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Tension between reducing sea-level rise and global warming through solar-radiation management

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Geoengineering using solar-radiation management (SRM) is gaining interest as a potential strategy to reduce future climate change impacts[1–3]. Basic physics and past observations suggest that reducing insolation will, on average, cool the Earth. It is uncertain, however, whether SRM can reduce climate change stressors such as sea-level rise or rates of surface air temperature change[1,4–6]. Here we use an Earth system model of intermediate complexity to quantify the possible response of sea levels and surface air temperatures to projected climate forcings[7] and SRM strategies. We find that SRM strategies introduce a potentially strong tension between the objectives to reduce (1) the rate of temperature change and (2) sea-level rise. This tension arises primarily because surface air temperatures respond faster to radiative forcings than sea levels. Our results show that the forcing required to stop sea-level rise could cause a rapid cooling with a rate similar to the peak business-as-usual warming rate. Furthermore, termination of SRM was found to produce warming rates up to five times greater than the maximum rates under the business-as-usual CO_2 scenario, whereas sea-level rise rates were only 30% higher. Reducing these risks requires a slow phase-out of many decades and thus commits future generations.

Geoengineering via solar-radiation management (SRM) has been proposed as a means to address climate change impacts[3,8]. Past studies analysed a wide range of SRM objectives including: returning global average temperature to the pre-industrial[9,10], holding global average temperature constant[11,12], limiting sea-level rise[13] and maximizing economic net-benefits[14,15]. It has been claimed that SRM might be designed to be Pareto improving[15] (that is, no region would be worse off). Other studies point out, however, that there could be 'international conflicts over some geoengineering'[16]. Previous work has questioned whether there could be 'geoengineering wars'[14] and conclude that a 'credible threat of unilateral geoengineering' (for example, by a 'rogue nation') may change the incentives for a global reduction in greenhouse-gas emissions[17]. These studies have broken important new ground, but they are mostly silent on climate stressors beyond surface air temperatures, precipitation or sea-level rise. However, the rate of surface air temperature changes[18] may be a key determinant of climate change impacts. This raises two important questions: (1) How large are the potential conflicts between regions primarily concerned with rising sea levels[19] and the rates of surface air temperature? (2) How large are the potential conflicts across generations owing to the need to maintain SRM (even in cases when serious negative impacts of SRM are discovered) to avoid potentially damaging abrupt warmings?

Fundamental physical reasoning suggests there is a potentially strong tension between two key determinants of climate change impacts: (1) the rate of surface air temperature changes[18] and

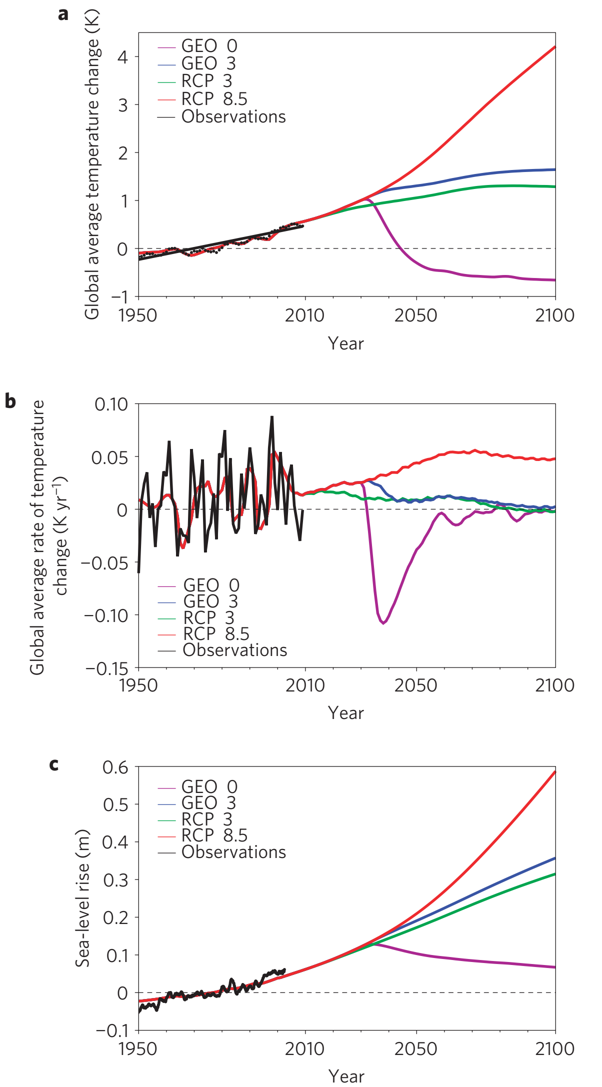

Figure 1 | Hindcasts and projections of surface air temperature, rate of temperature change, and sea-level rise. Surface air temperature (**a**), rate of temperature change (**b**), and sea-level rise (**c**), compared against observational data[25,26]. The geoengineering scenarios have the same greenhouse forcing as RCP 8.5, but with −5.5 W m^{-2} and −8.5 W m^{-2} of geoengineering forcing for GEO 3 and GEO 0 respectively, so that both RCP 3 and GEO 3 have roughly the same total forcing at 2100. Forcing is applied with an e-folding time of five years for both cases.

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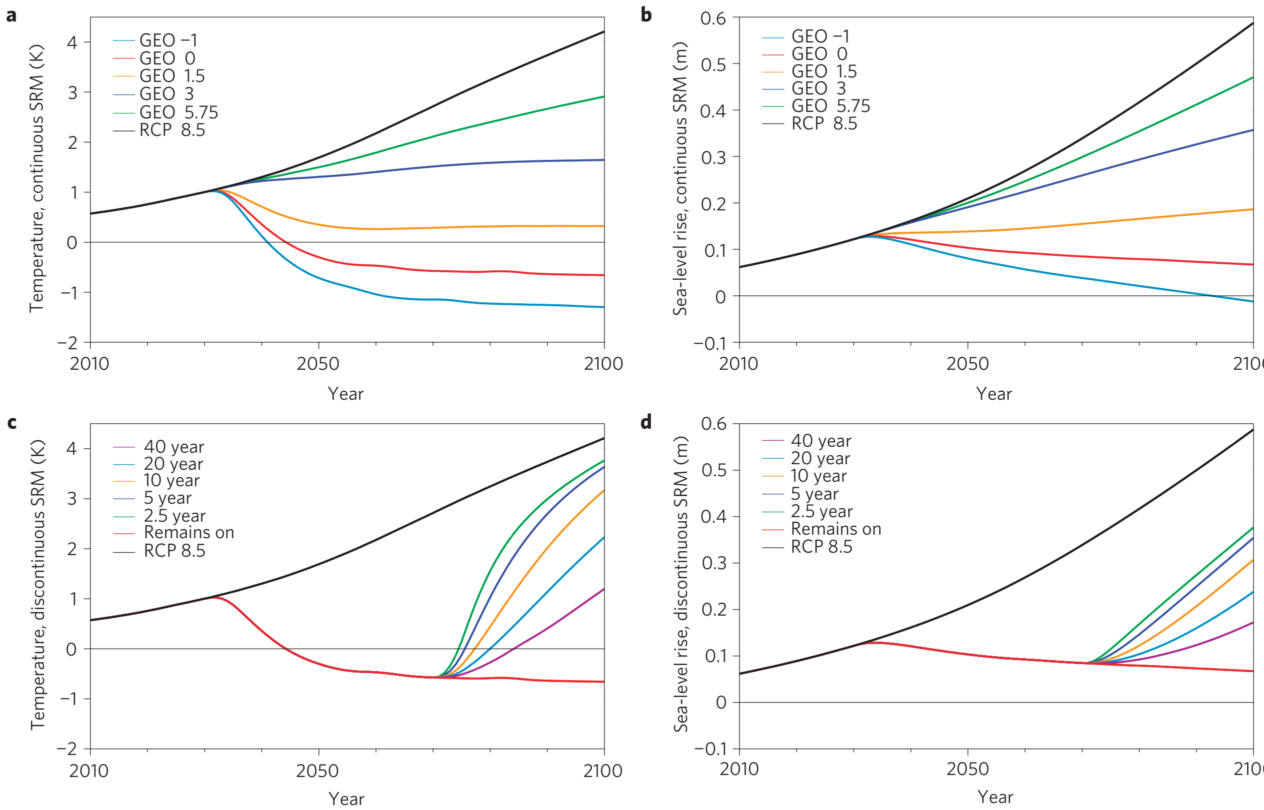

Figure 2 | Sensitivity of global average temperature and sea-level rise to controls on the geoengineering scenarios. Sensitivity to strength of forcing of the global average temperature (**a**) and sea-level rise (**b**). Sensitivity to the phase-out e-folding time of the global average temperature (**c**) and sea-level rise (**d**). The base geoengineering scenario, common to each panel, has a forcing of zero W m^{-2} relative to pre-industrial, a phase-in e-folding time of five years, and does not phase-out.

(2) sea levels[19]. A key factor controlling sea-level rise is oceanic thermal expansion[20], which is a delayed response to changes in surface air temperatures owing to relatively slow heat uptake by the ocean. Thus, surface air temperatures react faster than sea levels to changes in Earth's radiative balance. This divergence of response timescales implies that the radiative forcings required to achieve surface air temperature targets might not match the requirements for achieving sea-level targets. As a result, SRM has the potential to result in conflicts between decision-makers primarily concerned about sea-level rise versus the rate of temperature change. Finding a Pareto improving policy might be difficult.

We quantify the tension between the objectives to reduce the rate of surface temperature warming and sea-level rise using an intermediate complexity climate model (UVic; refs 21,22). We project possible future trends in global surface air temperature and sea-level rise for multiple SRM as well as greenhouse-gas mitigation strategies. We create 120 SRM geoengineering scenarios varying three determinants of SRM strategies: the forcing target, the phase-in time, and the phase-out time, in the case geoengineering is phased out. (See Methods for details of the scenarios). The considered forcings result in a wide range of surface air temperature and sea-level trajectories. The different phase-in times range from multiple decades to a fairly rapid deployment, similar to strategies discussed in response to a potential climate emergency[8,23]. We allow for the possibility that SRM geoengineering may be phased out or shut down owing to an unanticipated negative impact or some catastrophe that renders SRM geoengineering impossible[9]. We apply these strategies to the representative concentration pathway (RCP) 8.5 (an approximation for a 'business-as-usual' strategy where greenhouse-gas emissions grow unmitigated) and compare it against the other RCP scenarios, which approximate mitigation scenarios with considerable reduction in greenhouse-gas emissions[7]. The SRM strategies in this study are named in the same way as the RCP scenarios, that is RCP 6 and GEO 6 both have approximately +6 W m^{-2} of radiative forcing at 2100 but GEO 6 has the same greenhouse-gas concentrations as RCP 8.5.

Analysis of the model results suggests the SRM forcing required to halt sea-level rise is greater than the forcing required to halt surface warming (Fig. 1). The two SRM scenarios plotted represent two distinct objectives: (1) to stop sea-level rise (GEO 0) and (2) to stop surface air temperature rise (GEO 3). Both SRM scenarios are phased in with an e-folding time of five years. We find that the RCP scenario with the greatest reduction in greenhouse-gas forcings (RCP 3) is insufficient to halt sea-level rise. We find the scenario designed to stop sea-level rise (GEO 0) produces a considerable transient cooling, with a rate of temperature change double the peak business-as-usual warming.

The responses of global average surface air temperature and sea levels depend on the SRM scenarios (Fig. 2). All considered scenarios have a target forcing that equals the RCP 8.5 forcing (GEO 0), and the fastest phase-in rate and no phase-out is applied unless otherwise stated. The forcing target has the greatest effect on surface air temperatures and sea-level rise by 2100, and a rapid cooling begins at 2030 for the stronger forcing targets. The rapid cooling can be reduced with a longer phase-in interval. The phase-in duration has only a minor effect on surface air temperatures in 2100, but a slower phase-in leads to a greater sea-level rise over the twenty-first century (Supplementary Fig. S1). An abrupt termination of SRM would result in a rate of warming five times greater than the maximum projected rate of warming using the RCP 8.5 scenario. Increasing the duration of the phase-out interval significantly reduces these warming rates, but all cases exceed the maximum RCP 8.5 rate of warming

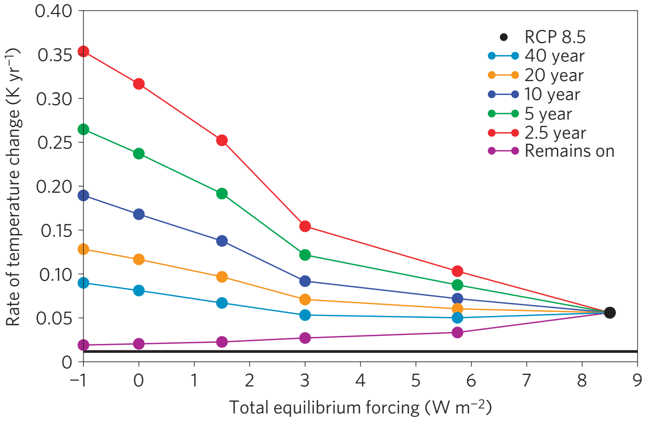

Figure 3 | The maximum warming rate for the period 2030–2100 as a function of the target forcing and the rate of phase-out. The geoengineering scenarios plotted all have a phase-in rate of five years. The black horizontal line shows the average rate of warming observed from 1960 to 2009.

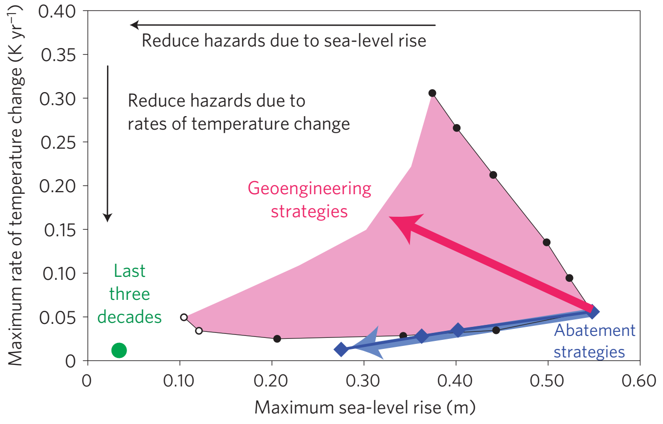

Figure 4 | The response of the maximum rate of temperature change and the maximum sea-level rise to the SRM scenarios. The RCP scenarios are plotted as blue diamonds with a blue arrow indicating the direction of increasing mitigation from RCP 8.5 to RCP 3. Geoengineering scenarios are plotted for a range of target forcings with increasing strength indicated by a red arrow. The lower and upper line of points show continuous and discontinuous forcing with a phase-out time of five years, and the polygon shows the range of behaviour for longer phase-out times. Points with a positive (negative) rate of temperature change are shown by a filled (open) symbol. The green dot represents the observations between 1980 and 2009 derived by linear trends to the observations[25,26].

by 2100 (Supplementary Fig. S1). The effect on sea level is much less dramatic, with sea level still significantly below RCP 8.5 levels by 2100, and the maximum rate of sea-level rise after phase-out is around 30% higher than under the RCP 8.5 scenario (not shown).

Previous studies argue that a key advantage of SRM is that it can be switched off quickly in the case of negative consequences[1,11]. Such discontinuous SRM can, however, cause abrupt and potentially disruptive warming[6,9] (Fig. 3). When terminating SRM, the resultant rate of warming depends strongly on the target forcing, as well as the duration and timing of the phase-out period (Supplementary Fig. S2). As an example: to stay below a maximum acceptable warming rate of 0.15 K yr^{-1} (well above what some have judged to be outside a 'tolerable window'[24]) with the maximum forcing target would require a phase-out timescale (e-folding time) of more than 20 years. (This result is robust to the consideration of several alternatives to the exponential decay function; see Supplementary Fig. S3.)

The different response timescales of sea levels and surface air temperatures introduce a potential tension between the goals of reducing sea-level rise and minimizing the rate of surface air temperature change (Fig. 4). Strong mitigation reduces both the maximum rate of temperature change and the maximum sea-level rise. For example, the RCP 3 scenario approximately halves the impact for both of these variables compared with the RCP 8.5 scenario. The strong and persistent SRM scenarios can reduce sea-level rise more than the strong mitigation scenarios, but at a cost of increased rates of temperature change (rapid cooling) and the further risk of drastically increased warming rates when terminating SRM. Shorter phase-in times with strong forcing can cause a rapid cooling and the peak rate of temperature change recorded will be from this cooling, however with shorter phase-in times the sea level will be lower for the same target forcing (Supplementary Fig. S4). Discontinuous SRM geoengineering can result in rapid warming, with a rate of up to five times greater than projected under RCP 8.5. Stopping SRM also results in higher sea levels.

Some have argued that combining SRM with greenhouse-gas mitigation might be a promising or 'low risk' strategy to limit sea-level rise and surface temperature changes[1,13]. Our analyses show that SRM strategies can introduce potentially nontrivial conflicts across space and time. Potential spatial conflicts are introduced by the strong tension between the objectives to limit the rate of surface air temperature changes and sea-level rise. Potential temporal conflicts arise from the commitment to maintain SRM for considerable times to avoid abrupt warming on SRM termination.

Methods

We use the UVic Earth System Model of Intermediate Complexity[21]. The thermosteric sea-level rise component is calculated from the ocean density derived from the model's temperature and salinity fields. We approximate the other sea-level contributions following Intergovernmental Panel on Climate Change methodology[20] (chapter 10; section 6 and appendix A). This method uses global average temperature to simulate the response of the glaciers and icecaps, and the Greenland and Antarctic ice sheets to changing climate conditions (see Supplementary Information). The 120 SRM geoengineering scenarios we developed have three controls: target forcing, phase-in time and phase-out time. The target forcing is the combined forcing of the RCP 8.5 scenario and the insolation change at equilibrium; we investigated target forcings of 5.75, 3, 1.5, 0 and −1 W m^{-2}. The SRM forcing is applied at 2030 as an exponential decay to full forcing with phase-in times of 5, 10, 15 and 20 years. The phase-out of SRM forcing occurs at 2070, if it is phased out, and follows an exponential decay with phase-out times of 2.5, 5, 10, 20 and 40 years. See the Supplementary Information for more details.

All figures show data smoothed by a running five-year backwards average and rates of change are calculated from the per-year change in the smoothed data.

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Author contributions
All authors jointly designed the study and wrote the paper. P.J.I. performed the model simulations and data analyses.

Additional information
The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.J.I.