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Mitigation of short-lived climate pollutants slows sea-level rise

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Under present growth rates of greenhouse gas and black carbon aerosol emissions, global mean temperatures can warm by as much as 2 °C from pre-industrial temperatures by about 2050[1,2]. Mitigation of the four short-lived climate pollutants (SLCPs), methane, tropospheric ozone, hydrofluorocarbons and black carbon, has been shown to reduce the warming trend by about 50% (refs 1,2) by 2050. Here we focus on the potential impact of this SLCP mitigation on global sea-level rise (SLR). The temperature projections under various SLCP scenarios simulated by an energy-balance climate model[1] are integrated with a semi-empirical SLR model[3], derived from past trends in temperatures and SLR, to simulate future trends in SLR. A coupled ocean–atmosphere climate model[4] is also used to estimate SLR trends due to just the ocean thermal expansion. Our results show that SLCP mitigation can have significant effects on SLR. It can decrease the SLR rate by 24–50% and reduce the cumulative SLR by 22–42% by 2100. If the SLCP mitigation is delayed by 25 years, the warming from pre-industrial temperature exceeds 2 °C by 2050 and the impact of mitigation actions on SLR is reduced by about a third.

Anthropogenic greenhouse gases (GHGs), including CO_2, have added 3 W m^{-2} forcing from the pre-industrial times to the year 2005 (ref. 5). This extra forcing will not only cause a large warming of our planet[6,7], but will also contribute to SLR (refs 8,9). Even if the world tries to limit global warming through significant reduction of the CO_2 emissions[10], for example, a reduction by about 50% by 2050 and 80% by 2075, the CO_2 concentrations will still peak at 440 ppm later this century, bringing the total GHG forcing to 4 W m^{-2} (ref. 7). The committed equilibrium warming associated with this forcing, if fully realized without the cooling effect of anthropogenic aerosols, would be about 3.2 °C (2–4.8 °C; ref. 7) and could potentially lead to significant changes in Earth's cryosphere and SLR.

Faced with such possibilities, numerous studies[1,2,11,12] have focused on non-CO_2 climate warming agents, particularly the so-called SLCPs, which contribute as much as 40% to radiative forcing[1,5]. As the lifetimes of these SLCPs are in the range of a week (black carbon), to a month (ozone), to a decade (methane and hydrofluorocarbons (HFCs)), an emission reduction of these SLCPs would lead to a reduction in their atmospheric concentrations and their radiative forcing within weeks to a few decades. Recent studies[1,2,13] have estimated that the mid-century warming could be reduced by about 0.6 °C, leading to a delayed onset of the 2 °C warming by several decades. Model studies show that even under aggressive mitigation of GHGs, sea level will continue to rise for centuries owing to the oceanic inertia[14]. The objective of this study is to examine the role of SLCP mitigation on the projected twenty-first-century SLR.

Our starting point is the simple climate–carbon–geochemistry model and the mitigation steps are described in ref. 1 (see Methods). The model in ref. 1 has been calibrated and validated with more complex three-dimensional models (see Methods). The SLCP mitigation steps are also consistent with those recommended in a recent international report[2]. The output from the model in ref. 1 is used in conjunction with the semi-empirical SLR model of ref. 3 to estimate the response of SLR to SLCP mitigation. The latter model basically relates global trends in temperatures (T') to global trends in SLR (Methods). The coefficients that relate SLRs to T' are derived by two different approaches.

In the SLR_{ther} approach, we used the output of T' and SLR from the Community Climate System Model (CCSM4; ref. 4) to obtain the coefficients. CCSM4, like other coupled climate models, does not account for SLR due to melting of land ice and hence the SLR from this approach is that due to only thermal expansion and is referred to as SLR_{ther}. Owing to the similar climate sensitivity of the model in ref. 1 (3 °C for doubling of CO_2) and CCSM4 (3.2 °C) and the ability of the former to reproduce the time evolution of the temperature response of CCSM4 for the projected greenhouse changes (Supplementary Fig. S1), we apply the relationship obtained from CCSM4 to the simulated temperature trends of the model in ref. 1 to estimate SLR_{ther} (see Supplementary Fig. S2a). As indicated by previous studies[14], SLR_{ther} may be viewed as bracketing the range of SLR projections on the lower end, because it excludes the contribution of land-based ice melt. In particular, recent observation-based estimations show that the land-ice melt (mountain glaciers, ice caps and ice sheets) contributed at least half of the observed SLR in recent years[15–18].

As process-based climate models such as CCSM4 do not include an interactive ice-sheet model, it is not possible to estimate the contributions of the land-based ice loss to future SLR from such models. Therefore, we derived the coefficients for SLR_{full} using the standard semi-empirical model of ref. 3 trained on observations of T' (ref. 19) and SLR (ref. 20). This approach implicitly allows for the effects of thermal expansion as well as those of melting land ice. For our projections, SLR_{full} provides the upper range of SLR.

The emissions scenarios used here are exactly the same as those in ref. 1 (such as black carbon, methane, NO_x, SO_2, HFCs, CFCs and others), except for the CO_2 emission. For the CO_2 emission path, we adopt the Representative Concentration Pathway (RCP)6.0 scenario, which we consider as the CO_2 business as usual (BAU) case, and the RCP2.6 for the mitigation case. The SLCP mitigation scenarios that were used in ref. 1

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Table 1 | Projected temperature change (ΔT) and SLR (ΔSLR)

Case	Mid-twenty-first century (2005–2050)			End of twenty-first century (2005–2100)		
	ΔT (°C)	SLR_R at 2050	ΔSLR (cm)	ΔT (°C)	SLR_R at 2100	ΔSLR (cm)
BAU_{full}	1.6 [1.0, 2.4]	1.1 ± 0.4 [0.4, 2.2]	30.1 ± 10.9 [12, 61]	3.5 [2.2, 5.3]	2.1 ± 0.6 [0.9, 4]	112.2 ± 34.0 [49, 219]
$CO_{2\ full}$	1.5 [0.9, 2.3]	1.1 ± 0.4 [0.4, 2.2]	30.1 ± 11.0 [11.9, 61]	2.4 [1.5, 3.6]	1.6 ± 0.5 [0.7, 3]	102.1 ± 30.9 [44, 199]
$SLCP_{full}$	1 [0.6, 1.5]	0.9 ± 0.33 [0.4, 1.8]	27.1 ± 10.0 [10.7, 56]	2.4 [1.5, 3.6]	1.6 ± 0.5 [0.7, 3]	87.1 ± 26.2 [38, 170]
$CO_2 + SLCP_{full}$	0.9 [0.6, 1.4]	0.9 ± 0.34 [0.4, 1.8]	27.1 ± 10.1 [10.6, 56]	1.2 [0.8,1.8]	1.1 ± 0.3 [0.5, 2]	77 ± 23.1 [34, 150]
BAU_{ther}	1.6 [1.0,2.4]	0.29 ± 0.006 [0.18, 0.4]	9.3 ± 0.2 [5.7, 14]	3.5 [2.2, 5.3]	0.39 ± 0.004 [0.24, 0.6]	26.4 ± 0.3 [16, 40]
$CO_{2\ ther}$	1.5 [0.9, 2.3]	0.28 ± 0.006 [0.17, 0.4]	9.3 ± 0.2 [5.7, 14]	2.4 [1.5, 3.6]	0.30 ± 0.004 [0.19, 0.5]	24.1 ± 0.3 [15, 36]
$SLCP_{ther}$	1 [0.6, 1.5]	0.15 ± 0.002 [0.09, 0.2]	6.4 ± 0.1 [3.9, 10]	2.4 [1.5, 3.6]	0.18 ± 0.002 [0.11, 0.3]	15.3 ± 0.2 [9, 23]
$CO_2 + SLCP_{ther}$	0.9 [0.6, 1.4]	0.15 ± 0.002 [0.09,0.2]	6.4 ± 0.1 [3.9, 10]	1.2 [0.8,1.8]	0.13 ± 0.002 [0.08, 0.2]	13.4 ± 0.2 [8, 20]

SLR_R is the annual rate of increase at a certain year (2050 or 2100) in cm yr^{-1}. The full case estimates SLR using ref. 3, and the ther case accounts only for the thermosteric SLR. The 90% confidence interval for ΔT is given in square brackets (see Supplementary Fig. S3a for probability distribution function). The ± range next to the central value for SLR_R and for ΔSLR denotes the uncertainties in the semi-empirical model for SLR from ref. 3. The combined uncertainty range due to the uncertainty in the climate sensitivity and the uncertainty in the model of ref. 3 for SLR_R and ΔSLR is shown in square brackets. See Supplementary Fig. S3b for the propagation of uncertainty from temperature to SLR.

(also by ref. 2) were from the International Institute for Applied Systems Analysis (IIASA) model[21] that included a set of measures for mitigating SLCPs, assuming maximum adaptation of available technologies.

The uncertainties in our projections of SLR are twofold. First is the uncertainty in the simulated T', which is due to the roughly threefold uncertainty in the assumed climate sensitivity (0.8 °C per W m^{-2}) with 90% probability of 0.5–1.2 °C per W m^{-2}; ref. 6. The probability distribution of T' and its impact on SLR are shown in Supplementary Fig. S3a,b. The 90% confidence intervals for the projected T' are shown in Table 1. The second source of uncertainty is in the coefficients that relate T' to SLR, which is largely contributed by two factors. The main factor is the uncertainty in the response of the mountain glaciers, ice caps and ice sheets to future warming. Our knowledge of this area is in its infancy. Only in recent years, we have been able to roughly quantify the role of land ice in the observed SLR trends of the past century[15–18]. The other factor contributing to the uncertainty in the model of ref. 3 is in the errors in the input data (T' and SLR). We adopted a 2006 version of the data[20] and tested different surface temperature data sets (HadCRUTv3, HadCRUTv4, GISS and NOAA; see Supplementary Information). Although the estimated coefficients of the four resulting models are nearly identical, the SLR values for the future yield from 2006 and 2011 versions of the SLR observational data set[20,22] differ by as much as 30% (see Supplementary Fig. S4)[23]. However, the percentage change in SLR due to SLCP mitigation, compared with a baseline scenario with no mitigation, was nearly the same at about 25% for both the 2006 and 2011 versions of the historical data sets. We adopt the uncertainty for the SLR model from ref. 3. Table 1 shows the uncertainty in the projected SLR due to the uncertainty in the model of ref. 3 as well as the range in the projected SLR due to the joint uncertainties in the climate model and in the SLR model of ref. 3. Owing to all of these uncertainties, we acknowledge that projections of SLR are valid mainly in a qualitative and relative sense. As a result, we focus on the percentage changes in SLR (compared with the reference case of no mitigation) rather than the absolute values of SLR trends. This approach minimizes propagation of errors due to the uncertainties listed above.

Figure 1 shows the projected twenty-first-century temperature trends for four scenarios: the BAU case (RCP6.0) with the CO_2 peaking at about 670 ppm by 2100 (Supplementary Fig. S5); the CO_2-stabilization case (denoted as CO_2 in Fig. 1) as in RCP2.6 with CO_2 peaking at 440 ppm and reducing to 420 ppm by 2100 (Supplementary Fig. S5); the SLCP case that starts with the BAU case and mitigation of only SLCPs as in ref. 1; the case of CO_2 and SLCP mitigation.

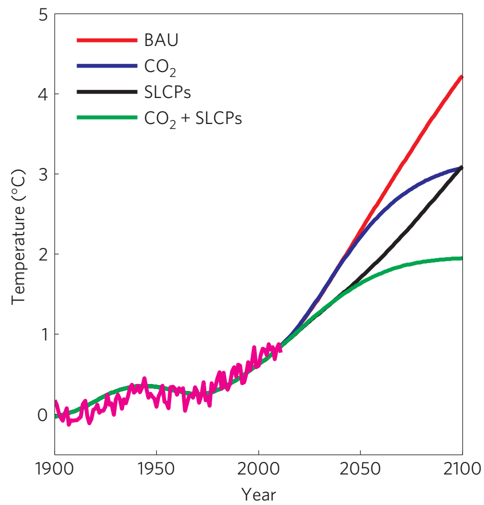

Figure 1 | Observed and simulated global mean surface temperature. The red line is for the BAU case, the blue line is for the CO_2 mitigation case, the black line is for the SLCP mitigation case and the green line is for the CO_2 + SLCP mitigation case. The temperature estimates are based on the central value of climate sensitivity. See Supplementary Fig. S3 for a probability distribution of temperature due to climate sensitivity uncertainty. The temperature curves shown are anomalies relative to the 1900–1910 mean. Observations are shown from 1900 to 2011 (ref. 19) in pink.

The simulated warming in the BAU case is 4.2 °C from pre-industrial to 2100, within the range of warming[24] projected under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios[10]. Without CO_2 mitigation, the planet will warm 3.5 °C during the twenty-first century. About 0.6 °C of this warming is due to the disappearance of the masking effect of sulphate cooling through reduction of SO_2 emissions (Supplementary Fig. S6). As concluded in ref. 1 and later reproduced by the United Nations Environment Programme studies[2,13], neither the mitigation of CO_2 nor that of SLCPs by itself is sufficient to limit maximum warming to below 2 °C. The CO_2 mitigation by itself reduces the projected warming by 1.1 °C by 2100 and SLCP mitigation reduces it by another 1.1 °C. By 2050, on the other hand, the SLCPs reduce projected warming by 0.6 °C and CO_2 only about 0.1 °C. In the near-term, SLCP mitigation is more effective than that of CO_2. However, by the year 2100 or beyond, the CO_2 mitigation effect will become critical for limiting the warming below 2 °C. Owing to the centuries to longer lifetimes

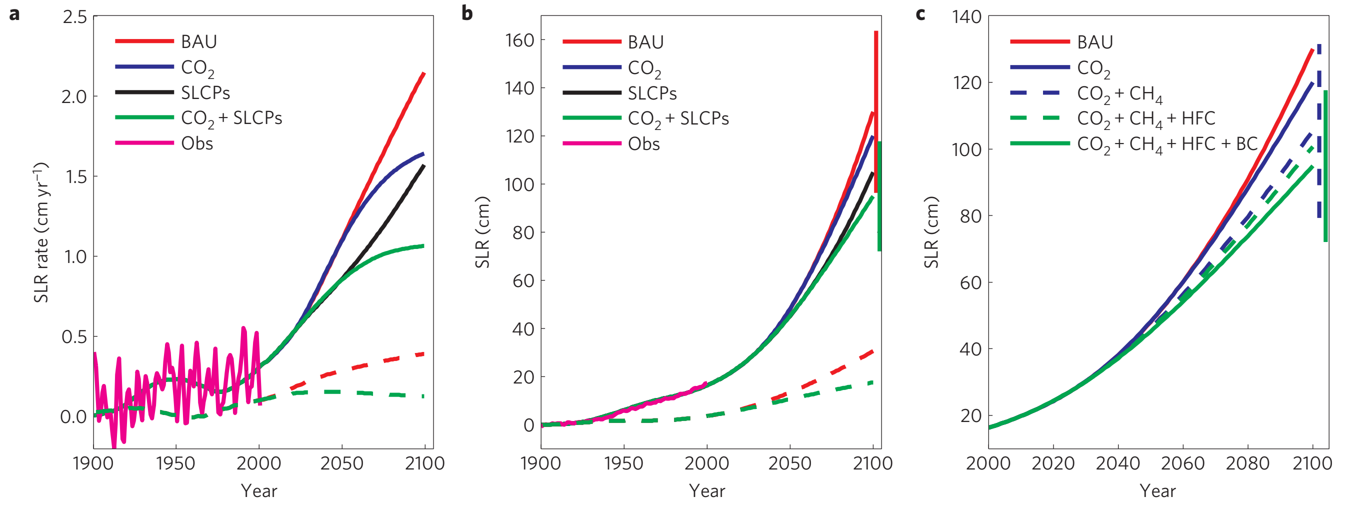

Figure 2 | SLR changes in different scenarios. **a**, The annual rate of SLR. **b**, SLR since 1900. Observations are shown from 1900 to 2001[20]. The uncertainty of model-projected SLR at the end of the twenty-first century is shown for the BAU and CO_2 + SLCP cases. The dashed lines indicate model simulations that consider only SLR due to thermal expansion. **c**, Contributions of individual SLCPs to SLR since 1900. The uncertainty of model-projected SLR at the end of the twenty-first century, due to the semi-empirical SLR model, is shown for the $CO_2 + CH_4$ and $CO_2 + CH_4$ + HFC + BC cases. Note that the contribution of CH_4 also includes the indirect contribution of CH_4 and CO to ozone forcing. CH_4, methane; BC, black carbon.

of CO_2, delaying mitigation actions to cut CO_2 will reduce its long-term effectiveness[25].

SLR results for the four scenarios are shown in Fig. 2 (the uncertainty ranges are given in Supplementary Figs S7 and S8) and summarized in Table 1. In comparison with the BAU case, mitigation of SLCPs can reduce the SLR_{full} rate by about 18% (from 1.1 cm yr^{-1} to about 0.9 cm yr^{-1}), and the SLR_{ther} rate by about 48% (from 0.29 cm yr^{-1} to 0.15 cm yr^{-1}), with negligible effect from CO_2 reduction before 2050. By 2100, however, CO_2 mitigation can reduce the SLR_{full} rate by about 24% (from 2.1 to 1.6 cm yr^{-1}), and the SLR_{ther} rate by about 25% (from 0.4 to 0.3 cm yr^{-1}). The SLCP mitigation would contribute about 24% of the SLR_{full} rate reduction, and 54% of the SLR_{ther} rate at 2100. With mitigation of both SLCPs and CO_2, the projected SLR rate is reduced by close to 50% for SLR_{full}, and 67% for SLR_{ther} by 2100.

The accumulated SLR by 2100 (from the pre-industrial level) for the BAU case is 130.1 ± 34 cm for SLR_{full} and 30.7 ± 0.3 cm for SLR_{ther} (Table 1 and Fig. 2b). It is clear that the SLR_{ther} is significantly lower than the observed SLR for the twentieth century (4.3 cm versus 19.9 cm; Supplementary Table S1). As the SLR_{ther} accounts only for the effect of oceanic heat uptake, which is estimated to have contributed around 44% of the observed SLR in the past 50 years[16], it is virtually certain that the SLR_{ther} will be also lower than the total SLR for the twenty-first century. If the future contribution to SLR from the thermosteric effect and the melting of the land ice[15–18] were to be the same as in the past half century, the model-predicted SLR_{ther} could be scaled up by at least a factor of 2, leading to a potential total SLR by 2100 of 62 cm, which reaches the upper bound of the IPCC Fourth Assessment Report (AR4) projection[6]. On the other hand, the SLR_{full} projects a much larger SLR by the end of the twenty-first century than that projected in IPCC AR4 (ref. 6) and other studies[26,27]. One of the causes may be traced to the fact that the model in ref. 3 accounts for the accelerated melt rate of continental glaciers and ice sheets based on the observed rates of the past few decades, and extrapolates such effects forward. A full account of the differences between the semi-empirical approach and the process-based estimates for the various components of SLR has not been made yet, and the land-based ice-loss projection is also an uncertain component of the overall projection.

With both the CO_2 and the SLCP mitigation, the projected SLR_{full} (from 2005 to 2100) is reduced by 31% from the BAU case; about 9% of that 31% is due to CO_2 mitigation and the balance of 22% is due to SLCPs. The projected SLR_{ther} increase is reduced by about 50%, of which about 8% is due to CO_2 mitigation and 42% is due to SLCP mitigation. Overall, SLCP mitigation is much more effective in curbing SLR in comparison with CO_2 mitigation on decadal to centennial timescales. It could also keep the cumulative SLR (from the pre-industrial era) lower during the twenty-first century than otherwise.

The individual contributions from the various SLCPs are shown in Fig. 2c. The methane mitigation has the largest effect in mitigating SLR with CO_2 next, followed by black carbon and HFCs. Most (~53%) of the methane effects on temperature and SLR, shown in Fig. 2c, are due to the direct greenhouse effect. As methane is also involved in complex photochemical destruction and chemical oxidation processes in the atmosphere, about 27% of its effects are due to indirectly reducing tropospheric ozone, stratospheric water vapour and CO_2. The balance of 20% is due to CO mitigation actions reducing production of tropospheric ozone and methane.

The characteristics of the simulated warming and SLR for CO_2 and SLCP mitigation by mid and the end of the twenty-first century are summarized in Table 1. Starting first with the temperature trends for the BAU case, if we follow the RCP6.0 for CO_2 emission (see Supplementary Fig. S5) and continue the present trend in mitigation of SO_2 emissions (reducing SO_2 emissions by 60% by 2050), both of which contribute to warming, we will exceed the 2 °C warming threshold before 2050 (Fig. 1). The SLR rate will increase by up to a factor of 3 by 2050 and by a factor of 6 by the end of the century if the high end of the SLR estimation is realized. Even the pronounced CO_2 mitigation considered here (Supplementary Fig. S5) will be unable to curb it because of the nearly negligible impact of this CO_2 mitigation on the warming and SLR by mid-twenty-first century. SLCP mitigation, on the other hand, reduces the mid-twenty-first century warming by 0.6 °C and delays the 2 °C warming by three decades to beyond 2050. However, even with SLCP mitigations, the effect on slowing the projected SLR (for mid-century) is small for SLR_{full} (10%), but relatively large for SLR_{ther} (30%).

By the end of the twenty-first century, the effect of CO_2 mitigation on temperature increases by tenfold to ~1.1 °C compared with the mitigation of 0.1 °C by 2050. This, in conjunction with the SLCP mitigation, is sufficient to avoid reaching the 2 °C threshold until 2100, and reduces the cumulative SLR by 31–50% (up to 35 cm). However, to achieve this goal, SLCP emission reduction has to begin now (2015). If, for example, we postpone CH_4 and black carbon mitigation until 2030–2040 instead of 2015 (Supplementary Fig. S9), the longer-term warming increases by another 0.2 °C and the pre-industrial to year 2100 warming will exceed 2 °C by mid century. According to the projections, the delayed actions can increase SLR by 9–11%.

Overall, the mitigation of CO_2 and SLCPs could not only keep the global warming under check, but can also reduce the projected SLR by 31–50%, and reduce the projected SLR rate by 50–66% by 2100. A delayed SLCP mitigation by about 25 years could reduce the impact of the CO_2 and SLCP mitigation on SLR by about 30%. Our study focuses only on the global mean SLR. Earlier studies indicate that the SLR is not uniform globally[28–30]. Owing to changes of the ocean circulation in response to global warming[28] and changes of the ice-sheet mass and associated gravity effect[29,30], certain regions would expect SLR significantly above the global mean.

Methods

The model in ref. 1. The model integrates an energy-balance climate model with the BERN CO_2–geochemistry model. An energy-balance climate model with a 300-m effective ocean mixed layer is then used to simulate the temporal evolution of global mean surface temperature. The main adjustable parameters of the model in ref. 1 are the slab ocean depth and climate sensitivity. With time-varying GHG and aerosol forcing (as prescribed in IPCC AR4), the model in ref. 1 is able to reproduce the twentieth-century trends in temperature (Fig. 1), ocean heat storage[1] and CO_2 concentrations[1]. In ref. 1, a 60-yr cycle of forcing was also included to mimic the multi-decadal variability of temperature. In this paper we did not extend that cycle into future projection, as it is not clear whether such a multi-decadal variation will be preserved in the twenty-first century. Full details of this model along with its validation (by comparing it to the observed twentieth-century changes in CO_2 concentrations, temperature and ocean heat content) are given in ref. 1. To further verify the performance of the model in ref. 1 in simulating future temperature, here we show under RCP scenarios that this model produces similar twenty-first-century surface temperature trends as simulated by a fully coupled state-of-art ocean–atmosphere model (Supplementary Fig. S1)—CCSM4 (ref. 4). As the aerosol indirect effect is not accounted for in CCSM4, we also exclude it from the model of ref. 1 in this simulation alone.

Scenarios. The CO_2 BAU scenario is RCP6.0 with a CO_2 concentration that peaks at about 670 ppm by 2100 (Supplementary Fig. S1b). In the CO_2 mitigation case, CO_2 emissions are reduced as in RCP2.6 with CO_2 concentration peaking at 440 ppm by mid-twenty-first century and reducing to 420 ppm at the end of the twenty-first century. In the BAU scenario the emissions of non-CO_2 GHGs peak at 2030 and remain at the 2030 level until 2100. We also follow the IIASA scenario[21] and assume that present air pollution laws for reducing SO_2 emissions in developed nations will be implemented worldwide, such that global SO_2 emissions will be reduced by 60% by 2050 as projected by the IIASA study[21]. The SLCP mitigation scenario of the model in ref. 1 and this study adopts IIASA projections for the maximum feasible reductions (with present technologies) for three of the four SLCPs: reductions of 50% in CO emissions and 30% in methane emissions by 2030; and 50% in black carbon emissions by 2050. It is important to note that methane emissions in the BAU case increase by about 35% (from the 2005 levels) by 2030 and thus a 30% reduction in methane emissions from the year 2005 is really about a 50% reduction from the potential peak emissions in 2030 in the BAU case. A similar situation applies to black carbon and CO emissions.

SLR model. The authors of ref. 3 proposed the following relation between the global rate of SLR at time t, dH_t/dt, the short-term (yearly) change in global average temperature, dG_t/dt, and the long-term change in global average temperature with respect to a baseline value at, say, T_0, $G_t - G_{T0}$:

$$dH_t/dt = a(G_t - G_{T0}) + b(dG_t/dt)$$

Thus, this semi-empirical SLR model links global average temperature changes to global mean SLR by estimating the parameters of a linear relationship between the two. Extensive validation of the relation is performed in ref. 3 through the use of atmosphere–ocean general circulation model output and its robustness is further tested in ref. 23. It should be emphasized that the projection of SLR from this semi-empirical model is used only in a relative sense. That is, instead of citing the magnitude of SLR we cite only the percentage difference compared with a reference case with no mitigation actions.

The estimates of the coefficients of the full model are based on a fit of the observed records of global temperature and SLR (ref. 3). The estimates of the model that delivers only the thermosteric components are based on a fit to CCSM4 output of global temperature and the thermosteric component of global sea-level change. We choose to limit the range of our projections to 2100, because of the potential limitations in the reliability of the semi-empirical model approach, whose nature is that of an extrapolation.

In our study, we obtain a, b, G_{T0} as 0.528, −3.631, −0.397, respectively, for the full model (SLR_{full}) on the basis of observations[19,20] (not significantly different from the estimates in ref. 3; the slight difference is due to the use of a different numerical routine for smoothing the time series of temperature before using them as predictors; this was necessitated because we translated the code from Matlab to R), and −0.066, 3.300, −0.051 for the thermosteric-only component (SLR_{ther}) on the basis of CCSM4 output[4], using a calibration period of 1900–2001 for SLR_{full} and from 1850 to 2005 for SLR_{ther}. Then, temperature output from our simple model simulations is used in place of G_t to estimate future rates of SLR (and the corresponding cumulative rise) under alternative emission scenarios.

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Author contributions

V.R. designed and led the study, A.H., Y.X., C.T. and W.M.W. contributed to the model simulations and data analysis, and all authors actively contributed to writing the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.