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Weakening of hurricanes via marine cloud brightening (MCB)

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Abstract

This paper examines the potential to cool ocean surface waters in regions of hurricane genesis and early development. This would be achieved by seeding, with copious quantities of seawater cloud condensation nuclei (CCN), low-level maritime stratocumulus clouds covering these regions or those at the source of incoming currents. Higher cloud droplet density would increase these clouds' reflectivity to incoming sunlight, and possibly their longevity. This approach is therefore a more localized application of the marine cloud brightening (MCB) geoengineering technique promoting global cooling. By utilizing a climate ocean/atmosphere coupled model, HadGEM1, we demonstrate that – subject to the satisfactory resolution of defined but unresolved issues – judicious seeding of maritime stratocumulus clouds might significantly reduce sea surface temperatures (SSTs) in regions where hurricanes develop. Thus artificial seeding may reduce hurricane intensity; but how well the magnitude of this effect could be controlled is yet to be determined.

We also address the important question as to how MCB seeding may influence precipitation. GCM modelling indicates that the influence of seeding on undesirable rainfall reductions depends on its location and magnitude. Much more work on this topic is required.

Keywords: **hurricanes; marine cloud brightening; sea surface temperature; cloud seeding; global climate modelling**

1. Introduction: rationale for cooling oceanic surface waters

The principal objective of this short paper is to present a first, somewhat rudimentary, General Circulation Modelling (GCM) modelling-based examination of the idea that marine cloud brightening (MCB) cloud seeding might be used to cool ocean surface waters in regions where the genesis and early development of hurricanes occurs, thereby weakening hurricane intensity. We also provide a limited assessment of the impact of MCB seeding on global rainfall patterns and amounts. Our clear view is that MCB seeding should never be deployed unless comprehensive studies show no adverse consequences of deployment that cannot be satisfactorily resolved.

Various hurricane research studies conducted in recent years have involved, directly or indirectly, the relationship between sea surface temperature (SST) and the energy and associated damage-wreaking potential of hurricanes. Expressing this issue in its most simplistic form, the energy available to feed hurricane development generally increases with increased SST, and so advertent significant reduction of SST in associated regions could weaken hurricanes to an appreciable degree. Analyses of accumulated hurricane data over about three decades, supported by computations, reveal a strong positive correlation between SST and maximum wind speed (DeMaria and Kaplan, 1994; Whitney and Hopgood, 1997).

We also mention some more subtle-related issues. SST values in excess of about 26 °C are necessary to provide sufficient potential instability for the growth of hurricanes (Holland, 1997). In a warmer climate scenario, SSTs will rise, but the resultant influence on hurricane activity depends on upper atmosphere warming and other factors. The rate of increase in the generation of potential instability and hurricane intensity slows down for values of SST above about 29 °C (Holland, 1997). Other theoretical and modelling work (Emanuel, 2005) suggests that with increased SSTs, longer storm lifetimes and intensities are likely. Recent model calculations suggest that the frequency of categories 4 and 5 storms will double by the end of the 21st century (Bender *et al.*, 2010). Other work predicts that tropical cyclone intensities will increase overall (Mann and Emmanuel, 2006) and specifically by between 2 and 11% by 2100 (Knutson *et al.*, 2010). Recently, improved climate and weather models indicate that predictions of hurricane activity are now viable for many years ahead (Knutson *et al.*, 2010).

Observational data on tropical cyclones over the last 35 years reveal a large increase in the number of hurricanes reaching categories 4 or 5 in regions of high SST in the Northern Atlantic, as well as in the Indian, North Pacific and South-West Pacific Oceans, where the largest increases have occurred (Bender *et al.* 2010). Further observational studies, using statistical analysis of the last 50 years of tropical cyclone data, show that anthropogenic factors (Mann and Emmanuel, 2006) are likely to be responsible for these trends in tropical cyclone activity, and not multi-decadal climate oscillations (Smith *et al.*, 2010). Emanuel (2005) and Wu *et al.* (2010) show that the influence of sea surface warming has been a major factor on hurricane activity.

The contribution of anthropogenic influences on observed changes remains controversial. Knutson *et al.* (2010) and Kossin *et al.* (2007) find that anthropogenic warming is not conclusively responsible for the increase in power dissipated by tropical cyclones. The results from Knutson *et al.* (2010) in particular is critical of the methods used by Holland (1997) and Emanuel (2005) while Kossin *et al.* (2007) question whether it is possible to predict future climatic conditions based on a 30 year record. Holland (1997) argue that when the SSTs are over 29.5 °C, the apparent linear increase of intensity no longer applies, as potential intensity is reduced by a warming upper troposphere. Webster *et al.* (2005) show that between the years of 1970 and 2004 and in the region between 10°–40° North and 30°–100° West, the increased frequency of high intensity hurricanes could be due to warmer SSTs. In addition, Webster *et al.* (2005) show results indicating increasing numbers of tropical cyclones in six basins including both the Pacific and Indian Oceans. However, Kossin *et al.* (2007) argues that only the Atlantic intensity has increased in a 23 year period between 1983 and 2005, with little evidence for an increase in other basins.

Emanuel (2005) shows a link between SST and hurricane intensity, but earlier work of Bister and Emanuel (2002) suggests that increasing potential intensity due to ozone loss is a cause of increasing hurricane intensity. There is still much scientific discussion in the literature about future intensification of hurricanes in a warmer world, which is beyond the scope of this article and is itself clearly a subject of further study. We assume herein that the link between SST and hurricane intensity in the region under consideration, is established, since the application of MCB would contain much of the maximum SST to below 29.5 °C. Furthermore, because most climate models (and the HadGEM suite used here) have limited vertical resolution (only 38 vertical levels), this effect cannot be examined with current supercomputer resources. In this paper, we argue that for similar SST conditions in a double-CO_2 world, with MCB, the hurricane intensity is likely to be similar to present values. However, a large number of remaining unknowns require further research.

In Section 2 we describe the MCB technique, the model used in these studies, and how we apply it to our hurricane weakening idea. Section 3 presents the results of these computations. Section 4 is dedicated entirely to examining the concomitant influence of the Solar Radiation Management (SRM) cloud seeding on precipitation. Section 5 provides a discussion of the hurricane weakening results.

2. Marine cloud brightening technique for SST reduction

The MCB idea (Latham 1990, 2002; Bower *et al.* 2006, Latham *et al.*, 2008, 2012; Salter *et al.*, 2008, Jones *et al.* 2009, 2011; Rasch *et al.*, 2010; Korhonen *et al.*, 2010; Bala *et al.*, 2011; Wang *et al.*, 2011) was developed for geoengineering purposes, i.e. it constitutes a possible method for stabilizing the earth's average surface temperature and polar sea-ice coverage (both poles) at roughly current values. Encouraging results as to the quantitative viability of this technique have emanated largely from GCM and other global-scale modelling (Latham 2006, Latham *et al.*, 2008, 2012; Jones *et al.*, 2009, 2011; Rasch *et al.*, 2010; Bala *et al.*, 2011) and are also supported by some high-resolution cloud modelling (Wang *et al.*, 2011; Latham *et al.*, 2012) and limited observational evidence (Latham *et al.*, 2008). However, much more modelling, as well as technological work, a limited-area field experiment and comprehensive unintended-consequences considerations are required before it will be clear whether this technique could ever be safely and usefully deployed on the required global scale. The possibility that deployment of MCB would cause precipitation reduction, particularly in the Amazon Basin, is examined in Section 4.

Marine stratocumulus clouds cover about a quarter of the ocean surface. They are characteristically a few hundred metres deep, with bases a few hundred metres above the ocean surface, and have albedos within the range 0.3–0.7 (Hanson, 1991). Our geoengineering idea is to disseminate sprays of roughly monodisperse seawater droplets (mean diameter in range 0.3–0.8 μm), possibly from spray-systems mounted on wind-powered, satellite-controlled, unmanned Flettner rotor vessels (Salter *et al.*, 2008) sailing in optimally located regions. A significant fraction of these particles will rise into the clouds and be nucleated to form additional droplets, thus elevating the cloud droplet number concentrations, the cloud albedo (Twomey, 1977) and possibly cloud lifetime (Albrecht, 1989). The amount of cooling could in principle be controlled, and GCM computations indicate that it would not be infeasible to produce 24 h, 5 year mean local negative forcings of up to at least -50 W m^{-2} (Latham *et al.*, 2008), corresponding to a significant lowering of the associated ocean surface temperatures.

This paper presents a first, limited exploration of the idea that MCB seeding – on a much more geographically limited scale than in its global temperature stabilization application – could be used for hurricane weakening. It describes a GCM modelling study, utilizing the Met Office HadGEM1 model (Martin *et al.*, 2006) already deployed in much of our geoengineering work. This climate model has an atmospheric resolution of 1.25° × 1.875° with 38 vertical levels, with an upper lid at 39 km. The oceanic component utilizes a latitude–longitude grid with a longitudinal resolution of 1°, and latitudinal resolution of 1° between the poles and 30° north/south, from which it increases smoothly to one third of a degree at the equator, giving 360 × 216 grid points in total, and 40 unevenly spaced levels in the vertical (a resolution of 10 m near the surface). The changes in the temperature and depth of the ocean thermocline due to solar heating and wind-mixing are included. Experimental use and case study implementation are as described in our previous atmospheric HadGAM modelling study (Latham *et al.*, 2008). Simulations were completed, each for 70 years from 2020 to 2090, with the last 20 years analysed, a control run with static carbon dioxide at 2020 levels (440 ppm), and a run with carbon dioxide concentration increasing by 1% per year up to double pre-industrial carbon dioxide levels (560 ppm at 2045). In these GCM studies we compute distributions of SST for two non-seeding situations: $1 \times CO_2$, corresponding to 'current', 2020 conditions (control), and $2 \times CO_2$, where the CO_2 level has risen to twice pre-industrial values. Additionally, we make runs in which cloud seeding occurs over either three large regions of persistent stratocumulus (Latham *et al.*, 2008, 2012; Jones *et al.*, 2009, 2011; Korhonen *et al.*, 2010), or over all regions of suitable clouds (Latham *et al.*, 2008; Korhonen *et al.*, 2010; Rasch *et al.*, 2010). These two seeding scenarios are deployed in our computations at both $1 \times CO_2$ and $2 \times CO_2$, and are called 'patchy' and 'full' respectively. The 'patchy' simulation seeds over the pale blue regions in Figure 1(a) and the 'full' seeding over the pale blue regions in Figure 1(b) (i.e. all maritime areas). In all the seeding runs it is assumed that the cloud droplet number concentration N is maintained at 375 cm^{-3}. All results presented are averages over the three maximum-occurrence North Atlantic hurricane months: August, September and October.

3. Results

Each of the three figures presented below shows values of SST differences (°C) between specified conditions within a geographical area bounded by latitudes 40° north and 40° south and longitudes 110° west and 40° east. The inner, dashed rectangle, present in all four figures, defines the hurricane development region (HDR) chosen for the present study, highly energetic and damaging hurricanes commonly develop in or around this region of the Tropical North Atlantic, to the east of the Gulf of Mexico in a box 10°–30° north and 30°–80° west.

Zhao and Held (2010) argue that hurricanes develop within the bounds of 10°–20° north and 30°–45° west. Our HDR covers a large portion of the region designated by Zhao and Held (2010). If the SST within this region is cooled by our proposed cloud seeding below about 26 °C, hurricanes will not form. If the SST is reduced by seeding to a temperature above 26 °C, they will be weakened.

Table I presents computed values of average SST (°C) and precipitation (mm day^{-1}) departures from

Table I. Departures (°C) of average sea surface temperature (SST) and precipitation rates (mm day^{-1}) values from control (no seeding, $1 \times CO_2$) for the four SST figures (Figure 2) and precipitation rate figures (Figure 3) presented below. 'Seed' is the type of seeding, 'HDR' is the hurricane development region (defined in the text), and the atmospheric CO_2 concentration is either the current value (control) or twice the pre-industrial value.

Figures	CO_2	Seed	HDR ΔT (°C)	Global ΔT (°C)	Precipitation (mm day^{-1})
1	×2	None	0.66	0.53	0.034
2	×2	Patch	0.13	−0.11	0.0068
3	×2	Full	−4.00	−5.04	−0.44
4	Control	Full	−4.61	−5.38	−0.48

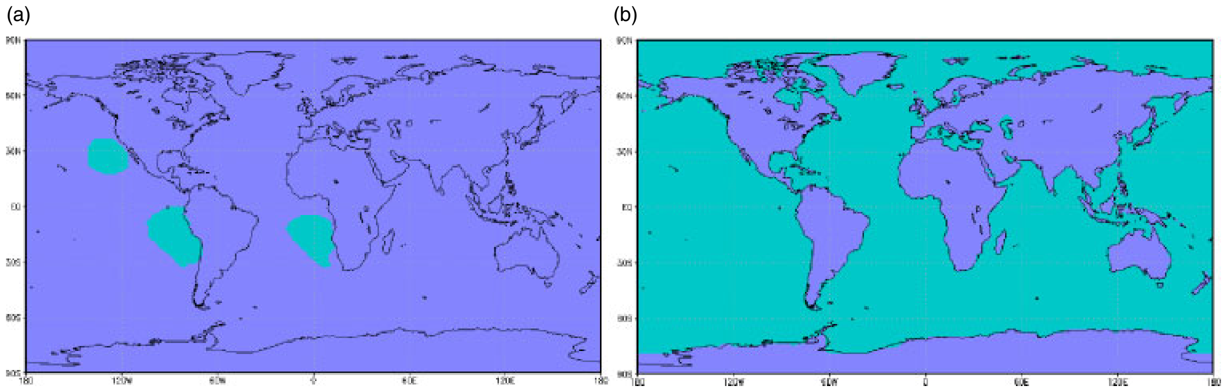

Figure 1. Maps showing seeding regions. (a) The 'patchy' seeding experiments. These areas cover 5% of the ocean surface. (b) The 'full' seeding, the areas covering 100% of the ocean surface.

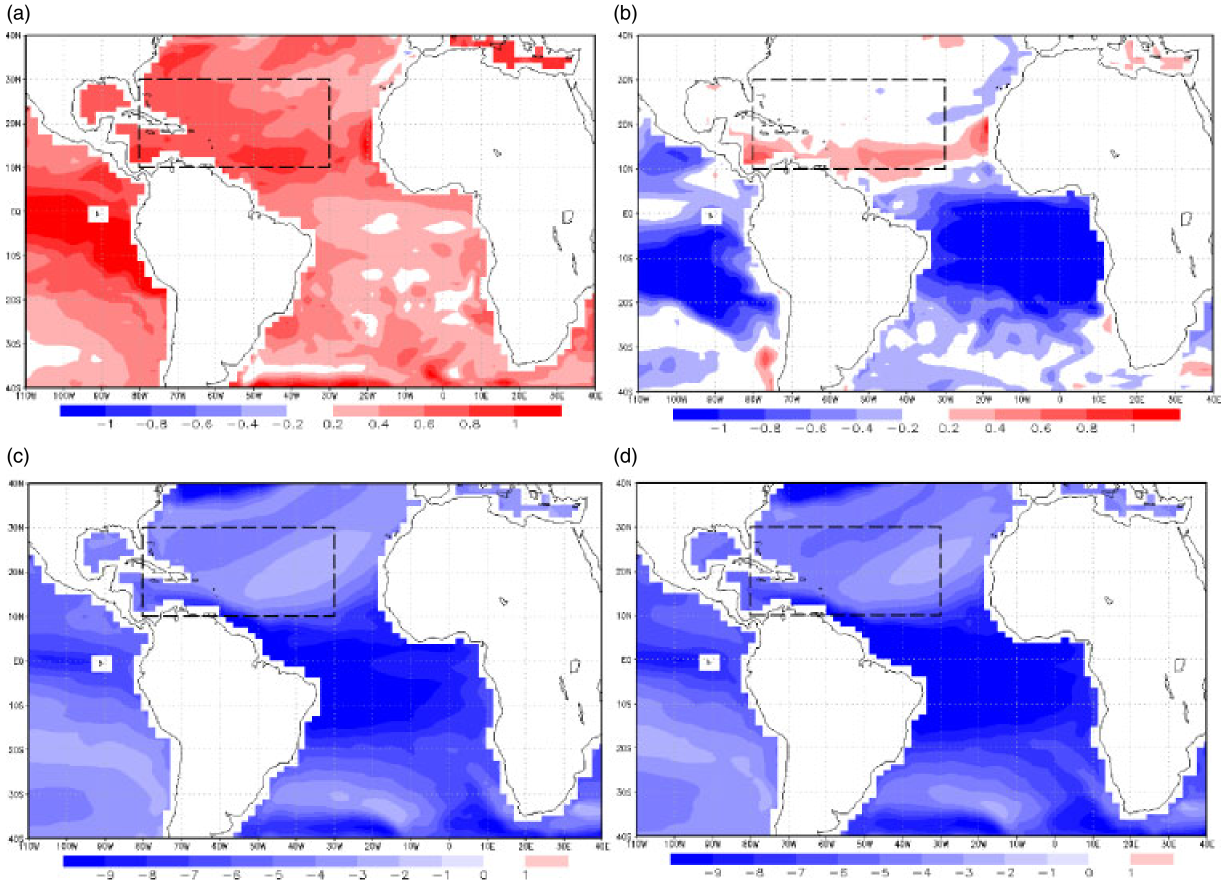

Figure 2. Sea surface temperature (SST) differences (°C). (a) Conditions $2 \times CO_2$ and $1 \times CO_2$, within an area bounded by latitudes 30° north and 30° south and longitudes 110° west and 60° east. There is no seeding. The inner, dashed rectangle defines the hurricane development region (HDR). The average difference in SST (from control) is 0.66 °C in the HDR and 0.53 °C globally. (b) Patchy seeding at $2 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average difference in SST (from control) is 0.13 °C in the HDR and −0.11 °C globally. (c) Full seeding at $2 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average difference in SST (from control) is −4.0 °C in the HDR and −5.04 °C globally. (d) Between full seeding at $1 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average reduction in SST produced by seeding is −4.6 °C in the HDR and −5.38 °C globally.

control for specified CO_2 concentrations and types of seeding (as discussed earlier), both within the HDR and globally.

Figure 2(a) shows the predicted distribution of the difference between SST values at $2 \times CO_2$ and $1 \times CO_2$ (control, no seeding). The predicted differences over land are not shown, in order to simplify presentation of the oceanic SST results. The average SST temperature difference between the $2 \times CO_2$ and $1 \times CO_2$ cases is 0.66 °C for the HDR, and 0.53 °C globally.

Figure 2(b) and (c) shows the predicted distribution of the difference between SST values at control ($1 \times CO_2$, no seeding) and at $2 \times CO_2$ with patchy and full seeding cases respectively. For patchy seeding the average SST temperature difference between $2 \times CO_2$ and $1 \times CO_2$ (no seeding), in the HDR, is reduced from 0.66 to 0.13 °C. For full seeding the average SST in the HDR is 5.0 °C below the $1 \times CO_2$ value. The globally averaged SST reductions for the two seeding techniques are −0.11 and −5.0 °C respectively.

Figure 2(d) is for the same conditions as Figure 2(c). The full seeding occurs in a $1 \times CO_2$ environment. In this case, the average SST reduction in the HDR is 4.6 °C. The corresponding reduction in globally averaged SST is 5.4 °C.

4. Influence of MCB on precipitation amounts

Concerns have been raised that deployment of MCB could cause unacceptable precipitation reductions in important areas, particularly the Amazonian Basin and South-East Asia.

Several GCM studies have covered this topic including Jones *et al.* (2009, 2011) and Latham *et al.* (2012), all using the HadGEM suite of models. They employed the three-patch seeding procedure described earlier, with the imposed cloud droplet number concentration $N = 375\ \text{cm}^{-3}$. Their most noteworthy finding was a significant reduction in precipitation for the whole averaged Amazon Basin. The reduction was in excess of $1\ \text{mm day}^{-1}$. Further support for the original Jones *et al.* (2009) findings was provided by Bala *et al.* (2011), who seeded all suitable clouds and found a smaller but significant rainfall reduction over a small fraction of this Amazonian region.

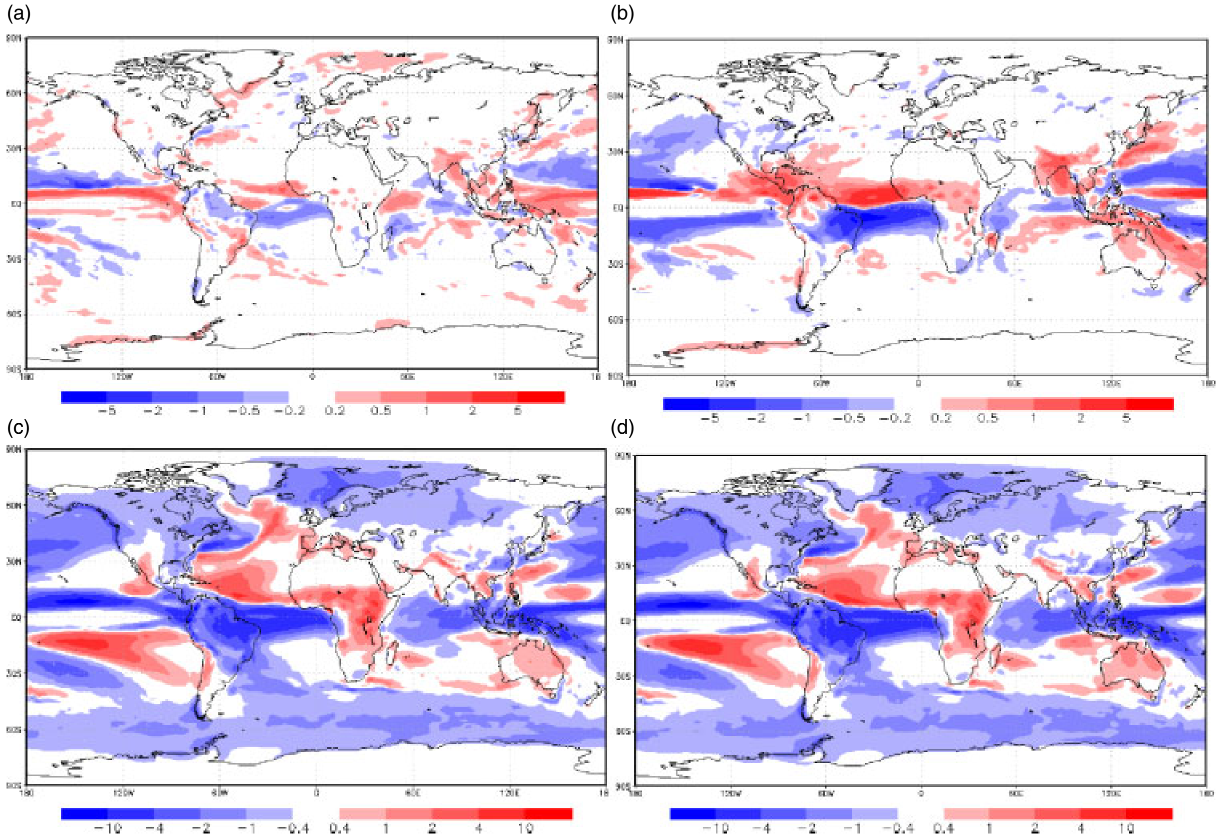

Figure 3. Precipitation rate (mm day^{-1}) differences. (a) Conditions $2 \times CO_2$ and $1 \times CO_2$. There is no seeding. The average difference in precipitation (from control) is 0.035 mm day^{-1} globally. (b) Patchy seeding at $2 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average difference in precipitation (from control) is 0.0068 mm day^{-1} globally. (c) Full seeding at $2 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average difference in precipitation (from control) is −0.45 mm day^{-1} globally. (d) Full seeding at $1 \times CO_2$ and control ($1 \times CO_2$, no seeding). The average difference in precipitation (from control) is −0.48 mm day^{-1} globally.

Latham *et al.* (2012) and our current work, illustrated in Figure 3(a–d), show the difference in global annual average precipitation rate P between the modified climates and the control simulation. Figure 3(a) shows the differences in precipitation rate P (mm day^{-1}) between conditions $2 \times CO_2$ and $1 \times CO_2$. There is no seeding. The average difference in precipitation (from control) is 0.035 mm day^{-1} globally. Figure 3(b) shows P differences between patchy seeding at $2 \times CO_2$ and control ($1 \times CO_2$ no seeding). The average difference in precipitation (from control) is 0.0068 mm day^{-1} globally. Figure 3(c) shows P differences between full seeding at $2 \times CO_2$ and control. The average difference in precipitation (from control) is −0.45 mm day^{-1} globally. Figure 3(d) shows P differences for full seeding at $1 \times CO_2$ and control. The average difference in precipitation (from control) is −0.48 mm day^{-1} globally. The results in Figure 3(a) and (b) are replots of data shown in Section 2 of Latham *et al.* (2012), which are discussed in some detail therein. Doubling concentrations with respect to pre-industrial levels leads to an increase in globally averaged P of 0.034 mm day^{-1}, related to increased evaporation in a warmer world. Patchy seeding in the $2 \times CO_2$ atmosphere reduces this increase in P to 0.0068 mm day^{-1}. The impacts of these precipitation changes on vegetation and productivity have been analysed by Jones *et al.* (2009). The full seeding of MCB in a $2 \times CO_2$ or control atmosphere results in reductions in precipitation rate of 0.44 and 0.48 mm day^{-1} globally. Full seeding leads to a reduction in precipitation over the Amazon, much of North America and much of South-East Asia; and there is an increase in precipitation over Africa and Australia.

The studies described above reinforce concerns regarding possible unacceptable precipitation reductions resulting from the deployment of MCB. On the other hand, the GCM computations of Rasch *et al.* (2010) – who seeded significantly larger cloudy areas than Jones *et al.* (2009) – ranging from 20 to 70% of the total area covered by suitable clouds, revealed no reduction of rainfall in this region. Also, when Jones *et al.* (2011) repeated their earlier (three-patch) studies, with the exception that they did not seed the Southern Atlantic (off Namibia) patch of stratocumulus cloud, they found no reduction of rainfall in the Amazonian region. Rasch *et al.* (2010) found that the global rainfall patterns were significantly sensitive to the fraction of suitable clouds seeded, as well as the amount of seeding, while Bala *et al.* (2011) showed that although MCB seeding reduced the total global rainfall, there was a net rainfall gain over land. As shown by Latham *et al.* (2012), the uncertainties in current climate model(s) precipitation values compared with CPC Merged Analysis of Precipitation (CMAP) observations exceed the possible precipitation modifications caused by application of MCB. This subject requires further research, and also further study as to why climate models perform so poorly in tropical regions.

We conclude therefore that it is possible that unacceptable rainfall changes may result from MCB seeding, and if these cannot be corrected MCB should never be deployed. However, the above discussion indicates that the rainfall changes are very sensitive to the location, areal coverage and amount of seeding. Much more work is required before it will be clear whether MCB seeding could be a useful geoengineering tool. One favourable feature possessed by MCB is that for a considerable time into the future (if the technique proved viable and was deployed) only a small fraction of suitable clouds would need to be seeded. Thus there is, in principal, flexibility as to which cloudy areas should be seeded – and which should not – and to what degree. This feature might be valuable in avoiding unacceptable consequences.

5. Discussion

As mentioned earlier, we do not yet know whether the MCB cooling technique designed to exploit the Twomey effect (i.e. cloud albedo enhancement resulting from an increase in cloud droplet number concentration) can be made to function as effectively as our GCM modelling assumes, and if it does, whether its deployment would have significant adverse consequences – such as rainfall reduction in sensitive locations, as discussed in Section 4. This statement pertains both to MCB fully global effects and more localized ones, as in the case of hurricane weakening.

The modelling results presented in the previous section indicate that the SST in regions where hurricanes develop might be appreciably reduced by such cloud seeding, thereby raising the possibility of significantly weakening hurricane development, and thus lessening the damage that hurricanes weak. The magnitude of the cooling produced in relevant oceanic regions depends on the fraction of suitable cloud cover seeded and the location and amount of the seeding, both of which could be controlled to a significant extent. Determination of the optimal amounts and locations of seeding for the required SST reductions in HDRs needs significant further investigation

The 'patchy' seeding, which involves the three oceanic regions of most persistent stratocumulus cloud coverage, which has been employed in several GCM studies of MCB (Latham *et al.*, 2008; Jones *et al.*, 2009, 2011; Korhonen *et al.*, 2010), is found (see previous section) to produce an SST reduction which roughly compensates for the warming resulting from CO_2 doubling. Seeding all suitable clouds produces major over-compensation. It follows that, in principle, if this technique was ever deployed globally, it may be possible to select seeding regions that do not produce associated adverse consequences, such as reduction of rainfall over adjacent land regions, thereby affecting water resources. As mentioned earlier, if such adverse consequences could not be removed, no case would exist for deploying MCB.

If it transpires that the values of SST reduction emanating from our GCM computations and presented herein are roughly correct, it could be possible – subject to satisfactory resolution of all important technology and safety considerations – to weaken hurricanes in the HDR sufficiently to reduce damage appreciably while sustaining local rainfall amounts. Simple calculations based on observationally based relationships between SST and maximum wind speed (DeMaria and Kaplan, 1994, Whitney and Hopgood, 1997) together with the SST-reduction values emanating from our computations suggest that cooling produced by MCB may well be able to reduce hurricane intensity by one category, perhaps two, in some circumstances. We do not know, at this stage, whether it could prevent the formation of a significant number of hurricanes.

As stressed before, this study is simply a first look at a possibly useful application of MCB. If further work is justified, it would be necessary to take account of other complexities and subtleties, some of which have been identified herein.

If the MCB technique discussed herein was to be deployed globally it would need to operate continuously and we would need to cool waters over several seasons to produce a noticeable effect (Rasch *et al.*, 2010). For patchy seeding, we do not seed in the HDR region defined above, we emphasize that MCB does not involve the seeding of storm-clouds or hurricanes. It is focused entirely on seeding propitiously located marine stratocumulus clouds in order to enhance their albedo to incoming sunlight.

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