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ABSTRACT

Propose: Currently, negotiation on global carbon emissions reduction is very difficult due to lack of international willingness. In response, geoengineering (climate engineering) strategy is proposed to artificially cool the planet. Meanwhile, as the harbor around one-third of all described marine species, coral reefs are the most sensitive ecosystem on the planet to climate change. However, until now, there is no any quantitative assessment on impacts of geoengineering on coral reefs. In this study, we model impacts of stratospheric aerosol geoengineering on coral reefs.

Design/methodology/approach: We will use the HadGEM2-ES climate model to model and evaluate impacts of stratospheric aerosol geoengineering on coral reefs.

Findings: This study shows that a) stratospheric aerosol geoengineering could significantly mitigate future coral bleaching throughout the Caribbean Sea; b) Changes in downward solar irradiation, sea level rise and sea surface temperature caused by geoengineering implementation should have very little impacts on coral reefs; c) although geoengineering would prolong the return period of future hurricanes, this may still be too short to ensure coral recruitment and survival after hurricane damage.

Originality/value: This is the first time internationally to quantitatively assess impacts of geoengineering on coral reefs.

Keywords: Stratospheric Aerosol Geoengineering; Coral Growth; Hurricanes; Coral Bleaching; Coral Recruitment; Caribbean Sea

1. Introduction

Recent global warming has serious effects on coral reefs as the most sensitive ecosystems on the planet to climate change and results in widespread bleaching and mass mortality events (Baker et al, 2008). Although coral reefs make up only 0.2% in area of the marine environment, they are among the most biodiverse ecosystems in the ocean, estimated to harbor around one-third of all described marine species (Crabbe, 2009). Coral reefs support the livelihoods of millions of people especially those engaged in marine fisheries activities, and they also provide some important chemical compounds for many of the world's most prevalent and dangerous illnesses and diseases, e.g., the Caribbean Sea squirt can be used in the treatment of ovarian cancer (Miththapala, 2006). The growth and subsistence of corals depend on many environmental & climatic factors, including temperature, irradiance, hurricanes, calcium carbonate saturation, sedimentation, and nutrients (Crabbe, 2009). These factors influence the key physiological processes of photosynthesis and calcification as well as coral survival, and as a result scleractinian coral reefs occur only in select areas of the world’s oceans. Due to recent global warming, serious degradation has been observed on many coral reefs worldwide, and coral cover in the Caribbean has declined in some areas to ~10% in the early 2000s (Isabelle et al., 2013, Schutte et al., 2010). Some reefs can self-recover, while others need help from artificial restoration, and some are unable to undergo restoration because the substrate or environment is not suitable for coral growth.

In order to mitigate against the effects of global warming, a direct approach is to radically transform our societal metabolism towards a low/no fossil-carbon economy; this will require fundamental changes in the design, production and use of products. Due to the conflict between present abatement costs and future climate benefits, currently there is lack of strong global political will for serious mitigation. Given the extreme risk of an unmanageable temperature path in the future caused by essentially unrestrained fossil fuel burning, geoengineering (climate engineering), which is the intentional large-scale manipulation of the environment, has been suggested as an effective means of mitigating global warming from anthropogenic greenhouse gas emissions. Many of the proposed geoengineering schemes carried out on land or in the ocean are to use physical, chemical or biological approaches to remove atmospheric CO_2 (Budyko, 1977; Boucher et al., 2013; Zhang et al, 2015). These schemes are able to only sequester an amount of atmospheric CO_2 that is small compared with cumulative anthropogenic carbon emissions. Most of the geoengineering schemes carried out in the atmosphere or in space are based on increasing planetary albedo. The main idea is to reduce the amount of sunlight reaching the Earth in order to balance long wave greenhouse gas forcing (Zhang et al, 2015), for example in order to simulate the effects of large volcanic eruptions (e.g. Mount Pinatubo in the Philippines in 1991), one proposed stratospheric aerosol geoengineering scheme is to inject 5 megaton (Mt) sulfate aerosols into the stratosphere to block incoming sunlight (Israel, Y.A., 2005, Crutzen, P.J., 2006. Robock et al., 2009, Israel, Y.A., 2010). It would be very effective at back-scattering a portion of the incoming sunlight, cooling the surface. Annual costs for delivering these sulfate aerosols are estimated to be just \$2-8 billion (Kravitz et al, 2011; Zhang et al, 2015). Stratospheric aerosol geoengineering has low costs; short lead times for technical implementation and can rapidly mitigate climate change with significant global mean temperature decreases, so stratospheric aerosol geoengineering is viewed as one of the most promising geoengineering approach to be implemented in the future. Until now, there is internationally no any quantitative assessment on impacts of geoengineering on coral reefs. In this study, we will evaluate the consequences of impacts of a stratospheric aerosol geoengineering scheme on Caribbean coral reefs.

2. Study Region and Climate Modeling

In this study, we will concentrate on Caribbean coral reefs, which are severely threatened by climate-induced ocean warming (Hoegh-Guldberg, 1999). There are about 26,000 km^2 of coral reefs in the Caribbean region, approximately 7% of the shallow reefs of the world (Burke et al, 2011). These reefs provide numerous benefits to nearby human communities, e.g. shoreline protection from the hurricanes. However, the Caribbean Sea is generally regarded as the reef region with the lowest resilience (Gardner et al, 2011). Caribbean coral reefs have experienced unprecedented changes in the past 40 years. The coral cover has fallen sharply, from about 50% in the 1970s to 10% in the first decade of the 2000s (Gardner et al., 2011). It has serious consequences for reef biodiversity, ecosystem functioning and related environmental services

According to the 2013 Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations, the concentration of carbon dioxide (CO_2) in the atmosphere increased from a pre-industrial value of about 280 ppm to 391 ppm in 2011. In 2015, the concentration reached more than 400 ppm (Zhang et al, 2015). Representative Concentration Pathways (RCPs) are referred to as pathways of projections of future atmospheric greenhouse gas concentrations. RCP4.5 is named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+4.5 W/m^2) due to the increasing concentrations of atmospheric greenhouse gases. This stabilized forcing reflects a CO_2 equivalent concentration of 650 ppm. To compare with RCP4.5 scenario, we assume stratospheric aerosol geoengineering in 2020-2069 with daily injections of SO_2 at a rate of 5 Tg SO_2 per year, which is just one of the standard experiments in the Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al, 2011). In this paper, we will use HadGEM2-ES climate model simulations of stratospheric aerosol geoengineering to model and assess impacts of stratospheric aerosol geoengineering on coral reefs in the Caribbean Sea by comparison with RCP 4.5 scenario.

3. Coral Bleaching

The predominant source of nutrition for corals comes in the form of photosynthetic products produced by the zooxanthellae. Under unusually high sea temperatures, coral bleaching occurs when corals lose their zooxanthellae. Coral bleaching may result in coral mortality, catastrophic loss of coral cover and loss of critical habitat for associated reef fishes and other biota (Eakin et al, 2010).

Based on HadGEM2-ES climate model simulations of sea surface temperature, we can project changes of coral bleaching regions under stratospheric aerosol geoengineering (left column) and RCP4.5 (right column) scenarios. Figure 1 shows coral bleaching area in 2030, 2050 and 2069, respectively. Under RCP4.5 scenarios, in the northern Caribbean Sea, coral bleaching will occur with high probability, while in southern Caribbean Sea, coral bleaching will not occur except for some small regions near the southern coastline. However, if a stratospheric aerosol geoengineering scheme mentioned above is implemented during 2020-2069, it is predicted that coral bleaching will not occur except for some small regions near the southern coastline or east of Florida. This is because stratospheric aerosol geoengineering can control sea surface temperatures throughout almost all the Caribbean Sea below the thermal threshold of corals. In summary, implementation of stratospheric aerosol geoengineering could significantly mitigate coral bleaching.

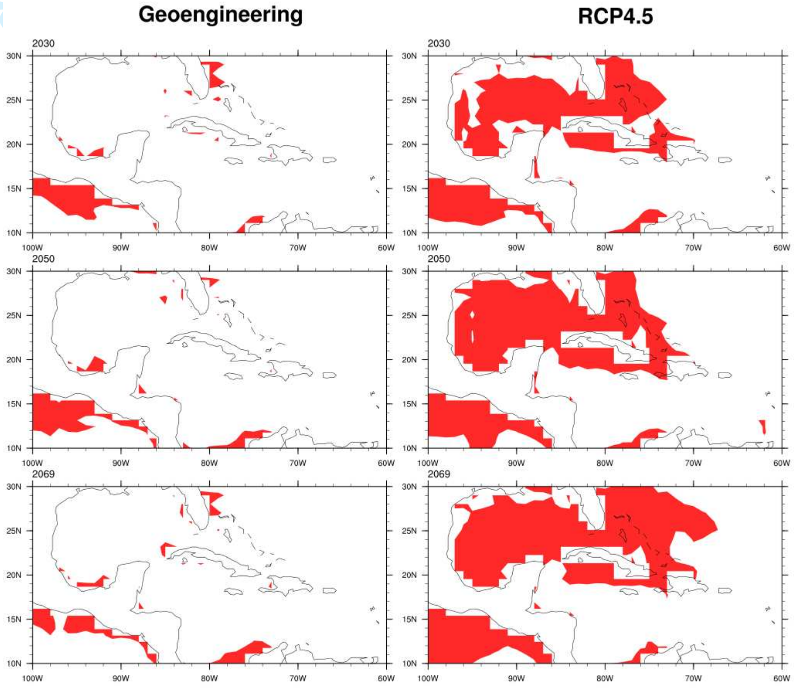

Figure 1. Projected coral bleaching area under stratospheric aerosol geoengineering (left column) and RCP4.5 (right column) scenarios in 2030, 2050 and 2069, respectively.

4. Hurricane Impacts and Coral Recruitment

Hurricanes and tropical storms in the Caribbean Sea can cause considerable damage to coral reefs with great destruction of corals. Across the Caribbean Sea, coral cover is reduced by 17%, on average, in the year following a hurricane impact. The frequency of hurricanes is higher in the north and east of the Caribbean Sea than in the south and west, so coral cover in the north and east of the Caribbean Sea impacted by hurricanes has declined at a significantly faster rate than that in the south and west. After hurricane impacts, corals show no evidence of recovery to a pre-storm state for at least eight years which is roughly equivalent to the average return period of hurricanes in the most hurricane-prone parts of the Caribbean during 1951-2001 (Gartner et al, 2005). Moreover, there was a significant negative correlation ($r=0.72$, $p<0.01$) between recruitment estimates and storm severity. Intermediate storm severity resulted in variable levels of recruitment of non-branching corals, while the severest storms resulted in significantly ($p<0.002$, students t-test) lower recruitment estimates (see Crabbe 2016).

Under stratospheric aerosol geoengineering implementation, the frequency of the strongest category 5 hurricanes can be reduced significantly compared to RCP4.5 scenarios. Figure 2 shows the projected return period of strongest category 5 hurricanes under RCP4.5 and geoengineering scenarios (based on Moore et al (2015) prediction). Between 2020-2069, under RCP4.5 scenarios, the projected return period of strongest category 5 hurricanes decreases from 3.828 years to 0.850 year. However, if a stratospheric aerosol geoengineering scheme is implemented during 2020-2069, the projected return period of strongest category 5 hurricanes decreases from 4.636 years to 1.572 year, and the maximal return period is 5.298 years and occurs in 2034. Although stratospheric aerosol geoengineering with 5 Tg SO_2 injection per year can significantly increase the hurricane return period in the Caribbean compared with RCP4.5 scenario, it is still much lower than eight years, the average return period between 1951-2001. Since corals need at least eight years to recovery after hurricane impact (Gartner et al, 2005), such hurricanes in the Caribbean Sea, which will occur during 2020-2070, will makes coral recruitment or recovery very challenging, so stratospheric aerosol geoengineering with 5 Tg SO_2 injection per year injection is not enough to completely mitigate the impacts from hurricane damage.

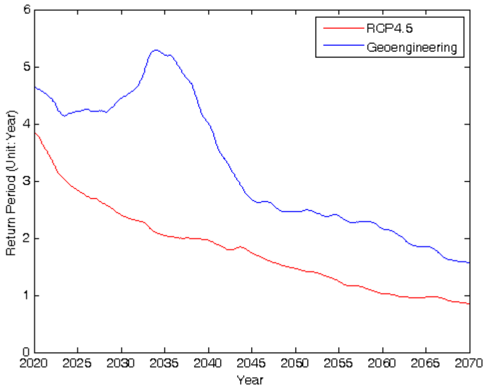

Figure 2. Projected return period of category 5 hurricanes under RCP4.5 and geoengineering scenarios.

5. Coral growth rate

Reef-building scleractinian corals maintain a symbiotic relationship with photosynthetic zooxanthellae, which limit them to the photic zone. Therefore, the growth of coral reefs depends largely on the amount of light available for photosynthesis. Corals can grow from the surface to depths where there is between 1-10 % of the surface irradiance (Chalker *et al.*, 1988).

Stratospheric aerosol geoengineering can mitigate climate change by decreasing the amount of solar radiance reaching the Earth. Based on simulations of the HadGEM2-ES climate model, it is clear that in most years between 2020-2069, the downward shortwave radiation arriving at the surface of the Caribbean Sea is not significantly reduced between 2020-2069 if compared with RCP4.5 scenarios (Figure 3).

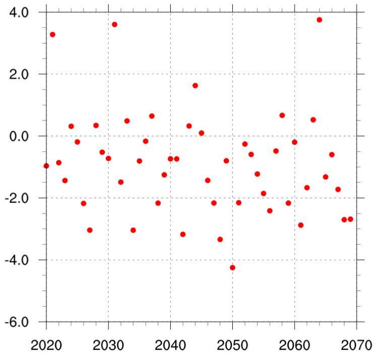

Figure 3. Change of annual mean shortwave radiation (%) arriving at the surface of the Caribbean Sea if stratospheric aerosol geoengineering is implemented from 2020-2069.

As sunlight decreases with water depth, future changes of sea level will also influence coral growth. Since stratospheric aerosol geoengineering can mitigate climate change and cool the earth, it can mitigate future sea level rise. Based on simulations of the HadGEM2-ES climate model, it is clear that in most years between 2020-2069, the sea level rise of the Caribbean Sea, calculated as part of the climate model we use, is reduced if compared with RCP4.5 scenario (Figure 4). The mean sea level rise mitigation from 2020-2069 due to geoengineering implementation is 0.029 m.

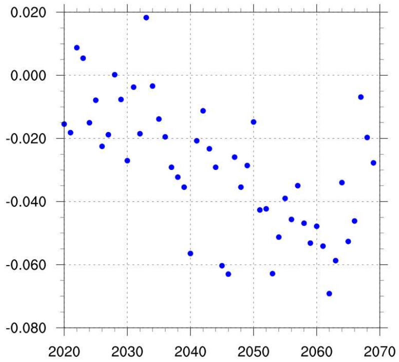

Figure 4. Sea level rising mitigation in the Caribbean Sea under aerosol geoengineering implementation when compared with RCP4.5 scenario (units are in m).

In order to assess the impact of solar radiation and sea level rise caused by stratospheric aerosol geoengineering implementation, we will use the following model (Bosscher and Schlager, 1992):

$$G=G_m \tanh (I_0 e^{-kz}/I_k),$$

where G_m is the maximum coral growth rate, z is the depth, I_0 is surface light intensity (i.e. downward shortwave radiation at the surface), I_k is the saturating light intensity and k is the extinction coefficient determined by the turbidity of the reef waters. Combining with observational data in the Caribbean Sea, when G_m=12.5mm yr^{-1}, k=0.1 m^{-1}, I_0=2000 μ Em^{-2}, I_k=450 μ Em^{-2}, the model represents maximal limits for coral growth; when G_m=7.5mm yr^{-1}, k=0.15 m^{-1}, I_0=2000 μ Em^{-2}, I_k=300 μ Em^{-2}, the model represents minimal limits for coral growth (Bosscher and Schlager, 1992).

Compared with an RCP4.5 scenario, HadGEM2-ES simulations show that between 2020-2069, stratospheric aerosol geoengineering could reduce annual surface shortwave radiation by 0.895% and mitigate sea level rising by 0.029m on average. Figure 5 shows projected change of maximal/minimal limits for coral growth under stratospheric aerosol geoengineering implementation. For depth less than 10 m, minimal/maximal coral growth limits would be reduced by <0.13%; when the depth increases from 10 m to 30 m, the minimal coral growth limits would be reduced by 0.13-0.46% and the maximal limits would be reduced by 0.13-0.59%. For depths larger than 30m, the minimal coral growth limits would be reduced by ~0.46% and the maximal coral growth limits would be reduced by ~0.6% (Figure 5).

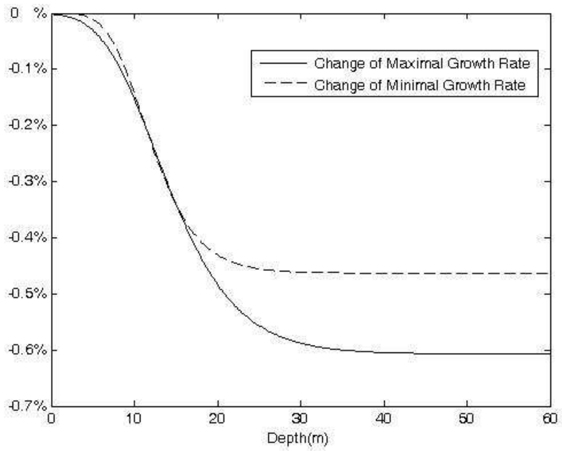

Figure 5. Projected change of maximal and minimal coral growth ratio under aerosol geoengineering implementation when compared with RCP4.5 scenario.

Sea water temperature variation is another important factor for coral growth. *Acropora palmata* is a model branching coral species in the Caribbean. On the fringing reefs around Discovery Bay off the north coast of Jamaica, there was a predominantly linear relationship between logarithmic rate of growth of *Acropora palmata* vs. rate of change of sea surface temperatures (SSTs), over the period 2002–2007 with $R^2 = 0.935$ (Crabbe, 2007):

$$\text{Log growth rate} = 0.1477 * \text{Change of SSTs} + 0.0228.$$

Based on this formula and using simulated sea surface temperature from the HadGEM2-ES climate model, we can project future *Acropora palmata* growth rates under RCP4.5 (red line) and geoengineering (blue line) scenarios (Figure 6). From this, it is clear that when sea surface temperature is lower than the thermal threshold for coral bleaching, there is little difference in coral growth under RCP4.5 and stratospheric aerosol geoengineering scenarios.

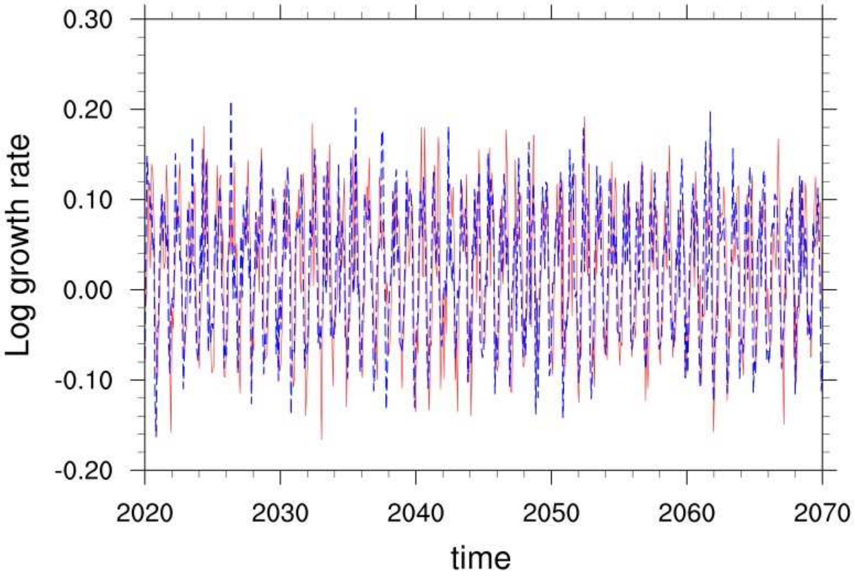

Figure 6. Projected coral growth rate in 2020-2070 under RCP4.5 (red line) and geoengineering (blue line) scenarios.

6. Discussions and Conclusions

Coral reefs provide an environment in which one-third of all marine fish species and tens of thousands of other species are found, and from which 6 million tons of fish are caught annually. Present and future increases in sea temperature are likely to have severe effects on the world's coral reefs within 50 years. Stratospheric aerosol geoengineering has low costs and can rapidly mitigate climate change, so it is viewed as one of the most promising geoengineering approach to be implemented in the future. In this study, we consider a stratospheric aerosol geoengineering in 2020-2069 with daily injections of SO_2 at a rate of 5 Tg SO_2 per year and concentrate its impacts on Caribbean coral reefs, which are currently threatened by climate-induced ocean warming. Stratospheric aerosol geoengineering could significantly mitigate coral bleaching. Under geoengineering implementation, coral bleaching in the Caribbean would not occur except for some small regions near the southern coastline or east of Florida, while under RCP 4.5 scenarios, coral bleaching will occur in most of north Caribbean Sea. At the same time, any changes in downward solar irradiation, sea level rise and the change of sea temperature variation in the Caribbean Sea caused by geoengineering implementation should have very little impacts on coral growth. For the impact on severe category 5 hurricanes, although geoengineering could prolong the return period of hurricanes during 2020-2069 if compared with RCP 4.5 scenario, it may not be enough for corals to recover after hurricane impacts. Therefore, stratospheric aerosol geoengineering with 5 Tg SO_2 injection per year may not be enough to ensure full mitigation of climate change for corals in the Caribbean. In addition, stratospheric aerosol geoengineering cannot avert the continued absorption of increasing anthropogenic CO_2 emissions by the global ocean which leads to rising acidity and to decreases in coral calcification and growth.

Acknowledgements

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