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Research article

The causes and consequences of 21st century global sea level rise on Morecambe Bay, U.K.

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Abstract

As 21st Century anthropogenic carbon emissions increasingly perturb Earth's atmospheric composition, an accessible understanding of how greenhouse gas driven climate change manifests on natural and human systems becomes crucial to public awareness. Here, we investigate the contemporary causes and consequences of global sea level rise (SLR), focusing on the impacts of coastal flooding on Morecambe Bay, Northwest England. We review and summarize current literature regarding terrestrial ice loss and ocean thermal expansion, delving into the uncertainties and assumptions. We define three SLR scenarios through to 2100 AD: 1) the Green Road (GR: 0.44m SLR), 2) Business as Standard (BS: 0.77m SLR) and, 3) Impending Doom (ID: 1.55m SLR). We adjust these SLR scenarios for regional isostatic and gravitational effects, and map them to local flood projections for Morecambe Bay. Even under the most optimistic - GR - scenario, we find permanent flooding is inevitable by 2100, necessitating adaptation strategies. Under BS and ID scenarios, significant inundation of industrial and residential areas is projected, with permanent displacement of up to 15000 homes and moderate to severe disruption to national transport networks, including the UK's West Coast rail-link. Moreover, national power and industrial infrastructure at Heysham Nuclear Power Station and BAE Systems, Barrow would be impacted under our worse-case scenario. Directed mitigation and informed decision-making are crucial for minimizing economic and social impacts, emphasizing a need for public awareness of the future impacts of environmental change and its local manifestation.

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Introduction

Climate change is an inherently societal problem both in its causes and consequences. The trajectory that Earth's near-future climate will take radically depends on how effectively global greenhouse gas (GHG) emissions can be managed through decarbonization and how well society can adapt to the abrupt climate transition already underway. Much stress is placed on individuals, and it is understandable that many, particularly the younger generation, can become overwhelmed by it. This outlook is partially due to the confusing, contradictory manner by which climate change and its impacts are reported in the media: often in the bleakest terms that invokes a sense of futility or even nihilism and, at the opposite end of the political spectrum, denial, along with accusations of conspiracy.

In this paper, we wish to summarize the current state-of-knowledge on climate change and global sea-level rise from the most recent peer-reviewed scientific literature. We will try - in layman's terms – to review what is known with certainty and is well constrained, but also to outline the main limitations and uncertainties regarding future model projections. Our intention is to broaden the discussion and the language to include those who may have found the science impenetrable, providing the reader with accessible but robust science, and with sufficient knowledge to inform opinion and to make positive, personal decisions. We then define three potential future climate scenarios, and through application of accessible flood-risk mapping tools, will illustrate how sea-level rise (SLR) manifests on flooding across the locality of Morecambe Bay, NW England to the end of this century.

Having made this grandstand claim, we find that climate change and SLR is an extraordinarily complex and nuanced topic. There are myriad drivers, controls and sources contributing to an increased overall volume of water contained within the Earth's oceans, that ultimately results in what is termed *eustatic SLR* (Figure 1). Moreover, there are modulating feedback processes that can reduce or amplify SLR across regional and

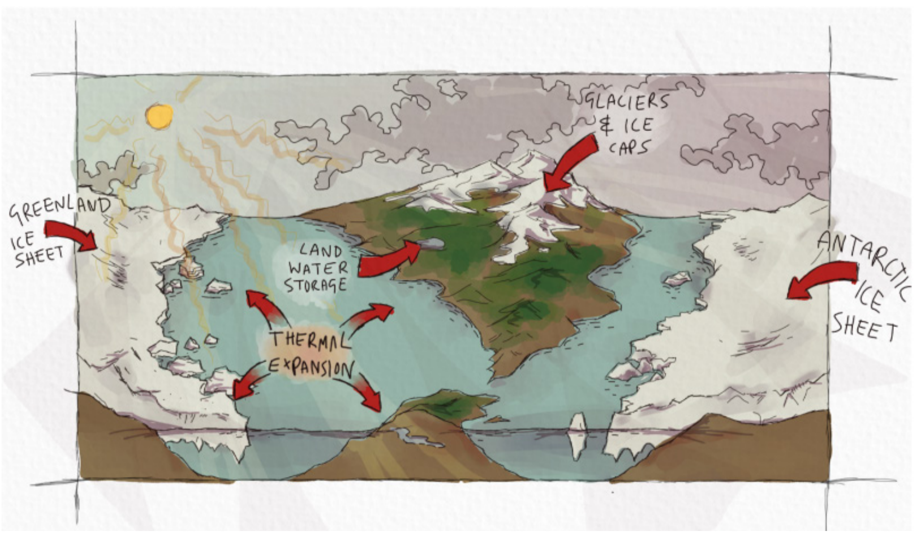

Figure 1. Schematic of primary sources of global (eustatic) SLR: Thermal expansion (42%), Polar Ice Sheets (36%), Glaciers and Ice Caps (20%), and Land Water Storage (2%). Polar Ice Sheet loss is increasing and set to surpass losses from other sources in the next decade (original artwork - this study).

local scales. As part of our study, we will also briefly discuss these regionally interacting causes and, by illustration, consider how they can actually moderate future SLR-driven flooding on Morecambe Bay. We finally assess the impact of the three flood-risk scenarios on local communities and discuss the wider consequences for regional and national transport hubs and networks, power and industrial infrastructure.

We find that even under the most optimistic scenario there will be some, but not catastrophic, permanent flooding across Morecambe Bay. Hence, preventative adaptation strategies, such as the construction of coastal defenses and managed retreat/land-use changes, would be a pragmatic solution to maintain key infrastructure, industry and protect communities. However, under less optimistic scenarios, where emissions targets to limit the temperature increase to 1.5°C above pre-industrial levels in accordance with the COP21 (2015) Paris Agreement are not met (as per our current trajectory), then levels of coastal inundation increase significantly. Such flooding severely impacts residential, commercial and industrial zones at major conurbations where permanent displacement and disruption occurs including to national transport networks and power generation infrastructure. In these cases, mitigation strategies could limit the economic and social impacts but at enormous cost, emphasizing the importance of public education, awareness and preventative action to transition and attain net-zero economies within the next decades.

Current understanding

Our review of eustatic SLR follows the roadmap of the sea-level "jigsaw" (Palmer *et al.* 2018), where each component of SLR is calculated separately before being summed up along with regional adjustment offsets (Figure 2). The main drivers are influenced by multiple variables, themselves modulated by positive and negative amplifiers and feedbacks. The first-order control on eustatic SLR is atmospheric Carbon Dioxide (CO_2) concentration - the primary GHG - and its impact via global radiative forcing which results in planetary temperature change.

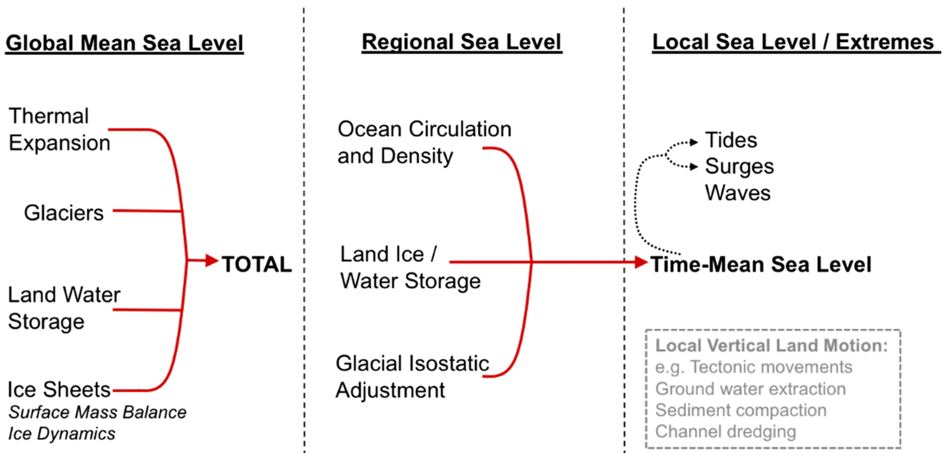

Figure 2. Unpacking the sea-level jigsaw: the multiple global components that determine eustatic SLR (from Palmer *et al.* 2018, CC BY 3.0 license).

The greenhouse effect and global temperature

There exists a near linear correlation between cumulative GHG emissions and global temperature rise which is now unequivocally recognized to be driven by increased anthropogenic activity related to fossil fuel combustion (IPCC 2021a). The link between atmospheric CO_2 concentration and global temperature was first identified in the 19th century (Tyndall, 1861). Since the onset of the industrial revolution, the concentration of GHGs in the atmosphere has increased at a rate unprecedented in the last 0.8 Ma (IPCC 2021a). Yet, despite these strong causal links, long-term global climate forecasting remains an exceedingly difficult task.

The Earth's atmosphere, oceans and land-surface are inherently complex systems - with interdependent flows of mass and energy operating across multiple scales through widely different mediums – all of which have to constrained and modelled in four dimensions. Moreover, how future climate evolves is dependent on multiple human actions that compound the myriad natural "background" processes, many of which we do not fully understand. Primarily, the Earth's temperature varies directly in response to atmospheric GHG concentrations, which in turn, is partially influenced by anthropogenic emissions as well the natural carbon cycle. Because of this incipient uncertainty, climate scientists have defined a system of potential "future pathways" by which to model climate projections, the leading proponent of which is the Intergovernmental Panel on Climate Change. The IPCC is a scientific body established by the United Nations in 1988, with 195 member states to monitor the state and evolution of climate change, and the aim to inform global policy makers.

The most recent report - IPCC Assessment Report 6 (AR6 – IPCC 2021a) uses a system of shared socioeconomic pathways (SSPs), defined by specific CO_2 emissions and their associated radiative forcing. The concept of an SSPs deviates slightly from previous IPCC reports as well as other scientific and government bodies (e.g. UK Meteorological Office - Palmer *et al.* 2018) who use Representative Concentration Pathways (RCPs). While they have key differences - notably SSPs are applied with added context of what policies and change are associated with each scenario - both SSPs and RCPs use similar broad parameters based on radiative forcing, allowing for direct intercomparison (Figure 3).

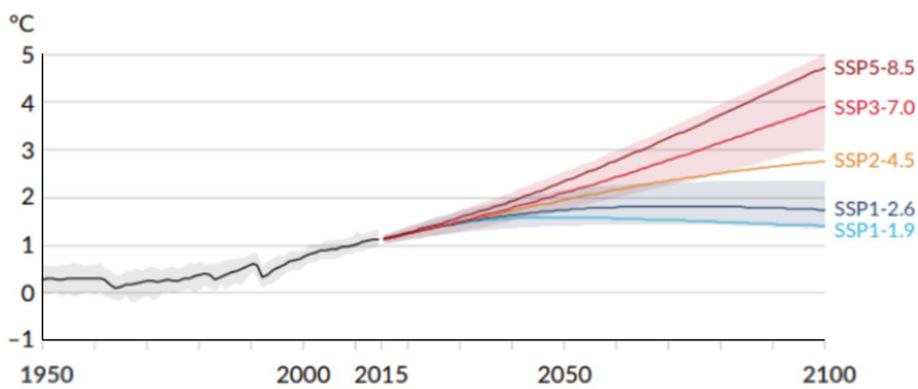

Figure 3. Global surface temperature change relative to 1850-1900 obtained by combining CMIP6 simulations with observations based on simulated warming (from IPCC 2021a, Figure SPM.8a).

IPCC Climate projections are calculated using the latest generation of General Circulation Models (GCMs) and, most recently, rely on the Coupled Model Intercomparison Project Phase 6 (CMIP6) as the leading ensemble of temperature forecasts. IPCC-AR5 did though, use CMIP5 projections (IPCC 2013) which pose an issue in comparing different SLR projections, as CMIP6 forecasts predict a greater temperature range than CMIP5 (Payne *et al.* 2021). This in turn has ramifications on the primary findings of, for example, UN and other Governmental reports which may rely on outdated RCP-based (CMIP5) projections.

Despite the rapidly changing science and forecasts, the most recent CMIP6 and associated ice mass loss assessments demonstrate that we are tracking one of the worst-case IPCC (2021a) emissions scenario of SSP5-8.5 (Slater *et al.* 2020). These findings act to emphasize the importance of generating accurate regional SLR data, particularly for the upper-end predictions, to create adaptation strategies that effectively mitigate impact. It also serves as a warning to policy makers, as rapid temperature rise will accelerate SLR through rapid cryospheric retreat and ocean thermal expansion (IPCC 2021a), leading to extensive flooding and coastal inundation.

Increased temperatures through enhanced GHG emissions are also driving more extreme weather events - which yields more frequent and intense storms and precipitation, including for example, enhanced winter snowfall events which can offset ice mass loss (Bailey and Hubbard, 2025), or on the other hand, increase the risk of inundation within river basins (Bates *et al.* 2023). Temperatures are increasing almost four times faster across high latitudes than the global mean (Rantanen *et al.* 2022). Such warming is amplified through positive feedback mechanisms, such as albedo reduction across Greenland's dark zone causing its ice surface to absorb increased incoming radiation and enhancing melt (Ryan *et al.* 2017a).

The current rate of eustatic SLR of 4.6 – 5.5 mm per year is unprecedented over the last three millennia (IPCC 2021a). Well-established and documented casual mechanisms exist between global temperature rise and SLR (Palmer *et al.* 2018) and the four main contributors driving an increased volume of water in the oceans are: 1) thermal expansion of the ocean, 2) loss of polar ice sheets, 3) glacier retreat, and, 4) reduced land-water storage.

The polar ice sheets

The Greenland and Antarctic Ice Sheets (GrIS and AIS) store the equivalent of ~65 m of SLR between them and are the largest contributors to SLR, but are also the source of the greatest uncertainty (Shepherd *et al.* 2017; Figure 4; Figure 5). These uncertainties are attributed to poorly understood processes within ice sheet models (ISM), compounded by implicit limitations related to boundary conditions, resolution, and by an insufficient satellite remote-sensing archive that does not capture the timescales of internal variability in the climate-cryosphere system (Bamber *et al.* 2019). The relatively low levels of confidence in current ISM predictions, compounded by emerging potential amplifiers, such as hydrofracture-damage (Chandler & Hubbard, 2023) that could accelerate deglaciation and SLR - represent a significant wildcard.

Despite this, ISM skill and accuracy has improved remarkably from the first IPCC report (FAR - IPCC, 1990), when ice sheets were assumed to be static entities. The fourth report (AR4 – IPCC 2007) was the first to implement transient models of polar ice sheets, and the fifth report (AR5 – 2013) presented "dynamic" ISMs but those

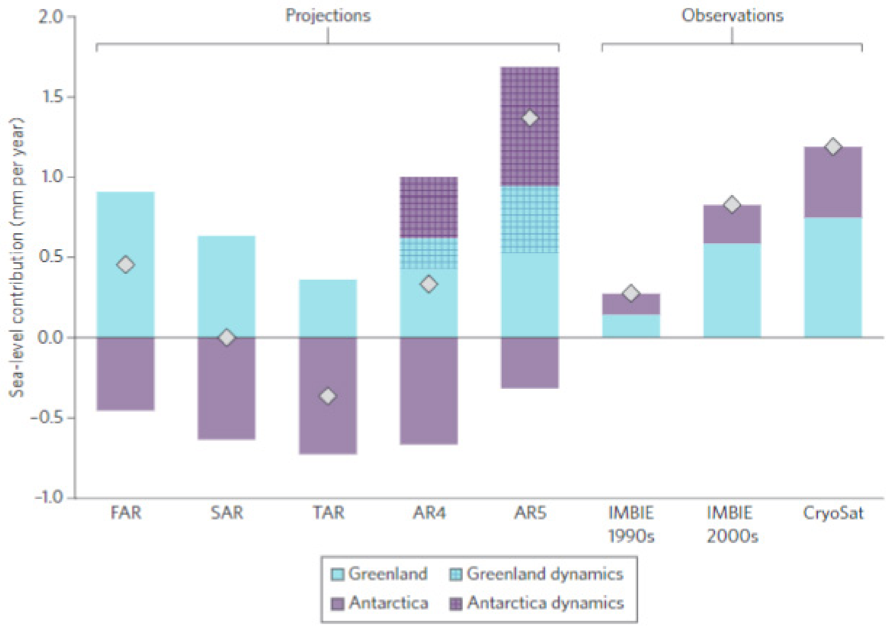

Figure 4. Mean global SLR contributions from polar ice sheets (mm/a). Blue and purple bars represent Greenland and Antarctica; hatching denotes dynamic contributions. Grey diamonds represent net contribution to eustatic SLR. FAR = first assessment report, SAR = second assessment report, TAR = third assessment report (from Shepherd and Nowicki 2017, with the permission from Springer Nature).

processes included were severely limited and heavily parameterized. More recently, a consensus has been attained from an observational perspective, and the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE) delivered much-needed agreement revealing a direct relationship between temperature and SLR from the GrIS (IMBIE, 2020). The data from IMBIE tracks the past contributions of the GrIS and AIS through multiple satellite measurements, which have been directly compared with AR5 SLR models to validate and predict future contributions (see Figure 7). The IPCC AR6 (2021a) yield significantly different SLR outcomes compared to AR5 (2013), and such predictions will continue to evolve as ISMs and constraining data improve.

While there is a strong relationship between global warming and mass loss for the GrIS (IMBIE 2020), this is not the case for Antarctica (IMBIE, 2018). This is due to more complex processes operating in Antarctic as its mass loss is primarily driven by submarine melting and calving; its loss though is also largely counteracted by enhanced precipitation (Payne *et al.* 2021). Major uncertainties due to positive "dynamic" feedback processes - marine ice sheet and marine ice cliff instabilities - could though drive abrupt collapse of the West AIS with SLR contributions of 1m or more speculated (DeConto & Pollard 2016). Similar processes are also apparent at marine terminating sectors of the GrIS - such as in the NE at 79 Glacier, which is currently undergoing similar instability and frontal retreat, though the GrIS is generally considered to be less vulnerable than the Amundsen Sector of Antarctica.

Coupled ISMs are the primary method of determining future contributions from ice sheets, though there are notable shortcomings and challenges ahead. A recent alternative, that yields a minimum SLR commitment from the GriS was analytically determined by

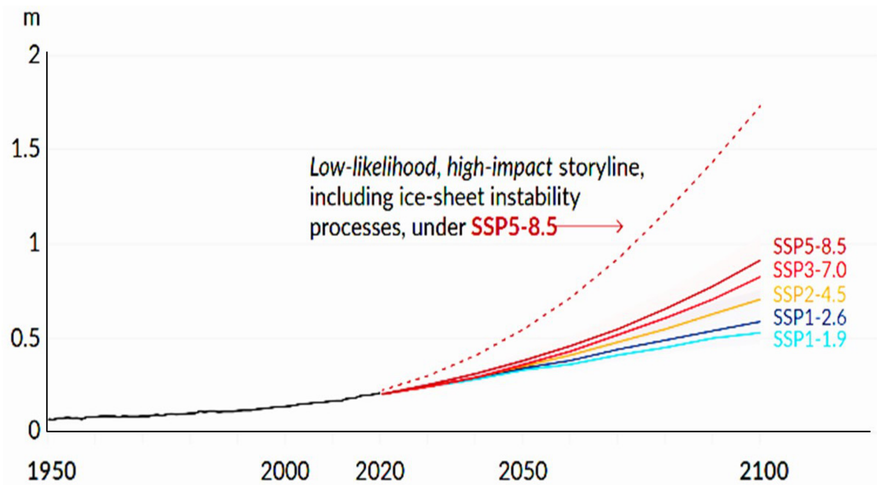

Figure 5. Mean global SLR relative to 1900. Historical observations from tide-gauges pre-1992, and from altimeter measurements thereafter. The dashed curve indicates the potential impact of ice dynamic processes that remain very uncertain, and this (dashed) curve does not constitute part of the likely range calculation (from IPCC 2021a, Figure SPM.8d).

Box *et al.* (2022). Their analysis - which calculates the ice sheet's disequilibrium with its 2000 to 2019 mean climate yields a conservative 27cm committed SLR that can be directly communicated to the public, though the approach does lack a timeframe.

The contributions from Greenland and Antarctica to SLR increased by a factor of four between 1992-2019 (IPCC 2021a). Global atmospheric and oceanic warming has driven these contributions either though ice sheet "dynamic losses" related to flow acceleration, thinning and retreat or from reduction in the surface mass balance (SMB) – the net sum of mass increase primarily through snow accumulation and mass loss through melt and sublimation (Hubbard *et al.* 2000), due to enhanced surface melt (Payne *et al.* 2021; Ryan *et al.* 2017b). From 1992 - 2018, SMB contributed to just over 50% of Greenland's net mass loss, and is attributed to human induced climate change with a direct relationship between warming and ice loss (IMBIE 2020).

Satellite ensemble studies reveal that Greenland is tracking the upper-end scenario of ice loss, with the most negative year in 2011, due to changes in cloud cover and air circulation (IMBIE, 2020; Slater *et al.* 2020; Box *et al.* 2022). There is a high confidence that these losses are attributed to human activity, and that the losses will continue into the 21st century under all emissions scenarios (IPCC 2021a; Figure 6). SMB changes will account for over 80% of future GrIS contributions (Goelzer *et al.* 2020), primarily due to atmospheric forcing, which is predicted to have a greater impact on surface melt than ocean forcing. During the last interglacial, temperature rise over Greenland was linked to peak SLR in the period, providing additional evidence of the link between temperature and GrIS mass loss (IPCC 2013).

While precipitation and snowfall has increased over the AIS since the 1970s - acting to offset SLR, the East and West, as well as the Peninsula ice sheets, have all lost ice at their retreating marine-terminating margins (IPCC 2021a). The Peninsula has contributed to SLR at an increasing rate from 1992 onwards due to ice shelf and tidewater glacier retreat, and the West AIS due to warm ocean driven undercutting where ice shelf thinning has induced the accelerated flow of the fast-flowing ice streams, such as at Thwaits and Pine Island Glaciers (IMBIE, 2018). In Antarctica, ice dynamics

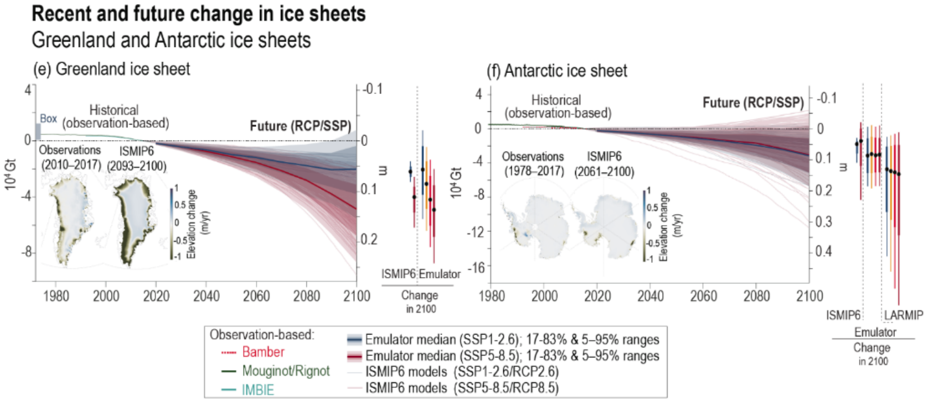

Figure 6. Projected ice sheet changes are shown a median, 5-95% range (light shading), and 17-83% range (dark shading) of cumulative mass loss and SLR equivalent from ISMIP6 simulations under SPP1-2.6 and SSP5-8.5 (shading and bold lines), with individual simulations as thin lines (from IPCC 2021b).

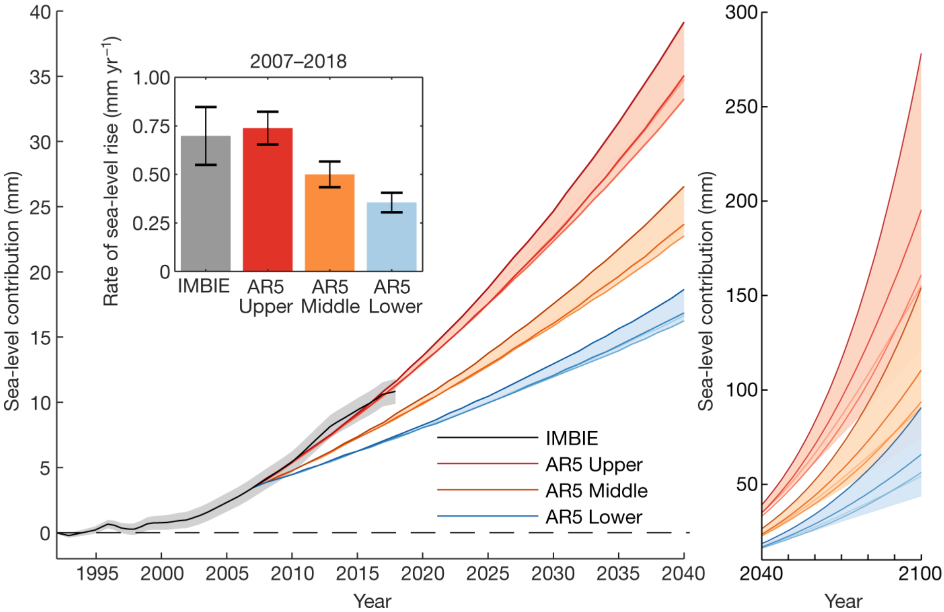

Figure 7. Observed and predicted mass changes and SLR contribution from Greenland according to IPCC AR5 projections from 1992-2040 (left) and 2040-2100 (right), including upper, mid and lower estimates of modelled SMB and rapid ice dynamic contributions. Darker lines represent pathways from the five AR5 scenarios in order of increasing emissions: RCP2.6, RCP4.5, RCP6.0, SRES A1B and RCP8.5 (from IMBIE team 2020, reproduced with the permission of Springer Nature).

are considered to be the dominant contributor to SLR, and hence become somewhat decoupled from actual warming (Payne *et al.* 2021). The positive feedback mechanisms: marine ice cliff and grounding line instabilities, introduce deep uncertainties into SLR predictions, especially related to contributions from the West AIS, which drive current AIS contributions to SLR at ~0.4 mm per year (IPCC 2021a). The uncertainties regarding the possible collapse of the Amundsen Sector with multimeter SLR (>1 m) are hotly debated, but are considered highly improbable, at least by 2100 (IPCC 2021a).

Thermal expansion and other controls

As the oceans warm, the density of its waters decreases (Oppenheimer 2019), yielding a linear relationship between the "thermostatic expansion" of the ocean and temperature rise (IPCC 2021). The rate of ocean warming has doubled between 1970 and 2017 along with the rate of thermostatic SLR, and is likely to continue responding to anthropogenic forcing for centuries to come (IPCC 2021a).

From 1971-2018, thermal expansion accounted for 42% of all SLR (Global Sea Level Budget Group, 2018). Due to good physical understanding, long observational records and well constrained boundary conditions, there is greater certainty and high confidence in predictions of its future eustatic SLR contribution (van de Wal *et al.* 2022). CMIP6 output is used to drive ocean thermostatic expansion forecasts and, whilst results are considered robust, the magnitude of SLR is dependent on the specific SSP and warming scenario applied (Oppenheimer, 2019).

Two further components contribute to global SLR: changes in the global inventory of glaciers and ice caps and changes in land-based water storage (Palmer *et al.* 2018). There are over 200,000 glaciers and ice masses globally outside of the Greenland and

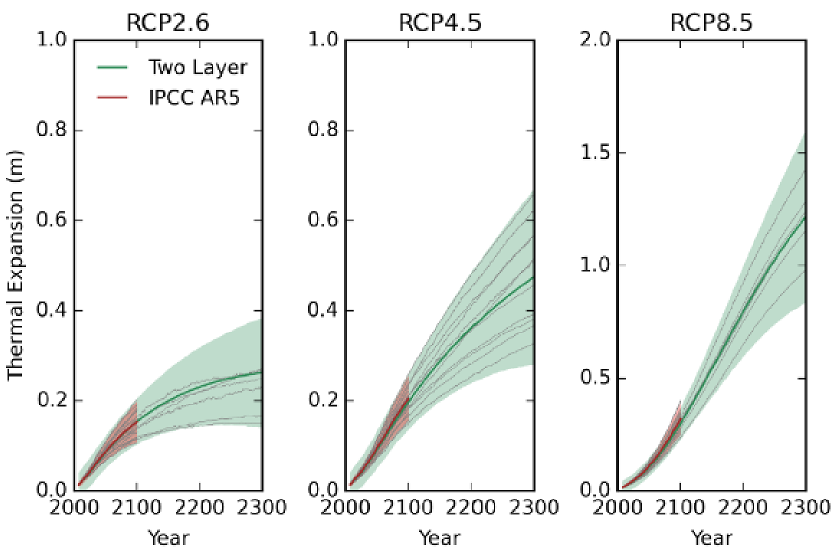

Figure 8. Global mean SLR associated with thermal expansion relative to baseline period 1986-2005. Time-series include i) 21 member AR5 ensemble (red – with shaded area indicating 90% confidence); ii) 14 member two-later model ensemble (green), and iii) individual CMIP5 projections (grey lines, table 2 - from Palmer *et al.* 2018, CC BY 3.0 license).

Antarctic ice sheets, covering ~706,000 km^2 with an estimated volume equivalent to ~0.324 m SLR (IPCC 2021a; Glambie 2025). The limited observational record of these glaciers has led to relative uncertainty in modelling future glacier contributions from specific glacierized regions such as Patagonia and Himalya, though aggregated global projections appear to smooth out regional variations and are more consistent with the results from regional-scale studies using more sophisticated models (Oppenheimer 2019). Though there is limited potential for SLR contribution from glaciers due to the relatively small net proportion of ice they store (Grinsted 2022), due to their smaller area and wider latitudinal range, they are highly sensitivity and have already undergone dramatic shrinkage in response to recent global warming, contributing ~0,75 mm SLR per year since 2000. Glacier response times vary from years to decades due to their widely varying thermal regimes and flow rates, refreezing of meltwater downstream, and this SLR contribution will likely remain roughly constant over the next 75 years (IPCC 2021a; Glambie 2025).

Land-water storage fluctuations include changes in surface water, ground water, soil moisture, snow and permafrost. They have primarily been attributed to increased irrigation in dryland agricultural areas such as mid-eastern Australia and mid-western USA, that have severely depleted ground water storage sources, though shrinkage of lakes is also linked to climate variability (Cazenave *et al.* 2012). These changes currently represent a relatively small proportion (<5%) of total SLR and are driven through both direct human impact, such as dams and the draining of groundwater, and indirectly though changes in the hydrological cycle (Cooley *et al.* 2021). Changes in land-water storage cause short term variation in sea level due to interannual changes in the water cycle, but also longer-term changes, especially related to the melting/drying of permafrost and decreasing surface moisture. Overall, there is low confidence in predicting some processes, such as long-term groundwater storage which are further compounded by uncertainties related to changing precipitation recharge and intensity (IPCC 2021a).

Future eustatic SLR scenarios

The sum of these four primary components yield the net change in ocean volume that drives eustatic SLR. Based on our review, we define three scenarios that encompass the best, the most likely and the potentially worst-case SLR outcomes for 2100 (Table 1):

1. The most recent AR6 low emissions scenario SSP1-2.6, where warming is limited to below 2°C in accord with the Paris (COP21) Agreement - we refer to as the "Green Road" (GR). Here, net-zero emissions are attained by the second half of this century, yielding 0.44 m of SLR that plateaus by this time.
2. The AR6 "Business as Standard" (BS) scenario SSP5-8.5 associated with 0.77 m of SLR due to a 4.4°C rise under a doubling of current GHG emissions.
3. We include an "Impending Doom" (ID) scenario including important amplification processes currently not included in ISMs which drive non-linear deglaciation of Greenland and Antarctica, with 1.55m SLR (van de Wal *et al.* 2022).

The GR and BS scenarios attempt to encompass the range of possible SLR scenarios where processes with low confidence related to ice sheet instabilities are ignored. For these scenarios the IPCC (2021a) provides the most accurate and peer reviewed predictions using advanced GCMs coupled to ISMs verified though available observations. We hence use the SSP1-2.6 (warming below ~2°C), and SSP5-8.5 (warming below ~4.4°C) scenarios for the GR and BS respectively. Our worst-case (ID) includes ice sheet processes with deep uncertainty that are considered low probability (IPCC 2021a). We scanned the most recent research by Van de Wal *et al.* (2023) for this scenario, as it considers the potential of each component and explores how currently unknown and poorly understood ice sheet processes could drive abrupt SLR.

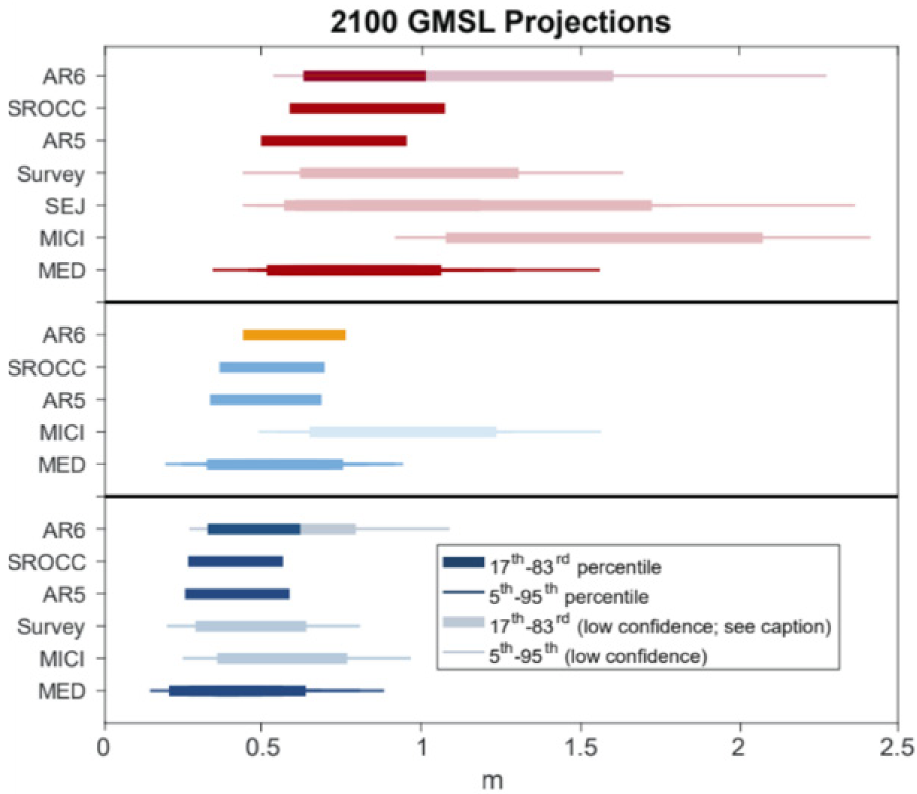

Figure 9. Global mean SLR projections for 1995-2014 (right), for RCP8.5/SSP5-8.5 (top), RCP4.5/SSP2-4.5 (middle) and RCP2.6/SSP1-2.6 (bottom). Thick bars span the 17-83 percentile projection range, and the thin bars span the 5-95% projection range. Different assessments are represented by MED (including only those ISM processes that are of at least medium confidence), MICI (ISM projections that include dynamic marine ice-cliff instability), and SEJ (structured expert judgement) of SLR contributions, including to a 2020 "survey" of glaciological and climate experts (from IPCC 2021a, Figure 9.25).

Table 1. Our SLR projections for 2100 broken down into their constituent contribution components. Green Road (GR) taken from the IPCC AR6 predictions based on SSP1-1.26 (IPCC 2021a) and Business as Usual (BS) from SSP5-8.1. Impending Doom (ID) scenario is adopted from high end forecasts for practitioners which includes low confidence Greenland and Antarctic ice sheet dynamical instabilities (van de Wal 2022).

Regional SLR	**Contributions by 2100 / m**		
Source	Green Road	Business as usual	Impending Doom
Antarctic Ice Sheet	0.11	0.12	0.59
Greenland Ice Sheet	0.06	0.13	0.29
Thermal Expansion	0.14	0.3	0.36
Glaciers and Ice Caps	0.09	0.18	0.27
Land-water Storage	0.03	0.03	0.04
Total/m	0.44	0.77	1.55

Impact on Morecombe Bay

Regional modulators of sea level rise

The local manifestation of eustatic SLR varies significantly due to regional modulators. Though investigations into the local impacts of SLR have improved (IPCC 2021a), miss-information is rife and there are no standard protocols for determining local flooding for the majority of countries. In the UK, for example, assessment reports by Bates *et al.* (2023) and the Govt Office for the Institute of Studies (Edwards, 2017) evaluate the consequences of SLR and flooding in terms of *expected annual damage* (EDA). Though directed towards policy makers and planners, this approach fails to explore the full scope of impacts that concern public understanding. Edwards (2017) discusses the potential social and economic impacts in a general manner for the whole of the UK, but there is little regional, and no local information.

Before application of the three SLR scenarios to Morcombe Bay, they must be adjusted for regional effects (Table 2). Eustatic SLR is modulated regionally due to changing gravitational fields associated with the redistribution of Earth's mass and as a result of the vertical uplift of continents due to post ice-age unloading - known as glacial isostatic adjustment (GIA, e.g. Patton *et al.* 2024). In terms of gravitational effects, we specifically refer to changes in ice sheet mass loss (melting) and water redistribution across the planet. Palmer *et al.* (2018) provide maps of how each major gravitational contributor impacts regionally across the UK. To determine these regional adjustments, we multiply the contribution from each SLR scenario by the ratio between the global and local effects ("mass fingerprint") of each source. At Morecambe Bay the gravitational multipliers are -0.1 for Greenland, 1.1 for Antarctica and 0.7 for glaciers and icecaps (Palmer *et al.* 2018). The localized GIA over the 75-year timescale is effectively constant at ~0.7 mm of vertical uplift per year (Kuchar *et al.* 2012). These regional effects are complex but surprisingly, act in tandem to mitigate SLR across much of the North and West of UK, coincident with the maximum footprint of the late glacial ice sheet at ~20ka BP (Hubbard *et al.* 2009). Once these regional offsets are applied, our three regionally adjusted SLR scenarios are projected onto Morecambe Bay, to assess their potential for coastal inundation.

Table 2. Local SLR scenarios adopted for Morecambe Bay with regional adjustments. The contributions (excluding glacio-isostatic rebound) are adapted from Palmer *et al.* (2018). Glacio-isostatic adjustment is updated with regional values from Kucher *et al.* (2012).

Regional SLR	**Contributions by 2100 / m**		
Source	Green Road	Business as usual	Impending Doom
Antarctic Ice Sheet	0.121	0.132	0.649
Greenland Ice Sheet	-0.006	-0.013	-0.029
Thermal Expansion	0.14	0.3	0.36
Glaciers and Ice Caps	0.063	0.126	0.189
Land-water Storage	0.027	0.027	0.036
GIA	-0.071	-0.071	-0.071
Total/m	0.274	0.501	1.134

Assessing flood risk across Morecambe Bay

We focus on three case studies within Morecambe Bay to explore the range of possible SLR flooding consequences within a location-specific context (Figure 10):

1. The rural wetland coastline between Silverdale and Carnforth.
2. The extended conurbation of Morecambe and Heysham.
3. The industrial town of Barrow-in-Furness

We achieve this using the Coastal Risk Screening tool (https://coastal.climatecentral.org/) - an interactive mapping tool that identifies areas threatened by SLR and coastal flooding. The tool utilizes a high resolution digital model of coastal elevations, yielding projections of future flooding. As inputs for this tool, the location of each of our case-study areas were applied under the three localized SLR scenarios defined above. The toolbox provides high resolution maps of predicted flooding based on the "bathtub" method that in-fills ("floods") all areas of land that fall beneath the projected RSL scenario applied above the mean higher high water (MHHW) line that has coastal connectivity.

Case study 1: Silverdale to Carnforth

Silverdale-Carnforth is a designated Area of Outstanding Natural Beauty (AONB), mostly comprised of wetlands and marshland, and is home to the RSPB Leighton Moss nature reserve (Figure 11). Its geography represents what might be considered a "low impact buffer zone" with capacity to absorb significant marine incursion. Such buffer zones act to protect coastlines from erosion and flooding by absorbing both water and its wave-force, so that any moderate SLR should have a relatively low-impact. The area also includes grazing farmland, some low-density residential areas and is a tourist destination for walkers and ornithologists.

We find that the GR and BS scenarios result in permanent loss of 1.14 and 1.36 km^2 respectively to marine incursion, which is doubled in the ID scenario, with 2.51 km^2 of

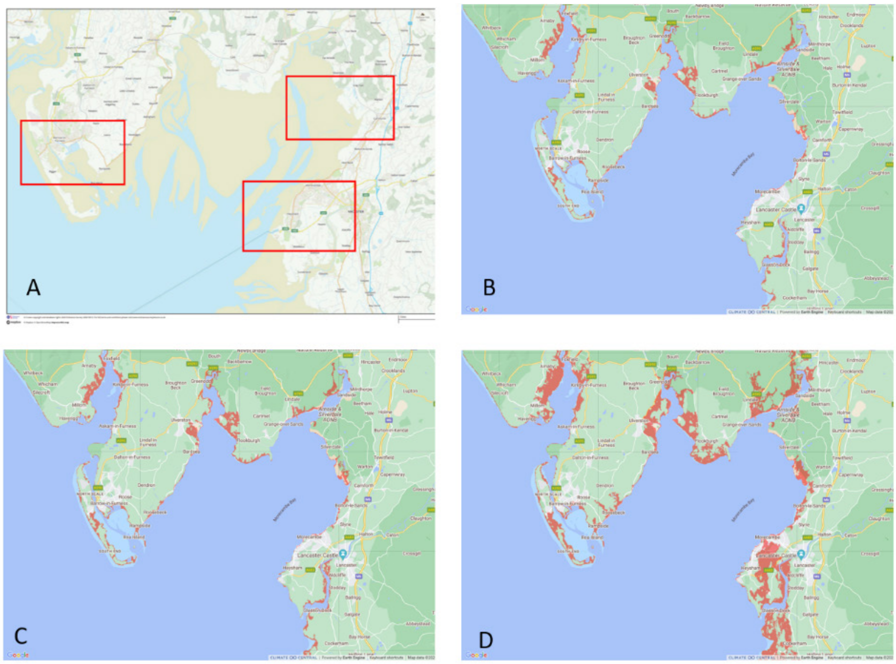

Figure 10. SLR projections for Morecambe Bay for 2100. Panel A is the topographic map of the entire area with our case studies (CS). CS1 - Silverdale to Carnforth (top right), CS2 - Morecambe and Heysham (bottom right), and CS3 - Barrow-in-Furness (top left). Panel B is the permanent area flooded (red) from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

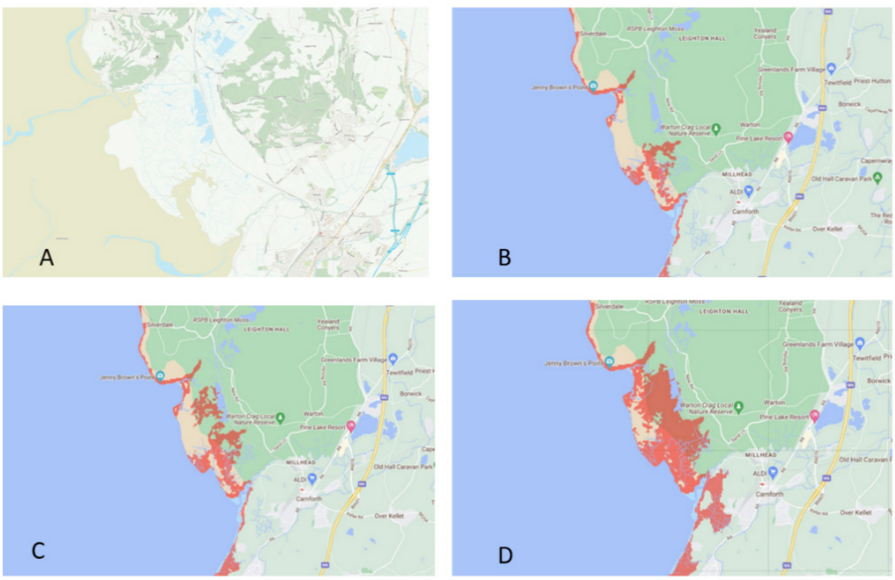

Figure 11. Projections for CS1 – Silverdale-Carnforth by 2100. Panel A is the O.S. map for this area. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

land lost. It is anticipated that the effect of buffering by the wetlands would reduce the severity of flooding, arguably leading to some positive environmental consequences such as the inundation of grazing areas that may lead to a potential expansion in wetland, creating additional habitat for wading birds and promoting peat-formation to sequester atmospheric carbon. Such benefits potentially offset local economic losses due to reduction in farmland. While the loss of grazing agricultural land will have some negative economic impacts, it may be argued that the potential benefits outweigh the economic losses.

This area does though have critical infrastructure comprising the A6 trunk road, M6 motorway, West Coast mainline, as well as a regional rail network. In all three SLR scenarios, the M6 is safe from direct flooding, being ~1.5 km distant from inundation in the worst-case ID scenario. The A6 is though vulnerable, becoming permanently flooded at Carnforth, where it would either require diversion, or levee construction.

The national and regional rail network follows a coastal route and carries the highest risk. Even under the best-case - GR scenario - with little defensive infrastructure in place, these key transport networks are vulnerable (Edwards 2017). The Carnforth-Carlisle railway link is critical for transportation of industrial freight serving, for example, BAE Systems in Barrow and for transport of spent nuclear fuel (SNF) to the Sellafield plant. This rail network is already frequently disrupted due to climate-driven flooding, landslides and embankment erosion (e.g. https://www.bbc.com/news/articles/cqj0jw025kdo).

Case study 2: Heysham and Morecambe

Morecambe is a traditional coastal tourist town of ~36,000 with attractions that include a sea front promenade, the art-deco Midland Hotel, shops, parks, and entertainment facilities, and the new Eden Project North (Figure 12). Morecambe also has an industrial zone - centered mostly on franchise retail and service outlets, but also hosts some small-scale industrial and manufacturing. Heysham, population ~17,000, was a traditional fishing settlement but since the 1970s has developed significantly with the expansion of Heysham Port, and Heysham Nuclear Power Station, owned by the energy provider - EDF.

Heysham port is predominantly a freight terminal that has routes to the Isle of Man, Republic of Ireland and Northern Ireland. Heysham Nuclear Power Station with a 1000-strong workforce, and with a generation capacity of 11,500 GWs, supplies the Northwest region via the National Grid. While the Heysham nuclear power plants are situated directly on the coast, they are elevated on bedrock.

Under GR, BS and ID scenarios, areas corresponding to 1.42, 1.76 and 12.16 km^2 are permanently inundated. Morecambe's entire seafront is increasingly impacted in all scenarios, with flooding, erosion and damage to commercial and tourist infrastructure - including the Midland Hotel and the Eden Centre site. Furthermore, the River Lune floodplain – including the White Lund Industrial Estate and the Lancaster "Marshes" with populations of ~7,000 and ~6,000 respectively, are permanently flooded under the ID scenario, displacing communities, residential and business zones, with significant economic and social upheaval.

Under all scenarios, Heysham Nuclear Power Station is safe from direct inundation, due to its elevated situation (~15 m asl). However, the 160-year planned life span of power plants, as well as the threat of storm-surges, means that protective measures are necessary to meet the requirements of such infrastructure to ensure protection under 1-in-10,000 year storm-event (Edwards 2017). Numerous outbuildings, support infrastructure, and the road and rail network are though susceptible and will be impacted.

UK's Ports are identified as particularly prone and at risk to flooding, with local SLR above 50 cm being highlighted as of grave concern (Edwards 2017). This is primarily due to the consequences of disruption of established commercial and industrial goods, with a high potential to impact negatively on the regional economy. In all scenarios, Heysham port infrastructure and road/rail network faces some degree of local flooding under its current defenses, and therefore considerable investment and protection will likely have to be made in future to reduce disruption and economic losses.

Case study 3: Barrow-in-Furness

The area chosen centers on Barrow Island, the UK's primary ship-building site that constructs nuclear submarines and other warships. It also consists of the port of Barrow, the Barrow/Walney Island Airport and extensive residential zones (Figure 13). BAE Systems shipyard is one of the UK's largest workforces and is of national strategic importance, with the Navy's most recent nuclear-powered fleet submarines (SSNs) under construction since 2023.

Even in the best-case - GR - scenario, a substantial area is flooded (3.26 km^2), primarily on Walney Island, across agricultural areas inland of Biggar sands, isolating the south and north. The village of Biggar is severely threatened, with permanent inundation of its residential areas, and complete inundation in the ID scenario. To the north of the Walney Island, the impact of flooding is less severe though the A590 linking it to the mainland is severed under all scenarios. Vickerstown, built for workers of Barrow's shipyard with a population of 11,000 will become permanently flooded and hence, coastal management of these conurbations is necessary either through managed withdrawal or sea defenses.

The key industrial areas are relatively well protected under all scenarios, with minor flooding to the runways of the Barrow/Walney airport. While this is only permanently flooded in the ID scenario, then high precipitation and seawater storm surges would likely lead to temporary flooding in either of the two - BS and ID - scenarios. The port, like Heysham, is at particular risk of flooding leading to significant economic impacts as this is a commercial nexus for goods and components for BAE Systems. It is also the site for launching ships and submarines produced by the shipyard. Despite this, the central infrastructure of BAE systems and its submarine building subsidiaries is protected from permanent inundation, apart from some supporting infrastructure such as minor service roads and carparks.

The island of Roa, with a population of ~100, is home to the local RNLI lifeboat station, which similarly experiences permanent flooding under all scenarios. While it is currently connected to the mainland by Roa transit road, this connection would be severed from the mainland under all scenarios and an extensive area flooded under the ID scenario. Raising the road would be viable, though this would also render it susceptible to storm surges and flooding, and thereby compromise RNLI services, potentially at times of greatest need.

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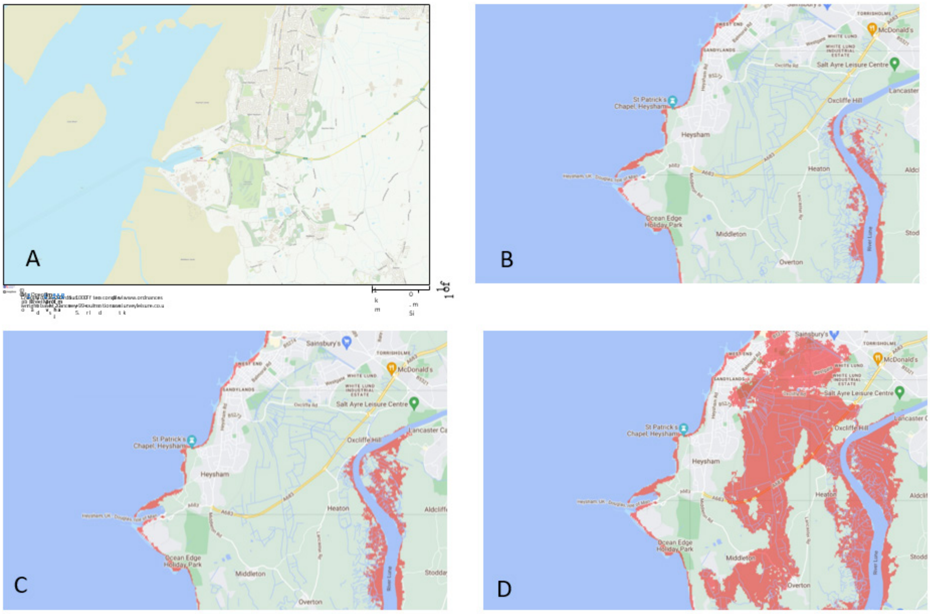

Figure 12. Projections for CS2 – Morecambe-Heysham by 2100. Panel A is the map for this area. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

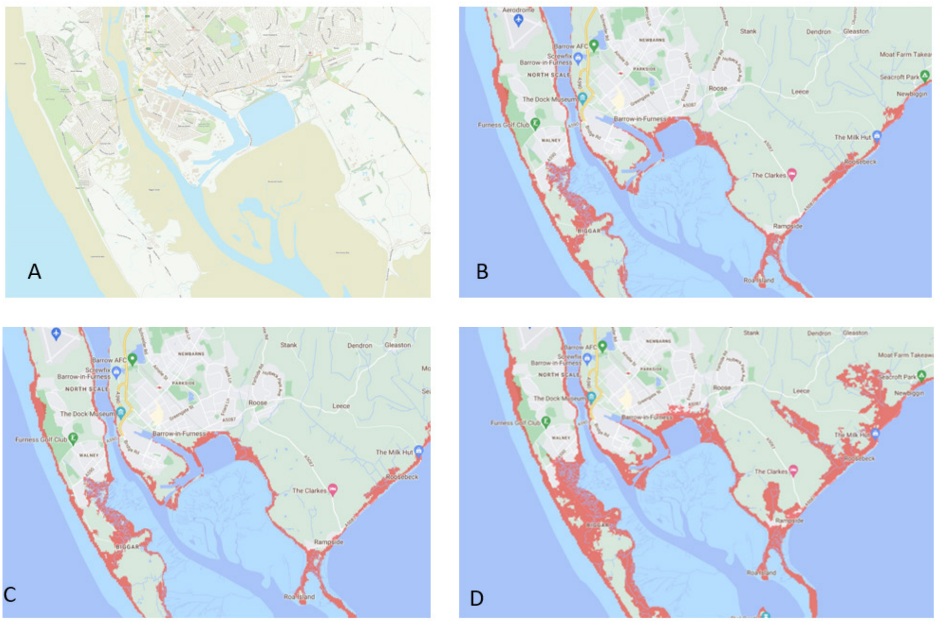

Figure 13. Projections for CS3 – Barrow-in-Furness by 2100. Panel A is the area map. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

Summary and outlook

This paper set out to briefly summarise and assess the drivers and local manifestations of rising sea-levels, and to gain a fuller appreciation of the key uncertainties and complexities surrounding this topic. It is why the potential consequences of SLR cannot be disentangled from its causes. A new appreciation of the fundamental components that contribute to the net global ocean volume enables us to evaluate current knowledge, and take a range of informed scenarios, rather than accepting headline statements without critical evaluation. We find low confidence in the predictions from Greenland and Antarctica subsequently leading to large uncertainties - up to 1 m – in future SLR estimates. Despite this, it is well established that anthropogenic GHG forcing is now driving global eustatic SLR of 3.7 - 4.5 mm/a (2006 – 2018), some three times greater than the rate between 1901 - 1971 of 1.3 mm/a (IPCC 2021a). Of this, thermal expansion accounts for just under half, Greenland for ~1 mm/a, glaciers and ice caps up to 0.75 mm/a and Antarctica ~0.5 mm per year (Slater *et al.* 2022).

Looking forward, circulation models driven by GHG emissions under our best (GR) and moderate (BS) yield 2.0 to 4.4 C of global temperature rise by 2100. Our resulting eustatic SLR scenarios range from 0.44 to 0.77 m but should the potentially vulnerable marine sectors of the polar ice sheets undergo dynamic instability and partial collapse, then abrupt SLR of up to ~1.5 m is possible, though highly unlikely, which forms the basis of our ID scenario. These eustatic SLR forecasts are modulated regionally through glacio-isostatic rebound and gravitational effects - which significantly mitigate potential inundation and impact resulting in a considerably lower net SLR for some localities, such as our case-studies in NW England.

Our SLR and flooding projections do not capture the full spectrum of characteristics of coastal flooding using a fully integrated hydrological model that considers all dynamics - including flash rainstorm and river flooding events coupled with erosive processes. In this light, our findings should be interpreted as conservative. One of the largest sources of inaccuracy is in the application of a simplistic 'bathtub' model that fills-up the low-lying land surface to the projected SLR datum. As the severity of flooding increases, dynamic effects such as prevailing wind and the attenuation of flood height from friction become more important, rendering the bathtub approach less accurate. Application of sophisticated hydrodynamic models provide an alternative approach by physically modeling storm and tide combinations, yielding more reliable flood risk predictions but come at a cost, as they do require significant computational resources and setup. Bathtub models assume that any land under the predicted SLR datum tidal stand will be permanently flooded, however in areas such as flood plains and wetlands there will likely be less flooding, while low-lying areas adjacent to coasts may experience more (Bates *et al.* 2023). Despite this, their advantage lies is in their efficiency when used with precise digital elevation models and realistic SLR forecasts, resulting in accurate maps for areas threatened by permanent SLR alone and for minor floods that may rise and fall slowly.

Across Morecambe Bay – all three of our coastal areas are impacted significantly under all climate and SLR scenarios. In the worst-case (ID) scenario there is extensive inundation of coastal areas with permanent and significant disruption to transport, industrial and residential infrastructure impacting ~40,000 people and ~15,000 homes. In our best-case (GR) scenario – relatively moderate flooding occurs in Silverdale to

Carnforth - which may even be considered to enhance local wetland conservation - but even this minor flooding requires mitigation and defenses to protect the rail network, and to preclude flooding of industrial and residential areas in Heysham, Morecambe and Barrow.

Figure 14. Eric Morecambe fleeing future rising seas at Morecambe promenade (original artwork – this study).

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