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Regional climate response to solar-radiation management

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Concerns about the slow pace of climate mitigation have led to renewed dialogue about solar-radiation management, which could be achieved by adding reflecting aerosols to the stratosphere[1–6]. Modelling studies suggest that solar-radiation management could produce stabilized global temperatures and reduced global precipitation[4–6]. Here we present an analysis of regional differences in a climate modified by solar-radiation management, using a large-ensemble modelling experiment that examines the impacts of 54 scenarios for global temperature stabilization. Our results confirm that solar-radiation management would generally lead to less extreme temperature and precipitation anomalies, compared with unmitigated greenhouse gas emissions. However, they also illustrate that it is physically not feasible to stabilize global precipitation and temperature simultaneously as long as atmospheric greenhouse gas concentrations continue to rise. Over time, simulated temperature and precipitation in large regions such as China and India vary significantly with different trajectories for solar-radiation management, and they diverge from historical baselines in different directions. Hence, it may not be possible to stabilize the climate in all regions simultaneously using solar-radiation management. Regional diversity in the response to different levels of solar-radiation management could make consensus about the optimal level of geoengineering difficult, if not impossible, to achieve.

Although using solar-radiation management (SRM) to lower the average planetary temperature is not a new idea[7], it has recently become the focus of greater attention. Several prominent climate scientists have raised it as a feasible, and potentially necessary, strategy for avoiding catastrophic impacts of climate change (for example, rapid sea-level rise, rapid and large increase in emission of methane from high latitudes)[1–3]. Research on SRM is still in its infancy, but so far modelling studies suggest that, although significant hydrological anomalies would be associated with stratospheric albedo modification, even at the regional level, such a geoengineered world bears much closer resemblance to a low-CO_2 world, than either world bears to an unmodified high-CO_2 world[4–6]. Increasing planetary albedo does not mitigate impacts directly related to elevated CO_2, such as acidification of the surface ocean[8].

Previous modelling studies have compared one or two scenarios with SRM to various business-as-usual controls. However, such approaches cannot provide much information about regional sensitivities to the levels of SRM that might result. Such regional analysis of a range of realistic scenarios will be an essential input to any process of geopolitical decision-making.

Here we use the climate prediction.net (cpdn) version of the Hadley Centre Coupled Model, version 3 (HadCM3L, the L denoting a lower-resolution ocean)[9,10] to test a set of transient stratospheric albedo modification scenarios, initiated in model-year 2005 (ref. 11). The 54 SRM scenarios (Fig. 1a) were designed to stabilize global temperatures from anthropogenic forcings under Special Report on Emissions Scenario (SRES) A1B from greenhouse gases, tropospheric sulphur aerosols and tropospheric ozone; and compared with a SRES A1B no-SRM control (see the Methods section).

All of the SRM scenarios produced stabilized five-year average global-mean surface air temperatures (SATs), at levels between approximately 14.6 and 15.7 °C (Fig. 1b)—roughly, plus or minus half a degree from the temperature at the time SRM activities are initiated—depending on the level of forcing applied, whereas the control scenario (shown in black) resulted in an increase in global-mean SAT of approximately 2.5 °C over the course of the 80-year simulations. For the control scenarios, seasonal temperature maps of the anomaly in SAT between the 1990s (the last common decade of data for both sets of simulations) and the 2070s show warming everywhere, but especially at the poles during local winter. These effects are largely neutralized in the runs with SRM, although there is greater cooling in the tropics than elsewhere (see Supplementary Fig. S1).

As theoretical frameworks[12] and previous modelling results[4] have predicted, we find a global net increase in precipitation under the control (no-SRM) scenario and net decreases under the scenarios with SRM (Fig. 1c). As a result of the component of the hydrological impact of long-wave forcing that is independent of temperature, SRM with stratospheric aerosols cannot simultaneously compensate for the impacts of rising greenhouse gases on both temperatures and the hydrological cycle[13]. Although it might be possible in principle to 'fine tune' the hydrological response by injecting aerosols with different optical properties at different latitudes or altitudes, no proposal yet exists for how this might be implemented in practice, and some variability in response remains inevitable. Hence, as Fig. 2 illustrates, SRM cannot compensate exactly for rising greenhouse gas concentrations at the global level. The geographical distribution of precipitation effects varies widely under both sets of simulations, with globally increased albedo sometimes mitigating the precipitation anomalies exhibited under the standard global warming scenario, but occasionally exacerbating them. Surface and subsurface runoff anomalies are generally mitigated with SRM (see Supplementary Figs S2 and S3). Previous studies have not examined how global patterns of these changes vary with different SRM scenarios.

To analyse the regional implications of different levels of SRM we examined mean temperature and precipitation anomalies over land in 23 macro-regions[14]. Detailed graphics depicting regional temperature and precipitation responses to the different forcing scenarios early and late in the simulations can be found in Supplementary Figs S4 and S5. Although increased stratospheric albedo cools all regions considered compared with the A1B control, precipitation responses vary. In most regions, our simulations support the general

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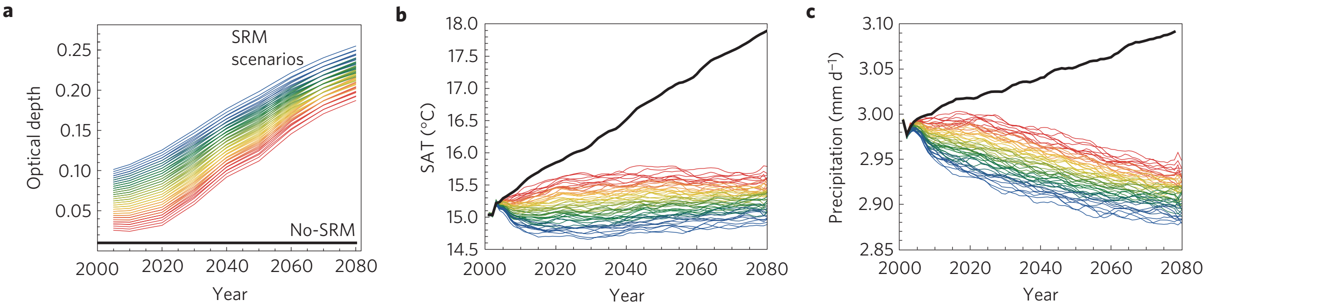

Figure 1 | Time series of global optical depth, temperature and precipitation of the 54 scenarios examined. a–c, SRM and no-SRM scenarios (**a**), five-year average global-mean near-surface (1.5 m) air temperature (**b**) and five-year average global-mean precipitation rate (**c**), all displayed over the length of the 80-model-year simulations.

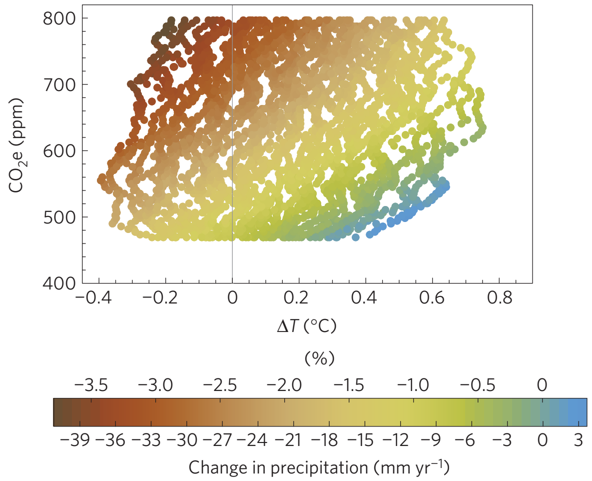

Figure 2 | Relationship between change in precipitation rate as a function of change in global-mean near-surface air temperature and equivalent carbon dioxide concentration. Temperature and precipitation changes (from 1990s baseline) are five-year averages over the initial-condition subensembles for each SRM scenario.

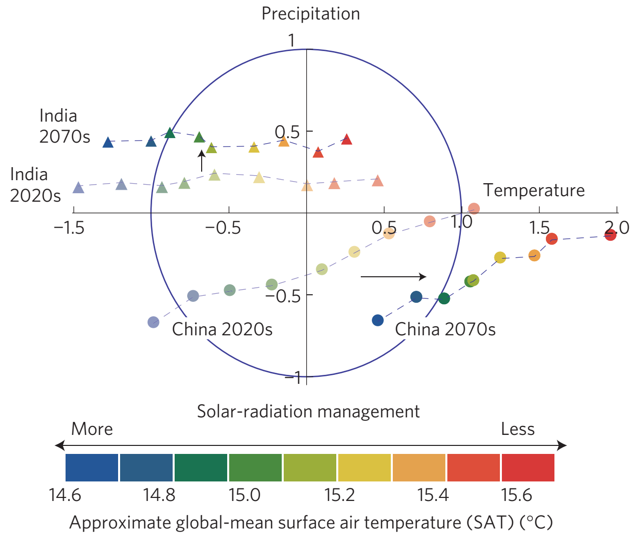

Figure 3 | Modelled response to different levels of average global solar-radiation management (SRM) over time in India and China. Interannual-variability-normalized regional temperature and precipitation summer (June, July and August) anomalies (averages for the 2020s minus the 1990s and 2070s minus the 1990s) in units of baseline standard deviations for the region including India (triangles) and the region including eastern China (circles). SRM-modified climates for these two regions migrate away from the baseline in disparate fashions.

assumption that the more SRM that is implemented, the greater the reduction in precipitation. However, there are some exceptions, such as Central America and the Amazon, and to a lesser extent, southern Africa and the Mediterranean, although these regional details are probably sensitive to the model used. In most regions and seasons, there is a SRM scenario that produces precipitation rates closer to the baseline value than the control scenario, but again there are exceptions, such as Southeast Asia and western North America in the summer. Precipitation in some regions, such as Canada and northern Asia, is relatively sensitive in these simulations to the SRM scenario employed. Other regions, such as Australia and eastern Africa are insensitive to the scenario.

If the aim of SRM is to 'restore late-twentieth-century climate', one way of defining this target would be to return a region's average temperature and precipitation to within one standard deviation of its baseline climate. Early in the simulations, a variety of SRM scenarios achieve this (see Supplementary Fig. S4). However, by the end of the simulations, when SRM has compensated for increasing anthropogenic forcings for six to seven decades, there is often no scenario that can place a region back within one standard deviation of both its baseline temperature and precipitation (see Supplementary Fig. S5). In other words, as the level of modification required to compensate for anthropogenic greenhouse gas forcing increases, the relative appeal of different levels of SRM depends on the region considered and the variable (temperature or precipitation) that is deemed most important.

This point is illustrated clearly in Fig. 3, which shows the summer temperature and precipitation anomalies in the 2020s and 2070s for the regions containing India and eastern China, normalized by the ensemble-mean interannual variability of their baseline (late-twentieth-century) climates. In the 2020s, most scenarios return the climate of both eastern China and India to within a standard deviation of the baseline. By the 2070s, the scenarios that return regional climates to within the one-standard-deviation circle are mutually exclusive. However, because of the large temperature anomalies in the no-SRM scenario by the 2070s, the net regional temperature–precipitation anomalies in these and other regions under the no-SRM scenario are much larger than those in any of the SRM scenarios.

Figure 4 shows the level of SRM that brings the regional climate back closest to its 1990s climate (that is, to the centre of a circle such as the one shown in Fig. 3), that is, the amount of SRM that minimizes combined temperature and precipitation anomalies in units of regional baseline standard deviations. Again, we find that different levels of SRM will probably be desired by different regions.

HadCM3 has been shown to reproduce the observed water vapour feedbacks associated with volcanic eruptions (the proxy

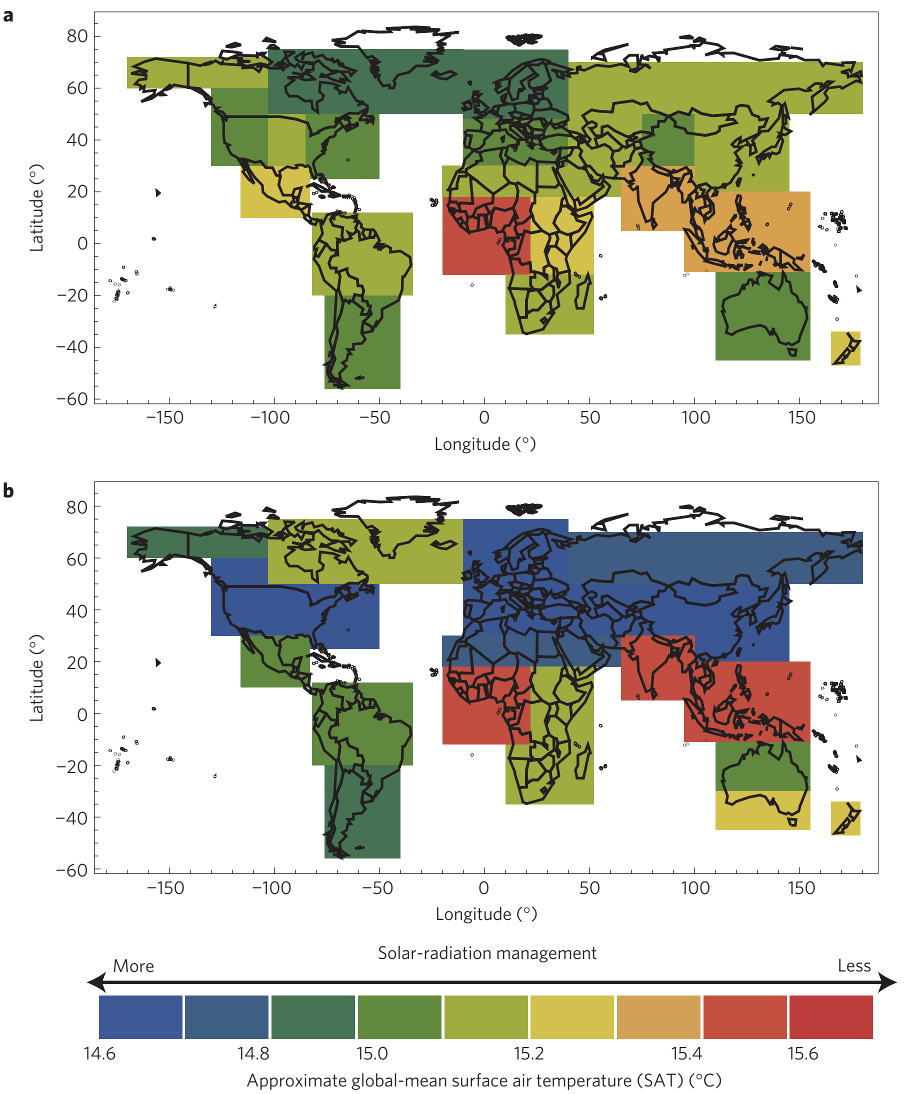

Figure 4 | 'Optimal' solar-radiation management (SRM) scenarios for the summer for each region. (For regions that straddle the Equator, the wetter season was selected.) **a**,**b**, The 'optimal' scenario is defined as minimum combined temperature and precipitation anomalies in standard deviations from the baseline (1990s) climate, for the 2020s (**a**) and the 2070s (**b**).

process we use to mimic the SRM forcings) fairly well[15]. However, it is well known that present general circulation models are limited in their ability to estimate local and regional precipitation[16] and circulation response in models of this class to volcanic forcing may be imperfect[17]. Some have proposed the application of non-uniform SRM forcings, such as stratospheric forcings concentrated over the poles, or even tropospheric forcings with both latitudinal and longitudinally varied distribution over the oceans, to control the regional impacts of global cooling by SRM (ref. 18). SRM implemented as such would probably produce different regional precipitation effects as well. However, although the specific patterns might be different under any actual implementation of SRM, none of these interventions will have purely local impacts and it seems most unlikely that some form of the regional divergence that we observe would not appear.

Previous modelling exercises have demonstrated that unless net carbon dioxide emissions are reduced close to zero, with substantial reductions in emissions of shorter-lived greenhouse gases, long-wave forcing would continue to rise and SRM would be needed to compensate for global warming for centuries before it could be phased out[19]. However, as our simulations progress, regional geoengineered climates migrate away from the baseline origin. Although all of the regions are closer to their 1990 conditions (especially in terms of temperature) under most of the scenarios, the most desirable level of SRM will very probably become more and more dependent on the region and variable considered the longer these activities are carried out as long-wave forcing continues to increase.

Although the analysis of this Letter has examined mean temperature and precipitation anomalies over land in 23 macro-regions, it is important to note that these are not the only metrics that might be used in designing a SRM intervention. For example, in some regions sustaining annual or seasonal water resources (for example, by protecting snow pack, or by assuring the continued operation of a monsoon system), or retaining summer sea ice, might be chosen as more important (and perhaps conflicting) objectives. Even within a region there may often not be an agreed metric. For example, indigenous peoples may want to preserve the summer Arctic sea ice that is critical to their way of life, whereas maritime industries may prefer summers with an ice-free Arctic Ocean.

Even if the specific aims of SRM were agreed, predicting this kind of detail in the direct and indirect consequences of SRM is generally beyond the capabilities of the models used at present for SRM research. SRM at the levels considered in this Letter may result in a variety of unexpected and unintended consequences. For example, aerosols from the eruption of Mount Pinatubo produced more diffuse light through scattering and in the year following the eruption a deciduous forest in Massachusetts experienced a 23% enhancement in photosynthesis because the plant canopies use diffuse light more efficiently than direct sunlight[20]. Some stratospheric particles can provide reaction sites for the catalytic destruction of stratospheric ozone[21]. If SRM were started and then stopped, while greenhouse gas concentrations continued to increase, the result would be unprecedented rates of rapid warming[22] that have the potential to prove devastating to many terrestrial ecosystems. Of course, SRM alone would do nothing to stop the rise in atmospheric concentration of carbon dioxide that will have differential impacts on species within terrestrial biota[23] and lead to continued ocean acidification and the probable demise of many or all coral reefs[24].

Our results do not provide a definitive illustration of regional climate impacts associated with potential future SRM schemes, nor can we assume that minimizing the net normalized temperature and precipitation anomalies from the 1990s would be the objective of any given region should SRM be undertaken, although some such quantitative metric would be required to define the objectives of any SRM intervention. Rather, our results demonstrate that not only would 'optimal' SRM activities imply different things for different regions, but that international negotiations over the amount of SRM could become inherently more difficult the longer such activities were used to compensate for rising greenhouse gas concentrations. Although greenhouse gas emissions result from economic activity all over the world, the intentional modification of albedo could be undertaken by just one or a few parties. Consideration by diplomatic and other communities of how global governance of such activities might best be managed is in an even earlier stage of development than the science and engineering[25]. The results presented here suggest that as our understanding improves, serious issues of regionally diverse impacts and inter-regional equity may further complicate what is already a very challenging problem in risk management and governance.

Methods

HadCM3L has 19 vertical levels in the atmosphere and 20 vertical layers in the ocean (with higher vertical resolution near the surface). The resolution of the model is 2.5° in latitude by 3.75° in longitude in both the atmosphere and the ocean[9]. SRM activities were mimicked in the model by modifying the natural volcanic forcing inputs, which are implemented as zonally uniform variations in stratospheric optical depth at 0.55 μm. The stratosphere in the model corresponds to the top five vertical layers of the atmosphere and the aerosol mass is distributed proportional to the air mass at each level. In this experiment, both SRM and no-SRM scenarios applied globally uniform stratospheric forcings. One-hundred and thirty-five SRM scenarios were formulated, designed to offset the net forcings associated with long-lived greenhouse gases, tropospheric sulphur aerosols and tropospheric ozone; and spanning the uncertainties associated with these anthropogenic forcings. The main anthropogenic climate forcings included in the cpdn version of HadCM3L are from long-lived greenhouse gases, tropospheric ozone and sulphur aerosols (direct and first indirect effect). All simulations use identical standard settings of model physics parameters and are initiated from historically forced runs from 1920 to 2005.

Forcing profiles were generated from decadal SRES A1B greenhouse gas concentrations[26], tropospheric ozone burdens[27] and sulphur aerosol burdens[28] and incremental variations in the associated range of forcing estimates from the most recent Intergovernmental Panel on Climate Change Working Group 1 Assessment Report[29]. As the goal of this experiment was to identify the impacts associated with optimal SRM schemes, the scenarios span the entire range of potential forcing values, even those that are highly unlikely. Forcings were converted to stratospheric optical depth values using UK Met Office diagnostics. HadCM3 was found to produce a forcing of approximately $-2.5\,\mathrm{W\,m^{-2}}$ for every 0.1 units of stratospheric optical depth. The SRES A1B control simulations use a volcanic forcing file with a constant optical depth of 0.01, a standard value for mean volcanic activity[30]. Both SRM and no-SRM scenarios applied globally uniform stratospheric forcings.

Scenarios were tested using 10-member subensembles, which made small perturbations to initial conditions, for a total SRM scenario ensemble size of 1,350 and a no-SRM control ensemble size of 10. Initial-condition subensembles were averaged together for the analysis. A total of 7,331 simulations were carried out for this experiment using computing resources donated by the general public, and data presented are derived from a subset of 550 of these simulations.

Of the 135 SRM scenarios considered, a least-squares-fit analysis was used to select 54 for which the global SAT trend was less than $\pm 0.006\,^{\circ}\mathrm{C\,yr^{-1}}$ (most SRM scenarios produced global temperature trends that rose slightly over the length of the simulation). Temperature and precipitation anomalies were calculated and normalized using global and regional data for model years 1990–1999 from 30 standard physics simulations run in previous cpdn experiments. Variability is represented as the baseline simulation ensemble-mean standard deviation of annual temperature or precipitation, respectively. We find that our results as presented in the general discussion of our regional analysis in the main text, and in Figs 3 and 4, are robust to an alternative normalization using a 116-decade control run. See Supplementary Notes and Fig. S6 for further discussion.

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Author contributions

K.L.R. designed and carried out the experiments and carried out the data analysis, M.G.M. and M.R.A. supervised the design and interpretation. The manuscript was written by K.L.R. and edited by M.G.M. and M.R.A.

Additional information

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