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Coral bleaching under unconventional scenarios of climate warming and ocean acidification

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Elevated sea surface temperatures have been shown to cause mass coral bleaching[1–3]. Widespread bleaching, affecting >90% of global coral reefs and causing coral degradation, has been projected to occur by 2050 under all climate forcing pathways adopted by the IPCC for use within the Fifth Assessment Report[4,5]. These pathways include an extremely ambitious pathway aimed to limit global mean temperature rise to 2 °C (ref. 6; Representative Concentration Pathway 2.6—RCP2.6), which assumes full participation in emissions reductions by all countries, and even the possibility of negative emissions[7]. The conclusions drawn from this body of work, which applied widely used algorithms to estimate coral bleaching[8], are that we must either accept that the loss of a large percentage of the world's coral reefs is inevitable, or consider technological solutions to buy those reefs time until atmospheric CO_2 concentrations can be reduced. Here we analyse the potential for geoengineering, through stratospheric aerosol-based solar radiation management (SRM), to reduce the extent of global coral bleaching relative to ambitious climate mitigation. Exploring the common criticism of geoengineering—that ocean acidification and its impacts will continue unabated—we focus on the sensitivity of results to the aragonite saturation state dependence of bleaching. We do not, however, address the additional detrimental impacts of ocean acidification on processes such as coral calcification[9,10] that will further determine the benefit to corals of any SRM-based scenario. Despite the sensitivity of thermal bleaching thresholds to ocean acidification being uncertain[11,12], stabilizing radiative forcing at 2020 levels through SRM reduces the risk of global bleaching relative to RCP2.6 under all acidification–bleaching relationships analysed.

Coral reefs are the iconic ecological communities of tropical seas, providing extensive ecosystem goods and services to around 500 million people[13]. However, coral reefs are under increasing pressure from anthropogenic climate change and in particular the effects of ocean warming[1,2]. Coral bleaching has been observed to occur in response to a wide range of chemical and biological parameters, yet most evidence indicates that elevated sea surface temperatures (SSTs) are the dominant cause of both localized and mass bleaching events[1]. Elevated sea temperatures of only 1–2 °C above the average summer maximum increase the excess excitation energy associated with photoinhibition during photosynthesis, which causes the disintegration and expulsion of symbiotic zooxanthellae[14]. Mass coral bleaching can, although does not necessarily, result in extensive coral mortality[2]. Climate projections tell us that conditions causing bleaching at present will occur more frequently on coral reefs over the coming decades[3–5].

SRM could be achieved through the delivery of specific aerosols or aerosol precursors (in this study SO_2) to the stratosphere, increasing the planetary albedo, cooling the planet and ameliorating the temperature rise resulting from increasing atmospheric CO_2 concentrations[15]. Coral growth rates have previously been linked to volcanic and anthropogenic aerosol emissions[16]. Inadvertent SRM has therefore already been shown to influence coral reefs.

A widely cited objection to SRM is that although it acts to ameliorate global warming, atmospheric CO_2 concentrations continue to rise and ocean acidification continues unabated[15]. Important trade-offs therefore exist when considering the benefits of SRM to coral reefs—known to be sensitive to ocean acidification[10]—when compared with greenhouse gas mitigation scenarios. Aragonite saturation state (Ω_{arag}) is a measure of the thermodynamic potential for the aragonite form of $CaCO_3$ to form or dissolve and is strongly influenced by ocean acidification[17]. The possibility of a reduced Ω_{arag} acting synergistically with high SSTs to drive coral bleaching at lower temperatures has been suggested[11]. As such, any benefits of SRM-based geoengineering of lower SSTs may be offset by the influence of ocean acidification on the thermal bleaching threshold. We explore this potential trade-off by projecting global coral bleaching under scenarios of mitigation and SRM and considering a liberal range of acidification–bleaching relationships. It should be noted that this is just one potential impact of ocean acidification, and although acidification effects on coral bleaching are highly uncertain[11,12,18], negative impacts are also projected in relation to calcification and reproduction processes with higher confidence (for example, refs 9,10).

Bleaching is projected under the IPCC's (Intergovernmental Panel on Climate Change's) RCPs 2.6 and 4.5 (ref. 6), using ensembles of perturbed initial-condition simulations undertaken with the Hadley Centre Global Environmental Model version 2 (HadGEM2-ES) Earth system model[19]. In addition we project bleaching change under an SRM scenario (Fig. 1). The SRM simulation is identical to RCP 4.5 until 2020, and then injects sulphur dioxide into the stratosphere to stabilize global radiative forcing from 2020 until the end of the experiment in 2075. This SRM simulation represents a potentially realistic scenario similar to that of the Geoengineering Model Intercomparison Project (GeoMIP) G3 experiment[20]. The atmospheric concentration of CO_2 associated with the SRM simulation is identical to RCP 4.5 (Fig. 1). These scenarios result in contrasting pathways of the bleaching-relevant parameters, tropical SST and $\Omega_{\mathrm{arag-}}$ (Fig. 1).

The SRM simulation results in lower tropical SSTs than RCP2.6, the most ambitious mitigation scenario considered so far in coral bleaching projections[4,5,21]. By 2050 Ω_{arag} is considerably lower (that is, relatively more damaging) under the SRM simulation than

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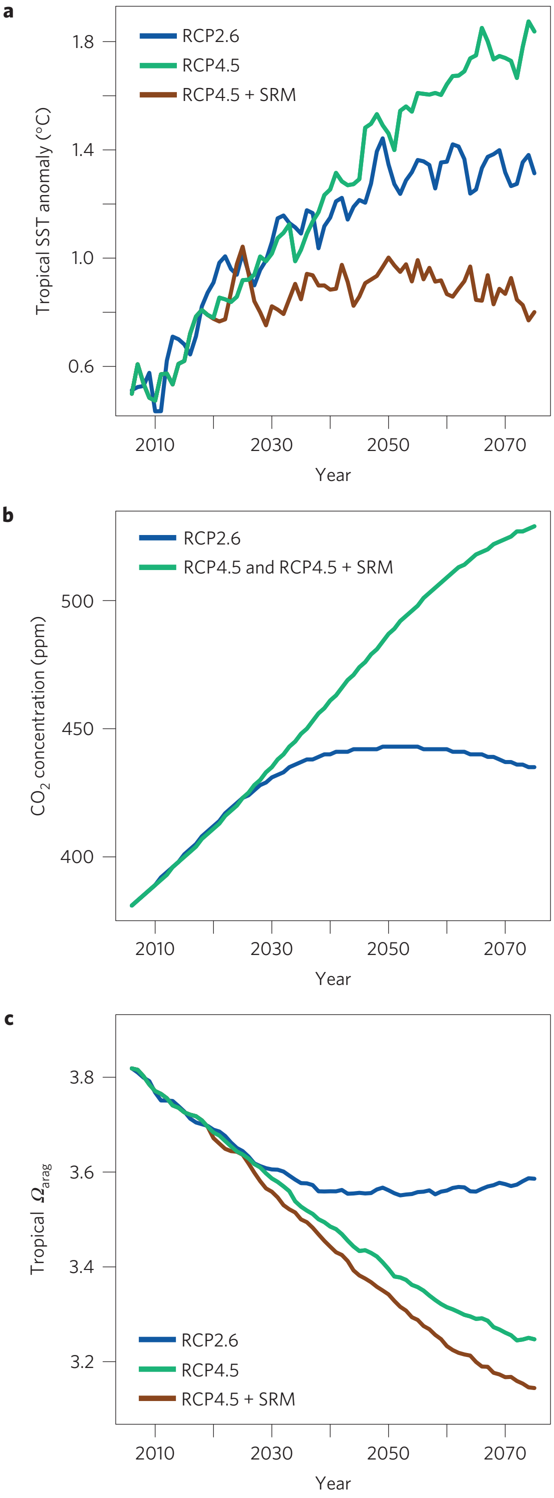

Figure 1 | Scenarios of warming and ocean acidification. a–c, The mean tropical SST anomaly relative to pre-industrial levels (**a**), atmospheric CO_2 concentration (**b**) and mean tropical Ω_{arag} (**c**) associated with the three coral bleaching scenarios.

RCP2.6 with this reduction especially apparent in the tropics (Fig. 2). Figure 1c illustrates that the lower Ω_{arag} in the SRM simulation reflects both the influence of higher atmospheric CO_2 (the difference between RCP2.6 and RCP4.5) and the influence of lower temperatures on CO_2 solubility (the difference between the RCP4.5 and the SRM simulations).

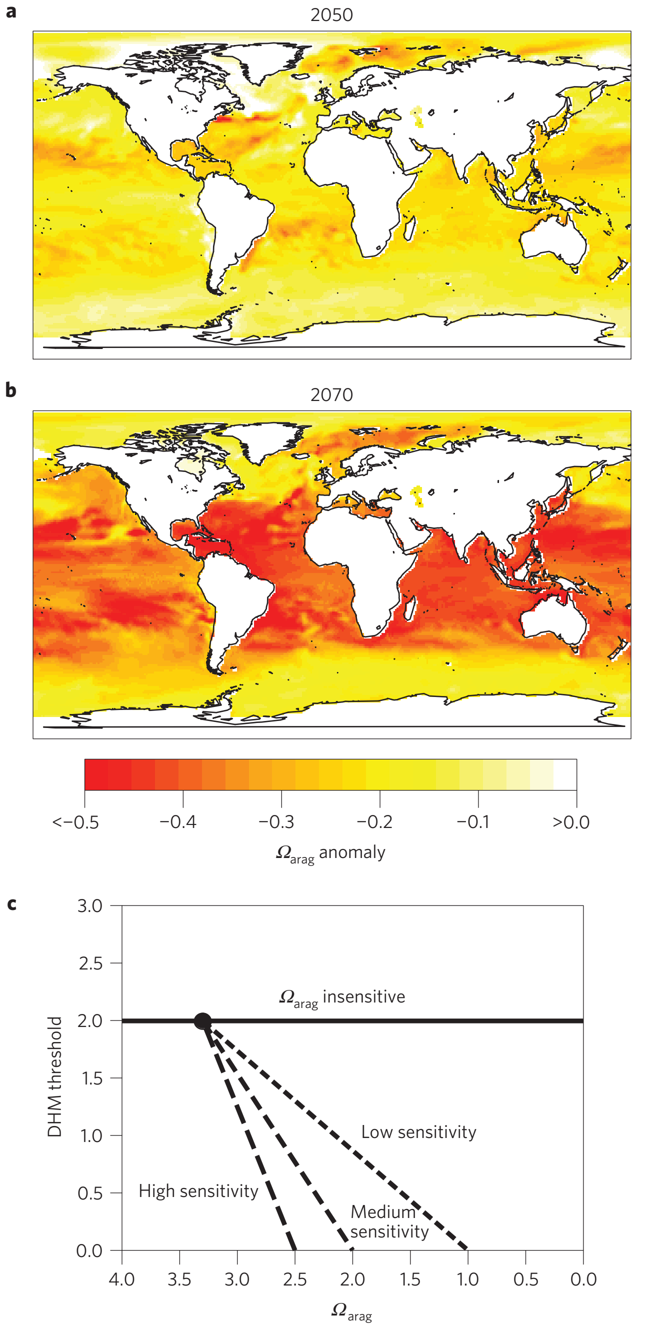

Figure 2 | Aragonite saturation state and bleaching thresholds. a,**b**, Ω_{arag} anomaly of the RCP4.5 + SRM simulation relative to RCP2.6 in 2050 (**a**) and 2070 (**b**). **c**, The four relationships between DHM threshold and Ω_{arag} used in this study.

Bleaching projections use previously established 'degree heating months' (DHM) methods with assessments made for each of the major coral regions (Supplementary Fig. 1) and then global projections produced by weighting regional projections by the relative extent of global reef present in each region. Our projections are based on all available grid cells within a region and not only the specific coral reef grid cells. This is because Earth system model outputs are unsuited for use at such a high level of spatial resolution and thermal stress within coral regions is therefore best assessed at the regional scale[22]. A DHM was calculated as 1 month of SST, that is, greater than the 1985–2000 maximum monthly mean for that grid cell. The annual accumulation of DHM for a given year was

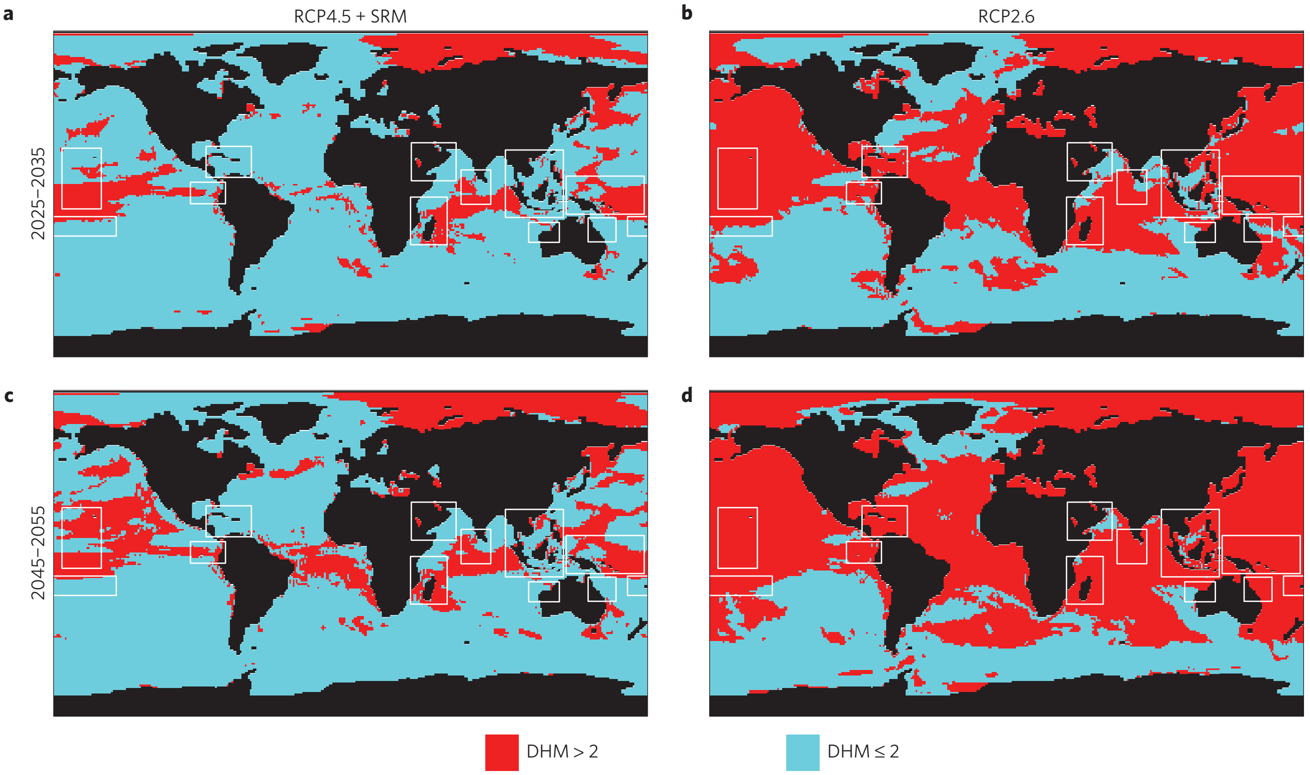

Figure 3 | DHM under RCP2.6 and RCP4.5 + SRM. a–d, Projected mean annual DHM in the years 2025–2035 and 2045–2055 for the SRM (**a**,**c**) and RCP2.6 simulations (**b**,**d**). The major global coral regions are outlined in white.

calculated as the maximum 4 month accumulation of DHM in a given year[23].

We assess the sensitivity of bleaching projections to different relationships between bleaching threshold and Ω_{arag} by extending the methodology of ref. 4. As well as using a conventional bleaching threshold of DHM = 2 that is not sensitive to changes in Ω_{arag}, we also use three published relationships that have bleaching thresholds linearly declining from DHM = 2 to DHM = 0 as Ω_{arag} declines from a present-day value of 3.3 to 2.5, 2.0 and 1.0 respectively[4] (Fig. 2c). These relationships include the highest bleaching–Ω_{arag} sensitivity proposed in the literature. Unlike previous studies[4] that have approximated a mean tropical Ω_{arag} based on the concentration of atmospheric CO_2, we calculate aragonite saturation state across all grid cells from dissolved carbon and alkalinity concentrations, temperature, salinity and assuming the calcium concentration to be in a fixed ratio with salinity. The physical and chemical fields used within this carbonate chemistry calculation are all simulated interactively within the HadGEM2-ES (ref. 19) model, with Ω_{arag} bias corrected to a present-day mean value of 3.3 in the tropics (30° N–30° S).

Spatial projections of DHM values highlight the disparity between thermal stress under the SRM and RCP2.6 simulations in the years 2025–2035 and 2045–2055 (Fig. 3). The RCP2.6 simulation results in most of the surface ocean, and especially the tropics, experiencing annual thermal stress at the DHM > 2 threshold by 2025–2035. The spatial extent of areas exceeding this threshold increases by 2045–2055. Although annual thermal stress at the DHM > 2 threshold still occurs under the SRM simulation, its spatial extent is widely reduced relative to RCP2.6 in both 2025–2035 and 2045–2055.

The projected percentage of global coral reefs experiencing bleaching under different Ω_{arag} sensitivities is shown in Fig. 4. By the year 2050, RCP 4.5 results in >95% of global reefs experiencing annual bleaching regardless of Ω_{arag} sensitivity. Even under the high mitigation scenario RCP 2.6, >90% of global reefs are projected to experience annual bleaching by the mid-twenty-first century regardless of Ω_{arag} sensitivity. These results closely match projections from the full CMIP5 (Coupled Model Intercomparison Project Phase 5) ensemble[5], with the limited influence of Ω_{arag} sensitivity on RCP2.6 and RCP4.5 bleaching reaffirming the findings of ref. 4.

The projected bleaching under the SRM experiment is shown to be consistently lower than RCP 4.5 and RCP 2.6 regardless of the sensitivity of bleaching thresholds to Ω_{arag} (Fig. 4). When, however, the Ω_{arag} sensitivity of the bleaching threshold increases, the SRM experiment is shown to result in a greater extent of global bleaching and the benefit of this scenario relative to RCP2.6 and RCP4.5 strongly diminishes (Fig. 4). This is partly because the projected extent of annual bleaching under RCP2.6 and RCP4.5 is close to saturation by 2040 in our simulations but also a result of the lower tropical Ω_{arag} values associated with the SRM scenario (Fig. 1) resulting in the greatest sensitivity of bleaching to ocean acidification.

Comparison between the SRM scenario, RCP 2.6 and RCP4.5 highlights the magnitude of potential bleaching trade-offs between a geoengineered world of lower SST and lower Ω_{arag} values and a higher SST world with higher Ω_{arag} values. Our findings emphasize the need to better characterize the sensitivity of bleaching thresholds to Ω_{arag}.

The actual effects of the RCP and SRM scenarios simulated will depend not only on the impact of SSTs and ocean acidification on bleaching but on the aggregated impact of both stressors on coral reefs. Historical evidence indicates that the dominant near-term risk to reefs is rising SSTs (refs 1,2,24), whereas the historical impact of ocean acidification is harder to demonstrate[18]. Bioclimatic envelope studies that do not account for coral bleaching suggest that if net radiative forcing is maintained below 3 W m^{-2}, reasonably favourable conditions for coral reefs can be maintained, even when achieved by SRM with persisting ocean acidification[24]. In addition,

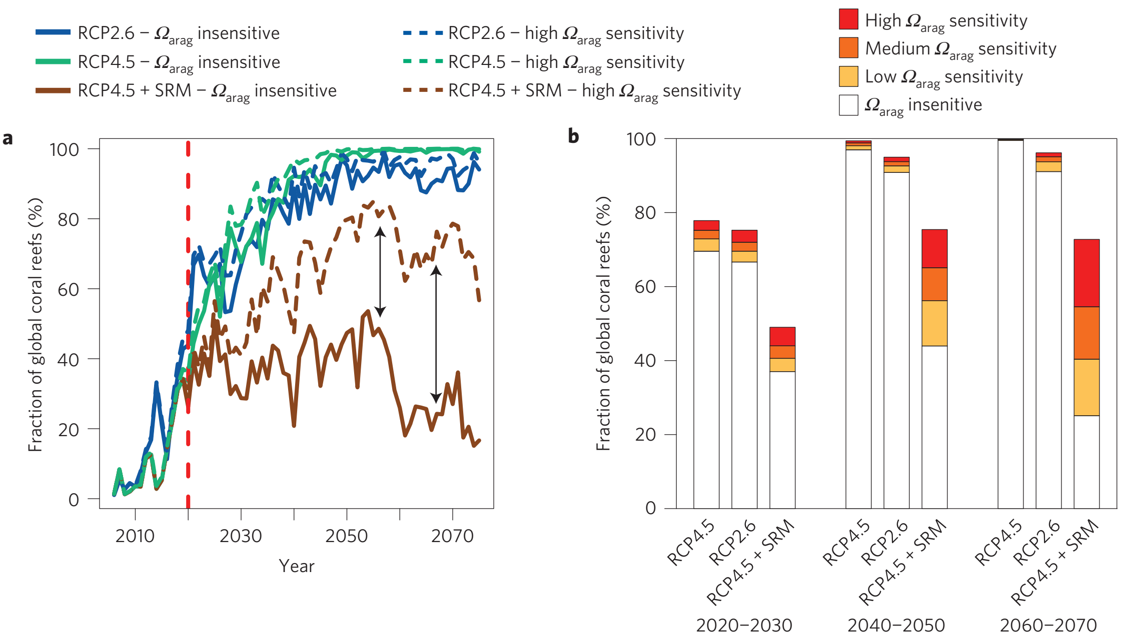

Figure 4 | Annual coral bleaching under different Ω_{arag} sensitivities. a,**b**, The projected extent of global coral reefs annually bleaching based on the exceedance of degree heating months (DHM > 2) bleaching thresholds for the RCP 4.5, RCP 2.6, and RCP 4.5 + SRM simulations (**a**) and the projected mean extent of reefs annually bleaching in the decades 2020–2030, 2040–2050 and 2060–2070 under all bleaching-Ω_{arag} sensitivities (**b**).

regional ecological modelling studies that link DHM bleaching metrics and other environmental drivers to coral mortality suggest that in combination with good management practices some reefs may survive a scenario such as RCP2.6 albeit with lower coral cover than that present today[21,25]. Indeed, it remains important to distinguish between the environmental conditions that cause bleaching—from which corals may recover—and those that induce such severe stress that bleaching results in coral mortality.

Decisions regarding the potential efficacy of SRM-based geoengineering with regard to coral reefs should not solely be based on mitigating bleaching. Ocean acidification also affects coral reproduction and calcification[9,10]. Ref. 26 indicated that regardless of the effect of bleaching, global reefs may be in a state of net dissolution with atmospheric CO_2 concentrations of 560 ppm. This represents the most pessimistic of projections in terms of the sensitivity of reef calcification to ocean acidification and neglects the possibility of adaptation, for example, the fact that many coral species show resilience to ocean acidification through pH upregulation[27]. Nonetheless, atmospheric CO_2 approaches 560 ppm by the end of our SRM simulations and owing to tropical cooling ocean acidification impacts are greater than at the same atmospheric CO_2 concentration in the absence of SRM. As such, using an SRM strategy to delay reductions in atmospheric CO_2 would be highly inadvisable from a holistic perspective of coral reef protection. This may be especially the case for deep cold water coral ecosystems as ocean acidification in the deeper ocean layers lags behind atmospheric CO_2 (ref. 28).

An optimum approach to preserve coral reefs would most likely advocate a mitigation intensive scenario such as RCP2.6 (ref. 6) that addresses global-scale ocean acidification concerns[17] in combination with detailed monitoring and the option of deploying carefully researched local or global SRM to limit thermal stress if unacceptable thresholds are reached. It is of utmost importance that the community thoroughly explores all potential options and defines such thresholds well in advance of these impacts being felt.

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Author contributions

L.K., P.C. and P.R.H. designed and conducted the research and analysis. A.J.W. and P.R.H. performed the HadGEM2-ES simulations. L.K., P.C., P.R.H., A.J.W. and P.J.M. wrote 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 L.K.

Competing financial interests

The authors declare no competing financial interests.