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Stabilisation of global temperature at 1.5°C and 2.0°C: Implications for coastal areas

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Summary

The effectiveness of stringent climate stabilisation scenarios for coastal areas in terms of reduction of impacts/adaptation needs and wider policy implications has received little attention. Here we use the Warming Acidification and Sea level Projector Earth systems model to calculate large ensembles of global sea-level rise and ocean pH projections to 2300 for 1.5ºC and 2.0ºC stabilisation scenarios, and a reference unmitigated RCP8.5 scenario. The potential consequences of these projections are then considered for global coastal flooding, small islands, deltas, coastal cities and coastal ecology. Under both stabilisation scenarios, global-mean ocean pH (and temperature) stabilise within a

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century. This infers significant ecosystem impacts are avoided, but detailed quantification is lacking, reflecting scientific uncertainty. In contrast, sea-level rise is only slowed and continues to 2300 (and beyond). Hence, while coastal impacts due to sea-level rise are reduced by climate stabilisation, potential impacts continue to grow for centuries. Sea-level rise in 2300 under both stabilisation scenarios exceeds unmitigated sea-level rise in 2100. Therefore, while the need for adaptation to sea-level rise is reduced by climate stabilisation, adaptation remains essential in densely populated and economically important coastal areas. Given the multiple adaptation steps that this will require, an adaptation pathways approach has merits for coastal areas.

Main Manuscript

1. Introduction

People and economic activity concentrate in coastal areas [1, 2], which also contain vital environmental assets like saltmarshes, mangroves and coral reefs that underpin multiple ecosystem services. Hence, the impacts of climate change, including sea-level rise (SLR) and declining ocean pH, are a major threat to coastal zones. These are both being observed and are expected to continue, but the magnitude of effects can vary regionally [3–5].

Climate change mitigation comprises actions to limit the magnitude or rate of long-term climate change, usually by reduced human emissions of greenhouse gases. Several studies have analysed climate mitigation for coastal areas [6–8]. Many climate change factors respond directly to mitigation at a similar timescale to global temperature stabilisation. However, for sea level, there is a long time delay in response and while the rate of SLR slows under mitigation, sea levels still continue to rise for centuries.

The Paris Agreement committed signatories to “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” [9]. While sea level is not explicitly considered, it was an important background factor in discussions about the Agreement which was strongly driven by small islands developing States (SIDS) who feel especially threatened by this aspect of climate change [10].

Hence this paper has two aims: (1) to analyse the potential changes in coastal areas, including impacts and adaptation needs, under stringent stabilisation targets relative to an unmitigated scenario; and (2) to consider the implications of such stabilisation for the future of coastal areas, including adaptation and management policy. This includes brief consideration of ecological effects that are anticipated for coastal systems under climate change and climate stabilisation. The focus is on sea level and pH as two relevant climate parameters. Given the long timescale of SLR we consider a number of time periods out to 2300 and examine and contrast emission scenarios leading to temperature stabilisation at 1.5ºC and 2.0ºC with an unmitigated emission scenario. This timeframe is much longer than traditional analyses, which usually stop in 2100, and is necessary to see the full implications of climate change on coastal areas. Potential impacts are illustrated using appropriate indicators, as explained. These indicators should not be taken as projections.

Projections of temperature, sea level and ocean pH are developed with the Warming Acidification and Sea level Projector (WASP) Earth System model for stabilisation and unmitigated emissions [11, 12]. They each comprise a large set of ensemble projections. Changes in ocean pH are less studied than SLR and temperature: with limited adaptation options available, reduction in CO_2 emissions is currently viewed as the main practical way to address its impacts, although there are potential geoengineering options [13]. Undesirable effects of ocean acidification and warming may also be reduced indirectly by management of other anthropogenic stressors such as pollution drivers that interact adversely with climate drivers [14]. In contrast, many direct adaptation options are available for SLR (e.g., flood defences, flood proof buildings, setbacks for new construction and restoring coastal ecosystems and geomorphological processes).

The paper is structured as follows. First, the methods to generate climate change scenarios are applied to the stabilisation and unmitigated cases, and the resulting projections of SLR and ocean pH are analysed (Section 2). Second, the corresponding consequences of SLR under the same scenarios are analysed for global flooding and for selected vulnerable hotspots: small islands, deltas and coastal cities (Section 3). Third, we consider the coastal ecological effects of stabilised and unmitigated climate change (Section 4). Finally, the implications of these results are discussed, including climate and coastal policy implications (Section 5).

2. Projections of sea-level rise and ocean pH under 1.5°C and 2.0°C stabilisation scenarios

A warming of global surface temperatures leads directly to global-mean SLR from two main processes: (1) ice melt – the cryosphere adds additional water to the ocean; and (2) thermosteric changes – warming of ocean waters leads to thermal expansion. Both these processes will continue for many centuries after a rise and stabilisation of surface air temperatures due to the long timescale of cryospheric adjustment to elevated air temperatures (especially the large ice sheets), and the long timescale of the deep ocean temperature warming to surface warming [15]. This is often referred to as the 'commitment to SLR' [15, 16]. Additional changes in global sea level are caused by anthropogenic effects that are not directly related to surface temperatures, such as changes to global land-water storage [17].

To project global-mean SLR and ocean pH, the WASP Earth system model [11, 12] is used to produce a large ensemble of 9×10^4 simulations (see Supplementary Material), configured to be in good agreement with the range of projections of global mean surface warming and SLR from the Climate Model Intercomparison Project phase 5 (CMIP5) ensemble [12] following the SimHist ensemble therein. While the projection ranges of warming, SLR and the thermal expansion contribution to SLR are in close agreement between the WASP and CMIP5 ensembles across scenarios ranging from high end RCP8.5 to significantly mitigated RCP2.6 [12], the WASP model is computationally efficient. Here, we utilise this computational efficiency to produce new ensemble projections for scenarios representing climate stabilisation at politically-agreed targets, and compare these climate stabilisation levels to an unmitigated scenario.

Three future scenarios are considered (as described in the Supplementary Material): (1) RCP8.5 [18] representing unmitigated emission under business as usual (Fig. 1, red), (2) stabilisation at 2.0°C warming (Fig. 1, blue), and (3) stabilisation at 1.5^{o}C warming (Fig. 1, grey), consistent with the Paris Agreement (Fig. 1a).

The WASP ensemble projected trajectories of surface warming, SLR and surface ocean pH are shown in Fig. 1 for the three scenarios with key results listed in Table 1. The uncertainty in future warming projections for RCP8.5 (Fig. 1a, red) reflects the uncertainty in the equilibrium climate sensitivity and uncertainty in the transient response of the climate system, with the WASP ensemble showing similar projection ranges to the CMIP5 projections [12]. For the 1.5°C and 2.0°C stabilisation scenarios (Fig. 1a, grey and blue), the uncertainty in warming prior to 2100 reflects the uncertainty in how quickly the stabilisation targets will be reached. After 2100, the uncertainty in warming decreases as the carbon emissions in the numerical experiments are tuned in each ensemble member to ensure that the stabilisation target warming is followed. The stabilisation scenarios both reach their target warming levels, while the high-end RCP8.5 continues to warm past 2100 due to significant ongoing emissions, reaching 5.5°C to 14.8°C warming above preindustrial by 2300 (Table 1). It should be noted that while the warming and SLR projections from the WASP ensembles are historically tuned to give similar ranges to the CMIP5 ensemble-based AR5 projections (see Supplementary Material and [12]), there are additional uncertainties not included within our projections (Fig. 1). In particular, historically unprecedented processes are not considered. This could include sudden future ice-sheet collapse or future warming exceeding expectations due to non-linear feedbacks, such as accelerated methane release from warming permafrost. If these processes occurred, higher rises in sea level would be a likely consequence.

The range of future SLR projections in the WASP ensemble of simulations (Fig. 1b) reflect the uncertainty in the cryospheric response to future warming, uncertainty in the ocean heat uptake response to future warming and uncertainty in the simulated future warming itself. For the stabilisation scenarios, some simulations see an overshoot of the warming target during the 21st century while others never exceed the stabilisation (Fig. 1a, grey and blue shaded). This temperature history has an impact on the SLR projections: projected SLR at year 2100 is correlated with simulated warming at 2035 (which is when the maximum range of temperatures occurs across the ensemble before stabilisation later in the 21st century) with a coefficient of determination (R^2) of 0.19: the simulations with the larger warming overshoot above 1.5°C in 2035 tend to have larger SLR at 2100 than those with less overshoot (Fig. 1a and 1b grey). This is consistent with SLR being more related to the time integral of warming than the instantaneous warming at any particular time. However, the majority of the variation in the ensemble SLR projections for a specific warming target arises from variation in the model sensitivities of SLR to warming. This suggests that more SLR should be expected for scenarios with warming overshoot, but that the effect is less than the total uncertainty in SLR due to the sensitivities of the cryosphere and ocean heat uptake to surface warming. For RCP8.5, the WASP ensemble ranges agree well with the CMIP5 projections [12].

For the 1.5°C and 2.0°C scenarios, SLR continues despite the ensemble-median temperature stabilising in the mid 21st Century. By 2100, projected SLR is 0.39 ± 0.09m and 0.49 ± 0.10m under 1.5^{o}C and 2.0°C stabilisation, respectively. There is a large overlap between the two stabilisation scenarios, indicating a lack of climate sensitivity due to the commitment to SLR. By 2300, SLR is projected at 0.89 ± 0.23m and 1.17 ± 0.29m for the 1.5°C and 2.0°C scenario, respectively, and the benefits of stronger mitigation are more apparent. Compared with the unmitigated RCP8.5 scenario, median SLR in 2300 is reduced by 2.76m (75%) and 2.48m (68%) under 2.0^{o}C and 1.5°C stabilisation, respectively. Expressed as a linear rate of SLR from 2100 to 2300, the median changes are 2.5mm/yr, 3.4mm/yr and 14.7mm/yr under the three scenarios, respectively. At the 95th percentile, the RCP8.5 could exceed 20 mm/yr, seven times faster than satellite observations of SLR during the early 21st Century [3].

The range of projected changes in surface ocean pH in the WASP ensembles for the 1.5°C and 2.0°C scenarios reflects the uncertainty in the future atmospheric CO_2 trajectory compatible with each stabilisation target (Fig. 1c, grey and blue). For RCP8.5 there are prescribed CO_2 concentrations resulting in limited range in terms of surface ocean pH (Fig. 1c, red). The preindustrial surface ocean pH in the WASP model is 8.2, and this decreases to 8.1 by the early 21st century (Fig. 1c) as atmospheric CO_2 increases and dissolves in the surface ocean as inorganic carbon. For stabilisation at 1.5°C, projected surface ocean pH declines to 8.08 ± 0.04 in 2100 and to 8.09 ± 0.04 by 2300. For stabilisation at 2.0°C, projected surface ocean pH declines to 8.02 ± 0.06 in 2100 and to 8.04 ± 0.06 in 2300. Under the RCP8.5, surface ocean pH declines to 7.75 ± 0.01 by 2100 and 7.45 by year 2300. Hence, the benefits of stabilisation in terms of reducing the surface ocean pH change are dramatic. Relative to RCP8.5, stabilisation at 1.5°C and 2.0°C reduce the change in surface ocean pH from preindustrial by 73% and 60% by year 2100, and by 85% and 79% by year 2300, respectively.

For the temperature stabilisation pathways, the uncertainty in our projections of surface ocean pH and SLR increase with time. Our projections with WASP assume that climate sensitivity is constant in time. However, century scale feedbacks can alter the climate sensitivity [19], and may affect the CO_2 concentration and projected surface ocean pH for a given climate stabilisation target beyond year 2100. Our SLR projections beyond year 2100 assume a smooth path towards the eventual equilibrium SLR for a given climate stabilisation. However, some processes may occur relatively suddenly, such as ice-sheet collapse [3], and this adds additional uncertainty to SLR beyond year 2100 that is not encapsulated within the WASP model projections.

3. Impacts of sea-level rise under climate stabilisation

SLR has a range of impacts on coastal areas, including: (1) increased coastal flooding and inundation; (2) coastal morphodynamic changes, especially erosion; (3) ecosystem changes such as wetland change and loss; and (4) hydrological and salinisation effects in coastal surface and ground waters [20–22]. There is a complex interplay between these factors and morphodynamic and ecosystem change can influence coastal flooding, for example. In this analysis, we mainly focus on the potential of coastal flooding and inundation as the impacts could be dramatic [23]. Importantly, SLR is not occurring in isolation and multiple climate and non-climate drivers are shaping coastal areas [24], although the magnitude of these drivers varies significantly in space. Some key examples are population growth, urbanisation, changing sediment supply and land uplift/subsidence, resulting from natural (i.e. glacial isostatic adjustment) and anthropogenic subsidence (due to ground fluid extraction) processes [25, 26]. Hence, it is important to set SLR and climate change in this broader context. Coastal adaptation is also critical to consider as this can greatly reduce impacts [23, 27, 28], and protection already allows large populations to remain in locations that would otherwise be highly hazardous, such as the western Netherlands [29] and parts of China's coastal lowlands [30].

3.1 Global Coastal Flood Impacts

To analyse the possible benefits of stabilisation in terms of reduced coastal flooding, the three global-mean SLR scenarios shown in Fig. 1 were assessed at a global scale using the Dynamic Interactive

Vulnerability Assessment modelling framework (DIVA, version model 2.0.1, database 32) (see Supplementary Material). Storm characteristics are assumed constant and erosion is not considered – changes in both these factors may enhance the impacts presented. Expected number of people flooded per year is used as an impact indicator. To address uncertainty, the 5th, 50th and 95th percentiles of the sea-level projections were considered, together with the five Shared Socioeconomic Pathways (SSP), which reflect a range of future population and economic conditions to 2100 [31, 32]. Beyond 2100, a stable population and population distribution is assumed, following the impact assessment community convention [33] and the results are indicative. Adaptation in the base year was represented by protection in the form of sea dikes, estimated following a demand-for-safety function where safety (and dike height) mainly vary with population density and wealth [23]. Dikes are initialised in 1995 with no subsequent upgrade so that the impacts (and adaptation needs) due to SLR are apparent.

Fig. 2(a) illustrates the expected number of people flooded annually around the coasts to 2300 under these assumptions. Absolute impacts grow with time under all scenarios, but this growth is slower under climate stabilisation. Reduced impacts are apparent during the 21st Century, and this reduction grows in the 22nd and 23rd centuries. Fig. 2(b) shows that 1.5^{o}C stabilisation (grey) has a greater relative reduction in impacts than 2.0^{o}C stabilisation (blue). The range overlaps at first and separates in the later 22nd Century. The mean reduction in impacts is 60% and 72% in 2100, and 36% and 43% in 2300, respectively, compared to the RCP8.5 scenario. The absolute growth in impacts means that while stabilisation avoids significant impacts, coastal risk still grows progressively under both climate stabilisation scenarios to 2300. Hence, total risk can only be maintained at current levels with significant adaptation in addition to climate stabilisation.

The effects on small islands, deltas and coastal cities are examined in more detail below.

3.2 Small Island Developing States

Globally, there are more than 50 Small Island Developing States (SIDS) and many more small islands which are highlighted to be at high risk from climate change in multiple Intergovernmental Panel on Climate Change (IPCC) reports (e.g. [34, 35]). In the Paris Agreement, SIDS are mentioned on five occasions and noted as being "particularly vulnerable" due to their "significant capacity constraints". This is particularly acute as many islands are variously remote (e.g. Marshall Islands), geographically dispersed (e.g. Federated States of Micronesia), poorly developed (e.g. Haiti), lack a skills base, and/or low-lying (e.g. Maldives) [36].

Climate change will affect SIDS through multiple factors, including SLR, oceanic warming, changing cyclones and changes to precipitation and temperature patterns [35]. Higher sea levels and wind-driven water levels are anticipated to increase flooding and erosion, plus increase the likelihood of salinisation of freshwater resources [37]. Low island nations such as the Maldives, Kiribati, Tuvalu and Turks and Caicos Islands are particularly threatened. Significant shoreline changes are observed on small islands, but it is difficult to attribute these to SLR (e.g. [38, 39]). Even islands which are not low in elevation (e.g. Grenada, Seychelles, Fiji) are threaten as infrastructure is concentrated at low elevations close to the coast (e.g., [40]). Indeed, 50% of Caribbean and Pacific islanders live within 1.5km of the coast [41]. With many islands relying on tourism, sustaining this industry is a major concern.

Some scientists paint a bleak prospect for small islands under SLR, with the recent loss of entire islands in the Solomon Islands being considered indicative of their wider future [42]. Other scientists are more optimistic and consider that coral islands may grow with SLR [43–45]. For example, [46] mapped Pacific islands from 1897 to 2013 and found a net gain in land, despite SLR. This suggests that some islands may cope with slow SLR if left to accrete naturally. Such accretion can take various forms, including vertical accretion due to overtopping waves and/or horizontal accretion as new sediment welds to islands. Developed islands which are constrained by coastal defences may be less able to accrete. An example of this is Malé, Maldives (average height 1m above mean sea level and surrounded by dead reef, limiting new coral-derived sediment supply). Here, SLR poses a serious threat when considered alongside energetic swell waves which periodically cause flooding [47]. The RCP8.5 SLR scenario threatens Malé this century, while SLR associated with 1.5°C and 2.0°C pose a significant threat by 2300.

Climate stabilisation offers substantial benefit to small islands, buying time to adapt to SLR, including possible relocation, upgraded defence or even artificial raised island construction [48]. The reduction in coastal ecosystem impacts due to stabilisation discussed in Section 4 offers substantial but unquantified benefits sustaining island livelihoods and the wider environment, including allowing natural accretion. SIDS need help and time to build the capacity to plan and finance adaptation. Migration is seen as the final adaptation option for many low-lying islands in the face of SLR [49] and longer term planning is being considered by several island nations in the form of land purchases or other arrangements [49, 50]. Migration in islands is already a widespread practise (e.g. Vunidogoloa, Fiji [51]; Guna, Panama, [52]; the Maldives [53]), reflecting multiple social, economic, and developmental drivers. Planning for SLR and changing environmental conditions must be considered in light of these broader issues.

3.3 Deltas

Unlike small islands, deltas are not specifically mentioned in the Paris Agreement, but they are also highly vulnerable with large flood plains containing much larger populations. Deltas in mid and low latitudes provide homes to about 500 million people worldwide [54] with a concentration in south, south-east and east Asia [55]. These deltas are experiencing rapid environmental change reflecting changes in the catchments, such as reduced sediment flux due to dams, and within the deltas themselves due to changes such as urbanisation and flood defence. Deltas naturally subside due to sediment compaction and crustal loading, and this is widely enhanced by oxidation due to drainage and sub-surface fluid withdrawal. This subsidence adds significantly to relative SLR in deltas [56]. [57] estimated present mean subsidence of 3.6 mm/yr across a sample of 46 major deltas worldwide, with a range of 22 mm/yr subsidence in the Indus delta, Pakistan to land surface rise in the Krishna delta, India reflecting sediment aggregation. As a result, significant land areas in many deltas are already below normal high tides and depend on defences and drainage to be habitable [58]. Therefore, deltaic areas are highly vulnerable to climate change and SLR [54, 57]. Stabilising sea level will not stop non-climate factors, and deltas will continue to change in a hypothetical stable climate, including experiencing relative SLR due to subsidence, as occurred in the Rhine delta, the Netherlands over the last millennia [29].

Given the multiple interacting processes shaping deltas, it is difficult to diagnose the effect of a single driver such as climate-induced SLR, or climate change as a whole (e.g., climate-induced changes in run-off from the associated catchment). Further, the process of determining the relative importance of these effects can be frustrated by the moderating effects of human activity within the delta. Taking the Ganges-Brahmaputra delta in Bangladesh as an example these include changing upstream land use and catchment regulation (dams and barrages) [59, 60]; extensive land cover change in the delta, including extensive polder systems which regulate hydrology and sediment flux and the creation of extensive shrimp farms; and regional and local subsidence [61], with over one metre local loss of elevation in many polders due to drainage, oxidation and consolidation [62]. These in turn have had profound morphodynamic and hydrodynamic consequences such as reducing flow and encouraging channel siltation, which are only now being recognised (e.g., [63]). In comparison to observed climate-induced SLR to date, these anthropogenic influences dominate observed changes here and in many other populated deltas. An extreme example is the Nile where the sediment supply that produced the delta has been almost totally removed due to a large single dam on the main river (at Aswan) [64].

Figure S1 shows the reduction in relative SLR to 2100 as a function of stabilisation and subsidence. For a hypothetical no subsidence case, stabilisation at 2.0^{o}C and 1.5^{o}C avoids 33% to 47% of the relative rise, respectively, while for a uniform subsidence of 6 mm/yr, the reduction in relative SLR is only 18% to 25%. (Note that much higher rates of subsidence exceeding 10 mm/yr are observed in some coastal cities on deltas [65], but this is not considered here).

As with small islands, climate stabilisation will reduce impacts in deltas, but climate-induced SLR continues, and is compounded and maybe dwarfed by non-climate changes as listed above. Again long-term adaptation and planning needs to be considered in deltas, with examples emerging such as the draft Bangladesh Delta Plan 2100 [66]. In the face of SLR and subsidence, deltas management has three fundamental choices: (1) retreat; (2) protect (e.g., replicate the strategy adopted by the Netherlands); or (3) build elevation (with sedimentation). Innovative management regimes are being considered in terms of working with nature and promoting sedimentation in the Mississippi and Ganges-Brahmaputra deltas [67, 68]. This approach is in its infancy, but provides deltas with a sustainable option against SLR and subsidence, assuming that upstream sediment supplies are sustained. Climate stabilisation means that such adaptation strategies are more likely to be successful.

3.4 Coastal Cities

Coastal urbanisation has been a defining feature of the world's coast through the 20th and early 21st century. In 2005 there were 136 coastal cities with more than one million people and a total population of 400 million people [69]. While coastal cities continue to grow in size and in number, there are expectations that unmitigated SLR will lead to their widespread abandonment (e.g., [70, 71]), reinforced by widely reproduced media images [72]. However, based on empirical experience many cities have adapted to both extreme events and significant relative SLR (i.e. subsidence), and such adaptation seems feasible over the coming decades [27].

Here, we follow [27] and estimate required dike heights as an indicator of stabilisation benefits across 136 coastal cities (see Supplementary Material) for median SLR under our three scenarios. The projected dike heights only become distinct after 2100 (Fig. 3). By 2300, the dike heights under the unmitigated (RCP8.5) scenario (red) are more than 2 m higher than under the stabilisation scenarios, with a commitment to further raising beyond 2300. Population in the flood plain increases through time, with the differences across scenarios being small to 2050 and larger thereafter. Hence, defence failure would affect larger numbers of people and increase impacts: this would become increasingly catastrophic with time, especially under the unmitigated scenario.

There is limited analysis of the implications of large magnitudes of SLR on individual coastal cities, with a few cities such as Amsterdam, New York and London being exceptions. The Thames Estuary 2100 (TE2100) Project considers the adaptation options and related issues against up to 5 m of SLR

[73, 74]. It takes an explicit adaptation pathways approach. This recognises that adaptation will be a process comprising a series of upgrades into the future, rather than a single decision, and the required magnitude of each upgrade is uncertain [75]. The focus of the TE2100 Project was to 2100, but the analysis can be applied to post-2100 change. According to our analysis, by 2300 SLR of more than 2.5 m occurs for the RCP8.5 scenario across the 5th to 95th percentile range, which means that one viable protection option is available: a new downstream barrage (or a major retreat). In contrast, under both stabilisation scenarios a much wider range of options are available to 2300. Hence, the availability of the TE2100 analysis informs adaptation for London beyond 2100, including for the SLR scenarios considered here.

4. Coastal ecological effects under climate stabilisation

In contrast to the SLR effects already discussed, ecological effects of climate change are more complex to define because they reflect the interdependencies between multiple climate drivers, biotic and environmental context, and anthropogenic activity [76]. Species must adapt to rising CO_2 whilst simultaneously acclimatising to shifts in environmental conditions, including sea surface temperature (SST) rise and SLR that operate over longer timescales, and exhibit considerable spatial variation [14, 77–79]. In addition, ecosystems are open and may interact with adjacent ecosystems [80]. Such complexities are difficult to anticipate across the spectra of future scenarios and the severity and direction of ecosystem response can depend on timing and local context [14, 38]. Whilst climate-related impacts are already being detected in some coastal marine ecosystems (e.g. regime shifts, [81]), understanding of key thresholds above natural variability in coastal marine ecosystems is limited [82]. Seagrasses, for example, when exposed to plausible near-future climatic conditions, exhibit higher rates of photosynthesis, carbon fixation and growth. Such growth enhancement, however, compromises the plants biomechanical properties, increasing long-term vulnerability to storm conditions and compromising protective functions [83]. Similarly, the response of a species to a particular ensemble of climatic conditions can depend on life stage or physiological condition, which are seldom assessed [84], or on uncertain changes in biotic interactions [85]. Hence, understanding ecological responses under climate change is a major challenge [86], not least because the linkages between the projections of SST rise, SLR, acidification and the biological community are insufficiently constrained. Most relevant experimental investigations only consider one or two climatic variables, although more sophisticated experimental designs are being developed [87]. Most importantly, the basic science about the effects of warming between 1.5°C to 2°C has received little attention [88, 89]. These are not a linear function of temperature rise [14, 90], precluding extrapolation and interpretation of the climate scenarios produced in this paper. Further, species and ecosystem responses integrate multiple drivers of change [37, 91], increasing the risk of negative ecosystem responses [92]. Estimates of species and ecosystem vulnerability tend to focus on large-change scenarios such as RCP8.5 in 2100 and a limited range of drivers (e.g. [93–95]), rather than expected climate change in the coming decades [96] or anticipated changes in species composition, interaction and behaviour following acclimation and/or adaptation to novel circumstances [97].

Limited evidence is available, but several studies [95, 98–100] suggest that large benefits will accrue for coastal ecosystems if global warming is stabilised at or below 2°C, although most available analyses exceed 1.5°C before 2100. As noted in Section 3.2, atolls may be able to keep pace with SLR, but the interdependencies that exist between neighbouring habitats, such as coral reefs, seagrass and mangroves [80] mean that impacts are unlikely to be avoided, especially in low lying areas [4]. Whilst some species appear to be resilient to moderate levels of pH reduction and warming [101, 102], the fate of others, such as reef building corals, is not yet clear [78, 103], but see [104, 105].

Increases in temperature and precipitation extremes [106, 107] are likely to be sufficient to cause functionally important shifts in habitat type (e.g. algal to coral dominated reefs [108]) and/or lead to local or regional mass mortality [109]. Similarly, SLR has the potential to increase flood frequency in tropical coastal habitats [110, 111] and generate substantive saltmarsh degradation and/or loss if not compensated by accretion [46], whilst elevated atmospheric [CO_2] may enhance plant growth [112] but impair soil microbial community structure [113]. As the interplay between these and other interacting factors, including those not related to a changing climate (e.g. [114]), can be important in determining ecosystem response, there remains considerable uncertainty in projecting the most likely coastal ecological effects under climate stabilisation.

5. Discussion

The analysis presented here emphasises the different timescales by which stringent climate mitigation leading to temperature stabilisation affects coastal areas. Climate variables linked to temperature and greenhouse emissions, such as SST and ocean pH, can be stabilised over the timescale of about a century. Changes to other relevant climate variables for coasts, such as the characteristics of tropical and extratropical cyclones, which depend on surface and atmospheric temperature, are likely to behave similarly. Further pH and SST stabilisation avoids significant, but not all, coastal ecosystem impacts. However, this is poorly quantified reflecting scientific uncertainty, including a lack of understanding of how different climate and non-climate drivers might interact.

In contrast, the timescale of SLR is much longer and while slowed, SLR continues for at least three centuries under both 1.5^{o}C and 2.0^{o}C stabilisation. (A hypothetical global cooling would be required to stabilize sea level [115] more quickly.) For example, our median estimate of global SLR by year 2100 for RCP8.5 is 0.72m, relative to the 1986-2005 average. This rise occurs 65 years later for stabilisation at 2.0°C and 130 years later for stabilisation at 1.5°C. Hence, many 21st Century impacts are delayed rather than avoided with mitigation and SLR remains a long-term challenge under greenhouse gas and temperature stabilisation.

The simulations in this paper project that large rises in sea level of up to 5 m by 2300 might occur under RCP8.5, which could be further increased by potential processes not included in our model such as rapid future collapse of the Greenland ice sheet. Such large sea level rise will fundamentally change the world's coast, eroding or submerging coastal areas, except for those areas where natural systems have sufficient sediment supplies to compensate for SLR and/or where humans choose to protect. While protection is technically feasible and likely to occur in many urban areas following current practise, provision of such adaptation raises questions of delivery, maintenance, governance and ultimately residual risk – the consequences of any failure would often be catastrophic, and could dwarf the consequences of recent disasters, such as Hurricane Katrina's impact on New Orleans [27]. Climate stabilisation reduces these challenges and gives substantially more time to adapt to the SLR that does occur. This includes natural adjustments such as wetland and atoll accretion, as well as human adaptation.

This analysis reinforces the earlier IPCC conclusions that the best societal response to SLR is climate change mitigation to reduce SLR to manageable levels, and adaptation in response to the residual unavoidable rise [4, 116]. As already noted, median global rises in sea level for 1.5^{o}C and 2.0^{o}C stabilisation by 2300 are about 0.9 m and 1.2 m, respectively. Without adaptation, these changes are of concern to populated and economically important low-lying areas in SIDs explicitly mentioned in the Paris Agreement, as well as small islands in general, deltas and coastal cities as considered here.

However, over these long timescales, adaptation is feasible and essential as SLR cannot be avoided. A stronger message of the need for long-term preparation and planning for SLR is required. The adaptation pathways approach, as exemplified by the Thames Estuary 2100 project for London, could be adapted and followed more widely around the world's developed coasts to prepare for this change including the uncertainties [75, 117]. Such analysis allows recognition of when problems might emerge, what the potential solutions are, and how they might be integrated with wider plans for coastal development. Such adaptation will be a multi-step process over many decades and longer [118]. In locations society wishes to protect, the approach of building elevation as opposed to building dikes is worthy of more consideration, as this addresses the fundamental issue of growing residual risk. For example, Singapore will raise all new land claim to allow for SLR and other low-lying areas as redevelopment allows [119]. Urban areas in small islands require particular attention as their options under rising sea levels are most limited.

Our projections of SLR represent one model (tuned to emulate the AR5 projections deriving from the CMIP5 ensemble [12]), and hence are consistent with the AR5 SLR scenarios [20]. We note earlier studies [120, 121] using semi-empirical models estimated higher rises in sea level by 2300 for 2^{o}C stabilisation. We also recognise the potential role of physical processes that have not yet been observed or that are not fully understood which might increase SLR projections, especially under the unmitigated case. As climate science develops so the approach used here can be repeated, re-evaluating our results.

One of the main benefits of lower long-term temperature goals is the reduced likelihood of irreversible deglaciation of the large-ice sheets. Some authors suggest we may be close to or have even crossed such thresholds for the Greenland [122] and Antarctica ice sheets [123]. This highlights the need to continue investigations of SLR and its different components both with and without climate stabilisation. This should be combined with monitoring of SLR.

The Paris Agreement [9] signalled a transformational political change in greatly limiting temperature rise. Does 1.5^{o}C stabilisation offer coastal areas distinct outcomes to 2.0^{o}C stabilisation? The range of resulting SLR scenarios still partially overlap in 2300, although 2.0^{o}C stabilisation has higher rises, and resulting impacts and adaptation needs. Understanding the difference between these two futures also requires consideration of the feasibility of adaptation for SLR and non-climate changes such as subsidence in deltas. Nonetheless, both climate stabilisation scenarios show a large reduction in potential impacts as opposed to the unmitigated RCP8.5 scenario, and the avoided impacts grow with time. Hence, the results clearly show that even with stringent mitigation, society will also need ongoing adaptation to SLR in coastal areas to avoid significant damage.

6. Conclusions

This contribution has considered the effect and implications of stringent climate stabilisation scenarios for coastal areas in terms of reduction of impacts/adaptation needs to 2300. This is a longer timescale than earlier analyses. Simulations of climate stabilisation to 1.5^{o}C and 2.0^{o}C show that ocean pH and temperature stabilise within a century. This means that significant coastal ecosystem impacts are avoided, but detailed quantification is not possible with current understanding. More systematic scientific investigation of these changes would be useful. In contrast, sea-level rise is only slowed compared to unmitigated emissions and continues to 2300 (and beyond). Hence, while coastal impacts due to sea-level rise are reduced by climate stabilisation, the potential impacts continue to grow for at least several centuries. Importantly, sea-level rise under stabilisation in 2300 exceeds unmitigated sea-level rise in 2100, raising concerns for vulnerable areas such as small islands, deltas and coastal cities. Hence, consideration of adaptation to sea-level rise remains essential under both the climate stabilisation scenarios considered here. The best societal response to sea-level rise is climate change mitigation to reduce the rise to manageable levels, and adaptation in response to the residual unavoidable rise. Given the long timescale of the issue, linking adaptation with wider coastal development planning has strong merits. As adaptation will involve multiple steps, exploration of adaptation pathways would be an appropriate approach to guide such planning.

The implications of climate mitigation leading to atmospheric temperature stabilisation for sea-level rise is in need of more recognition and assessment. The physics that lead to the commitment to sea-level rise were reported in the first IPCC Assessment [124] and again in the third IPCC Assessment [125]. Then the impact and adaptation implications were discussed in the fourth and fifth IPCC Assessments [4, 116]. Nonetheless, the climate policy process has continued to focus on temperature mitigation as if it was a universal solution to human-induced climate change. As this paper demonstrates in more detail than earlier assessments, for sea-level rise this is not the case and the policy process needs to consider the implications of this fundamental physical constraint. While this paper has focussed on 1.5ºC and 2.0ºC stabilisation, this conclusion is true for sea-level rise under any temperature stabilisation scenario.

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Data Accessibility
The datasets supporting this article have been uploaded as part of the Supplementary Material.

Competing Interests
We have no competing interests.

Authors' Contributions
RN and SB designed and wrote the bulk of the paper, PG and IH conducted the climate simulations,

TW conducted the coastal city analysis, JL contributed on climate science and science-policy links, MS and JG drafted the coastal ecosystems section, DL JH, CW and JM contributed to the global coastal flood analysis.

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Figures:

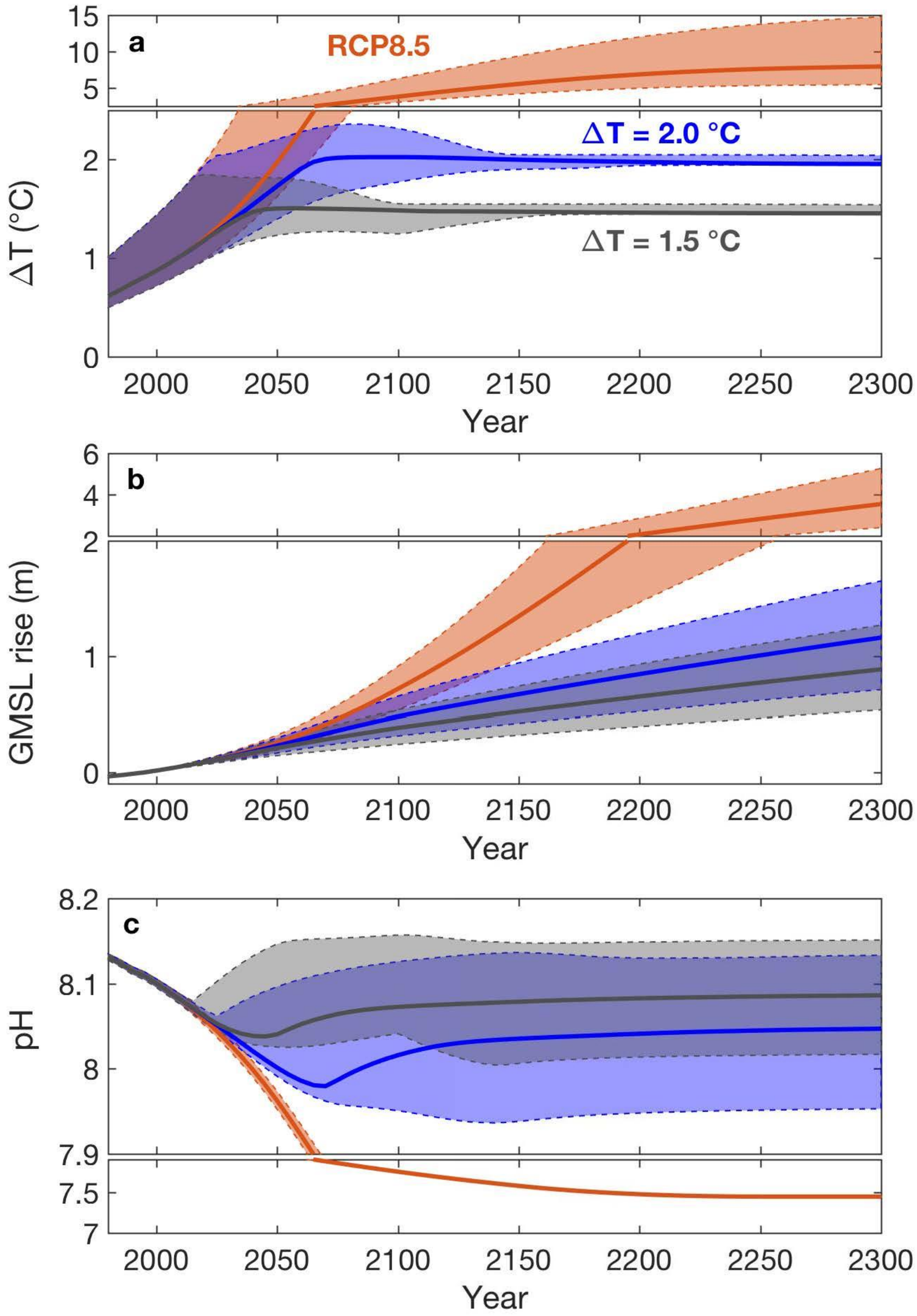

Figure 1. Future temperature rise, sea level and surface ocean pH projections to 2300 for a large (9 x 10^4) ensemble using the WASP Earth System Model. (a) Global temperature anomaly relative to pre-industrial, ΔT (°C), (b) Global Mean-Sea Level rise relative to 1986-2005 (m), and (c) surface ocean

pH. The median ensemble projections over time (lines) and the 90% ranges within the ensemble simulations (shaded areas, from the 5th to 95th percentiles) are shown for RCP8.5 (red) and 2.0°C (blue) and 1.5°C (grey) stabilisation scenarios.

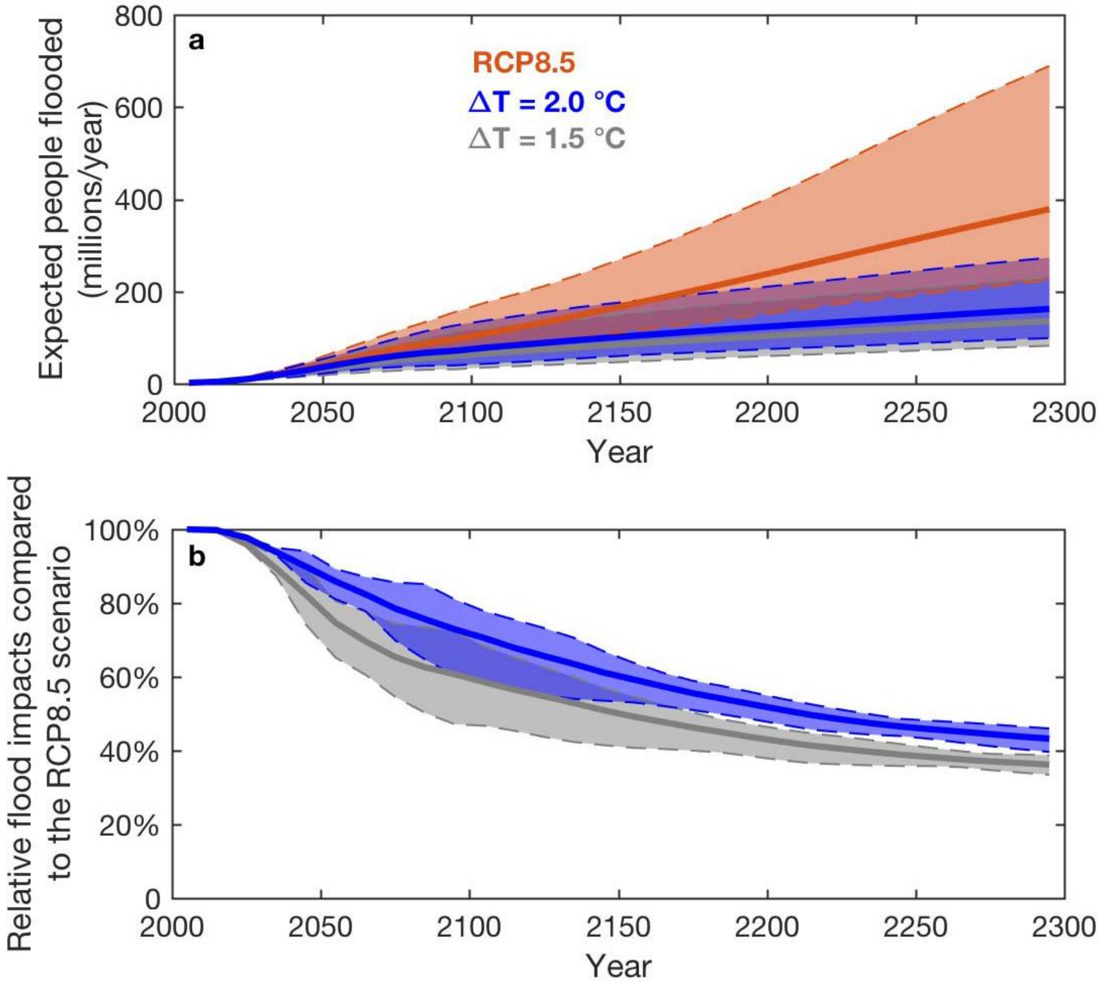

Figure 2. Climate stabilisation and global coastal flooding. (a) Expected number of people flooded (millions/yr.) versus time from 2000 to 2300 for stabilisation and unmitigated sea-level rise scenarios across all socio-economic scenarios for each emissions pathway. (b) Relative comparison of impacts under stabilisation, showing the percentage of impact, normalised by unmitigated (RCP8.5) impacts for the same socio-economic scenario. In both cases, this assumes no adaptation (i.e. dike upgrade) and the numbers are indicators, not projections. The mean ensemble projections over time (lines) and the range are shown for RCP8.5 (red) and 2.0°C (blue) and 1.5°C (grey) stabilisation scenarios.

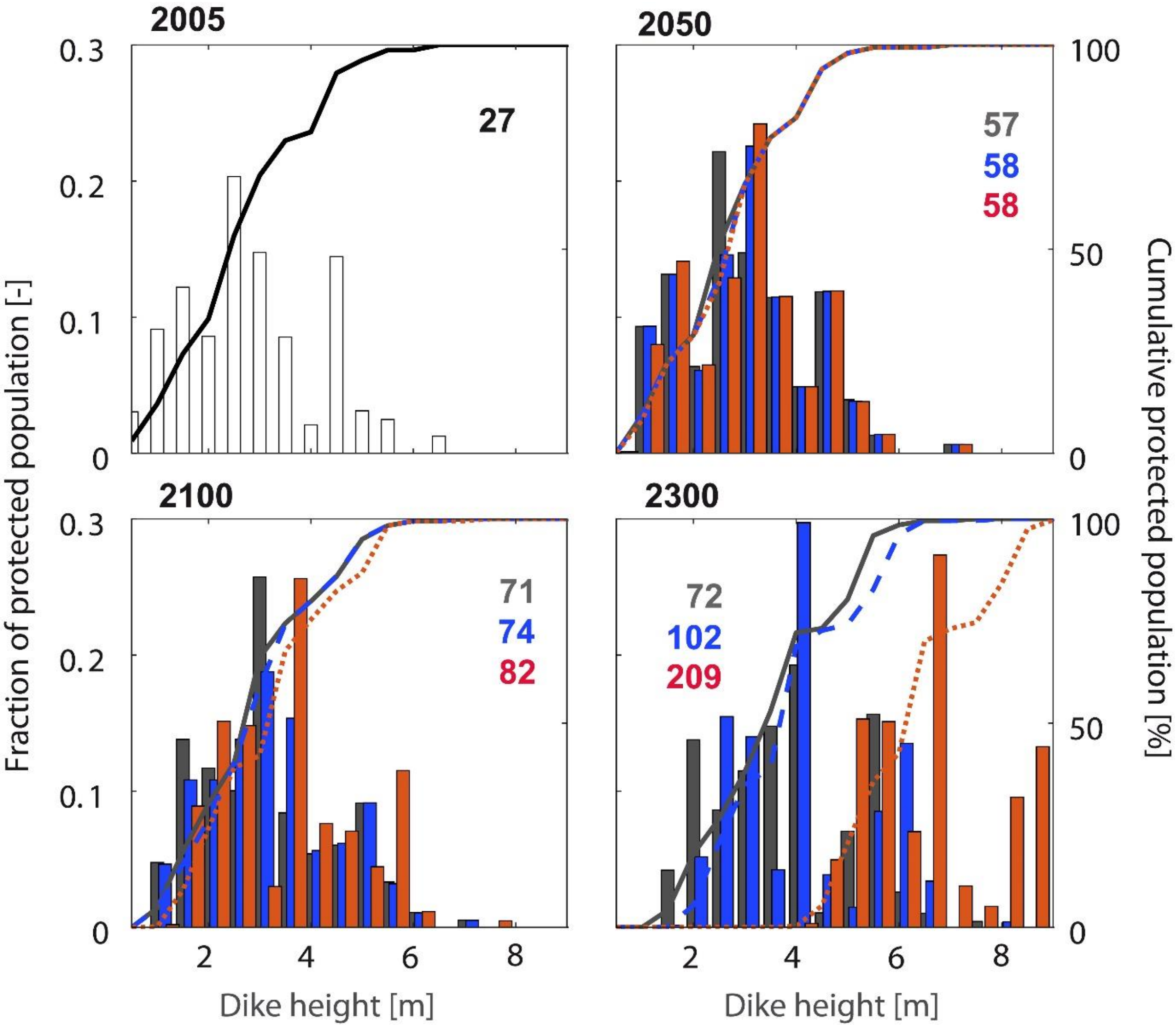

Figure 3. Estimates of the dike heights required to protect the major coastal cities under the three median climate scenarios from 2005 to 2300 (red: RCP8.5; blue: 2^{o}C; grey: 1.5^{o}C). The bars show the fraction of the floodplain population protected by the respective dike height while the lines show cumulative population. The numbers in the panels are cumulative number of people protected (in millions).

Tables:

Table 1. Summary results of the WASP Earth System Model for global mean temperature, global mean sea-level rise and ocean pH and the two stabilisation scenarios (1.5^{o}C and 2.0^{o}C) and the reference unmitigated (RCP8.5) emissions scenario. Results include the ensemble mean ± standard deviation and the 90% range (5th to 95th percentiles) in brackets.

Time	Global mean temperature (relative to pre-industrial) (^{o}C)			Sea-level rise (relative to 1986-2005 average) (m)			Ocean pH		
	1.5^{o}C	2.0^{o}C	RCP8.5	1.5^{o}C	2.0^{o}C	RCP8.5	1.5^{o}C	2.0^{o}C	RCP8.5
1986-2005	0.8±0.2 (0.7-1.3)			0.0			8.11±0.00 (8.10-8.11)		

2050	1.5 ± 0.2 (1.2-1.8)	1.8 ± 0.3 (1.4-2.2)	2.1 ± 0.5 (1.6-3.2)	0.21 ± 0.04 (0.14-0.28)	0.23 ± 0.04 (0.17-0.30)	0.26 ± 0.04 (0.19-0.32)	8.06 ± 0.04 (8.03-8.15)	8.01 ± 0.04 (7.97-8.11)	7.96 ± 0.01 (7.95-7.97)
2100	1.5±0.1 (1.2-1.6)	2.0±0.2 (1.8-2.3)	4.1 ± 1.0 (3.0-6.3)	0.39 ± 0.09 (0.24-0.54)	0.49 ± 0.10 (0.31-0.65)	0.72 ± 0.11 (0.54-0.91)	8.08 ± 0.04 (8.04 - 8.16)	8.02 ± 0.06 (7.95-8.13)	7.75 ± 0.01 (7.74-7.76)
2300	1.5±0.1 (1.4-1.5)	2.0±0.1 (1.9-2.0)	8.8±3.1 (5.5-14.8)	0.89 ± 0.23 (0.53-1.27)	1.17 ± 0.29 (0.71-1.65)	3.65±0.89 (2.40-5.27)	8.09 ± 0.04 (8.02 - 8.15)	8.04 ± 0.06 (7.95 – 8.13)	7.45±0.00 (7.74-7.75)

Figure Captions:

Figure 1. Future temperature rise, sea level and surface ocean pH projections to 2300 for a large (9 x 10^4) ensemble using the WASP Earth System Model. (a) Global temperature anomaly relative to pre-industrial, ΔT (°C), (b) Global Mean-Sea Level rise relative to 1986-2005 (m), and (c) surface ocean pH. The median ensemble projections over time (lines) and the 90% ranges within the ensemble simulations (shaded areas, from the 5th to 95th percentiles) are shown for RCP8.5 (red) and 2.0°C (blue) and 1.5°C (grey) stabilisation scenarios.

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Supplementary material

Methods

Warming Acidification and Sea-level Projector (WASP) Earth system model

The Warming Acidification and Sea-level Projector (WASP) Earth system model is a computationally efficient 8-box representation of the Earth system that is used for large ensemble simulations with varying parameter values [1]. WASP uses a hybrid method for projecting global-mean sea-level rise, with a mechanistic representation of sea-level rise due to ocean thermal expansion (the thermosteric contribution) combined with a semi-empirical representation of sea-level rise due to ice melt (the ice-melt contribution).

Following the methodology of [1]; see *SimHist* ensemble therein) WASP is used to run 10-million simulations with different model-parameter value combinations from years 1765 to 2012. Each simulation is checked for historical consistency to the range of simulations within the Climate Model Intercomparison Project phase 5 (CMIP5) ensemble. Only about 9×10^4 simulations, from the initial 10-million simulations, are consistent with the CMIP5 historical ensemble. The model-parameter values for these simulations are then used to make future projections out to the year 2300.

Historic CO_2 and radiative forcing is applied to the WASP model ensemble, starting in year 1765, followed by three future scenarios (Fig. 1): (1) RCP8.5 [2] representing unmitigated emission under business as usual (Fig. 1, red), (2) stabilisation at 2.0ºC warming (Fig. 1, blue), and (3) stabilisation at 1.5ºC warming (Fig. 1, grey), consistent with the Paris Agreement. The stabilisation scenarios follow RCP scenarios until the warming stabilisation target is crossed (RCP4.5 and RCP2.6 for the 2.0ºC and 1.5ºC stabilisation, respectively), and thereafter the annual carbon emissions are adjusted to maintain warming at the stabilisation target (Fig. 1a).

The thermosteric and ice-melt contributions to sea-level rise are simulated in WASP following Goodwin et al. (2017) [1] to year 2100. The thermosteric contribution is calculated from simulated ocean heat uptake after [3], while the ice-melt contribution is calculated using a semi-empirical approach [4] tuned to match the historic CMIP5 ensemble simulated ranges (see [1]). Beyond the year 2100, the ice-melt contribution per unit warming is assumed to slow over time with an exponential decay such that total ice-melt contribution to sea-level rise at equilibrium is equal to 2.3 m K^{-1} temperature anomaly [5]. The contribution to sea-level rise from changes in land-water storage is included up to the year 2100 (after [1]), using the projection ranges of [5] for land-water storage, and thereafter no land-water storage changes are considered to 2300 (Fig. 1b). The WASP model also projects the global-characteristic surface ocean pH over time for the three scenarios (Fig. 1c), calculating the change from the initial model pre-industrial surface ocean pH of 8.2 based on the Dissolved Inorganic Carbon increase in the surface ocean due to anthropogenic carbon uptake.

The Dynamic Interactive Vulnerability Assessment (DIVA) Model

DIVA is an integrated bio-geophysical coastal systems model driven by climate change and socio-economic development [6]. Climate change is represented by sea-level rise and other relevant climate factors such as storm characteristics are assumed to remain constant with time. Only the intersection of coastal topography and extreme sea levels, plus the modifying effect of defences, is considered when estimating flooding. Any erosion due to sea-level rise is not considered. The world's coast (excluding Antarctica) is represented by 12,148 linear coastal segments that have similar bio-physical and socio-ecological characteristics, and this is the basis for the analysis. For each coastal segment, global-mean sea-level rise derived from the WASP model as described above is downscaled to relative sea-level rise using estimates of segment-scale vertical land uplift or subsidence. These simulations consider vertical land movement due to isostatic effects [7] and enhanced subsidence in deltas to provide estimates of relative sea-level rise. Subsidence in 39 deltas was extracted from [8], with subsidence of 2mm/yr assumed as an average change in a further 77 deltas that are known to be subsiding. It is assumed that these vertical land movements continue at the same rate until 2300. Next, present extreme sea-level events (based on [9]) are adjusted by the magnitude of relative sea-level rise to determine flood levels over time. Hence, the land threatened by coastal flooding due to extreme sea levels can be defined assuming a planar water surface. The distribution of land elevation is derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model [10] and above 60°N and 60°S from the GTOPO30 dataset [11]. To calculate the people exposed to coastal flooding, the Global Rural Urban Mapping Project (GRUMPv1) dataset was employed [12, 13].

Future conditions are derived from sea-level rise scenarios (explained in the main text and under WASP in the supplementary material) and socio-economic scenarios which describe national changes in population and wealth. In this analysis, the five Shared Socioeconomic Pathways (SSPs) are considered [14, 15]. These reflect a range of potential and contrasting future population and economic conditions to 2100 and as a sensitivity analysis all of these scenarios are analysed. Population growth and decline assumes that changes follow the existing population distribution in each nation. Beyond 2100, a stable population is assumed for comparability following an agreement of the impact assessment community [16] and the 2100 population distribution is fixed to year 2300.

In addition, adaptation is explicitly considered in DIVA. In this analysis, adaptation is represented by protection in the form of sea dikes. These are estimated following a demand-for-safety function where safety (and dike height) increases with population density and wealth [17] (see also [6]). In this analysis, the dikes are initialised in 1995 and we assume no further upgrade so that the impacts (and any adaptation needs) due to SLR are apparent.
The output of the analysis is an estimate of risk – the expected annual population flooded. Given the assumptions made, especially the assumption of no adaptation and the very long time frame of the analysis, this parameter should be interpreted as an impact indicator rather than a projection of impacts. An increase in risk can be interpreted as an indicator of a demand for adaptation, as much as it can be interpreted as an indicator of impacts. Autonomous processes such as migration due to high flood frequency are not considered.

Coastal City Defence Heights and Protected Population

For the analysis, we extracted the following information from the database that was developed by [18] for the world's 136 largest coastal cities: population distribution for different elevation levels in 2005, protection standards for all cities, and population growth scenarios by country for 2050 and 2100 from the Organisation for Economic Co-operation and Development (OECD). Country population scenarios were translated into city scenarios based on an extrapolation of the country's urbanization rates. Following [18], it is assumed that city population growth has an upper limit of 35 million and in the absence of data we also assume that population and its distribution in 2300 will be the same as in 2100 (i.e., changes in dike heights and exposed population in 2300 compared to 2100 are only due to relative sea-level rise).
Protection standards that are expressed as return periods were translated to protection heights (expressed in meters above mean sea level) using the extreme sea-level data set developed by [9], which assumes that extreme events follow a Gumbel distribution. For adaptation during this century we assume that constant flood probability will be retained, which means that protection heights increase linearly with sea-level rise. For the long-range projection of 2300 it is assumed that all cities have upgraded to a protection standard equivalent to the 1,000-year still water level (i.e., events with 0.1% chance of occurrence in any given year).
We then use the relative sea-level rise scenarios, derived from the WASP model along with land uplift/subsidence rates (as described above under the DIVA model), and calculate the height of the flood defences, and the number of people across all 136 cities living in the protected flood plain.

Relative sea-level rise analysis for deltas

Figure S1 shows the reduction in relative sea-level rise in hypothetical deltas to 2100 as a function of the sea-level rise scenarios calculated by the WASP model in Section 2 and plausible rates of subsidence as observed in deltas over the last 50 years [8, 19, 20]. The delta subsidence is assumed to continue linearly from 2000 to 2100. For the low bounding case, no subsidence, stabilisation at 2.0ºC and 1.5ºC avoids 33% and 47% of the relative rise, respectively. For the high bounding case, 10 mm/yr, the corresponding reduction in relative sea-level rise is only 14 to 19%, respectively. Intermediate cases of 3 mm/yr and 6 mm/yr are also presented.

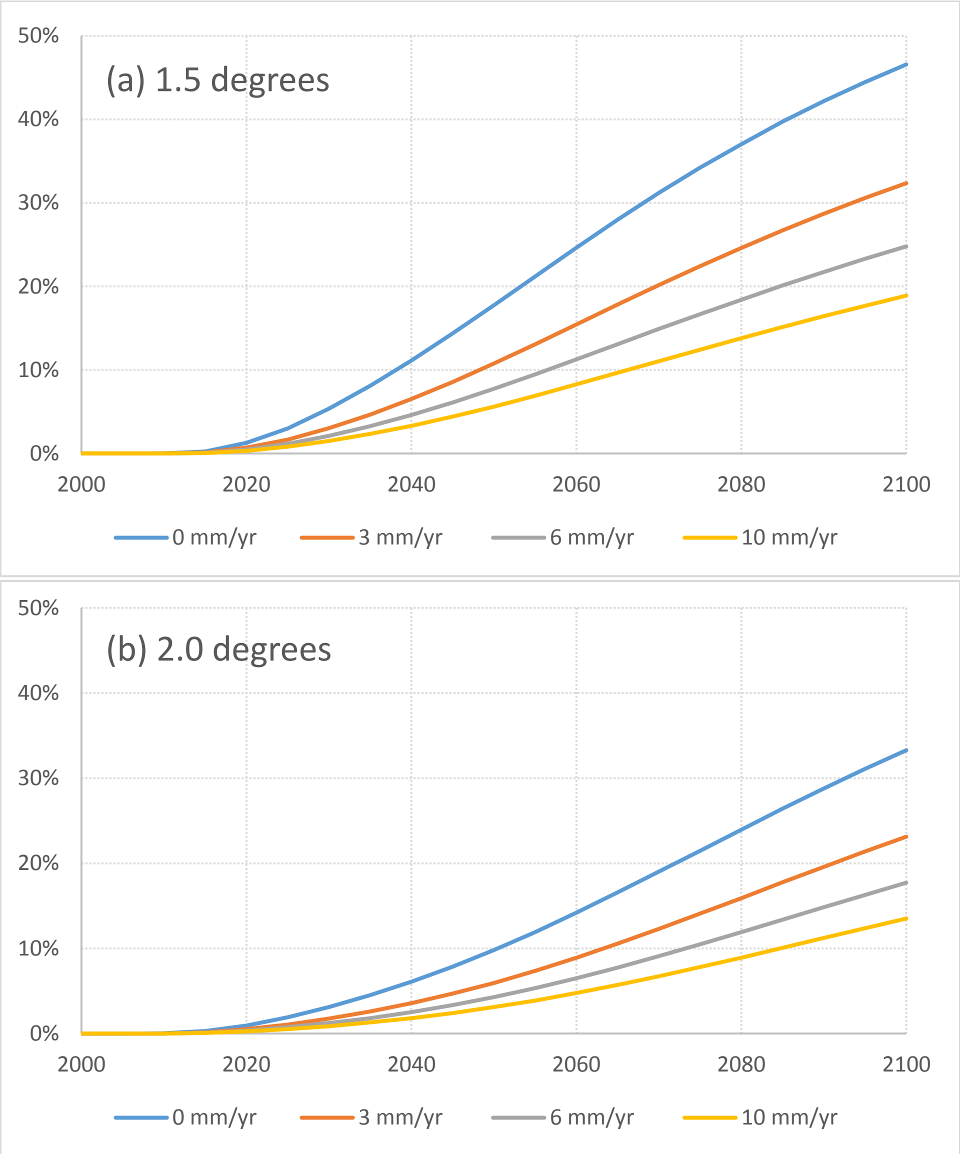

Figure S1. Reduction in relative sea-level rise in a hypothetical subsiding delta from the years 2000 to 2100 given climate stabilisation at (a) 1.5°C and (b) 2.0°C relative to the RCP8.5 scenario. Contrasting plausible subsidence rates are considered from 0 to 10 mm/yr.

Data

The datasets supporting this article have been uploaded as part of the Supplementary Material.

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