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Relative outcomes of climate change mitigation related to global temperature versus sea-level rise

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There is a common perception that, if human societies make the significant adjustments necessary to substantively cut emissions of greenhouse gases, global temperature increases could be stabilized, and the most dangerous consequences of climate change could be avoided. Here we show results from global coupled climate model simulations with the new representative concentration pathway mitigation scenarios to 2300 to illustrate that, with aggressive mitigation in two of the scenarios, globally averaged temperature increase indeed could be stabilized either below 2 °C or near 3 °C above pre-industrial values. However, even as temperatures stabilize, sea level would continue to rise. With little mitigation, future sea-level rise would be large and continue unabated for centuries. Though sea-level rise cannot be stopped for at least the next several hundred years, with aggressive mitigation it can be slowed down, and this would buy time for adaptation measures to be adopted.

Our intention here is to relate the rate of future global temperature change from the representative concentration pathway (RCP) mitigation scenarios to possible future sea-level rise to draw attention to the under-appreciated differences involved with temperature mitigation versus sea-level rise mitigation. Given the huge uncertainties involved with ice-sheet stability — which would directly affect how much sea-level rise could occur and how fast — and the questions regarding appropriateness of the different methods used to derive future sea-level rise[1], we provide illustrative ranges of possible future sea-level rise to highlight the mitigation problem.

Mitigation scenarios and climate change

The RCP mitigation scenarios are meant to be representative of a much larger number of scenarios[2]. But with just a small number of RCPs (four in total, results for three are shown here), it is feasible for global coupled climate models to perform the large number of computer-intensive simulations necessary to plausibly assess possible future climate change. A number of factors — such as population growth, gross domestic product, land use, and energy generation and consumption — contribute to a particular RCP emission pathway (see Supplementary Information for more details on the RCPs). There are a variety of combinations of the time evolution of these factors that can produce the same RCP emissions pathway. For example, to keep climate change below the widely cited desired target of 2 °C above pre-industrial levels[3], RCP2.6 specifies negative carbon dioxide emissions starting around the year 2070 (ref. 2). Negative emissions mean that more carbon dioxide is being removed from the atmosphere than is being emitted. One energy strategy that could contribute to achieving this goal in RCP2.6 would be for the primary energy sources in 2070 to consist of about 20% fossil fuel without carbon capture and storage (CCS), about 45% fossil fuel with CCS, and about 35% renewables and nuclear (some of which would include biomass and CCS as well). In contrast, RCP8.5 could imply 80% fossil fuels without CCS, no fossil fuel with CCS, and 20% renewables and nuclear; RCP 2.6 has a very large dependence on CCS and an important role for biomass, which is the largest single share of the renewables and nuclear category[4].

Globally averaged temperatures from simulations using the Community Climate System Model version 4 (CCSM4, a state-of-the-art coupled atmosphere–ocean global climate model (AOGCM); see Methods for more model details and equilibrium climate sensitivity compared with other models) show that, by following the aggressive RCP2.6 mitigation scenario, simulated global mean warming relative to pre-industrial climate is +1.77 °C in our model simulations at the end of the twenty-first century (five-year averages centred on 2100 minus 20-year pre-industrial average 1861–1880), which is below the 2 °C target (refer to horizontal blue lines and notation in Fig. 1). After 2100, globally averaged surface air temperature in RCP2.6 actually declines in the climate model. In a mid-range mitigation scenario (RCP4.5), globally averaged temperatures level out near 3 °C above pre-industrial by about 2200 (refer to horizontal blue lines and notation in Fig. 1). In either case, such mitigation measures act to stabilize climate and reduce the larger changes in climate seen in a scenario with much less aggressive mitigation (RCP8.5), which shows warming by the end of the century of 4.8 °C, and warming of 9.4 °C by 2300 (five-year averages centred on 2100 and 2300, respectively, compared with the pre-industrial average for 1861–1880). Compared with the more recent reference period (1986–2005), warming in RCP2.6 is 0.83 °C at 2100, declining after that to 0.66 °C at 2200 and 0.55 °C in 2300 (Fig. 1). Thus, in this future climate change scenario run with a global coupled climate model, the climate cools after 2100 compared with temperatures in the late twenty-first century. Meanwhile, warming compared with 1986–2005 in RCP4.5 is 1.70 °C by 2100, 2.18 °C at 2200 and 2.36 °C by 2300, indicating a move towards stabilization of warming after about 2200. However, for RCP8.5 with the least aggressive mitigation, warming compared with the 1986–2005 period is 3.91 °C at 2100, 7.25 °C by 2200 and 8.52 °C by 2300. In the more aggressive scenarios, stabilizing (RCP4.5) and even reducing (RCP2.6) globally averaged temperatures after 2100 presumably avoids many of the larger climate impacts seen in the higher scenario[5,6], and even could ameliorate some of the magnitude of possible future sea-level rise by 2100 (ref. 7). For example, in RCP2.6 in CCSM4, cooling at the surface after 2100 is greatest over the majority of land areas (up to about 1 °C per century in some areas) and at high latitudes,

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Arctic late summer sea-ice area is maintained and even recovers to values last seen in the early twenty-first century, and the Atlantic meridional overturning circulation, after weakening in the first part of the twenty-first century, returns to roughly year 2000 values by 2300 (ref. 6).

Climate change commitment and sea-level rise

There is a commitment to further sea-level rise even if temperatures stabilize[8,9]. This is because of several factors, the most quantifiable being thermal expansion of sea water. That is, as warming temperatures make their way deeper and deeper into the ocean through mixing processes in various ocean regions[10], an ever-increasing volume of water warms and expands, thus producing ongoing rises in sea level. There would also be commitment in the melting of ice sheets and glaciers that would contribute to further sea-level rise[11–13].

The actual magnitude of future sea-level rise has proved difficult to quantify[1,9]. Recent indications have been mixed, with some showing that ice melt could be accelerating, raising the spectre of more-rapid sea-level rise[14], and others indicating a possible slowing down of outlet glaciers and ice streams that accelerated in the 1990s[15]. Furthermore, models are not sufficiently reliable to project future dynamic behaviour of ice sheets, and as observations of ice sheets indicate complex responses to recent climate changes, the credibility of extrapolations is difficult to assess.

Thus, owing to limitations of our current knowledge of the physics involved with ice-sheet stability, and the early stages of incorporating complex ice-sheet formulations in the climate models used to project climate change, various ways to estimate future sea-level rise have been devised. The most readily quantifiable involves computing thermal expansion of sea water from global climate models[9]. Recent estimates of sea-level rise calculated for the time period 1972–2008 (ref. 16) indicate a contribution from thermal expansion of about 0.8 mm yr^{-1} to a total sea-level rise of about 1.8±0.4 mm yr^{-1}, with the rest accounted for mostly by melting of glaciers and ice sheets[16]. However, there is the possibility that groundwater mining may have contributed between 0.4 and 0.8 mm yr^{-1} to sea-level rise in recent decades[17,18]. Current *in situ* and satellite observations show that the land-based ice is perhaps losing mass at an accelerated rate since the 1990s[14,19–22]. The estimated mass loss of mountain glaciers and ice caps was about 402±95 Gt yr^{-1} in 2006 (refs 19,20), making up about one-third of the global sea-level rise. The mass loss of the combined Greenland and Antarctic ice sheets is estimated to be more than 300 Gt yr^{-1}, which makes up about one-third of the observed global sea-level rise[14,22], leaving the contribution of seawater thermal expansion for roughly the other third. However, palaeoclimate evidence from the last interglacial period indicates a possible much larger role for ice-sheet melt from ice-sheet instability compared with thermal expansion for total sea-level rise[23]. The key uncertainty relates to timing. A few hundred years of warming (the time frame of this Perspective) may not be sufficient to trigger a multi-metre sea-level rise response, which took place over a much longer time period during the last interglacial.

Glaciers, ice sheets and sea-level rise

Future estimates of sea-level rise related to climate change commitment should presumably take into account aspects of possible future melting of glaciers and ice sheets. There have been several methods employed to do this. One is the example given in the Intergovernmental Panel on Climate Change (IPCC)'s fourth assessment report (AR4) of scaling-up estimated ice-sheet and glacial discharge observed over the recent time period into the future (Methods). This contribution is then added to that from thermal expansion[7,9]. Another method is so-called semi-empirical, whereby past time evolution of globally averaged surface air temperature or radiative forcing is tied to past sea-level rise, and this relationship is then used to project future sea-level rise that could be related to future

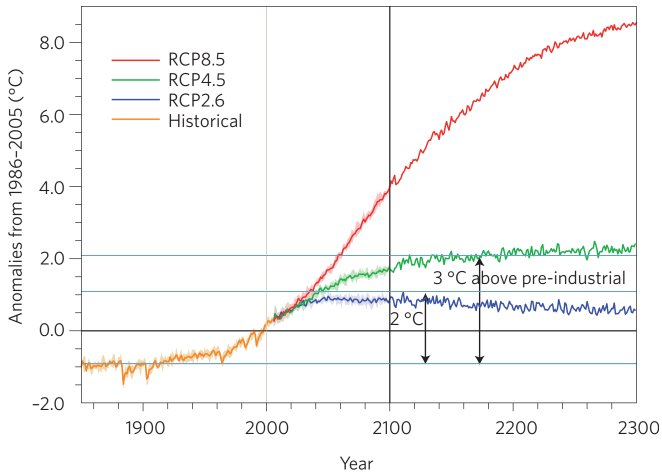

Figure 1 | Globally averaged surface air temperature. Time series of globally averaged surface air temperature anomalies from CCSM4 (using 1986–2005 as base period), for 1850 to 2005 (orange), and three RCP scenarios (RCP2.6, blue; RCP4.5, green; RCP8.5, red). Ensemble averages are solid lines (five-member ensembles to 2100, single members after 2100). Shading before 2100 is ±one standard deviation of the ensemble member values. Temperature changes of 2 °C and 3 °C compared with pre-industrial values are indicated with horizontal blue lines.

temperature increase[24,25]. A criticism of semi-empirical methods is that the training period from the twentieth century may not include all the ice-sheet instability processes and their connections to global temperatures that could affect the rate of future sea-level rise, particularly beyond 2100 (ref. 1), and some of these methods account for human-induced changes in the continental water balance involving reservoir impoundment but not groundwater mining.

For our purposes here, we will rely mainly on two methods of estimating sea-level rise. One will simply be the part due to thermal expansion of sea water computed from a global coupled climate model (CCSM4). The second will use the example in the IPCC AR4[9] whereby the contributions to sea-level rise from mass balance and area of glaciers and ice caps, ice-sheet surface mass balance and ice-sheet dynamics are linearly scaled by globally averaged surface air temperature in CCSM4 from the RCP simulations, with those contributions then added to the thermal expansion values from CCSM4 (Methods). A separate semi-empirical calculation based on globally averaged surface air temperature from the global climate model will represent the possibility of larger increases of sea level that have been posed in the literature, keeping in mind the caveats inherent in such methods as noted above[25]. Estimates of total sea-level rise are given here only to illustrate climate change commitment as it relates to mitigation, which is the main focus of this Perspective. Other methods, such as those using kinematic techniques[26], generally produce values encompassed by the range in the lower thermal expansion values and the higher semi-empirical methods. The Methods summarizes the sea-level rise calculations. Owing to the considerable uncertainties with total future sea-level rise, error bars are instructive only relative to the methods employed in the respective calculations and are not indicative of certainty of actual future sea-level rise associated with any particular method.

Sea-level rise in a cooling climate

The climate change commitment in thermal expansion can readily be demonstrated. In the lowest mitigation scenario, RCP2.6, even as global temperatures cool from +0.83 °C at 2100, to +0.66 °C at 2200 and +0.55 °C by 2300 (five-year averages centred on the year specified, compared with the 1986–2005 average; Fig. 1), sea-level rise owing to thermal expansion continues to increase, from

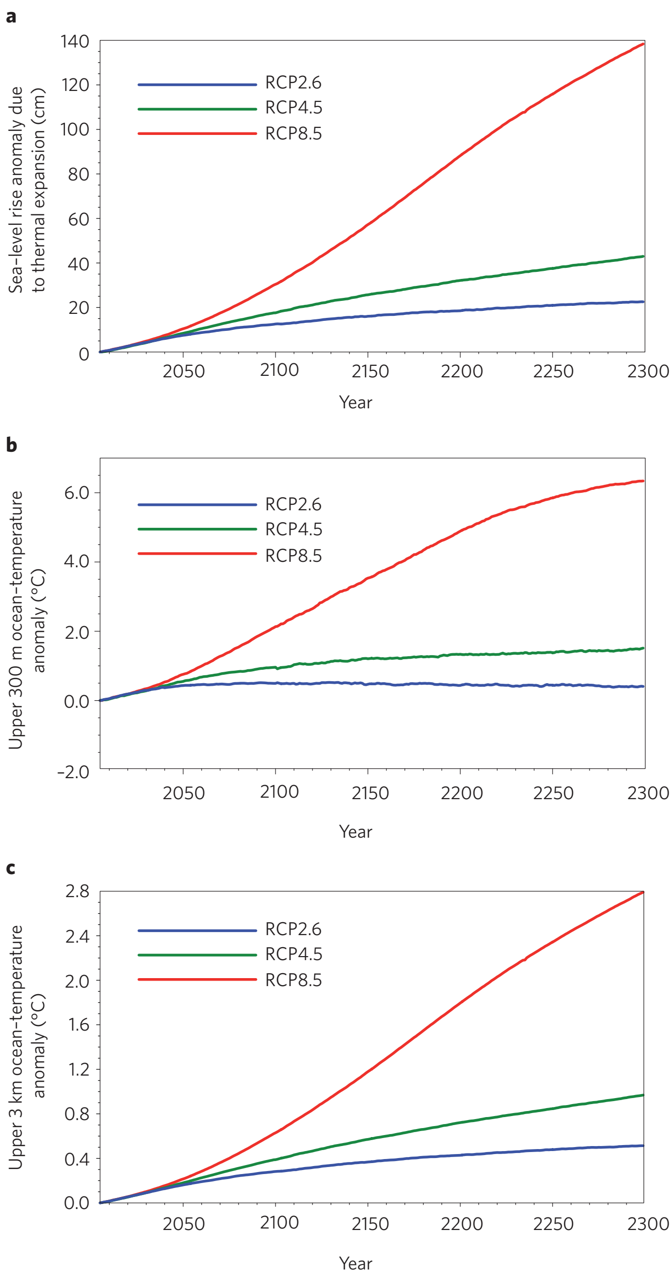

Figure 2 | Global sea-level rise anomaly due to thermal expansion and ocean-temperature anomalies. a, Globally averaged annual mean sea-level rise anomaly (relative to 1986–2005) due only to thermal expansion from CCSM4 for the three RCP scenarios. **b**, Globally averaged annual mean upper 300 m ocean-temperature anomaly (relative to 1986–2005) for the three scenarios. **c**, Globally averaged annual mean upper 3 km ocean-temperature anomaly (relative to 1986–2005) for the three scenarios. Note different vertical scales in middle and lower panels.

+14.2 cm at 2100 to +20.7 cm at 2200 and +24.2 cm at 2300 (Fig. 2a; standard deviation values are small and are not given here; see Methods). This is because of ongoing increases in ocean heat content in the upper 3 km of the ocean (0.31 °C in 2100, 0.46 °C at 2200 and 0.54 °C by 2300; Fig. 2c). It is clearly the deeper ocean that is contributing to this ongoing increase of sea-level rise owing to thermal expansion as the upper 300 m of the global ocean in RCP2.6 cools after 2100 (from 0.65 °C to 0.60 °C to 0.56 °C; Fig. 2b) along with the decreases in surface air temperature noted above (Fig. 1). Thus, even though the surface layer is cooling, heat is still being mixed down into the deeper layers from the intermediate layers, and that produces ongoing thermal expansion of the entire column. The processes that produce this warming of the deeper ocean include deep mixing in the North Atlantic and around Antarctica, vertical ocean circulations involving the subtropical ocean cells, particularly in the Pacific, and subgrid scale parameterizations including, for example, cross-isopycnal diffusion[10]. The actual rate of warming of the deep ocean will differ from model to model depending on how they account for these processes, but AOGCMs, such as the CCSM4 and the sample of four models taken from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Supplementary Table S1), all show that as globally averaged surface air temperatures cool in RCP2.6 after 2100, globally averaged sea level from thermal expansion continues to rise at least to 2300. The time evolution of globally averaged temperature and sea-level rise owing to thermal expansion in these four models is generally comparable to CCSM4 in Fig. 1 and Fig. 2a, respectively, with the variations of the sea level roughly scaling with global temperature change in most models as noted in Supplementary Table S1.

For a less-aggressive mitigation scenario (RCP4.5) in CCSM4, global temperatures begin to stabilize by 2100 at a value near 3 °C above pre-industrial (+1.70 °C compared with 1986–2005) and only increase another 0.18 °C from 2200 to 2300 (Fig. 1). However, sea level continues to increase owing to thermal expansion in this scenario after 2100, from an anomaly of +19.5 cm (five-year average centred on the year specified, compared with 1986–2005) at 2100, to +33.8 cm at 2200 and +44.4 cm at 2300. This is because upper 300 m ocean-temperature anomalies (from 2100 to 2300, +1.09 °C to +1.65 °C) and upper 3 km ocean-temperature anomalies (from 2100 to 2300, +0.42 °C to +1.00 °C) continue to increase. For the scenario with the least mitigation (RCP8.5), the temperature anomaly at 2100 compared with 1986–2005 is +3.91 °C with a sea-level rise anomaly from thermal expansion of +32.3 cm, and that increases steadily to +89.8 cm by 2200 and +139.4 cm by 2300.

To put these model results into context, idealized experiments with global coupled climate models that either reduce carbon dioxide concentrations in the future, or suddenly stop carbon dioxide emissions entirely, show ongoing future increases in sea-level rise owing to thermal expansion caused by continued growth of total ocean heat content[27–29]. The recent simulations by the sample of four global coupled climate models included in CMIP5 — with a range of climate sensitivities and temperature responses in the RCP simulations that bracket those for CCSM4 (Supplementary Information) — indicate, for RCP2.6, similar results to Fig. 2, in that all models have decreases in globally averaged surface air temperature after 2100 but increases in sea-level rise owing to thermal expansion as noted above (Supplementary Table S1). A counter-example where a decrease in globally averaged temperature in RCP2.6 led to a decrease in sea-level rise owing to thermal expansion comes from a simplified low-resolution model[30]. Most other results from such simplified models show increases in thermal expansion to 2300 when emissions are suddenly zeroed at 2100 and temperatures decrease[9]. Thus, the weight of evidence from global coupled climate model simulations that use scenarios where carbon dioxide concentrations and global temperatures decrease in the future support the result that sea-level rise owing to thermal expansion would continue to increase because of ongoing increases in ocean heat content, even as surface air temperatures decrease, for at least several hundred years.

Contributions from glaciers and ice sheets

By taking into account an estimate of additional contributions to sea-level rise from glacier and ice-sheet melting and ice-sheet instability, the example from IPCC AR4 shows a total sea-level rise anomaly in RCP2.6 (five-year average centred on the year specified, compared with the 1986–2005 base period) of +24.6 cm by 2100, and further increases to +38.7 cm at 2200 and +49.6 cm by 2300 (Fig. 3a). Similarly for RCP4.5, there is also an ongoing increase, from +36.7 cm in 2100, +71.3 cm at 2200 and +102.6 cm by 2300 (Fig. 3b). For RCP8.5, by 2100 sea level is estimated by this method to rise by +55.5 cm at 2100, +153.4 cm at 2200 and +250.2 cm by 2300 (Fig. 3c).

To show how a possible higher estimate of sea-level rise could relate to climate change commitment, the semi-empirical method (Fig. 3, upper range of shading) suggests, for the low RCP2.6 scenario, a sea-level rise at 2100 compared with 1986–2005 of about 100 cm, with a further rise to roughly 195 cm at 2200 and nearly 280 cm by 2300. This agrees with the thermal expansion and IPCC example results in Fig. 3 in showing continuing increases of sea level in RCP2.6 (Fig. 3c), even though global temperatures decrease after 2100 in that scenario (Fig. 1). For the IPCC AR4 method where mass balance and ice-sheet discharge are a function of globally averaged surface air temperature, there are decreases in the sea-level contribution in RCP2.6 from those sources. But the ongoing increases in thermal expansion are larger, thus producing the increases of total sea-level rise in RCP2.6 seen in Fig. 3c.

For the other two scenarios, the semi-empirical method also indicates greater increases than the IPCC AR4 example, with sea-level rise of nearly 115 cm and 145 cm by 2100 in RCP4.5 and RCP8.5, respectively, with an eventual increase approaching 440 cm and 960 cm for RCP4.5 and RCP8.5, respectively, by 2300. These values inform the upper range of the shading in Fig. 3 that encompasses the larger estimates. But the limit of the higher end of the shading is depicted as being indistinct to reflect that these are only estimates. There is no real way of knowing if these higher total sea-level rise values are credible, or if higher or lower values are more likely.

No matter what method is used for computing future total sea-level rise, the mechanisms of the ongoing increase in sea level, even in RCP2.6 when surface temperatures are decreasing after 2100, are related in part to downward diffusion of heat from upper layers to lower layers, downward transport of heat by mean ocean circulations, and a weakening of the processes that produce cold deep water — Antarctic Bottom Water formation and the meridional overturning circulation in the North Atlantic[10]. Thus there is less cold water penetrating to deeper depths, which produces a net increase in the heat content of deeper layers, in addition to the downward transport of heat and the gradual diffusion of heat from upper layers to lower layers. These processes introduce a timescale of centuries to essentially warm up the entire depth of the ocean in proportion to the net heat input at the surface. And as these deeper layers continue to warm, there is ongoing thermal expansion that contributes to sea-level rise, even when surface temperatures are decreasing.

Limitations in our knowledge and modelling tools mean that reliable estimates of the magnitude of future sea-level rise still contain considerable uncertainties, as highlighted here. We especially call attention to the extrapolation nature of the IPCC example and the semi-empirical method. In lieu of credible simulations of coupled ice-sheet dynamics in climate models, there are significant caveats associated with any estimate of future sea-level rise out to 2300. There is at present no way to reliably evaluate the upper limits on future sea-level rise. The most credible calculation from the models comes from the sea-level rise owing to thermal expansion, but that is almost certainly a low estimate given the likelihood of further contributions from ice-sheet melting. However, our purpose is to make the point that even with aggressive mitigation measures in RCP2.6 that limit global warming to less than 2 °C above pre-industrial values by 2100, and with decreases of global temperature in the twenty-second and twenty-third centuries, because of climate change commitment, sea level continues to rise after 2100 in RCP2.6. With more moderate mitigation in RCP4.5 and little mitigation in RCP8.5, there are even larger ongoing increases of sea level. Thus, though we could possibly level off and even decrease global temperatures and reduce the climate impacts in the atmosphere and at Earth's surface, it is more difficult to stabilize sea-level rise. Even with the likelihood of ongoing sea-level rise at least for several centuries in these scenarios, with aggressive mitigation in RCP2.6 the increases in sea level are likely to be much less than those in the less-aggressive scenario RCP4.5, and very much less than in RCP8.5. This is significant because aggressive mitigation buys time to enact adaptation measures.

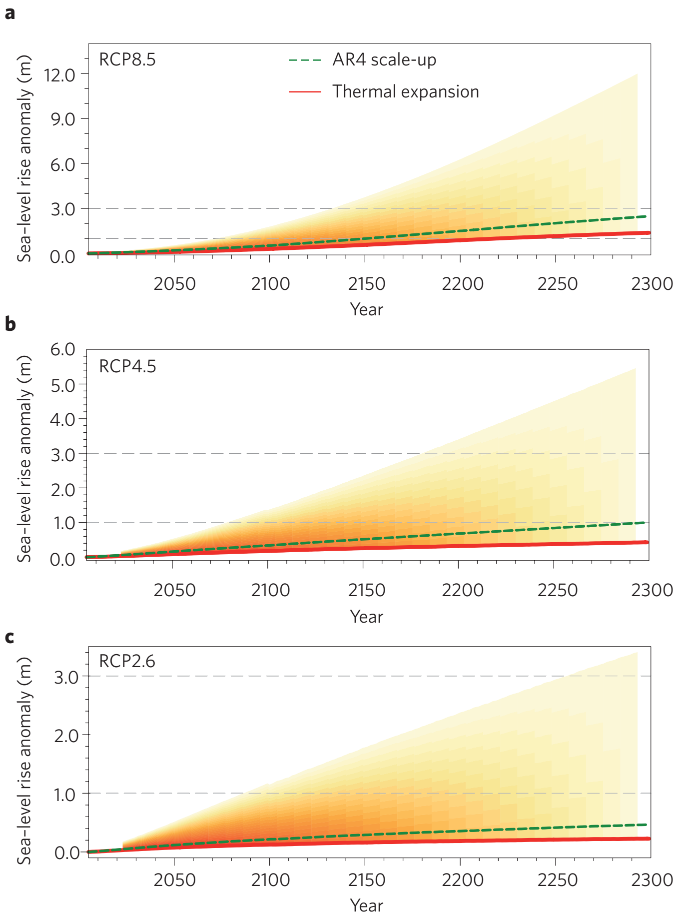

Figure 3 | Global sea-level anomalies. Globally averaged sea-level rise anomaly (relative to 1986–2005) owing to thermal expansion (red line, as in Fig. 2), and the example from the IPCC AR4 (dashed green line) for RCP8.5 (**a**), RCP4.5 (**b**) and RCP2.6 (**c**). Note different vertical scales in the three panels; 1 m and 3 m sea-level rise values are grey dashed lines in each panel. Shading highlights uncertainty in future total sea-level rise projections, with lighter shading becoming less certain. Estimates calculated from a semi-empirical method lie near the upper limit of the shading that becomes less distinct with higher values.

Methods

The CCSM4 includes a finite volume 1° version of the Community Atmosphere Model (CAM4), with improved components of ocean, land and sea ice compared with CCSM3[31]. CCSM4 has been shown to credibly simulate a number of aspects of observed climate[6,10]. Grid points in the atmosphere are spaced roughly every 1° in latitude and longitude, and there are 26 levels in the vertical. The ocean is a version of the Parallel Ocean Program (POP) with a nominal latitude–longitude resolution of 1° (down to 1/4° in latitude in the equatorial tropics) and 60 levels in the vertical. No flux adjustments are used in CCSM4. Equilibrium climate sensitivity of CCSM4 is 3.20 °C (ref. 6), within the likely range given in the IPCC AR4 of 2.0 °C to 4.5 °C, and close to the most likely value of about 3 °C (ref. 9). A sample of four other AOGCMs from the CMIP5 multi-model data set shown in the Supplementary Information show that the response of the CCSM4 is in the middle of the range of temperature responses for the RCP scenarios simulated by those models (with equilibrium climate sensitivities from those models that range from 2.45 °C to 4.42 °C). CCSM4 can thus be considered representative of the current class of AOGCMs used for climate change studies.

The future climate simulations begin on 1 January 2006, and follow three mitigation scenarios termed RCPs[3,4]. These scenarios are meant to represent classes of mitigation scenarios that produce emission pathways following various assumed policy decisions that would influence the time evolution of the future emissions of greenhouse gases, aerosols and ozone, as well as specifications of land-use/land-cover change[3,4]. More information regarding carbon dioxide emissions and concentrations in the RCPs is given in the Supplementary Information.

The method used to calculate sea-level rise described in the IPCC AR4 is an example of contributions to sea-level rise coming from sources other than thermal expansion and involves accounting for mass balance and area of glaciers and ice caps, ice-sheet mass balance and ice-sheet dynamics as a function of globally averaged surface air temperature (for a full description, see ref. 9).

The semi-empirical model of sea level rise[24,25] relies on estimates from observations and model simulations of the coefficients of a linear relationship between the rate of sea-level rise at time t, $dH(t)/dt$, where $H(t)$ represents the global mean sea level at time t; the global warming from a reference period, $T(t) - T(0)$, where $T(t)$ represents global average temperature at time t; and a measure of instantaneous global warming, $dT(t)/dt$ as in: $dH(t)/dt = a^*(T(t) - T(0)) + b^*dT(t)/dt$. With empirically derived estimates of the coefficients a and b and an estimate of the value $T(0)$, the future global temperature ($T(t)$, for any future t) can be used to infer projections of global sea-level rise.

Uncertainties in estimates of sea-level rise are large, as seen above. For the calculations performed here, the range of results from five-member ensembles from CCSM4 is used for thermal expansion, and the error bars from the IPCC AR4 example are scaled linearly with globally averaged temperature and are applied to the sea-level rise estimates. To calculate the standard deviations for the ocean-temperature anomaly and thermal expansion values, the ensemble mean time series is removed from the raw time series of the sea-level anomaly (thermal expansion only) or from the global ocean heat content ensemble members. Then the standard deviation is calculated for each of the ensemble members, and the average standard deviation is computed across the ensemble members. However, the standard deviations for all these values are small (less than 2% of the anomalies) owing to the similarity of the ensemble members and the fact that there is little interannual variability. Thus, only the ensemble mean values for vertically averaged ocean temperatures, sea-level rise from thermal expansion and the IPCC AR4 scale-up example are given in the text.

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Additional information

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