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Consequences of twenty-first-century policy for multi-millennial climate and sea-level change

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Most of the policy debate surrounding the actions needed to mitigate and adapt to anthropogenic climate change has been framed by observations of the past 150 years as well as climate and sea-level projections for the twenty-first century. The focus on this 250-year window, however, obscures some of the most profound problems associated with climate change. Here, we argue that the twentieth and twenty-first centuries, a period during which the overwhelming majority of human-caused carbon emissions are likely to occur, need to be placed into a long-term context that includes the past 20 millennia, when the last Ice Age ended and human civilization developed, and the next ten millennia, over which time the projected impacts of anthropogenic climate change will grow and persist. This long-term perspective illustrates that policy decisions made in the next few years to decades will have profound impacts on global climate, ecosystems and human societies — not just for this century, but for the next ten millennia and beyond.

There is scientific consensus that unmitigated carbon emissions will lead to global warming of at least several degrees Celsius by 2100[1], resulting in high-impact local, regional and global risks to human society and natural ecosystems[2]. Despite this consensus, international efforts to address the challenge of global climate change have been and remain limited in scope[3]. We suggest that one important factor contributing to this impasse is the focus of the scientific community on near-term climate changes and their uncertainties. In particular, the scientific emphasis on the expected climate changes by 2100, which was originally driven by past computational capabilities, has created a misleading impression in the public arena — the impression that human-caused climate change is a twenty-first-century problem, and that post-2100 changes are of secondary importance, or may be reversed with emissions reductions at that time. Socioeconomic and policy discussions regarding climate change have also focused primarily on near-term impacts to the end of this century. The viewpoint that the near term is the most relevant timeframe with regard to socioeconomic impacts and adaptation reflects an implicit discounting of future impacts, as well as an assumption that successful mitigation measures could reverse the negative impacts of climate change over the next few hundred years.

Anthropogenic increases in CO_2, however, have effects that extend well beyond 2100; a considerable fraction of the carbon emitted to date and in the next 100 years will remain in the atmosphere for tens to hundreds of thousands of years[4–9]. The long residence time of an anthropogenic CO_2 perturbation in the atmosphere, combined with the inertia of the climate system, implies that past, current, and future emissions commit the planet to long-term, irreversible climate change[1,10–16]. As a result, many key features of future climate change are relatively certain in the long term, even if the precise timing of their occurrence is uncertain.

Here, we argue that it is necessary to view near-term climate changes in the context of a long-term perspective that places the scope and severity of the problem in a readily understandable context. To address the possibility that human actions may initiate future global climate change on a geological timescale rather than the scale of a few human generations, we present several different scenarios of global temperature and sea-level change over the next 10,000 years. These scenarios are referenced to our best scientific understanding of climate and sea-level change over the past 20,000 years. This long-term view shows that the next few decades offer a brief window of opportunity to minimize large-scale and

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potentially catastrophic climate change that will extend longer than the entire history of human civilization thus far. Policy decisions made during this window are likely to result in changes to Earth's climate system measured in millennia rather than human lifespans, with associated socioeconomic and ecological impacts that will exacerbate the risks and damages to society and ecosystems that are projected for the twenty-first century[2] and propagate into the future for many thousands of years. This deep-time perspective thus provides a basis for weighing the different national and international policy actions required to address anthropogenic climate change. We conclude by recommending that, to avoid severe and persistent impacts from long-term climate change, there is a need for policies that lead to complete decarbonization of the world's energy systems.

The long-term perspective

Since 1990, the five assessment reports by Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC) have assessed projections of climate change and its impacts that have focused largely on the twenty-first century. Initial interest in climate change from post-twenty-first century greenhouse gas (GHG) forcing came with the recognition that both the carbon cycle[5,6] and the climate system[17–20] have large inertia, such that even if carbon emissions are stabilized or reduced, atmospheric CO_2 concentrations and surface temperatures would remain high and sea level would continue to increase for millennia. The implication is that, in the absence of efficient, large-scale capture and storage of airborne carbon, carbon emissions that have already occurred or will occur in the near future result in a commitment to climate change that will be irreversible on timescales of centuries to millennia and longer[13,18,21,22].

Most recently, the IPCC's Fifth Assessment Report (AR5) assessed the evidence that cumulative emissions of CO_2 control the magnitude (but not necessarily the rate) of long-term warming, thus facilitating the identification of emissions quotas that would limit global warming to the temperature target mandated by a specific climate policy[23–27]. Long-term irreversible climate change in response to carbon emissions is thus now clearly documented in the scientific literature, leading the AR5 WGI Summary for Policymakers[28] to conclude that the persistence of climate change after emissions are stopped "represents a substantial multi-century commitment created by past, present, and future emissions of CO_2".

In this Perspective, we extend the view beyond the still relatively limited future time horizon emphasized by the IPCC AR5. We synthesize results from carbon cycle, climate and land–ice models that show that human perturbations to GHG concentrations produce a climate change commitment lasting for many millennia. In particular, we note that 20–50% of the airborne fraction of anthropogenic CO_2 emissions released within the next 100 years remains in the atmosphere at the year 3000[8,14], that 60–70% of the maximum surface temperature anomaly and nearly 100% of the sea-level rise from any given emission scenario remains after 10,000 years[14,29], and that the ultimate return to pre-industrial CO_2 concentrations will not occur for hundreds of thousands of years[7,9]. If CO_2 emissions continue unchecked, the CO_2 released during this century will commit Earth and its residents to an entirely new climate regime.

Past and future long-term temperature

The palaeoclimate record helps to place our understanding of the size and rapidity of recent and future climate changes in the context of Earth's natural climate variability. Our long-term perspective on past changes is based on recently developed global proxy temperature reconstructions of the past 20,000 years[30,31]. These reconstructions document the period of warming that ended the last Ice Age, and the subsequent interglacial interval of relative climate stability during which human civilization emerged and diversified (Fig. 1c).

The transition from the peak of the Last Glacial Maximum (LGM) ~21,000 years ago to the start of the present Holocene interglaciation 11,700 years ago represents the last major episode of global warming in Earth's history, when atmospheric CO_2 concentrations increased by ~80 ppm (from ~190 ppm to ~270 ppm)[32–34] (Fig. 1b) and global mean temperature rose ~4 °C (ref. 35; Fig. 1c). The Holocene interglaciation stands out as an interval of relative climate stability during which atmospheric CO_2 only varied between about 260 and 280 ppm (ref. 36; Fig. 1b). The historically documented 0.85 °C global-average warming that has occurred since about 1900[37] is close to the largest range of variations that occurred far more slowly over the previous 10,000 years[30].

We combine this 20,000-year palaeo perspective with temperature projections for the next 10,000 years (Fig. 1c), which are an order of magnitude longer in duration than nearly all previously published projections of irreversible climate change[10,13,16,25], allowing better assessment of the potential for recovery towards pre-anthropogenic-perturbation conditions. The projections are based on simulations performed with the University of Victoria Earth System Climate Model (UVic ESCM)[14,38] (versions 2.8 and 2.9) and with two versions of the Bern3D-LPX model[39]. The two versions of both the UVic and Bern models have different representations of carbon-cycle processes (see Supplementary Information), thus providing a better estimate of uncertainty in the carbon cycle.

Results are for a stipulated equilibrium climate sensitivity (ECS) of 3.5 °C, which is similar to the ensemble mean ECS derived from multiple comprehensive models (3.2 °C) in the AR5[40]. We also use the Bern3D-LPX model for projections that evaluate ECS values ranging from 1.5 to 4.5 °C (Fig. 1), which the AR5 assessed as the likely sensitivity range (66–100% probability), and has remained essentially unchanged since first assessed by Charney[41]. Projections are based on a set of four future emission scenarios with total releases of carbon between 1,280 and 5,120 Pg C (see Supplementary Information). Projections for representative concentration pathway (RCP) 8.5 and its extensions to 2300 are included for comparison. The highest emission scenario in our projections (release of 5,120 Pg C to the atmosphere) is substantially lower than known and currently attainable carbon reserves and resources, which are estimated to be between ~9,500 and 15,700 Pg C (ref. 42).

Depending on the emission scenario, the model projections with a prescribed ECS of 3.5 °C indicate that the magnitude of anthropogenic warming relative to pre-industrial conditions would range from approximately half (~2 °C) to nearly twice (~7.5 °C) the warming that occurred during the transition from the end of the LGM to the start of the current interglacial interval (Fig. 1c). Deglacial warming proceeded incrementally over nearly 8,000 years, however, whereas much of the projected warming will occur over the next few centuries, and thus at significantly faster rates (Fig. 1e).

Current annual emission growth rates (~2.5% per year) are twice as large as in the 1990s (average of 1% per year), and they continue to track the high end of emission scenarios used for IPCC projections[27,43]. Moreover, the current (1750–2013) cumulative human carbon footprint is about 580 ± 70 Pg C (ref. 44), and is already rapidly approaching the low-end scenario considered here (cumulative emissions of 1,280 Pg C from the year 2000). This suggests that unless policy measures to reduce emissions are enacted soon, scenarios such as RCP4.5 or the 1,280 Pg C emission scenario seem all but guaranteed, both of which lead to temperature increases that approach or exceed the 2 °C guardrail[25,45] commonly associated with Article 2 of the United Nations Framework Convention on Climate Change[46], "to avoid dangerous anthropogenic interference with the climate system". At the same time, high-end scenarios, such as RCP8.5 (ref. 47) and the 5,120 Pg C emission scenario, with even larger impacts, become increasingly likely. Model projections based on the RCPs[25] and each of the four emission scenarios shown in Fig. 1 indicate that twenty-first century global average warming

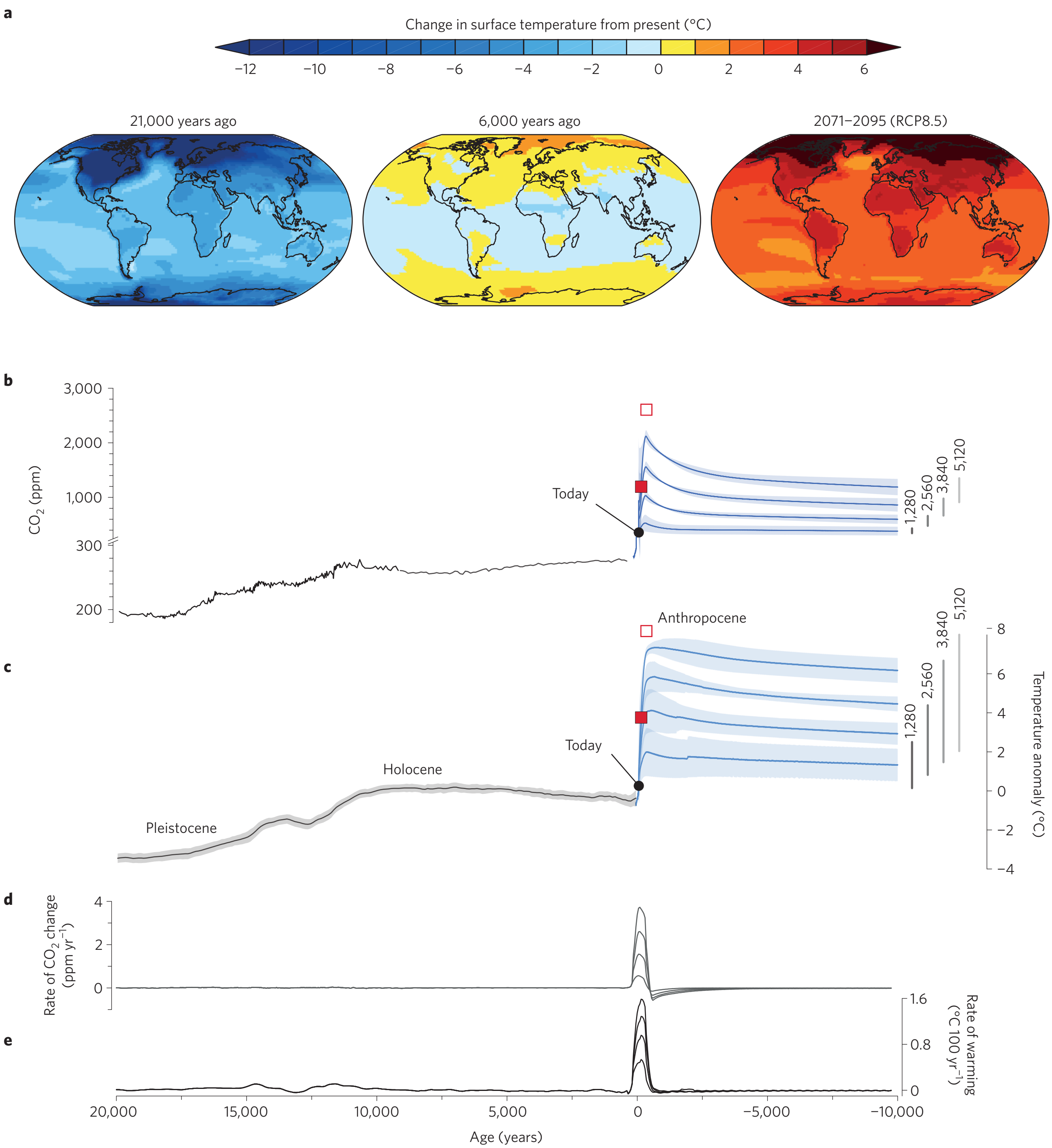

Figure 1 | Past and future changes in concentration of atmospheric carbon dioxide and global mean temperature. a, Maps showing model-simulated temperature anomalies for the Last Glacial Maximum (21,000 years ago), the mid-Holocene (6,000 years ago), and projection for 2071–2095 based on the upper-end scenario used in the IPCC Working Group I AR5 (RCP8.5)[87]. **b**, Changes in CO_2 from ice cores for the past 20,000 years[32,34,36] and for four future emission scenarios (1,280, 2,560, 3,840, and 5,120 Pg C), with changes in CO_2 for each emission scenario (mean and one standard deviation) derived from four runs with two fully coupled climate–carbon-cycle Earth System Models of Intermediate Complexity (UVic and Bern3D-LPX) (see Supplementary Information). CO_2 levels for RCP8.5 for 2100 (red filled square) and its extension for 2300 (red open square) are shown for comparison (values are CO_2-equivalent)[47]. Vertical grey bars show range of CO_2 increase for the four emission scenarios based on a range in equilibrium climate sensitivity (1.5–4.5 °C) derived from Bern3D-LPX model runs. Note change in *y* axis scale at 300 ppm. **c**, Global temperature (mean and one standard deviation) reconstructed from palaeoclimate archives for the past 20,000 years[30,31] and from four simulations with the UVic and Bern3D-LPX models for each of the four emission scenarios for the next 10,000 years, based on an equilibrium climate sensitivity of 3.5 °C (see Supplementary Information). Temperature anomalies are relative to the 1980–2004 mean. Vertical grey bars show range of temperature increase for the four emission scenarios (1,280, 2,560, 3,840, and 5,120 Pg C) based on a range in equilibrium climate sensitivity (1.5–4.5 °C) from Bern3D-LPX model runs. Temperature projections (mean values) for RCP8.5 for 2081–2100 (red filled square) and its extension for 2281–2300 (red open square) are shown for comparison[25]. **d**,**e**, The rates of change in CO_2 (**d**) and temperature (**e**), using a 500-year smoothing window.

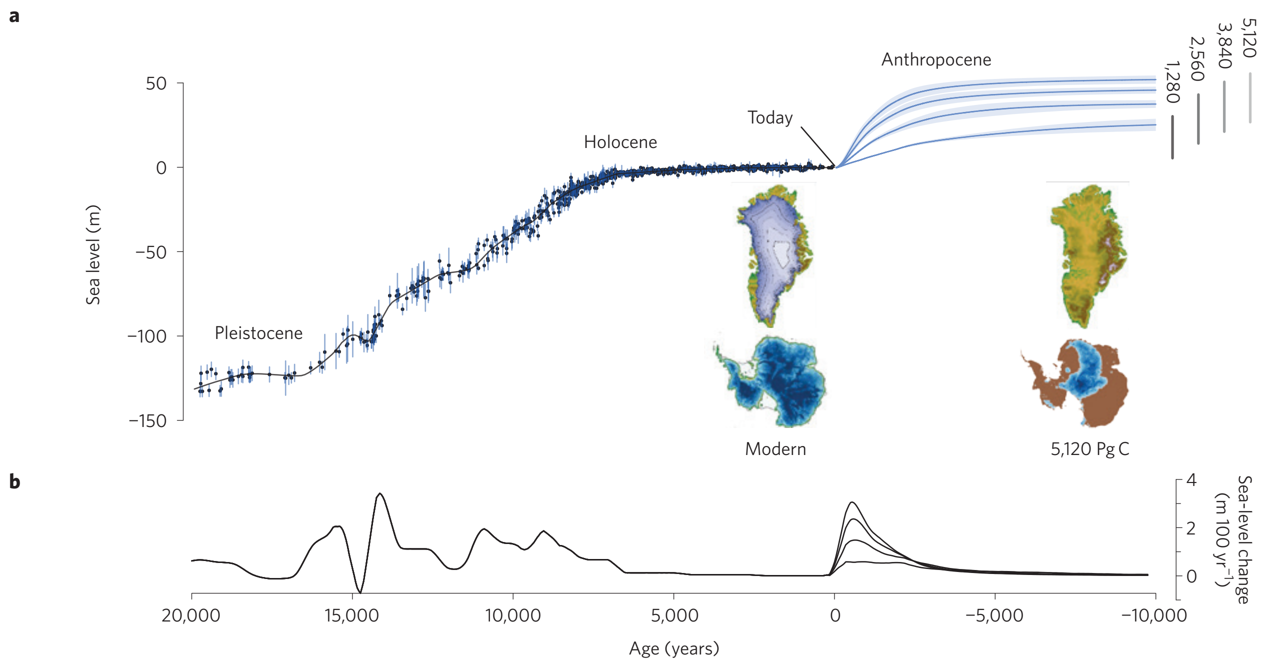

Figure 2 | Past and future changes in global mean sea level. a, Long-term global mean sea-level change for the past 20,000 years (black line) based on palaeo sea level records (black dots with depth uncertainties shown by blue vertical lines)[60] and projections for the next 10,000 years for four emission scenarios (1,280, 2,560, 3,840, and 5,120 Pg C). Time series for future projections (mean and one standard deviation) are based on thermosteric contributions from the UVic and Bern3D-LPX models, from modelled land-ice changes driven by UVic model runs with an equilibrium climate sensitivity of 3.5 °C, and from Bern3D-LPX model runs in which the total land-ice contribution was estimated from the relation between the UVic and land-ice model results (see Supplementary Information). Vertical grey bars show range of long-term sea-level rise for each emission scenario derived from a range in equilibrium climate sensitivity (1.5–4.5 °C) from Bern3D-LPX model runs. Images show reconstructions of the Greenland (top) and Antarctic (bottom) ice sheets for today (left) and for the 5,120 Pg C emission scenario (right). **b**, The rates of change in global mean sea level (using a 500-year smoothing window).

will substantially exceed even the warmest Holocene conditions, producing a climate state not previously experienced by human civilizations[30]. Temperatures will remain elevated above Holocene conditions for more than 10,000 years, with gradual recovery reflecting the long timescales involved in the removal of emitted CO_2 by mid-term (thousands of years) carbonate dissolution and by long-term (tens of thousands of years and longer) seafloor deposition of the products of silicate weathering as calcium carbonate[7,8]. Given that deglacial warming led to a profound transformation of Earth and ecological systems, the projected warming of 2.0–7.5 °C above the already warm Holocene conditions (at much faster rates than experienced during deglaciation) will also reshape the geography and ecology of the world.

Past and future long-term sea level

A rise in global mean sea level (GMSL) occurs largely in response to some combination of a decrease in land-water storage, an increase in ocean heat uptake causing thermal expansion[48], and an increase in mass loss from land ice (glaciers and ice sheets). The corresponding response times of GMSL to perturbations to these components vary from short (10^0 yr) for land water, to intermediate (10^1–10^2 yr) for shallow-to-intermediate ocean temperatures and glaciers, to long (10^2–10^3 yr) for deep-ocean temperatures (due to the slow mixing of the energy perturbation into the large ocean thermal reservoir[17,49–51]) and the ice sheets[19]. In addition, several factors cause sea-level rise to vary regionally, including changes in atmospheric and ocean dynamics[52–55] and deformational, gravitational and rotational effects associated with the loss of glaciers and ice sheets[56–59].

The long-term palaeo sea-level perspective is based on a compilation of relative sea-level data that, when accounting for local and regional effects on sea level, yields an estimate of changes in GMSL for the past 20,000 years[60] (Fig. 2a). This reconstruction suggests that sea level at the LGM was ~130 m lower than present, with the majority of the decrease caused by excess land ice, particularly associated with the former Northern Hemisphere ice sheets. GMSL began to rise ~20,000 years ago by ice loss associated with increasing Northern Hemisphere summer insolation[61], with subsequent rise continuing in response to warming largely from rising GHGs[62]. Near-modern sea levels were reached ~3,000 years ago. The 130 m rise in GMSL during the last deglaciation attests to the long-term sensitivity of sea level to a warming of just a few degrees, as do sea-level high stands 5–20 m above present during previous intervals of Earth's history when temperatures were ~1 to 3 °C warmer than today[63–65]. The palaeo record also illustrates that although orbital forcing, CO_2 and global temperature reached interglacial levels by about 11,000 years ago[31] (Fig. 1), GMSL continued to rise another ~45 m over the next eight millennia[60] (Fig. 2a). This lag of sea-level rise behind temperature forcing reflects the long timescale of ice-sheet response to a climate perturbation.

Future sea-level rise is similarly expected to be a multi-millennial response to greenhouse-induced atmospheric warming. Here, we use process-based physical models to project the contributions to GMSL rise over the next 10,000 years from ocean thermal expansion, glaciers, and the Greenland and Antarctic ice sheets (Fig. 2). The GMSL projections are obtained with the same scenarios of carbon emissions used in our temperature projections (see Supplementary Information).

Thermal expansion. The thermal expansion component of GMSL rise is derived from the 10,000-year simulations performed with the UVic ESCM and Bern3D-LPX models. All scenarios show a relatively rapid rise to a peak of thermal expansion followed by a slow decrease for the remainder of the 10,000 years (Supplementary Fig. 1), roughly tracking the gradual long-term atmospheric cooling that occurs as CO_2 declines after peak emissions. For the 1,280 Pg C emission scenario, the thermal expansion component reaches a maximum of 1.1 m above present sea level after ~2,300 years and then slowly falls to 0.8 m above present 10,000 years in the future. Under the 5,120 Pg C emission scenario, the thermal expansion component peaks at 3.4 m ~2,300 years in the future and then slowly falls to 2.8 m after 10,000 years.

Glaciers. The sea-level contribution from glaciers is limited by the total amount of water stored in them, which was estimated in the glacier model used here as a global mean value of 0.37 m, not including glaciers peripheral to the Antarctic ice sheet[66]. The glacier contribution, therefore, is a relatively small component of GMSL change on the multi-millennial timescales considered here. We simulated the glacier response to the global mean temperature rise resulting from the four emission scenarios using a global glacier model[66], which includes surface mass balance and simplified ice dynamics. The model estimates the volume change of each glacier in the world based on temperature and precipitation changes. For all emission scenarios, a new equilibrium is approached within a few centuries, with maximum sea-level rise from this source ranging from 0.25 m for the 1,280 Pg C emission scenario to 0.34 m for the 5,120 Pg C emission scenario, or about 70 to 90% of the current inventory (Supplementary Fig. 1). As the number of low-elevation glaciers decreases, the sensitivity of glacier melt to warming decreases, such that there is little difference in the glacier contribution to sea-level change between the 3,840 and 5,120 Pg C scenarios.

Greenland ice sheet. The Greenland ice sheet stores the equivalent of about 7 m of GMSL rise[67]. The long-term sea-level contribution from the Greenland ice sheet is based on results from an ice-sheet model coupled to a regional energy–moisture balance model[68] (see Supplementary Information). For the 1,280 Pg C emission scenario, incomplete melting of the Greenland ice sheet yields up to 4 m of sea-level rise over 10,000 years. For the 2,560, 3,840 and 5,120 Pg C emission scenarios, Greenland becomes ice free by about 6,000, 4,000 and 2,500 years from now, respectively (Supplementary Fig. 1).

Antarctic ice sheet. The Antarctic ice sheet stores the equivalent of ~58 m of GMSL rise[67]. Its potential sea-level contribution within the next 10,000 years far exceeds that of all other possible sources[69]. We simulate the transient response to the four emission scenarios considered here with an ice-sheet model that represents ice flow in sheet, stream and floating shelf components in a consistent way[69] (see Supplementary Information).

The lowest emission scenario considered here (1,280 Pg C) results in the loss of a substantial part of the Antarctic ice sheet, corresponding to as much as 24 m of GMSL rise over 10,000 years (Supplementary Fig. 1). Most of the mass loss occurs in the marine-based portions of the ice sheet following removal of a small volume of ice at the ice-sheet margin (the so-called ice plug) currently hindering their discharge[70]. This is due to the marine ice-sheet instability associated with a reverse bed slope beneath the ice sheet where it is grounded below sea level[71], which may have already been triggered in some regions of the Amundsen Sea sector of West Antarctica[72–74]. Under higher emission scenarios, the surface-elevation feedback — currently negligible due to surface temperatures that are well below freezing over most of Antarctica — also contributes significantly to future mass loss as warming leads to surface melting[69]. For the 5,120 Pg C emission scenario, the resulting sea-level rise reaches as much as 45 m in 10,000 years, or more than four times that of all the other contributions combined for that scenario (Supplementary Fig. 1).

Global and regional sea-level rise over the next 10 millennia. For an ECS of 3.5 °C, thermal expansion and mass loss from glaciers and the Greenland and Antarctic ice sheets are estimated to result in GMSL rise ranging from about 25 to 52 m within the next 10,000 years, depending on the emission scenario considered here (Fig. 2a). These values exceed the IPCC forecast for the year 2100, the sea-level estimate that is usually discussed, by two to three orders of magnitude, reflecting the inappropriateness of that timescale for addressing the long response times of GMSL[17,19,75]. Figure 2c shows that future rates of GMSL rise could reach 2–4 m per century — values that are unprecedented in more than 8,000 years.

We emphasize, however, that the projected sea-level rise will not be uniform globally, being especially influenced by the gravitational, deformational, and rotational effects of the loss of ice sheets[58,76,77]. Using a model that simulates these processes[57], we computed global patterns of sea-level change. Figure 3 shows the projected changes in relative sea level (ocean surface height relative to land height) for the 1,280 Pg C emission scenario. Of the processes considered here, the two that contribute most to the regional variability are future ice melting (Fig. 3a) and the ongoing isostatic response of Earth to the most recent deglaciation (Fig. 3b). Each process contributes a distinct pattern that is evident in the total projection (Fig. 3c). The results in Fig. 3 demonstrate that local sea-level

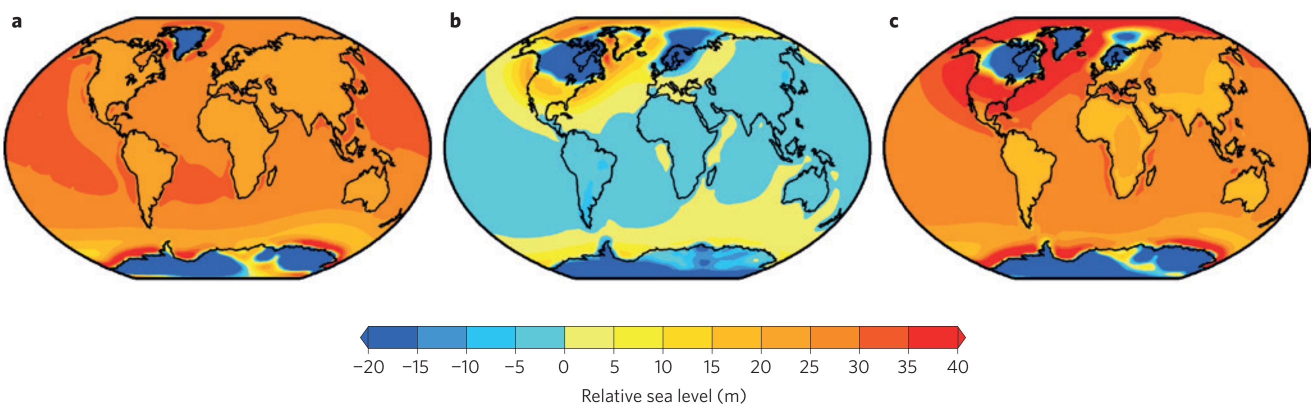

Figure 3 | Maps of projected relative sea-level change at 10,000 years after 2000 AD. a, The contribution to relative sea-level change associated with mass loss from the Greenland and Antarctic ice sheets based on the 1,280 Pg C emission scenario and output from UVic ESCM version 2.8. The results include changes to Earth's shape, gravity and rotation associated with the transfer of mass from the ice sheets to the oceans[57,58]. **b**, The contribution to relative sea-level change due to the ongoing deformation of Earth (and consequent gravitational and rotational changes) in response to the most recent deglaciation (see Supplementary Information). **c**, The sum of the results in **a** and **b**. The global mean contributions from ocean warming and melting of glaciers are not included (they sum to less than 1 m for the 1,280 Pg C emission scenario).

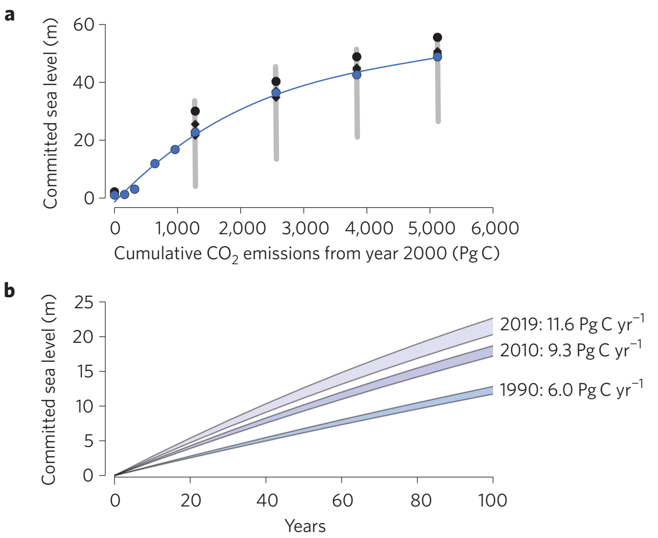

Figure 4 | Relation between future cumulative emissions and committed sea-level rise. a, Relation between future cumulative carbon emissions and long-term sea-level rise after 10,000 years. Symbols represent results from UVic (circles: blue for version 2.8, black for version 2.9) and Bern3D-LPX (diamonds) models for an equilibrium climate sensitivity of 3.5 °C. The Bern3D-LPX values include land ice contributions estimated from the relation between UVic temperature and modelled land ice (see Supplementary Information). Vertical grey bars show the spread in committed sea level for a range in equilibrium climate sensitivity from 1.5 to 4.5 °C. **b**, Committed sea-level rise after 10,000 years that would result from emitting carbon for 100 years at annual rates from the past (1990 and 2010) and projected for the near future (2019; ref. 27). Ranges on the rates are 5.7 to 6.3 Pg C yr^{-1} for 1990, 8.8 to 9.8 Pg C yr^{-1} for 2010, and 10.8 to 12.4 Pg C yr^{-1} for 2019.

change can be markedly different from the global mean estimate, which is ~21 m in Fig. 3c (this value includes a contribution from isostatic processes[58,78]). Departures from the global mean change are particularly evident in areas that have experienced past and/or future deglaciation where land uplift dominates and results in a net sea-level fall (blue colours in Fig. 3). However, the majority of coastlines will experience a rise that is within ~20% of the GMSL value. Maps of the projected sea-level change for the 2,560, 3,840, and 5,120 Pg C emission scenarios are included in Supplementary Fig. 2.

Another outcome of our sea-level analysis is the demonstration that, similar to global mean temperature[25], there is a well-defined relation between cumulative emissions of CO_2 and GMSL (Fig. 4a) that provides an objective framework for deciding on an emissions quota to limit future sea-level rise to some stipulated value. Unlike the near-linear relation with global mean temperature[25], however, the relation with GMSL suggests a decreasing sensitivity with increasing carbon emissions, which likely is likely to reflect the retreat of the Antarctic ice sheet to less vulnerable regions (that is, less ice at higher latitudes and land elevations above sea level). Our modelling suggests that the human carbon footprint of about 470 Pg C by 2000 (ref. 79) has already committed Earth to a GMSL rise of ~1.7 m (range of 1.2 to 2.2 m), while release of another 470 Pg C will result in a further committed rise of ~9 m (Fig. 4a) that is largely derived from the Antarctic ice sheet (Supplementary Fig. 3). Figure 4b evaluates this relation for various constant annual emission rates integrated over time. The sobering result encapsulated in this figure is that even if emissions were capped or reduced to some lower rate, we would still be committed to GMSL rise that is substantially larger than that experienced over much of recorded human civilization. The only means to prevent a further commitment to GMSL rise is to achieve net-zero emissions.

We next demonstrate the likely severity of impacts from committed sea-level rise as a result of continuing to increase cumulative emissions, likely at an increasing rate. Previous work showed that with a sustained warming of 3 °C over the next 2,000 years, 25–36 countries will lose at least 10% of their areas to sea-level rise[80]. We assess the fraction of the global population that would be directly impacted by the sea-level change shown in Fig. 3c associated with the lowest of the four emission scenarios considered here (1,280 Pg C). Figure 5 shows that because of high population densities along the coastal zone of the world, there are 122 countries in which at least 10% of their current population-weighted area will be directly affected by coastal submergence, while there are 25 coastal megacities that will have at least 50% of their population-weighted area affected. The total population on land below this threshold and connected to the ocean is 1.3 billion, or 19% of the global population in 2010. Figure 6 shows that the geography of many countries with low-lying coastal zones will be dramatically changed through coastal submergence associated with this low-end emission scenario considered here, with essentially complete flooding and submergence of entire megacities. We note that with ~580 Pg C of anthropogenic carbon emissions already released[44], we are ~30% of the way to this scenario. With current annual emission rates now at ~10 Pg C yr^{-1} (ref. 44), we are ~120 years from reaching this scenario. If on average we continue to emit more than 10 Pg C yr^{-1} (which seems likely given our current[44] and projected[27] increasing levels of emissions), the timescale will be shorter.

The projected sea-level response for the highest emission scenario is ~45% of the change estimated to have occurred during the last deglaciation (Fig. 2). In that past event, most of the sea-level rise proceeded incrementally over nearly 13,000 years. In the future, however, much of the projected rise for the higher scenarios will occur in less than 3,000 years, in some cases at rates comparable to the fastest rates of the last deglaciation, which at times reached several metres per century (Fig. 2). While GMSL has been relatively stable during much of the history of settled human civilization[60], our future is likely to involve continuous rapid GMSL rise for at least the next few thousand years; the rate and magnitude will depend strongly on the near-term policy decisions that set the trajectory of anthropogenic emissions.

Policy implications

What can the history of climate over the past 20,000 years teach us about our current predicament? Does placing the future of climate in the context of the past, emphasizing the long timescales in the climate system and the carbon cycle, lead to any specific actions or policies that differ from what the more common view of climate change over the current century already requires?

One important issue is whether timescales of thousands to tens of thousands of years should matter to our evaluation of climate risks. A conventional approach is to devalue the costs of future impacts using some exponential discount rate[81]. Indeed, it is reasonable to discount costs in the future — paying now to avoid future costs results in an opportunity cost (that is, the loss of money could be used for immediate benefit). Even with a low discount rate, future climate impacts on thousand-year time scales would be valued as zero, irrespective of the levels of certainty and magnitude. On the other hand, some behavioural studies have argued for a hyperbolic form of discounting, which asymptotes to a low and constant value over time, as most people do place some small value on the distant future[82]. But this only slightly changes the answer; as ice sheets melt, for example, the adverse impacts of sea-level rise would still be worth very little in monetary terms, yet would be experienced by hundreds of future human generations and require abandonment of coastal megacities. Can this simple accounting really be correct?

Whether or not society chooses to take the necessary steps to mitigate climate change is not a purely economic calculation.

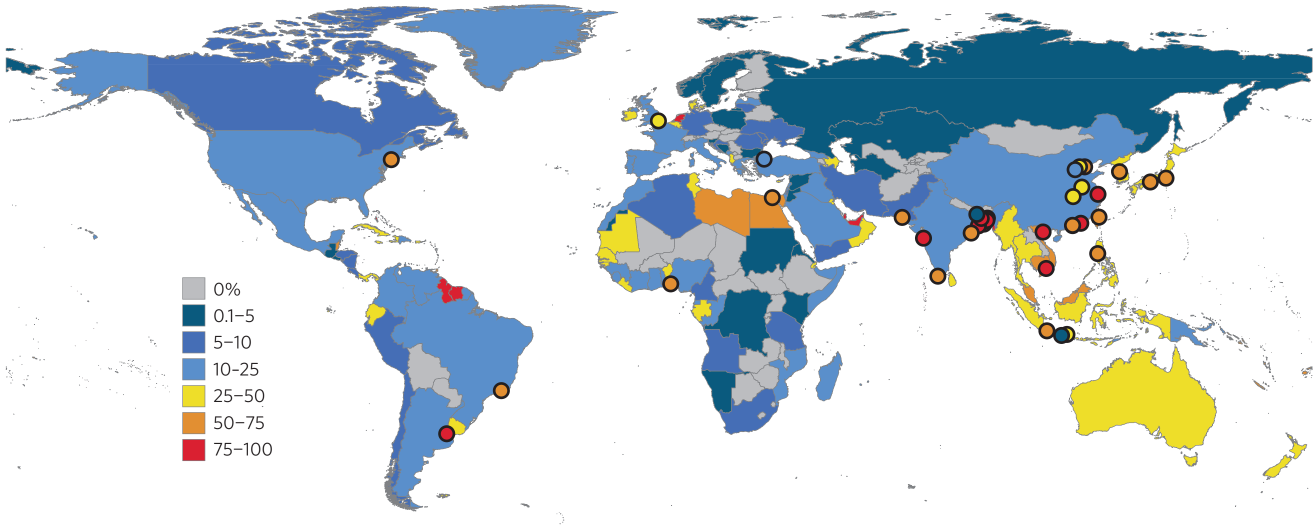

Figure 5 | Populated areas affected by sea-level rise. Shown is the percentage of the population-weighted area for each nation or megacity (urban agglomeration with population 10 million or greater) below the projected long-term local mean sea level from emitting 1,280 Pg C. Population-weighted area describes the area of a country that falls below the projected long-term local mean sea level, weighted by its population. A 10% value thus indicates that 10% of the population of that country lives within the area that will be submerged. Sea-level rise is based on land-ice modelling forced by temperatures from version 2.8 of the UVic model and includes regional effects (see Fig. 3 and Supplementary Information). Unaffected megacities (value 0%) are not shown, and exposure north of 60° N or south of 56° S latitude is not included.

Ultimately, this decision depends on human values, particularly on our valuation of intergenerational equity, food and water security, maintenance of ecosystem services, biodiversity, and the preservation of unique environments (such as coral reefs and glaciers). Are future generations entitled to the same environmental stability and biodiversity that has been afforded our generation and hundreds of generations before us?

What is clear from our analysis is that the decisions being made today will have profound and permanent consequences for future generations as well as for the planet; yet future generations are not part of today's decision making, and today's decision makers do not have to live with most consequences of their decisions. Discount rates may describe the economic view of how much we are willing to pay, but they do not answer the deeper moral and ethical questions of how much we should pay.

Science can never be used to answer a question concerning the importance of intergenerational equity, morality or ethics, nor can it ever be used to prescribe a particular policy; these are inherently value judgments. However, science is able to examine the implications of different policy options, especially when those options entail substantially different climate risks[2,83]. Policies can also be developed or modified to reflect the latest science, as risks are revised to incorporate new observations and new understanding. But in the end, the formulation of policy requires engaging a broad range of stakeholders — the citizens of our planet, representing an incredible diversity of religious, political, cultural, economic, and ethical viewpoints. It also requires dealing with ethical, political, legal, financial and social issues, including reasonable application of the precautionary principle. An evaluation of climate change risks that only considers the next 85 years of climate change impacts fails to provide essential information to stakeholders, the public and the political leaders who will ultimately be tasked with making decisions about policies on behalf of all, with impacts that will last for millennia.

A second important implication emerging from our results is that to avoid severe impacts, there is a need for policies that lead to a new global energy system that has net-zero or net-negative CO_2 emissions, and not simply for policies aimed at near-term emissions reductions. As discussed above, it is clear that peak warming and peak sea-level rise depend on cumulative CO_2 emissions, and that a marginal reduction in emissions is insufficient to prevent future damages. Climate interventions involving carbon dioxide removal require further research to decrease costs and increase efficiency[84], while strategies such as solar radiation management with stratospheric aerosols face major obstacles, including poorly understood risks[85]. Even if these latter efforts were effective, they do not replace the need for a global energy system with net-zero (or net-negative) carbon emissions. Indeed, the long timescales of the carbon cycle and climate system require that such interventions, once deployed, persist for tens of thousands of years without fail unless carbon is removed from the atmosphere.

A net-zero emissions energy system, however it develops, will look completely different from our current energy system. A complete transformation is required[86] in what some have termed the fourth industrial revolution. The first two revolutions involved mechanization and electrification. The third revolution — the advent of the computer — transformed our ability to transmit and process enormous volumes of data, and now affects almost every aspect of our lives. The fourth revolution must inevitably lead to decarbonization of current energy systems. Transformation to net-zero emissions will require that resources must be managed in a completely different and sustainable way, entailing profound changes not only in energy generation, but also in land use and agriculture. The term fourth industrial revolution not only indicates the scale, scope, and long-term character of the task but also carries an optimistic message. The previous three industrial revolutions created new jobs, new wealth and shifted power structures. There is no reason why the fourth industrial revolution should not yield similar opportunities for growth and positive change.

In each of the 21 Conferences of the Parties (COP) to the UN Framework Convention on Climate Change since the framework was first signed in 1992, negotiations have emphasized short-term emissions goals. Such short-term emissions targets are important, as they represent tangible steps that individual countries are taking towards reducing emissions. Some of these reductions will come from the deployment of non-fossil fuel technologies and increasing energy efficiency. But accelerated investment in the technologies required to achieve deeper reductions over the long term — such

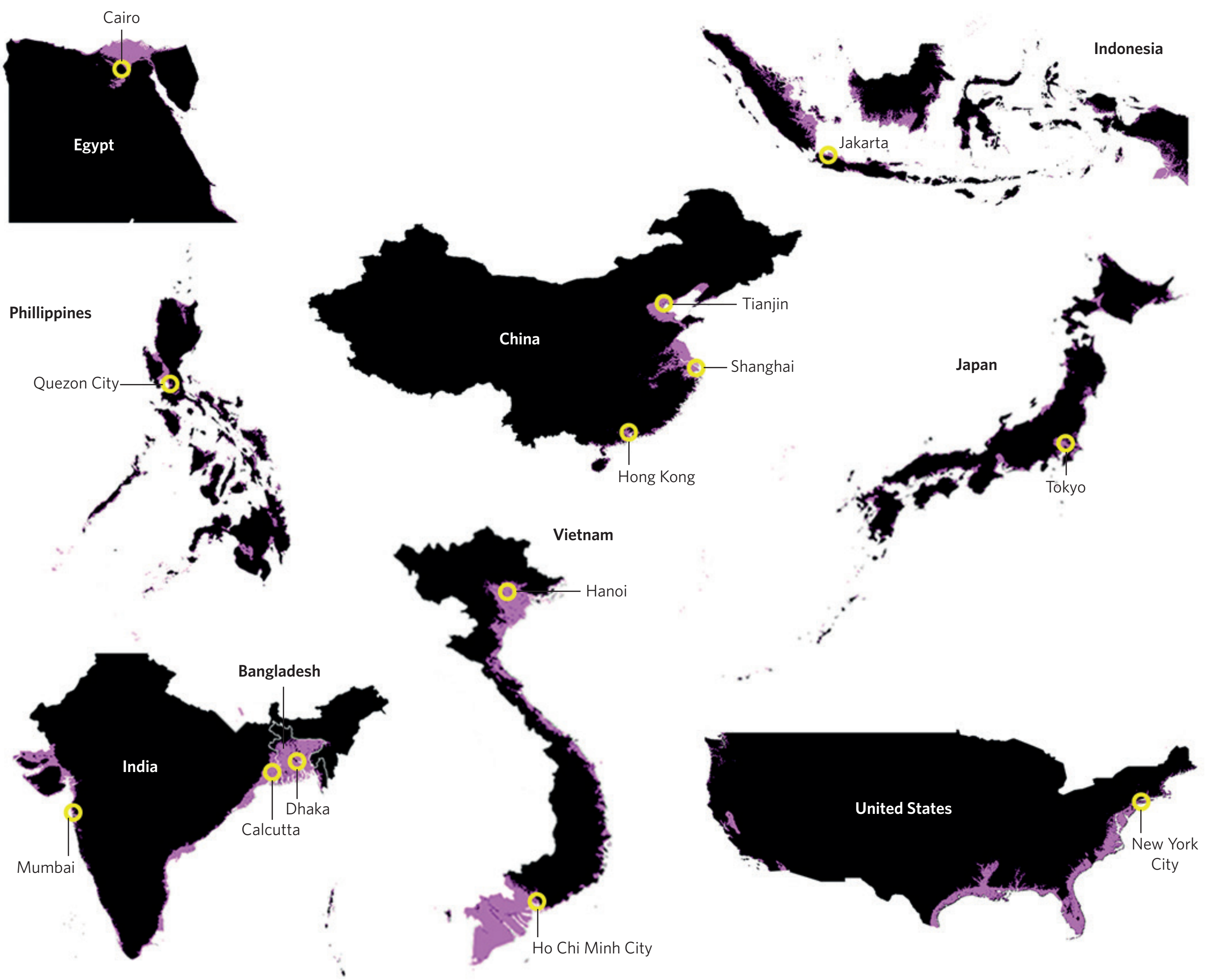

Figure 6 | Projected submerged areas in heavily populated areas affected by sea-level rise. The maps show areas of submergence for countries with at least 50 million people living on land affected by long-term sea-level projection based on the 1,280 Pg C emission scenario. Sea-level rise is based on land-ice modelling forced by temperatures from version 2.8 of the UVic model and includes regional sea-level effects (see Fig. 3 and Supplementary Information). For each country, the cities with the most people on affected land (purple areas) are also shown (yellow circles), plus select others (Shanghai and Hong Kong, China; Mumbai, India; Osaka, Japan; and Ho Chi Minh City, Vietnam), all with total populations 10 million or greater in the urban agglomeration, and with at least half of the total population on affected land. We note that there are many more cities with lesser but still substantial populations not shown on the maps that would similarly be inundated.

as electric or fuel-cell vehicles, or advanced biofuels — will not necessarily result from these new agreements. These and other disruptive technologies are unlikely to have a major impact on emissions if one's perspective on the problem of human-caused climate change does not extend beyond 2100.

Taking the longer, 10,000-year view means that a balance is needed between policies that focus on lowering near-future emissions and policies that accelerate the development and deployment of new technologies that can transform our energy systems and infrastructure in the long term. This is not merely a call for more research, but also for a reexamination of financial incentives, energy regulations, international agreements and the global equity considerations they entail, because key elements of innovation occur as much during widespread deployment as they do in the laboratory. The success of the COP21 Paris meeting, and of every future COP, must be evaluated not only by levels of national commitments, but also by looking at how the various commitments will lead to the proliferation of non-fossil energy systems, and ultimately to the point when zero-carbon energy systems become the obvious choice for everyone.

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Author contributions

P.U.C., S.A.M., A.C.M., and J.D.S. conceived the study. P.U.C. and M.E. designed and led the study, and with A.L., S.A.M., B.D.S., D.P.S., T.F.S., A.J.W., and R.W. wrote the first draft of the paper. M.E. and P.L.P. contributed the carbon cycle and climate modelling, A.L. and R.W. contributed the glacier and ice-sheet modelling, G.A.M. contributed the relative sea-level modelling, and S.K. and B.H.S. contributed the sea-level impact analyses. All authors contributed to the analysis and finalization of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.U.C.

Competing financial interests

The authors declare no competing financial interests.