

## Can Marine Cloud Brightening Reduce Coral Bleaching?

Journal:	<i>Atmospheric Science Letters</i>
Manuscript ID:	ASL-12-118.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Latham, John; NCAR, Kleypas, Joanie; NCAR, Hauser, Rachel; NCAR, Parkes, Ben; University of Leeds, ICAS, SEE Gadian, Alan; University of Leeds, NCAS, ICAS, SEE
Keywords:	Coral Bleaching, Marine Cloud Brightening, Sea Surface Temperature, Cloud Seeding, Global Climate Modelling

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Can Marine Cloud Brightening Reduce Coral Bleaching?

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**KEYWORDS:** Coral Bleaching; Marine Cloud Brightening; Sea Surface Temperature; Cloud Seeding; Global Climate Modeling.

Abstract

Increases in coral bleaching events over the last few decades have been largely caused by rising sea surface temperatures (SST), and continued warming is expected to cause even greater increases through this century. We use a Global Climate Model to examine the potential of Marine Cloud Brightening (MCB) to cool oceanic surface waters in three coral reef provinces. Our simulations indicate that under doubled CO<sub>2</sub> conditions, the substantial increases in coral bleaching conditions from current values in three reef regions (Caribbean, French Polynesia, and Great Barrier Reef) were eliminated when MCB was applied, which reduced the SSTs at these sites to roughly their original values.

1.Introduction

The continued increase in carbon dioxide emissions into the atmosphere has generated greater interest in engineering strategies to ameliorate the effects of climate change (Shepherd *et al.*, 2009; SRMGI, 2011). Some of these involve Solar Radiation Management (SRM), i.e. “shading” the planet from incoming sunlight and thus slowing the rate of warming at the Earth’s surface. One such SRM technique is Marine Cloud Brightening (MCB): (Latham, 1990; Latham, 2002; Bower *et al.*, 2006; Latham *et al.*, 2008; Jones *et al.*, 2009; Rasch *et al.*, 2009; Korhonen *et al.*, 2010; Bala *et al.*, 2011; Jones *et al.*, 2011; Latham *et al.*, 2012a; Latham *et al.*, 2012b). MCB geoengineering is designed to produce a cooling that in principle can maintain the Earth’s average surface temperature and polar sea-ice cover at roughly current values in the face of increasing atmospheric CO<sub>2</sub> concentrations, at least up to the 2xCO<sub>2</sub> point. MCB involves seeding low-level marine stratocumulus (ice-free) clouds with sub-micrometer-sized seawater droplets. The particles have sufficiently high salt-mass to act as cloud condensation nuclei (CCN), thereby increasing the cloud droplet number concentration (CDNC) and the cloud optical thickness. The resulting effect is an increase in

cloud albedo for incoming shortwave radiation (Twomey, 1987). Also, smaller cloud droplets coagulate more slowly, thus suppressing precipitation development and increasing cloud lifetime (Albrecht, 1989). The engineering design for MCB includes deployment of ocean-based vessels strategically placed to release seawater CCN into the turbulent boundary layer beneath marine stratocumulus clouds.

MCB was originally developed as a means of counteracting warming on a global scale. However, MCB could in principle also be used to target sub-global regions of particular interest. That is, seeding sites could be selected

- to maximize a desired effect (e.g., reduction in warming)
- to minimize adverse effects (e.g., reduction in precipitation).

Some previous modeling studies have illustrated a cooling effect by seeding the three regions of most extensive marine stratocumulus clouds: off the west coasts of Africa, North America, and South America: (Jones *et al.*, 2009; Jones *et al.*, 2011; Latham *et al.*, 2012a; Latham *et al.*, 2012b). Seeding these three regions, for example, produced a significant reduction in surface temperatures (SST) where hurricanes traditionally develop in the Atlantic, raising the possibility of weakening them (Latham *et al.*, 2012b). Mostly the three seeding regions covered less than 10% of the marine stratocumulus regions but some larger regions are considered in some of the papers.

The influence of SRM on marine ecosystems has recently been addressed by Russell *et al.* (2012). In this paper we evaluate computationally the potential for MCB seeding in these same three regions to significantly reduce tropical SSTs in three major coral reef provinces - the Caribbean, French Polynesia, and the Great Barrier Reef – and thereby reduce rates of coral bleaching.

## 2. Methods

### 2.1 Simulations of SST with and without MCB

SST values were extracted from model calculations conducted with the Hadley Centre Global Environment Model (HadGEM1), version 6.1 of the UK Meteorological Office Unified Model. Further details of this model are provided in Latham *et al.* (2012a; 2012b).

HadGEM1 was modified to have a fixed CDNC in the three aforementioned regions of low-level (about 1 km high) marine stratocumulus clouds. The normal (natural) value of CDNC in HadGEM1 is about  $60 \text{ cm}^{-3}$ . For the MCB simulations, the CDNC was given a value of  $375 \text{ cm}^{-3}$  at all model levels between 0 km and 3 km, which is consistent with the treatment used in Jones *et al.* (2009; 2011), Latham *et al.*, (2008; 2012a; 2012b) and Parkes *et al.* (2012).

Three simulations were completed to determine the effects of MCB on SST values. They were (1) a Control simulation forced by an atmospheric  $\text{CO}_2$  concentration of 440 ppm; (2) a  $2\times\text{CO}_2$  simulation forced by an atmospheric  $\text{CO}_2$  concentration of 560 ppm; and (3) a  $2\times\text{CO}_2$ -MCB simulation that includes

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MCB in the three regions of marine stratocumulus. For the 2xCO<sub>2</sub> simulations, the model was run from 2020 to ~ 2045 with increasing CO<sub>2</sub> until 2045, and then held stable at double CO<sub>2</sub> values until 2090. For each 70-year simulation the 10-day averaged SSTs of the final 20 years (2070-2090) were used for the coral bleaching analysis

**2.2 Coral bleaching calculations**

For each simulation, the SSTs were used to calculate coral heat stress and bleaching. Heat stress in corals occurs once the temperature exceeds some pre-determined threshold above the climatological maximum. This threshold is traditionally set at 1°C (*Liu et al.*, 2003), or alternatively, is allowed to vary regionally as a function of the natural variability of the year-to-year maxima. In the latter case, the threshold is typically determined as  $n \cdot SD_{max}$ , where  $n$  is an empirically determined factor, and  $SD_{max}$  is the standard deviation of the annual maxima over the climatological period. We apply a threshold of  $2.45 \cdot SD_{max}$  following Donner (2009).

Coral bleaching occurs when heat stress accumulates over a period of time. This is typically calculated as degree heating weeks (DHW), which is the accumulation of the heat stress over a 12-week period (*Liu et al.*, 2003). When weekly data are used, mild bleaching occurs once the DHW > 4, and severe bleaching occurs once DHW > 8.

SSTs of the final 20-year Control case were used to calculate the climatological SST maximum for every ocean cell within each region, including those that do not include reefs. In both the Caribbean and the Great Barrier Reef regions, many of the coastal grid cells were not resolved in the model; here, we assume that changes in offshore temperatures are largely representative of those affecting adjacent reefs. The climatological values derived from the Control run were used in the DHW calculations for each ocean cell for the three regions, for both the 2xCO<sub>2</sub> and 2xCO<sub>2</sub>+MCB cases. To adjust for the 10-day average SSTs of the model output (versus weekly averages), a bleaching event was designated as mild when DHW=3–5, and severe when DHW ≥ 6. These values are slightly lower than the 7-day DHW of 4 and 8, respectively. Bleaching events were calculated separately for the 1°C and  $2.45 \cdot SD_{max}$  heat-stress thresholds (Figure 2).

**3. Results**

**3.1 Global SST**

The changes in SST between the Control and 2xCO<sub>2</sub> simulations (Figure 1A) are consistent with patterns produced in other coupled GCM studies mentioned earlier. Temperature increases of between 0.5 K and 2 K occurred over much of the tropical area, (Figure 1A). The effects of MCB on SSTs in the 2xCO<sub>2</sub> simulations more than cancel these temperature increases (Figure 1B). In the case of the three-patch MCB in the 2xCO<sub>2</sub> atmosphere, the global temperatures decrease by 0.12 K. Full-area seeding at 2xCO<sub>2</sub> leads to much greater cooling over the entire climate system and reduces tropical temperatures by more than 5 K, which is too large to be beneficial, causing extra thermal stress on coral.

### 3.2 Temperatures in coral reef regions

In all three coral reef regions the doubling of atmospheric carbon dioxide raised the annual average temperatures by at least 0.5 K relative to the Control scenario, whereas including MCB restored SSTs to near the Control values (Table 1). The greater cooling in French Polynesia (Figure 1B) illustrates the cooling effect of MCB in waters off Peru that are then transported by ocean currents westward across the Pacific.

Coral bleaching events were rare based on SSTs from the Control case (Table 2); only French Polynesia exhibited bleaching for either heat-stress threshold. The number of bleaching events in the 2xCO<sub>2</sub> case was dramatically higher for all three regions. For the 2xCO<sub>2</sub>+MCB case, however, bleaching events were almost entirely eliminated in all three regions.

## 4. Discussion

The possible utilization of MCB for examining the sub-global-scale topic of coral bleaching amelioration possesses a number of positive and negative attributes. On the positive side, our model-based analysis indicates that MCB seeding in key patches of marine stratocumulus would not only lower temperatures over all three major reef-regions studied, but could also restore temperatures to the Control levels. Coral reef ecosystems may thus be beneficiaries of MCB geoengineering. Other sub-global locations for which calculations predict that cooling due to MCB can compensate for the warming produced by fossil-fuel burning are the Arctic (*Parkes et al.*, 2012) and the hurricane-generating waters of the tropical Atlantic (*Latham et al.*, 2012b). MCB has additional advantages such as: (1) it does not require a long spin-up time (about 1 year) to achieve a cooling effect; (2) once halted, the effects of MCB on clouds are easily and quickly reversed (the life-time of salt particles in the atmosphere is about 10 days (*Salter et al.*, 2008)); and (3) the utilization of mobile MCB spray vessels could provide a high degree of control, given the relative ease of adjusting their positioning, as well as the flux of sea-salt spray particles that act as CCN. The regions where MCB would be most effective are those where marine stratocumulus clouds are frequently present or where surface currents deliver waters that have been cooled by MCB. The flexibility in the location of MCB seeding may permit fine-tuning to maximize its effectiveness, and to minimize side effects.

*Latham et al.* (2012a) present a detailed three-stage plan for field-testing MCB, should this be authorized, on a spatial scale of about 100 km x 100 km, which seems very likely to be too small to produce any significant climate effects. It would be based on – but on a much smaller scale than – the successful VOCALS field experiment (*Wood et al.*, 2011) which involved exhaustive studies of marine stratocumulus clouds. A field study of the impact of MCB on coral bleaching at a selected site would utilize some but by no means all of the equipment and procedures required for the 3-stage field experiment.

However, there are a number of possible disadvantages and limitations of MCB seeding designed to reduce coral bleaching: (1) Use of MCB may

reduce the photosynthetically available radiation (PAR) reaching the surface, which would affect both the depth of light penetration (which affects the depth limits of corals and seagrass beds), as well as primary production in the water column; (2) Although blocking short-wave radiation leads to a reduction in ocean temperatures in these reef regions, it does not reduce the process of ocean acidification, which is a direct consequence of rising atmospheric CO<sub>2</sub>, and is detrimental to coral growth and reef development; and (3) As with any SRM geoengineering technique, the MCB process would have to be continued indefinitely. Cessation of MCB, particularly if atmospheric CO<sub>2</sub> concentrations continue to rise, could result in very rapid warming, which for coral reefs is the most common condition leading to coral bleaching. The estimated annual cost of deploying MCB to inhibit coral bleaching around the major reefs is about \$40M. However, social, ethical and political costs related to compensation are extremely hard to estimate, and may dominate the costs.

As mentioned earlier, a primary requirement of SRM research is to fully examine all possible adverse consequences of deployment, and to abandon this work if significant ones cannot be remedied. Previous modeling analyses of the potential adverse effects of MCB have largely been restricted to global applications of MCB and mostly to the possibility that rainfall would be reduced in particular regions. *Jones et al.* (2009), for example, found that MCB reduced rainfall significantly in the Amazonian region, but later (*Jones et al.* 2011) found that altering the locations of seeding largely eliminated this problem. *Bala et al.* (2011) also found that MCB seeding would cause a substantial reduction in rainfall, but that virtually all of this loss was over the oceans, with no net loss over land. Whether or not appreciable rainfall reduction occurs specifically over Amazonia appears to depend on the choice of seeding site(s). Thus there exists a useful element of flexibility regarding the unforeseen consequences issue. *Latham et al.* (2012a; 2012b) provide a more detailed account of research into this issue.

Another major consideration relates to governing the research associated with geoengineering, including MCB. This is not a trivial consideration, particularly for the large-scale deployments necessary to achieve the experimental ends suggested by the modeling in this paper. A governance framework – the processes, mechanisms, institutions, and individuals guiding ordered rule and collective action (*Folke et al.*, 2005) – will be necessary to guide and inform MCB research and will almost certainly need to be developed in advance of field testing (*Shepherd et al.*, 2009; *Keith et al.*, 2010). Establishing such a framework will assist scientists, decision makers, and the public with evaluating and managing both known and as-yet-unknown risks and benefits of MCB.

Among the governance questions to consider are: How can ongoing, independently-run assessments of geoengineering research and its outcomes be achieved? How may newly acquired knowledge be best incorporated into existing governance and research structures? Also, means of allowing public scrutiny and input, and research and decision transparency will be important to incorporate when developing SRM or MCB governance. Issues of liability



and equity with regard to MCB decision-making and application will need to address how to attend to the needs of the voiceless and those left worse off from MCB use. In essence, effective governance will frame ways in which MCB and other geoengineering efforts are best regulated as a “public good” (Rayner *et al.*, 2009). Governance will benefit from integrating existing research protocols and lessons-learned with geoengineering-specific governance guidelines and ideas such as those generated by the Oxford Principles (Rayner *et al.*, 2009) and groups like the Solar Radiation Management Initiative (SRMGI, 2011).

We conclude that MCB seeding would likely lower tropical SSTs and thus lower the risk of coral reef bleaching for several decades. However, various technological and governance hurdles remain before a fully operational MCB system can be put in place. As with any SRM geoengineering technique, much more work is also required before we can fully gauge whether MCB will cause adverse consequences that cannot be remedied - in which case it should not be utilized. Given the current rate of CO<sub>2</sub> increase in the atmosphere, however, MCB should continue to be evaluated as a measure to prevent particularly dangerous aspects of climate change.

## References

- Albrecht, BA (1989), Aerosols, cloud microphysics, and fractional cloudiness, *Science*, 245, (4923), 1227-1230, DOI: 10.1126/science.245.4923.1227.
- Bala, G, Caldeira, K, Nemani, R, Cao, L, Ban-Weiss, G, and Shin, HJ (2011), Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle, *Climate Dynamics*, 37, (5-6), 915-931, DOI: 10.1007/s00382-010-0868-1.
- K.Bower, T.W.Choularton, J.Latham, J.Sahraei and S.Salter, 2006. Computational Assessment of a Proposed Technique for Global Warming Mitigation Via Albedo-Enhancement of Marine Stratocumulus Clouds. *Atmos. Res.* 82, 328-336.
- Donner, SD (2009), Coping with commitment: Projected thermal stress on coral reefs under different future scenarios, *Plos One*, 4, (6), DOI: 10.1371/journal.pone.0005712.
- Folke, C, Hahn, T, Olsson, P, and Norberg, J (2005), Adaptive governance of social-ecological systems, in *Annual Review of Environment and Resources*, edited, pp. 441-473.
- Jones, A, Haywood, J, and Boucher, O (2009), Climate impacts of geoengineering marine stratocumulus clouds, *Journal of Geophysical Research-Atmospheres*, 114, DOI: 10.1029/2008jd011450.
- Jones, A, Haywood, J, and Boucher, O (2011), A comparison of the climate impacts of geoengineering by stratospheric SO<sub>2</sub> injection and by

- brightening of marine stratocumulus cloud, *Atmospheric Science Letters*, 12, (2), 176-183, DOI: 10.1002/asl.291.
- Keith, DW, Parson, E, and Morgan, MG (2010), Research on global sun block needed now, *Nature*, 463, (7280), 426-427, DOI: 10.1038/463426a.
- Korhonen, H, Carslaw, KS, and Romakkaniemi, S (2010), Enhancement of marine cloud albedo via controlled sea spray injections: a global model study of the influence of emission rates, microphysics and transport, *Atmospheric Chemistry and Physics*, 10, (9), 4133-4143, DOI: 10.5194/acp-10-4133-2010.
- Latham, J (1990), Control of global warming, *Nature*, 347, (6291), 339-340, DOI: 10.1038/347339b0.
- Latham, J (2002), Amelioration of global warming by controlled enhancement of the albedo and longevity of low-level maritime clouds, *Atmospheric Science Letters*, 3, (2-4), 52-58, DOI: 10.1006/asle.2002.0048.
- Latham, J, Rasch, P, Chen, CC, Kettles, L, Gadian, A, Gettelman, A, Morrison, H, Bower, K, and Choularton, T (2008), Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 366, (1882), 3969-3987, DOI: 10.1098/rsta.2008.0137.
- Latham, J, Bower, K, Choularton, T, Coe, H, Connolly, P, Cooper, G, Craft, T, Foster, J, Gadian, A, Galbraith, L, Iacovides, H, Johnston, D, Launder, B, Leslie, B, Meyer, J, Neukermans, A, Ormond, B, Parkes, B, Rasch, P, Rush, J, Salter, S, Stevenson, T, Wang, H, Wang, Q, and Wood, R (2012a), Marine cloud brightening, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 370, 4217-4262, DOI: 10.1098/rsta.2012.0086.
- Latham, J, Parkes, B, Gadian, A, and Salter, S (2012b), Weakening of hurricanes via marine cloud brightening (MCB), *Atmospheric Science Letters*, 13, (4), 231-237, DOI: 10.1002/asl.402.
- Liu, G, Strong, A, and Skirving, W (2003), Remote sensing of sea surface temperature during 2002 barrier reef coral bleaching, *EOS Transactions of the American Geophysical Union*, 84, 137-141, DOI.
- Parkes, B, Gadian, A, and Latham, J (2012), The effects of marine cloud brightening on seasonal polar temperatures and the meridional heat flux, *ISRN Geophysics*, 2012, DOI: 10.5402/2012/142872.
- Rasch, PJ, Latham, J, and Chen, CC (2009), Geoengineering by cloud seeding: influence on sea ice and climate system, *Environmental Research Letters*, 4, (4), DOI: 10.1088/1748-9326/4/4/045112.
- Rayner, S, Redgwell, C, Savulescu, J, Pidgeon, N, and Kruger, T (2009), Memorandum on draft principles for the conduct of geoengineering research., in *U.K. House of Commons Science and Technology Committee Enquiry into the Regulation of Geoengineering*, edited, p. 5, <http://www.sbs.ox.ac.uk/centres/insis/Documents/regulation-of-geoengineering.pdf>.



- Russell, LM, Rasch, PJ, Mace, GM, Jackson, RB, Shepherd, J, Liss, P, Leinen, M, Schimel, D, Vaughan, NE, Janetos, AC, Boyd, PW, Norby, RJ, Caldeira, K, Merikanto, J, Artaxo, P, Melillo, J, and Morgan, MG (2012), Ecosystem Impacts of Geoengineering: A Review for Developing a Science Plan, *Ambio*, 41, (4), 350-369, DOI: 10.1007/s13280-012-0258-5.
- Salter, S, Sortino, G, and Latham, J (2008), Sea-going hardware for the cloud albedo method of reversing global warming, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 366, (1882), 3989-4006, DOI: 10.1098/rsta.2008.0136.
- Shepherd, J, Caldeira, K, Cox, P, Haigh, J, Keith, D, Launder, B, Mace, G, MacKerron, G, Pyle, J, Rayner, S, Redgwell, C, and Watson, A (2009), Geoengineering the Climate: Science, governance and uncertainty, in *Royal Society Policy document*, edited, p. 82.
- Solar Radiation Management Governance Initiative (SRMGI) (2011), Solar radiation management: the governance of research. Environmental Defense Fund, edited, p. 70, The Royal Society and TWAS.
- Twomey, S (1987), Influence of internal scattering on the optical properties of particles and drops in the near-infrared *Applied Optics*, 26, (7), 1342-1347, DOI.
- Wood, R, Mechoso, CR, Bretherton, CS, Weller, RA, Huebert, B, Straneo, F, Albrecht, BA, Coe, H, Allen, G, Vaughan, G, Daum, P, Fairall, C, Chand, D, Klenner, LG, Garreaud, R, Grados, C, Covert, DS, Bates, TS, Krejci, R, Russell, LM, de Szoeke, S, Brewer, A, Yuter, SE, Springston, SR, Chaigneau, A, Toniazzo, T, Minnis, P, Palikonda, R, Abel, SJ, Brown, WOJ, Williams, S, Fochesatto, J, Brioude, J, and Bower, KN (2011), The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): goals, platforms, and field operations, *Atmospheric Chemistry and Physics*, 11, (2), 627-654, DOI: 10.5194/acp-11-627-2011.

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TABLES

**Table 1.** Changes in sea surface temperatures between the 2xCO<sub>2</sub> experiments and the Control, as described in Section 3.1 (all values in C). The three regions, Caribbean, Great Barrier Reef and Polynesia are shown in black rectangles in Figure 1.

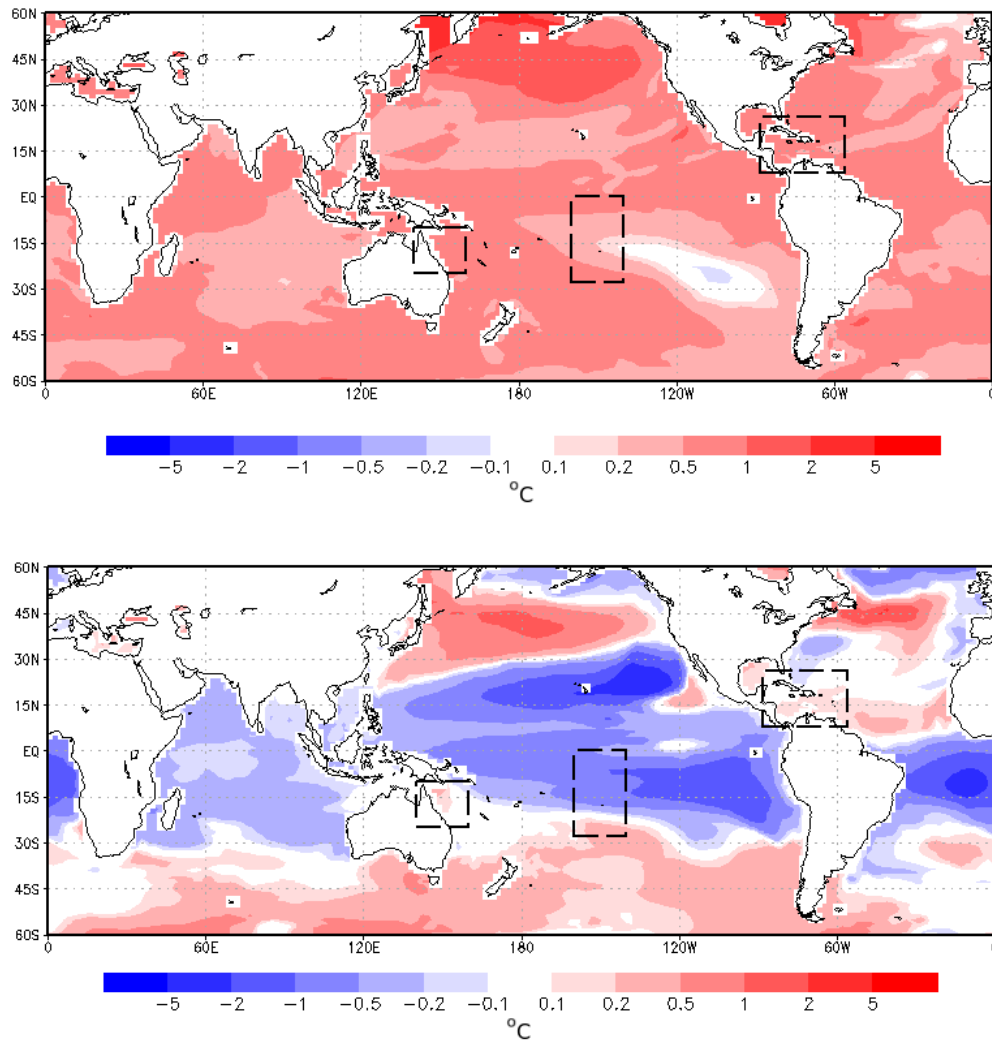
Region	2xCO <sub>2</sub> – Control	2xCO <sub>2</sub> +MCB – Control
Global	0.67	–0.12
Caribbean	0.53	–0.04
Great Barrier Reef	0.55	0.13
Polynesia	0.64	–0.58

[NB: 2xCO<sub>2</sub>+MCB ALL CLOUDS – CONTROL: Global temperature change = -6.5 C]

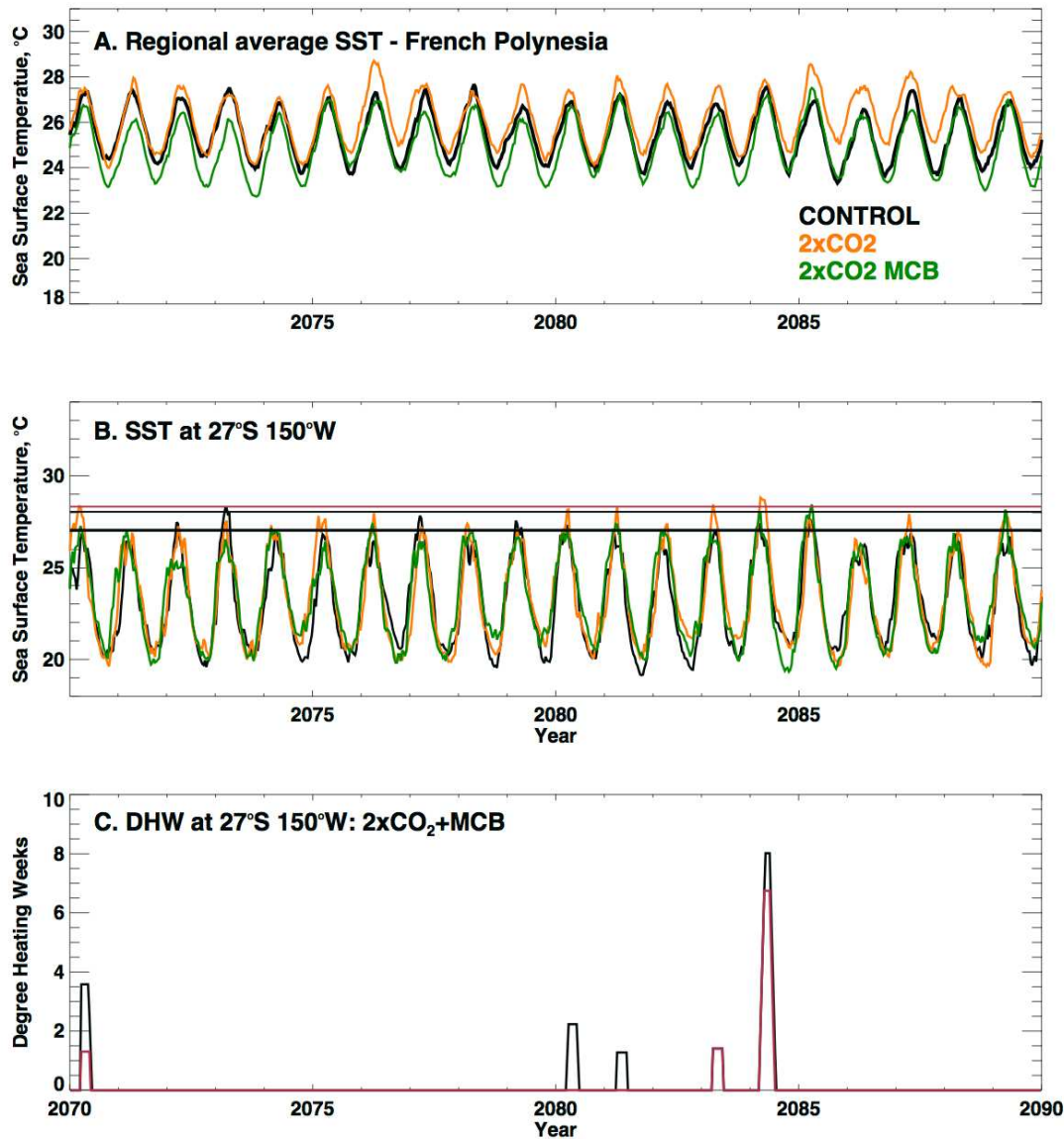
**Table 2.** The number of mild and severe bleaching events over a 20-year period for the three simulations: Control, 2xCO<sub>2</sub>, and 2xCO<sub>2</sub>+MCB. Bleaching events are calculated based on two heat-stress thresholds: 1°C above the climatological maximum, and 2.45 x *SD*<sub>max</sub> above the climatological maximum. Climatological maxima were calculated based on the Control. Note that the Control provides the background number of bleaching events expected under normal conditions. Numbers in parentheses are the number of ocean cells within each reef region.

Region	Control		2xCO <sub>2</sub>		2xCO <sub>2</sub> +MCB	
	Mild	Severe	Mild	Severe	Mild	Severe
Caribbean (439)						
1°C	0	0	294	104	0	0
2.45 <i>SD</i> <sub>max</sub>	0	0	655	177	3	0
Great Barrier Reef (179)						
1°C	0	0	323	71	0	0
2.45 <i>SD</i> <sub>max</sub>	0	0	311	36	0	0
French Polynesia (899)						
1°C	95	2	1056	1884	32	0
2.45 <i>SD</i> <sub>max</sub>	3	0	850	1502	2	0

## FIGURES.



**Figure 1.** (A) Change in annual average sea surface temperature (C) between the 2xCO<sub>2</sub> and CONTROL simulations. (B) Change in annual average sea surface temperature (C) between the CONTROL and 2xCO<sub>2</sub>+MCB simulations. The dashed black boxes in both panels represent the three coral reef regions.



**Figure 2.** A. Regional average sea surface temperature (SST) for French Polynesia, comparing SST for the three cases. B. SST for a single cell within the French Polynesia region, showing the climatological maximum (thick black line), and the 1°C (thin black line) and 2.45  $SD_{max}$  (thin red line) thresholds above the climatological maximum. C. The degree heating weeks (DHW) based on the 1°C (thin black line) and 2.45  $SD_{max}$  (thin red line) thresholds.