8.5 *medium confidence* projections 87th percentile value for GMSL and its components at 2150 (i.e., top of the *likely* range). Sea level target values: Total GMSL = 1.91 m Antarctica = 0.67 m Greenland = 0.36 m Glaciers = 0.32 m Land water = 0.07 m Thermosteric = 0.69 m

Table 1 (continued)

Name	Scenario	Storyline elements	Target GMSL rise
Story H1	RCP8.5	High warming scenario – as Story C – with substantial ice sheet instability processes active for both Greenland and Antarctica.	van de Wal et al. (2022) SSP5-8.5 high-end estimate for GMSL and its components at 2300. Sea level target values: Total GMSL = 10.45 m Antarctica = 6.01 m Greenland = 2.51 m Glaciers = 0.32 m Land water = 0.11 m Thermosteric = 1.52 m
Story H2	RCP8.5	High warming scenario – as Story C – with runaway ice sheet instability processes active in Antarctica, which overwhelmingly dominates future ice sheet contributions.	IPCC AR6 SSP5-8.5 *low confidence* projections 83rd percentile including the including value for GMSL and its components at 2300. Total GMSL = 16.23 m Antarctica = 13.55 m Greenland = 1.76 m Glaciers* = 0.32 m Land water = 0.11 m Thermosteric = 1.52 m

select a set of targets to base our selection of a single Monte Carlo member on. These targets include the total GMSL rise and the individual sea level components, since the relative contributions of these will affect the local relative sea level projections that we present in section 2.3.

Story A represents a plausible lower bound to inform minimum adaptation needs and is based on the lower bound of the *likely* range projections under SSP1-2.6. In addition to the strong emissions reductions associated with SSP1-2.6, which see negative CO2 emissions before the end of the 21st century, this storyline implicitly assumes that the sea level rise response to greenhouse gas emissions is relatively low. As with all the storylines presented here, Story A is illustrative and would ideally be co-developed or refined with stakeholders based on risk appetite and decision-making context.

Story B is based on the 50^{th} percentile of the IPCC *likely* range projections under the SSP2-4.5 climate change scenario. This scenario, in which CO_2 emissions peak around the middle of the 21st century and fall to below 20 $GtCO_2$ per year by the end of the 21st century, is the most consistent with current international greenhouse gas emissions pledges. If these emissions pledges are not met, then we would expect to follow a higher greenhouse gas emissions scenario, such as SSP3-7.0. Story B assumes a moderate response of sea level rise to greenhouse gas forcing.

Story C is based on the upper bound of the AR6 *likely* range projections under the SSP5-8.5 scenario. While some commentators have argued that this type of high greenhouse gas emissions scenario is implausible, there are several reasons why we choose to include it. Firstly, we cannot rule out the potential for "backtracking" on climate pledges and/or carbon cycle feedbacks that could lead to continued increases in CO_2 emissions throughout the 21st century. Secondly, similar outcomes to SSP5-8.5 cannot be excluded for lower emissions pathways but higher values of climate sensitivity. Thirdly, given the substantial uncertainty in the future ice sheet response it is prudent to adopt a precautionary approach. Story C implicitly assumes a strong sea level rise response to greenhouse gas emissions but does not include the more speculative ice sheet feedback processes such as Marine Ice Cliff Instability.

The final pair of storylines, H1 and H2, represent two high-end estimates of future sea level rise based on the recent literature for the year 2300. The two high-end estimates assume a strong warming scenario with identical values for glaciers, land water and global thermosteric sea level rise, but differ markedly in the ice sheet contributions and therefore the total GMSL rise. Story H1 is based on van de Wal et al. (2022) and has a total sea level rise of 10.4 m with 5.9 m and 2.6 m contributions from the Antarctic and Greenland ice sheets, respectively. Story H2 is based on the 83rd percentile *low confidence* sea level projections of AR6, as featured in the Summary for Policymakers (IPCC 2021a), and has a total rise of 16.3 m with 12.7 m and 1.7 m contributions from Antarctica and Greenland, respectively. The physical processes underlying these storylines include rapid disintegration of marine ice shelves and widespread onset of ice instabilities in Antarctica, and rapid ice mass loss in Greenland from both surface mass balance and dynamical ice processes (see Box 9.4, Fox-Kemper et al, 2021). We refer the reader to van de Wal et al. (2022) for further discussion on these physical processes and lines of evidence.

To generate each storyline we extract the single member of the Monte Carlo simulation that best fits a literature-based value of GMSL rise and its components (Table 1).

To illustrate our methods, we use Story C as an example (Fig. 4). To generate a storyline, we first extract a subset of Monte Carlo members that match the target GMSL rise to within 1% (Fig. 4b). Each member consists of physically consistent time series for the individual components provided by the Monte Carlo correlation structure. From these

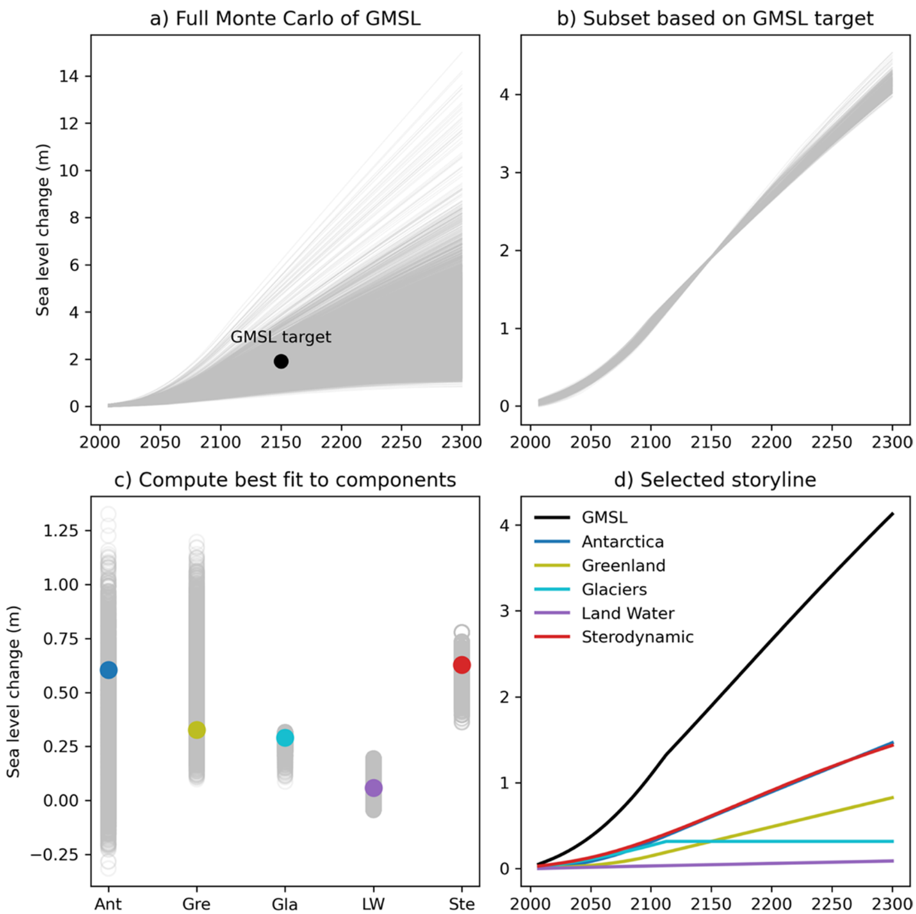

Fig. 4 An example of storyline generation based on Story C. **a**) The full Standard Monte Carlo simulation under RCP8.5. The GMSL target at 2150 is represented by the black circle. **b**) The subset of Monte Carlo members that match the GMSL target at 2150 to within +/- 1%. **c**) The range of GMSL component values across the subset of members (open grey circles) and the component target values (solid-coloured circles). **d**) The final selected storyline of GMSL rise with components as shown in the figure legend

candidates, we select the single Monte Carlo member that best fits the relative contributions to the total GMSL rise, based on a least squares method (Fig. 4c, d). Following this approach, every storyline matches the target total GMSL rise to within 1% and the percentage contributions from components to within about 2% (Table S1). We note that the choice of GMSL tolerance of 1% is somewhat arbitrary and the framework could support different user choices if needed.

Since the target values are generally based upon percentiles of the different component distributions, typically the sum of component percentiles does not equal the GMSL percentile. This is due to the correlation structure among the components and/or assumptions about how the uncertainties should be combined (e.g., Palmer et al. 2020; van de Wal et al. 2022). This explains why, for example, the sum of component target values for Story H2 (17.26 m) exceeds the GMSL rise target value (16.23 m) (Table 1). However, for a single Monte Carlo simulation of future sea level rise, the total GMSL rise is exactly the sum of the individual components. In our approach, the total GMSL takes priority and the least-squares fit to components is based upon scaled component values that equal the target GMSL total by construction.

2.3 Localisation of GMSL storylines

The GMSL rise storylines are converted into local information on relative sea level (RSL) rise for the United Kingdom using essentially the same methods as described by Palmer et al. (2018b). The barystatic GMSL terms - i.e. those that results from changes in the terrestrial storage of ice and water - are converted to a local expression of RSL using the GRD[2] patterns from Slangen et al. (Slangen et al. 2014; Figure S3). While previous studies have shown that the GRD patterns for a given mass change distribution are highly robust (e.g. Palmer et al. 2020), we acknowledge that this approach neglects uncertainty in the mass change distribution itself. The GRD patterns effectively represent a local scaling factor that is combined with the corresponding GMSL component timeseries. Following AR5, SROCC and Palmer et al. (2018b, 2020) the ice sheet components are split into a contribution from surface mass balance and ice dynamic processes. Since the DeConto et al (2021) projections for the Antarctic contribution to future GMSL rise only include the net contribution, we use the ice dynamics GRD pattern (Figure S3a) to scale the net Antarctic timeseries in Story H1 and H2 because these processes overwhelmingly dominate the total contribution in those simulations. In any case, given the similarities between the Antarctic GRD patterns (Figure S3a,b) for the UK, details of how the timeseries and GRD patterns are combined should not substantively affect our results.

Like the barystatic GMSL terms, the global thermosteric component of GMSL rise is converted to the expression of local sterodynamic RSL rise using a scaling factor that represents the linear relationship between the two quantities in CMIP5 climate model simulations, following the approach used in UKCP18 (Palmer et al. 2018b). For each RCP scenario, we take a weighted average of the linear regression coefficients from across 21 CMIP5 models (Table S2) for grid boxes adjacent to the British Isles to ensure even sampling across the models. This approach neglects any spatial patterns across the British Isles, which we justify by the limitations of CMIP5 models to represent the local bathymetry and key processes, such as tides (e.g., Hermans et al. 2020; Tinker et al. 2023). We maintain the CMIP5-based approach used in Palmer et al. (2018b) for consistency with the UKCP18 probabilistic projections, noting that this is a potential short-coming of our approach that could be further explored in future studies. For example, Lyu et al. (2020) show a stronger ocean dynamic sea level response around the UK in CMIP6 compared to CMIP5, of approximately +0.1 m by 2100 under SSP5-8.5/RCP8.5 for the ensemble mean. However, these differences are minor compared to the ice sheet contributions and unlikely to substantively affect the range of storyline outcomes presented here.

The GIA contribution to RSL for the local expression of the GMSL storylines comes from the BRITICE_CHRONO observationally constrained estimate used in UKCP18 (Palmer et al. 2018b; Bradley et al. 2023). This estimate is based on a 15-member ensemble that spans different solid earth model parameters and ice histories. We take the ensemble mean as our estimate of GIA for all storylines (Figure S4). This contribution is characterised by negative values (i.e., RSL fall) of up to about 1 mm yr^{-1} in the north of the UK

[2] Gravity, Rotation and solid-earth Deformation

and positive values in the south and Shetland Isles of up to about 1 mm yr^{-1}. For the period out to 2300, a 1 mm yr^{-1} rate translates to about 0.3 m sea level rise or fall, based on the assumption that GIA is time-independent.

The results presented in this paper focus on the UK capital cities as a useful set of locations to illustrate the range of RSL outcomes for a given GMSL storyline. The localisation factors for the Greenland ice sheet and variations in the effect of GIA on RSL show the greatest geographic dependence across the UK (Table S2). By a "localisation factor" for a contribution to RSL rise we mean the ratio between the local contribution and the global mean for each component. As noted in previous studies, e.g., Howard et al (2019), the near-zero contribution from Greenland to RSL rise in the UK means that the relative contribution from Antarctica and Greenland to the total ice sheet GMSL rise is an important determinant of UK RSL rise (see section 3).

3 Sea level storylines for UK capital cities

In this section we present the timeseries associated with each of the five storylines described in section 2.2. In addition to GMSL timeseries, we present the local expression of each storyline in terms of RSL change for each of the UK capital cities and consider the timing of sea level rise milestones following Slangen et al. (2022). We show maps of the spatial pattern of RSL rise at 2300. The storyline results are presented in order of increasing GMSL rise at 2300.

Story A (Fig. 5) is a low-end scenario and intended to help inform minimum adaptation requirements in the coming centuries. In this storyline, GMSL rise reaches 0.8 m by 2300 at a rate that decreases from the mid-21st century. Antarctica makes a negative contribution to future GMSL rise due to the dominance of positive surface mass balance over the ice sheet associated with greater moisture transport from a warmer atmosphere. Given the relatively weak climatic forcing and sea level response in this storyline, GIA plays a strong role in the local RSL rise. For example, the strong negative contribution to RSL from GIA for Belfast and Edinburgh limits the peak RSL to about 0.2 m with local sea level falling from the late- and mid-22nd century, respectively. Conversely, the positive contribution of GIA for Cardiff and London contributes to a RSL rise of about 0.7 m by 2300. In Story A, all UK capital cities experience a local RSL rise that is lower than for GMSL. This universal result is primarily related to the near-zero local contribution from Greenland associated with GRD (Figure S3d, e). Rates of sea level rise peak before 2050 and slowly decline thereafter, with Belfast and Edinburgh showing negative rates over the second half of the period. For London (Cardiff), the 0.25 m and 0.5 m sea level rise milestones are reached in 2066 (2070) and 2166 (2184), respectively (Table S3). For Belfast and Edinburgh, the 0.25 m milestone is not reached.

Story B (Fig. 6) represents the storyline that is most consistent with current international emissions pledges on greenhouse gas emissions and assumes a moderate sea level response. The total sea level rise at 2300 for UK capital cities ranges between about 1.1 and 1.6 m, with GIA the dominant process that accounts for these geographic differences. In a qualitatively similar result to Story A, all UK capital cities experience a local RSL rise that is lower than for GMSL. The rate of sea level rise peaks around the end of the 21st century and then slowly declines with a drop in rate following the complete loss of glacier mass in about 2250. For Story B, all UK capital cities reach the sea level rise milestone of 1.0 m with London first in 2161 and Edinburgh last in 2263 (Table S3). 1.5 m of rise is

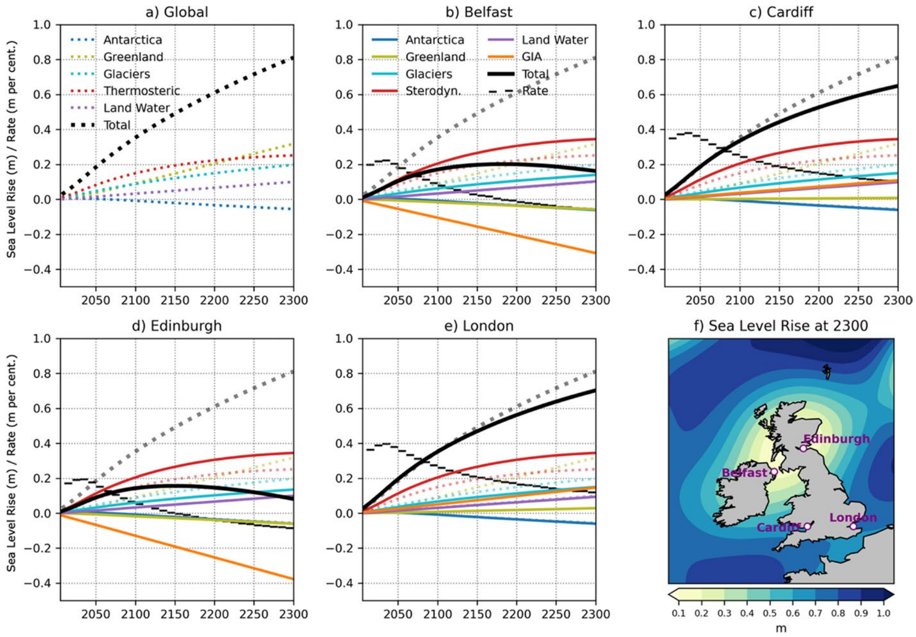

Fig. 5 Timeseries and spatial map of sea level change associated with Story A, which is based on the lower end of the IPCC AR6 *likely* range projections under SSP1-2.6: **a**) timeseries of GMSL change and individual components (repeated in subsequent panels as dotted lines where full lines are local values); **b**) timeseries of total RSL change and components for Belfast; **c**) timeseries of total RSL change and components for Cardiff; **d**) timeseries of total RSL change and components for Edinburgh; **e**) timeseries of total RSL change and components for London; **f**) spatial pattern of RSL change at 2300. The rate of sea level rise is given in metres per century

reached for London and Cardiff in 2247 and 2256, respectively. While the 1.5 m milestone is not reached by Edinburgh or Belfast, the positive rates at 2300 suggest that it could be reached in the centuries that follow.

Story C (Fig. 7) assumes some combination of back-tracking on international greenhouse gas emissions pledges and/or carbon cycle feedback processes that lead to increasing radiative forcing until about 2200 before stabilising, based on the RCP8.5 scenario (Meinshausen et al. 2011) with a high climate sensitivity and sea level response. In this storyline, UK capital cities experience a total sea level rise of between 3.5 and 4.1 metres by 2300. After an initial acceleration of the rate of rise over the 21st century, the rate slowly declines following the complete loss of glacier mass in the early 22nd century. London and Cardiff experience slightly larger rates of sea level rise than for GMSL, but Belfast and Edinburgh remain lower than GMSL. The 1.0 m sea level rise milestone is reached around the end of the 21st century for all UK capital cities (Table S3) and Story C shows the earliest timing for the 0.25, 0.5, 0.75 and 1.0 m sea level rise milestones of all the storylines presented (Table S3). The rate of sea level rise at 2300 remains above 1 m per century for all UK capital cities, implying substantial further rise in the centuries that follow.

Story H1 (Fig. 8) represents a high-end storyline of future GMSL based on the estimate of van de Wal et al. (2022). The underlying Monte Carlo simulation uses the RCP8.5 high emissions scenario and the DeConto et al (2021) Antarctic ice sheet model simulations that

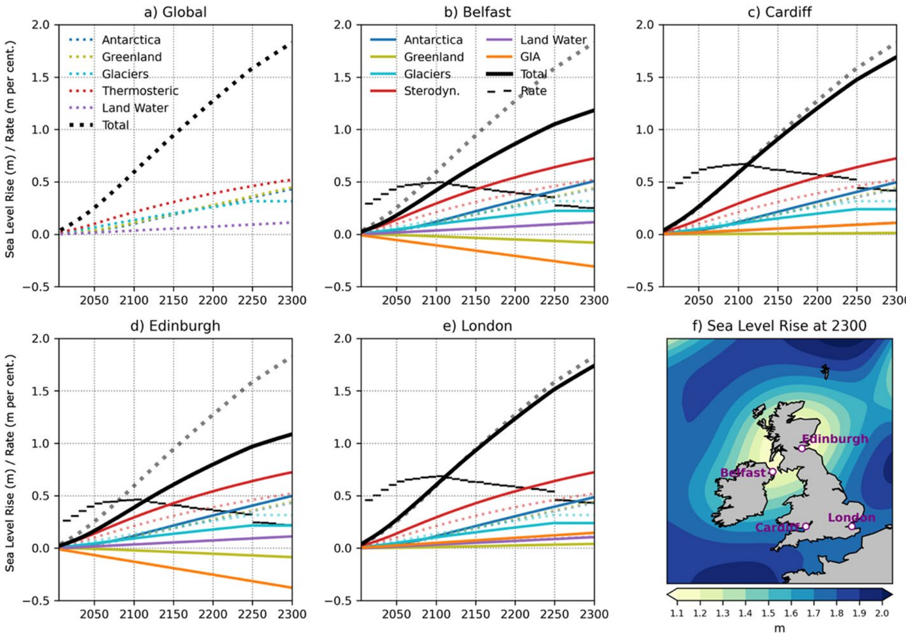

Fig. 6 Timeseries and spatial map of sea level change associated with Story B, which is based on the IPCC AR6 50th percentile projection under SSP2-4.5: **a**) timeseries of GMSL change and individual components (repeated in subsequent panels as dotted lines where full lines are local values); **b**) timeseries of total RSL change and components for Belfast; **c**) timeseries of total RSL change and components for Cardiff; **d**) timeseries of total RSL change and components for Edinburgh; **e**) timeseries of total RSL change and components for London; **f**) spatial pattern of RSL change at 2300. The rate of sea level rise is given in metres per century

represent self-sustaining dynamic ice feedback processes. The inclusion of the DeConto simulations results in the characteristic acceleration of the Antarctic ice loss and total sea level rise from the late 21st century, with relatively small rates of rise over the first half of the century. The GMSL at 2300 is 10.4 m, with values at UK capital cities ranging from about 8.2 m to 9.2 m. Local rates of sea level rise peak after 2150, with maximum values of around 50 mm per year or 5 m per century. The relatively large contribution from the Greenland ice sheet in Story H1 explains why all UK cities experience less sea level rise than GMSL in this storyline (i.e., the associated GRD patterns lead to a strong attenuation of the local signal, Figure S3d,e). Given the larger climatic forcing and sea level response in this storyline, GIA makes a smaller relative contribution to geographic differences than for Story A-C.

Story H2 (Fig. 9) is the most severe case considered in our study and is based on the low-likelihood high-impact storyline presented in the IPCC AR6 WG1 Summary for Policy Makers (IPCC 2021a). As with story H1, the underlying Monte Carlo simulation uses the RCP8.5 high emissions scenario and the DeConto et al (2021) Antarctic ice sheet model simulations that represent self-sustaining dynamic ice feedback processes. In this case, the total rise at 2300 is strongly dominated by Antarctica with a smaller relative contribution from Greenland than in Story H1 (Fig. 9). The GMSL rise at 2300 is 16.3 m with UK capital city values ranging from about 16.3 to 17.0 m.

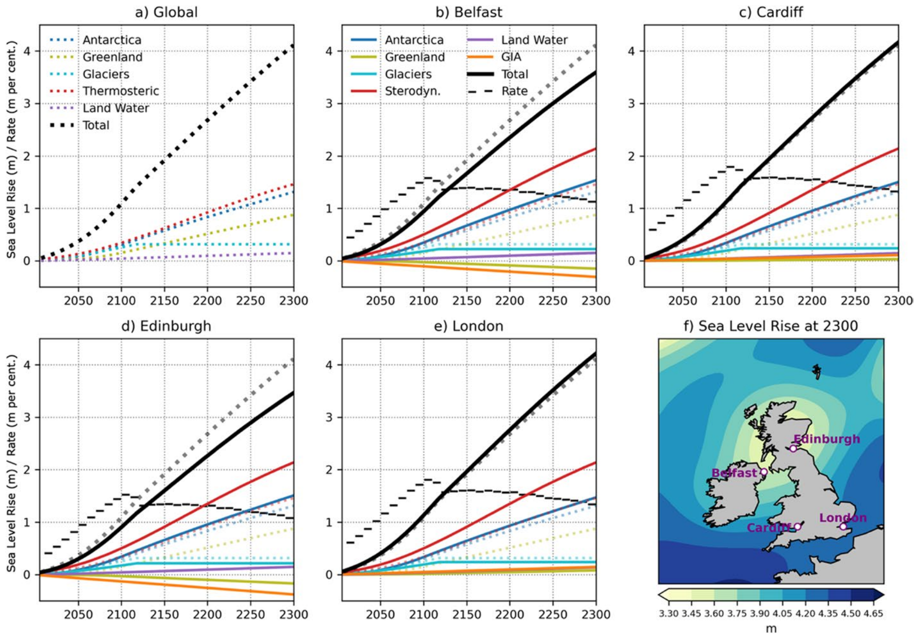

Fig. 7 Timeseries and spatial map of sea level change associated with Story C, which is based on the upper end of the IPCC AR6 *likely* range projections under SSP5-8.5: **a**) timeseries of GMSL change and individual components (repeated in subsequent panels as dotted lines where full lines are local values); **b**) timeseries of total RSL change and components for Belfast; **c**) timeseries of total RSL change and components for Cardiff; **d**) timeseries of total RSL change and components for Edinburgh; **e**) timeseries of total RSL change and components for London; **f**) spatial pattern of RSL change at 2300

As intended, timeseries of GMSL change for Story A and Story C span the total *likely* range of the IPCC AR6 projections across the SSP1-2.6 and SSP5-8.5 scenarios (Fig. 10a). Story H2 shows a similar time evolution to the AR6 low-likelihood high-impact storyline. The p-box approach taken for the AR6 storyline means that the ice sheet contributions for the period up to 2100 is based on structured expert judgement of Bamber et al. (2019), while the period after 2100 the Antarctic contribution is based on DeConto et al (2021). This explains the larger rates of rise seen for the AR6 timeseries up to 2100 than seen for H2, which uses the DeConto et al (2021) simulations as the basis of the Antarctic contribution throughout. The spatial pattern of change around the UK for Story A, B and C (Fig. 10b-d) is dominated by glacial isostatic adjustment (GIA; Figure S4) and spatial variations are generally limited to a few tenths of a metre. Story H1 shows a spatial pattern (Fig. 10e) with strong additional influences from the Antarctic ice dynamics GRD pattern (Figure S3a) and the Greenland surface mass balance GRD pattern (Figure S3e), reflecting the larger contributions from these sources compared to Story A, B and C. Spatial differences across the domain for Story H1 are larger than the Story A-C and exceed 1 m. The spatial pattern for Story H2 is dominated by the GIA (Figure S4) and Antarctic ice dynamics GRD (Fig. 3a) patterns, owing to the smaller contribution from Greenland than in Story H2. Story H2 shows similar magnitude differences across the spatial domain to Story H1. In general, the spatial patterns across all storylines show the largest sea level rise for the south and southwest of the UK.

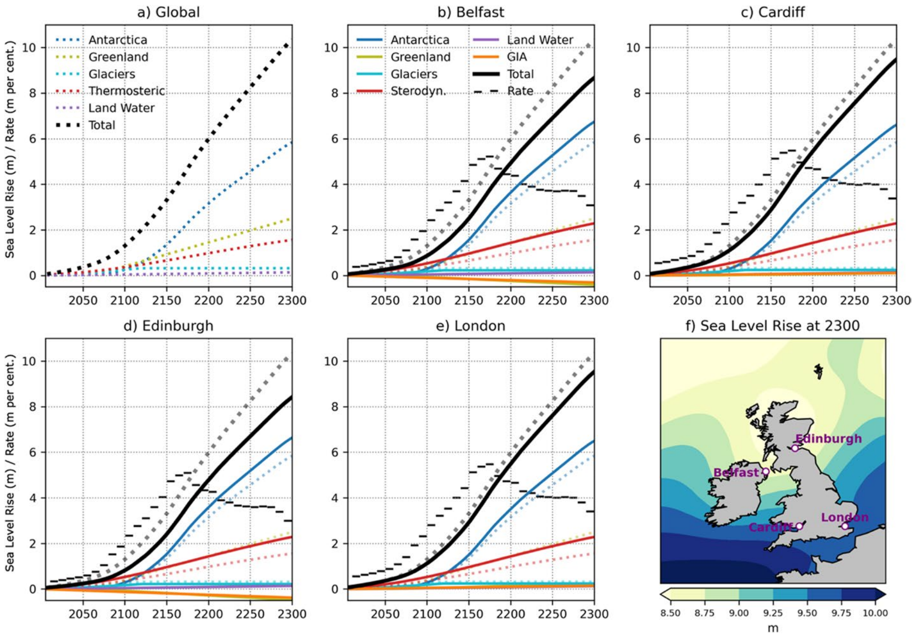

Fig. 8 Timeseries and spatial map of sea level change associated with Story H1, which is based on the high-end estimate of van de Wal et al. (2022): **a**) timeseries of GMSL change and individual components (repeated in subsequent panels as dotted lines where full lines are local values); **b**) timeseries of total RSL change and components for Belfast; **c**) timeseries of total RSL change and components for Cardiff; **d**) timeseries of total RSL change and components for Edinburgh; **e**) timeseries of total RSL change and components for London; **f**) spatial pattern of RSL change at 2300

4 Discussion and conclusions

We have presented a set of five sea level rise storylines for the UK that are intended to span a range of possible outcomes in the published literature, including the low-likelihood high-impact storyline presented in the IPCC AR6 Summary for Policy Makers (IPCC 2021a). The storylines themselves represent singular trajectories of GMSL and corresponding RSL using the same physically consistent methods as employed by Palmer et al. (2018b, 2020) constrained by the published values, which are often only given for specific years or limited ranges of years. The storylines have been devised in consultation with UK Environment Agency who have specified the following needs: (i) continuous-in-time projections that promote flexibility of decision time-horizons and adaptive planning pathways approaches; (ii) multi-century projections to inform long-lived infrastructure; (iii) to span the overall uncertainty space (including outside the UKCP18 probabilistic projections) with a relatively small number of singular trajectories. In addition, the storylines are highly consistent with the current UKCP18 national sea level projections since they are based on the same underlying Monte Carlo simulations.

The storylines presented here are intended to be illustrative, rather than exhaustive. Additional storylines could be developed in collaboration with stakeholders that are tailored to specific decision-making needs. For example, further discussion around high-end or “H++” storylines could be tailored to the risk tolerance of more specific sectors or

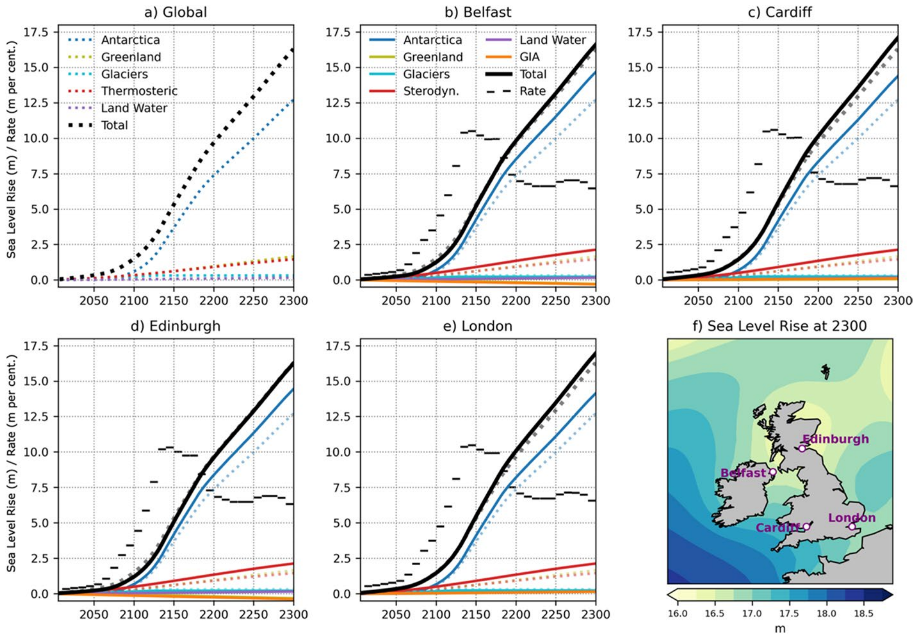

Fig. 9 Timeseries and spatial map of sea level change associated with Story H2, which is based on low-likelihood high-impact storyline presented in IPCC AR6 (IPCC 2021a): **a**) timeseries of GMSL change and individual components (repeated in subsequent panels as dotted lines where full lines are local values); **b**) timeseries of total RSL change and components for Belfast; **c**) timeseries of total RSL change and components for Cardiff; **d**) timeseries of total RSL change and components for Edinburgh; **e**) timeseries of total RSL change and components for London; **f**) spatial pattern of RSL change at 2300

decisions (Lowe et al. 2018; Hinkel et al. 2019). There is also potential to build in additional risk factors, such as the possibility of systematic changes in extreme waves or surges (e.g., Howard et al, 2019) and/or changes in the Atlantic meridional overturning circulation (e.g., Jackson et al, 2015), which is known to have a substantial effect on sterodynamic RSL change (e.g. Couldrey et al, 2023). Further work could usefully exploit dynamical downscaling efforts to better represent the sterodynamic patterns of change (e.g., Hermans et al. 2020) and potentially provide projection timeseries that include expressions of local sea level variability to inform downstream impacts studies.

Our framework could be extended to develop storylines for other parts of the world, including low-end sea level storylines, that explore the plausible best-case potential sea level changes and provide the basis for estimating minimum levels of adaptation (Le Cozannet et al. 2017). For low-end storylines physical processes uncoupled to climate forcing are proportionally more important. For example, as we saw in storyline A, GIA plays a key role in determining spatial variations in sea level change for the UK, while for locations in South Asia, reductions in land-water mass from groundwater depletion can result in mean sea level changes at some locations are significantly lower than the global average under the weaker future forcing pathways (Slangen et al. 2014; Harrison et al. 2021). For these locations alternative low-end storylines could be constructed from differing spatial patterns of groundwater mass loss and/or different estimates for total global land water storage contributions to GMSL.

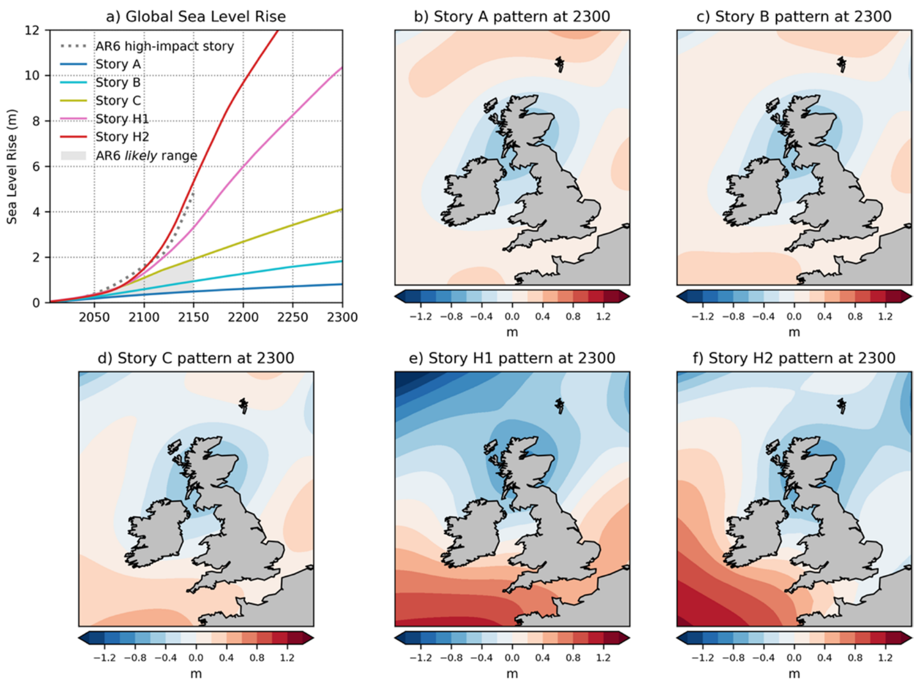

Fig. 10 **a**) Timeseries of global mean sea level (GMSL) change that correspond to the five storylines presented in this study (Table 1) expressed in metres relative to the 1986-2005 average. The shaded region shows the combined *likely* range of the IPCC AR6 GMSL projections across the SSP1-2.6 and SSP5-8.5 scenarios. The dotted line shows the AR6 low-likelihood high-impact storyline as presented in the Summary for Policy Makers (IPCC 2021a). **b-f**) Spatial patterns of relative sea level rise across the UK at 2300 associated with each of the five storylines. Spatial patterns are expressed in metres relative to the area-weighted average across the domain

The framework could also be extended to consider natural vertical land movement in local relative sea level storylines, which can contribute considerable rates of sea level rise on the same order of magnitude as geocentric estimates (Wöppelmann and Marcos 2016). For example, tectonic vertical land movement to release stress accumulation during earthquakes may result in sudden uplift or subsidence, depending on location and magnitude, and contribute to impacts such as coastal inundation. This is especially important in tectonically active regions (e.g., South Pacific, Martínez-Asensio et al. 2019) with low-lying coastlines. Such storylines could involve adding rates of vertical land movement from past events or modelled tectonic constraints, tailored to stakeholder risk tolerance levels.

The high-end scenarios presented here strongly motivate research into potential early warning indicators, particularly for the ice sheet contributions, which remain the greatest threat on multi-century timescales (see Box 9.4, Fox-Kemper et al, 2021). Observational monitoring of GMSL and its components, including key ice sheet instability processes, is therefore a high priority for research, in addition to development of improved understanding and modelling capabilities. Regular reviews of the scientific literature are needed to assess our changing understanding of the background likelihood space and identify scientific and/or stakeholder needs for updated storylines.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-024-03734-1.

Acknowledgements We are grateful to several colleagues from the UK Met Office and Environment Agency who participated in discussions that helped inform the development of this work: Richard Wood; Anne Pardaens; Harrier Orr; and Andy Beverton.

Code availability Python code used to generate the storylines and figures presented in this paper is available from the corresponding author on reasonable request.

Author contributions M Palmer and B Harrison co-led the analysis. M Palmer led the writing of the paper. J Weeks produced the Monte Carlo schematic. All other figures were produced by M Palmer. B Harrison, J Gregory, H Hewitt, J Lowe and J Weeks contributed to the writing of the paper.

Funding This work was partly funded by the Met Office Hadley Centre Climate Programme, funded by the Department of Science, Innovation and Technology (UK).

Data availability Timeseries of storyline projections presented in this paper are available as part of the supplemental materials.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors consent to publication of the manuscript and associated data.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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