

## Should we choose geoengineering to reverse global warming?

Since 1850 when industrialization began human activities such as burning of fossil fuels and deforestation have released about 2000 billion tonnes of carbon dioxide (CO<sub>2</sub>) emissions into the atmosphere and caused a global mean warming of 0.8°C (ref. 1). In a 'business as usual' future scenario, we are likely to turn the planet into a 'hot house' with an additional warming of 3–5°C by 2100 (ref. 1).

The latest Intergovernmental Panel on Climate Change (IPCC) report<sup>1</sup> has presented several evidences for the ongoing climate change in the industrial era: ~0.8°C increase in global mean temperature, ~20 cm mean sea-level rise, increased ocean heat content and decline in glaciers and snow cover worldwide. The most visible change is in the Arctic where the ice extent and volume have declined by about 50% and 75% respectively, since 1979 (ref. 2). The impacts of climate change on important sectors such as water resources, agriculture, forestry, fishery, etc. have been also assessed extensively. Several alarming scenarios such as dieback of Amazon forests, failure of crops, intense cyclones, breaking of Antarctic ice sheets and release of CO<sub>2</sub> and CH<sub>4</sub> from permafrost soils in high latitudes have been projected to occur in the future.

What should human civilization do in the case of such planetary emergencies? Will halting CO<sub>2</sub> emissions rapidly stop and reverse climate change? If CO<sub>2</sub> emissions are stopped, will the climate system cool down immediately? The answer to the last two questions is a 'no', because of inertia in the system. Due to thermal inertia (which arises mainly from the ocean that has a mass of  $1.36 \times 10^{21}$  kg), there is a delay between peak emissions and maximum warming: the climate system would continue to warm for several decades after halting emissions.

There are also other inertias: our energy system and social behaviour. For example, a coal power plant built today cannot be dismantled easily tomorrow because of a change in climate policy. Huge capital costs are involved in commissioning a plant which may have a lifetime of about 50 years. Similarly, lifestyle changes cannot take place overnight; they take multiple decades. These factors are normally taken into account when solutions to avert large climate changes are considered – actions to reduce

emissions should be taken today so that we can achieve zero emissions decades later.

Coming back to the question of what should be done in case of a climate emergency, are there solutions other than rapid emission reductions? In the last 15 years or so, there have been serious discussions on geoengineering as a strategy to reverse global warming. By definition, geoengineering refers to intentional large-scale engineering solutions designed to ameliorate the detrimental impacts of climate change. There are two categories of geoengineering proposals<sup>3</sup>: solar radiation management (SRM) and carbon dioxide removal (CDR) methods. SRM schemes would attempt to increase the amount of solar radiation reflected by our planet. Placement of mirrors in space or reflective aerosols in the stratosphere, and enhancement of the reflectivity of marine clouds are some examples. CDR methods propose to accelerate the removal of atmospheric CO<sub>2</sub> through either natural processes or artificial industrial means. Large-scale afforestation/reforestation, ocean fertilization, accelerated weathering of silicate and carbonate rocks and direct air capture of CO<sub>2</sub> are some of the proposed CDR methods.

Since most CDR methods rely on natural biological and chemical processes, they are inherently less risky. They also directly address the root cause of the problem which is elevated atmospheric CO<sub>2</sub>. However, since natural CO<sub>2</sub> removal processes are slow, CDR methods are unlikely to reverse climate change rapidly in an emergency scenario where temperatures should be brought down within 1–10 years.

Can SRM methods reverse climate change in such a short time span? Are SRM schemes effective and cheaper? Do we have natural analogues? Hereafter, I use the term 'geoengineering' to refer to only SRM methods. The last decade witnessed a spurt in research activities in the SRM proposal of injecting sulphate aerosols into the stratosphere. The proposal is to inject SO<sub>2</sub> into the stratosphere where it would be oxidized to form the sulphate aerosols, H<sub>2</sub>SO<sub>4</sub> (droplets of sulphuric acid). These aerosols can scatter more sunlight back to space. The lifetime of aerosols in the stratosphere is about 1–2 years. Volcanic eruptions serve as excellent natural analogues – Mount Pinatubo eruption in 1991 injected ~20 Mt of SO<sub>2</sub>

into the stratosphere and cooled the planet by 0.5°C in 1992. The planet gradually warmed back as the aerosols fell out of the atmosphere in the next year or so. Therefore, the aerosol SRM and in principle all SRM schemes have the potential to cool the planet rapidly.

Interestingly, a few grams of sulphate aerosols is sufficient to offset warming from a tonne of CO<sub>2</sub>. Annual injections of about 5 Mt of SO<sub>2</sub> (equivalent to a Pinatubo eruption every 4 years) would be required to offset the 'business as usual' CO<sub>2</sub> emissions in the 21st century. The cost of countering climate change could be as cheap as US\$ 5 billion per year<sup>4</sup>, which is only a fraction of the conventional climate change mitigation costs which are estimated at approximately US\$ 250 billion per year. Affordability, effectiveness and rapidity are the features that have made the aerosol SRM scheme attractive. Though modelling studies indicate that the cancellation of climate change would not be exact in all regions, they show that the residual changes in all regions would be too small compared to the scenario with no geoengineering – SRM has the potential to reduce the severe impacts of climate change.

Are there secondary effects associated with the aerosol SRM proposal? Will there be acid rain when the stratospheric H<sub>2</sub>SO<sub>4</sub> is washed out from the atmosphere? The current tropospheric SO<sub>2</sub> emission from fossil fuel burning is about 110 Mt per year<sup>1</sup>. These aerosols have a lifetime of only 10 days because tropospheric weather processes (clouds and rainfall) remove them rapidly. Compared to these large tropospheric emissions, the proposed stratospheric injections are too small to have any significant effect on acid rain. The effect of sulphate aerosols on the stratospheric dynamics and ozone depletion is not completely understood though volcanic eruptions in the past have been shown to disturb ozone photochemistry, leading to ozone depletion. Ozone depletion will increase the amount of ultraviolet light reaching the surface damaging terrestrial and marine ecosystems. Other known secondary effects are an increase in diffuse light at the surface and a corresponding decline in direct sunlight with some consequences for plant photosynthesis, solar power generation and optical astronomy.

What are the downsides of SRM? There are at least three known risks: (1) Ocean acidification, which is harmful to marine life, is caused by elevated CO<sub>2</sub> levels in the atmosphere. SRM does not address this issue at all. (2) Unless we actively remove CO<sub>2</sub> using CDR methods, elevated CO<sub>2</sub> levels would persist in the atmosphere for as long as a thousand years. The implication is that SRM would have to be maintained as long as CO<sub>2</sub> concentrations are high. (3) Halting SRM, for whatever reason, when CO<sub>2</sub> levels are high in the atmosphere would lead to rapid climate warming. Warming rates can be an order of magnitude more than in a case which did not have geoengineering to begin with. Such a scenario will stress the ecosystems and human adaptation.

What are the risks for India? SRM could result in reduced monsoon rainfall, and weakened global water cycle if global mean warming is exactly cancelled<sup>5</sup>. However, these reductions in rainfall can be averted if small amounts of residual warming in the geoengineered world are allowed. Severe risk of reduced rainfall in tropical countries such as India may arise if the injected aerosols are concentrated in the tropical stratosphere. What this implies is that a certain amount of optimization is required to minimize the damages and maximize the benefits.

After carefully assessing the benefits and risk of geoengineering, one is faced with this dilemma: should there be a role for geoengineering in reversing climate change? This question has created two camps, one for geoengineering and the other against it. The last decade has witnessed intense debates in scientific meetings. Developing a consensus on geoengineering is as challenging, if not more, as arriving at a consensus on emission reductions in climate negotiation meetings. The original climate change problem involves, besides science, social, economic, technological and political dimensions. Such complexity has made the problem unmanageable as of now. Geoengineering brings in additional dimensions such as moral, ethical and legal: do we have the right to manipulate nature for our own good? Who would control the knob on the global thermostat if we opt for geoengineering? Who would pay for the damages from geoengineering? Until and unless a global agreement that addresses these issues is reached, it is hard to foresee a geoengineered world that would benefit the entire human civilization. Given the history of international cooperation on matters related to the welfare of global commons, geoengineering seems like a non-starter. However, because of the cheaper price tag, unilateral action on geoengineering by a single country or a group of countries is a possibility, which could lead to international conflicts.

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