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Key Points:

- We present a pragmatic and flexible framework to inform robust exploration of high-end sea level rise (H++) in coastal resilience planning
- Our framework features a screening process, a database of plausible projections, and a decision-exploring initiative
- Our dynamic framework can accommodate user feedback and emerging scientific knowledge on ice sheet instability mechanisms

Supporting Information:

Supporting Information may be found in the online version of this article.

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A New Framework to Explore High-End Sea Level Rise for the UK: Updating H++

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Abstract The UK high-plus-plus (H++) scenario for high-end sea level rise is used in sensitivity testing for significant infrastructure (e.g., nuclear facilities) and forms part of the Environment Agency planning guidance in England. However, the existing H++ scenario, developed as part of the UK Climate Projections in 2009 (UKCP09), does not reflect the latest science knowledge on ice sheet instability processes and has limitations, as revealed in consultations with users of this information. Here, we outline a new, co-produced H++ framework to inform decision-making that involves: (a) screening decisions against an updated H++ storyline that reflects major scientific advances since UKCP09; (b) evaluating adaptation options and damage costs against a wider library of alternative, plausible storylines; and, (c) a decision-exploring initiative to facilitate long-term strategic thinking. Our H++ screening storyline is based on the Intergovernmental Panel on Climate Change Sixth Assessment Report low-likelihood high-impact sea level rise assessment. In response to user needs, all storylines within the H++ framework provide time-continuous, geographically-specific sea level rise projections for the UK to 2300 and information on sea level rise rates. For all UK capital city locations, our screening storyline projects high-end sea level rise greater than: 1 m by 2100; 4 m by 2150; 9 m by 2200; and, 15 m by 2300. At all locations, maximum rates reach over 100 mm/yr. Our H++ framework can be adapted for different climate impact drivers, sectors or regions, and respond to emerging evidence and user feedback, supporting robust adaptation planning and decision-making under deep uncertainty.

Plain Language Summary Globally, sea levels are rising because of climate change. Climate models indicate sea levels will continue rising for centuries. There is potential for several meters or more of sea level rise outside the expected range if “runaway” ice sheet processes are triggered. Despite incomplete scientific understanding of these processes, coastal planners managing the Thames Barrier, decision-makers operating nuclear power facilities, and others, need to prepare for the possibility of “high-end” sea level rise. We propose an update to the existing high-end sea level rise scenario for the UK (the “H++ scenario”) published in 2009. Our update involves steps to explore how high-end sea level rise could affect decision-making: (a) screening decisions using an updated high-end sea level rise projection that is plausible, but not necessarily probable, and describes the amount of rise and the processes driving it; (b) consideration of adaptation options and damage costs against a wider library of alternative sea level rise possibilities; and, (c) strategies (e.g., decision-gaming) to explore and verbalize the decision-making process under different futures. Sea level projections are available to 2300 for coastal locations around the UK, including information on rates. Our flexible approach could be adapted for different climate hazards, sectors or regions.

1. Introduction

Sea level rise under climate change presents major socioeconomic challenges and risks to coastal infrastructure, communities and ecosystems across the world (Oppenheimer et al., 2019). The Working Group 1 contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) projected global mean sea level (GMSL) will rise by 0.56 m (0.44–0.76 m, *likely* range) by 2100 and by 0.92 m (0.66–1.33 m, *likely* range) by 2150 under an intermediate greenhouse gas emissions scenario (SSP2-4.5), and 0.77 m (0.63–1.01 m, *likely* range) by 2100 and 1.32 m (0.98–1.88 m, *likely* range) by 2150 under a very high greenhouse gas emissions scenario (SSP5-8.5) (Fox-Kemper et al., 2021). The *likely* range characterizes the central two-thirds of the probability distribution and includes “processes for which projections can be made with at least *medium confidence*” (Fox-Kemper et al., 2021).

Within sea level rise projections there is deep uncertainty (Lempert et al., 2003) in the potential for rapid ice mass loss due to ice sheet instability mechanisms (e.g., Bakker et al., 2017). These mechanisms include: (a) Marine Ice Sheet Instability (MISI), where an ice sheet grounded below sea level on downward sloping bedrock rapidly retreats, increasing the ice flow, and; (b) Marine Ice Cliff Instability (MICI), where exposed ice cliffs above a threshold height structurally fail and retreat by calving, exposing taller, unstable cliffs. Ice sheet instability behavior is self-sustaining and becomes the rate-determining step regardless of further climate forcing. Therefore, subsequent greenhouse gas emission reductions may be ineffective at slowing these processes once triggered (Golledge et al., 2015). An assessment of literature suggested on crossing a “tipping point” critical global warming of 1–3°C above pre-industrial levels, MISI could drive West Antarctic ice sheet collapse, contributing several, irreversible meters of sea level rise over centuries to millennia (Winkelmann et al., 2023).

Plausible projections of “high-end” sea level rise consider processes such as ice sheet instability that could lead to GMSL rise above the projected *likely* range (i.e., the upper tail of the probability distribution, van de Wal et al., 2022). However high ambiguity and *low confidence* in high-end sea level rise projections present major challenges for decision-making (Kopp, Oppenheimer, et al., 2023; Marchau et al., 2019). Recent high-end sea level rise literature has reflected advances in modeling Antarctic ice sheet dynamics (e.g., DeConto et al., 2021) and the growing recognition of the need to provide sea level rise information that more fully represents different climate futures (Dayan et al., 2021; Fox-Kemper et al., 2021; Hinkel et al., 2019; Kopp, Oppenheimer, et al., 2023; Stammer et al., 2019; van de Wal et al., 2022). For example, the AR6 Summary for Policymakers presented a physical climate storyline (Shepherd et al., 2018) of high-end sea level rise that projected GMSL rise of 1.6 m by 2100 and 4.82 m by 2150 under SSP5-8.5 (Fox-Kemper et al., 2021; IPCC, 2021; O'Reilly & Oppenheimer, 2024).

Around the United Kingdom (UK), the rate of sea level rise is increasing, slightly faster than global trends (Kendon et al., 2025). Over the last 30 years, sea levels around the UK have risen by around 4.2 ± 1.0 mm/yr (Kendon et al., 2025), compared to a long-term rate of 1.5 ± 0.1 mm/yr since the 1900s that excludes vertical land movement (Kendon et al., 2021; Woodworth et al., 2009). The Antarctic ice sheet is a critical component in sea level projections for the UK, driving the greatest uncertainty and having a pronounced local amplification due to changes in the Earth's gravity, rotation and solid-Earth deformation (GRD) (Palmer, Howard, et al., 2018). Palmer et al. (2024) generated storylines of future local relative mean sea level rise for the UK based on three IPCC AR6 *likely* range and two high-end projections of GMSL. In a storyline based on a moderate sea level response to current international emissions pledges (RCP4.5/SSP2-4.5), UK coastlines are projected to see about 1–2 m of sea level rise by 2300. This increases to about 3–4 m in a storyline based on the upper bound of the AR6 *likely* range (RCP8.5/SSP5-8.5) and to about 8–17 m based on the AR6 high-end storyline (Palmer et al., 2024).

Sea level rise poses enormous challenges to UK coastal communities. Mean sea level rise (Gregory et al., 2019) is the dominant driver of projected changes in coastal sea level extremes over the 21st century for the UK compared to changes in tides, waves and storm surge events (e.g., Howard et al., 2019; R. J. Perks et al., 2023; Voudoukas et al., 2018), increasing the risk of coastal flooding and erosion. By the 2050s, around 30% of England's coastline currently under a “Hold-the-Line” policy will require realignment of coastal defenses and, in many cases, the relocation of properties (Sayers et al., 2022). National sea level projections are used to inform climate change risk assessments (e.g., Betts and Brown, 2021), national adaptation programmes (e.g., Department for Environment, Food & Rural Affairs, 2023) and Shoreline Management Plans, and to assess location adaptation options.

In the UK, high-end sea level rise projections are used in sensitivity testing for nationally significant infrastructure projects, new settlements and urban extensions, forming part of Environment Agency regulatory requirements for coastal planning in England (e.g., flood risk allowances, Environment Agency, 2022a, 2022b; Weeks, Fung, et al., 2023). Within these applications, “high-plus-plus” (H++) describes high-end sea level rise, focusing on the increased climatic hazard. This is distinct from low-likelihood high-impact (LLHI) scenarios, where impact considers exposure and vulnerability in addition to hazard. The devastating coastal flooding in the winter of 1953 is an example of a high-impact event experienced in the UK, where 24,000 properties were flooded and 32,000 people were evacuated (Wadey et al., 2015). The event sparked widespread measures to be implemented in the UK, including a national tide gauge network and major defensive systems including the Thames Barrier. Such measures significantly reduced both the exposure and vulnerability of communities to coastal flood events, consequently reducing the impacts of a similar magnitude surge event in December 2013 (Wadey et al., 2015).

The H++ concept was initially developed for the Thames Estuary 2100 (TE2100) plan to build resilience against potential higher sea level rise not well-captured in climate models (Ranger et al., 2013). The adaptive approach used to generate salient H++ information for adaptation planning has inspired the development of other high-end sea level rise projections (van de Wal et al., 2022). The initial H++ was based on expert judgment and later revised as part of UK Climate Projections released in 2009 (UKCP09) (Lowe et al., 2009). UKCP09 presented one range for H++ of 0.93–1.90 m at 2095 that represented all UK coastal waters. In practice, the Environment Agency stated only the upper end of this range in their guidance (e.g., Environment Agency, 2022a). H++ is used as a “credible maximum scenario” in current UK flood risk guidance (e.g., Office for Nuclear Regulation et al., 2022). However, we note that it is not possible to define a “maximum” sea level rise scenario due to deep uncertainty in key processes (e.g., Kopp, Oppenheimer, et al., 2023).

During the planning of the updated UK Climate Projections released in 2018 (UKCP18), there was insufficient new science to warrant an update to existing H++ information (Palmer, Howard, et al., 2018). The UKCP09 H++ sea level rise projection remained unchanged, although the growing amount of scientific evidence that could underpin a future H++ update was noted in UKCP18 (Palmer, Howard, et al., 2018) and the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Oppenheimer et al., 2019). However, consultations with coastal practitioners and decision-makers (the “users” of sea level rise information) and advances in ice sheet modeling capability have since indicated a need to update the existing H++ scenario (Weeks, Fung, et al., 2023; Section 2.1). For example, the UKCP09 H++ range at 2095 does not fully meet the needs of users such as nuclear facility operators who need to consider climate change over the whole facility lifetime. The facility lifetime includes “design, planning, construction, operation, [...] decommissioning and eventual release” (Office for Nuclear Regulation et al., 2022; Weeks, Fung, et al., 2023) and could extend beyond 160 years (Wilby et al., 2011).

Here, we present a new H++ framework to incorporate high-end sea level rise information into risk-based coastal adaptation planning and decision-making. Our new H++ framework serves as an update to the UK's existing H++ scenario and has been co-produced between the Met Office (a provider of national sea level rise information including H++) and the Environment Agency (a super-user of national sea level rise information including H++, see Weeks, Fung, et al., 2023). We define a “super-user” as an organization who uses sea level information to generate guidance for numerous and widespread downstream users. While we focus primarily on the UK, the framework and methods to generate local relative mean sea level rise information are generic and can be applied worldwide. They are also complementary to decision-making practices such as dynamic adaptive planning pathways.

In Section 2, we present the steps within our H++ framework, including a screening process, a database or “library” of sea level rise projections, and decision-gaming or other decision-exploring initiatives. In Section 3, we discuss applications of our framework, both in the UK and beyond, and considerations for scientific research.

2. Materials and Methods

2.1. Co-Exploring the Problem Space and Opportunities

In 2021, the AR6 published a LLHI assessment of high-end sea level rise information using a storyline framing (Fox-Kemper et al., 2021; Garner et al., 2021; Kopp, Garner, et al., 2023). Our definition of a “storyline” herein is a physically-based, self-consistent, plausible pathway of future sea level change (Baldissera Pacchetti et al., 2024; Shepherd et al., 2018). The AR6 LLHI assessment was based on several lines of evidence, including advances in ice sheet modeling (DeConto et al., 2021) and provided time-continuous LLHI information to 2150. Although comparable with the UKCP09 H++ range at 2095, for both global and UK sea level rise the AR6 LLHI storyline values at 2150 far exceeded the 1.9 m maximum of the UKCP09 H++ range (IPCC, 2021; Weeks, Fung, et al., 2023). Following the publication of the AR6, a workshop attended by scientists and government stakeholders was held to explore the implications of the latest science on UK sea level projections and research priorities. The workshop highlighted the need to update the UKCP09 H++ scenario considering science that has emerged and further develop the science and practice of high-end scenarios (Weeks, Fung, et al., 2023).

Targeted discussions were subsequently held between the Met Office and the Environment Agency approximately quarterly from 2022 to 2024 to co-explore an update to H++. During these discussions, the Environment Agency raised many desirable features for an update to the existing scenario, as outlined in Table 1. These include

Table 1

Desired Features for an H++ Update Defined in Consultation With the Environment Agency

Desired features for an H++ update

- (i) A well-illustrated scenario space that spans a wide range of possible outcomes setting H++ in context with other scenarios;
- (ii) Easy to explore with “what if” questions;
- (iii) Underpinned by clear, easy-to-use and scientifically robust data;
- (iv) Can provide updated sea level rise information responding to Conference of the Parties (COP) and future global warming level commitments;
- (v) Allows exploration of the impacts associated with rates of sea level rise;
- (vi) Includes time-horizons that extend to at least 2200 for long-term infrastructure and land use planning and;
- (vii) Ability to update following emerging evidence, including tracking whether thresholds have been met or early warnings triggered.

Note. Source: Harriet Orr and Andy Beverton.

the provision of information on rates of sea level rise, a well-illustrated scenario space that spans a range of possible outcomes, and time-horizons extending beyond 2100 for long-term resilience planning (Palmer & Weeks, 2024). The ability to apply updates to the information to reflect evolving evidence and policy landscapes, while preserving the fundamental framework, was also highlighted as desirable. It was agreed the use of “H++” terminology would be retained for familiarity and meaning to the UK community.

Several plausible projections of high-end sea-level rise exist in the literature (e.g., Fox-Kemper et al., 2021; van de Wal et al., 2022). However, it is not possible to assign robust likelihood statements to these projections due to the deep uncertainty and *low confidence* associated with the physical processes driving them, creating challenges for communicating this information to coastal decision-makers (Kopp, Oppenheimer, et al., 2023; Simm et al., 2021; Stammer et al., 2019). Providing a single H++ scenario does not address the varying risk tolerance of users (i.e., the level of risk a user is willing to assume, Oppenheimer et al., 2019; Hinkel et al., 2019), which means the sensitivity to a particular scenario is context-specific and time-specific (Stammer et al., 2019; Weeks, Fung, et al., 2023). In addressing the challenge of communicating uncertainty, storylines have become an increasingly favored tool to explore climate risk and assist decision-making, by focusing on plausibility rather than probability (Betts and Brown, 2021). Storyline approaches to high-end sea level rise have been used in national climate assessments for the US (Sweet et al., 2017, 2022), the Netherlands (Van Dorland et al., 2023) and recently developed for the UK (Palmer et al., 2024). With the ability to explore “what-if” questions, storylines offer the opportunity to place emphasis on different physical processes and therefore tune information to meet varying risk tolerances (Stammer et al., 2019).

The users of high-end sea level rise information are typically those involved in high value decisions on critical facilities in the coastal zone (e.g., significant flood defenses, power stations, radioactive waste repositories), who typically have a low risk tolerance (Hinkel et al., 2019; Oppenheimer et al., 2019). These users tend to carry out more detailed studies of the potential costs and benefits of adaptation using multiple lines of evidence, rather than using a single range or projection. Moreover, we recognize that it is not and never will be possible to provide a single, definitive, high-end projection, highlighting a need for precaution. Therefore, we propose an update to the existing H++ scenario that is not a single range or projection, but a dynamic framework. Our H++ framework employs the storylines approach to explore advances in plausible projections of high-end sea level rise in the published literature and to provide information on long-term committed sea level rise (i.e., the amount of sea level rise already locked-in due to past emissions). Our framework is not an update to guidance based on H++ information itself, which would be the responsibility of a super-user or user. However, our framework and associated information has been co-produced, and meets the needs of a wide range of users. Our approach is therefore suitable for incorporation into sector-specific guidance on adaptation.

Our H++ framework follows iterative steps to explore decision-making under high-end sea level rise, as summarized in Table 2. The steps broadly feature (a) a screening process that flags sensitivities in adaptation measures to high-end sea level rise (Section 2.2); (b) a library of storylines, for users who have shown sensitivity to the screening process, to support robust evaluation of adaptation options against damage costs (Section 2.3); and, (c) a decision-exploring initiative such as decision-gaming, to prime and stress-test strategic, long-term decision-making and facilitate feedback (Section 2.4). The screening process in combination with the library can be

Table 2

Summary of Steps Within the H++ Framework

		
Screening process	Library of storylines	Decision-exploring initiative
Understanding whether sea level rise could cross thresholds of concern under conditions of concern	Understanding how alternative sea level rise storylines affect the robustness of measures	Understanding information needs and priming long-term strategic thinking
A single, self-consistent and physically-based time-series (storyline) of future high-end sea level rise based on a plausible projection from the literature	A database of alternative sea level rise storylines based on plausible projections from the literature, each assigned to a confidence band	A safe space to explore potential high-end sea level rise and to consider and verbalize decisions under deep uncertainty

used to identify whether existing resilience measures can perform under a range of conditions, whether vulnerabilities exist, or whether additional measures can provide benefit (e.g., improvements to coastal defenses). Decision-gaming or other decision-exploring initiatives can be used to enhance the understanding of consequences over long timeframes and thus the robustness of decisions under deep uncertainty.

Sea level rise information within the framework can be updated when useful storylines emerge through new scientific research or policy positions. Specifically, key elements of the framework should be consistent with the latest science published as part of the IPCC reporting cycles, but periodic updates may be needed if there are substantial advances in the scientific understanding. Decision-gaming is a valuable tool for facilitating collaboration, knowledge exchange, and feedback between provider and user communities. These are crucial to understand risk appetite and refine the library, supporting evaluation and learning.

Coastal zones are becoming major population centers of the world, increasing the number of people who will be affected by sea level rise over the coming decades (Haasnoot et al., 2021). If the long-term adaptation commitment is not acknowledged, adaptation options will diminish over time and become increasingly costly with high losses (Haasnoot et al., 2021). Environment Agency guidance focuses on supporting high value decisions regarding critical infrastructure, new settlements and significant urban extensions (Environment Agency, 2022b). At the city scale, the ongoing influence of early adaptation decisions alongside the changing profile of exposure and vulnerability will need to be considered by risk owners and decision-makers. These factors will need to be combined with information provided in the screening process and library of storylines, which focuses on the changing climatic hazard profile from sea level rise.

2.2. Co-Designing the H++ Screening Process

The purpose of the screening process is to flag whether high-end sea level rise could reach the vicinity of thresholds of concern under conditions of concern (i.e., the spatiotemporal characteristics of the elevated water levels) for a decision-making context. Users are presented with a “screening storyline,” a single, self-consistent, physically-based and robust time-series of future high-end sea level rise. The screening storyline provides users with contextual information on high-end sea level rise and how it might unfold over time. This is designed to support evaluation of whether adaptation measures are sensitive to hazards associated with high-end sea level rise and whether further analysis is needed. Hazards may include erosion, wave overtopping, tidal flooding and tide locking. As part of the co-design process, the Environment Agency stipulated the following requirements for a screening storyline: (a) to be geographically-specific (i.e., at the local scale around the UK coast); (b) to maintain consistency where possible with the projected ranges provided by UKCP18; (c) to provide information on rates of sea level rise; and, (d) to be time-continuous extending beyond 2200 (see Table 1).

We considered the following plausible projections of high-end GMSL change on which to base our screening storyline: Dayan et al. (2021); van de Wal et al. (2022); and the AR6 (Fox-Kemper et al., 2021). Each of these studies took a process-based approach for estimating the different components of GMSL rise. The AR6 LLHI assessment used a “p-box” approach (Le Cozannet et al., 2017) to assess a range of evidence, including expert

elicitation (Bamber et al., 2019) and model simulations for the ice sheet components (DeConto et al., 2021). We refer to the 83rd and 95th percentiles of the AR6 LLHI storyline assessment presented in Fox-Kemper et al. (2021) as LLHI1 and LLHI2 respectively. Dayan et al. (2021) relied on evidence from physical-based models and a mathematical elicitation approach implemented by Bamber et al. (2019), resulting in relatively high projections to 2050. van de Wal et al. (2022) combined both practitioner needs and scientist perspectives and assessed multiple lines of evidence to construct a high-end projection of sea level rise, which resulted in a lower Greenland ice sheet contribution compared to the AR6's LLHI1. The elicitation approach relied on by Dayan et al. (2021) is subject to individual biases, while the expert judgment approach taken by van de Wal et al. (2022) is subject to both individual and group biases. We choose to base our screening storyline on the AR6's LLHI1 storyline for the following reasons: (a) the IPCC is the international authoritative voice for policy-relevant climate science and (b) by using a p-box approach, the AR6 considered multiple lines of evidence and took a precautionary approach to uncertainty. We acknowledge that all approaches provide useful and complementary information.

The trade-off between false positives and false negatives is unavoidable in any screening test where uncertainty means that no one scenario can reflect the future. In generating our screening storyline, we choose to take a precautionary approach that errs on the side of false positives (where actual sea level rise is lower than projected) over false negatives (where actual sea level rise is higher than projected). This was reflected in our choice of the AR6's LLHI1 as the basis of our screening storyline over other high-end projections in the literature. While a false positive will lead to some more exploration of risks using the library of storylines, a false negative may lead to a user erroneously dismissing sea level rise as a threat for an indeterminate period. Since damages tend to scale non-linearly with sea level rise, and adaptation options for higher levels will tend to require much longer lead times (e.g., re-location of settlements or major infrastructure), failure to spot the threat in a timely way could be particularly problematic.

2.2.1. Generating the H++ Screening Storyline

To generate a screening storyline that meets the requirements of the Environment Agency, we employ the storyline framework of Palmer et al. (2024). Palmer et al. (2024) applied constraints based on literature projections to the UKCP18 450,000 member Monte Carlo ensemble of GMSL change that extends to 2300 (Palmer, Harris, & Gregory, 2018; Palmer, Howard, et al., 2018). This constraint procedure selected a single ensemble member to form a time-continuous, multi-centennial GMSL storyline. For example, "Story H1" in Palmer et al. (2024) is based on applying constraints from the van de Wal et al. (2022) projection for GMSL under SSP5-8.5, and its components, at 2300. The framework of Palmer et al. (2024) includes different sets of Monte Carlo ensembles reflecting two options for representing the Antarctic ice sheet dynamic component: (a) scenario-dependent contributions following Levermann et al. (2014) which includes basal ice-shelf melting; and (b) scenario-dependent simulations of DeConto et al. (2021). DeConto et al. (2021) is premised on ice sheet instability mechanisms, which are not represented in Levermann et al. (2014).

We choose to generate an H++ screening scenario of GMSL that encompass the highest magnitudes considering both Antarctic ice sheet data sets as a precautionary approach. Our DeConto Monte Carlo ensemble only draws from the simulations of DeConto et al. (2021), as described in Palmer et al. (2024), and we make no extrapolation or other statistical approximations or assumptions. We note Morlighem et al. (2024) used a revised calving parameterization compared to DeConto et al. (2021) and found negative feedbacks stabilize the hypothesized retreat associated with MICI, reducing its role in the West Antarctic Ice Sheet in the 21st century. However we use the DeConto Monte Carlo ensemble for consistency with the AR6 LLHI assessment. While our screening storyline is ultimately based on the same lines of evidence underpinning the AR6 assessment, we acknowledge it will require future revision to reflect evolving scientific consensus. This may include knowledge on current "unknown unknowns"; mechanisms which may increase or decrease rates of sea level rise.

Information on rates of future sea level rise can be a more useful metric to some users. For example, the resilience of UK salt marsh and peatland systems depends on whether rates of accretion can keep up with the rate of sea level rise (Grenfell et al., 2016; Masselink & Jones, 2024). We therefore also compute a separate H++ screening storyline of GMSL in terms of rate of sea level rise (Table 3). The methodology for generating both screening storylines can be found in the Supporting Information S1.

The time-evolution of our screening storylines are informed by physical modeling where possible. The Monte Carlo ensembles are based on science that is traceable to physical model simulations. In addition, the screening

Table 3

Screening Storyline of Global Mean Sea Level Rise and Local Relative Mean Sea Level Rise by Total Change (m) and by Rate (mm/yr) of Change at 2050, 2100, 2150, 2200 and 2300 Time Horizons for UK Capital City Locations: Northern Ireland (Belfast), Wales (Cardiff), Scotland (Edinburgh) and England (London)

Screening storyline		2050		2100		2150		2200		2300	
Total change	Rate of change	m	mm/yr	m	mm/yr	m	mm/yr	m	mm/yr	m	mm/yr
Belfast		0.37	11	1.13	35	4.62	105	9.40	77	16.3	67
Cardiff		0.47	13	1.38	39	5.01	107	9.91	80	17.09	70
Edinburgh		0.35	10	1.07	34	4.49	103	9.17	75	15.91	65
London		0.48	13	1.40	39	5.03	106	9.90	79	17.05	69
Global		0.49	15	1.66	47	5.46	106	10.34	82	17.81	73

Note. Values are expressed relative to the UKCP18 baseline (1981–2000).

storyline is based on the AR6 LLH1 assessment by applying constraints at 2100 and 2150. The high rates of sea level rise are driven by the DeConto et al. (2021) simulations, which also drive high rates in the AR6 low confidence sea level projections (Fox-Kemper et al., 2021). Our H++ screening storyline results in relatively high plausible Greenland and Antarctic ice sheet contributions to GMSL rise compared to other high-end projections. At 2200 the Antarctic ice sheet and Greenland ice sheet contributions in the screening storyline are comparable to the upper bound of Dayan et al. (2021)'s HESs-B scenario to within 20 cm. At 2300, the Greenland and Antarctic ice sheet contributions in the screening storyline are around 1 m and 6 m higher respectively than the contributions in van de Wal et al. (2022)'s +8°C–10°C scenario (see Palmer et al., 2024 for a detailed component-level comparison of high-end projections). The simplistic approach to the time-evolution of glaciers taken by Palmer, Howard, et al. (2018), Palmer et al. (2020) results in a linear time-series that stops abruptly around 2150, when the total ice mass is exhausted. While this is a limitation of their study, there may be some justification in this behavior, given the potential for Arctic Amplification (Pithan & Mauritsen, 2014; Wunderling et al., 2020).

2.2.2. Generating Local Relative Mean Sea Level Rise Screening Storylines

In line with user requirements, both H++ screening storylines are localized by applying scaling values to the components of GMSL change following the established methods used in UKCP18 (Palmer, Howard, et al., 2018) and Palmer et al. (2024), which was rooted in AR5 methods. The localization approach taken in Palmer, Howard, et al. (2018) was similar to that described in earlier studies (e.g., Kopp et al., 2014; Slangen et al., 2014). The *likely* range sea level rise projections of Palmer, Howard, et al. (2018) were broadly similar compared to the AR6 for global and UK sea level rise to 2150, despite methodological and model advances (Slangen et al., 2023; Weeks, Fung et al., 2023). Further details of the localisation methodology can be found in Supporting Information S1.

Within our framework, local relative mean sea level rise storylines are geographically-specific, and will be made available for all UK coastal locations (Table 3). The localized screening storylines by total change (Figure 1) and by rate (Figure S4 in Supporting Information S1) of change are shown here for UK capital city locations: Northern Ireland (Belfast); Wales (Cardiff); Scotland (Edinburgh); and, England (London) (Table 3). The proximity of the UK to Greenland results in substantial attenuation of the local Greenland ice sheet signal associated with GRD effects. Conversely, the Antarctic ice sheet contribution is regionally amplified. At 2300, local relative mean sea level rise is lower than GMSL rise for all UK capital city locations to within 11%. Sea level rise reaches more than 1 m by 2100, more than 4 m by 2150, more than 9 m by 2200, and more than 15 m by 2300 for all locations. As seen in the screening storyline of GMSL rise, maximum rates of local relative sea level rise reach over 100 mm/yr at all UK capital cities. The sharply increasing rates peak just before 2150, driven by the Antarctic contribution. The Antarctic ice dynamics GRD and the glacial isostatic adjustment patterns dominate the spatial pattern at 2300 (Figure 2), consistent with findings from Palmer et al. (2024).

The absence of local information in the UKCP09 H++ scenario was a limitation for users. In particular, for some regions, the UKCP09 H++ lower bound overlapped with the upper bound of the 95th percentile of UKCP18 projections under RCP8.5 (e.g., Figures 1b and 1d). The localized screening storyline sits above the upper bound of UKCP18 *likely* range projections for all UK capital city locations to 2300. The localized screening storyline, based on the AR6 LLH1, crosses the lower bound to the center of the UKCP09 H++ range at 2095 for all UK

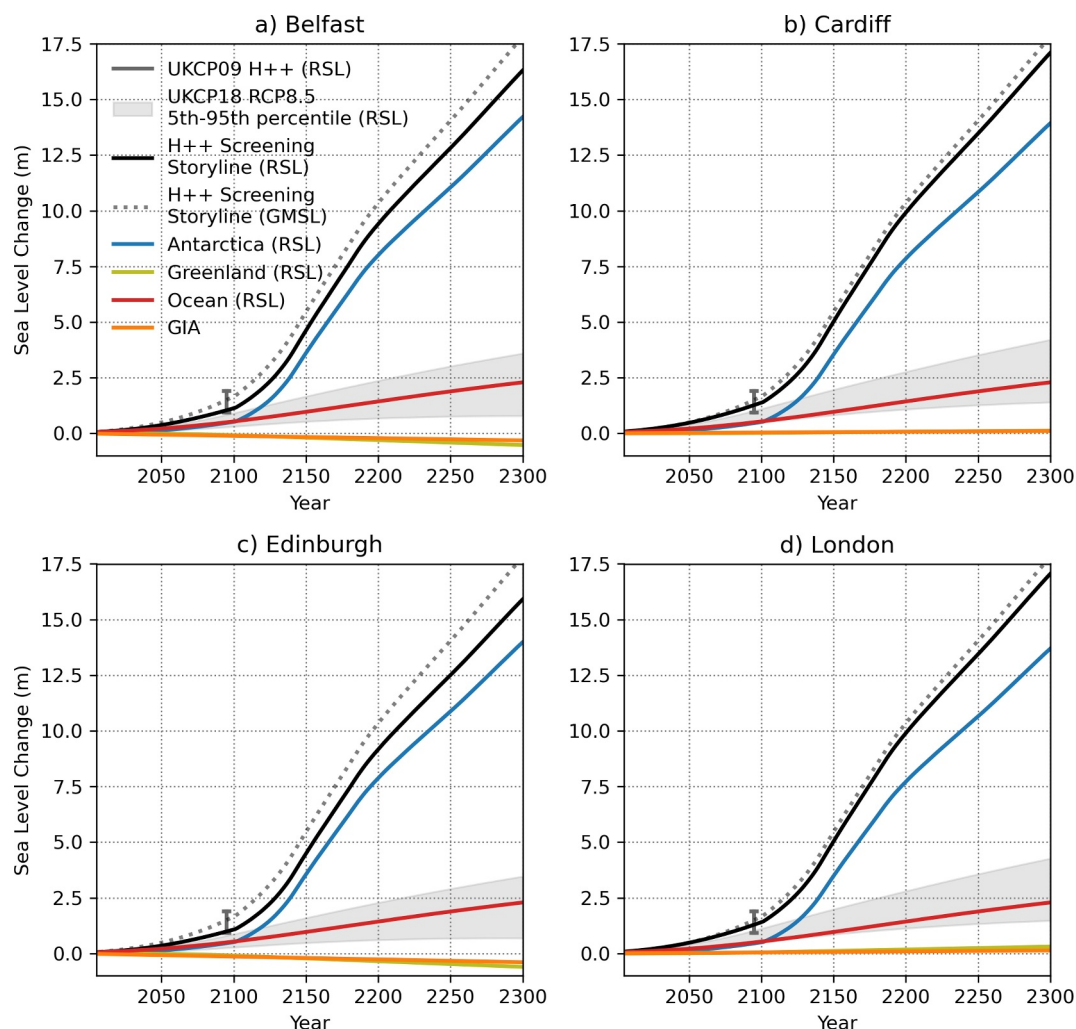


Figure 1. Screening storyline total (black line) and leading order component contributions (colored lines) to local relative mean sea level (RSL) change in meters for UK capital city locations: (a) Belfast, (b) Cardiff, (c) Edinburgh and (d) London. Screening storyline total (gray dotted) global mean sea level change, the UKCP09 H++ range at 2095 (gray line), and the UKCP18 5th–95th percentile range of RSL rise under the RCP8.5 emissions scenario are also shown for comparison (gray shaded). Note: GIA = glacial isostatic adjustment and values are expressed relative to the UKCP18 baseline (1981–2000).

capital city locations and the projections are therefore consistent (Weeks, Fung, et al., 2023). The UKCP09 H++ should not be interpreted as incorrect; the science has evolved so that we are able to more fully explore different future pathways under deep uncertainty and provide information that is more useful and usable.

2.3. Co-Designing the Library of Storylines

The library is a database of alternative sea level rise storylines incorporating high-end projections from the literature and is designed to suit different risk tolerances. Users can draw on the library to assess adaptation options and damage from impacts against a range of high-end sea level rise storylines, advocating robust decision-making. Our library initially includes the five storylines presented in Palmer et al. (2024), featuring two high-end storylines and three storylines spanning the AR6 *likely* range projections. This responds to a need to present information across the whole scenario space (Table 1). To avoid a “race to the bottom” (i.e., choosing the lowest high-end sea level rise projection for financial convenience), users must provide justification if they choose to dismiss storylines with higher projected sea level rise in the library.

Ice sheet instability processes could be triggered due to a combination of anthropogenic influence and internal variability (Holland et al., 2019; van de Wal et al., 2022). Therefore, high-end sea level rise cannot be ruled out for

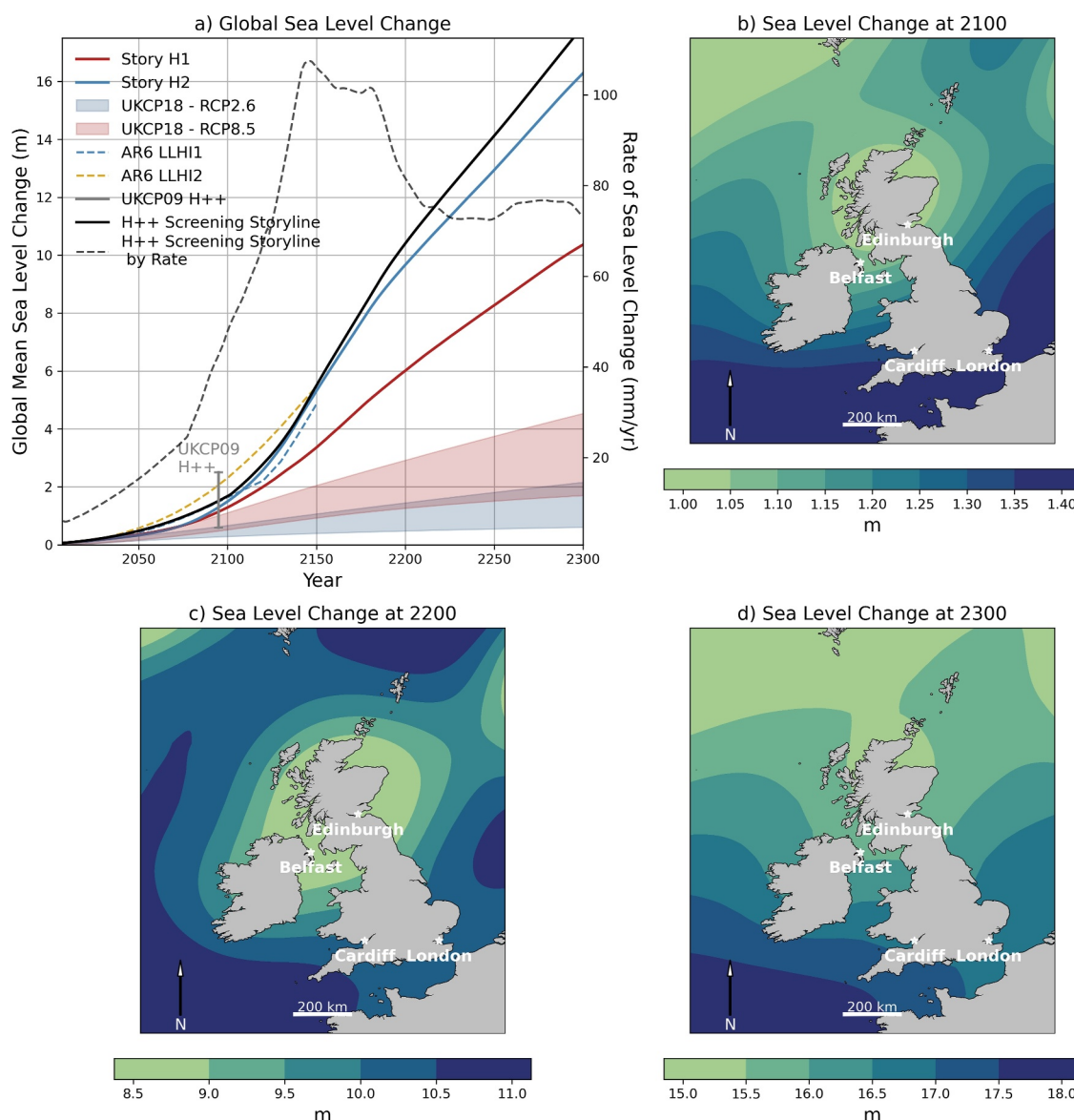


Figure 2. (a) The H++ screening storyline compared with: the UKCP18 5th–95th percentile range of the extended projections to 2300 under RCP2.6 (shaded blue) and RCP8.5 (shaded red); UKCP09 H++ range; Story H1 (solid red) and Story H2 (solid blue) high-end storylines from Palmer et al. (2024); the 83rd and 95th percentiles of the AR6 low-likelihood high-impact storyline assessment (LLHI1 and LLHI2 respectively). (b–d) the spatial pattern of relative sea level change for the H++ screening storyline at 2100, 2200, and 2300. Note: projections are expressed relative to the UKCP18 baseline (1981–2000) and different colourbar ranges are used for panels (b–d).

emissions scenarios lower than SSP5-8.5. Due to the current state of knowledge, a high-end projection under intermediate emissions cannot be defined (van de Wal et al., 2022). However, our risk-based framing requires us to explore a wide range of plausible outcomes to develop robust investment decisions. In the future, further projections that reflect emerging evidence may be added to our library. This includes storylines exploring finer-scale ice sheet processes (e.g., hydrofracturing) or other tipping point processes (see Section 3.4), and projections framed by global warming levels (e.g., Fox-Kemper et al., 2021) or different climate forcings (e.g., pathways aligned with current emissions pledges, Hausfather & Peters, 2020) to reflect evolving policy discussions (e.g., COP commitments).

A feature of the library will be a transparent indication of the scientific consensus of evidence underpinning the storylines to support decision-making. This is important considering the changing landscape of climate modeling capability, forcing scenarios and process understanding. Our library employs a dynamic confidence banding

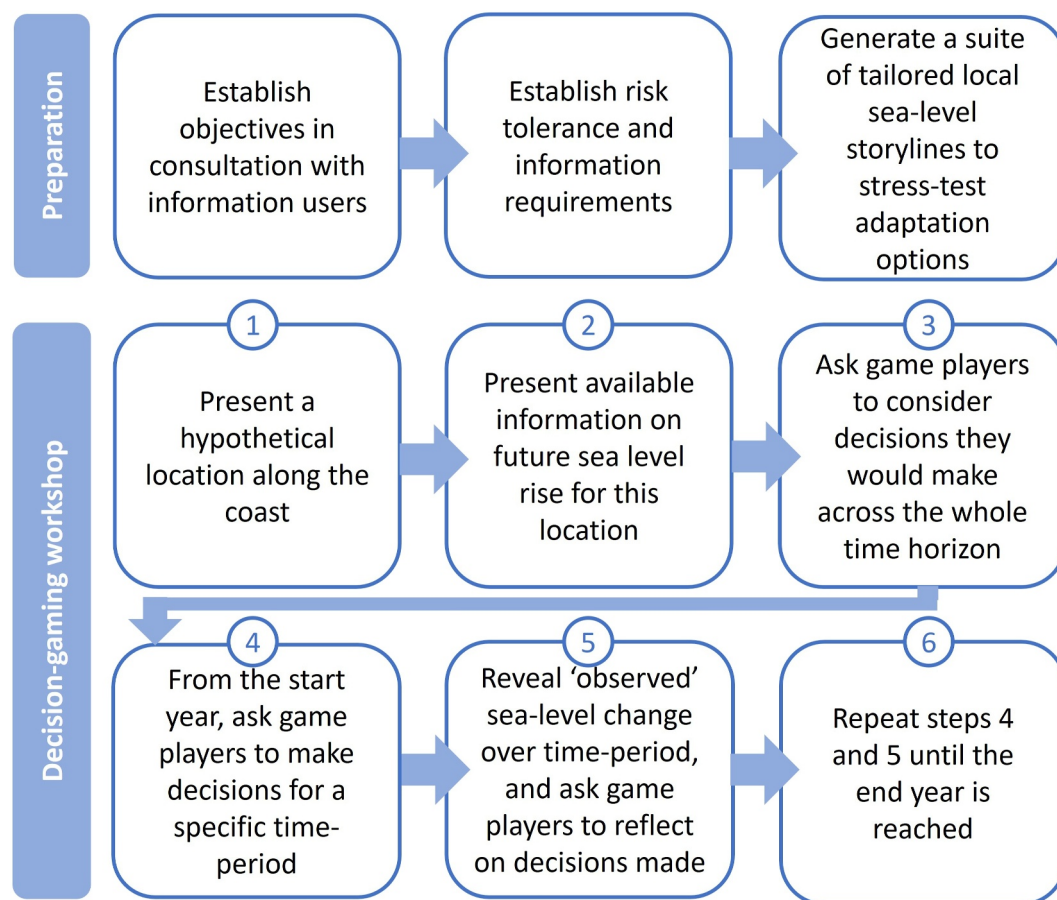


Figure 3. Summary of decision-gaming workshop held for decision-making within long-term investment scenarios.

system based on the well-established method used in the IPCC Assessment Reports. This considers the degree of agreement and the amount, type, consistency and quality of evidence underpinning each storyline. Our library supports the application of frameworks focused on different aspects such as the quality of climate information (e.g., Giorgi, 2020; Baldissera Pacchetti et al., 2021). For transparency, each storyline is labeled with information on the expert group that assigned the confidence band. Determining whether a storyline is physically implausible may never be possible. However, for a pragmatic approach, the expert group may decide to archive a storyline that is based on out-of-date assumptions. Archiving may also be possible when a storyline has substantially diverged from the observed trajectories of total GMSL and its contributing components.

2.4. Co-Designing a Decision-Gaming Approach

The Environment Agency's Long Term Investment Scenarios (LTIS; Environment Agency, 2014, 2021) assess flood and coastal erosion risk management strategies over the next 50 years to identify the level of optimal investment against future damage costs. LTIS is underpinned by evidence provided in the National Flood Risk Assessment and the National Coastal Erosion Risk Map. The high-end storyline approach used in this paper was applied to LTIS in a workshop setting with two aims: (a) to improve understanding of long-term decision-making in practice and (b) to explore which aspects of H++ information were most helpful to decision makers. The workshop was co-designed by the Met Office and Environment Agency and used a “decision-gaming” approach, inspired by wargaming methods that stress-test strategic decision-making (Perla, 1985). Gaming approaches can communicate storylines (Shepherd et al., 2018) and prime long-term strategic thinking (Haasnoot et al., 2024; Lawrence et al., 2025), and have catalyzed the uptake of decision-making frameworks such as dynamic adaptive pathways planning (Lawrence & Haasnoot, 2017). Our resulting co-developed game procedure is presented in Figure 3 and further methodological details can be found in the Supporting Information.

The workshop was attended by around 10 game players, who consisted of consultants, flood and coastal risk management experts, climate change advisors, and Environment Agency staff involved in LTIS. The information provided in the workshop primarily focused on the changing climatic hazard profile for a hypothetical coastal location, with sea level rise chosen to be the sole climate impact driver to simplify and isolate decisions. The game progressed through 10-year timesteps, allowing the game players to explore the lifetime of the flood risk management system established at the beginning of the game. Defense design lifetimes may typically be 100 years, however their actual lifetimes could be significantly longer. The time window of 2020–2150 was chosen to explore how the climatic hazard profile could change both within and beyond the LTIS timeframe and defense lifetimes. On these timescales, the practicality of defense maintenance or replacement could become complicated by future development and the baseline assumptions used in an adaptation strategy may break down.

Four sequential areas of discussion and approach manifested during the game, as shown in Table 4. A unique and valuable insight from the workshop was hearing the decision process verbalized, providing information on the use and interpretation of the data. The time-series aspect of the approach allowed a more detailed exploration of a chronologically changing picture of extreme coastal flood risk. This exploration facilitated deeper discussion and richer understanding of decision points. Decision points represent a temporal instance by which an adaptive strategy is required to commit to an adaptation option in order to maintain the standard of protection prescribed by the strategy. The decision point can consider: the remaining time the existing option can provide a suitable standard of protection; the planning and construction time (i.e., lead-in) of the new option; and, development opportunities not directly associated with the new option (e.g., extensive development in adjacent areas may provide opportunity to commit early). The incorporation of new science on high-end sea level rise extending beyond existing guidance timeframes also provoked discussion on limits of adaptation and details of when strategies may face tough choices, such as adopting walk away policies or committing significant investment.

Our H++ framework recommends employing decision-gaming (or other decision-exploring initiatives) as a complementary tool to the screening process and library to explore long-term decision-making. Collaboration, knowledge exchange and feedback facilitated by decision-gaming resulted in greater understanding of user information needs and risk tolerance to generate tailored storylines, informing the content of the library. Future gaming workshops could be co-developed between users and knowledge brokers or climate research organizations such as the Met Office. Our approach could be adapted to develop stress-tests against additional hazards (e.g., compound flooding), to explore different temporal thresholds (e.g., high-impact storm events as seen in 1953 and 2013) and to incorporate more detailed early warning system information (e.g., tracking ice mass loss, see Section 3.2). In our game, broad information was provided on the hypothetical location's population, vulnerability and assets. However, a more rigorous approach to explore risk and impact would involve defining a specific location of interest and building a risk profile for a decision-making context with decision-makers and risk owners (e.g., community planners). This would likely require several iterations for refinement, applying learnings from global initiatives (e.g., Haasnoot et al., 2024) and several storylines that span the overall uncertainty space. Game players could choose to incorporate socioeconomic, political and cultural indicators to complement hazard-based decision points (Stephens et al., 2018). Our simple gaming approach was designed to be high-level and low-resource, and therefore potentially accessible to a wide range of actors. However, we acknowledge that there will be cases where funding could still restrict the uptake of this approach, especially for more complex projects. In such cases, the approach can be used at the initial screening stage to establish the issues that need to be addressed.

2.5. Reflecting on the Co-Production Process

Co-producing high-end sea level rise information is challenging due to both complexity in the development of scientific information and in its application. From the science perspective, there are challenges to observe, understand and simulate key processes (e.g., basal melt in ice shelf cavities) that drive deep uncertainty. In application, there can be challenges in incorporating deep uncertainty into risk management and decision-making and in defining risk tolerances. The decision environment is complex, involving multiple actors (with diverse values, perspectives and interests) and hazards that span a range of temporal and spatial scales (Haasnoot et al., 2024). Sustained governance structures are required to support long-term funding, planning, monitoring and the development of effective early warning systems (Haasnoot et al., 2024; Hermans et al., 2025).

Table 4
Key Phases of Strategic Approach During the LTIS Decision-Gaming Workshop as a Factor of Time

Game phase	Theme	Game status	Discussion observations	Chosen strategic approach
Initial time-steps	Visioning	Initial projections of future change provided and characteristics (industry, population, existing defense system) of the project area were determined by the game players	Conversations around understanding options, establishing baselines and thresholds for decision points	Understanding infrastructure system tolerances and adaptation options
Early/mid game	Monitoring	Increasingly high local relative mean sea level rise “observations” were provided that began to approach the existing system's maximal standard of protection	Monitoring of information with reference to decision points and thresholds. Review of adaptation option validity	Review options and maintain course
Mid/late game	Adaptation commitment	Provided “observations” continue to increase. Interannual variability threatens exceedance of baseline thresholds	Acknowledgment that some decision points will have been met, significant adaptation measures implemented Continued review of validity of adaptation options alongside reflection on the role flood defense investment plays in shaping development within the defended area	National strategic thinking given a stronger role in shaping strategy. Consideration was given to which areas should continue to be protected, which required transition and who should be making these decisions
End game	Limits	Observations of local relative mean sea level rise reach ~2 m, defined by game players as the system's maximal ability to provide protection within the game	Conversation moved much more toward acknowledging that magnitude of change and overall timeframe would mean that wider issues (politics, industry, global change/disruptions) need to be factored into decision-making in a more active way Difficult topics explicitly discussed: limits of adaptation, day-to-day risk surpassing maximal risk tolerances, end of life options (e.g., walk away, environmental sacrifice)	Not applicable—End of game

Climate change is disrupting existing decision-making systems and the pace of adaptation in the UK is not keeping up with observed climate change (Climate Change Committee, 2021). There is a greater recognition that climate change is causing impacts and disruption in the present day but despite this realization, there is still a major gap between risk and a well-adapted society. UK coastal adaptation has had long-standing policies, such as the inclusion of sea level rise allowances in government guidance. However, sea level rise related risks (e.g., to infrastructure from coastal flooding and erosion or to the viability of coastal communities) were still categorized under the highest urgency scores in the UK's Third Climate Change Risk Assessment (Kovats et al., 2021). There is also greater awareness of the barriers to adaptation. One of these relates to the availability and understanding of climate change scenarios information (New et al., 2022). Collaborative, co-designed and transdisciplinary approaches can improve the uptake of climate information (Kopp et al., 2019). However these require time from both provider and user communities to define, create, test and refine information. Any governance and institutional barriers will need to be addressed to support long-term adaptation strategies and effective monitoring, evaluation and learning activities (Haasnoot et al., 2024).

Our co-produced framework incorporates a “learning by doing” approach towards climate-informed decision-making. Having conversations and shared activities over 3 years has helped build understanding and capacity within a super-user organization and has enabled reflection on how to scale the learnings for other users. Spending time listening to each other was valuable to understand user needs for scientific information and to understand what science can and cannot provide. Complex information, terminology and working processes, both scientific and industry-specific, were absorbed over time and became more familiar. The scientific insight installed a greater confidence in changing existing approaches due to the greater understanding of inaction and maladaptation. The decision-gaming workshop provided a “thinking space” for users to explore aspects of adaptation and strategic planning that can otherwise feel intangible. These aspects include exposing the limits of adaptation under current governance and investment systems.

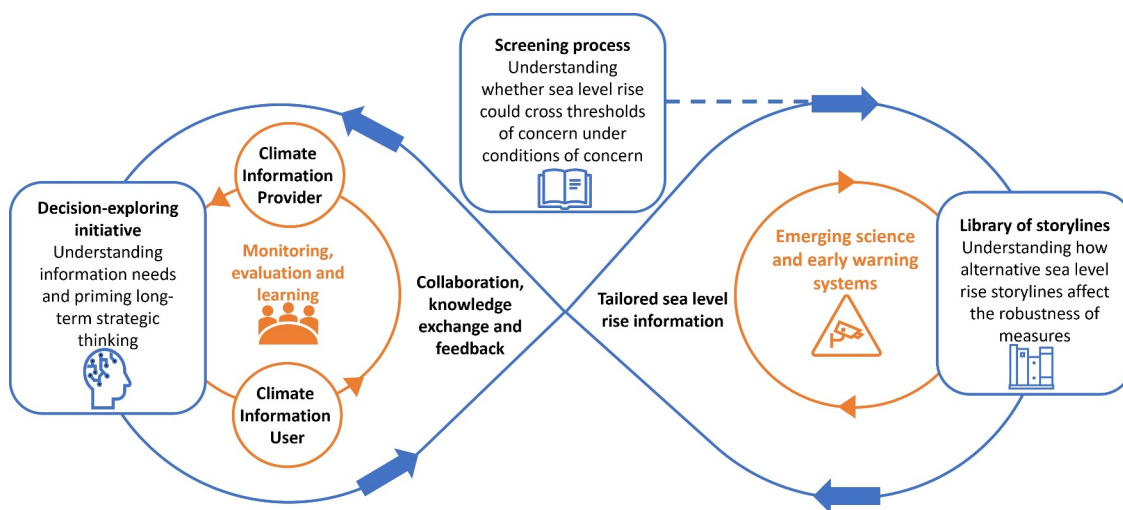


Figure 4. The co-produced H++ framework underpinned by monitoring, evaluation, and learning to produce information that is tailored and reflects emerging scientific evidence. The framework is our recommendation for how to explore sea level rise information in the presence of deep uncertainty.

To promote robust decision outcomes, the new H++ framework recommends exploring decisions under high end sea level rise using sea level information provided in the screening process and library of alternative storylines, and using decision-gaming (or other decision-exploring initiatives) to explore sea level rise within and beyond strategic planning time horizons (Figure 4). Monitoring, evaluation and learning underpin the H++ framework, including exploring global applications to understand effective tools and methods (e.g., Lawrence et al., 2025; Vincent et al., 2018). Iterating across the framework loop also allows the user community to identify gaps in information for the science community, who will then work to refine the information, closing the loop. A continued dialogue and several iterations may be needed to fully inform adaptation decisions, potentially including additional bespoke research to explore the full range of socioeconomic implications. Monitoring emerging scientific evidence and early warning systems will be crucial to refine information within the framework and mitigate against “surprise” increases in sea level rise.

3. Discussion and Application

3.1. Applications to UK Coastal Decision-Making

The high-end projections provided in our H++ framework represent the plausible future sea level rise extending through and beyond typical operational asset lifetimes for long-lived infrastructure (e.g., power installations, transport infrastructure) and are not intended to be used directly as a design standard. By providing time-continuous information beyond 2100, our framework aligns with established risk assessment approaches (International Organization for Standardization, 2019, p. 14090), supporting threshold analysis (e.g., identifying when a flood defense's standard of protection will be exceeded) and assessment of system vulnerabilities (i.e., exploring which critical components of a system have greatest exposure and sensitivity to climate change impacts). Our H++ framework is flexible and supports the review and evolution of risk assessments (Nicholls et al., 2014; Nicholls, Hanson, et al., 2021) by being responsive to emerging evidence.

The decision-gaming workshop prompted thinking about long-term, pre-emptive (as opposed to reactive) and reflexive decision-making. The time-step nature of the game enabled appreciation and exploration of the risk of adaptation lock-in and path dependency. Considering adaptation over the next century also brought in the need to consider non-climatic global changes, where political, cultural or financial changes may render baseline assumptions invalid. Similarly, the impact that adaptation investment has on shaping the future appearance of a location was acknowledged as an issue deserving of attention.

By following our framework, decision-making and asset design can be made with: (a) a suitable degree of precaution; (b) headroom for resilience if things don't go as expected; (c) an understanding of adaptation limits where more radical interventions may be needed (such as where infrastructure relocation or removal might be the

only option); and (d) an awareness of the ongoing and progressive impacts of climate change that may affect environment and society beyond current planning timeframes. In the following sections, we explore how the information provided within our H++ framework will benefit different adaptation planning and decision-making contexts. In addition, we outline the needs from the science community to support these applications.

3.2. The Need for Monitoring and Early Warning Systems: The Thames Estuary 2100 Plan

The Thames Estuary 2100 Plan (TE2100) adopts adaptation pathways in a dynamic adaptive planning approach to managing future tidal flood risk in London (Department for Environment, Food & Rural Affairs and Environment Agency, 2023; Ranger et al., 2013). TE2100 has a range of potential options for adapting to future sea level rise. These include combining short term “low-regret” interventions (e.g., raising defenses) to buy time, with long-term options (e.g., installing a new barrier) that can provide a higher standard of protection with significantly higher costs. The pathway to each option comprises a series of decision points and intervention milestones. Decision points, and progress toward them, are derived from: (a) key thresholds of extreme water level that would threaten the flood defense system (e.g., overtopping of defences); (b) how long it would take to implement an adaptation intervention (lead-in time); and, (c) key indicators of change in the estuary (e.g., mean sea level).

Mean sea level rise (amongst others) is a key indicator of change for TE2100 that dictates when improvements to the flood defense system are required. Both *likely* range and high-end projections of future sea level rise, alongside regular monitoring of sea level observations, are required to understand timing of decision points and progress toward them. Our H++ framework will, for the first time, provide robust time-continuous high-end sea level rise information spanning the lifetime of TE2100. Our H++ framework supports the consistent derivation of high-end sea level information with the existing lower UKCP18-based narrative scenarios used in TE2100 (Figure 2a), as well as the opportunity for consistency with any updated climate information products used in future.

For the purpose of TE2100, and other flood risk management programmes that rely on indicators or “signposts” for decision-making, large-scale monitoring of GMSL rise and of local relative mean sea level rise are necessary (Haasnoot et al., 2018; Hermans et al., 2017). E-Rise is an example project that detected acceleration in UK sea level rise to better understand the likely lead time for TE2100 coastal defense upgrades or replacements (Nicholls et al., 2019; University of Southampton, 2016). Observation-based projections can provide near-term independent information to complement model-based projections (Wang et al., 2025). However in addition to total water level, it is important to understand the underlying processes driving sea level change. This will guard against “surprise” increases in component contributions that are outside of historical variability.

Reconciling sea level projections with observations is an important step in improving our understanding. Slagen et al. (2023) compared the AR6 GMSL *likely* range projections with observations from 2007 to 2018, finding good agreement across most components. Studies of the sea level budget, which compare the observed total sea level change with the sum of the component contributions, can help identify missing processes (e.g., Camargo et al., 2023; Wang et al., 2021). However, local scale budget closure has typically exhibited large differences, driven partly by the resolution of the observation record. Coordinated efforts such as the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE; Otosaka et al., 2022), which combine satellite-based estimates, can help inform contributions at the process level. For example, IMBIE has revealed the importance of accounting for interannual variability in Greenland surface mass balance and Antarctic ice dynamics in sea level projections (Slater et al., 2020).

Early warning indicators could also provide useful information about unstable systems that could lead to accelerated sea level rise (Hermans et al., 2025; Lenton, 2011; Lenton et al., 2023; Scambos et al., 2017). This includes evidence of tipping point behavior associated with ice shelf loss and ice sheet instability in the Antarctic Ice Sheet (Naughten et al., 2021; Rosier et al., 2021). Due to unknown unknowns (van de Wal et al., 2022), a robust approach to mitigate against “surprises” would involve identifying a range of early warning indicators across GMSL components and establishing effective observational monitoring systems. Such systems will need to be linked to the responsible agencies and compatible with our H++ framework.

3.3. The Need for Information on Long Timescales and Committed Sea Level Rise: Nuclear Facility Planning and Waste

Infrastructure and strategic planning decisions in the UK require environment change and hazard information stretching far into the future (i.e., over a century), particularly where operational life spans are long or there is potential harm to the environment or society.

Having an understanding of the high-end sea level rise hazard profile within a decision framework, both toward 2100 and beyond can support the operation of Geological Disposal Facilities (GDF) that are used for long-term storage of nuclear waste. GDFs are expected to commence receiving waste from the 2050s and remain operational for 100 years or more (Committee on Radioactive Waste Management, 2025; Environment Agency, 2024) and are required by National Policy to “...assess the potential impacts of the credible maximum scenario and demonstrate that, in principle, adaptation would be possible” (Department for Business, Energy and Industrial Strategy, 2019). Operators are also required to complete Environmental Safety Cases that demonstrate long-term passive (unmaintained) post-closure safety over centuries to millennia associated with radioactive waste. A maximum sea level rise scenario cannot be defined due to deep uncertainty. However by providing multi-centennial sea level rise storylines with transparent confidence bands, our H++ framework can be useful for GDF operators making decisions over the operations and initial post-closure periods of such facilities.

Other challenges are posed by existing coastal infrastructure or facilities that may cease to function or have the potential to cause harm if eroded or inundated. Coastal landfills are examples of existing long-term storage that risk leaking solid and liquid waste and will need to be managed carefully to understand their current limits and where future thresholds sit alongside the changing hazard profile driven by sea level rise (Nicholls, Beaven, et al., 2021).

The long timescale response of ocean heat uptake and ice sheet mass loss to global emissions mean there is high confidence sea levels will “continue to rise for centuries... and will remain elevated for thousands of years” (Fox-Kemper et al., 2021). Based on historical emissions and current global mitigation pledges, Nauels et al. (2019) found that 1 m of GMSL rise is already committed by 2300. The AR6 found that GMSL is committed to rise over the next 2,000 years by about 19–22 m based on a 5°C peak warming, and by about 2–6 m based on a 2°C peak warming (Figure 5). Our H++ screening storyline projects that GMSL will rise by over 10 m by 2200 and by around 18 m by 2300. This illustrates a future where relatively high GMSL rise occurs rapidly due to the onset of ice sheet instability mechanisms. Tracking change in total Antarctic ice mass loss over time will be an important metric for committed sea level, due to its high ice mass storage (up to 58 m, Fretwell et al., 2013), high inertia, and potential for self-sustaining feedback mechanisms.

Century timescales are relevant for adaptation planning since a lot of existing or planned infrastructure will have long lifetimes. London was founded about 2000 years ago and has many cultural assets and residential infrastructure that are hundreds of years old. On multi-century time scales, future sea level rise of multiple meters is inevitable (Le Cozannet et al., 2023). London and much of the UK (and, locations globally) will require adaptation in response (Le Cozannet et al., 2023; Turner et al., 2023). Restricting adaptation planning to within the coming century significantly underestimates the scale of future responses required. Sea level projections toward 2200 are in demand for long-term infrastructure adaptation planning (Turner et al., 2023). Embedding multi-century sea level rise information into strategic planning sooner rather than later can mitigate situations where existing infrastructure restricts future development (Le Cozannet et al., 2023; Palmer & Weeks, 2024; Turner et al., 2023). In providing multi-centennial information, our H++ framework allows users to explore a broader range of planning time horizons and develop “no regret” approaches (Turner et al., 2023).

3.4. Beyond Antarctic Ice Sheet Instability

The crossing of Earth system tipping points is a major threat of climate change, with the potential to drive both abrupt and irreversible impacts on human timescales (Lenton et al., 2023). So far, we have primarily focused on enhanced Antarctic ice mass loss, which is of particular concern for UK (and Northern Hemisphere) coastlines due to GRD regional amplification. However, the Greenland ice sheet also features many self-amplifying and damping ice sheet-climate feedbacks, such as the melt-elevation feedback (Armstrong McKay et al., 2022; Boers & Rypdal, 2021; Winkelmann et al., 2023). Freshening induced by Greenland ice melt could drive Atlantic

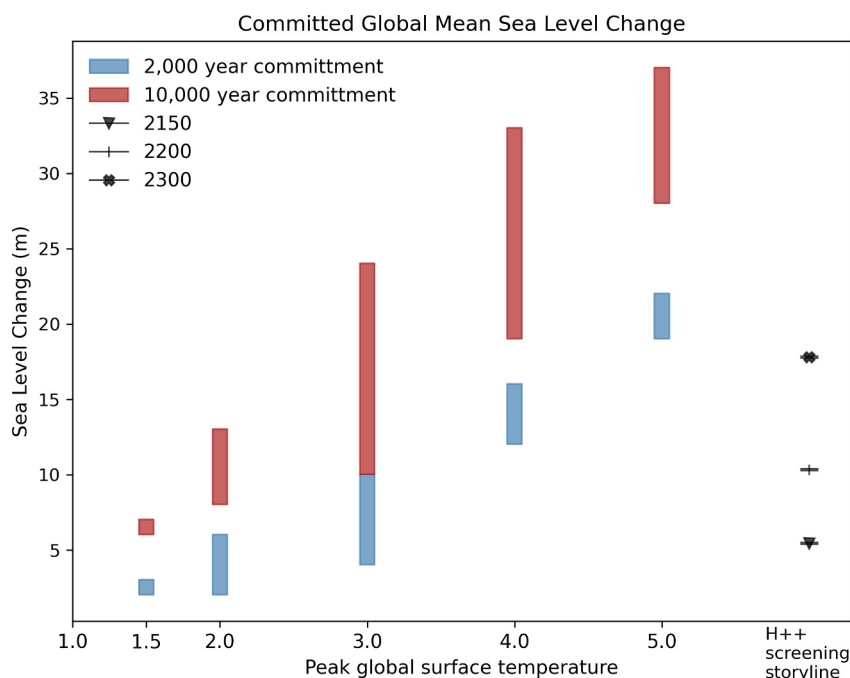


Figure 5. Committed global mean sea level change at 2,000 years and 10,000 years presented in the AR6 at different peak global surface temperature warming levels (Fox-Kemper et al., 2021). The H++ screening storyline is also presented at time horizons 2150, 2200 and 2300 (black markers).

Meridional Overturning Circulation (AMOC) weakening, linked to cascading impacts on regional climate dynamics (Jackson et al., 2015).

The library in our H++ framework can accommodate storylines exploring additional tipping point systems relevant for local relative mean sea level change. For example, AMOC weakening could reduce northward transport of saline water at UK latitudes, leading to halosteric sea level rise (Couldrey et al., 2021). Large-scale steric changes could then be communicated onto the North West European shelf via barotropic adjustment (Bingham & Hughes, 2012; Dangendorf et al., 2014). For North West Europe, a rise in dynamic sea level with a possible magnitude of 0.4–0.5 m (Levermann et al., 2005; van Westen et al., 2025) could constitute one of the most impactful consequences of a severe weakening of the AMOC. Quantifying the local dynamic sea level variability is important for exploring the interaction of higher sea levels with storm surge events and the risks to communities posed by extreme sea levels (Bulgin et al., 2023; R. J. Perks et al., 2023), as well as the additional effect on surge extremes of any potential change in storminess due to an AMOC weakening (Howard et al., 2024). While an AMOC collapse was simulated simplistically in our decision-gaming workshop, a more elaborate storyline would help prime strategic thinking about these potential abrupt changes.

3.5. Beyond UK Coastal Decision-Making

The H++ framework we have presented is a generic concept that could be adapted for other climate impact drivers, sectors or regions. For example, within the regulated infrastructure sector there are many sensitivities to precipitation but the projections remain uncertain. The screening process combined with a library of storylines might offer an alternative that could be used alongside probabilistic approaches. Similarly, as the financial sector begins to embrace physical risks alongside transition risk there are avenues to apply this approach to contingency planning across time-scales.

Applying the approach to other regions would involve developing storylines tailored to the local hazard context. For example, vertical land movement processes can be significant drivers of local relative mean sea level change, which can in turn drive hazards of concern to coastal communities (Levy et al., 2024). This includes areas where there is high subsidence due to groundwater abstraction (e.g., Southeast Asia or the U.S.; Peng et al., 2024; Govorcin et al., 2025) or seismically active regions (e.g., New Zealand, Naish et al., 2024). Spatial variability and

non-linear temporal changes in such processes drive challenges for generating local relative mean sea level projections (Peng et al., 2024; Tay et al., 2022), which rely on accurate observational data (Ng et al., 2025). Future storylines could be developed by collaborating across disciplines to explore how processes driving vertical land movement might evolve (Palmer et al., 2024; Weeks, Ahmed, et al., 2023).

4. Conclusion

High-end sea level rise information underpins widespread guidance used by coastal zone adaptation planners and decision-makers across the UK. We have presented a new, co-produced H++ framework that is intended to address several shortcomings of current Environment Agency guidance based on the UKCP09 H++ scenario. Current guidance advises risk-averse users to consider a relative mean sea level rise for the UK of 1.9 m over the 21st century in their adaptation planning processes. Given improved scientific understanding and knowledge of planning processes (e.g., adaptation pathways), this guidance is no longer fit-for-purpose. Users may need to resort to additional ad hoc assumptions to support their decision-making.

Our new H++ framework consists of a screening process and a library (database) of storylines to support robust evaluation of adaptation options and damage costs, and decision-gaming (or other decision-exploring initiatives) as a helpful priming device to provide context and to understand uncertainties within and beyond strategic planning timeframes. Our new H++ framework responds to several criteria stipulated by the Environment Agency, providing information that (a) is locally available; (b) is time-continuous to 2300 to support planning for long-term infrastructure and land use; (c) supports analysis based on rates of sea level rise; (d) has consistency with UKCP18 sea level projection methods and (e) is flexible and can be updated for consistency with future national climate information, and to reflect future policy positions and emerging evidence. Ongoing monitoring, evaluation, and learning are imperative to review and refine the scientific information and ensure relevance, credibility and legitimacy.

Decision-making and adaptation planning for future sea level rise is challenging due to the long-term committed rise, the growth of uncertainty in time, and deep uncertainty on multi-century timescales associated with incompletely understood ice sheet processes. There are unresolvable uncertainties that need to be acknowledged and that no amount of information can address before decisions have to be made. Our new H++ framework takes a flexible and pragmatic approach in the face of irreducible uncertainty, acknowledging the inability to select a single “worst case” or maximum sea level rise scenario due to deep uncertainty. It also accommodates evolving evidence and information from early warning systems that underpin expectations of future sea level rise. The Environment Agency provide guidance on assessing the changing climatic hazard profile for critical facilities. While our new H++ framework focuses on sea level rise, additional coastal flood hazard drivers (e.g., storm surge) could potentially be accommodated in future developments under the same generic framework. Our new H++ framework could also be adapted and applied to other climate impact drivers, sectors or regions and combined with information on vulnerability and exposure to support robust decision-making.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The H++ global and local relative mean sea level rise screening storylines presented within this paper are provided as timeseries in the Supporting Information and via the Zenodo repository (Weeks & Palmer, 2025). Global and local relative mean sea level storylines associated with the library are available as Supporting Information to Palmer et al. (2024) and have been made available via the Zenodo repository, converted to the UKCP18 baseline (Weeks & Palmer, 2025). The IPCC AR6 projections are publicly available via the Nasa-IPCC Sea Level Projection Tool and the Zenodo repository (Fox-Kemper et al., 2021; Garner et al., 2021; Kopp, Garner, et al., 2023). UKCP18 sea level data around the UK coastline is publicly available on the UK Centre for Environmental Data Analysis (CEDA) archive (Met Office Hadley Centre, 2018) and the associated localization code is publicly available via the Met Office Projecting Future Sea Level (ProFSea) tool (R. Perks & Weeks, 2023). We thank all projection authors, teams and funding agencies for making these projections and tools publicly available.

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