

Research



Cite this article: Nicholls RJ *et al.* 2018
Stabilization of global temperature at 1.5°C
and 2.0°C: implications for coastal areas. *Phil.
Trans. R. Soc. A* **376**: 20160448.
<http://dx.doi.org/10.1098/rsta.2016.0448>

Accepted: 5 February 2018

One contribution of 20 to a theme issue ‘The Paris Agreement: understanding the physical and social challenges for a warming world of 1.5°C above pre-industrial levels’.

Subject Areas:

climatology, oceanography, civil engineering, environmental engineering

Keywords:

sea-level rise, ocean pH, climate mitigation, climate adaptation, coastal impacts

Author for correspondence:

Robert J. Nicholls
e-mail: r.j.nicholls@soton.ac.uk

Electronic supplementary material is available online at <https://dx.doi.org/10.6084/m9.figshare.c.4010371>.

Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas

Robert J. Nicholls¹, Sally Brown¹, Philip Goodwin³, Thomas Wahl⁴, Jason Lowe^{5,6}, Martin Solan³, Jasmin A. Godbold^{2,3}, Ivan D. Haigh³, Daniel Lincke⁷, Jochen Hinkel⁷, Claudia Wolff⁸ and Jan-Ludolf Merken⁸

¹Faculty of Engineering and the Environment, and ²Biological Sciences, University of Southampton, Highfield, Southampton SO17 1BJ, UK

³Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton SO14 3ZH, UK


⁴Civil, Environmental, and Construction Engineering and National Center for Integrated Coastal Research, University of Central Florida, 12800 Pegasus Drive, Orlando, FL 32816-2450, USA

⁵Reading Unit, Met Office Hadley Centre, University of Reading, Reading, UK

⁶Priestley International Centre for Climate, University of Leeds, Leeds, UK

⁷Global Climate Forum, Neue Promenade 6, 10178 Berlin, Germany

⁸Geographisches Institut, Christian-Albrechts-Universität zu Kiel, Ludewig-Meyn-Strasse 14, 24098 Kiel, Germany

 RJN, 0000-0002-9715-1109; PG, 0000-0002-2575-8948; TW, 0000-0003-3643-5463; JL, 0000-0002-8201-3926; MS, 0000-0001-9924-5574; JAG, 0000-0001-5558-8188; IDH, 0000-0002-9722-3061; DL, 0000-0003-4250-5077; JH, 0000-0001-7590-992X

The effectiveness of stringent climate stabilization 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 (SLR) and ocean pH projections to 2300 for 1.5°C and 2.0°C stabilization 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 stabilization scenarios, global mean ocean pH (and temperature) stabilize within a century. This implies significant ecosystem impacts are avoided, but detailed quantification is lacking, reflecting scientific uncertainty. By contrast, SLR is only slowed and continues to 2300 (and beyond). Hence, while coastal impacts due to SLR are reduced significantly by climate stabilization, especially after 2100, potential impacts continue to grow for centuries. SLR in 2300 under both stabilization scenarios exceeds unmitigated SLR in 2100. Therefore, adaptation remains essential in densely populated and economically important coastal areas under climate stabilization. Given the multiple adaptation steps that this will require, an adaptation pathways approach has merits for coastal areas.

This article is part of the theme issue 'The Paris Agreement: understanding the physical and social challenges for a warming world of 1.5°C above pre-industrial levels'.

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 stabilization. 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 island developing states (SIDS) who feel especially threatened by this aspect of climate change [10].

Hence this paper has two aims (i) to analyse the potential changes in coastal areas, including impacts and adaptation needs, under stringent stabilization targets relative to an unmitigated scenario and (ii) to consider the implications of such stabilization for the future of coastal areas, including adaptation and management policy. This includes a brief consideration of ecological effects that are anticipated for coastal systems under climate change and climate stabilization. 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 stabilization at 1.5°C and 2.0°C 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 stabilization 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 CO₂ 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]. By 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 stabilization and unmitigated cases, and the resulting projections of SLR and ocean pH are analysed (§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 (§3). Third, we consider the coastal ecological effects of stabilized and unmitigated climate change (§4). Finally, the implications of these results are discussed, including climate and coastal policy implications (§5).

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

A warming of global surface temperatures leads directly to global mean SLR from two main processes: (i) ice melt—the cryosphere adds additional water to the ocean—and (ii) thermosteric changes—warming of ocean waters leads to thermal expansion. Both these processes will continue for many centuries after a rise and stabilization 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 in 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 the electronic 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 use this computational efficiency to produce new ensemble projections for scenarios representing climate stabilization at politically agreed targets and compare these climate stabilization levels to an unmitigated scenario.

Three future scenarios are considered (as described in the electronic supplementary material): (i) RCP8.5 [18] representing unmitigated emission under business as usual (figure 1, red), (ii) stabilization at 2.0°C warming (figure 1, blue) and (iii) stabilization at 1.5°C warming (figure 1, grey), consistent with the Paris Agreement (figure 1*a*).

The WASP ensemble projected trajectories of surface warming, SLR and surface ocean pH are shown in figure 1 for the three scenarios with key results listed in table 1. The uncertainty in future warming projections for RCP8.5 (figure 1*a*, 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 stabilization scenarios (figure 1*a*, grey and blue), the uncertainty in warming prior to 2100 reflects the uncertainty in how quickly the stabilization 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 stabilization target warming is followed. The stabilization 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–14.8°C warming above pre-industrial by 2300 (table 1). It should be noted that while the warming

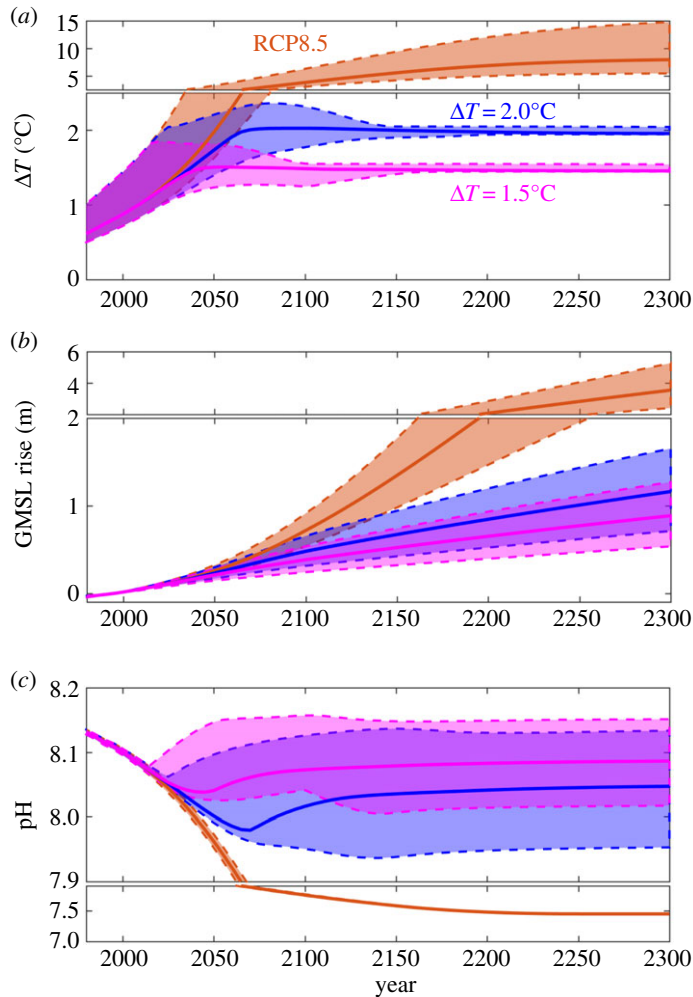


Figure 1. Future temperature rise, sea level and surface ocean pH projections to 2300 for a large (9×10^4) ensemble using the WASP Earth system model. (a) Global temperature anomaly relative to pre-industrial, ΔT ($^{\circ}\text{C}$), (b) global mean sea-level (GMSL) rise relative to 1986–2005 (m) and (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 $^{\circ}\text{C}$ (blue) and 1.5 $^{\circ}\text{C}$ (grey) stabilization scenarios.

and SLR projections from the WASP ensembles are historically tuned to give similar ranges to the CMIP5 ensemble-based AR5 projections (see electronic supplementary material and [12]), there are additional uncertainties not included within our projections (figure 1). In particular, historically unprecedented processes are not considered. This could include sudden future ice-sheet collapse or future warming exceeding expectations due to nonlinear 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 (figure 1*b*) reflects 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 stabilization scenarios, some simulations see an overshoot of the warming target during the twenty-first century while others never exceed the stabilization (figure 1*a*, 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

Table 1. Summary results of the WASP Earth system model for global mean temperature, global mean SLR and ocean pH and the two stabilization scenarios (1.5°C and 2.0°C) and the reference unmitigated (RCP8.5) emissions scenario. Results include the ensemble mean \pm s.d. and the 90% range (5th to 95th percentiles) in parentheses.

time	global mean temperature (relative to pre-industrial) (°C)		SLR (relative to 1986–2005 average) (m)		ocean pH		
	1.5°C	2.0°C	RCP8.5	1.5°C	2.0°C	1.5°C	2.0°C
1986–2005	0.8 \pm 0.2 (0.7–1.3)			0.0		8.11 \pm 0.00 (8.10–8.11)	
2050	1.5 \pm 0.2 (1.2–1.8)	1.8 \pm 0.3 (1.4–2.2)	2.1 \pm 0.5 (1.6–3.2)	0.21 \pm 0.04 (0.14–0.28)	0.23 \pm 0.04 (0.17–0.30)	8.06 \pm 0.04 (8.03–8.15)	8.01 \pm 0.04 (7.97–8.11)
2100	1.5 \pm 0.1 (1.2–1.6)	2.0 \pm 0.2 (1.8–2.3)	4.1 \pm 1.0 (3.0–6.3)	0.39 \pm 0.09 (0.24–0.54)	0.49 \pm 0.10 (0.31–0.65)	8.08 \pm 0.04 (8.04–8.16)	8.02 \pm 0.06 (7.95–8.13)
2300	1.5 \pm 0.1 (1.4–1.5)	2.0 \pm 0.1 (1.9–2.0)	8.8 \pm 3.1 (5.5–14.8)	0.89 \pm 0.23 (0.53–1.27)	1.17 \pm 0.29 (0.71–1.65)	8.09 \pm 0.04 (8.02–8.15)	8.04 \pm 0.06 (7.95–8.13)

occurs across the ensemble before stabilization later in the twenty-first 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 (figure 1a,b 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 stabilizing in the mid-twenty-first century. By 2100, projected SLR is 0.39 ± 0.09 m and 0.49 ± 0.10 m under 1.5°C and 2.0°C stabilization, respectively. There is a large overlap between the two stabilization scenarios, indicating a lack of climate sensitivity due to the commitment to SLR. By 2300, SLR is projected at 0.89 ± 0.23 m and 1.17 ± 0.29 m for the 1.5°C and 2.0°C scenarios, respectively, and the benefits of stronger mitigation are more apparent. Compared with the unmitigated RCP8.5 scenario, median SLR in 2300 is reduced by 2.76 m (75%) and 2.48 m (68%) under 2.0°C and 1.5°C stabilization, respectively. Expressed as a linear rate of SLR from 2100 to 2300, the median changes are 2.5 mm yr^{-1} , 3.4 mm yr^{-1} and 14.7 mm yr^{-1} under the three scenarios, respectively. At the 95th percentile, the RCP8.5 could exceed 20 mm yr^{-1} , seven times faster than satellite observations of SLR during the early twenty-first 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 CO₂ trajectory compatible with each stabilization target (figure 1c, grey and blue). For RCP8.5 there are prescribed CO₂ concentrations resulting in limited range in terms of surface ocean pH (figure 1c, red). The pre-industrial surface ocean pH in the WASP model is 8.2, and this decreases to 8.1 by the early twenty-first century (figure 1c) as atmospheric CO₂ increases and dissolves in the surface ocean as inorganic carbon. For stabilization 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 stabilization 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 2300. Hence, the benefits of stabilization in terms of reducing the surface ocean pH change are dramatic. Relative to RCP8.5, stabilization at 1.5°C and 2.0°C reduces the change in surface ocean pH from pre-industrial by 73% and 60% by year 2100, and by 85% and 79% by year 2300, respectively.

For the temperature stabilization pathways, the uncertainties 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 CO₂ concentration and projected surface ocean pH for a given climate stabilization target beyond year 2100. Our SLR projections beyond year 2100 assume a smooth path towards the eventual equilibrium SLR for a given climate stabilization. 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 stabilization

SLR has a range of impacts on coastal areas, including (i) increased coastal flooding and inundation; (ii) coastal morphodynamic changes, especially erosion; (iii) ecosystem changes such as wetland change and loss; and (iv) hydrological and salinization 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, urbanization, 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].

(a) Global coastal flood impacts

To analyse the possible benefits of stabilization in terms of reduced coastal flooding, the three global mean SLR scenarios shown in figure 1 were assessed at a global scale using the Dynamic Interactive Vulnerability Assessment modelling framework (DIVA, v. model 2.0.1, database 32) (see electronic 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 socio-economic pathways, which reflect a range of future population and economic conditions to 2100 [31,32]. Beyond 2100, a stable population and population distribution are 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 initialized in 1995 with no subsequent upgrade so that the impacts (and adaptation needs) due to SLR are apparent.

Figure 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 stabilization. Reduced impacts are apparent during the twenty-first century, and this reduction grows in the twenty-second and twenty-third centuries. Figure 2*b* shows that 1.5°C stabilization (grey) has a greater relative reduction in impacts than 2.0°C stabilization (blue). The range overlaps at first and separates in the later twenty-second century. The mean impacts relative to the unmitigated RCP8.5 scenario are 60% and 72% in 2100, and 36% and 43% in 2300, respectively. The absolute growth in impacts means that while stabilization avoids significant impacts, coastal risk still grows progressively under both climate stabilization scenarios to 2300. Hence, total risk can only be maintained at current levels with significant adaptation in addition to climate stabilization.

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

(b) Small island developing states

Globally, there are more than 50 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 in 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 salinization 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 threatened as

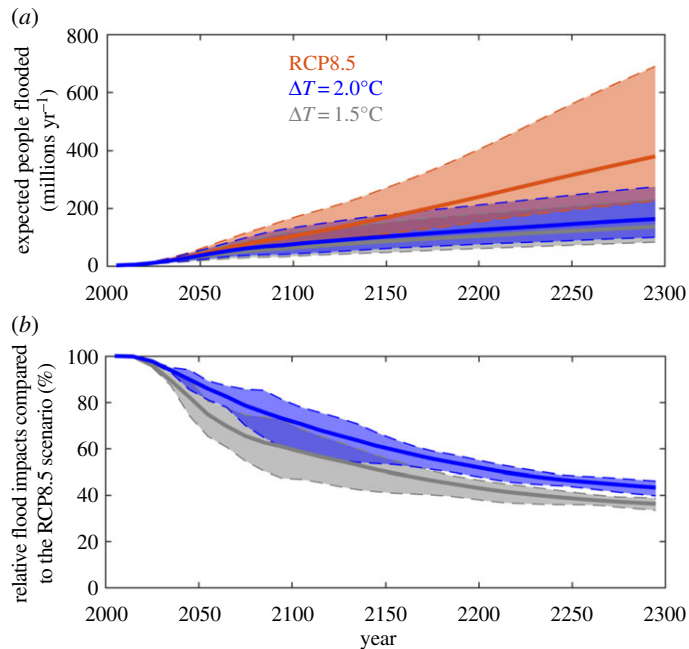


Figure 2. Climate stabilization and global coastal flooding. (a) Expected number of people flooded (millions yr⁻¹) versus time from 2000 to 2300 for stabilization and unmitigated SLR scenarios across all socio-economic scenarios for each emissions pathway. (b) Relative comparison of impacts under stabilization, showing the percentage of impact, normalized 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) stabilization scenarios.

infrastructure is concentrated at low elevations close to the coast (e.g. [40]). Indeed, 50% of Caribbean and Pacific Islanders live within 1.5 km 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, Kench *et al.* [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 1 m a.m.s.l. 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 poses a significant threat by 2300.

Climate stabilization 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 stabilization discussed in §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 practice (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 the light of these broader issues.

(c) Deltas

Unlike small islands, deltas are not specifically mentioned in the Paris Agreement, but they are also highly vulnerable to large floodplains containing much larger populations. Deltas in mid and low latitudes provide homes to about 500 million people worldwide [54] with a concentration in south, southeast 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 urbanization 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] with estimated present mean subsidence of 3.6 mm yr^{-1} across a sample of 46 major deltas worldwide, with a range of 22 mm yr^{-1} 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]. Stabilizing 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 1 m 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 recognized (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].

Electronic supplementary material, figure S1, shows the reduction in relative SLR to 2100 as a function of stabilization and subsidence. For a hypothetical no subsidence case, stabilization at 2.0°C and 1.5°C avoids 33% to 47% of the relative rise, respectively, while for a uniform subsidence of 6 mm yr^{-1} , the reduction in relative SLR is only 18% to 25%. (Note that much higher rates of subsidence exceeding 10 mm yr^{-1} are observed in some coastal cities on deltas [65], but this is not considered here.)

As with small islands, climate stabilization 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 need to be considered in deltas, with examples emerging such as the draft Bangladesh Delta Plan 2100 [66]. In the face of SLR and subsidence, delta management has three fundamental choices: (i) retreat; (ii) protect (e.g. replicate the strategy adopted by The Netherlands); or (iii) 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 stabilization means that such adaptation strategies are more likely to be successful.

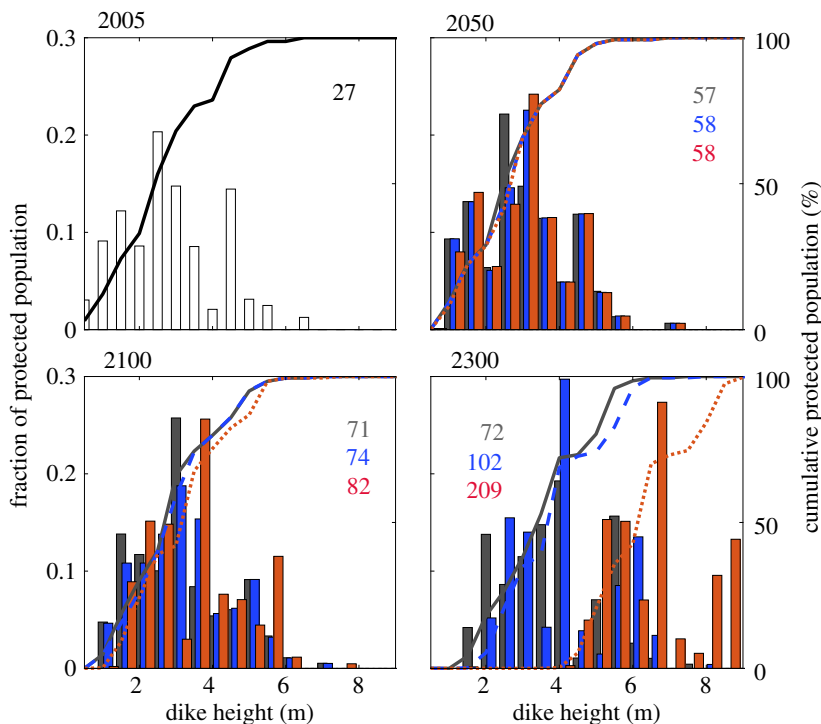


Figure 3. Estimates of the dike heights required to protect the major coastal cities under the three median climate scenarios from 2005 to 2300 (red: RCP8.5; blue: 2°C; grey: 1.5°C). The bars show the fraction of the floodplain population protected by the respective dike height while the lines show cumulative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

(d) Coastal cities

Coastal urbanization has been a defining feature of the world's coast through the twentieth and early twenty-first century. In 2005, there were 136 coastal cities with more than 1 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 stabilization benefits across 136 coastal cities (see electronic supplementary material) for median SLR under our three scenarios. The projected dike heights only become distinct after 2100 (figure 3). By 2300, the dike heights under the unmitigated (RCP8.5) scenario (red) are more than 2 m higher than under the stabilization scenarios, with a commitment to further raising beyond 2300. Population in the floodplain 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 recognizes 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). By contrast, under both stabilization 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 stabilization

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 CO₂ while simultaneously acclimatizing 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]. While 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 and 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 stabilized at or below 2°C, although most available analyses exceed 1.5°C before 2100. As noted in §3b, 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]. While 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], while elevated atmospheric [CO₂] 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 stabilization.

5. Discussion

The analysis presented here emphasizes the different timescales by which stringent climate mitigation leading to temperature stabilization affects coastal areas. Climate variables linked to temperature and greenhouse emissions, such as SST and ocean pH, can be stabilized over the timescale of about a century. Changes in 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 stabilization 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.

By contrast, the timescale of SLR is much longer and while slowed, SLR continues for at least three centuries under both 1.5°C and 2.0°C stabilization. (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 0.72 m, relative to the 1986–2005 average. This rise occurs 65 years later for stabilization at 2.0°C and 130 years later for stabilization at 1.5°C. Hence, many twenty-first century impacts are delayed rather than avoided with mitigation and SLR remains a long-term challenge under greenhouse gas and temperature stabilization.

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 SLR 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 practice, 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 stabilization 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°C and 2.0°C stabilization 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 TE2100 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°C stabilization. We also recognize 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 stabilization. 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°C stabilization offer coastal areas distinct outcomes to 2.0°C stabilization? The range of resulting SLR scenarios still partially overlap in 2300, although 2.0°C stabilization 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 stabilization 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. Conclusion

This contribution has considered the effect and implications of stringent climate stabilization 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 stabilization at 1.5°C and 2.0°C show that ocean pH and temperature stabilize 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. By contrast, SLR is only slowed compared to unmitigated emissions and continues to 2300 (and beyond). Hence, while coastal impacts due to SLR are reduced significantly by climate stabilization, especially after 2100, the potential impacts continue to grow for at least several centuries. Importantly, SLR under stabilization in 2300 exceeds unmitigated SLR in 2100, raising concerns for vulnerable areas such as small islands, deltas and coastal cities. Hence, consideration of adaptation to SLR remains essential under both the climate stabilization scenarios considered here. The best societal response to SLR is climate change mitigation to reduce the risk 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 stabilization for SLR are in need of more recognition and assessment. The physics that lead to the commitment to SLR 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 SLR this is not the case and the policy process needs to consider the implications of this fundamental physical constraint. While this paper has focused on 1.5°C and 2.0°C stabilization, this conclusion is true for SLR under any temperature stabilization scenario.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. R.J.N. and S.B. designed and wrote the bulk of the paper, P.G. and I.D.H. conducted the climate simulations, T.W. conducted the coastal city analysis, J.-L.M. contributed on climate science and science–policy links, M.S. and J.A.G. drafted the coastal ecosystems section, D.L., J.H., C.W. and J.-L.M. contributed to the global coastal flood analysis.

Competing interests. We declare we have no competing interests.

Funding. R.J.N., S.B., P.G. and I.D.H. were funded by a joint United Kingdom Natural Environment Research Council and United Kingdom Government Department of Business Energy and Industrial Strategy grant 'ADJUST1.5', numbered NE/P01495X/1. R.J.N. and S.B. were also funded by UK funded Department for Business, Energy and Industrial Strategy through the project 'The implications of global warming of 1.5°C and 2°C'. M.S. and J.A.G. were supported by the Shelf Sea Biogeochemistry programme (SSB WP2, (NE/K001906/1), 2011–2017), jointly funded by the Natural Environment Research Council (NERC) and the Department for Environment, Food and Rural Affairs (Defra). T.W. was supported by NOAA's Climate Program Office, Climate Monitoring Program (grant no. NA17OAR4310158). D.L. and J.H. have received funding from European Union's Horizon 2020 research and innovation programme under grant agreement no. 642018 (GREEN-WIN project). J.-L.M. was funded by the European Commission's Seventh Framework Programme's collaborative project RISES-AM (contract FP7-ENV-2013-two-stage-603396).

Acknowledgements. Five anonymous reviews greatly improved an earlier draft of this paper. Abiy Kebede helped in preparing the manuscript.

References

1. Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ. 2015 Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment. *PLoS ONE* **10**, e0118571. (doi:10.1371/journal.pone.0118571)
2. McGranahan G, Balk D, Anderson B. 2007 The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban.* **19**, 17–37. (doi:10.1177/0956247807076960)
3. Church JA *et al.* 2013 Sea level change. In *Climate change 2013. The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (eds TF Stocker *et al.*). Cambridge, UK: Cambridge University Press.
4. Wong PP, Losada IJ, Gattuso J-P, Hinkel J, Khattabi A, McInnes KL, Saito Y, Sallenger A. 2014 Coastal systems and low-lying areas. In *Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (eds CB Field *et al.*), pp. 361–409. Cambridge, UK: Cambridge University Press.
5. Hoegh-Guldberg O, Bruno JF. 2010 The impact of climate change on the world's marine ecosystems. *Science* **328**, 1523–1528. (doi:10.1126/science.1189930)
6. Nicholls RJ, Lowe JA. 2004 Benefits of mitigation of climate change for coastal areas. *Glob. Environ. Change Hum. Policy Dimen.* **14**, 229–244. (doi:10.1016/j.gloenvcha.2004.04.005)
7. Pardaens AK, Lowe JA, Brown S, Nicholls RJ, de Gusmão D. 2011 Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions. *Geophys. Res. Lett.* **38**, L12604. (doi:10.1029/2011GL047678)
8. Brown S, Nicholls RJ, Pardaens AK, Lowe JA, Tol RSJ, Hinkel J. Submitted. Benefits of climate change mitigation for reducing the impacts of sea-level rise in G-20 countries.
9. United Nations. 2015 Paris Agreement. See http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
10. Ourbak T, Magnan AK. In press. The Paris Agreement and climate change negotiations: small islands, big players. *Reg. Environ. Change*. (doi:10.1007/s10113-017-1262-x)
11. Goodwin P. 2016 How historic simulation-observation discrepancy affects future warming projections in a very large model ensemble. *Clim. Dyn.* **47**, 2219–2233. (doi:10.1007/s00382-015-2960-z)
12. Goodwin P, Haigh ID, Rohling EJ, Slangen A. 2017 A new approach to projecting 21st century sea-level changes and extremes. *Earth's Future* **5**, 240–253. (doi:10.1002/2016ef000508)

13. Shepherd JG. 2012 Geoengineering the climate: an overview and update. *Phil. Trans. R. Soc. A* **370**, 4166–4175. (doi:10.1098/rsta.2012.0186)
14. Godbold JA, Solan M. 2013 Long-term effects of warming and ocean acidification are modified by seasonal variation in species responses and environmental conditions. *Phil. Trans. R. Soc. B* **368**, 20130186. (doi:10.1098/rstb.2013.0186)
15. Williams RG, Goodwin P, Ridgwell A, Woodworth PL. 2012 How warming and steric sea level rise relate to cumulative carbon emissions. *Geophys. Res. Lett.* **39**, L19715. (doi:10.1029/2012GL052771)
16. Levermann A, Clark PU, Marzeion B, Milne GA, Pollard D, Radic V, Robinson A. 2013. The multimillennial sea-level commitment of global warming. *Proc. Natl Acad. Sci. USA* **110**, 13745–13750. (doi:10.1073/pnas.1219414110)
17. Wada Y, Lo M-H, Yeh PJ-F, Reager JT, Famiglietti JS, Wu R-J, Tseng Y-H. 2016 Fate of water pumped from underground and contributions to sea-level rise. *Nat. Clim. Change* **6**, 777–780. (doi:10.1038/nclimate3001)
18. Meinshausen M *et al.* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change* **109**, 213–241. (doi:10.1007/s10584-011-0156-z)
19. Rohling EJ, Marino G, Foster GL, Goodwin PA, von der Heydt AS, Köhler P. 2018 Comparing climate sensitivity, past and present. *Ann. Rev. Mar. Sci.* **10**, 261–288. (doi:10.1146/annurev-marine-121916-063242)
20. Church JA, Woodworth PL, Aarup T, Wilson WS (eds). 2010 *Understanding sea-level rise and variability*. Chichester, UK: Wiley-Blackwell.
21. Gornitz V. 2013 *Rising seas. Past, present, future*. New York, NY: Colombia University Press.
22. Pugh D, Woodworth P. 2014 *Sea-level science. Understanding tides, surges, tsunamis and mean sea-level changes*, 2nd edn. Cambridge, UK: Cambridge University Press.
23. Hinkel J *et al.* 2014 Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl Acad. Sci. USA* **111**, 3292–3297. (doi:10.1073/pnas.1222469111)
24. Valiela I. 2009 *Global coastal change*. London, UK: Wiley-Blackwell.
25. Brown S *et al.* 2014 Shifting perspectives on coastal impacts and adaptation. *Nat. Clim. Change* **4**, 752–755. (doi:10.1038/nclimate2344)
26. Nicholls RJ, Wong PP, Burkett V, Woodroffe CD, Hay J. 2008 Climate change and coastal vulnerability assessment: scenarios for integrated assessment. *Sustainability Sci.* **3**, 89–102. (doi:10.1007/s11625-008-0050-4)
27. Hallegatte S, Green C, Nicholls RJ, Corfee-Morlot J. 2013 Future flood losses in major coastal cities. *Nat. Clim. Change* **3**, 802–806. (doi:10.1038/nclimate1979)
28. Diaz DB. 2016 Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Clim. Change* **137**, 143–156. (doi:10.1007/s10584-016-1675-4)
29. Van Koningsveld M, Mulder JPM, Stive MJF, Vandervalk L, Vanderweck AW. 2008 Living with sea-level rise and climate change: a case study of the Netherlands. *J. Coast. Res.* **24**, 367–379. (doi:10.2112/07A-0010.1)
30. Han M, Hou J, Wu L. 1995 Potential impacts of sea-level rise on China's coastal environment and cities: a national assessment. *J. Coast. Res.* **SI14**, 79–95.
31. Moss RH *et al.* 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756. (doi:10.1038/nature08823)
32. O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP. 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122**, 387–400. (doi:10.1007/s10584-013-0905-2)
33. Frieler K *et al.* 2017 Assessing the impacts of 1.5°C global warming—simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev.* **10**, 4321–4345. (doi:10.5194/gmd-10-4321-2017)
34. Tsyban A, Everett JT, Titus J. 1990 World oceans and coastal zones. In *The IPCC impacts assessment* (eds WJM Tegart, GW Sheldon, DC Griffiths), pp. 6.1–6.28. Canberra, Australia: Australia Government Publishing Service.
35. Nurse LA, McLean RF, Agard J, Briguglio LP, Duvat-Magnan V, Pelesikoti N, Tompkins E, Webb A. 2014 Small islands. In *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (eds VR Barros *et al.*), pp. 1613–1654. Cambridge, UK: Cambridge University Press.

36. Nicholls RJ, Cazenave A. 2010 Sea-level rise and its impact on coastal zones. *Science* **328**, 1517–1520. (doi:10.1126/science.1185782)
37. Storlazzi CD, Elias EPL, Berkowitz P. 2015 Many atolls may be uninhabitable within decades due to climate change. *Sci. Rep.* **5**, 14546. (doi:10.1038/srep14546)
38. Cazenave A, Cozannet GL. 2014 Sea level rise and its coastal impacts. *Earth's Future* **2**, 15–34. (doi:10.1002/2013EF000188)
39. Romine BM, Fletcher CH, Barbee MM, Anderson TR, Frazer LN. 2013 Are beach erosion rates and sea-level rise related in Hawaii? *Glob. Planet. Change* **108**, 149–157. (doi:10.1016/j.gloplacha.2013.06.009)
40. Kumar L, Taylor S. 2015 Exposure of coastal built assets in the South Pacific to climate risks. *Nat. Clim. Change* **5**, 992–996. (doi:10.1038/nclimate2702)
41. Mimura N, Nurse L, McLean RF, Agard J, Briguglio L, Lefale P, Payet R, Sem G. 2007 Small islands. In *Climate change 2007: impacts, adaptation, and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson), pp. 687–716. Cambridge, UK: Cambridge University Press.
42. Albert S, Leon JX, Grinham AR, Church JA, Gibbes BR, Woodroffe CD. 2016 Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environ. Res. Lett.* **11**, 054011. (doi:10.1088/1748-9326/11/5/054011)
43. Beetham E, Kench PS, Popinet S. 2017 Future reef growth can mitigate physical impacts of sea-level rise on atoll islands. *Earth's Future* **5**, 1002–1014. (doi:10.1002/2017EF000589)
44. McLean R, Kench P. 2015 Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdis. Rev. Clim. Change* **6**, 445–463. (doi:10.1002/wcc.350)
45. Webb AP, Kench PS. 2010 The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Glob. Planet. Change* **72**, 234–246. (doi:10.1016/j.gloplacha.2010.05.003)
46. Kench PS, Thompson D, Ford MR, Ogawa H, McLean RF. 2015 Coral islands defy sea-level rise over the past century: records from a central Pacific atoll. *Geology* **43**, 515–518. (doi:10.1130/g36555.1)
47. Wadey M, Brown S, Nicholls RJ, Haigh I. 2017 Coastal flooding in the Maldives: an assessment of historic events and their implications. *Nat. Hazards* **89**, 131–159. (doi:10.1007/s11069-017-2957-5)
48. Jamero ML, Onuki M, Esteban M, Billones-Sensano XK, Tan N, Nellas A, Takagi H, Thao ND, Valenzuela VP. 2017 Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nat. Clim. Change* **7**, 581–586. (doi:10.1038/nclimate3344)
49. Kelman I. 2015 Difficult decisions: migration from small island developing states under climate change. *Earth's Future* **3**, 133–142. (doi:10.1002/2014ef000278)
50. Constable AL. 2017 Climate change and migration in the Pacific: options for Tuvalu and the Marshall Islands. *Reg. Environ. Change* **17**, 1029–1038. (doi:10.1007/s10113-016-1004-5)
51. McNamara KE, des Combes HJ. 2015 Planning for community relocations due to climate change in Fiji. *Int. J. Disaster Risk Sci.* **6**, 315–319. (doi: 10.1007/s13753-015-0065-2)
52. Pressly L. 2017 The island people with a climate change escape plan. See <http://www.bbc.co.uk/news/magazine-41337815>.
53. Speelman LH. 2015 Empirical analysis of migration in small islands: the role of environmental and social factors. Doctoral thesis, University of Southampton, UK.
54. Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck M. 2006 Effective sea-level rise and deltas: causes of change and human dimension implications. *Glob. Planet. Change* **50**, 63–82. (doi:10.1016/j.gloplacha.2005.07.004)
55. Woodroffe CD, Nicholls RJ, Saito Y, Chen Z, Goodbred SL. 2006 Landscape variability and the response of Asian megadeltas to environmental change. In *Global change and integrated coastal management: the Asia-Pacific region* (ed. N Harvey), pp. 277–314. Berlin, Germany: Springer.
56. Syvitski JPM. 2008 Deltas at risk. *Sustainability Sci.* **3**, 23–32. (doi:10.1007/s11625-008-0043-3)
57. Tessler ZD, Vörösmarty CJ, Overeem I, Syvitski JPM. 2018 A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology* **305**, 209–220. (doi:10.1016/j.geomorph.2017.09.040)

58. Syvitski JPM *et al.* 2009 Sinking deltas due to human activities. *Nat. Geosci.* **2**, 681–686. (doi:10.1038/ngeo629)
59. Darby SE, Dunn FE, Nicholls RJ, Rahman M, Ridley L. 2015 A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges-Brahmaputra-Meghna delta. *Environ. Sci. Process. Impacts* **17**, 1587–1600. (doi:10.1039/c5em00252d)
60. Whitehead PG *et al.* 2015 Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: low flow and flood statistics. *Environ. Sci. Process. Impacts* **17**, 1057–1069. (doi:10.1039/c4em00619d)
61. Brown S, Nicholls RJ. 2015 Subsidence and human influences in mega deltas: the case of the Ganges–Brahmaputra–Meghna. *Sci. Total Environ.* **527**, 362–374. (doi:10.1016/j.scitotenv.2015.04.124)
62. Auerbach LW *et al.* 2015 Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nat. Clim. Change* **5**, 153–157. (doi:10.1038/nclimate2472)
63. Pethick J, Orford JD. 2013 Rapid rise in effective sea-level in southwest Bangladesh: its causes and contemporary rates. *Glob. Planet. Change* **111**, 237–245. (doi:10.1016/j.gloplacha.2013.09.019)
64. Stanely DJ, Warne AG. 1993 Sea level and initiation of predynastic culture in the Nile Delta. *Nature* **363**, 435–438. (doi:10.1038/363435a0)
65. Kaneko S, Toyota T. 2011 Long-term urbanization and land subsidence in Asian megacities: an indicators system approach. In *Groundwater and subsurface environments: human impacts in Asian coastal cities* (ed. M Taniguchi), pp. 249–270. Tokyo, Japan: Springer.
66. GED 2017 Bangladesh Delta Plan 2100, draft under expert review. Government of the People’s Republic of Bangladesh, Bangladesh Planning Commission, General Economic Division. See http://www.plancomm.gov.bd/wp-content/uploads/2017/delta_plan/Bangladesh_Delta_Plan_2100_DRAFT.pdf (accessed 21 January 2018).
67. Day J, Kemp GP, Freeman A, Muth DP. 2014 *Perspectives on the restoration of the Mississippi Delta: the once and future delta*. Dordrecht, the Netherlands: Springer.
68. Nowreen S, Jalal MR, Alam Khan MS. 2014 Historical analysis of rationalizing south west coastal polders of Bangladesh. *Water Policy* **16**, 264–279. (doi:10.2166/wp.2013.172)
69. Hanson S, Nicholls R, Ranger N, Hallegatte S, Corfee-Morlot J, Herweijer C, Chateau J. 2011 A global ranking of port cities with high exposure to climate extremes. *Clim. Change* **104**, 89–111. (doi:10.1007/s10584-010-9977-4)
70. Spanger-Siegfried E, Fitzpatrick MF, Dahl K. 2014 *Encroaching tides: how sea level rise and tidal flooding threaten U.S. East and Gulf coast communities over the next 30 years*. Cambridge, MA: Union of Concerned Scientists.
71. Clark PU *et al.* 2016 Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nat. Clim. Change* **6**, 360–369. (doi:10.1038/nclimate2923)
72. Kahn B. 2015 Here are 10 striking images of future sea levels. See <http://www.climatecentral.org/news/images-of-future-sea-levels-19213>.
73. Tarrant O, Sayers P. 2012 Managing flood risk in the Thames Estuary—the development of a long-term robust and flexible strategy. In *Flood risk: planning, design and management of flood defence infrastructure* (ed. P Sayers), pp. 202–326. London, UK: ICE Publishing.
74. Lavery S, Donovan B. 2005 Flood risk management in the Thames Estuary looking ahead 100 years. *Phil. Trans. R. Soc. A* **363**, 1455–1474. (doi:10.1098/rsta.2005.1579)
75. Ranger N, Reeder T, Lowe J. 2013 Addressing ‘deep’ uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO J. Decis. Process.* **1**, 233–262. (doi:10.1007/s40070-013-0014-5)
76. Godbold JA, Hale R, Wood CL, Solan M. 2017 Vulnerability of macronutrients to the concurrent effects of enhanced temperature and atmospheric pCO₂ in representative shelf sea sediment habitats. *Biogeochemistry* **135**, 89–102. (doi:10.1007/s10533-017-0340-y)
77. Boyd PW, Cornwall CE, Davison A, Doney SC, Fourquez M, Hurd CL, Lima ID, McMinn A. 2016 Biological responses to environmental heterogeneity under future ocean conditions. *Glob. Change Biol.* **22**, 2633–2650. (doi: 10.1111/gcb.13287)
78. van Hooidonk R, Maynard J, Tاملander J, Gove J, Ahmadi G, Raymundo L, Williams G, Heron SF, Planes S. 2016 Local-scale projections of coral reef futures and implications of the Paris Agreement. *Sci. Rep.* **6**, 39666. (doi:10.1038/srep39666)

79. Calosi P, Melatunan S, Turner LM, Artioli Y, Davidson RL, Byrne JJ, Viant MR, Widdicombe S, Rundle SD. 2017 Regional adaptation defines sensitivity to future ocean acidification. *Nat. Commun.* **8**, 13994. (doi:10.1038/ncomms13994)
80. Saunders MI *et al.* 2014 Interdependency of tropical marine ecosystems in response to climate change. *Nat. Clim. Change* **4**, 724–729. (doi:10.1038/nclimate2274)
81. Wernberg T *et al.* 2016 Climate-driven regime shift of a temperate marine ecosystem. *Science* **353**, 169–172. (doi:10.1126/science.aad8745)
82. Henson SA, Beaulieu C, Ilyina T, John JG, Long M, Seferian R, Tjiputra J, Sarmiento JL. 2017 Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nat. Commun.* **8**, 14682. (doi:10.1038/ncomms14682)
83. de los Santos CB, Godbold JA, Solan M. 2017 Short-term growth and biomechanical responses of the temperate seagrass *Cymodocea nodosa* to CO₂ enrichment. *Mar. Ecol. Prog. Ser.* **572**, 91–102. (doi:10.3354/meps12153)
84. Cripps G, Lindeque P, Flynn KJ. 2015 Have we been underestimating the effects of ocean acidification in zooplankton? *Glob. Change Biol.* **20**, 3377–3385. (doi:10.1111/gcb.12582)
85. Schile LM, Callaway JC, Suding KN, Kelly NM. 2017 Can community structure track sea-level rise? Stress and competitive controls in tidal wetlands. *Ecol. Evol.* **7**, 1276–1285. (doi:10.1002/ece3.2758)
86. Payne MR *et al.* 2016 Uncertainties in projecting climate-change impacts in marine ecosystems. *ICES J. Mar. Sci.* **73**, 1272–1282. (doi:10.1093/icesjms/fsv231)
87. Pansch A, Winde V, Asmus R, Asmus H. 2016 Tidal benthic mesocosms simulating future climate change scenarios in the field of marine ecology. *Limnol. Oceanogr. Methods* **14**, 257–267. (doi:10.1002/lom3.10086)
88. Anonymous. 2016 The maximum climate ambition needs a firm research backing. *Nature* **537**, 585–586. (doi:10.1038/537585b)
89. Mitchell D, James R, Forster PM, Betts RA, Shiogama H, Allen M. 2016 Realizing the impacts of a 1.5°C warmer world. *Nat. Clim. Change* **6**, 735–737. (doi:10.1038/nclimate3055)
90. Bulling MT, Hicks N, Murray L, Paterson DM, Raffaelli D, White PCL, Solan M. 2010 Marine biodiversity–ecosystem functions under uncertain environmental futures. *Phil. Trans. R. Soc. B* **365**, 2107–2116. (doi:10.1098/rstb.2010.0022)
91. Stuart-Smith RD, Edgar GJ, Barrett NS, Kininmonth SJ, Bates AE. 2015 Thermal biases and vulnerability to warming in the world’s marine fauna. *Nature* **528**, 88–92. (doi:10.1038/nature16144)
92. Kroeker KJ, Kordas RL, Crim RN, Singh GG. 2010 Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* **13**, 1419–1434. (doi:10.1111/j.1461-0248.2010.01518.x)
93. Poloczanska ES *et al.* 2013 Global imprint of climate change on marine life. *Nat. Clim. Change* **3**, 919–925. (doi:10.1038/nclimate1958)
94. Solan M, Whiteley NM. 2016 *Stressors in the marine environment. Physiological and ecological responses; societal implications.* Oxford, UK: Oxford University Press.
95. Cheung WWL, Reygondeau G, Froicher TL. 2016 Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science* **354**, 1591–1594. (doi:10.1126/science.aag2331)
96. Barnett TP, Pierce DW, AchutaRao KM, Gleckler PJ, Santer BD, Gregory JM, Washington WM. 2005 Penetration of human-induced warming into the world’s oceans. *Science* **309**, 284–287. (doi:10.1126/science.1112418)
97. Somero GN. 2010 The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine ‘winners’ and ‘losers’. *J. Exp. Biol.* **213**, 912–920. (doi:10.1242/jeb.037473)
98. Rogelj J *et al.* 2016 Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* **534**, 631–639. (doi:10.1038/nature18307)
99. King AD, Karoly DJ, Henley BJ. 2017 Australian climate extremes at 1.5°C and 2°C of global warming. *Nat. Clim. Change* **7**, 412–416. (doi:10.1038/nclimate3296)
100. Schleussner CF *et al.* 2016 Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change* **6**, 827–835. (doi:10.1038/nclimate3096)
101. Schram JB, Schoenrock KM, McClintock JB, Amsler CD, Angus RA. 2016 Testing Antarctic resilience: the effects of elevated seawater temperature and decreased pH on two gastropod species. *ICES J. Mar. Sci.* **73**, 739–752. (doi:10.1093/icesjms/fsv233)

102. Crespo D *et al.* 2017 New climatic targets against global warming: will the maximum 2°C temperature rise affect estuarine benthic communities? *Sci. Rep.* **7**, 3918. (doi:10.1038/s41598-017-04309-0)
103. Frieler K, Meinshausen M, Golly A, Mengel M, Lebek K, Donner SD, Hoegh-Guldberg O. 2013 Limiting global warming to 2°C is unlikely to save most coral reefs. *Nat. Clim. Change* **3**, 165–170. (doi:10.1038/nclimate1674)
104. Howells EJ, Abrego D, Meyer E, Kirk NL, Burt JA. 2016 Host adaptation and unexpected symbiont partners enable reef-building corals to tolerate extreme temperatures. *Glob. Change Biol.* **22**, 2702–2714. (doi:10.1111/gcb.13250)
105. Chakravarti LJ, Beltran VH, van Oppen MJH. 2017 Rapid thermal adaptation in photosymbionts of reef-building corals. *Glob. Change Biol.* **23**, 4675–46688. (doi:10.1111/gcb.13702)
106. Wang ZL, Lin L, Zhang XY, Zhang H, Liu LK, Xu YY. 2017 Scenario dependence of future changes in climate extremes under 1.5°C and 2°C global warming. *Sci. Rep.* **7**, 46432. (doi:10.1038/srep46432)
107. Matthews TKR, Wilby RL, Murphy C. 2017 Communicating the deadly consequences of global warming for human heat stress. *Proc. Natl Acad. Sci. USA* **114**, 3861–3866. (doi:10.1073/pnas.1617526114)
108. Tuckett CA, de Bettignies T, Fromont J, Wernberg T. 2017 Expansion of corals on temperate reefs: direct and indirect effects of marine heatwaves. *Coral Reefs* **36**, 947–956. (doi:10.1007/s00338-017-1586-5)
109. Le Nohaic R *et al.* 2017 Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Sci. Rep.* **7**, 14999. (doi:10.1038/s41598-017-14794-y)
110. Vitousek S, Barnard PL, Fletcher CH, Frazer N, Erikson L, Storlazzi CD. 2017 Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci. Rep.* **7**, 1399. (doi:10.1038/s41598-017-01362-7)
111. Spencer T, Schuerch M, Nicholls RJ, Hinkel J, Lincke D, Vafeidis AT, Reef R, McFadden L, Brown S. 2016 Global coastal wetland change under sea-level rise and related stresses: the DIVA wetland change model. *Glob. Planet. Change* **139**, 15–30. (doi:10.1016/j.gloplacha.2015.12.018)
112. Kirwan ML, Guntenspergen GR, Morris JT. 2009 Latitudinal trends in *Spartina alterniflora* productivity and the response of coastal marshes to global change. *Glob. Change Biol.* **15**, 1982–1989. (doi:10.1111/j.1365-2486.2008.01834.x)
113. Sui X, Zhang RT, Yang LB, Zhong HX, Wand JF, Ni HW. 2015 Effects of long-term elevated CO₂ fumigation on microbial communities in a wetland soil. *J. Res. Sci. Technol.* **12**, S93–S96. (doi:1544-8053/15/01 S093-04)
114. Larkin ZT, Ralph TJ, Tooth S, McCarthy TS. 2017 The interplay between extrinsic and intrinsic controls in determining floodplain wetland characteristics in the South African drylands. *Earth Surf. Processes Landforms* **42**, 1092–1109. (doi:10.1002/esp.4075)
115. Bouttes N, Good P, Gregory JM, Lowe JA. 2015 Nonlinearity of ocean heat uptake during warming and cooling in the FAMOUS climate model. *Geophys. Res. Lett.* **42**, 2409–2416. (doi:10.1002/2014GL062807)
116. Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD. 2007 Coastal systems and low-lying areas. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds ML Parry *et al.*), pp. 315–356. Cambridge, UK: Cambridge University Press.
117. Nicholls RJ, Reeder T, Brown S, Haigh ID. 2015 The risks of sea-level rise for coastal cities. In *Climate change: a risk assessment* (eds D King, D Schrag, Z Dadi, Q Ye, A Ghosh), pp. 94–98. London, UK: Foreign and Commonwealth Office.
118. Haasnoot M, Kwakkel JH, Walker WE, ter Maat J. 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Change* **23**, 485–498. (doi:10.1016/j.gloenvcha.2012.12.006)
119. NCCS. 2012 Climate Change & Singapore: Challenges. Opportunities. Partnerships. National Climate Change Strategy 2012, Creating a climate for sustainable growth, securing a liveable environment for our future. National Climate Change Secretariat, Prime Minister's Office, Republic of Singapore. See <https://www.nccs.gov.sg/sites/nccs/files/NCCS-2012.pdf>.

120. Schaeffer M, Hare W, Rahmstorf S, Vermeer M. 2012 Long-term sea-level rise implied by 1.57°C and 2°C warming levels. *Nat. Clim. Change* **2**, 867–870. (doi:10.1038/nclimate1584)
121. Jevrajeva S, Moore JC, Grinstead A. 2012 Sea level projections to AD 2500 with a new generation of climate change scenarios. *Glob. Planet. Change* **80–81**, 14–20. (doi:10.1016/j.gloplacha.2011.09.006)
122. Robinson A, Calov R, Ganopolski A. 2012 Multistability and critical thresholds of the Greenland ice sheet. *Nat. Clim. Change* **2**, 429–432. (doi:10.1038/nclimate1449)
123. Ritz C, Edwards TL, Durand G, Payne AJ, Peyaud V, Hindmarsh RCA. 2015 Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature* **528**, 115–118. (doi:10.1038/nature16147)
124. Warrick R, Oerlemans J. 1990 Sea level rise. In *Climate change: the IPCC scientific assessment. Report prepared for Intergovernmental Panel on Climate Change by working group I* (eds JT Houghton, GG Jenkins, JJ Ephraums), pp. 257–282. Cambridge, UK: Cambridge University Press.
125. Watson RT *et al.* 2001 Climate change 2001: synthesis report. Summary for policymakers. See <https://www.ipcc.ch/pdf/climate-changes-2001/synthesis-syr/english/summary-policymakers.pdf>.