Marine Cloud Brightening:
current research and remaining challenges

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Abstract

Marine Cloud Brightening, or MCB, has been proposed as a method to cool the climate by limiting the amount of solar energy entering the Earth system. MCB aims to spray small seawater droplets from seafaring vessels into the marine boundary layer to enhance cloud albedo. This paper examines the obstacles still facing the actual implementation of MCB, such as uncertain cloud-aerosol interactions and technological development of spray production and deployment methods. Though cloud-aerosol interactions can be uncertain in models, there is reasonable confidence that MCB aerosols must be within a narrow range of sizes to produce the desired cooling effect. These aerosols would be most efficiently generated via the Rayleigh jet principle, though higher-energy methods, such as using supercritical seawater, have been proposed as well. The spray would be produced on autonomous Flettner-rotor vessels capable of harnessing energy from the wind.

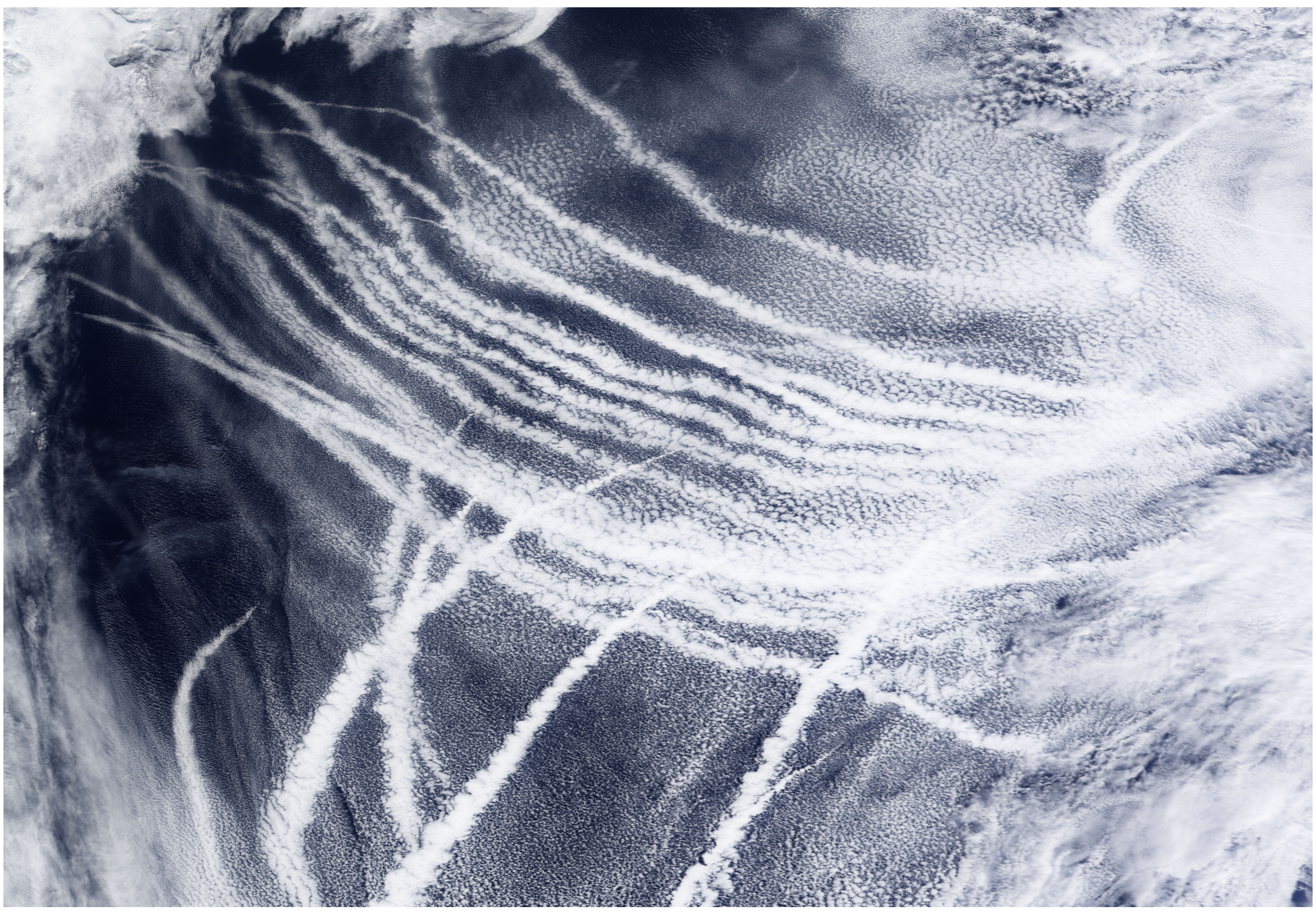

Figure 1 – *Pollution particles from ship tracks over the Pacific Ocean helps seed marine stratocumulus clouds via the Twomey effect. MCB hopes to achieve a similar effect using benign sea salt particles (Kennedy, 2012).*

Introduction

As anthropogenic greenhouse gas emissions continue to grow, limiting temperature increase by mitigating carbon output will become more difficult (IPCC, 2014). As a result, various "geoengineering" techniques have been proposed as an alternative way to cool the climate. Some geoengineering schemes, called Solar Radiation Management (SRM), attempt to accomplish this cooling by limiting the amount of shortwave solar energy entering the Earth system (e.g. Crutzen, 2006; Kravitz et al., 2013). SRM is commonly associated with stratospheric sulfate injection, a method whose geographic range and chemical interactions are hard to control (e.g. Pidgeon et al., 2013; Robock, 2016). Marine Cloud Brightening (MCB), a different SRM scheme originally proposed by Latham (1990; 2002), has the potential to avoid these downsides and have regional benefits (such as restoring sea ice or weakening hurricanes) (Latham et al., 2012b; 2014).

MCB involves increasing marine stratocumulus cloud albedo through seeding. In broad terms, seawater would be atomized near the ocean surface into monodisperse droplets with a diameter of around 0.8 μm (Latham et al., 2008; Salter et al., 2008). As these droplets evaporate and are carried by wind and updrafts through the marine boundary layer, their residual NaCl crystals act as cloud condensation nuclei (CCN) for low-level marine stratocumulus. By being large enough to activate additional water condensation within the cloud, these particles would increase cloud droplet number concentration (CDNC) and therefore cloud albedo (see Twomey, 1977). Model studies estimate that achieving the necessary global -3.7 Wm^{-2} radiative forcing to counterbalance a doubling of CO_2 (from the pre-industrial standard of 275 ppm) would require an albedo increase of 0.06 across 3% of global area (Latham et al., 2008; Wang et al., 2011). As marine stratocumulus clouds occupy around a quarter of all ocean area, enough suitable clouds should, in theory, exist in order to apply MCB on a sufficient scale (Latham et al., 2008).

While the theory behind MCB has been promising in models, obstacles still prohibit actual application of MCB. Namely, NaCl aerosols must produce the desired increase in CDNC without unforeseen adverse effects, and these aerosols must be generated and deployed at-scale. This paper will highlight current MCB research regarding cloud-aerosol interactions and engineering challenges, and will not focus on issues such as MCB's (and SRM's in general) effect on large-scale energy fluxes (see Jones et al., 2009) and the atmospheric hydrological cycle (see Bala et al.), nor the public policy implications which pertain to geoengineering as a whole.

Cloud-aerosol interactions

At its most basic level, MCB aims to utilize the aerosol indirect effect, also called the Twomey Effect (Twomey, 1977). Twomey identified the ability of air pollutant particles to increase cloud albedo (as in Figure 1), and later studies showed that the presence of aerosols can also increase cloud lifetime by preventing precipitation (Albrecht, 1989). Thus, MCB could produce a bilateral decrease in radiative forcing. However, changes in ambient conditions and size distribution of CCN can greatly affect both these outcomes; due to this layer of complexity, aerosol-cloud interactions are one of the least-understood physical processes contributing to radiative forcing (Carslaw et al., 2013). While early MCB simulations did not account for such variability, subsequent studies on cloud-aerosol microphysics and transport dynamics have helped identify optimal and sub-optimal seeding schemes.

The first uncertain step in MCB seeding is the air currents and updrafts needed to transport aerosol particles from point of emission vertically through the marine boundary layer. Early MCB studies assumed a uniform distribution of injected aerosol at cloud-level of 375 cm^{-3} (and as high as 1000 cm^{-3}), and Wang et al. confirmed with a cloud-resolving model that CCN produced near sea level do move upward throughout the boundary layer within a few minutes (Wang et al., 2011). However, their horizontal distribution is much less homogeneous, and the resultant localized gradients in CCN concentration can invoke dynamical feedbacks which may reduce albedo, as in Figure 2 (Wang et al., 2009; 2011).

A second and equally important consideration is the ability for injected aerosols to increase CDNC. Injected NaCl particles should activate condensation and create more numerous, smaller cloud droplets given anticipated cloud properties in various ambient conditions (Bower et al., 2006). Of the sets of conditions tested by Wang et al. (2011), two were found to support MCB: first, in a weakly-precipitating boundary layer, additional CCN stabilized the clouds and further reduced precipitation; and second, when cloud formation is limited by presence of CCN, the additional particles strengthened albedo. Conversely, in very wet (highly-precipitating) and very dry (low supersaturation) regimes, cloud seeding was not found to be effective. Interestingly, cloud seeding in areas already affected by pollution or natural dimethyl sulfide (DMS) particles also proved ineffective, as adding NaCl to already-brightened clouds only serves to inhibit their albedo (Korhonen et al., 2010; Wang et al., 2011).

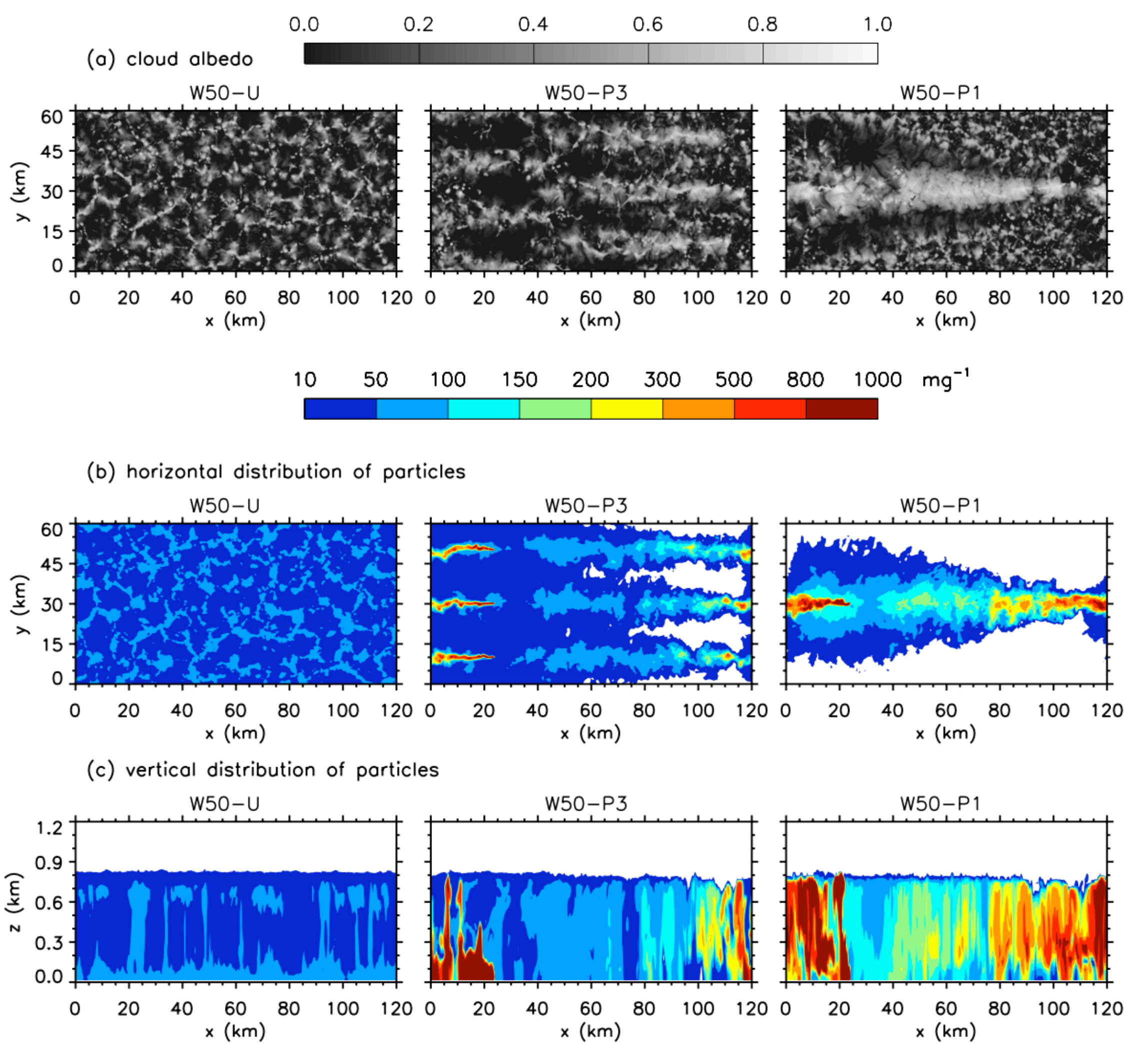

Figure 2 – *Simulation results from no aerosol sprayers (left), three sprayers (middle), and one sprayer (right) of (a) cloud albedo, (b) mean number concentration of boundary-layer injected particles, and (c) vertical particle number concentration along the path of the central sprayer. Though sprayers increase albedo and number concentrations in some areas, these increases are often accompanied by corresponding decreases in adjacent areas (Wang et al., 2011).*

Challenges:

Remaining challenges and uncertainties include evaporative cooling from droplet production and the well-documented adverse effects of injecting wrongly-sized aerosols. As sprayed seawater droplets evaporate, an intense local cooling effect occurs which negatively affects the droplets' (and aerosol's) buoyancy (Cooper et al., 2013). Smaller spray droplet size (resulting in less total evaporation) and fans providing an initial updraft at injection source have been proposed to address this issue for MCB (Cooper et al, 2013; Salter et al., 2008).

Numerous studies have shown that aerosols too large or too small not only reduce the effectiveness of MCB, but could even produce an adverse net positive radiative forcing (Alterskjær and Kristjánsson, 2013; Connolly et al., 2014; Feingold et al, 2009; Latham et al., 2012). For example, giant cloud condensation nuclei (GCCN) with radii on the order of 20-μm can cause non-precipitating stratocumulus to precipitate, leading to decreased cloud water content and lifetime (Feingold et al, 2009). Additionally, Alterskjær and Kristjánsson found that MCB-order injections of Aitken particles (with radii on the order of 0.04 μm) may increase radiative forcing by up to 8.4 Wm^{-2}, due in part to Aitken-mode sea salt's high supersaturation requirement. Thus, droplet and resultant aerosol particle size is a critical determining factor of MCB's feasibility. The following section will discuss methods of reliably producing and deploying such particles.

Droplet creation and deployment

To produce the -3.7 Wm^{-2} radiative forcing desired by MCB, an average spray rate sufficient to seed 45 m^3s^{-1} of clouds is necessary (Salter et al., 2008). With a reasonable number of injection sources, this corresponds to atomizing 30 kgs^{-1} of seawater at a median droplet diameter of 0.8 μm (and up to 4 μm) (Salter et al., 2008; Neukermans et al., 2014). The resultant ~10^{17} s^{-1} CCN injection rate per source should reduce global solar energy input by 2000 TW (Salter et al., 2008). However, no spray nozzles capable of meeting these requirements currently exist commercially. As a result, several groups have tried developing the necessary hardware.

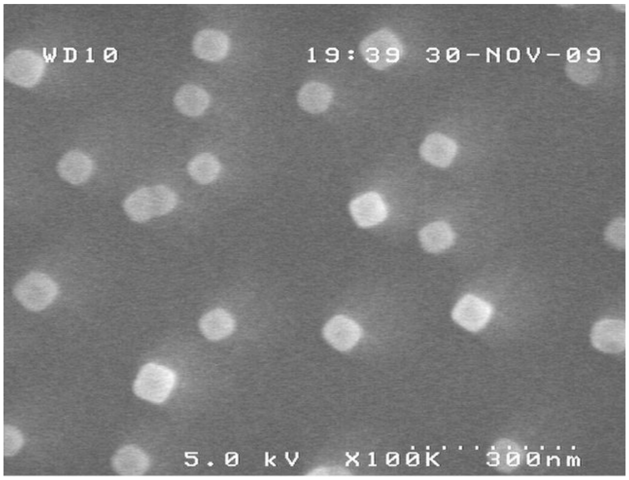

Figure 3 - *Salt particles sprayed from cone-jets at 100,000x magnification. The average size of these particles is 59.8 nm, and their parent droplets were observed to evaporate almost instantaneously upon emission (Cooper et al., 2013).*

Among the considered spray methods have been Rayleigh jets, Taylor cone jets, supercritical fluids, and effervescent spray (see Appendix A of Connolly et al) (Connolly et al., 2014; Cooper et al., 2013; Neukermans et al., 2014). To achieve the desired droplet size and narrow size variance, Rayleigh jets are the most energy-efficient (Connolly et al., 2014). Cooper et al. found Taylor cone jets, which use an electric field to scatter droplets, to be the most effective at producing MCB-specific particles (see Figure 3). However, since both these jets rely on forcing fluid through small orifices at a high pressure, lower fluid viscosity improves efficiency; thus, Neukermans et al. found that using supercritical seawater with lower surface tension improved the Rayleigh nozzles' performance (though it required much more energy). Which technique proves to be more effective in practice will depend on the energy limitations of their deploying mechanism.

MCB deployment vessels:

To sufficiently deploy cloud seeding aerosols for a reasonable cost, a fleet of mobile, autonomous crewed vessels is necessary. Furthermore, these vessels need some capacity for storing or generating large amounts of power to drive their spraying—preferably, given the current climate predicament, they would do so without fossil fuels. In an effort to meet these criteria, Salter et al. have proposed a GPS-guided vessel design powered by the wind via Flettner rotors (see Figure 4). Flettner rotors are large, cylindrical columns which spin and propel the vessel perpendicularly to a wind current using the Magnus effect (Salter et al., 2008). Flettner rotors have a much higher weight-to-thrust ratio than conventional sails and require 90-95% less power than conventional ships with the same thrust (Salter et al., 2008)

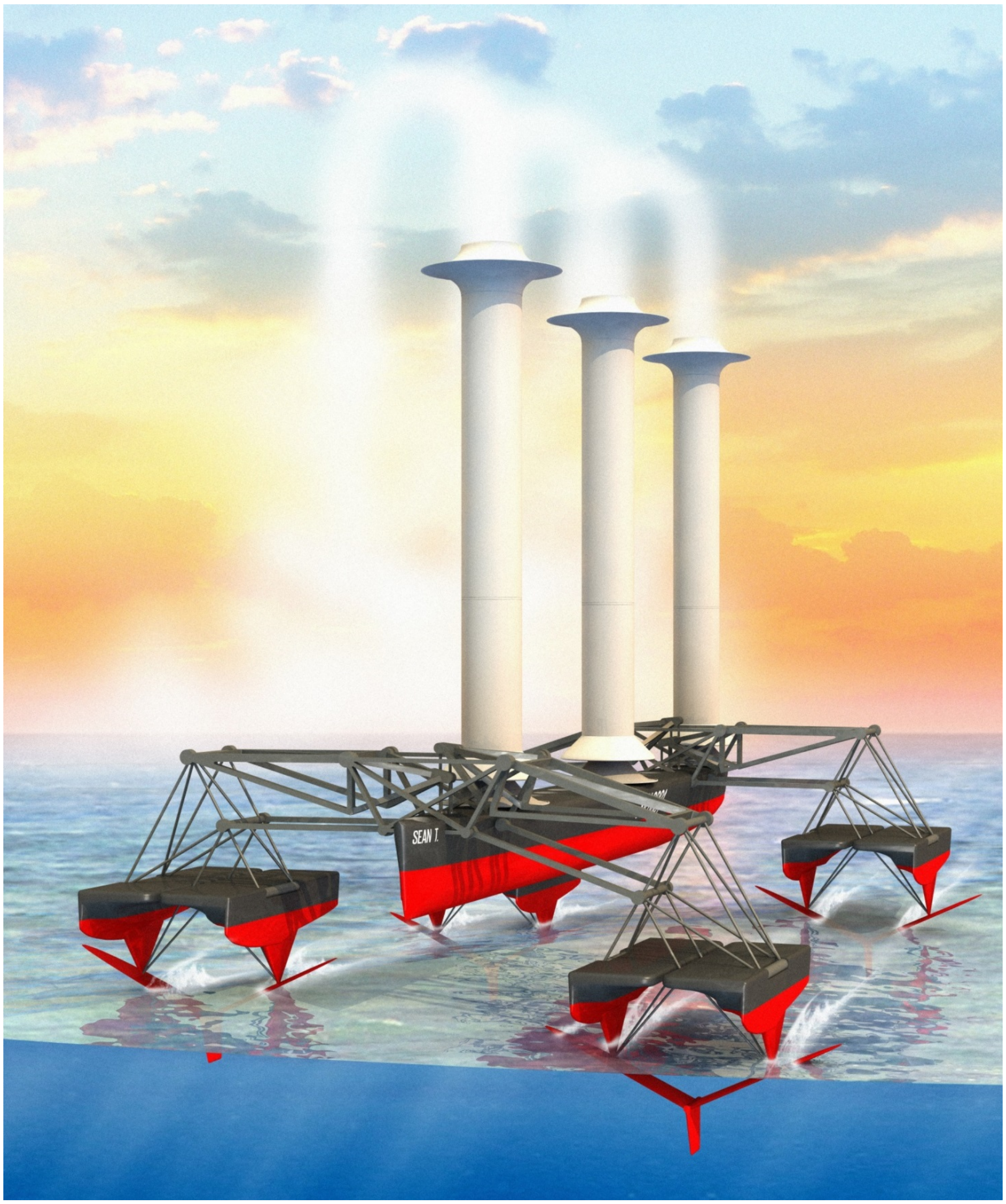

Figure 4 – *Artist's impression of the latest MCB vessel design (© John MacNeill). Ridges called Thom fences are included atop the rotors to reduce the effect of tip-vortex drag (Salter et al., 2008). This design iteration generates electricity as the hydrofoils change pitch (S. Salter, personal communication, March 30, 2017).*

The vessels can generate power renewably from large, 2.4 m diameter underwater turbines (Salter et al., 2008) or (in more recent iterations) hydraulics connected to hydrofoils which generate electricity as the vessels move (S. Salter, personal communication, March 30, 2017). The turbines should provide enough power for onboard control systems, as well as seawater pressurization, filtration, and atomization (together with fans providing a 12 ms^{-1} initial updraft) (Salter et al., 2008).

According to Salter et al., around 1500 of these vessels are required to achieve the desired total spray rate. After an investment of around £27 million for research and development, £30 million for tooling, and 5 years, each vessel could be produced for £1-2 million. Since the vessels are autonomous, operating costs are expected to be low. For the degree of global change these vessels could bring, a total expenditure of around £2 billion is not very significant.

Conclusions

MCB, a form of SRM attractive due to its regional adjustability and use of benign sea salt, requires more research on interactions between NaCl aerosol particles and clouds, high-volume spraying technology, and autonomous deployment vessels. While the engineering challenges are easily solved with increased funding, the lingering scientific questions of cloud-aerosol interactions are more complex in nature. These sorts of interactions—namely aerosol indirect effects—are among the least certain and least confidently represented physical processes in Earth system models. As a result, developing spraying technology may have impacts extending far beyond MCB research. The ability to spray aerosols into a variety of cloud types presents an interesting research opportunity for atmospheric science in general. Coupled with satellite observations of cloud properties, these experimental injections could help shed light on long-uncertain aerosol-cloud interactions (Wood et al., 2017). Perhaps, then, there will be greater incentive to fund research into the science and technology behind MCB. Having access to such innovations may prove useful should we ever need to pursue SRM as a response to climate warming.

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