COOLING CANADA'S ARCTIC CLIMATE

2023 was the warmest year on record, both globally, and within Canada, which led to record-breaking droughts, lowered lake levels and an unprecedented fire season, along with new reports of accelerated permafrost melting[1]. Canada's climate is warming at approximately double the global rate due to "polar amplification", with northern regions regularly exposed to mean temperatures several ºC above mid-20th century normals. Aside from the increasing atmospheric concentration of greenhouse gases (GHG), explanations for these record temperatures include a strong El Niño event, and reductions in planetary albedo. To date, concerted international action to reduce GHG emissions has had little impact on the annual increase in atmospheric CO_2 and many experts now think there is little hope of achieving the GHG emissions reductions needed to stabilize global temperatures at 1.5 ºC above pre-industrial levels. Hansen et al. (2023) argue that further warming will occur for decades even if GHG emissions cease[2]. Efforts to remove CO_2 directly from the atmosphere are in early stages and the large-scale feasibility of proposed approaches is unproven. Hence, we argue it is necessary to explore a third option: methods to reduce solar radiation arriving on the planetary surface, known generically as Solar Radiation Modification, SRM. This is seen as an option of last resort, that is both feasible and could be implemented quite rapidly, but which requires research to determine the best method(s) and develop the technology to make them effective.

Trials of SRM methods should be focused on Canada's Arctic as regional cooling would be directly beneficial to Canada, while contributing to global efforts to mitigate climate change. Further benefits would likely be achieved through international collaborations targeting wider regions. Cooling the Arctic is of particular interest because recent retreat of reflective sea ice is a major contribution to polar amplification.

INTRODUCTION

Possible strategies: Compensating for reduced Arctic albedo, and reducing natural methane emissions from northern ecosystems

Here we propose Canadian researchers should assess the feasibility and risks of methods to increase the reflection of incoming solar radiation during northern hemisphere summers, hence reducing the rate of warming in northern Canada and contributing to global efforts to mitigate global heating. This will not mitigate GHG emissions but will allow the worst effects of rising global temperatures to be avoided and allow more time for atmospheric GHG emissions to be controlled. Two methods are widely discussed within an international community of scientists and engineers. **Stratospheric Aerosol Injection** (SAI) is the release into the stratosphere of reflective particles most likely dispersed as gaseous sulphur dioxide, SO2 from high altitude aircraft. The SO2 particles then act as cloud condensation nuclei (CCN) to increase stratospheric cloud formation. SAI emulates aerosol particles ejected by natural volcanic eruptions, but the particles would be dispersed over much wider areas for greater effect at much lower concentrations. Consistent with natural volcanic aerosols, the particles would be carried by high altitude air movements, possibly remaining aloft for several months but eventually scrubbed out in rainfall. At ground level, the visual effect would be almost imperceptible; some critics have suggested skies would develop a continuous milky blue haze, but there is little scientific evidence for this. There are some concerns about increased acidic rainfall, but it is unclear this would be ecologically significant. There is some evidence that large scale SO2 emissions can contribute to ozone depletion; notably during the 1991 Mt Pinatubo eruption which caused an increase in stratospheric sulphate aerosols. This has led to a few modelling studies which suggest some ozone depletion would occur with SAI.[3] Concerns about impacts on global weather patterns deserve investigation, but as there have been no properly controlled experiments, there is no available data showing major disruptions to weather patterns (compared to what has already occurred due to GHG increase). **The expectation is that cooling the planetary climate system can only reduce the severity of extreme weather events.** Meteorologists can determine how to minimize the chances of negative side-effects of SAI and maximize the benefits. Any decision to carry out an extended SAI program would require agreement of many countries: ideally a consensus agreement negotiated among UN member nations. Practical concerns include the energy needed to lift chemical payloads to altitudes between 6,000 and 12,000 m for the duration and scale of the effort.

Clouds of different types are known to have differential effects on earth's radiation balance. The overall effect of high altitude (cirrus) clouds is to increase atmospheric greenhouse warming, whereas low altitude (stratus and cumulus) clouds contribute more strongly to reflecting solar radiation and therefore reduce surface heating during daylight hours. **Marine Cloud Brightening** (MCB) is a relatively simple approach to increase albedo of low altitude stratocumulus clouds over open oceans, discussed extensively over the last 30 years or so. The climate change mitigation benefits seem to be clear, but some technical hurdles remain. The favoured approach is to loft salt water particles into the mixed layer, where they form CCN, exactly as natural sea-spray also contributes to cloud formation. Some recent tests of equipment have been carried out in the USA, Israel and Australia.

On the other hand, **Cirrus Cloud Thinning** (CCT), first proposed circa 2008, aims to reduce greenhouse warming caused by high altitude cirrus clouds. It requires the release of ice-nucleation molecules at altitudes above 450 hPa (pressure) to freeze water droplets — making clouds more "transparent". As with SAI, there are concerns about energy costs and increased acidic rainfall. At least two recent climate modelling studies report CCT is unlikely to be effective, so we are not recommending this approach.

A fourth method is release of **Iron Salt Aerosols** (ISA) into the upper troposphere. The main objective is to provide direct and persistent **reduction of tropospheric methane** (CH_4) concentrations — producing a significant reduction in long term GHG forcing. Several additional benefits are claimed—including the creation of CCN and increased cloud albedo, similar to MCB. ISA is a complex approach and unproven in practice. There are likely to be snags, but advocates claim the climate mitigation benefits could be very significant at lower cost than SAI or MCB; peer-reviewed papers add credibility to these claims.

OPTIONS FOR CONSIDERATION

Stratospheric Aerosol Injection (SAI)

The anticipated rate of injection of SAI would be approximately 10% of current global emissions of SO_2. Above the tropopause, the air is cold and very stratified, though subject to continual high velocity winds. The Brewer-Dobson circulation carries tropical air from the troposphere into the stratosphere and then towards the poles, where it returns to the surface[4]. For trial purposes, SAI carried out at 50°N would lead to rapid northward and circumpolar dispersal of aerosol particles, with most of the SO_2 falling out in the Arctic region within a couple of months. This effect has been verified by observations of plume dispersal from several recent volcanic eruptions occurring at different latitudes.

Expectations for the successful implementation of SAI are derived from several observations of the effects of large volcanic eruptions (notably Mt Pinatubo in 1991 which produced aerosol plumes sufficient to reduce global mean temperatures by about 0.5 ºC for two years). However, projections of the efficacy of a human SAI program are derived from global climate models (GCM) in which releases of aerosols are added to alternative scenarios of GHG forcing. The SAI simulations must account for: the time needed to gain international consensus, carry out the necessary engineering research and begin deployment; the time needed to ramp up to the full program, and the amounts to be released annually to achieve a required amount of global cooling. A recent comprehensive study by MacMartin et al (2022)[5] found that releasing approximately 20 megatonne (MT) of SO_2 per year would achieve a cooling of about 1.5 ºC. The costs of deploying SAI using custom-designed aircraft operating at altitudes up to 20,000 metres have been estimated by Smith (2020)[6] at around US$1500 per tonne of sulphate, or about US$18 billion per year per 1.0 ºC of global cooling achieved.

Marine Cloud Brightening (MCB)

The original concept for MCB was proposed by John Latham and coworkers in the UK to seed stratocumulus clouds with tiny sea water particles to increase the concentration of cloud condensation nuclei (CCN), thereby increasing cloud formation and albedo. Modelling studies have confirmed the likely **effectiveness of a global program to enhance ocean albedo by MCB** and reduce global mean temperatures. Recently these results have been verified empirically by "the great inadvertent aerosol experiment": New regulations introduced by the International Maritime Organization in 2020 to cut sulphur dioxide emissions from ocean ships have reduced air pollution from shipping by 80%, but also reduced the albedo of the ship tracks. This has been projected to raise global temperatures by around 0.05 ºC by 2050, corresponding to approximately two additional years of current-level GHG emissions.

In general, the best areas to carry out MCB will be at lower latitudes where solar radiation is maximal and (ideally) in ocean regions where natural stratocumulus cloud formation occurs frequently. Several modelling studies have indicated that MCB could adversely affect natural precipitation patterns; however, there should be scope to select areas best suited for beneficial reductions in planetary albedo where risks of adverse side effects can be minimized.

Ship-borne turbines have been conceived and developed to loft plumes of seawater droplets (to create CCN) several hundred meters above the ocean surface. However, a major obstacle is designing a system to produce droplets of optimal size needed to maximize the cloud brightening effect. Various approaches are being considered. (We suggest a national or international challenge to university engineering faculties and private sector engineering research groups, with a substantial prize for the most successful design.) An ongoing Australian project aims to cover an area large enough to reduce ocean warming in the region of the Great Barrier Reef, which is now threatened by excessively warm seawater, among other factors. **If this project proves effective in lowering sea surface temperatures, it will indicate there is potential to apply this method in the Canadian Arctic**, with the objective of increasing regional albedo to compensate for the loss of sea ice, hence mitigating the polar amplification effect. If sufficient cooling of Arctic waters could be achieved (during summer), increased ice-formation should occur during winter—leading to a slowing or reversal of the current loss of sea ice.

We advocate an MCB trial project in cooperation with First Nations stakeholders in northern Canada. Researchers in Australia and the UK (and elsewhere) would be invited to collaborate on (1) comparative modelling studies of the potential impacts of MCB, with a particular focus on the Canadian Arctic; (2) development of ship-borne technology needed to generate plumes of sea water aerosols; and (3) carry out summertime field experiments in Canadian Arctic waters[7]. The field experiments would require a suitable vessel with port facilities, probably at Churchill. Local indigenous groups will need to be consulted during planning. The overall benefits of MCB for Arctic cooling will be greatest during summer months when daylight periods are long and solar zenith angles are high. The ultimate objective would be to assemble an international fleet of aerosol-lofting ships which would ply the northern and southern oceans on annual cruises.

Iron Salt Aerosol (ISA) dispersal

The ISA method has been researched by Franz Oeste and coworkers for about 20 years. Advocates claim ISA dispersal has multiple climate change mitigation benefits. Dust coated in ferric chloride (FeCl3), termed “iron dust”, would be dispersed into the troposphere (using aircraft, balloons, drones, or ships) to emulate dust releases which occur naturally world-wide. Ship-borne dispersal similar to the method used for lofting salt-spray for MCB appears the least energy-intensive but would restrict implementation mainly to ocean surfaces. The main benefits are (a) degradation of tropospheric methane (CH4); (b) enhanced cloud albedo similar to that obtained from the MCB approach; (c) ocean iron fertilization to boost phytoplankton CO2 uptake, adding to the natural deep ocean carbon sink. Recently, Oeste has been patenting a more efficient approach called “Climate Catalyst”. The idea is that the material released into the troposphere would be a customized mix of photocatalytic chemicals, selected to maximize the particular benefits that are most required.

Practical application of ISA dispersal

Oeste and coworkers have estimated that doubling current natural iron releases into the troposphere “would enable the prevention or even the reversal of global warming”, requiring annual dispersal of 300,000 tonnes of iron. They suggested ISA would be deliberately released in flue gases, from steel manufacturing and power generation plants, ships and aircraft. An alternative approach is a network of automated buoys engineered to release ISA (or Climate Catalyst) particles when weather conditions are ideal. The network would be managed from a control centre and service vessels would continually visit the buoys for resupply and maintenance or replacement as necessary.

One major concern about ISA dispersal is that chlorine dissociated from FeCl3 **would also degrade ozone** (O3) to some extent. This could slow or even reverse the gradual recovery of stratospheric O3 levels from past damage caused by chlorofluorocarbons. However, recent research concludes "no negative effect on stratospheric O3 is anticipated."[8] Further, if FeCl3 were released only into the troposphere, its dominant effect would presumably be to degrade tropospheric O3, a significant GHG, harmful to human health, and a known toxin for some crop plants. **Clearly these concerns need further investigation before large-scale implementation of ISA dispersal, and they constitute a significant reason for this research to go forward.**

RECOMMENDATIONS

The Project Save the World/CPG panels generally agreed on the potential importance of these approaches but concurred that more research is needed. However, we emphasize that recent accelerating trends in global temperature increases, both on land and in ocean surface waters, along with increasing evidence of large scale impacts on humans and natural ecosystems, strongly indicate the world is rapidly approaching a state where carrying out SRM field tests is far less risky than the risks of delayed action. Even though there is general agreement that "decarbonisation" of global energy systems must occur as a matter of urgency, a growing number of researchers claim that increasing planetary albedo is the fastest way to reduce global radiative forcing, given that global GHG emissions have continued to rise with little prospect this trend will reverse in the near future. The consequences of inaction, despite widespread acknowledgement of risks, include: imminent crossing of multiple environmental tipping points (notably permafrost thaw and loss of boreal forest in Canada); sea-level rise of 60 to 70 metres; collapse of the Atlantic Meridional Overturning Circulation (AMOC); widespread loss of biodiversity.[9] The timing of these events is unclear but the evidence suggests many are already in progress, and major impacts will occur within a century.

SAI is one method that appears to have great potential, but necessarily crosses international boundaries and therefor will require much negotiation and diplomacy for any single country to carry out. Ideally, there must be international consensus, likely brokered by the UN, to carry out regional trials of SAI. A collaborative Arctic trial would be very attractive but the present situation in Russia makes this almost inconceivable in the immediate future. An alternative strategy would be to focus initially on cooling the southern oceans and Antarctic – a project in which Canada could contribute significant expertise.

Small scale field tests cannot provide definitive proof of concept, though trials of MCB along Australia's east coast should be large enough to determine basic effectiveness. Canada is fortunate to have a large land area that is sparsely populated. It could therefore play a leading role, by supporting medium scale trials of MCB within its jurisdiction. Targeting the Arctic for these trials would be a logical approach, as success would bring direct benefits to Canada. More research into ISA dispersal is needed, particularly with regard to its effects on stratospheric ozone, and because it could compensate for decreased emissions of bioavailable iron[10].

We recommend Canadian involvement in international partnerships to investigate the true potential of Arctic-scale and global-scale application of SAI, MCB and ISA dispersal. We emphasize that all three approaches emulate naturally occurring processes and none should have long-lived impacts: If unforeseen negative consequences were detected, **halting operations**

would return environmental conditions to -- the still problematic -- status quo within a few days (MCB sea salt aerosols) to a few months (ISA and SAI).

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[1] https://www.cbc.ca/news/canada/edmonton/the-world-s-permafrost-is-rapidly-thawing-and-that-s-a-big-climate-change-problem-1.6674976

[2] J Hansen et al. 2023. Global warming in the pipeline. Oxford Open Climate Change. https://academic.oup.com/oocc/article/3/1/kgad008/7335889

[3] See https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JD028146

[4] E.g. N Butchart 2014. The Brewer-Dobson circulation. Rev. Geophysics. https://doi.org/10.1002/2013RG000448

[5] D G MacMartin et al. 2022 Scenarios for modelling solar radiation modification. PNAS. https://doi.org/10.1073/pnas.2202230119

[6] W Smith. 2020 The cost of stratospheric aerosol injection through 2100. ERL https://doi.org/10.1088/1748-9326/aba7e7

[7] We assume knowledge gained from the MCB project recently carried out in the region of the Great Barrier Reef can be applied to the Canadian Arctic, recognizing there will be some challenges due to the relative remoteness of the region and low temperatures, even in Arctic summer. Possible adverse effects on regional precipitation patterns would need to be assessed, in addition to detailed observation of local weather systems to achieve maximum benefit.

[8] Ming, T et al. 2021. A nature-based negative emissions technology able to remove atmospheric methane and other greenhouse gases. Atmos. Pollut. Res. 12: 101035. https://www.sciencedirect.com/science/article/pii/S1309104221000891

[9] Given that climate change will drive increases in drought, famine, and disease, we believe such events will drive population migrations and armed conflicts, causing loss of human lives in the hundreds of millions.

[10] Fossil fuel (particularly coal) burning releases small amounts of iron salts which correct for chronic iron deficiencies in some agricultural soils world-wide. A rapid transition to renewable energy sources over the next few decades is therefore likely to render these soils iron-deficient, affecting global food production. Tropospheric ISA dispersal could be a good alternative source of iron fertilization.