DRAFT

Climate Engineering

Background

Climate engineering (sometimes referred to as "geoengineering") refers to the deliberate, large-scale manipulation of the planetary environment to counteract the effects of anthropogenic climate change. Climate engineering generally utilizes one of two methods: solar radiation management (SRM) or carbon dioxide removal (CDR), and is occasionally presented as a third climate policy strategy beyond adaptation and mitigation. This MTP paper provides a high-level outline of climate engineering, while focusing particularly on SRM as a climate engineering method. ***A separate MTP paper is available and provides a more fulsome analysis of Negative Emission Technologies, which covers technologies that fall under CDR.***

Commenté [F[1]: This is not really correct. Both methods would be more accurately described as aiming to 'reduce climate forcing' or 'reduce the drivers of climate change' or something like that. They are generally discussed in the context of proactive measures that would help avoid some level of climate change, rather than something done reactively to deal with the consequences of change already experience, which is what 'counteract the effects' seems to imply

Why Climate Engineering?

As there is a significant gap between national pledges under the Paris Agreement and the emissions pathways consistent with holding global temperature to 1.5C above pre-industrial levels, pressure will grow to research and deploy climate-engineering technologies to limit the effects of climate change. At the same time, Canada's previous position in international fora has been that the deployment of climate engineering technologies should not occur without adequate governance structures, or before more research on the issue occurs, to ensure a comprehensive understanding of risks and consequences – both positive and negative.

Commenté [F[2]: Again, wording is not appropriate. The argument is really that there will be a need to augment emission reduction efforts, not to let climate change and then limit the effects of that change. I think this is more than a semantic issue – it goes to the underlying reason for thinking about these engineering approaches.

Drivers: Gaps in Research/Global/National Governance

Consensus on climate engineering governance has been difficult to achieve in international fora, particularly due to the limited understanding of the risks and science of the issue. Certain forms of climate engineering have potential to create adverse, unanticipated, and irreversible environmental, social, and economic impacts. As such, many have expressed ethical objections to its deployment.

Commenté [F[3]: I found this sentence rather odd – I'm not aware there has really been an effort to achieve consensus at this point. There has been research, there have been discussions (as noted in the next para), but I don't believe there has been a forum in which governments sat down and tried to reach consensus on this issue.

Commenté [F[4]: While they are all legitimate objections, the list in the previous sentence does not capture the reason for ethical objections. Ethical objections arise primarily because of the transboundary consequences of climate engineering – e.g. a country doing something to avoid warming in their territory causing drought or deprivation elsewhere in the world. Ethical concerns also arise because implementation of climate engineering may impose financial and other burdens on future generations (because stopping would un-mask the forcing that has been masked).

Although research on climate engineering has intensified in recent years, mechanisms to govern climate engineering and associated research at the international and domestic levels are limited or non-existent. Although climate engineering has been discussed at international fora, including the United Nations Environmental Assembly (UNEA) and the Conference of the Parties to the Convention on Biological Diversity (COP CBD), formal negotiations on a framework for research governance have stalled, most recently in March 2019 at UNEA in Nairobi.

There is currently no comprehensive legislative framework to govern climate-engineering activities in Canada. Although certain aspects of the *Canadian Environmental Protection Act, 1999* (CEPA), the *Fisheries Act* and the *Migratory Birds Convention Act, 1994* might apply to specific forms of climate engineering, some climate engineering activities could potentially ~~likely~~ be deployed in Canada without regulatory oversight. There is also a threat of unilateral deployment by states or individuals prior to international consensus on climate engineering, particularly given the low costs of some climate engineering methods. As such, the challenges of patchwork governance on these issues are exacerbated. Given these factors, further discussion of climate engineering governance is warranted within ECCC and other government departments, as well as provincial/territorial governments, Indigenous groups, and other relevant partners.

Commenté [F[5]: Should also state that ongoing engagement at the international level is essential – this is more of an international governance issue than it is a domestic issue at this point.

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There are ethical challenges associated with climate engineering, particularly the idea that it can give the public a false sense of security that climate change is "solved." This in turn could lead to greater CO2 emissions. As such, the international community has focused much of its climate policy action on adaptation and mitigation, and has often been hesitant to even discuss climate engineering. Despite this, climate engineering has been seen by some as a third pillar of climate policy alongside adaptation and mitigation. Given the length of time needed to conduct proper research on climate engineering (likely years), some have argued that there is an urgency to develop these techniques for deployment, *if or when* they are deemed necessary.

Climate Engineering Methods

Climate engineering technologies fall under two broad categories: carbon dioxide removal (CDR) and solar radiation management (SRM).

Carbon Dioxide Removal

CDR refers to the removal of carbon dioxide from the atmosphere, whether through direct removal or through indirect measures that sequester CO2 (including afforestation). These technologies are also known as Negative Emissions Technologies (NET). NET is a subset of CDR focusing solely on carbon-dioxide removal technology.

There are a number of CDR techniques, including forest management, soil management, biochar, bio-energy with carbon capture and storage, direct air capture of CO2 from ambient air and storage, carbon mineralization, and ocean fertilization (~~Dumping~~ spreading/distributing iron or other ~~micro-~~nutrient~~s~~ to promote ~~marine algal growth~~enhanced marine primary productivity) and ocean pumping.

Some forms of CDR are currently available at a low cost, including afforestation and ocean fertilization. While afforestation is widely accepted, ocean fertilization represent a potential for widespread, long lasting and severe effects on the marine environment. As such, ocean fertilization is prohibited under London Protocol and London Convention, with the exception of legitimate scientific research, which would require a permit. Other CDR technologies are not yet available at scale, due to the technology being in early development stages or not yet economically viable.

It is important to emphasize that both CDR and SRM technologies could create adverse environmental consequences. Although the risks of large-scale CDR are perhaps less extreme than the termination effects associated with SRM, there remain other potential environmental consequences. Adverse environmental effects associated with some forms of CDR include adverse impacts on ecosystems and natural cycles. Unlike SRM, the IPCC modelled emissions pathways rely on the use of CDR to ~~absorb~~ remove carbon from the atmosphere. In Canada, certain CDR technologies have received public support, including Squamish British Columbia's Carbon Engineering. Formed in 2009, Carbon Engineering piloted direct-air capture technologies to remove carbon dioxide directly from ambient air. This technology, a form of NET, is already largely accepted.

For more information, see MTP on NET

Commenté [F[6]: As noted above, I'm not convinced this is really the core ethical issue. To me, this is more of a communication issue – the need to convey what climate engineering really is and what it is and is not doing. It would be an ethical issue only if it was being (mis)represented as a solution.

Commenté [F[7]: If you are going to talk about CDR, I think you have to talk about ocean fertilization. I concur with organizing this around the three categories listed in Eric's comment above. However, I find it a bit odd that this paper states at the outset that CDR will be covered in another paper, but yet it leads off with CDR here. I would suggest that either it all be combined into one paper (my preference) or you make a clear separation into one paper on CDR and one paper on SRM. As it stands, it is rather confusing.

Commenté [C[8]: Question for the working group:

Should we also include marine geoengineering here?

Or should we separate CDR into three categories. Natural (e.g., soil and forest management); marine geoengineering (e.g., ocean fertilization); and NETs (e.g., carbon capture and storage, direct air capture). Note that the NET paper is now with NRCan.

Commenté [F[9]: These two sentences are internally inconsistent. The middle sentence of this paragraph suggests that NET and CDR are synonyms; the third sentence says they're not (and doesn't make sense as written). Need to establish clear and consistent nomenclature.

Commenté [F[10]: What is meant here? I think there may be some confusion. The ocean 'biological pump' is the mechanism by which ocean fertilization leads to enhanced ocean uptake of carbon. It is not a CDR technique per se.

Commenté [F[11]: I think it should be made clear somewhere in here that enhanced ocean uptake of CO2 leads directly to increased ocean acidification (with related ecosystem implications). It would be good to introduce this here because it arises again in the context of SRM.

Commenté [F[12]: Please re-word. The IPCC does not do any modelling. The IPCC assesses the published climate science literature.

DRAFT

Solar Radiation Management

Solar Radiation Management refers to technologies that reflect solar radiation back into space before it can warm the planet. There are a number of ways to conduct SRM, including surface-based, troposphere-based, stratosphere-based, or space-based. While all of these methods look to achieve a similar goal, certain methods might present greater risks and ethical concerns, particularly stratospheric, tropospheric, and space-based methods. SRM research is currently moving forward globally, despite the lack of governance mechanisms on the issue. There could be significant risks and trade-offs associated with this. Particularly, there are significant risks in allowing uncontrolled SRM experiments led by rogue countries or private actors, particularly because of weak or non-existent governance on this issue.

While similar in purpose, SRM and CDR are fundamentally different in approach. CDR is a potential mitigation mechanism, while SRM is a preventative measure. Although SRM has the potential to slow the rate of global warming, it does not directly add or remove carbon from the atmosphere. While CDR is used to calculate IPCC long-term pathways in recent reports, SRM is excluded from these calculations due to remaining uncertainties.

Different methods of SRM can create adverse environmental impacts including the termination effect, ozone depletion, impacts on the hydrological cycle, and even changes in regional climate.

Types of Solar Radiation Management

1. Surface Albedo Enhancement

SRM through surface albedo enhancement refers to methods that enhance the reflectivity of the earth by whitening surfaces, whether cities, oceans, crops, deserts, or ice sheets. These proposals have involved painting city roofs white, covering deserts in reflective plastics, and creating a layer of reflective microbubbles below the surface of lakes and oceans. Additionally, one other method proposed “ICE 911”, a project to spread glass beads in the Arctic to slow ice melt, is very controversial. ECCC has had several conversations with ICE 911 in 2018. Proponents of the project were told that dumping glass beads in Canada would be treated as prohibited dumping under the CEPA, until they can send information to complete an assessment framework showing that the activity would be legitimate scientific research and can be done so as not to cause marine pollution. ICE 911 chose to pursue their first permit under the U.S. ocean dumping scheme in Alaska.

Another method proposed is the planting of deciduous trees in areas where coniferous trees dominate. This is because that during winter, deciduous trees lose their leaves, allowing solar radiation to be reflected back into space by the snow below. This method could be deployed at a large scale with a low associated cost. Different forms of surface albedo enhancement have different risks and benefits.

While painting city roofs white has no associated risks, it is unlikely to have significant impacts. In contrast, surface albedo enhancement in deserts or lakes/oceans can be highly effective, but could create serious adverse environmental impacts on the ecosystems involved.

2. Cloud-Albedo Enhancement (Tropospheric)

Commenté [F[13]: Somewhere in this section, it should be noted that SRM methods only offset temperature increase. They do not offset ocean acidification associated with ongoing CO2 emissions

Commenté [F[14]: This is not correct and should be deleted.

Commenté [F[15]: I would also delete this sentence – the introduction in the previous paragraph already says what SRM does and it is clear that it has nothing to do with adding of removing carbon.

Commenté [F[16]: Please re-word. The IPCC does not produce pathways or do calculations. It assesses scientific literature.

Commenté [F[17]: This is not really true. SRM is excluded from scenario or pathway calculations assessed by the IPCC because the pathways deal with emissions. SRM is completely independent of emission pathway. Has nothing to do with uncertainties.

Commenté [F[18]: This doesn't really say much, does it?

Commenté [F[19]: I think you mean 'at' the surface, not below.

Commenté [F[20]: Why are we singling out individual proposals. There are many proposals that could be listed, but I don't think any should be specifically mentioned here – it gives the impression that this one is somehow more mature or plausible than others (which I don't believe is the case).

Commenté [F[21]: This all seems superflouous for a document that is ostensibly about providing a concise overview of the topic rather than specific interactions/issues.

Commenté [F[22]: I have not heard of this as a SRM scheme and couldn't find anything on this in my quick google search. What is the source?

Commenté [F[23]: It seems to me that if judgment statements like this are to be included, they should be supported by reference to literature. In particular, stating that painting city rooftops white is unlikely to have significant impact may be true at the global or regional scale, but not at the urban scale where it is viewed as a way to offset urban heat island – there are many scientific papers on this.

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SRM through cloud albedo enhancement often refers to the practice of marine cloud brightening, which involves spraying sea salt into the lowest clouds above the ocean. In doing so, these salt particles help to brighten clouds and increase their reflectivity. Proposals to conduct this form of SRM include launching a fleet of ships to patrol the ocean while spraying seawater into the troposphere. It is important to note that there is a termination effect for this type of SRM, as these particles dissipate within days. This refers to the reality that for many forms of SRM must be continuous to maintain their effects. If SRM methods are halted abruptly, the termination effect might create extremely rapid warming and potentially disastrous impacts on natural and human systems.

Commenté [F[24]: It is not yet a 'practice'.

Commenté [F[25]: It is not the salt particles themselves that brighten clouds. It is their role in changing cloud droplet size and lifetime.

There also remain some uncertainties regarding the effectiveness of cloud-albedo enhancement. It is likely that this form of SRM could also create changes in regional climate. Given the need for a large fleet of ships (or planes) to conduct this form of SRM, the costs of deployment would likely be high. However, other proposals to conduct this form of SRM, including through the use of drone ships, could be deployed at a much lower cost.

3. Stratospheric Aerosols

Stratospheric aerosol injection is perhaps the most controversial form of SRM, and involves releasing reflective particles (e.g., sulfate aerosols) into the upper atmosphere to scatter sunlight back into space. Similar to cloud albedo enhancement, this form of SRM also faces a termination effect, as particles slowly fall back to earth unless continuously replenished. Despite this, this technique would very likely be effective, particularly as it looks to mimic the natural cooling the Earth experiences after major volcanic eruptions.

Commenté [F[26]: What is the basis for this statement?

The technology needed to conduct SRM using stratospheric aerosols largely exists, and could be available for a relatively low cost. Proposals have included spraying sulfate aerosols from high-altitude aircraft. However, these current technologies would also create a range of adverse environmental side-effects, including chronic health issues linked to increased fine particulate matter, depletion of the ozone layer, increasing acid deposition leading to acid rain, and changes to the hydrological cycle. The World Health Organization currently attributes 4.2 million deaths every year to ambient air pollution. Aerosol injection has the potential to increase the death toll from air pollution, and would have a disproportionate impact on the most vulnerable members of society.

Commenté [F[27]: While perhaps factually correct, I think this is potentially very misleading – at least one published paper that I was able to find (in 1 minute of searching) suggests geoengineering would cause 26,000 premature deaths, which is 0.6% of the WHO total deaths related to air quality. See https://keith.seas.harvard.edu/files/tkg/files/eastham_et_al._-_2018_-_quantifying_the_impact_of_sulfate_geoengineering_o.pdf

Climate modeling will be needed to fully assess the impacts on the hydrological and climate cycles. We could expect more rain in certain areas and less in others. However, researchers are looking at way to minimize the environmental and human health impacts through research on different aerosol types (e.g., calcium carbonate). The hope is that these alternatives would reduce solar radiation, while neutralizing acids associated with anthropogenic emissions that contribute to ozone loss.

4. Space-Based

Space-based SRM involves preventing solar energy from reaching the atmosphere in the first place. This method could include the deployment of space-based sunshades or reflectors to obstruct solar radiation with mirrors or dust. Although theorized, the technologies to conduct space-based SRM do not yet exist at the necessary scale. Additionally, the costs to develop and deploy space-based SRM technologies would likely be very high.

International Context

The United Nations Convention on Biological Diversity has called for a moratorium on climate engineering activities that might affect biodiversity until there is adequate scientific basis and appropriate consideration of the social, economic, and environmental risks associated with the deployment of these climate-engineering technologies. However, the convention allows for small-scale scientific research.

At the Thirtieth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer in November 2018, parties discussed the role that climate engineering methods might play in impacting the ozone layer. Particularly, SRM climate engineering through stratospheric aerosols has been identified as one potential future threat to the ozone layer. Some parties expressed their concern that climate engineering technologies are not fully understood and might have risks that outweigh any benefits. At the 41st Open Ended Working Group of the Parties to the Montreal Protocol, held in July 2019, Parties considered a report by the Protocol's Scientific Assessment Panel on the potential impact on the ozone layer of various SRM approaches that have been considered. Several parties, including Canada, agreed that the panel should provide updates on this issue in the context of its quadrennial scientific assessment reports, noting that the Panel should remain focused on relationships between SRM and the ozone layer, given the broader work on SRM being undertaken by the IPCC.

Climate Engineering was also discussed at the UNEA in Nairobi in March 2019. The Swiss delegation tabled a proposal calling for an expert review of climate engineering technologies, processes, and risks. Although this became the highest-level discussion of climate engineering governance in an international fora, opposition from the United States, Saudi Arabia, and Brazil stalled the proposal and led to its eventual withdrawal. These states expressed a preference that the IPCC address climate engineering, as they are set to discuss the issue in AR6, expected in 2021.

Ongoing Research

Although international dialogue surrounding climate engineering and SRM is limited, research in the field is intensifying. While researchers previously focused almost exclusively on theoretical and climate modelling of SRM technologies, researchers are conducting a growing number of real-world experiments. In 2011, British academics planned an outdoor SRM experiment, but cancelled the project after public backlash. Also in 2011, cloud physics researchers conducted an experiment off the coast of California that closely resembled a marine cloud brightening experiment. There are four major SRM pilot projects currently proposed that have gained recent attention: the Marine Cloud Brightening Project, Ice 911 (surface albedo enhancement), Sky River (major cloud seeding proposal in China), and the Stratospheric Controlled Pertubation Experiment (SCoPEx) (small-scale stratospheric aerosol tests led by Harvard University Researchers). It is important to note that none of these field research projects are led by government, and all involve academic researchers or other 3rd party organizations.

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Canadian Context

While there is no comprehensive legislative framework in Canada that governs climate engineering, specific provisions of existing Canadian law might be applicable to some aspects of SRM. It is unclear whether any legislation at the provincial/territorial level might be applicable to climate engineering. However, it is important to note that the Canadian territories will likely be ~~much~~ affected much more than other Canadian jurisdictions, given the region's climate.

Commenté [F[28]: What is the basis for this assertion?

For example, the deposit or release of harmful substances into fish-bearing waters or areas where there are migratory birds is prohibited under subsection 36(3) of the *Fisheries Act,* and section 5.1 of the *Migratory Birds Convention Act, 1994*. This could include the release of albedo-enhancing particles deemed harmful.

In 2013, the London Protocol adopted an amendment on ocean fertilization to provide a permit system, and a means to distinguish between marine geoengineering techniques that should be prohibited and regulated, allowed in cases of legitimate scientific research, or permitted more generally. Until this amendment is in force for Canada (an amendment to CEPA is required), Canada prohibits all disposal of substances at sea under CEPA and can ask for an assessment of the activity and waste. Once assessed, ECCC can rule that a project is exempted or prohibited. Although there is no permitting mechanism established, a permit is defined by CEPA as the only method to grant an exemption. Despite this, ICE 911, an initiative looking to conduct surface albedo enhancement in the Arctic has developed what they claim is "100% safe" glass microsphere technology to conduct SRM. This proposed approach, which releases a substance on sea ice, is considered to be disposal at sea. This means that ICE 911 proposal requires assessment before it can be authorized under a permit, or be exempted from needing a permit.

Commenté [M[29]: Seeking clarification on this

Commenté [F[30]: Again, not sure why this specific issue is being raised again in this document. How about an appendix or something in which some specific examples like this are listed, rather than including in the main text

In addition, the *Weather Modification Information Act* requires proponents to notify the department if they intend to take actions to modify precipitation. Although this Act would likely not apply to small-scale climate engineering research, it might apply to large-scale deployment of SRM methods, particularly stratospheric aerosol methods that might affect the hydrological cycle.

Commenté [M[31]: Seeking clarification

As stratospheric aerosol injections involve the use of sulfur dioxide, the CEPA could regulate SRM activities that specifically involve the release of toxic substances. Additionally, it could be possible to require an impact assessment for SRM activities in specific circumstances.

Ethical Considerations

Given the range of social, economic, and environmental risks associated with climate engineering, the somewhat limited scientific understanding of the processes involved, the presence of a termination effect, and the lack of research, national, or international governance mechanisms, SRM has generally been regarded as the more controversial climate engineering approach (when compared to CDR). It is important to acknowledge that while SRM can limit the effects of global warming, it is not a "silver bullet" solution to the challenges of climate change and should not be considered one.

Commenté [F[32]: This needs to be re-worded. It does not limit the effects of warming, it is aimed at avoiding/reducing warming

There are also ethical considerations behind the decision of whether to pursue further research or eventually deploy climate engineering technologies in the first place. Many of the risks of these technologies have been acknowledged. However, if these technologies can present an effective solution to climate-related ecological disasters, are governments obligated to continue to research and prepare these technologies for potential deployment? Questions of this nature warrant careful consideration in discussions on climate engineering.

Considerations

- Even with lower-risk forms of climate engineering, it is important to note that climate engineering *should not* be considered a substitute for mitigation and adaptation.
- Further research is needed to determine the merits and risks of SRM climate engineering. Despite this, academic and private organizations have already begun to field-test some of these SRM techniques at small scales.
- The merits and risks associated with CDR technologies have been studied in greater detailed than those associated with SRM. The Government of Canada has previously supported some CDR technologies, including Squamish BC's Carbon Engineering and their direct air capture technologies. However, it should be noted that the environmental impacts of CDR technology deployment at a large scale remain largely unknown.
- Although climate engineering relates primarily to long-term decarbonization, research on climate engineering has already begun to move from theoretical modelling to real-world demonstration projects. Regardless of the Government's own position on the merits/risks of climate engineering, it may be necessary to develop a framework to govern academic and 3rd-party research on climate engineering in Canada, particularly as this research is likely to continue regardless, and could entail substantial risks.

Commenté [F[33]: This sentence doesn't make sense

Recommendations

Commenté [F[34]: Shouldn't there also be a recommendation that ECCC undertakes dedicated research on climate engineering in order to inform future policy and regulatory considerations?

- ECCC needs to develop and agree on the key principles that should guide the development of domestic policy and how to operationalize them in Canada.
- Given the increased attention to climate engineering in international fora, it is recommended that Canada begin engage in international discussion on climate engineering research and policy.
- ECCC needs consider the development of a domestic research governance system in order to allow small-scale field research to proceed legitimately as per international agreements to which Canada is a party.
- As research on climate engineering will continue to intensify in the coming years, it is recommended that Canada explore means of implementing a moratorium on large-scale experiments or deployment of atmospheric climate engineering methodologies.

Solar Radiation Management: A Brief Introduction

G.M. Flato – 24 July 2019

Climate Research Division, ECCC

Solar radiation management (SRM) is one category of activities or interventions that fall under the umbrella of Geoengineering or Climate Engineering, that is, deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming[1]. SRM involves interventions that increase reflection of solar radiation (sunlight), thereby reducing incoming energy and hence providing a cooling effect that would offset greenhouse gas warming. Techniques that have been proposed include: injection of reflective (sulphate) aerosols into the stratosphere (in some ways mimicking the cooling effect that arises from explosive volcanic eruptions); launching of space-based mirrors or other reflective material; injecting salt-water spray into the lower atmosphere over the ocean to alter the reflectivity or lifetime of marine clouds; modifying the surface by planting more reflective crops; and painting or coating building rooftops or other surfaces with more reflective material. It should be noted that SRM does not address the causes of global warming (namely greenhouse gas emissions), but rather seeks to offset the warming that would otherwise occur.

SRM has gained attention as a climate change intervention because it has the potential to act very quickly and could be implemented at relatively low cost (as compared to many carbon dioxide removal, CDR, approaches). For example, sulphate aerosols injected into the stratosphere have an essentially instantaneous cooling effect, although large amounts would have to be transported to offset a substantial part of anthropogenic warming[2]. Such aerosols also have a relatively short lifetime in the atmosphere (a couple years) and so on-going effort is required, and if terminated, would almost immediately unmask the warming that had been avoided.

There is a fairly large and growing body of scientific literature on SRM, including global climate model simulations that illustrate the potential effectiveness and unintended consequences (like changing rainfall patterns) of stratospheric aerosol injection or space-based technologies. These unintended consequences give rise to a range of ethical and international governance/liability issues, and the termination effects constitute an ongoing commitment to SRM technology and an ongoing exposure to the risks associated with interruption. The Climate Research Division has been involved in SRM simulations using its global Earth System Model, and is participating in current international model intercomparison projects on this topic[3], but at this point there is not a dedicated SRM (or geoengineering) research program in the Department at the scale that would be needed to fully inform domestic and international policy and regulatory development.

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[1] https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf

[2] https://iopscience.iop.org/article/10.1088/1748-9326/aae98d

[3] http://climate.envsci.rutgers.edu/GeoMIP/

Geoengineering
Impacts of stratospheric sulfur injections on radiation and climate

Context

The ultimate goal of this project is to use the CCCma full Earth System Model, including ocean, carbon, and sea ice feedbacks to determine impacts of sulfur injection on stratospheric ozone and tropospheric chemistry and do the comparison with results from other modelling systems and observations.

Short term

First stratospherically extended version of CCCma aerosol microphysics model to simulate stratospheric sulfur injections

The current version of the atmospheric global climate model (CanAM5) will be modified to simulate possible future solar radiation management (SRM) techniques based on stratospheric sulfur injection. This will require two developments for CanAM5. First, the vertical model domain in CanAM5 will be extended into the stratosphere to create a dynamical middle atmosphere version of CanAM5. Simulations of stratospheric dynamical processes will be conducted and evaluated. Second, the tropospheric aerosol microphysics model (PAM) in CanAM5 will be modified to allow simulations of stratospheric aerosol processes. Specifically, particulate sulfuric acid and a stratospheric source of SO_2 will be added. Concentrations of stratospheric sulfur oxidants will be included in the model based on simulations with CMAM.

Medium term

A unified model for stratospheric and tropospheric aerosol to account for different techniques for stratospheric sulfur injection and comparing modeling results with observations for Pinatubo eruption

To evaluate the model it will be validated by simulating the eruption of Mount Pinatubo in 1991 and comparing with available observations. Since SRM applications can be a very different regime from a volcanic eruption additional validation of the model will be performed by comparison with model data from existing SRM applications. Model experiments will be performed to identify the sensitivity of aerosol concentrations to key SRM processes. Results from these simulations will be used to determine and compare the efficiency of different SRM deployment strategies.

Further model improvements will be made based on results of the model evaluation. For instance, different techniques for stratospheric sulfur injection and the formation of new aerosol particles near the injection source will be investigated. Parameterizations of aerosol optical properties and the treatment of radiative transfer in the upper atmosphere will be evaluated and improved, as necessary. For example, improvement of non thermal equilibrium processes in the current radiative transfer calculations in CanAM5 may need to be addressed.

Furthermore, an interactive representation of gas-phase chemical processes for stratospheric ozone and the exchange of aerosols and gases between the stratosphere and troposphere may need to be included in the model. Natural sources of stratospheric aerosols and gases may also be added to the model, if necessary. Overall, model improvements for sulfur injection, radiation, and chemistry will lead to a fully coupled Earth System Model which includes ocean, sea ice, carbon and ozone feedbacks.

<u>Ongoing</u>

A full Earth System Model determining the impacts of sulfur injection

The Earth System & SRM Model will be used to determine impacts of sulfur injections on climate and air quality. In particular, the impacts of SRM techniques on regional temperatures in Canada and the Arctic will be investigated. Furthermore, earlier studies showed that SRM may lead to complex and perhaps undesirable changes in hydrological and carbon cycles. Therefore, impacts of SRM techniques on precipitation rates, soil moisture, and carbon sinks will be investigated, too.

Results of the CCCma Earth System Model will be compared to results from other modelling systems and climate scenarios. Model results will be made available to the international research community through participation in geoengineering model intercomparison project. Furthermore, the impacts of SRM techniques and potential future volcanic eruptions will be considered for the development of the seasonal and decadal prediction model system (CanSISE).

Resource Requirement in Short-term

- 1 x SE-RES
  - Develop and evaluate a stratospherically extended dynamical version of CanAM5
  - Develop and evaluate aerosol microphysical parameterizations for stratospheric sulfur
- 1 x PC
  - Configure and test a stratospherically extended version of CanAM5
  - Develop, implement, and test data sets for stratospheric sulfur emissions and oxidant concentrations
  - Develop diagnostic tools for stratospheric processes
  - Maintain and manage model data sets and a single column model version for stratospheric aerosol processes in support of collaborations with external experts

Additional Resources Requirement (medium-term and ongoing) term

- 1 x SE-RES
  - Plan and analyze:
    - Simulations of the Eruption of Mt Pinatubo
    - Model sensitivity experiments to identify key processes and uncertainties for SRM
    - Earth System model simulations to investigate impacts of SRM on carbon cyle and chemistry
    - Contribute to development of seasonal prediction modelling system to account for volcanic eruptions
  - Participate in model intercomparison projects
  - Develop and evaluate new parameterizations of aerosol microphysical, chemical, and radiative processes in the stratosphere
  - Collaborate with other experts to facilitate the development of new parameterizations
- 1 x PC-02
  - Configure and test CanAM and CanESM for simulations of stratospheric volcanic eruptions and SRM
  - Conduct simulations in support of SRM model intercomparison projects and research

- Develop, implement, and test data sets for emissions and stratospheric model boundary conditions
- Develop improved model diagnostic tools
- Investigate and improve code efficiency and coupling of different model components

Platform alignment

Response to the reviewers

We thank the reviewers for their critical assessment of our work. In the following we address their concerns point by point.

Reviewer 1

General comments

Reviewer Point P 1.1 — Moseid et al. compare surface downwelling shortwave radiation from CMIP6 models and from ground stations. They show the discrepancy between modeled and observed SDSR is partly caused by erroneous aerosol and aerosol precursor emission inventories, thus providing important information for the evaluation of ESM. While the research topic is essential, the methodology can be improved to clarify the impacts of clouds and cloud-aerosol interaction. Instead of using all-sky SDSR, I would suggest the authors compare the sunny-day SDSR from CMIP6 and from ground stations throughout the whole text.

Reply: We thank the reviewer for their comment and agree that the manuscript should include a more detailed description of the impact of clouds and cloud-aerosol interactions. This has been added both in the introduction section and in the discussion section.
Unfortunately neither GEBA nor CMIP6 models provide sunny day SDSR. Previous studies such as Allen et al. (2013) have used the GEBA data set to create a clear sky proxy for a selection of stations to compare with the clear sky flux variable of CMIP models. However, this is beyond the scope of our study.

Reviewer Point P 1.2 — To be more accurate, I would also suggest the authors compare the SDSR conditions on the atmospheric relative humidity, which is associated with the scattering from water vapor.
Note that the clear-sky SDSR from climate models is usually used for calculating cloud radiative forcing and is not the same as sunny-day SDSR.

Reply: We are looking at long time fluctuations in SDSR. Water vapor has not changed in a sufficient magnitude in recent decades to have an effect on decadal fluctuations in SDSR (Wang and Yang (2014), Hoyt and Schatten (1993),Ramanathan and Vogelmann (1997),Solomon et al. (2010)). We therefore assume in this study that the SDSR effects of water vapor scattering is negligible. We do ,however, improve the manuscript in the explanation of the effect of clouds on SDSR. A paragraph on Clouds and SDSR has been added in the introduction, and the section connected to the current Figure 3 has been improved for clarity.

Minor comments

Reviewer Point P 1.3 — The title: I would not use the "1961-2014" in the title. It provides little information.

Reply: Fixed.

Reviewer Point P 1.4 — The title: compare to -> compare with.

Reply: Fixed.

Reviewer Point P 1.5 — The title: maybe the authors should include "aerosol", which is the theme of the paper

Reply: Fixed.

Reviewer Point P 1.6 — Figure 3: Please double check the cloud fraction and the calculation of anomaly. If the trend is reversed, it explains everything.

Reply: This is double checked and the presented Figure is correct. In the future version of this manuscript this figure will be made into a table for clarity.

Reviewer 2

General comments

Reviewer Point P 2.1 — It would improve the paper if more background information in the introduction section was provided on the key drivers of SDSR i.e. clouds and greenhouse gases can also influence SDSR in addition to aerosol effects.

Reply: We added a more detailed description in the introduction section of what can influence SDSR, especially in regards to clouds, but also greenhouse gases and solar irradiance.

Reviewer Point P 2.2 — Throughout the paper there are numerous mentions to the fact that aerosols play a key role in the dimming signal of SDSR observed and simulated across all regions. However, the same cannot be said for the observed brightening signal in more recent years. A key question seems to be why are aerosols a key driver in the dimming but not brightening?
If the emission inventories and aerosols were in error throughout the whole period of study then surely the models would not be able to simulate the temporal evolution of both phenomenon across all regions?

Reply: We answer this point in two parts - first the role of aerosols in brightening:
We would like to point the reviewer to the following studies Allen et al. (2013), Chiacchio et al. (2015) and Wild (2011), which show that indeed aerosols are a key driver to the observed brightening in recent years. The reduction of antropogenic aerosol emission leads to brightening. We would also like to thank the reviewer for mentioning this point that we did not explicitly say in the original manuscript, but has now been added in the second paragraph of the introduction.
Then the final question on emission inventories: Correct, this is why we are proposing errors in emission inventories as a possible reason for discrepancies in the regions where the models are not able to simulate the temporal evolution of dimming (and brightening).

Reviewer Point P 2.3 — The paper states that the CMIP6 models are able to represent the observed SDSR signal over Europe relatively well. However, I think there are a few interesting discrepancies which should be discussed further. Prior to 1980 the observations do not show much of a dimming signal (in fact the observed anomaly is slightly positive at times) but the CMIP6 models do show a consistent dimming signal. Is there a specific reason for the absence of a dimming in the observations, when we know there were large concentrations of aerosols over Europe at this time? Contrary to what was mentioned in point 2 above Europe is the only region where there is a simulated brightening signal in both the model and observations, implying that models are able to reproduce brightening signal over certain regions. It would be good to know if there a reason for this over Europe and does it occur over other regions like for example North America.

Reply: The referee is right that Figure 1b does show some interesting discrepancies in the beginning of the time period in the study that was not mentioned in the original manuscript. The observational data set used in this study starts in 1961, and the anomaly shown in the figure is made as a difference from the the mean value of SDSR from 1961-1966. Since the European dimming started before 1960 (Wild, 2011) the "true" European SDSR anomaly might not be achieved using this data set, as is also seen by the weak European dimming in Storelvmo et al. (2018) using the same data set.
The reason for the discrepancy between model SDSR and observed SDSR Europe in the mid 1970s is unknown at this time, but has been added as a comment in the manuscript in Section 3.1 first paragraph. The observed and simulated brightening in Europe duplicate each other well and thereby we propose that the emission inventories of aerosols in Europe are estimated well.
North America has not been shown in Figure 1, but is included here in the reply as supplementary Figure S1. See Leibensperger et al. (2012b) and Leibensperger et al. (2012a) for a closer look at the climatic effects in North America to anthropogenic aerosol emissions. We chose Europe and Asia as areas of focus to give the readers a clean impression of one example region where the models perform well and one example region where they do not perform well. The comparison of results for North America in our study together with previous findings in North America climatic effects is complicated, and is beyond the scope of this study.

Reviewer Point P 2.4 — For the analysis over China the paper suggests that the error between the models and observations of SDSR are due to the errors in emission inventories that translate into errors in the calculation of atmospheric burden of aerosols. (1)Are we certain that the errors in the emission inventories are that large to account for the discrepancy in model and observed SDSR? Is there an estimate of the uncertainty for the CMIP6 emission inventory and how does CMIP6 compare to other global and regional emission inventories? (2) Can these differences explain some of the inconsistencies of models with observations? I am not convinced that the observed trend reversal in SDSR over China in ~1990 can be explained by errors in the emission inventories alone. (3) Are we anticipating a slowing down of SO2 emissions in China from the 1990s onwards? As far as I understand, anthropogenic emissions of aerosols and their precursors (particularly SO2) have largely been increasing over China up until 2010 when air pollutant control measures were then implemented to reduce emissions. Therefore, if aerosols were driving the temporal change in SDSR over China a dimming signal should have been observed up until this point, but it isn't. This is present in the observed and simulated change in SDSR over India but not China. (4) How do this discrepancy match with the conclusions of the paper and what else could be driving the SDSR trend over China throughout this period? I think this needs to be explored further in the paper as the assumed underlying trend in emissions (and therefore aerosols) and SDSR do not seem to match over China and from what I can tell it cannot be reconciled by errors in the emission inventories alone.

Reply: To make it easier for the reader we have marked up numbers to the questions in the reviewer point. (1) We are not certain that the errors in the emission inventories are large enough to account for the discrepancy in model and observed SDSR alone, but we propose that this error plays an important part. Unfortunately there is no estimate of uncertainty in the CMIP6 emission inventories, but this is planned to be included in the next generation of CMIP emission inventories (see Hoesly et al. (2018)). Because there is no estimation of uncertainty we do not have evidence to say that errors in emission inventories are small to cause a discrepancy between model and observation.
(2) The CMIP6 emission inventory is made using CEDS that makes datasets based on EDGAR, as in written in more detail in Hoesly et al. (2018). There is probably some differences between the CMIP6 data set and other regional emission data sets, but this study does not look further into finding such differences. We propose at least some of the discrepancy between model and observed SDSR is caused by errors in emission inventories, but we do not have enough evidence to propose all discrepancy is emission sourced. We recognize that the manuscript have given the wrong impression to the reader that errors in emission inventories *alone* cause all discrepancy, and this has been made clearer throughout the text.
(3) During the review process we found more information regarding the observed trend reversal in the GEBA data in China. According to the CMIP6 data set of sulfate emission we do not expect a slow down of emitted SO_2 from 1990, but rather from around 2005. The observed trend reversal in SDSR does therefor not fit with CMIP6 emitted sulfate. However, previous studies have found the trend reversal in SDSR is to a considerable extent caused by the fact that the Chinese radiation network was replaced with new measurement devices between 1991 and 1993, which caused a spurious upward jump in the records (Wang and Wild (2016), Wang and Yang (2014), Yang et al. (2019)). With this new information we have added a section under discussion where the trend reversal in China is in focus, where we do not disregard the trend reversal completely. The trend reversal begins in 1989 - before the instrument were replaced, and we see a distinct signal of a trend reversal in Japan which is downwind form China, with this in mind we try to disentangle the observed SDSR in China in our new section under discussion.
(4) The conclusions of the paper proposes that errors in anthropogenic aerosol emission inventories plays a part in the discrepancy seen between model and observed SDSR. Even if the trend reversal in the observed SDSR in China was to be an artifact the models would largely underestimate the magnitude of dimming. In regards to the trend reversal, the assumed underlying trend of increasing sulfate emission until 2010 as proposed by the reviewer (and CMIP6) is being questioned in this manuscript. We thank the reviewer for this comment and we have updated our discussion section to include possible causes of the mismatch, and we are performing a station-test to see where the stations with the strongest trend reversal is found that will be added in the supplementary of the manuscript.

Reviewer Point P 2.5 — Only limited discussion within the paper is provided on clouds and aerosol-cloud interactions, which needs to be improved throughout the paper. Within section 3.3 a link is made between cloud cover change and SDSR but how much of an influence do clouds have on all-sky SDSR? How reliable are the observed and simulated cloud cover changes and can some uncertainty bounds be placed on them? Is a regional cloud cover change of 1-2% significant in terms of SDSR? In figure 3 the temporal change in observed cloud cover is similar to that in observed SDSR so even if clouds can't explain the magnitude and all of the observed change then surely they must be exerting some influence on SDSR? Is it possible to compare a clear-sky derived observed SDSR to that from model simulations to eliminate any influence of clouds on the signal?

Reply: We thank the reviewer for this comment, and we have included more information on aerosol-cloud interaction in the introduction, results and discussion. Previous studies have found that the link between cloud cover and SDSR trends depends on what region you are looking into. For Europe cloud cover has most of an effect on SDSR on the shorter time scales, and the dimming and following brightening observed in Europe is dominantly caused by changes in anthropogenic aerosol emission and thereby the aerosol absorption and scattering (Norris and Wild, 2007). For China cloud cover made a negligible contribution to all sky SDSR trend in GEBA until 1989. After 1980 the heavily discussed trend reversal is observed in China, and Norris and Wild (2009) suggests half of the observed brightening between 1990 and 2002 is caused by a reduction in cloud cover. Please note that this paper was published before the proposal of the trend reversal being an artifact of a change in instrumentation (Wang and Wild, 2016). Which complicates the story. In North America cloud cover is found to have played an important role in the observed brightening (?). The observed cloud cover in Figure 3 shows a reduction in cloud cover in the dimming period, and an increase in the brightening period, which is the opposite of what is expected in cloud cover played an important part in dimming and brightening in China. We have decided to replace Figure 3 with a table and make the manuscript more clear on what role cloud cover plays in all-sky SDSR. Other studies have made clear-sky derived observed SDSR (Norris and Wild (2007),Norris and Wild (2009)) when assessing the cloud signal for Europe and China (mentioned above in this reply), but this goes beyong the scope of our study.

Reviewer Point P 2.6 — The previous comparison of CMIP5 models to observed SDSR by Storelvom et al., (2018) is mentioned throughout this study, with similar results presented here for CMIP6 models. A key question is therefore why has there been no improvement in simulating observed SDSR between CMIP5 and CMIP6 models? This is despite some changes to individual aerosol schemes within models and also different historical aerosol precursor emission datasets being used. Some discussion is needed on what is continually missing from the models and what are the model developments to focus on to improve the future simulation of SDSR.

Reply: To answer this question we must first find out whether the source of the error is within the model's codes or within the emission inventories, or a combination. Storelvmo et al. (2018) argues that the discrepancy between observed and modelled SDSR may be attained to errors in the treatment of processes that translate aerosol emissions into clear-sky and all-sky radiative forcings. Here, we show that simulated SDSR develops similarly in time, but opposite in sign, to simulated atmospheric burden of SO2. By doing this we narrow down the potential source of error by suggesting that the atmospheric burden in the models are at fault, and that the processes translating burden into clear-sky and all-sky radiative forcings are behaving as expected. The final answer of what is at fault is still not found, but we suggest to have found a piece of the puzzle in the emission inventories.
Future studies include doing model experiments with changes in emission to see what it takes for the models to recreate the magnitude of dimming that is observed. We thank the reviewer for this comment and we have added a section in the bottom of the conclusion that explains what our next step is.

Reviewer Point P 2.7 — Further details are required, either in Table 1 or a new table, on each of the CMIP6 models used in this study. In particular, it would be useful to know horizontal resolution and some information on the individual chemistry and aerosol schemes in each model. This could provide useful information to the reader of the potential causes of discrepancies between models. In addition, it would be good to have a record somewhere of the actual output used from the ESGF (e.g. temporal period, variant ID, CMIP table ID etc). Furthermore, if there is data now available for additional CMIP6 models then it would be useful to include it, as long as it further informs the current study.

Reply: We thank the reviewer for this comment and we have added information on the resolution of the models in Table 1, in addition to a supplementary section on where to find the data used in this paper, including the model schemes. More data has been published since the first submission of this paper, and we have therefore decided to include more models in this study. In addition, some of the models already in the paper has now released more data in some of the experiments that they didn't have in the original manuscript, and this data has now been included in this study.

Reviewer Point P 2.8 — The methods section (2.3) appears to lack important details of what model data is being used (see point 7) and how the gridded model data has actually been compared to the observations which are at point locations. In calculating the regional means at observation locations, do the number of sites used change over time period and does this have any impact on the results? Furthermore, in the results section the clear-sky SDSR is discussed but is not mentioned in the methods section. I also think that it is important to use multiple ensemble for meaning purposes when using coupled experiments members from models so that the internal variability in each model can be shown (this would give a range of variability important to show on some of the Figures for certain variables).

Reply: We thank the reviewer for this comment and agree that the methods section was indeed lacking both clarity and details. This has been fixed in the new version of the manuscript. We have added three ensemble members per model for the historical simulation, which will be presented in the new version of Figure 1. This figure will then present the internal variability per model in addition to the comparison to observations.

Reviewer Point P 2.9 — A General comment on the figures is that they could be improved to make them easier to read by using better colours (I found the light green very bright), tick marks on the axis and line types that are easier to distinguish between different model experiments. Also, if it is possible to include a measure of observational and model uncertainty on any of the figures then this would improve the comparisons. When values from figures are continually referred to in the text it would help the reader if there is reference table containing some of the key numbers included (like the supplementary table).

Reply: We thank the reviewer and have chosen a different a color chart for the figures, more tick marks, and different line types to better differ the graphs. Uncertainty estimates have been included in Figure 1. A reference table with key numbers is an excellent idea, and has been added to the manuscript.

Minor comments

Reviewer Point P 2.10 — Page 1, line 9 – Reword this sentence as mentioning SO2 emissions, which are not aerosols, and then other aerosols relevant to SDSR. Be more precise in this statement.

Reply: Clarified and fixed.

Reviewer Point P 2.11 — Page 1, line 13 – Can you say how much error is associated with aerosols and emission inventories that might contribute to error in SDSR?

Reply: Unfortunately the emission inventory data set for CMIP6 does not have estimates of uncertainty, which is why we use the word "partly" in line 13 as we have no evidence telling us how much of the discrepancy can be attributed to emission estimates.

Reviewer Point P 2.12 — Page 2, Line 30 – Is this statement true across all regions? What about for Europe?

Reply: This statement is only true globally based on previous studies. Added the word "global" to clarify.

Reviewer Point P 2.13 — Page 2, line 35 – For the introduction it would be good to include a bit more detail on what the GEBA observations on their own show before introducing any comparisons to models.

Reply: We thank the reviewer for pointing this out, as the introduction to global dimming mentioned several citations that all used GEBA to identify dimming (and regional brightening), which was not exclusively mentioned. This has now been clarified in the text.

Reviewer Point P 2.14 — Page 2, line 46 – here the study says that two observational datasets are used but only one has been mentioned in the previous paragraph. Please include details of what is the second dataset used in this study.

Reply: The second observational data set has been added to the previous paragraph. "We also use observational cloud cover data to briefly assess the role of cloud cover in the historical development of SDSR".

Reviewer Point P 2.15 — Page 2, line 47 – please reword sentence "An explanation of the methods used to obtain and analyse the data complete Section 2."

Reply: Fixed.

Reviewer Point P 2.16 — Page 3, line 57 – it would be good to include the error in the observations on all figures to show the uncertainty in the observations.

Reply: Unfortunately sources of error in observation differs from station to station and we only have a general estimation of error from the instruments used. We have chosen to include a light grey line with the "raw" observational data in the background of the smoothed black observational line in time series graphs to show the variability of observations. A section discussing the observations in China has also been added in the discussion section on the manuscript.

Reviewer Point P 2.17 — Page 3, line 60 – Please clarify if this temporal gap filling technique allows for all 1487 stations to have a complete record of observations over the entire 1961-2014 and how this technique impacts the observations. If the number of stations used changes over the entire time period then it could be important for the analysis.

Reply: Fixed.

Reviewer Point P 2.18 — Page 3, line 74 – insert 'is' between "these the"

Reply: Fixed.

Reviewer Point P 2.19 — Page 4, line 93 – replace 'stales' with "stalls"

Reply: Fixed.

Reviewer Point P 2.20 — Page 4, line 94-95 – "So these experiments will show to what extent the removal of cloud cover change from global warming has an effect on SDSR." – I am sure that this is the case as there will be still be variability in the cloud fields simulated by climate models in these experiments. In addition, as the aerosol fields are changing in these experiments, they will also impact the simulated clouds in the models. Therefore, to make this statement further evidence would be required from each model that the cloud fields are being properly constrained to isolate their impacts on SDSR.

Reply: We are not stating that all cloud cover change is removed, only the cloud cover change that is induced by global warming - as global warming essentially is removed in these experiments. Cloud cover will change due to aerosol emissions and thereby impact SDSR - but not due to global warming. Changed the wording from "cloud cover change from global warming" to "cloud cover change caused by global warming" to clarify.

Reviewer Point P 2.21 — Page 4, line 107 – It would be good to show on a figure the spatial distribution of the GEBA observations within each defined region.

Reply: Storelvmo et al. (2018)s Figure 1 is an excellent figure showing the spacial distribution of the stations used in both this and her study in addition to the trends of the stations in colours. I have added a reference to that figure in the text.

Reviewer Point P 2.22 — Page 4, line 110-112 – Please clarify exactly how anomalies have been calculated. Are anomalies calculated for each individual observation site within a region first before then calculating a regional mean value?

Reply: Clarified.

Reviewer Point P 2.23 — Page 4, line 112 - Supplementary table number is not shown

Reply: Fixed.

Reviewer Point P 2.24 — Page 4, line 113 – Provide more information on exactly what model data has been obtained from the ESGF (perhaps in a separate table) e.g. CMIP table ID, variant label etc. (see general comment 8)

Reply: Added a table in supplementary.

Reviewer Point P 2.25 — Page 4, line 115 – I think it would be more prudent to use more ensemble members for coupled experiments and with this an idea of the internal variability for each model could be obtained for variables such as cloud cover and SDSR.

Reply: Three ensemble member are now being used in the historical experiment, and the manuscript has been updated to explain this.

Reviewer Point P 2.26 — Page 4, line 116 – It is not clear if the 10-year running mean is used for the model data, observation data or both?

Reply: Fixed and clarified in the methods section.

Reviewer Point P 2.27 — Page 5, line 121 – it is hard to see from Figure 1 a) as to whether the global SDSR representation in the models is similar to the observations at all. There is clearly a difference in magnitude but there does not appear to be a strong dimming signal in many of the models. Is this just the scale on the figure or is there not much change in the model at all? Can the Figure be improved in any way to make this easier to see?

Reply: There is no strong dimming or brightening signal in the models when they have been interpolated to all the GEBA stations. But there is a very weak downward trend followed by a weak positive trend in most of the models, although the trend reversal seems to happen at different times. This figure will be improved by adding ensemble members and change from a timeseries-graph to a semi-decadal mean box plot. The models generally does not represent the *global* change in SDSR as observed and this point is made clearer in the text.

Reviewer Point P 2.28 — Page 5, line 122 – Change "these discrepancy originate" to "this discrepancy originates"

Reply: Fixed.

Reviewer Point P 2.29 — Page 5, line 125 – More discussion on European model observational differences (see general comments point 3)

Reply: Added.

Reviewer Point P 2.30 — Page 5, line 135 – I think that this is only true for certain models as others seem to have opposite temporal changes compared to observations e.g. NorESM2.

Reply: We agree and have clarified the text.

Reviewer Point P 2.31 — Page 5, line 138 – It is hard to say without tick marks on the figures as to whether the end points in models are similar to the observations. For example, is a -10 Wm-2 anomaly in 2014 from GEBA considered to be similar to a -6 Wm-2 from NorESM2?

Reply: The new figures have more clear tick marks, and the text has been changed to more accurately describe the behaviour of the models. The end points in observations are not comparable to NorESM2 and CNRM-ESM2-1 and this has been cleared out in the text.

Reviewer Point P 2.32 — Page 5, line 140 – please explain what "temporal forcing evolution" means in this context.

Reply: This line has been removed due to the added discussion of the trend reversal in China in observations.

Reviewer Point P 2.33 — Page 6, line 156-157 – does this imply that the greenhouse gases impact on SDSR over China throughout this period?

Reply: Yes, and this has been added to the text. However we also note that MIROC6 tells the opposite story and we cannot draw conclusions on what effect greenhouse gases without their SST-warming have on SDSR from these results.

Reviewer Point P 2.34 — Page 6, line 157-158 – I am not sure this is true for all models. The temporal evolution of SDSR from CanESM5 seems quite different in the historical and piClim-histall but perhaps not so much in MIROC6.

Reply: The reviewer is right and we have changes the text to highlight the difference between piClim experiments and historical for CanESM5.

Reviewer Point P 2.35 — Page 6, line 167 – Aerosols have a key role in dimming but not it appears brightening – why not? (see general comment 2)

Reply: The reduction of aerosol emission have a key role in brightening, as is seen in Europe where brightening occurs at the same time as anthropogenic aerosol and aerosol precursor gases was reduced. This is further explained in the reply for general comment 2.

Reviewer Point P 2.36 — Page 6, lines 168-169 – similar to point above in that there are differences between these simulations which don't appear to be the temporal driver of SDSR but perhaps can influence it? It would be good to show the actual differences between models in these simulations and what influence other factors (like clouds and greenhouse gases) can have on SDSR.

Reply: Clouds and greenhouse gases can influence SDSR, but is as mentioned in the introduction not a dominant driver of SDSR changes. It is therefore expected to see small differences in between these simulations. The overall picture of models showing dimming with anthropogenic aerosol emissions, and no dimming without it remains whether or not you include greenhouse gases or SST changes. This has been made clearer in the text.

Reviewer Point P 2.37 — Page 6, line 173 – how has all-sky SDSR been decomposed into clear-sky?

Reply: This is diagnostics that is outputted from the models. The general idea is that clear-sky SDSR from models represents the amount of sunlight reaching the surface if all shortwave effects from clouds were removed. Clear-sky SDSR is not to be confused with sunny day SDSR which is from actual cloud free days.

Reviewer Point P 2.38 — Page 6, line 179-180 – Can the clear-sky and all-sky changes be shown on the same figure to compare differences?

Reply: This figure has been replaced by a table and the table will include all-sky changes as well to more easily compare the two (three including cloud cover).

Reviewer Point P 2.39 — Page 6, line 182-189 –How have the changes in model cloud cover been calculated? This needs to be in the methods section. Also line 183-184 states that cloud cover changes mask the clear-sky SDSR signal. This implies that the clear-sky decrease would have been even larger without changes to clouds indicating that clouds do have an important influence on SDSR in models. I think this needs to be explained more - see general comment section 5 for more details.

Reply: a paragraph on how cloud affect SDSR has been added in the introduction which will be referred to in this current section. Cloud cover is a standard output from climate models and has not been calculated by the author, and the source of the data has been added in the supplementary explaining how we obtained the data. The new table will present both clear sky and all sky SDSR which will show that most models do have a stronger dimming when cloud effects have been removed, meaning that clouds historically in China have had a "masking" effect on SDSR in the model simulations. This has now been clarified in the text.

Reviewer Point P 2.40 — Page 7, line 193 – "session" should be "section"

Reply: Fixed.

Reviewer Point P 2.41 — Page 7, line 194 – "In this session we found the clear-sky SDSR to be stronger than all-sky SDSR, indicating the simulated dimming is primarily caused by aerosol-radiation interactions." But also that clouds have an influence on SDSR too.

Reply: Cloud have an influence on SDSR - but aerosols are the primary cause of dimming.

Reviewer Point P 2.42 — Page 7, line 205 – "SO2 burden" is mentioned but should this not be SO4 burden.

Reply: Fixed.

Reviewer Point P 2.43 — Page 7, line 205-206 – Given that all models have the same SO2 emissions, do we know why the changes in SO4 burden are so different between NorESM2 and CESM2? Could this indicate some of the potential problems in translating emissions into atmospheric burden or aerosols, which lead to errors in SDSR?

Reply: Burdens are a result of emission and deposition. The emissions in both models are the same but the deposition is dependent on many different processes within each model. The atmospheric circulation in CESM2 and NoreSM2 differs, among other things, so for example a sulfate particle may be brought higher up in the atmosphere in NorESM2 - giving sulfate a longer lifetime and thereby making NorESM2 have a higher sulfate burden.

Reviewer Point P 2.44 — Page 7, line 210 – can a more scientific term be used than "real story".

Reply: Definitely. Fixed.

Reviewer Point P 2.45 — Page 7, line 210-211 – This sentence makes the assumption that aerosols are the sole driving force in SDSR and that it is only the emissions and removal processes that could be in error. Other potential causes could be mentioned like the model translation of emissions to burden which leads to the larger differences in simulated SO4 burdens between models. Also see major comments above.

Reply: The model burden is translated from emission and removal processes. If there is an error in burden than the error is sourced in either emissions or removal professes. The difference in burden magnitude between the models is not seen as problematic as their effect on SDSR is comparable to each other. The burdens are calculated using the grid boxes with GEBA stations and with their difference in circulation one would not assume the exact same burden per gridbox anyway. TODO bad answer

Reviewer Point P 2.46 — Page 7, line 212 – "the precursor of SO2", should this not be SO4?

Reply: Fixed.

Reviewer Point P 2.47 — Page 7, line 215-218 – Should we be expecting a trend reversal in SO2 emissions over China between 1980 and 1990? At this point in time emissions would have been increasing over China and emissions have only begun to reduce recently (since 2010). See general comment point 4

Reply: This is up for debate and is further investigated in the new section under Discussion.

Reviewer Point P 2.48 — Page 8, line 235 – Is it possible to include the clear-sky proxy from GEBA here and compare to that from models on Figure 3 to show how well models simulate the aerosol radiation interactions?

Reply: Unfortunately that is not easily done and is beyond the scope of this study. There is currently a project working on creating clear sky proxies at ETH Zurich under Dr Martin Wild.

Reviewer Point P 2.49 — Page 8, line 238 – change "shown in Figure displayed" to "(Fig. 2) show"

Reply: Fixed.

Reviewer Point P 2.50 — Page 8, line 242 – But the magnitude of the dimming was not sufficient to reproduce that observed (same as Allen?) and implies emissions are not high enough historically?

Reply: Correct.

Reviewer Point P 2.51 — Page 8, line 247 - change "burden of SO2" to "burden of SO4".

Reply: Fixed.

Reviewer Point P 2.52 — Page 8, Lines 246-249 - The study only shows change in SDSR is opposite to SO4 burden over Europe and not the case over China so can we really say that the process of translating burden to forcings are ok? What about over other regions? Might not just be due to errors in atmospheric burdens, but other factors combining?

Reply: Model translation from burden to forcing is not region dependent, but burden is. Therefore if the translation is ok in one region we assume the translation works as expected. But the burden is based on emissions which is highly region dependent, and we propose that errors in emission plays a part in the discrepancy of radiation between observations and model simulations, but keep the possibility open for other factors we do not yet know about to also play a role.

Reviewer Point P 2.53 — Page 8, Line 250 – "The models of this study ..." changed to "The models used in this study ..."

Reply: Fixed.

Reviewer Point P 2.54 — Page 9, line 254-255 – Should we expect a reversal of emissions across China over this period?

Reply: This is debated in the section added under discussion on the observed trend reversal in China.

Reviewer Point P 2.55 — Page 9, line 256 – Is this referring to Figure 3 in Hoesly et al., (2018)? Make clearer.

Reply: Fixed.

Reviewer Point P 2.56 — Page 9, line 258 – should we expect BC and OC to influences SDSR much? Need to mention these aerosol components earlier in the manuscript if going to mention now as no introduction to them at all. All discussion previously has been made about SO4 so why suddenly bring them in now?

Reply: The mentioning of these aerosols and their effect on SDSR have been added in the introduction.

Reviewer Point P 2.57 — Page 9, line 259-261 – Do these studies give an uncertainty in emission inventories and can this be used to see if it can account for the differences between model and observed SDSR.

Reply: Unfortunately none of these studies presents number for uncertainty in emission inventories, but Aas et al. (2019) show annual average trend in sulfate in aerosols from 2000-2015 and found that the standard deviation was larger than the actual trend for East Asia, and none of the locations used in that study was located in China Aas et al. (2019)[Tab. 1].

Reviewer Point P 2.58 — Page 9, line 270 – change "CMIP6 experiment models" to "experiments, CMIP6 models"

Reply: Fixed.

Reviewer Point P 2.59 — Page 9, line 273 – mention that the dimming is underestimated by the models.

Reply: Fixed.

Reviewer Point P 2.60 — Page 9, line 276-279 – Would we not have anticipated the SO4 burden to have increased across China over this period as SO2 emissions are anticipated to have also increased? Are the errors in SO4 burden and SO2 emissions really that large to account for the observed discrepancy in SDSR? More work to back up this statement and other factors should be included in conclusions. Uncertainty in emission inventories probably do contribute to this but the trend changes in SDSR and anticipated emission changes don't match for China, so this cannot be the sole reason and needs to be expanded on. see general comment point 4.

Reply: As we do not know the estimation uncertainty for emission we do not have evidence to rule out that the emission inventories can have large errors. The observed trend reversal in China have a new discussion section which expands the understanding of the anticipated emission inventories of China and the observed SDSR changes.

Reviewer Point P 2.61 — Page 10, line 285-287 – how would these future investigations improve our understanding of SDSR temporal evolution?

Reply: Clarified.

Reviewer Point P 2.62 — Fig. 2b – why is CanESMS so different in Hist-Nat and does show that other drivers influence the SDSR trend?

Reply: We do not know why CanESM5 differs from the others in it's hist-nat experiment, but this single experiment is unfortunately not enough evidence to say that other drivers influence the SDSR trend - except for in CanESM5 only.

Reviewer Point P 2.63 — Fig. 3b – Can the uncertainty in cloud cover from observations and models be shown?

Reply: We will make this figure into a table and there show the standard deviations from three ensemble members in addition to mentioning the uncertainty of the CRU data in the methods section of the manuscript.

Reviewer Point P 2.64 — Fig. 4 – CESM2 seems to show a small change, can you confirm that this model has interact aerosols included? If not then why such a small change compared to others?

Reply: Aerosols interact with the climate in CESM2.

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1 Supplementary Material

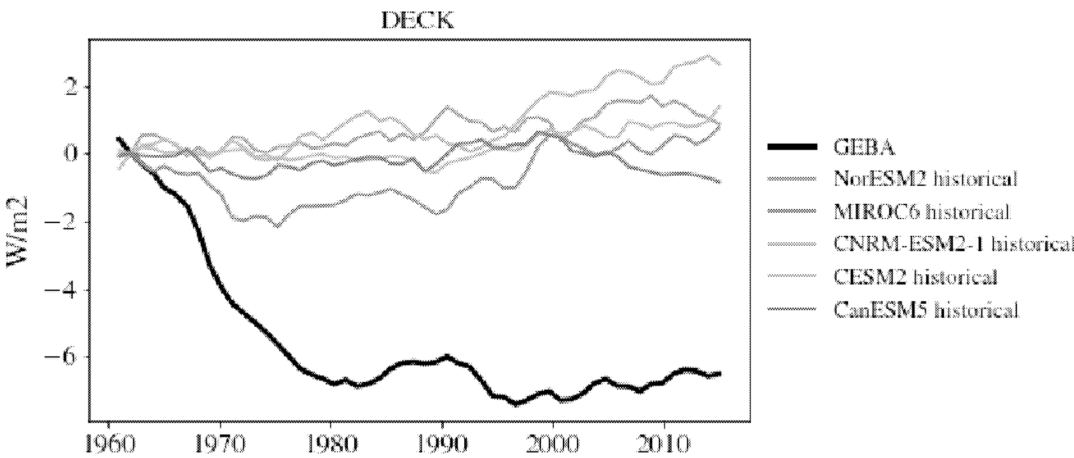

Figure S1: SDSR anomaly north america

Author response

We thank the reviewer for her/his thorough assessment of our work. The following changes have been made to the manuscript:
- The term trend reversal has been removed and changed to post-1990 trend change and emphasis on this trend change has been reduced.
- We have expanded Section 4.1 in the manuscript to express the need for more studies evaluating observational SDSR datasets.
- Added a brief discussion around Norris and Wild (2009) in regards to the japanese post-1990 brightening.
- Added some of the references suggested by the reviewer in Section 4.2 regarding sulfur dioxide emissions.

In the following we address the reviewers concerns point by point.

Reviewer 1

General comments

Reviewer Point P 1.1 — The authors have thoroughly revised the manuscript and it now appears much improved than before, providing a more comprehensive assessment of observed SDSR trends and those simulated by CMIP6 models. I have provided a few detailed comments on the discussion of the new section 4.1 below and a few more minor comments further down on the revised manuscript.
I found the new section 4.1 very interesting, in that most (80%) of the observed positive trend in SDSR over China in the 1990s is down to instrument error. This "jump" in the 1990s also occurs in the Japan dataset (Fig. 2e) so I wonder is this could be due to the same issue here? The error in Chinese observations has been discussed in 4.1 but having read this and looking at Figure 10 in the Yang et al., (2018) paper I think more emphasis needs to be made in the text that the trend reversal is mostly an instrumental error. The trend reversal is consistently mentioned in other sections of the text and perhaps too much emphasis is still made that the models are not capturing this trend, even though we now know the observations presented over China in this period are mostly in error. There are also more similarities between the temporal trend in the SO2 emissions and the new homogenised dataset e.g. increasing emissions up to 2005, which coincides with the minimum SDSR in the Yang et al., (2018) homogenised data.

Reply: We thank the reviewer for their comment. We agree that "trend reversal" has been still too strong a statement and we have reworded it to "trend change after 1990" throughout the manuscript. We disagree, however, that the issue is simply an "instrument error". To our understanding the measurement sampling protocol was changed at the time, with 6 instead of 3 measurements per day. Difficult for further analysis is that the new homogenized data from Yang et al., 2018 have so far not been included in the GEBA database. The revised section 4.1 explains now to our best knowledge what we know and not know. We believe the gap filled GEBA data set we use can not to be discarded yet. As the reviewer rightfully points out, we do see a "jump" also in Japan, albeit delayed wrt to China. We have no indication that Japan went through a nation wide instrument upgrade or change in measurement

protocol at this point. Noticeably Norris and Wild (2009) pointed to possibly, different cloud cover trends in China and Japan making the interpretation of the respective SDSR trends and timings difficult. Figure 1b in Wang and Wild (2016) also shows that multiple sun duration measurements recorded the chinese "jump" in addition to the SDSR instruments. We do not have access to the data used in Yang et al. (2018), and we would need both access and further evaluation of both the GEBA data and the homogenized data to favor one over the other. We have therefore chosen to reduce the focus of the trend reversal, respectively jump, without fully excluding it as a possibility. What remains is a signifcant trend change around the year 1990. We do, however, agree with the reviewer that the trend reversal was still given too much emphasis in the revised version of the manuscript, so we have reduced the emphasis even further.
Regarding the emissions trend of SO2 (Figure A2 in the newer manuscript) versus the trend in the homogenized data (Green line in Figure 10 in Yang et al. (2018)) there are still apparent differences between the two. Emissions of SO2 show a flattening in the end of the 1990s just before a very strong increase until again flattening in 2005, while even the new homogenized chinese SDSR data show arguably no strong trend changes between 1995 and 2010. We therefore conclude in the newer manuscript:
The modeled emissions of SO_2 as shown in Figure A2 over China showed no trace of a significant change in trend after 1990 in our observed SDSR timeseries as discussed in the previous section.

Reviewer Point P 1.2 — However, given the above I do not believe that this finding would change the main outcome of this paper much in that CMIP6 models underestimate the observed dimming signal over Asia and are unable to reproduce the recent brightening potentially due to uncertainties in the emission inventories. However, I think the direction of and timing of the temporal trends in observed and simulated SDSR over China (and Asia) would possibility match up better than with those observations currently presented in the manuscript i.e. the new observations show a dimming signal until 2005 and then brightening. I was wondering if there is anyway to include the dataset from Yang et al., (2018) on any of the figures in the manuscript to provide a more direct comparison of the new and old observations with the model simulations? Also, I think some minor changes to text to include more reference to this observational change would be beneficial. This could go some way to addressing the current comparison for China (and also for Asia in Fig 2c), where the obvious discrepancy in the figures is the sharp change in observations in the 1990s, which we now know was not really observed.

Reply: Unfortunately the dataset from Yang et al.(2018) is not available to us, and we refer to our reply to point P1.1 in that we do not disregard the observations of the "jump" completely. Without further studies evaluating the two observational datasets we reach the same conclusion as the reviewer in that models do not accurately represent observations, independent of which observational dataset we choose to compare with. Section 4.1 includes a brief update of our analysis based on the homogenized data:
We can use Figure 2(f) to compare our model data to these homogenized data, and see that even without a larger "jump" in the data there are still large discrepancies between model and observation, both in the shape and magnitude of the brightening period after 1990. All models show dimming in the flattening period of the new homogenized data. All models apart from CanESM5 show an averaged negative trend between the 6-year-means of 2003-2008 and 2009-2014, where the homogenized data show a brightening. Models do not accurately represent the strength of dimming, or the time evolution

of SDSR observed in China with or without the early 1990s brightening.
We underline that further studies on the observational datasets would prove very beneficial for the studying of model performance such as in our study.

Reviewer Point P 1.3 — As mentioned above the CMIP6 models would still underestimate the magnitude of the dimming signal across China and do not represent the observed brightening from 2005, highlighting that there are uncertainties in the magnitude and timing of emissions over China. Therefore, potentially including some brief discussion on the recent literature of emission estimates of SO2 over China, particular for recent years, would prove beneficial and aid the conclusions of the paper regarding SO2, SO4 and SDSR (e.g. Lu et al., 2010; Koukouli et al., 2018; Zheng et al., 2018).

Reply: We thank the reviewer for these excellent paper suggestions. Koukouli et al. (2018) used satellite observations to make a new estimates for SO_2 emission between 2005 and 2015, and Lu et al. (2010) used technology based methodology to make estimates from 2000 to 2008. Figure 1 attached to to these author replies show the CMIP6 emission of SO_2 in China as diagnosed by four of the models in the study, together with the estimations found in Koukouli et al. (2018) and Lu et al. (2010).
These results has been taken into account and a brief discussion has been added in the newest version of the manuscript:
Previous studies estimating SO_2 emissions include Lu et al. (2010), that found sulfur dioxide emissions in China increased by 53 % between 2000 and 2006 using technology based methodology, and thereby found similar results to that of Hoesly et al. (2018). Lu et al. (2010) also compared AOD derived SDSR to GEBA based SDSR data as shown in streets et al and found the GEBA based SDSR data to not accurately represent SDSR development in East Asia, this further underlines the need for more studies evaluating SDSR observations. Other studies such as Koukouli et al. (2018) have used satellite observations to estimate a new emission inventory for SO2 between 2005 and 2015 in China. We note that the year 2005 in Figure A2 is directly after the sharp increase in SO_2 emissions, and the biggest difference between the estimation made by Koukouli et al. (2018) and the SO_2 emission inventories in CMIP6 are a decrease in emissions after the year of 2011. This decrease in SO_2 emissions would intuitively result in a brightening, which is identified over the same time period in the homogenized data by Yang et al. (2018)(Fig 10 therein).

Reviewer Point P 1.4 — A general comment (and mentioned specifically below) is to consider making more reference in the results to the fact that aerosols influence multi-decadal trends in SDSR and other variables (clouds) are more important for short term variability.

Reply: This has been added as is mentioned in the replies to the minor comments below.

Minor comments

Reviewer Point P 1.5 — Within the revised manuscript there appear to be references to Figures, tables and Appendix items that need to be updated. For example, the results section refers to a Figure 5 but I have not seen a Figure 5 in the revised manuscript. Also there does not appear to be a reference to Figure A1 in the text.

Reply: These reference errors are not present in the actual new revised manuscript, but are present only in the "track changes" file that was added in the author response. The "track changes" file was made using the latex function `diff` which do not always handle references between two manuscript versions correct, as has been made clear here by the reviewer. We doubled checked references and they appear to be correct now.

Reviewer Point P 1.6 — Page 2 line 31-33 – Not sure I understood this sentence properly, could do with clarifying a bit

Reply: We have tried to clarified the sentence:
Extraterrestrial influences like the 11-year cycle of the sun have not created any important trends on decadal time scales in Earths surface solar radiation in the past century (Eddy et al., 1982; Wild, 2009).

Reviewer Point P 1.7 — Page 2 lines 39-41 – Could link to the updated IPCC definitions, aerosol radiation interactions (Ari) and aerosol-cloud interactions (Aci).

Reply: Both terms ari and aci has been added with a reference to IPCC

Reviewer Point P 1.8 — Page 5 line 140 – I think hist-piNTCF does not fix CH4 at pre-industrial levels so this might need to be removed from the description.

Reply: According to Table 1 in Collins et al. (2017) hist-piNTCF has historical development of CH4, so the reviewer is right and this has been fixed in the manuscript.

Reviewer Point P 1.9 — Page 7, line 213 – remove 'the' before 1961

Reply: Fixed.

Reviewer Point P 1.10 — Page 8 line 229 – remove 'between'

Reply: Fixed.

Reviewer Point P 1.11 — Page 9 line 258 – perhaps refer to multidecadal dimming signals

Reply: Thank you for the suggestion. The sentence has been changed to:
SDSR in the experiments hist-nat and hist-GHG do not show signs of dimming or brightening over the investigated period in China, which confirms that water vapor or stratospheric aerosols are not the dominant cause for multidecadal dimming signals in the fully coupled historical model simulations. This is supported by previous work as mentioned in the introduction.

Reviewer Point P 1.12 — Page 9 line 261 – perhaps include 'changes in' before anthropogenic aerosol emissions'

Reply: Added.

Reviewer Point P 1.13 — Page 9, line 274-275 – perhaps again include reference to 'multidecadal trends in' all sky SDSR

Reply: Added.

Reviewer Point P 1.14 — Page 9, line 283-284 – but could this be due to the errors in the observations pointed out in Section 4.1?

Reply: See our revised discussion in the new Section 4.1 where we do not disregard the original GEBA data (reply to P1.1.) but de-emphasize the reversal term.

Reviewer Point P 1.15 — Page 10 line 310-311 – Potentially remove/reword 'not by changing cloud cover' as could be misleading. Yes aerosols change the brightness of clouds but what about aerosol the effect on cloud lifetime?

Reply: We agree this sentence was misleading and has been rewritten to:
The aerosol indirect effect changes the radiative properties of clouds in two ways, by making them appear brighter, and by altering their lifetime (Boucher et al., 2013). Therefore, a weak change in cloud cover followed by a strong change in all sky and clear sky SDSR points to both the direct and the brightening indirect aerosol effect being the primary cause of SDSR change, as an altered lifetime of clouds would imply cloud cover changes.

Reviewer Point P 1.16 — Page 11 lines 329 – The calculation of the impact of changes in cloud cover on SDSR is presented but not really discussed. A simple sentence on the implications of this finding would improve its usefulness.

Reply: This calculation was made to give the reader an idea of the order of magnitude of how much cloud cover changes can affect SDSR, but can not be used to correct the SDSR model results for the effect of cloud cover changes as we do report complex simulations and observations in Table 2. We did add a sentence explaining the implications of this finding, as the reviewer suggested.
A rough calculation of the effect of 1 % cloud cover increase on SDSR in China is found in Section A3 in the Appendix, indicating that such an increase could result in a dimming of 1-3.5 Wm^{-2}. As such it shows that observed and modelled changes in cloud cover, as reported in Table 2, can lead to important contributions to the dimming and brightening signals in SDSR. However, this calculation is idealized, does not isolate the cloud cover change effect in the model results and does not explain the inconclusive data reported in Table 2.

Reviewer Point P 1.17 — Page 11 line 336-337 – Based on the all-sky and clear-sky results can you say then that the dimming is primarily caused by direct aerosol radiation interacts, with a smaller impact from aerosol-cloud interactions?

Reply: If one has an all sky SDSR and clear sky SDSR anomaly of equal magnitude in a cloud free atmosphere, we could say the direct effect (ari) was dominating the all sky SDSR anomaly. However, if the atmosphere is cloudy, one cannot draw the conclusion that the direct effect (ari) was dominating over aci. All sky SDSR is not the sum of clear sky SDSR and cloud SDSR anomalies, as aci may reflect beams of radiation that would have been reflected by ari given clear sky conditions. Therefore it is impossible to say whether aci or ari dominates all sky SDSR anomaly in China, when we know the country is not cloud free. This is why we write "aerosol effects" are dominating, including both ari and aci.

Reviewer Point P 1.18 — Page 11 line 340 – should you not specifically mention sulphate aerosols here, as not all aerosol scatter shortwave radiation?

Reply: This is the introductory sentence to the sulfate section, so we added the word "reflective" so clarify that we are not talking about all aerosols.
In the atmosphere, the presence of a reflective aerosol is the cause for scattered shortwave radiation, and the emission of its precursor is only an indirect indicator of its presence.

Reviewer Point P 1.19 — Page 12 line 358-359 – Based on section 4.1 can we say that GEBA, as it is presented in Figure 4b provides a reasonable representation of the historical development of SDSR over China?

Reply: See our revised discussion in the new Section 4.1 where we do not disregard the original GEBA data (reply to P1.1.) but de-emphasize the reversal term. We have modified the sentence slightly:
Assuming GEBA data provide a reasonable representation - within uncertainty bounds as discussed in section 4.1 - of the historical development of SDSR...

Reviewer Point P 1.20 — Page 15 line 458 – should we expect a trend reversal in emissions given that this was mostly identified as an observation error in section 4.1?

Reply: As discussed above we de-emphasize the term reversal, but we do not disregard the original GEBA data. We point out that the modelled SO_2 emissions do not fit with neither homogenized data (Yang et al., 2018) nor gap filled GEBA. Sentence has been simplified to:
The modeled emissions of SO_2 as shown in Figure A2 over China showed no trace of a significant change in trend after 1990 in our observed SDSR timeseries as discussed in the previous section.

Reviewer Point P 1.21 — Appendix A3 Line 518 – makes reference to rsds twice

Reply: One of them was meant to say "rsdscs", this has been fixed.

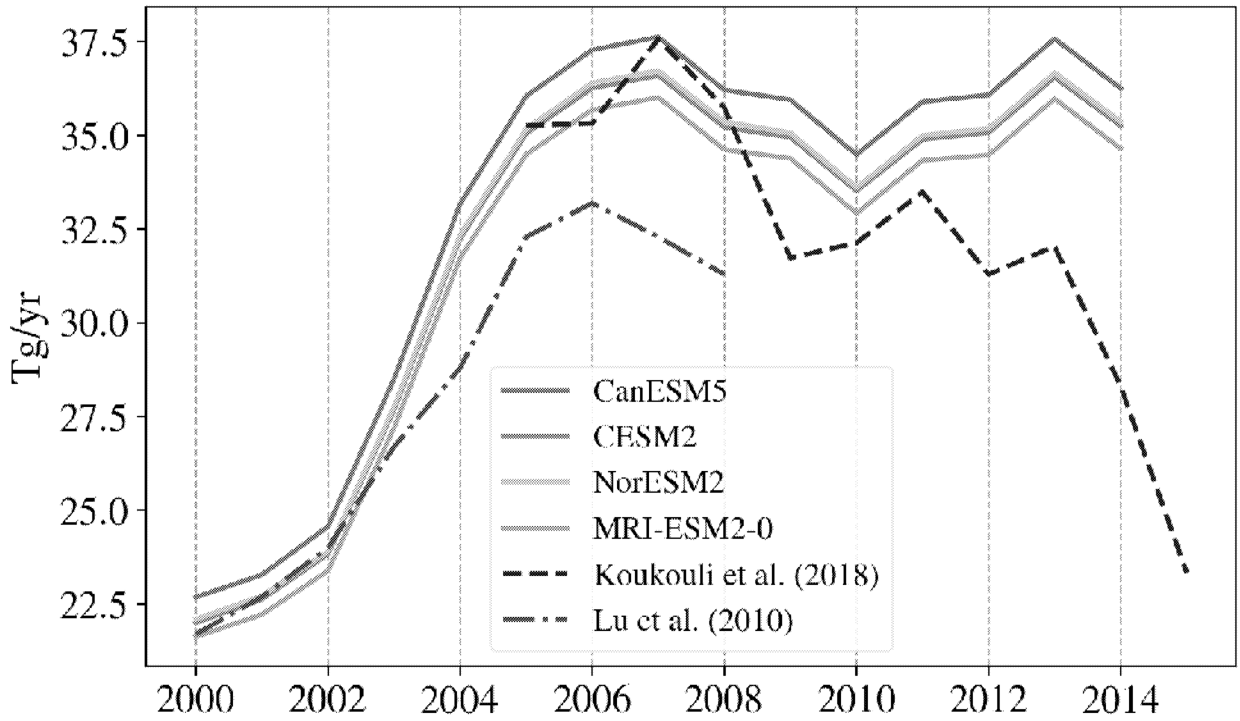

Figure 1: Emission of SO_2 in China, diagnosed by four of the models in this study. China is defined here as the area within latitudes [20°N–45°N], and longitudes [95°E–125°E]. In addition the results from Koukouli et al. (2018) and Lu et al. (2010) has been added.

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Bias in CMIP6 models as compared to observed regional dimming and brightening

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Abstract. Anthropogenic aerosol emissions have increased considerably over the last century, but climate effects and quantification of the emissions are highly uncertain as one goes back in time. This uncertainty is partly due to a lack of observations in the pre-satellite era, making the observations we do have before 1990 additionally valuable. Aerosols suspended in the atmosphere scatter and absorb incoming solar radiation, and thereby alter the Earth's surface energy balance. Previous studies show that Earth system models (ESMs) do not adequately represent surface energy fluxes over the historical era. We investigated global and regional aerosol effects over the time period 1961-2014 by looking at surface downwelling shortwave radiation (SDSR). We used observations from ground stations as well as multiple experiments from eight ESMs participating in the Coupled Model Intercomparison Project Version 6 (CMIP6). Our results show that this subset of models reproduces the observed transient SDSR well in Europe, but poorly in China. We suggest that this may be attributed to missing emissions of sulfur dioxide in China, sulfur dioxide being a precursor to sulfate, which is a highly reflective aerosol and responsible for more reflective clouds. The emissions of sulfur dioxide used in the models do not show a temporal pattern that could explain observed SDSR evolution over China. The results from various aerosol emission perturbation experiments from DAMIP, RFMIP and AerChemMIP show that only simulations containing anthropogenic aerosol emissions show dimming, even if the dimming is underestimated. Simulated clear sky and all sky SDSR do not differ largely, suggesting that cloud cover changes are not a dominant cause to the biased SDSR evolution in the simulations. Therefore we suggest that the discrepancy between modeled and observed SDSR evolution is partly caused by erroneous aerosol and aerosol precursor emission inventories. This is an important finding as it may help interpreting whether ESMs reproduce the historical climate evolution for the right or wrong reason.

1 Introduction

Aerosol particles scatter and absorb radiation and change the radiative properties of clouds, thereby altering Earth's energy balance (Boucher et al., 2013). Anthropogenic aerosol emissions have substantially increased over the last century, but the quantification of the effect has been characterized by large uncertainties. Earth system models (ESMs) are evaluated based on their ability to reproduce the climate evolution of the past 165 years, and the sparsity of aerosol-related observations in the pre-satellite era plays a dominant role in the uncertainty connected to these historical experiments. An improved understanding of the historical aerosol effect would increase the accuracy and credibility of ESMs future climate projections.

Aerosol particles cause changes in the amount of sunlight reaching the surface together with changes in insolation, cloud cover, water vapor and other radiatively active gases (Wild et al., 2018). Insolation at the top of the atmosphere changes on millennial timescales when the Earth's orbital parameters change, but the solar Extraterrestrial influences like the 11-year cycle nor solar historical time variations have created multidecadal important trends in surface radiation (Eddy et al., 1982) of the sun have not created any important trends on decadal time scales in Earths surface solar radiation in the past century (Eddy et al., 1982; Wild, 2009). Water vapor amount has not changed sufficiently in recent decades to have an effect on decadal fluctuations of incoming sunlight at the surface (Wild (2009), Wang and Yang (2014), Yang et al. (2019), Hoyt and Schatten (1993), Ramanathan and Vogelmann (1997), Solomon et al. (2010)), and radiatively active gases dominate in the longwave spectrum (Ramanathan et al. (1989)).

The relative roles of clouds, aerosols and their interactions in historical variations of surface downwelling shortwave radiation (SDSR) are still disputed, but previous studies have found that aerosol effects dominate on multidecadal timescales, while cloud effects are relevant on shorter timescales (Wild (2016), Romanou et al. (2007)). Aerosol effects can be divided into the direct and indirect effect. The direct effect is the scatter or absorption directly caused by a dry aerosol, also called the aerosol-radiation-interaction (ari) (Boucher et al., 2013), and the indirect effect is how aerosols change properties in clouds. These properties , also called aerosol-cloud-interactions (aci). Aci includes both a change in cloud lifetime and most importantly a change in cloud albedo, making the cloud appear brighter (Boucher et al., 2013).

Assuming aerosol effects dominate the multidecadal timescales, SDSR can serve as a proxy for aerosol effects. The Global Energy Balance Archive (GEBA) dataset contains measurements of SDSR as far back as in 1922 (Wild et al., 2017), and as such represents a unique and valuable dataset for evaluation of simulated aerosol effects prior to the satellite era.

Observed SDSR from the GEBA dataset reveals a widespread negative trend from the 1950s to the late 1980s, commonly referred to as "global dimming" (Liepert (2002), Wild (2016)). The magnitude of this dimming differs vastly between regions, which is expected if the cause of dimming were regionally different increases in aerosol emissions, as has been proposed by Wild et al. (2007), Sanchez-Romero et al. (2014), and Wild (2016). In some areas a positive trend in SDSR follows the dimming, and this SDSR increase has been termed "brightening" (Wild et al., 2005). Brightening is connected to the reduction in anthropogenic aerosol emission (Nabat et al., 2014). Fewer particles suspended in the air allow for more sunlight to reach the surface and thus an increase in the measured SDSR. Previous studies show that historical simulations from ESMs do not reproduce the observed global transient development of SDSR (Storelvmo et al. (2018), Wild (2009), Allen et al. (2013), Wild and Schmucki (2011)). The cause of this discrepancy is not known, but may be connected to uncertainties in aerosol emission inventories of the past, or, as Storelvmo et al. (2018) suggested, other uncertainties concern how models treat processes that translate aerosol emissions into radiative forcing.

In this study we use gap-filled data based on the GEBA dataset, together with several recent CMIP6 historical model experiments from eight climate models to investigate the aerosol effect in the time period 1961-2014, globally and regionally. In the middle of this time period (around the late 1990s), the main region of high anthropogenic aerosol emissions shifted from Europe and North-America to Asia. We have chosen to focus on the regions of Europe and Asia in this study, as the models exhibit diverging abilities to reproduce the observed SDSR in these regions. We also use observational cloud cover data to briefly assess the role of cloud cover in the historical development of SDSR. We explore the relation between regional SDSR and aerosol emissions using a set of ESM experiments with differing aerosol emissions; some have pre-industrial aerosol emissions, while others use the most recent and best available historical aerosol emission inventory (Hoesly et al., 2018). This paper thereby provides new insights into the question of whether state-of-the-art ESMs can adequately reproduce a part of the changes in the surface energy budget over the historical era. This is in turn an important indication of whether the ESMs reproduce the dominant processes governing the historical climate evolution.

The paper is structured as follows: In Section 2 we begin by presenting the two observational datasets used, followed by a detailed description of the experiments simulated by the eight models chosen to be part of this study. The methods used to obtain and analyse the data finalize Section 2. The results are presented in Section 3, starting with a global view of dimming and brightening before focusing on regional assessments of SDSR, clear sky SDSR, and cloud cover. Section 4 discusses the implications of our results and how they compare to previous studies, before final conclusions are presented in Section 5.

2 Data and Methods

2.1 Observations

The Global Energy Balance Archive (GEBA) holds data from ground-based stations measuring energy fluxes at the Earth's surface around the globe (Wild et al., 2017). Pyranometers were used in most of the measurement sites, which have an accuracy limitation of 3-5 % of the full signal (Michalsky et al. (1999), Wild et al. (2013)). We use the monthly mean data from 1487 stations in the time period 1961-2014 measuring downwelling shortwave radiation. The GEBA data set has been complemented by a machine learning technique (random forests (Breiman, 2001)) as explained in Storelvmo et al. (2018) to cover time periods of missing observations in the measurements and facilitate comparison to the gridded model data. This allows for all 1487 stations to have data on each time step, so that all regions have a complete record and the same amount of stations throughout the entire time period in question.

Monthly mean cloud cover data is provided by the Climatic Research Unit (University of East Anglia) and NCAS, and we are using version 4.02 of this dataset (CRU). CRU covers the period 1901-2017 (Harris et al., 2020) and consists of a climatology made from measurements at meteorological stations around the globe, interpolated to a 0.5° latitude/longitude resolution grid covering continental areas. Information on interpolation methods and procedures used to create the gridded data set are given in Harris et al. (2020) and references therein. In short, CRU has its foundation in station data, but is interpolated to a grid using angular-distance weighting. The cloud cover variable is largely derived as a secondary variable, based on measurements of other parameters such as sunshine hours and diurnal temperature range.

2.2 Models and CMIP6

Eight climate models (NorESM2, CanESM5, MIROC6, CESM2, CNRM-ESM2-1, GISS-E2-1-G, IPSL-CM6A-LR, MRI-ESM2-0) were chosen for this study, based on available data and their involvement in relevant model intercomparison projects within the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). As this study focuses on dimming and brightening, we have chosen experiments from model intercomparison projects (MIPs) that include perturbed historical simulations with which one can single out the effect of anthropogenic aerosol emissions in our diagnostic variables. An overview of models and experiments can be found in Table 1. This section will give a more detailed description of the experiments in Table 1 and explain why they were chosen.

Every model that takes part in CMIP6 has to deliver a set of common experiments, among these is the *historical* simulation. As can be seen in Table 1 all the models have provided historical simulation results. All other experiments listed in Table 1 are simulations covering the historical period (1850-2014) but with specific alterations dependent on what model intercomparison project they are a part of.

The Detection and Attribution Model Intercomparison Project (DAMIP) has the goal of improving estimations of the climate response to individual forcings (Gillett et al., 2016) and includes three relevant experiments. One experiment traces exclusively the impact of anthropogenically emitted aerosols as forcing agents over the historical period, and is called *hist-aer*. This means no anthropogenic greenhouse gas emissions or natural climate forcings are used in this simulation. The *hist-nat* experiment consists of only the perturbations due to the evolution of the natural forcing, e.g. from stratospheric aerosols ~~from volcanoes~~ of volcanic origin and solar irradiance variations. Finally, the *hist-GHG* experiment has only forcings from changes in the well mixed greenhouse gases. These experiments were chosen as they give a unique insight into how a fully coupled climate model attributes responses over the historical period to the different climate forcings.

While DAMIP provides a good framework for one of the main questions in CMIP6, namely how the Earth system responds to forcing, RFMIP, the Radiative Forcing Model Intercomparison Project, focuses on understanding the forcing itself. RFMIP contains a large set of experiments to further understand the radiative forcing of the past and the present (Pincus et al., 2016). We use two experiments from RFMIP, both with sea surface temperatures prescribed to pre-industrial values. One experiment includes both anthropogenic and natural aerosol emissions (*piClim-histall*) while the other only includes anthropogenic aerosol emissions (*piClim-histaer*). When sea surface temperatures are kept to pre-industrial values, the global surface temperature development stalls, and the simulation will keep to first order a pre-industrial climate. Sea surface temperatures changes would have an effect on cloud cover, which in turn can affect SDSR. These *piClim*-experiments will show the direct atmospheric forcing on SDSR due to greenhouse gases and aerosols, alone or in combination, without including cloud cover changes induced by global warming.

The third MIP included in this study is the Aerosol Chemistry Model Intercomparison Project (AerChemMIP), which is designed to answer questions regarding the specific effect of aerosols and other near-term climate forcers (NTCF) on climate. NTCFs include methane, tropospheric ozone, aerosols and their precursors (Collins et al., 2017). Three experiments have been selected from AerChemMIP, *histSST*, with all forcing agents included, and two perturbations which have pre-industrial aerosols emissions: (*hist-piAer*) and (*hist-piNTCF*). The hist-piNTCF experiment has in addition pre-industrial NTCF levels for ozone~~and methane~~. A difference in these two simulations would only appear if ozone ~~or methane~~ concentrations were computed in an interactive chemistry scheme. These two simulations are coupled and are comparable to the historical experiment. The experiment *histSST* uses all forcing agents and the sea surface temperatures derived from the historical simulation so that the temperature evolution, and hence its effect on SDSR, should be similar to the historical experiment, but removes responses involving a coupled ocean. These experiments together with the historical experiment were chosen to differentiate between historical changes in aerosol and tropospheric ozone, or whether a mixing layer in the ocean may have had an effect on dimming.

Data from all experiment ensembles from each of the MIPs listed above provide useful information on the role of anthropogenic aerosol emission in dimming and/or brightening.

2.3 Methods

The GEBA stations have been divided into regions based on the country and continent. The number of stations in a region is presented together with the first results in the caption of Figure 2. The number of stations per region remains constant throughout the time period because of our gap filling approach. A figure with the spatial distributions and trend of SDSR per station in GEBA used in this study is found in Figure 1 in Storelvmo et al. (2018).

All model output and CRU results have been co-located to GEBA station locations using the nearest neighbour method. This entails that if two GEBA stations are within one grid box of a model, data from that grid box will be retrieved twice by nearest neighbour interpolation, as every station has been weighted equally. A global mean is defined here as the mean of a variable across all GEBA station locations. A regional mean is a mean of a variable across the GEBA station locations registered to that same region in the GEBA data. When a result is shown as an anomaly, as opposed to an absolute value, the general formula has been to subtract the baseline value, defined as the mean of the first five years of the investigated time period (1961-2014), from the timeseries in question. To clarify - first an average value per year per region is calculated, and then a new mean is created from the first five years of this timeseries. This 5-year-mean is then subtracted from each year in the timeseries for the region in question and presented as an anomaly. We will often present data as 6-year-averages, as yearly variabilities are not the focus of this study. These 6-year-averages are simply made by dividing the timeseries over 54 years(1961-2014) in nine equal intervals and average these intervals together. When the atmospheric burdens of SO_4 is shown together with observed SDSR from GEBA the timeseries have been smoothed using a 10-year running mean, and this is the only data in the paper shown using this smoothing technique.

The "baseline" values for global SDSR and cloud cover in the models and observations of this study can be found in the Appendix in Table A1.

The model data has been retrieved from The Earth System Grid Federation (ESGF) (Cinquini et al., 2014). ESGF is a data management system consisting of multiple geographically distributed nodes that coordinate through a peer-to-peer (P2P) protocol (Fan et al., 2015). We have used three ensemble members for the *historical* experiment to present internal variability in the models, and one ensemble member from the rest of experiments shown, as not every experiment had requested more than one simulation. Table A2 in the Appendix shows the resolutions, aerosol schemes, and aerosol complexity of the models in this study, and Section A2 explains the variables and variant labels downloaded.

3 Results

3.1 Model variability

Figure 1 shows SDSR anomaly for each model of the study co-located to all GEBA stations, 1487 in total as compared to the observed SDSR anomaly. The aerosol effective radiative forcing (Aerosol ERF) corresponding to each model is obtained from Smith et al. (2020) and is listed in each panel to illustrate the strength of the aerosol radiative effect in the model.

Each climate model has its own internal variability and thereby represents its separate climate systems. SDSR is a highly variable metric on a year-to-year basis, which can be seen both in the GEBA data in black in Figure 1 and in following a single ensemble member per model. Within each model ensemble one can see that no member is equal to another, which is a clear signal of the internal variability of each model. The spread of all three ensemble members in a 6 year period can be read from the height (interquartile range) of the boxes in the 6-year-intervals, note that this spread is dominated by large interannual variabilities within each member. One example is GISS-E2-1-G, where each ensemble member has large interannual variabilities, the boxes present long whiskers and large interquartile ranges, but when comparing the ensemble member 6 year means one by one they mostly agree on their magnitudes of SDSR anomaly, so the intra-ensemble-spread is not large for GISS-E2-1-G. We find (not shown here) that the model with the least interannual variabilities is CNRM-ES2-1, while the model with the largest inter-ensemble disagreements is CanESM5.

Figure 1 also shows that the models in general do not agree with the observed global SDSR anomaly, shown in black. Dimming and brightening are tendencies in surface radiation that are observed on longer than interannual timescales, with this in mind SDSR from models will in general be presented as 6-year means for the remainder of this paper. The model MRI-ESM2-0 is showing the most similar SDSR evolution compared to the observed data according to Figure 1.

The model with the strongest aerosol ERF is CESM2, while the weakest aerosol ERF is presented by IPSL-CM6A-LR.

3.2 Dimming and brightening

The change in SDSR in the *historical* simulations from the eight models is presented together with GEBA data in Figure 2. Panel (a) of this figure corresponds to the results shown in Figure 1. Each model graph in Figure 2 represents the ensemble mean of the model in question averaged over 6 years, based on three ensemble members. GEBA data is shown in black, also as 6-year averages, but with the yearly time series shown in grey in the background. Model simulations show small changes of global SDSR compared to observations (Fig 2a). Global SDSR is observed to decrease over the 1487 stations until late 1980's before increasing again, clearly showing the global "dimming" and "brightening" as found in previous studies listed in the introduction.

None of the models outperform one another globally, and there is a discrepancy of about 2-3 W/m^2 between models and observations. To further identify from where this discrepancy originates, we consider some geographical regions separately. Asia and Europe are relevant regions in regards to anthropogenic aerosol emissions (as explained in Section 1) and thereby also relevant to global dimming and brightening. The historical SDSR evolution in Europe and Asia are presented in Figure 2 (b) and (c), respectively. European SDSR is relatively well represented by the model simulations. The yearly GEBA timeseries has values within the shaded area, that is showing the standard deviation of the total of 24 model ensemble values, in almost every 6 year period in Europe. The dimming in Europe is believed to have started before ~~the~~ 1961 (Wild, 2009), which partly explains why the initial European dimming in Figure 2(b) is weak. GEBA shows a short-term positive anomaly between 1970 and 1980, which is not caught by the models. This peak is currently unexplained, but a short assessment of its possible association to changes in cloud cover is found in Section A1 in the Appendix.

There is generally a large discrepancy between model simulations and observations of SDSR in Asia, as seen in Figure 2(c). The ground stations in Asia show a noticeable trend ~~reversal~~ change in SDSR in the transition from 1980s to 1990s that is not apparent in the model simulations. The historical model simulations show a consistent negative trend during the entire historical period in question in Asia. Historically, countries with relatively high emissions in Asia include India, Japan, and China (Hoesly et al., 2018), and the SDSR evolution for each of these countries are shown in Figure 2(d), (e), and (f), respectively.

Figure 2 (d) shows that the models capture a relatively strong negative trend of SDSR in India, with MIROC6 being the model with the most modest trend. There are evident differences between observations and simulations in both Japan and China. Ground stations in Japan show a sharp decrease in SDSR until the early 1970s followed by some variations until a new minimum value is reached around 1990 before an increase in SDSR is measured. The minimum value around 1990 and the following positive trend is similar to that of China. Japan is downwind of the Asian continent and thus believed to be influenced by aerosol emissions from China. Model simulations do not capture the magnitude of dimming in Japan, or the apparent brightening in the 1990s. The timing of minimum SDSR occurs differently in ~~between~~ models, which was also seen in Figure 2(a).

Observations from China (Figure 2(f)) show a trend ~~reversal~~ change in SDSR similar to the one identified in Figure 2(c) for Asia as a whole, with the minimum value found in 1989. We note that China consists of 119 GEBA stations while Asia as a whole consists of 311 stations, thus the Asian average is largely impacted by SDSR as measured in chinese stations. In general the historical model simulations show dimming throughout the historical period in China, meaning none of them show a similar trend ~~reversal~~ change to the one from the observational data set. This ~~trend reversal~~ post-1990 trend change is a source of discussion within the field, and a thorough assessment, relevant to the conclusions from this study, is found in Section 4.1.

3.3 Dimming and brightening over China in various CMIP6 experiments

In order to understand which forcing agents are responsible for the overall trends in SDSR in the models, we now investigate China for the experiments listed in Table 1. Figure 3(a) shows perturbed historical simulations as performed in DAMIP together with observations of SDSR. DAMIP has two experiments without historical anthropogenic aerosol emission (dashed/*hist-nat* and stippled/*hist-GHG* lines), and one experiment with historical anthropogenic aerosol emissions (solid lines/*hist-aer*). The experiment *hist-aer* is the only experiment in DAMIP exhibiting a distinguishable dimming signal. SDSR from *hist-aer* shows patterns similar to the *historical* simulations with continuous dimming throughout the period, ~~but also still without the trend reversal seen in the observed temporal evolution of~~ unlike the observed SDSR. SDSR in the experiments *hist-nat* and *hist-GHG* do not show signs of dimming or brightening over the investigated period in China, which confirms that water vapor or stratospheric aerosols are not ~~dominant for simulated dimming~~ the dominant cause for multidecadal dimming signals in the fully coupled historical model simulations. This is supported by previous work as mentioned in the introduction.

Out of the three experiments from AerChemMIP only *histSST* has prescribed sea surface temperatures ~~, and contains~~ and contains changes in anthropogenic aerosol emissions. This is consistent with the time evolution of SDSR in *histSST* as the simulations diverge from the other simulations as time progresses (Fig 3b). Keeping in mind that *histSST* also has anthropogenic GHG emissions in addition to natural forcers, the only difference from *histSST* to the *historical* experiment is the absence of a coupled ocean and the use of prescribed sea surface temperatures. The model MRI-ESM2-0 presents the strongest dimming in both DAMIP and AerChemMIP. The simulations with pre-industrial aerosols (*hist-piAer*) and pre-industial near term climate forcers, including aerosols and ozone (*hist-piNTCF*) show very small or negligible changes in the SDSR over the time period considered.

Recall that the experiments of RFMIP utilize pre-industial SST's, meaning essentially there is no global warming in these experiments. In the RFMIP experiments shown in Figure 3(c) both *piClim-histaer* and *piClim-histall* contain anthropogenic aerosol emissions, and all simulations show a continuous dimming throughout the period. There is no clear distinction between experiments containing GHG emissions in addition to anthropogenic aerosol emissions (solid lines/*piClim-histall*) and the experiments only containing anthropogenic aerosol emissions (stipled lines/*piClim-histaer*). This implies that greenhouse gases without their global warming effect do not affect multidecadal all sky SDSR in a significant way over China throughout the period, again supported by previous work mentioned in the introduction.

Overall there is a clear difference in SDSR between experiments that include anthropogenic aerosol emissions and experiments that do not. Dimming is apparent in every simulation containing anthropogenic aerosol emissions, but absent in the simulations using aerosols maintained at constant pre industrial levels. This points to anthropogenic aerosol emissions playing a key role in dimming. Whether the sea surface temperature is pre-industrial, prescribed historical, or decided by a coupled ocean model seems to be unimportant for the SDSR temporal evolution in China in most models.

No ~~trend reversal or distinct flattening of the dimming~~ distinct flattening or brightening is identified in any of the simulations in which dimming is identified, and therefore none of the model simulations show a temporal evolution of SDSR close to the one seen in observations over China.

All sky SDSR changes can be further decomposed by the models into a clear sky contribution as well as a contribution from changes in cloud cover or other cloud properties. In the next section we present the decomposed contributions to all sky SDSR in China to further understand the discrepancy seen in Figure 3.

3.4 Clear sky SDSR and cloud cover in China

So far we have only evaluated all sky SDSR, which is influenced by clouds and any aerosol radiative effects. Table 2 shows changes in cloud cover, all sky SDSR, and clear sky SDSR within three different time periods for the models and observational data sets of this study. Between the years 1961 and 1989 GEBA shows a strong negative change in all sky SDSR in Figure 2(f). In Table 2 we thus show changes in this time period by making two 3-year means and subtracting them from one another. This is done to avoid extreme values as we are working with metrics exhibiting large year to year variations. This has been done for two additional time periods which have been chosen based on the temporal development in the all sky SDSR as measured by GEBA in China (see Figure 2(f)), summarized in the second lowest row in Table 2.

In the first time period the models do not agree on the sign of cloud cover change, and the simulated all sky SDSR is weaker than the observed one, which was already established in the previous section. Clear sky SDSR do not differ largely from all sky SDSR within the models. For some models the negative change in clear sky SDSR is stronger than in all sky SDSR, meaning that the aerosol direct effect may contribute significantly to dimming for these models. The aerosol indirect effect ~~mainly~~ changes the radiative properties of clouds in two ways, by making them appear brighter, ~~not by changing cloud cover.~~ and by altering their lifetime (Boucher et al., 2013). Therefore, a weak change in cloud cover followed by a strong change in all sky and clear sky SDSR ~~point to both direct and~~ points to both the direct and the brightening indirect aerosol effect being the primary cause of SDSR change, as an altered lifetime of clouds would imply cloud cover changes.

In the second time period GEBA shows a positive change (which will be further discussed in Section 4.1), and CRU shows a cloud cover change of +3.0 %. Intuitively, an increase in cloud cover would not create a brightening at surface level. The observations are thus not consistent in this time period if only cloud cover effects were important. The models disagree in their sign of ~~both~~ cloud cover changes, all sky, and clear sky SDSR. In the final time period where GEBA shows a weak slightly positive change in all sky SDSR, every model in this study shows a dimming. All models apart from MIROC6 show simulated clear sky SDSR changes that are stronger than the changes found in all sky SDSR. Together with the inconsistent simulated cloud cover and all sky SDSR changes for this time period we suggest that both direct and indirect aerosol effect are responsible for the changes in SDSR found in the model simulations.

All models show dimming in clear sky and all sky SDSR in the first and last time period. Some models show a weak positive change in all sky SDSR in the same period as GEBA presents a strong brightening. Both observed and simulated changes in cloud cover neither ~~acts~~ act as a brightening mask for clear sky dimming nor ~~is~~ are convincingly a cause of dimming/brightening in either observed or simulated all sky SDSR. A rough calculation of the effect of 1 % cloud cover increase on SDSR in China is found in Section A3 in the Appendix, indicating that such an increase could result in a dimming of 1-3.5 Wm^{-2}. As such it shows that observed and modelled changes in cloud cover, as reported in Table 2, can lead to important contributions to the dimming and brightening signals in SDSR. However, this calculation is idealized, does not isolate the cloud cover change effect in the model results and does not explain the inconclusive data reported in Table 2. It is important to note that the robustness of observed cloud cover changes must be verified by satellite observations, which goes beyond the scope of this study.

In section 3.3 we showed that dimming was only apparent in simulations that included anthropogenic aerosol emissions. In this section we found the clear-sky SDSR to be close in value or even stronger than all-sky SDSR, indicating the simulated dimming is primarily caused by aerosol effects. Table 2 underlines previous findings, dimming in models are overall weaker than in observations. The next section will then show how the simulated aerosol burdens are connected to SDSR.

3.5 Atmospheric burden of SO_4

In the atmosphere, the *presence* of ~~an~~ a reflective aerosol is the cause for scattered shortwave radiation, and the emission of its precursor is only an indirect indicator of its presence. All CMIP6 simulations mentioned above have utilized the same anthropogenic sulfur dioxide gas emissions, however the resultant dimming differed considerably. SO_4 aerosol burdens should be more closely linked to the radiative effect. Therefore, we present here also the simulated anomalies in burden of SO_4 in the various models over Europe, a location where dimming and brightening is fairly well represented in simulations, and over China, where dimming and brightening is poorly represented in simulations (Figure 4(a) and (b) respectively). The sulfate burdens are co-located to GEBA station locations in the respective regions. As expected, sulfate aerosols have an important role in European dimming and brightening, as the simulated burdens of SO_4 show a strikingly similar pattern (but with opposite sign) as the observed SDSR over Europe for all models. The maximum burdens are found in the early to mid 1980s depending on the model, and the minimum SDSR around the same time. The various models differ in the magnitude of change in SO_4 burden over Europe but all show similar tendencies. MRI-ESM2-0 is the model with the largest changes, and GISS-E2-1-G is the model with the smallest changes in SO_4 burden. The same is observed over China, where MRI-ESM2-0 has an SO_4 burden at the end of the time period which is more than double the burden of the other models (except NorESM2). In contrast to Europe, the observed SDSR evolution does not mirror well the simulated SO_4 burden timeseries over the GEBA stations in China. In order for the SO_4 burden to be the main cause of the observed changes in SDSR, the Asian SO_4 burden would have to peak around the late 1980s, which is not seen in the models in Figure 4(b). All the simulated historical SO_4 burdens increase until 2010, showing no signs of either a trend reversal change or a flattening of aerosol induced dimming. Assuming GEBA data provide a reasonable representation - within uncertainty bounds as discussed in section 4.1 - of the historical development of SDSR and implicitly sulfur burdens in China, the problem in SO_4 burden must come from either the emissions, aerosol formation, transport or the removal processes of SO_4.

It appears, however, that the simulated burdens of SO_4 co-located to GEBA stations in China follow quite closely the time series of emitted SO_2 in the climate models over China (shown in Appendix Figure A2), which indicates that SO_4 formation and export of sulfur from the chinese Chinese region remains rather similar in the period investigated. Following the logic that emission correlate with burden which again anti correlates with SDSR changes, the temporal development of SDSR seen in GEBA cannot be explained from the current emission inventories, given sulfate aerosols play an important role in SDSR in China.

4 Discussion

The climate effect of aerosol emissions over the industrial era is poorly constrained, in part due to lack of observations and uncertainty in emissions. The uncertainty in past aerosol climate effects is an important reason for the large spread in climate projections for the future. Here, we investigate the effect of aerosols in GEBA which provides valuable observations of historical shortwave radiation at the surface.

We have shown that a subset of models participating in CMIP6 do not accurately represent the observed dimming and brightening trends globally and regionally in their *historical* simulation. This is comparable to that of Storelvmo et al. (2018) and Wild and Schmucki (2011), who showed that the CMIP5 and CMIP3 ensemble mean SDSR globally co-located to GEBA stations does not represent dimming or brightening. Our findings show that reproducibility of SDSR has not improved from CMIP5 to CMIP6. We find that most models show an underestimation of changes in SDSR to observations, and the development over time greatly differs between model and observations, especially in China. This is in agreement with Allen et al. (2013) who studied the CMIP5 ensemble mean and found a continuous dimming trend over China, but with a severely underestimated magnitude of modelled clear-sky SDSR during the dimming period compared to a clear-sky proxy based on GEBA data.
The simulated SDSR on decadal timescales over China does not differ significantly when comparing the RFMIP experiments (Figure 3) to the historical experiment. RFMIP experiments have pre industrial sea surface temperatures, and thus do not include global warming induced cloud cover changes. When experiments with historical cloud cover changes show dimming in the same magnitude as experiments without historical cloud cover changes, the dimming can be assumed to be dominated by aerosol effects in China. This complements the findings by Folini and Wild (2015) where sea surface temperatures correlate to cloud cover, not aerosol effects. Table 2 showed inconclusive connections between modelled and observed cloud cover,

but clear connections between clear sky SDSR and all sky SDSR, again pointing to aerosol effects dominating SDSR time evolution in China.

The climate models strongly underestimate the dimming observed in China, in addition to not representing ~~a trend reversal in the late 1980s~~the post-1990 trend change. This trend ~~reversal~~ change is the topic of discussion in the next section.

4.1 The post-1990 trend ~~reversal~~ change in China

Several studies have tried to explain the trend ~~reversal~~ change as presented here by GEBA in China in the transition from the 1980s to the 1990s. Streets et al. (2006) proposed a peak in combined emissions of SO_2 and black carbon in 1988-1989 as a possible explanation. A later study questions the quality of the observational data showing the trend ~~reversal~~ change (Tang et al., 2011), while recent studies propose the ~~trend reversal~~ post-1990 initial, strong brightening is to a considerable extent an artifact of a nation wide change in SDSR measurements (Wang and Wild (2016) Yang et al. (2018)). The change in SDSR measurements include a replacement of SDSR instrumentation~~in addition to~~, an increase in measurement frequency and in addition an update in the classification of SDSR stations, and Wang and Wild (2016) conclude that the upward trend ("jump" between 1990-1999) should be considerably weaker, and that only 20 % of the "jump" has actual physical causes. Yang et al. (2018) homogenized the data from Wang and Wild (2016) and Wang et al. (2012) and presented a new SDSR evolution (results can be seen in Yang et al. (2018) Figure 10). The newly homogenized data exhibit a significant dimming trend (-6.13 +- 0.47 W/m^2/decade) between 1958-1990, a flattening of the curve in 1991-2005, followed by a brightening trend (6.13 +- 1.77 W/m^2/decade) between the years 2005-2016. We can use Figure 2(f) to compare our model data to these homogenized data, and see that even without a larger "jump" in the data around 1990 there are still large discrepancies between model and observation, both in the form and magnitude of the brightening period after 1990. All models show dimming in the flattening period of the ~~new~~ newly homogenized data. All models apart from CanESM5 show an averaged negative trend between the 6-year-means of 2003-2008 and 2009-2014, where the newly homogenized data show a brightening. ~~Models~~ A similar "jump" to the one seen in China can be identified slightly later in Japan (fig 2e). To our knowledge, we have no information of neither a replacement of instruments nor update in the classification of SDSR stations in Japan. Norris and Wild (2009) investigated the role of clouds for historical SDSR observations in China and Japan, and found the post-1990 brightening in Japan to be statistically significant, while the Chinese brightening was found nonsignificant. In this paper (published before Wang and Wild (2016)) half of the post-1990 brightening in China, and one third for Japan, was attributed to a reduction in cloud cover. These results point to a need for more studies assessing and evaluating available observational SDSR data. However, models do not accurately represent the strength of dimming ~~, or~~ throughout the whole period, nor the change in trend after 1990 and thus the time evolution of SDSR observed in China, with or without the early 1990s "jump" in brightening.

4.2 Aerosol effect on dimming

Out of all the experiments presented in Table 1 and Figure 3, only those containing anthropogenic aerosol emissions showed dimming. This is expected as aerosols have been presented as the main cause of reduction in SDSR in China by previous studies (Wild, 2009; Yunfeng et al., 2001; Kaiser and Qian, 2002).

Storelvmo et al. (2018) argues that the discrepancy seen between observed and modelled CMIP5 model mean global SDSR can be attained to errors in the treatment of processes that translate aerosol emissions into clear-sky and all-sky radiative forcings. Here, we can see an anti-correlation between simulated SO_4 burdens from Figure 4(a) and (b), and simulated SDSR from Figure 2(b) and (f), respectively. Therefore we suggest that the simulated SDSR is dominantly a result of simulated SO_4 burdens. Simulated SDSR agrees relatively well with observed SDSR in Europe (Fig 2b), along with simulated SO_4 burden anti-correlating relatively well with observed SDSR in Europe (Fig ~~A2~~4a). This means that the model code translating burdens into SDSR in Europe can simulate changes in SDSR as a consequence of changed in aerosol emissions. If models translate burden into SDSR correctly in Europe, this does not necessarily mean that they translate burden into SDSR correctly in other regions. However, we suggest that the code translating burdens into SDSR should also work correctly in China, since also in China we find, that aerosols are the main cause of dimming, in agreement with (Wild, 2009; Yunfeng et al., 2001; Kaiser and Qian, 2002). Note also that we find no consistency between observed cloud cover changes, GEBA data and simulated cloud cover and SDSR anomalies in China (Table 2). By suggesting the translation process from burden to SDSR is behaving correct in both regions, the potential source of error causing discrepancies between observed and simulated SDSR can be traced to the causes of the simulated atmospheric burdens in the first place.

The sulfur dioxide emission inventory used as input for historical model simulations in CMIP6 is shown in Hoesly et al. (2018)(Figure 3), and the emissions as translated in four of the models of this study is shown in Figure A2.

Hoesly et al. (2018) have pointed to the need ~~to study in the future~~ for emission uncertainties, but this has not been done for these emissions. Aas et al. (2019) have studied global and regional trends in atmospheric sulfur and found that uncertainties in emissions were largest in Asia, even if their study only went back to 1990.

Previous studies estimating SO_2 emissions include Lu et al. (2010), that found sulfur dioxide emissions in China increased by 53 % between 2000 and 2006 using technology based methodology, and thereby found similar results to that of Hoesly et al. (2018) . Lu et al. (2010) also compared AOD derived SDSR to GEBA based SDSR data as shown in streets et al and found the GEBA based SDSR data to not accurately represent SDSR development in East Asia, this further underlines the need for more studies evaluating SDSR observations. Other studies such as Koukouli et al. (2018) have used satellite observations to estimate a new emission inventory for SO2 between 2005 and 2015 in China. We note that the year 2005 in Figure A2 is directly after the sharp increase in SO_2 emissions, and the biggest difference between the estimation made by Koukouli et al. (2018) and the SO_2 emission inventories in CMIP6 are a decrease in emissions after the year of 2011. This decrease in SO_2 emissions would intuitively result in a brightening, which is identified over the same time period in the homogenized data by Yang et al. (2018) (Fig 10).

The modeled emissions of SO_2 as shown in Figure A2 over China showed no trace of ~~either the trend reversal("jump")~~ a significant change in trend after 1990 in our observed SDSR timeseries ~~nor patterns similar to the proposed new homogenized data~~ as discussed in the previous section. Assuming sulfate burden is responsible for the observed multiyear trends of SDSR, we argue that errors in emissions inventories in China could be part of the problem.

5 Conclusions

Earlier studies have shown that previous generations of Earth System Models have not been able to reproduce the transient development of surface downwelling shortwave radiation (SDSR) in the last decades since 1960 when observations became available (Storelvmo et al. (2018), Allen et al. (2013)). This discrepancy is hypothesized to be related to increasing and then partially decreasing trends in global aerosol emissions and subsequent aerosol radiative effects, but the exact cause is unknown.

In this paper, we compared observations to model simulated surface downwelling shortwave radiation and cloud cover in specific regions for the time period 1961 to 2014. We found that in the *historical* experiments, CMIP6 models reproduce the transient development of SDSR well in Europe, but poorly in Asia. The multiple historical and associated perturbation experiments performed under CMIP6 reveal that only those simulations containing anthropogenic aerosol emissions show dimming, and the dimming is underestimated by most models. China exhibits a sharp positive trend in observed SDSR in the 1990s that is not found in historical model simulations. This "jump" has been suggested to be an artifact, but historical simulations also do not accurately represent the homogenized observed SDSR as proposed by Yang et al. (2018). We suggest that the continuous decrease in simulated SDSR is related to the continuous increase in atmospheric sulfate burden in the *historical* simulations over China. Following this logic, the observed transient development of SDSR points to the evolution of the sulfate burden in the models being wrong in this region. The sulfate burden is a result of sulfur dioxide emissions, gas-to-particle conversion and wet deposition. Sulfur dioxide emissions over China show neither sign of the observed trend ~~reversal~~ change from gap filled GEBA data nor of the brightening-followed-flattening ~~in SDSR~~from the homogenized data as proposed by Yang et al. (2018). Sulfur dioxide emissions used in the models over China have a strong increase in the early 2000s, which can be observed as a sharp dimming at the same time in Figure 2(f). We suggest that the cause of the discrepancy between model and observations in transient SDSR in China is partly in erroneous emission inventories.

As the observed climate change is the result of warming from greenhouse gases and simultaneous cooling from aerosol radiative effects, getting aerosol emissions correct is important in earth system models.
Since the SDSR measurements are not only sensitive to aerosol effects, they might not be the most accurate way to infer historic aerosol loads and forcing. Further studies could include other observations and proxies for aerosol effects in the historical era, such as long-term satellite retrieved aerosol optical depth, deposition of anthropogenic sulfur, organic carbon and nitrate in ice cores, as well as daily temperature range records.

Table 1. Model participation, as used in this study, in CMIP6 model intercomparison projects (MIP) and their experiments.

Experiment	NorESM2	CanESM5	MIROC6	CESM2	CNRM-ESM2-1	GISS-E2-1-G	IPSL-CM6A-LR	MRI-ESM2-0
historical	x	x	x	x	x	x	x	x
hist-aer	x	x	x			x	x	x
hist-GHG	x	x	x	x		x	x	x
hist-nat	x	x		x		x	x	x
piClim-histaer	x	x	x			x		
piClim-histall	x	x	x			x	x	
hist-piAer	x		x					x
hist-piNTCF	x		x		x			x
histSST	x		x		x			x

Table 2. Changes in Chinese cloud cover [%], all sky SDSR AS[W/m^2], and clear sky SDSR CS[W/m^2] between two 3-year means for three time periods. All model results are means made from three ensemble members of the historical simulation, colocated and extracted at Chinese GEBA station locations. Changes in cloud cover are from CRU gridded data and represent means colocated to chinese GEBA stations.

	[1961-1963] — [1987-1989]			[1990-1992]—[1997-1999]			[2000-2002]—[2012-2014]		
Data	[%]	AS[W/m^2]	CS[W/m^2]	[%]	AS[W/m^2]	CS[W/m^2]	[%]	AS[W/m^2]	CS[W/m^2]
NorESM2	-1.0	-4.6	-4.0	0.6	-1.0	-0.4	0.3	-3.9	-5.0
CanESM5	-0.4	-3.5	-4.6	-0.1	0.8	0.6	-1.7	-2.4	-5.7
MIROC6	0.4	-4.4	-3.6	1.2	-1.3	-0.4	0.5	-5.5	-5.3
CESM2	-1.0	-2.6	-3.6	-0.2	0.0	-0.2	0.0	-5.3	-6.7
CNRM-ESM2-1	-0.4	-3.3	-5.2	-0.6	1.1	-1.0	-0.9	-3.5	-6.5
GISS-E2-1-G	1.3	-3.7	-6.4	-0.2	-0.7	-1.2	2.5	-8.7	-9.9
IPSL-CM6A-LR	-1.2	-3.3	-5.0	0.5	-0.6	-0.1	-1.6	-0.4	-1.9
MRI-ESM2-0	-0.1	-7.1	-6.9	-0.3	-0.8	-0.9	-1.1	-4.9	-8.8
MODELMEAN	-0.3	-4.1	-4.9	0.1	-0.3	-0.4	-0.2	-4.3	-6.2
GEBA		-15.4			6.6			0.9	
CRU	0.1			3.0			-1.0		

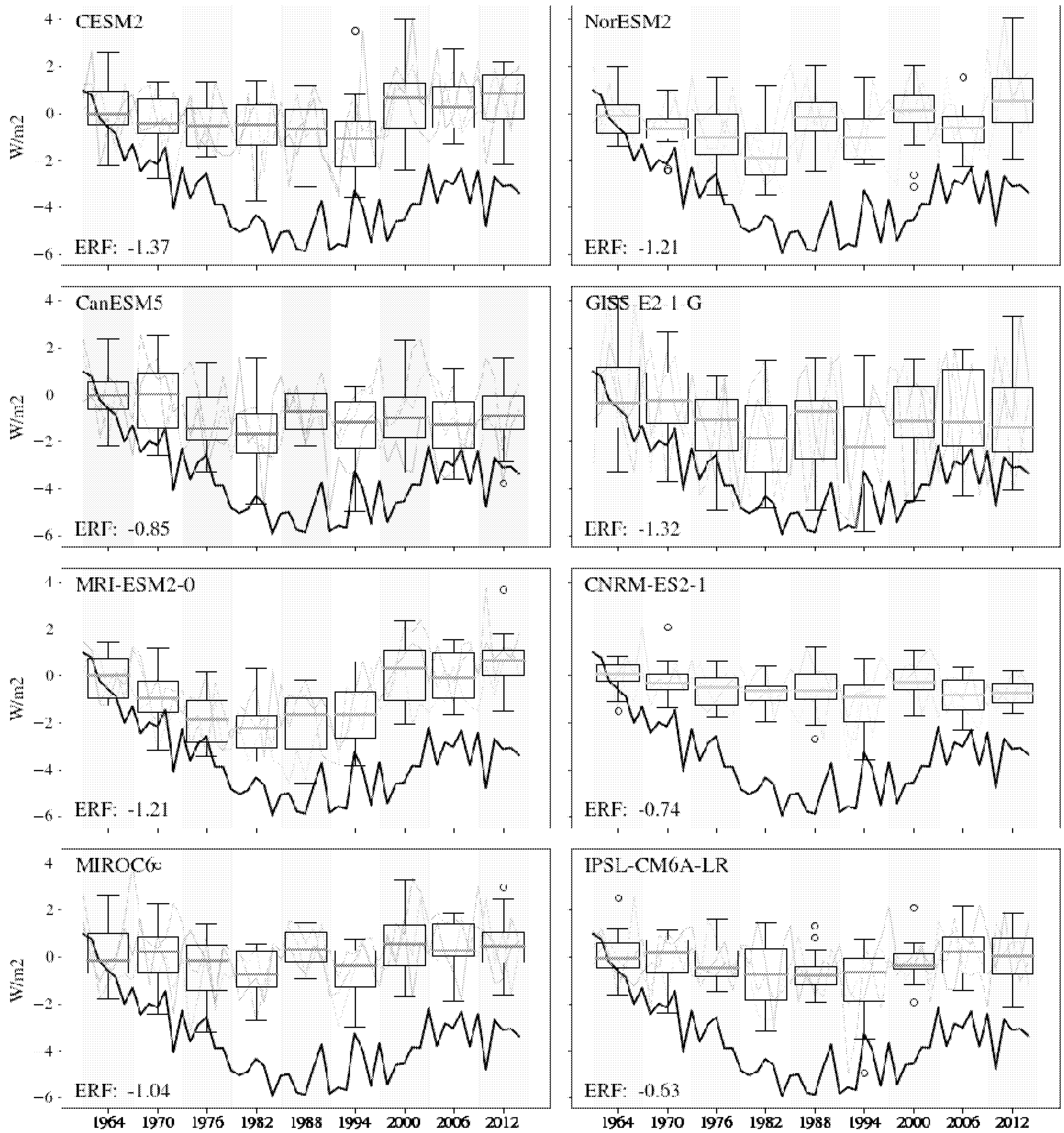

Figure 1. Global surface downwelling shortwave radiation (SDSR) anomaly at the surface for GEBA (black) and three ensemble members for the historical simulation of the eight models in this study. The boxes are made for 6-year intervals (shaded in background) based on 6 yearly means and three ensemble members per model. Colored lines behind boxes show yearly values of SDSR anomaly per ensemble member. The height of each box represents the interquartile range of the data, and the thick colored line within each box is the median. The whiskers show the minimum and maximum values of the selection of data, and the outliers are shown as a hollow dot. Results are co-located to all GEBA stations (1487) throughout the time period. The Aerosol ERF as found in Smith et al. (2020) per model is shown in the bottom left of each panel.

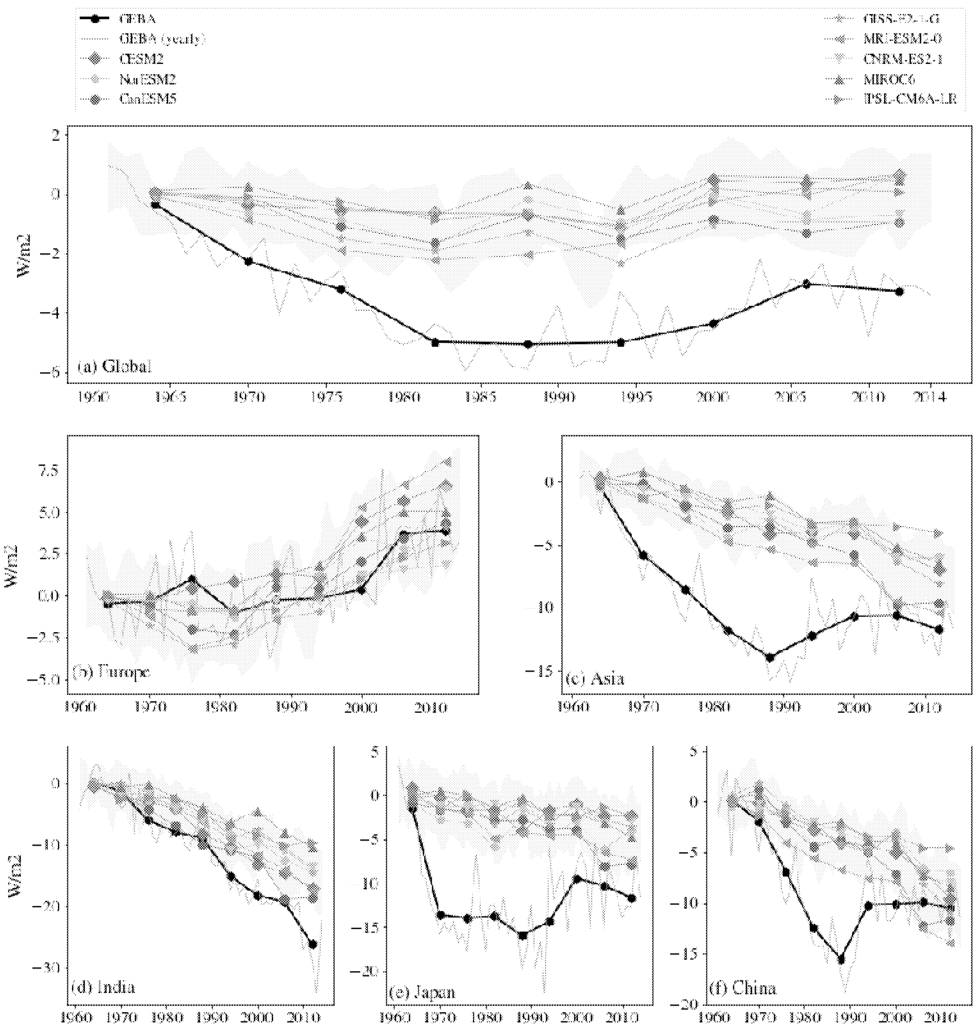

Figure 2. Six-year-averages of surface downwelling shortwave radiation (SDSR) anomaly at the surface for GEBA and eight earth system models. Results are co-located at (a) all GEBA stations (1487), (b) European (503), (c) Asian (311), (d), Indian (15), (e) Japanese (100), and (f) Chinese (119) stations. Numbers in parenthesis are number of ground stations in respective region. The entire 54-year period has beed divided into intervals of 6 years and then averaged together to make nine data points as shown by the markers. The grey shading represent one standard deviation from the yearly total ensemble mean.

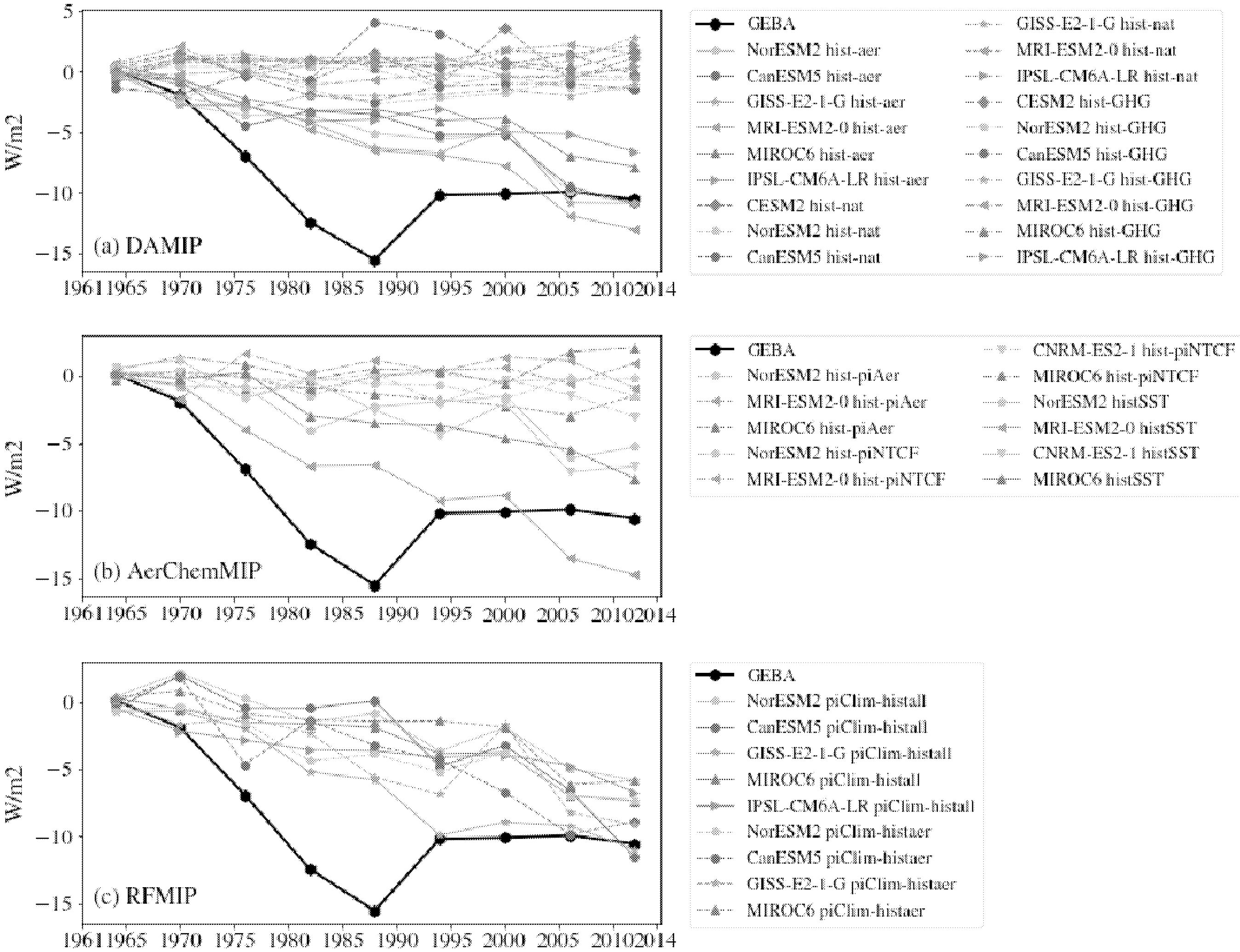

Figure 3. SDSR anomaly in China for all the CMIP6 simulations as listed in Table 1. All model results are co-located at GEBA station locations registered to China (119 stations). The entire 54-year period has beed divided into intervals of 6 years and then averaged together to make nine data points as shown by the markers.

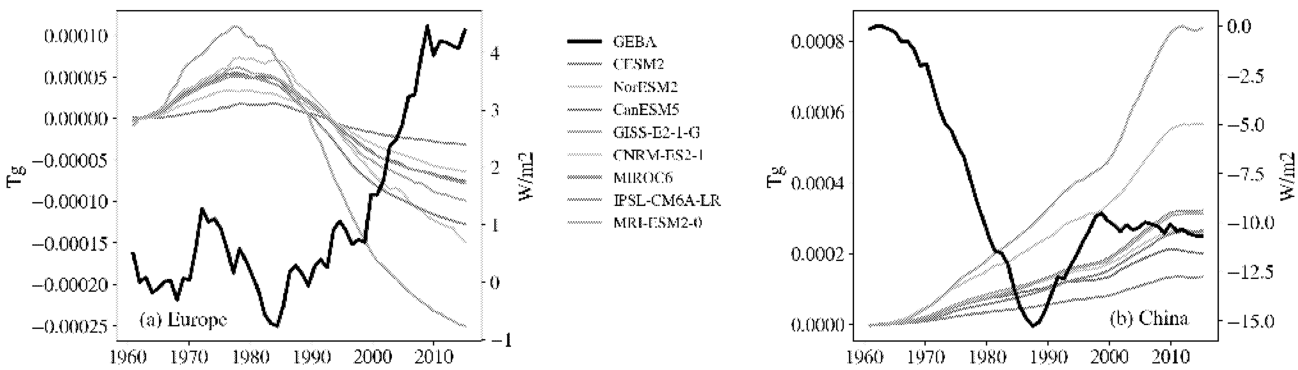

Figure 4. Anomaly of simulated atmospheric load of sulfate per model together with observed all sky SDSR anomaly in (a) Europe and (b) China. The GEBA data are shown as yearly anomalies, while the atmospheric loads have been smoothed using a 10-year running mean technique as explained in Section 2.3.

Appendix A: Additional information

A1 The European SDSR evolution

Figure A1 suggests cloud cover variation as a possible explanation of the local maximum in observed European SDSR during the period 1967-1978. Cloud cover exhibited a substantial minimum simultaneous to the maximum in SDSR. The peak is not reproduced in the historical runs of earth system models studied herein (see Figure 2(b). Cloud cover variations that are not externally forced, but are rather a result of internal variability, cannot be expected to be reproduced in fully coupled earth system models. This might serve as an explanation why the substantial peak in SDSR between 1967 and 1978 is not reproduced in the earth system models.

A2 The data downloaded from ESGF

Table A2 shows an overview of the eight models used in this study. For the historical simulations three ensemble members per model was downloaded, with the variant labels r[1,2,3]i1p1f[1,2] for the variables rsds, ~~rsds~~ rsdscs and clt. In addition the variable loadso4 and areacella was downloaded for one ensemble member per model in the historical simulation per model. In the remaining experiments listed in Table 1 only one ensemble member per model was downloaded for the variable rsds, this was done as not every model provides more than one simulation per experiment.

A3 Effects of cloud cover change on all sky SDSR

If we assume that $E_{\text{clear sky}}$ is the diurnal average clear sky SDSR in a region and that τ_{cloud} is the average cloud optical depth, we can compute idealized effects of cloud changes on SDSR using the Beer-Lambert law:

$$E_{\text{surf}} = E_{\text{toa}} \exp(-\tau / \cos\phi),$$

where τ and ϕ denote optical depth and solar zenith angle, respectively. The change in SSR per 1% change in cloud cover can then be computed:

$$\Delta E_{\text{surf per 1\%}} = 0.01 \times E_{\text{cloudy}} - E_{\text{clear sky}}$$

$$= 0.01 \times E_{\text{toa}} \exp(-\tau_{\text{cloud}} / \cos\phi + \ln(E_{\text{clear sky}} / E_{\text{toa}})) + 0.99 \times E_{\text{clear sky}} - E_{\text{clear sky}}$$

Idealized computation for China: Assuming that ϕ is between 30° and 70°, that $E_{\text{clear sky}}$ is between 100 W/m^2 and 350 W/m^2 and that E_{toa} =1362 W/m^2 in China, the theoretical effect of 1% increase in cloud cover on all sky SDSR is between -1 and -3.5 W/m^2, using the idealized computation described above.

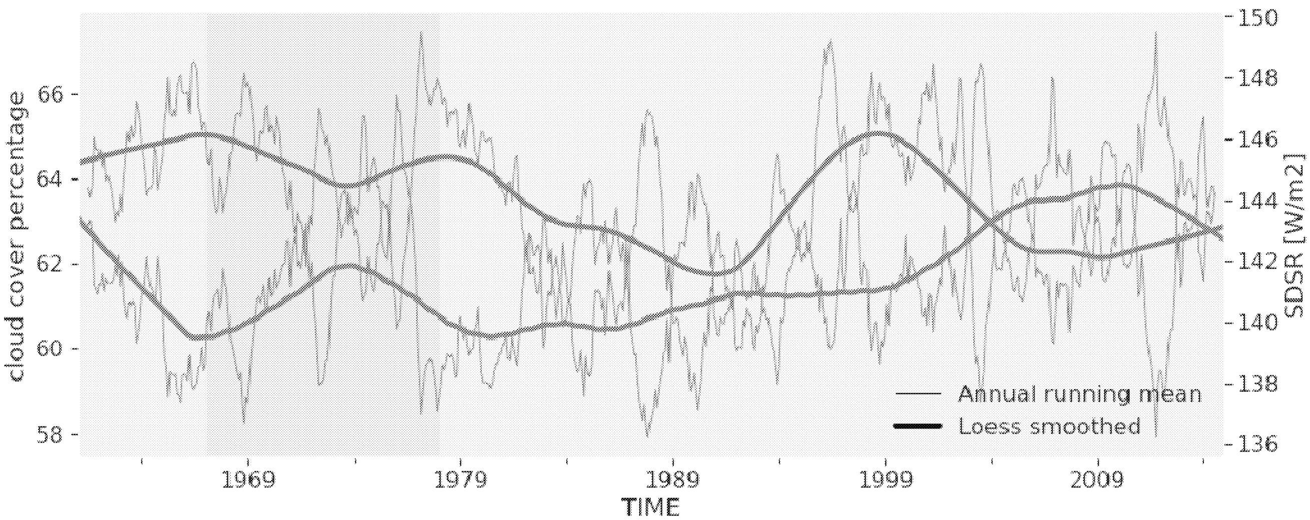

Figure A1. Timeseries of cloud cover (blue) and SDSR (red) between 1961 and 2014, co-located at GEBA sites in Europe. Thin lines show annual running means; bold lines show LOESS-smoothed variants. The shaded area delineates a period of interrupted dimming in Europe, between 1967 and 1978, which occurred simultaneous to a local minimum in the cloud cover trend.

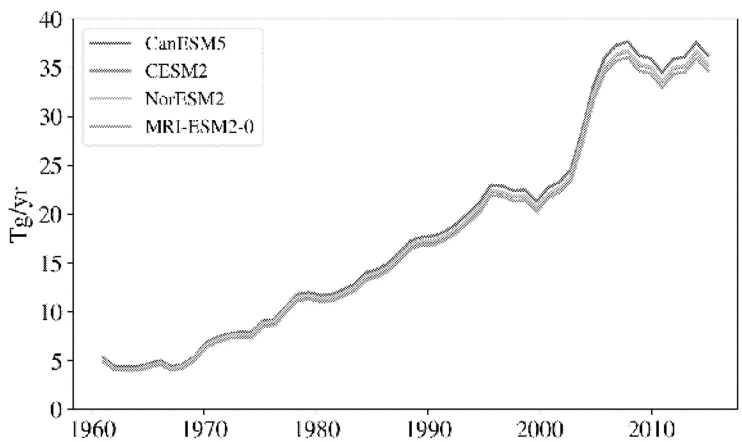

Figure A2. Emission of SO_2 in China, diagnosed by four of the models in this study. China is defined here as the area within latitudes [20°N–45°N], and longitudes [95°E–125°E].

Table A 1. Global all sky SDSR and cloud cover averaged over the years 1961-1966 (baseline values) as observed (GEBA for radiation, CRU for cloud cover) and as simulated in the ensemble mean of three ensemble members in the historical experiment by each of the models of this study. Data from both CRU and models are retrieved after co-location to all GEBA sites.

Model	SDSR [W/m^2]	Cloud Cover [%]
CESM2	186.3	63.9
NorESM2	186.8	55.6
CanESM5	189.5	56.2
GISS-E2-1-G	176.6	58.6
MRI-ESM2-0	193.8	56.2
CNRM-ES2-1	192.3	57.2
MIROC6	184.3	50.4
IPSL-CM6A-LR	185.7	54.5
CRU		**57.4**
GEBA	**171.6**	

Table A2. Details on the models used. IA: interactive aerosols NIA: not interactive aerosols.

Institution	Model	Resolution	Aerosol module	Complexity	Reference
NCAR	CESM2	1.25x0.9	MAM4	IA	Danabasoglu et al. (2020)
CCCma	CanESM5	2.81x2.81	CanAM4	IA	Swart et al. (2019)
CNRM-CERFACS	CNRM-ESM2-1	1.4x1.4	TACTIC_v2	IA	Séférian et al. (2019)
IPSL	IPSL-CM6A-LR	2.5x1.27	INCA fields	NIA	Boucher et al. (2020)
NCC	NorESM2-LM	2.5x1.875	OsloAero6	IA	Seland et al. (2020)
MRI	MRI-ESM2-0	1.125x1.125	MASINGAR mk-2r4c	IA	Yukimoto et al. (2019)
MIROC	MIROC6	1.4x1.4	SPRINTARS	IA	Tatebe et al. (2019)
NASA-GISS	GISS-E2-1-G	2.5x2.0	OMA fields	NIA	Kelley et al. (2020)

Author contributions. KM wrote most of the article and did all analysis of CMIP6 data. MS and TS contributed to design of the study and helped editing the text. DO, PN, JC and TT, NO, SB, GG contributed model data via the ESGF CMIP6 archive. IJ and MW contributed with observational data, and IJ wrote part of the appendix. All co-authors contributed to the analysis and gave feedback to the manuscript.

Competing interests. No competing interests

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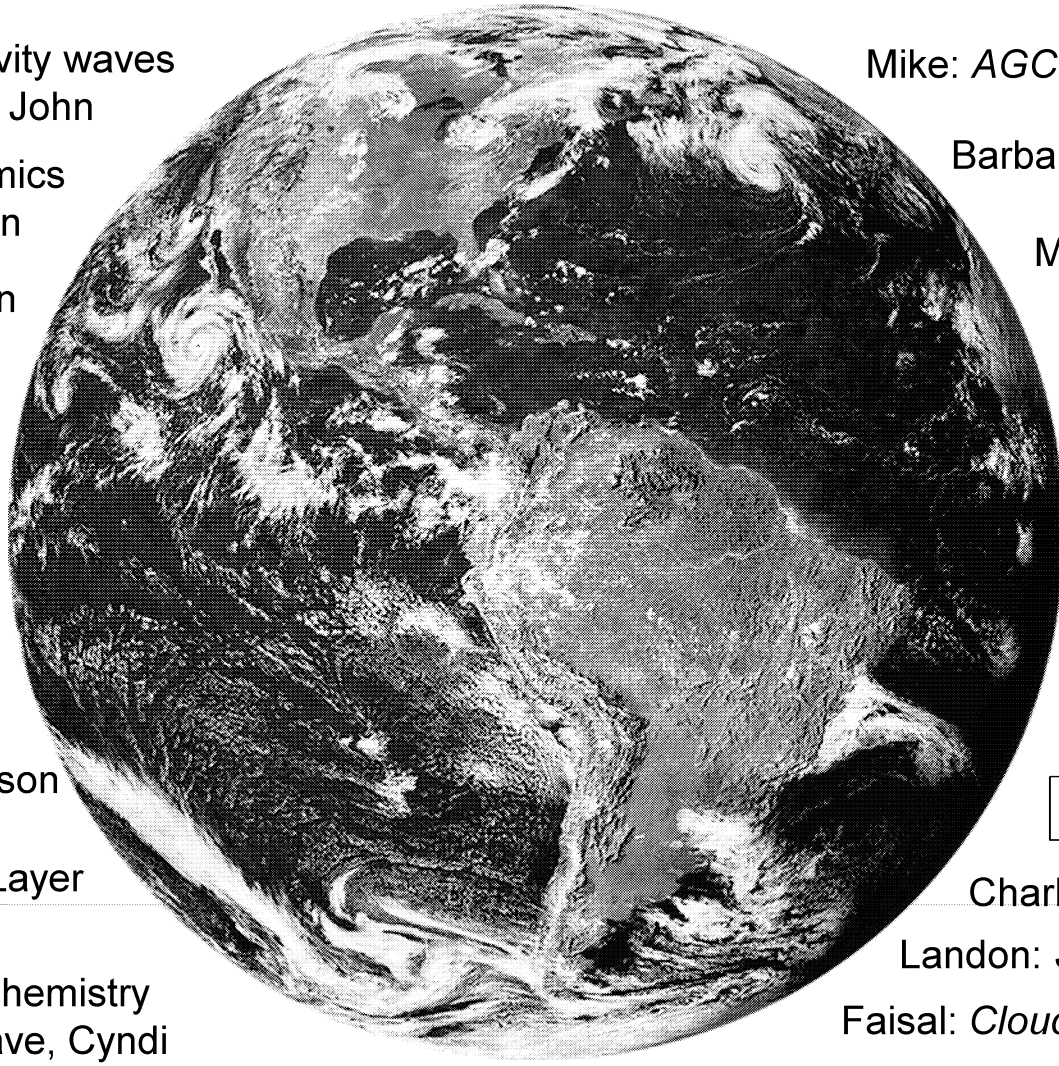
Canadian Atmospheric Model: Future Directions

Atmospheric Physics Group

3 Dec 2019

Present state and expertise



Research Scientists

Gravity waves
John

Dynamics
John

Convection
Norm

Aerosols
Knut, Cyndi

Clouds

Radiation
Jiangnan, Jason

Boundary Layer
Norm

Chemistry
Dave, Cyndi

Support Staff

Mike: *AGCM support, GEM interface*

Barbara: *SLCF, GEM interface*

Minwei: *GEM Interface*

Sarah: *PAM improvement*

Limited term

Charles: *Stratosphere dyn.*

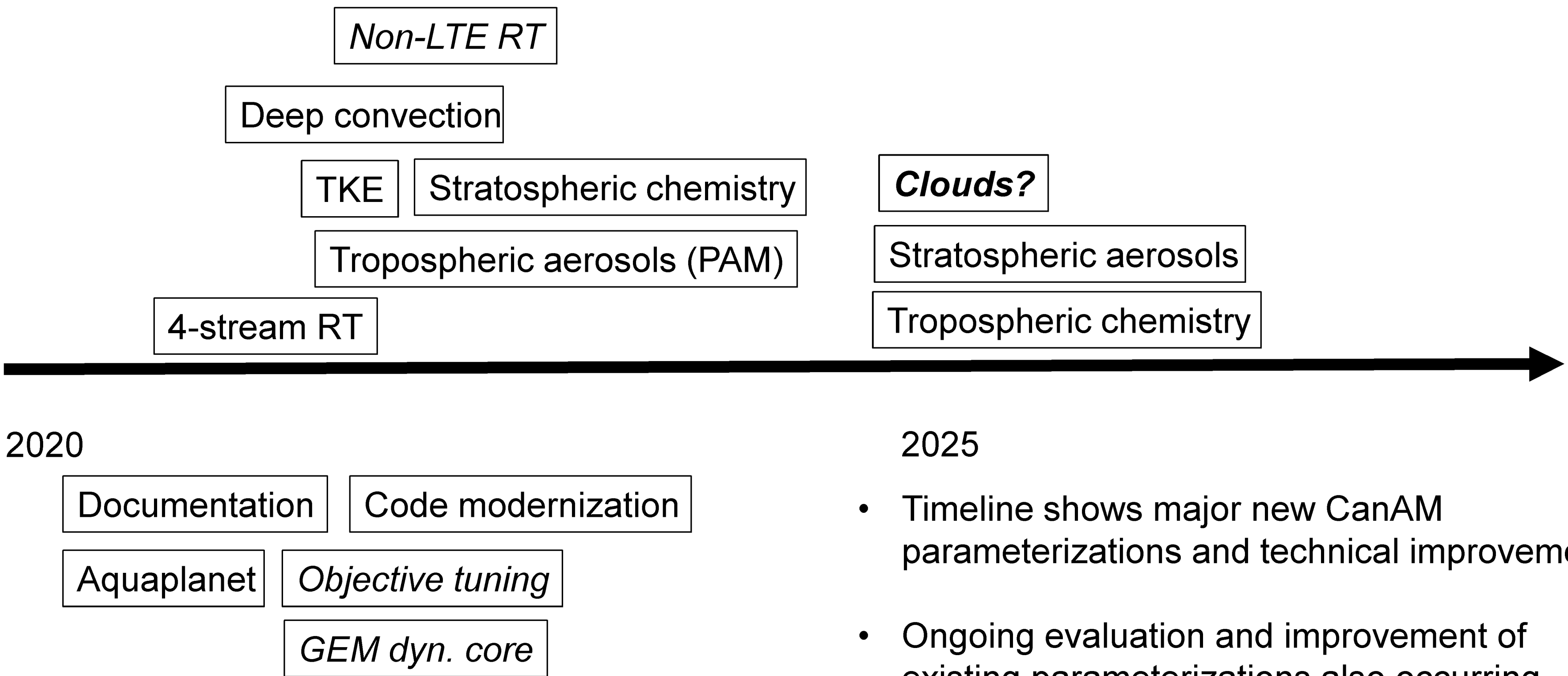
Landon: *Stratospheric aerosols*

Faisal: *Cloud radiation diagnostics*

Future CanAM Development

- Continuous evaluation and improvement of CanAM physics,
  - Many parameterizations were developed in-house
  - Requires on-going scientific expertise in physical atmospheric processes
- Goal to have CanAM be capable of modelling atmospheric processes, including aerosols and chemistry, from the surface to the stratosphere.
  - This will allow us to better address more science and policy relevant questions
  - SLCF, SRM, climate-air quality, seasonal prediction, etc..
- Harness analysis expertise within CCCma to more efficiently identify model properties and gaps.
- What gaps exist, or will exist, in process expertise?
  - Deep convection, boundary layer, clouds, others?
  - Do we have the necessary staff and (formal) collaborations to perform this work?

Future CanAM Development Timeline



- Timeline shows major new CanAM parameterizations and technical improvements
- Ongoing evaluation and improvement of existing parameterizations also occurring

Current State of resources

- Half of AP group are senior scientists, rest are mid/early career scientists
- As RES's progress in their career, they have larger projects, meaning less time for scientific/technical work
  - Technical work can be relieved through support staffing allocation and new hires.
  - This gives more time for scientific work, model development and application.

- We strive to maintain sufficient expertise at CCCma to continue to develop and support existing parameterizations
  - This is becoming challenging to sustain.
  - Gaps exist (clouds) and will exist in the near-term (convection and boundary layer).

Continued development of CanAM

- Continued active development of CanAM needs new people in strategic areas.
- Historical pathway for RES's in AP group have been through postdoc positions.
  - This has not been the case recently due to limited postdocs to the AP group
  - An acute issue since closure of network projects which were a supply of postdocs/students
- An increased number of postdocs available to the AP group is necessary
  - Postdocs bring their own expertise and overlap with more senior scientists.
  - Increased postdocs would provide a base from which we can hire qualified scientific personnel.
- Coordinate hiring with other ECCC groups (MRD, AQRD)?
- Use other means to access expertise, e.g., universities (guest worker, RAP)?

Biogeochemical carbon coupling influences global precipitation in CanESM2 SRM experiments

Jason Cole,
John Fyfe, Vivek Arora, John Scinocca
30 September 2019

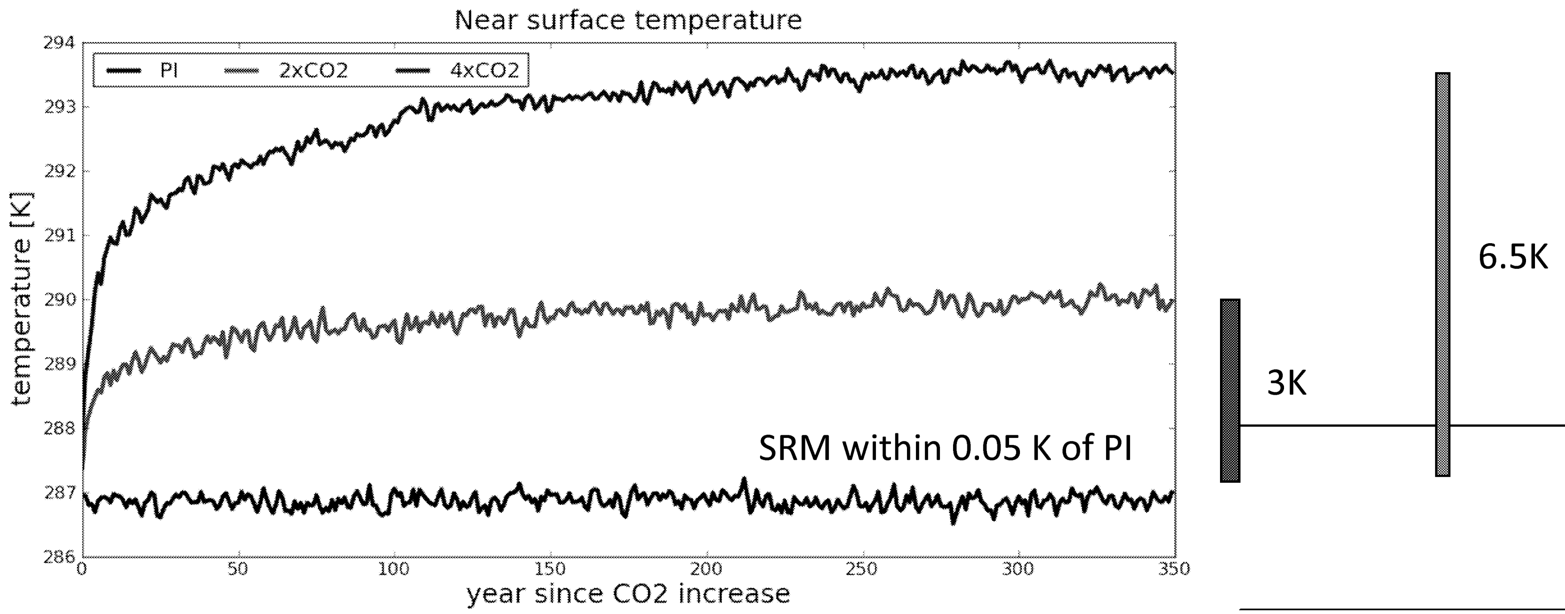
The experiment

Fyfe, et al. (2013), Biogeochemical carbon coupling influences global precipitation in geoengineering experiments, Geophys. Res. Lett.

Carbon decoupled
- carbon cycle "sees" 1xCO_2

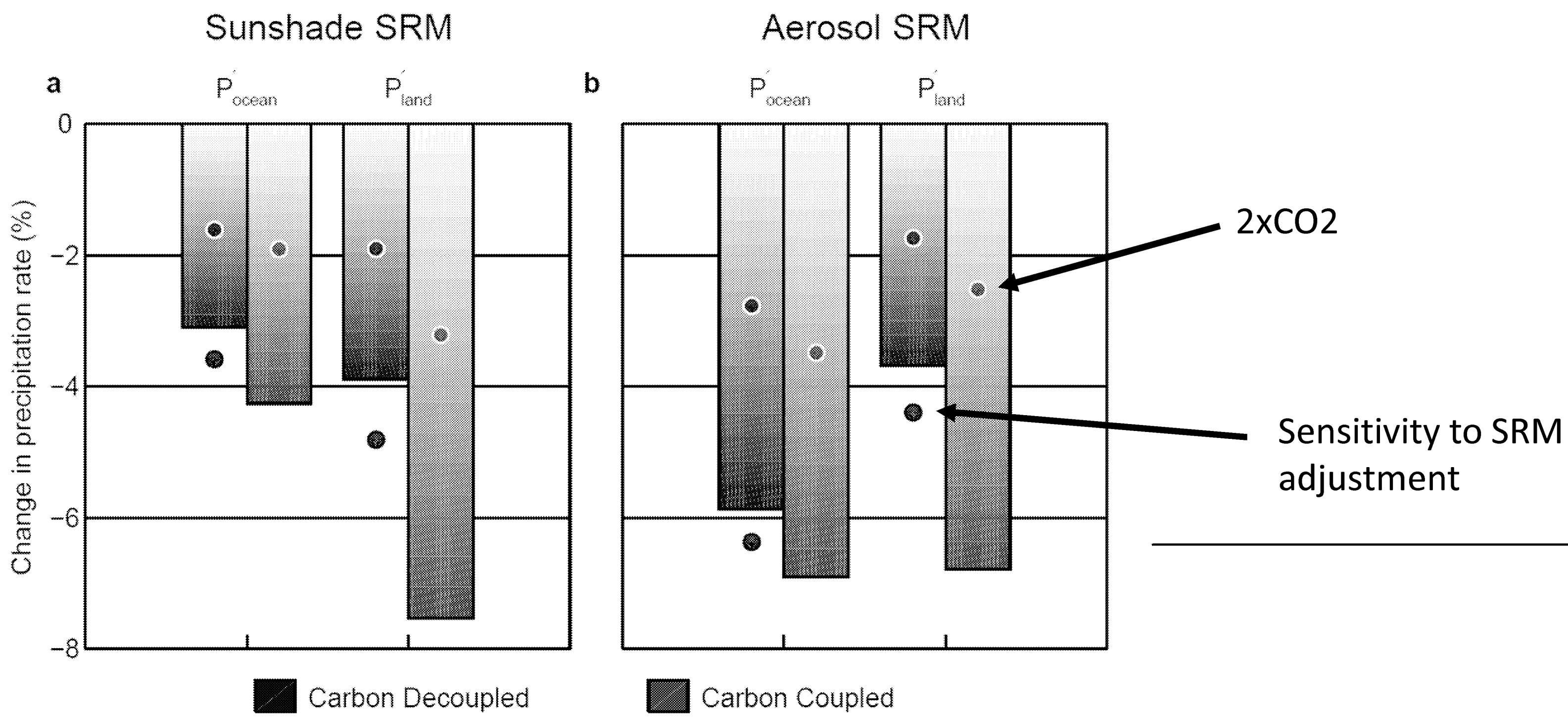
Carbon coupled
- carbon cycle "sees" CO_2 change

Experiments
- 350 year simulations, use last 200 years
- use reduced solar constant or prescribed stratospheric aerosol SRM (idealized)
- SRM offsetting abrupt 2xCO_2 and 4xCO_2 (target global mean sfc. temperature).



Results (Global Precipitation)

	Sunshade	Aerosol	Change SRM
Decoupled	-3.3%	-5.5%	-2.0%
Coupled	-4.9%	-6.9%	-2.2%
Change coupling	-1.7%	-1.5%	

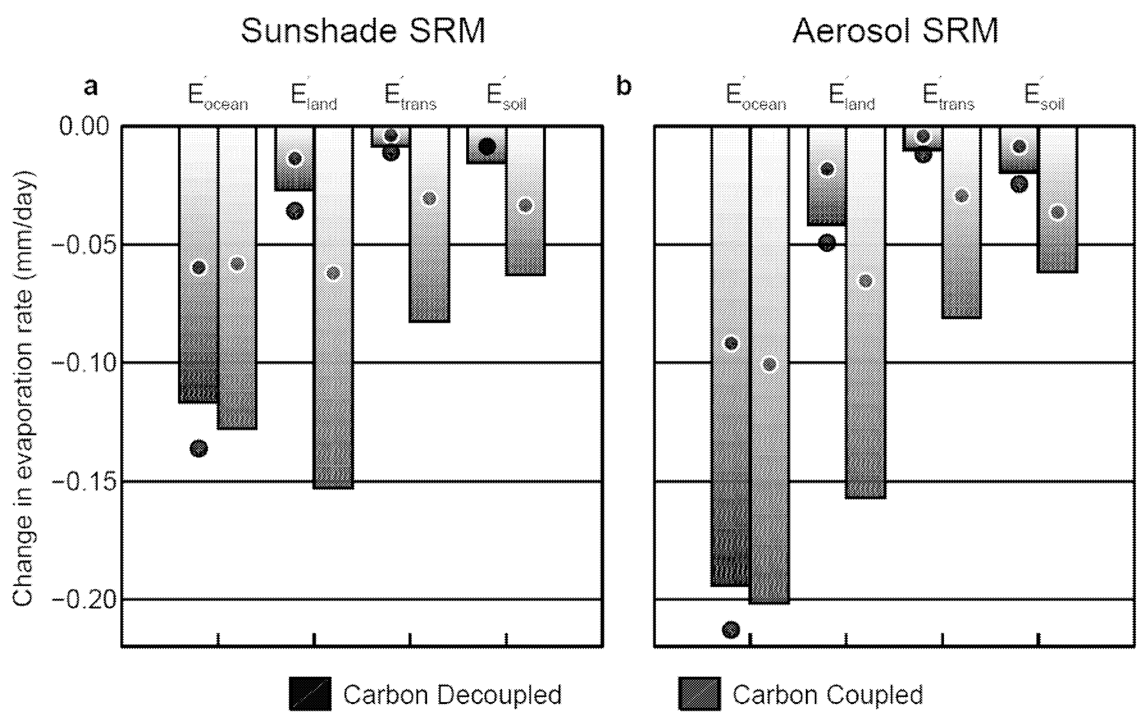


Results (Evaporation)

$$E'_{land} = (E'_{trans} + E'_{inter}) + (E'_{soil} + E'_{snow})$$

CO_2 ↑ implies that leaf area ↑ giving E'_{trans}↑ and E'_{inter} ↑

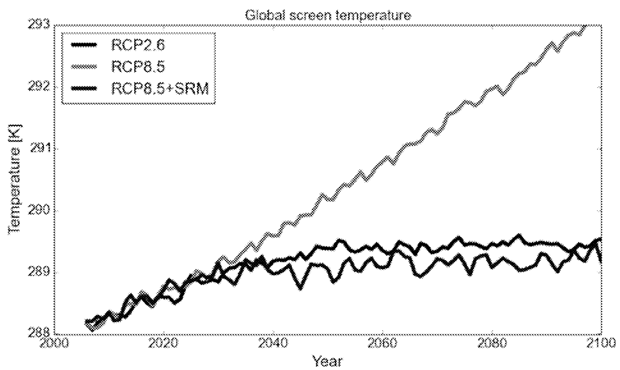
CO_2 ↑ implies that stomatal resistance ↑ giving E'_{trans}↓



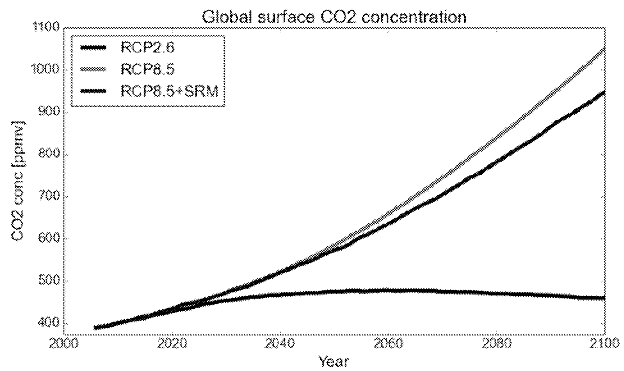
Extra slides

Specified CO_2 emissions

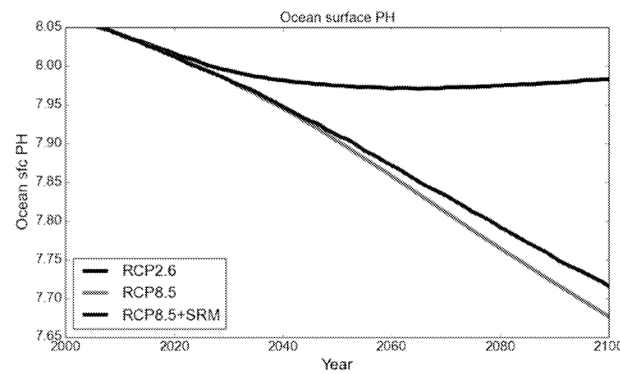
- this study used prescribed CO_2 concentrations.
- using prescribed emissions allow CO_2 to respond to SRM
  - For example: Keller, 2014; Vaughn, 2007; Matthews, 2007



- 3 member ensemble
- Time varying stratospheric aerosols
  - from 2030 onward
  - temperature RCP8.5 ~ RCP2.6
  - close to 2°C threshold



- land takes up more CO_2
- ~100 ppm reduction by 2100
- roughly same as afforestation



- reduced CO_2, less acidic ocean
- small but as large as some CDR

Biogeochemical carbon coupling influences global precipitation in CanESM2 SRM experiments

Jason Cole,
John Fyfe, Vivek Arora, John Scinocca
30 September 2019

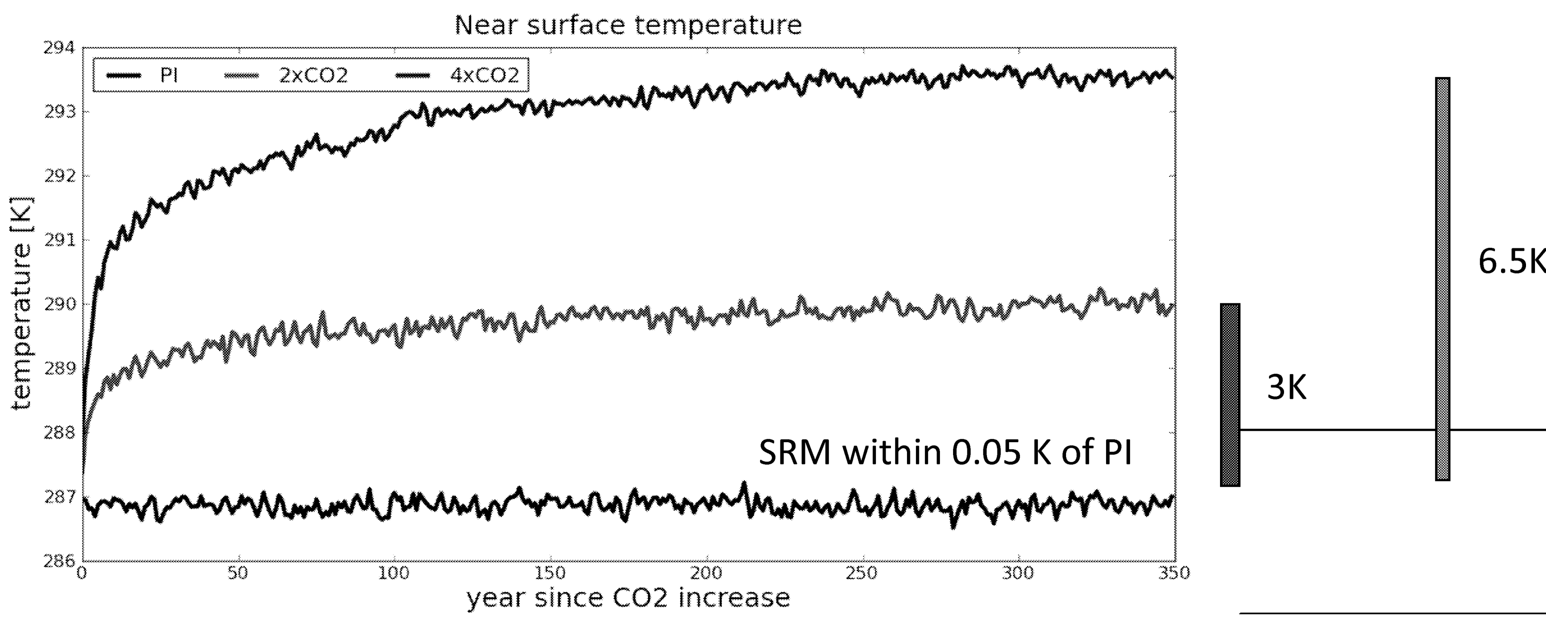
The experiment

Fyfe, et al. (2013), Biogeochemical carbon coupling influences global precipitation in geoengineering experiments, Geophys. Res. Lett.

Carbon decoupled
- carbon cycle “sees” $1xCO_2$

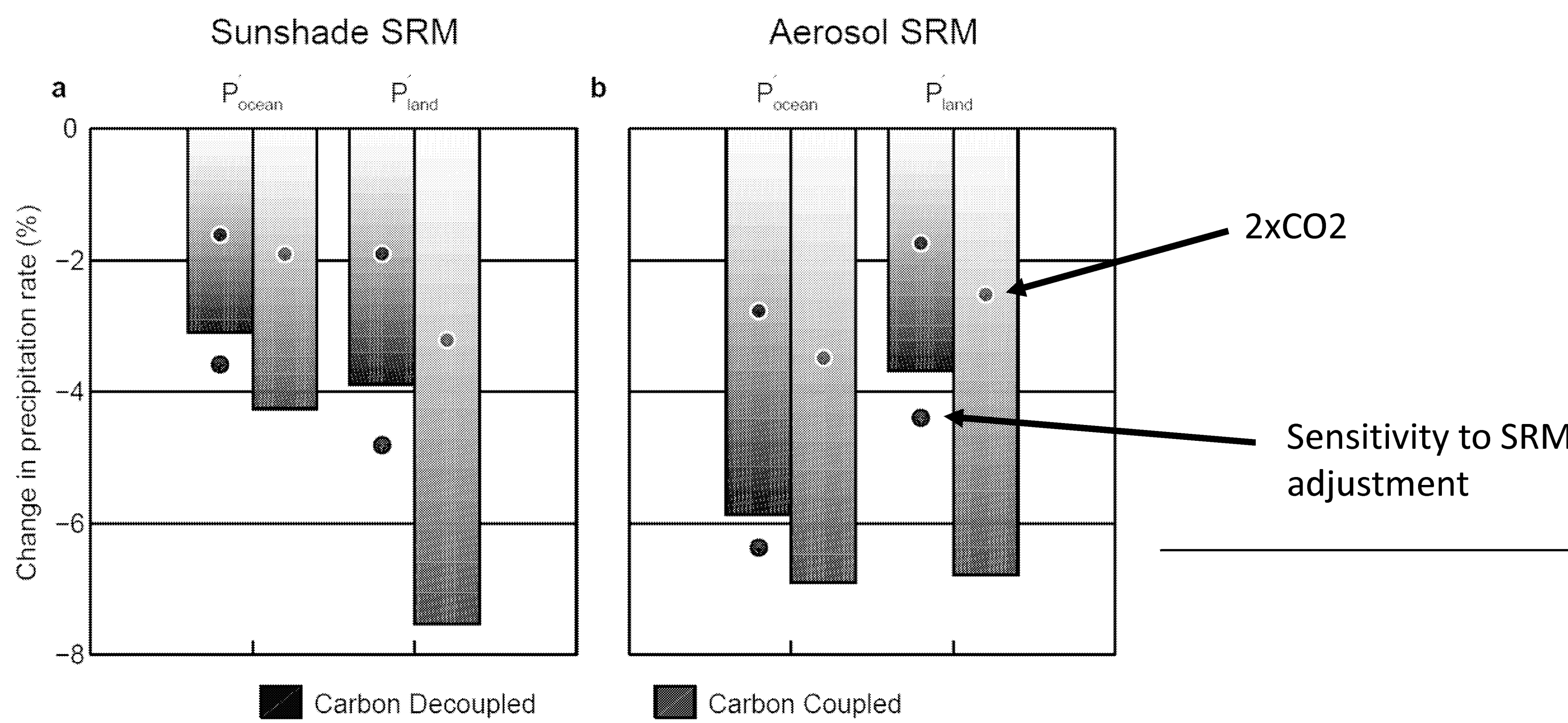
Carbon coupled
- carbon cycle “sees” CO_2 change

Experiments
- 350 year simulations, use last 200 years
- use reduced solar constant or prescribed stratospheric aerosol SRM (idealized)
- SRM offsetting abrupt $2xCO_2$ and $4xCO_2$ (target global mean sfc. temperature).



Results (Global Precipitation)

	Sunshade	Aerosol	Change SRM
Decoupled	-3.3%	-5.5%	-2.0%
Coupled	-4.9%	-6.9%	-2.2%
Change coupling	-1.7%	-1.5%	

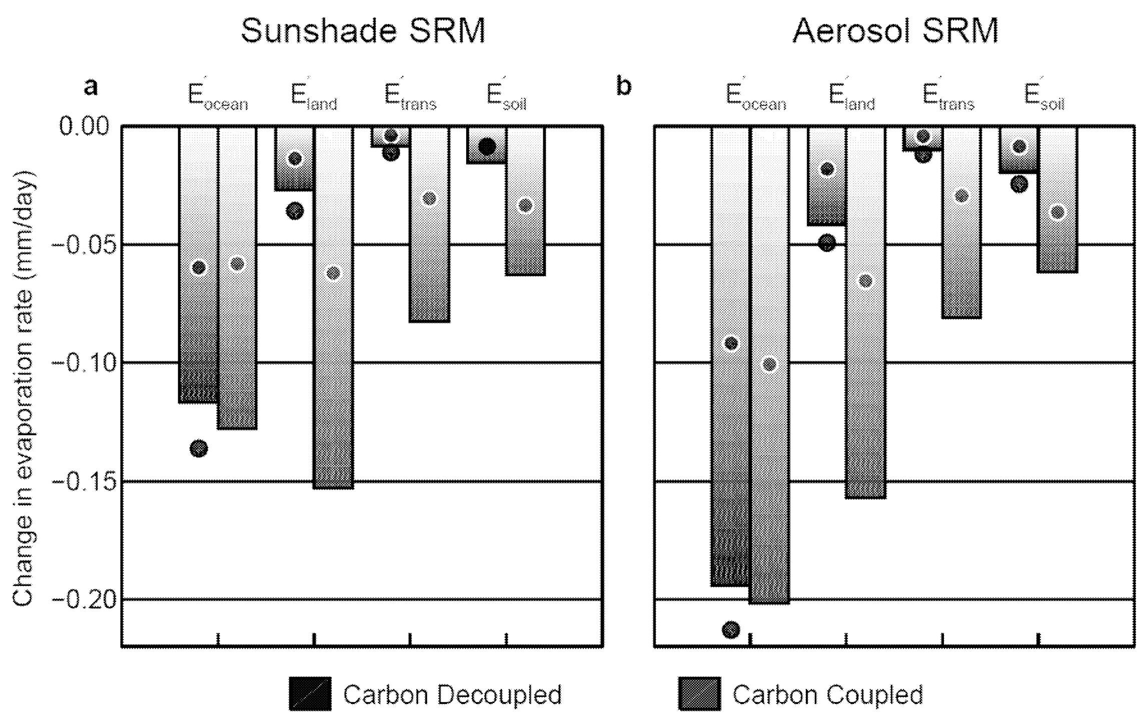


Results (Evaporation)

$$E'_{land} = (E'_{trans}+E'_{inter})+(E'_{soil}+E'_{snow})$$

CO_2 ↑ implies that leaf area ↑ giving E'_{trans}↑ and E'_{inter} ↑

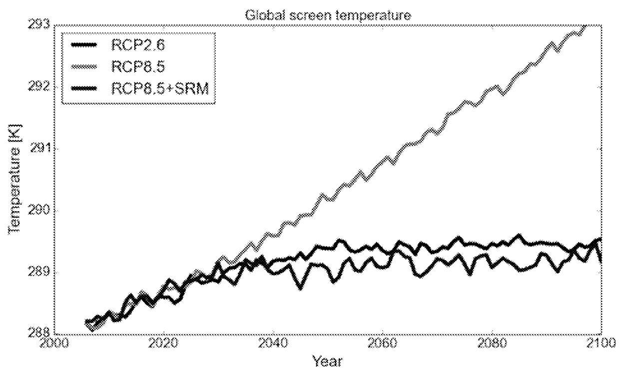
CO_2 ↑ implies that stomatal resistance ↑ giving E'_{trans}↓

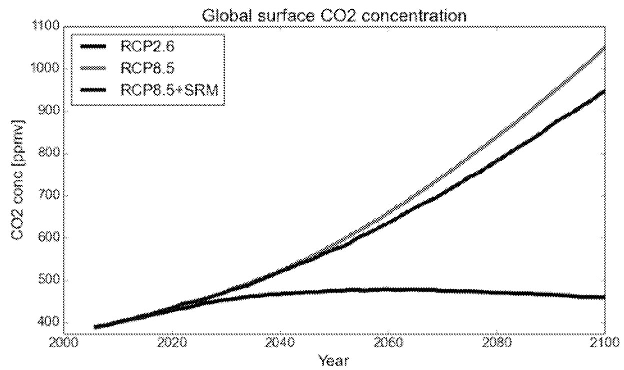


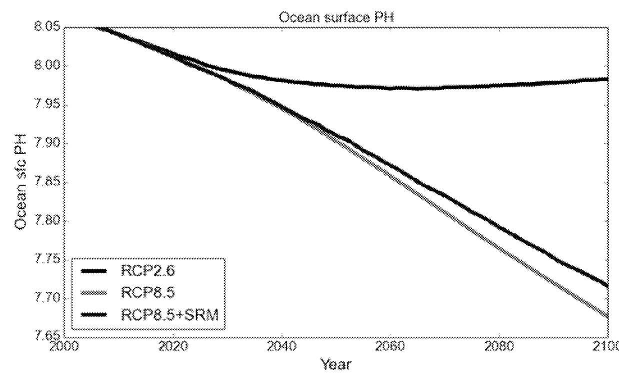
Extra slides

Specified CO2 emissions

- this study used prescribed CO2 concentrations.
- using prescribed emissions allow CO2 to respond to SRM
  - For example: Keller, 2014; Vaughn, 2007; Matthews, 2007







- 3 member ensemble
- Time varying stratospheric aerosols
  - from 2030 onward
  - temperature RCP8.5 ~ RCP2.6
  - close to 2°C threshold

- land takes up more CO2
- ~100 ppm reduction by 2100
- roughly same as afforestation

- reduced CO2, less acidic ocean
- small but as large as some CDR

UNIVERSITY OF WATERLOO

On the Linearity of External Forcing Response in Idealized Solar Geoengineering Experiments

John G. Virgin[1,2,3] & Christopher G. Fletcher[1]

1. University of Waterloo, 2. Environment & Climate Change Canada, 3. Healthcare of Ontario Pension Plan

INTRODUCTION

Despite the growing breadth of solar geoengineering experiment designs, idealized experiments using direct solar constant tuning have persisted in GeoMIP due to their insights into geoengineered climates and ease of implementation. From both a modeling and implementation standpoint, one element of uncertainty in idealized geoengineering experiments is the amount of solar constant reduction required to offset a given increase in CO_2. In the GeoMIP G1 experiment, where the solar constant is reduced to balance an abrupt quadrupling of CO_2 the inter-model spread in the required varies between 3.5-5% (Kravitz et al. 2013a, 2021). For modeling groups, determining the necessary reduction is typically achieved using a brute-force approach, where a heuristic equation (Equation 1, see below) is used to provide an initial guess for the globally averaged solar constant reduction needed to offset the radiative forcing from an abrupt quadrupling of CO_2. Then, the solar constant is tuned iteratively are used to achieve approximate top of atmosphere (TOA) energy balance closure (Kravitz et al., 2013b).

$$1.\ ERF_{CO2} = \frac{\Delta S_0}{4}(1-\alpha)$$

- ERF_{CO2} = Effective Radiative Forcing from quadrupled CO_2
- ΔS_0 = Solar constant offset
- α = TOA planetary albedo

The inter-model spread of the offset has been primarily attributed to rapid adjustments in the climate system as a response to both CO_2 increases and solar constant reductions (Russotto & Ackerman, 2018). Rapid responses in temperature, moisture, and clouds induce radiative perturbations which influence the efficacy of the initial solar constant offset.

Despite previous studies exploring rapid adjustments as a response to external agents, their role in idealized geoengineering scenarios- which involve multiple forcings on the climate system- remains unclear. Here, we decompose the rapid adjustments from both CO_2 and solar forcing in the G1 experiment using a series of single forcing experiments with the Community Earth System Model (CESM). We show that the required offset is not easily predicted using the heuristic equation from GeoMIP because rapid adjustments as a response to negative solar forcing have a net positive radiative effect. Furthermore, we find that adjustments from CO_2 and solar forcing do not add linearly due to enhanced boundary layer cloud reduction in the G1 simulation.

METHODS

Community Earth System Model (v1.2.2) Configuration:

- Community Atmosphere Model (CAM4) with 26 vertical levels and 4°x5° horizontal resolution
- Community Land Model, version 4 (CLM4)
- Prescribed pre-industrial ocean and sea ice climatologies.
- Cloud Object Simulator Package (COSP) enabled.

Experiment	CO_2 (ppm)	Solar Constant ($W\ m^{-2}$)
Control	284.7	1360.89
4xCO2	1138.8	1360.89
$SOLAR_e$	284.7	1317.19
$SOLAR_b$	284.7	1311.00
$G1_e$	1138.8	1317.19
$G1_b$	1138.8	1311.00

**30-year runs with fixed pre-industrial sea surface temperatures and sea ice. Subscript "b" denotes balance, while subscript "e" denotes equation.*

We decompose the ERF for each experiment using radiative kernels to quantify individual rapid adjustments and the Instantaneous Radiative Forcing (IRF) (Zelinka et al., 2012)

RESULTS

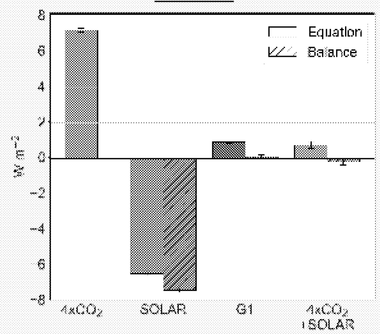


Fig 1. Global mean ERF for SOLAR, 4xCO2, G1, and 4xCO2+SOLAR experiments. Error bars denote ± 2 standard error using all 30 years for each experiment.

- Equation 1 predicts a ΔS_0 of 43.70 $W\ m^{-2}$ to offset the ERF_{4xCO2}
- ΔS_0 is insufficient to fully balance ERF4xCO2, and this is confirmed by the residual ERF of 0.93 $W\ m^{-2}$ in the $G1_e$

RESULTS (cont)

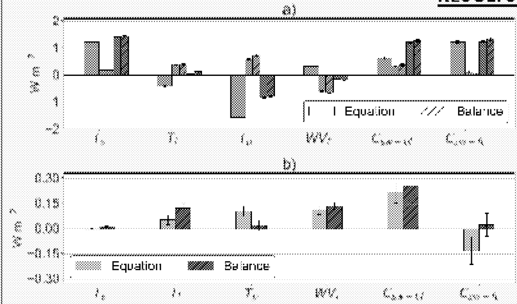


Fig 2 a) Global, annual mean non-zero radiative adjustments. b) Residual between the G1 experiment and the combined 4xCO2+SOLAR experiment output.

- The net radiative adjustment for $G1_e$ and $G1_b$ is 3.10 $W\ m^{-2}$ and 3.37 $W\ m^{-2}$, respectively.
- This is explained primarily by positive adjustments from stratospheric temperature (T_s) and both boundary layer and free troposphere clouds in the SW.
- Cloud response largely dominated by $4xCO_2$

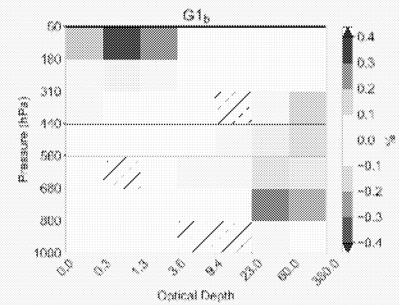


Fig 3. Global, annual (30 year) mean cloud fraction response (in %) for $G1_b$. The y and x-axes represent 7 cloud top pressure pressure (hPa) and optical depth (τ, dimensionless) bins with labels at bin edges. Hatching = not statistically significant ($p > 0.05$).

- $G1_e$ cloud fraction response (not shown) is qualitatively similar $G1_b$ (Figure 3).
- Cloud fraction decreases in the most optically thick bins
- Regionally, these decreases are pronounced in the subtropics/tropics

DISCUSSION & CONCLUSIONS

The total rapid adjustment increases the IRF for both $4xCO_2$ and SOLAR forcing experiments. In the context of the G1 experiment with $4xCO_2$ and SOLAR forcing combined, this reduces the impact of the solar constant offset, which necessitates a stronger reduction than predicted by Equation 1. A decomposition of radiative adjustments in G1 reveals a non-linear effect that accounts for 13%-17% of the total adjustment, amplifying the SW cloud adjustment through further reductions in boundary layer clouds. As LW heating caused the CO_2 IRF dries the lower free troposphere, relatively drier air is mixed downward from aloft to decrease optically thick boundary layer clouds (Kamae & Watanabe, 2012). This effect is slightly dampened by free troposphere warming, which acts to increase lower tropospheric stability and boundary layer relative humidity (Salvi et al., 2021). However, if a negative solar forcing is applied in conjunction with CO_2 forcing, the free troposphere exhibits less warming and the compensatory stabilizing effect is removed, which amplifies boundary layer cloud reduction. From a modeling perspective, our results illustrate the difficulty in achieving energy budget closure at the top of atmosphere for G1 via a trial-and-error approach. While rapid adjustments in $SOLAR_e$ and $SOLAR_b$ are qualitatively similar in this study, they vary as a function of the initial offset. If one were to run a solar forcing only experiment to quantify the net radiative adjustment as done here, which could then be factored back into Equation 1, it would not consider the relationship between the magnitude of adjustments relative to the solar constant offset.

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ACKNOWLEDGMENTS & CONTACT

The authors thank Karen Smith and Jason N.S. Cole for their thoughtful comments which helped strengthen the manuscript. We also acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC). All data produced for this study is with the open-source Community Earth System Model (CESM).

jgvirgin@uwaterloo.ca

Submitted and in Revision with Geophysical Research Letters

NSERC CRSNG

Subject: acp-2019-1210 (author) - manuscript accepted for final publication
From: <editorial@copernicus.org>
Date: 11/9/20, 19:19
To: <jason.cole@canada.ca>

You are receiving the following email copy due to your co-authorship of the manuscript acp-2019-1210. The original message was sent to the contact author defined upon manuscript registration. Please contact us in case of any discrepancies with regard to the manuscript.

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Title: Bias in CMIP6 models as compared to observed regional dimming and brightening
Author(s): Kine Onsum Moseid et al.
MS No.: acp-2019-1210
MS type: Research article
Iteration: Minor Revision

Presently, your manuscript is being transferred to the Copernicus Publications Production Office for typesetting and publication. To proceed, please log in with your Copernicus Office user ID to upload all files that are required for production no later than 19 Nov 2020 at:
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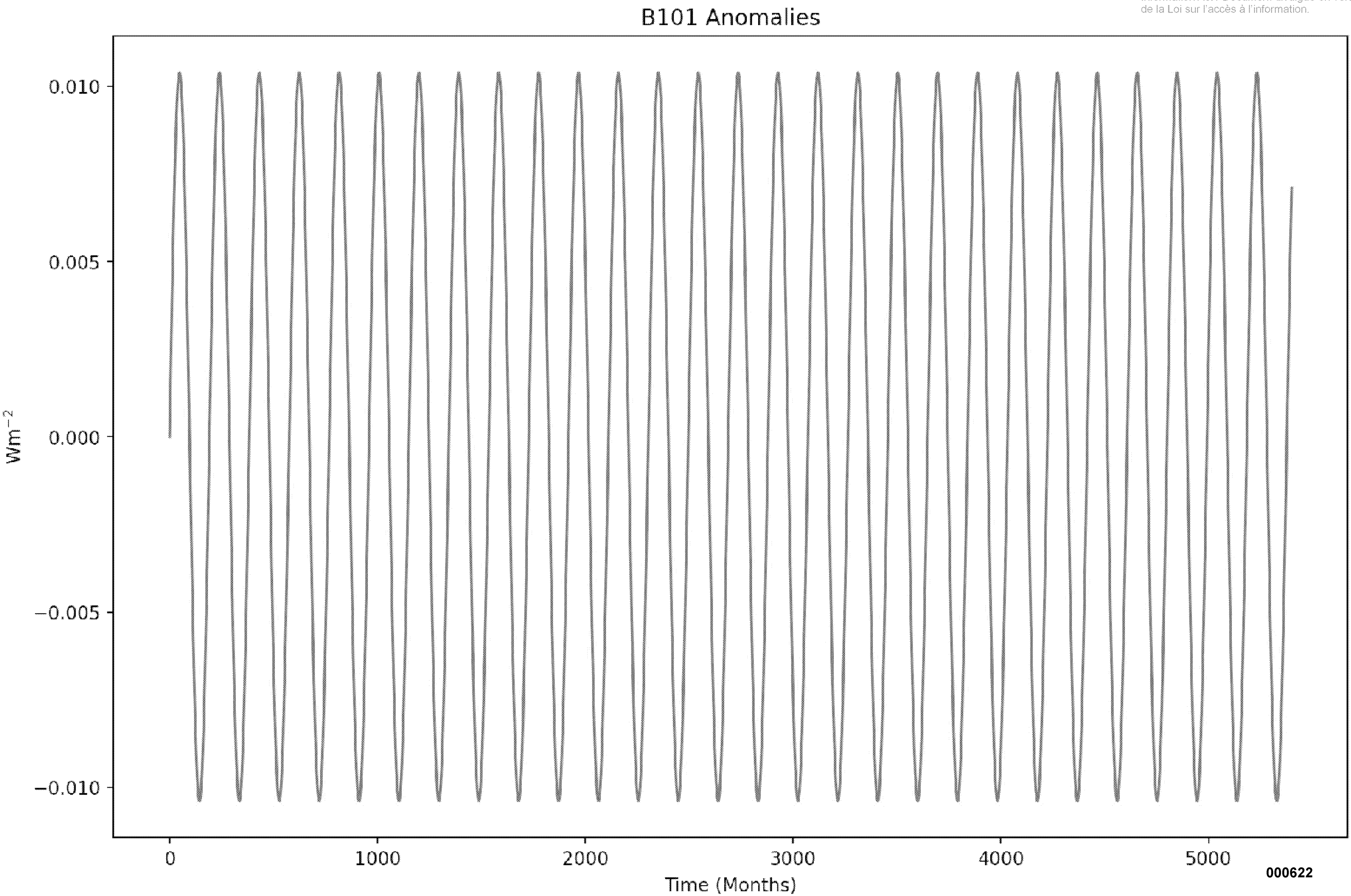
B101 Anomalies
0.010
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0.000
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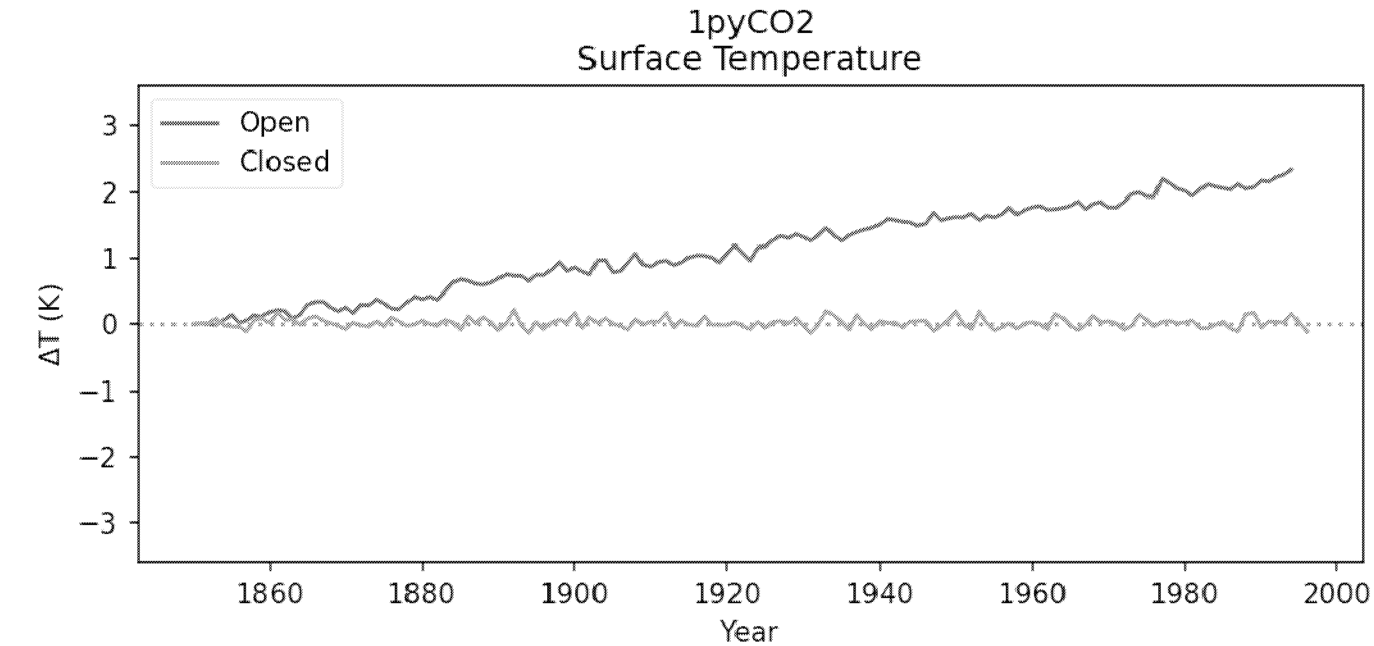
5000
Time (Months)


1pyCO2
Surface Temperature
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Closed
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ΔT (K)
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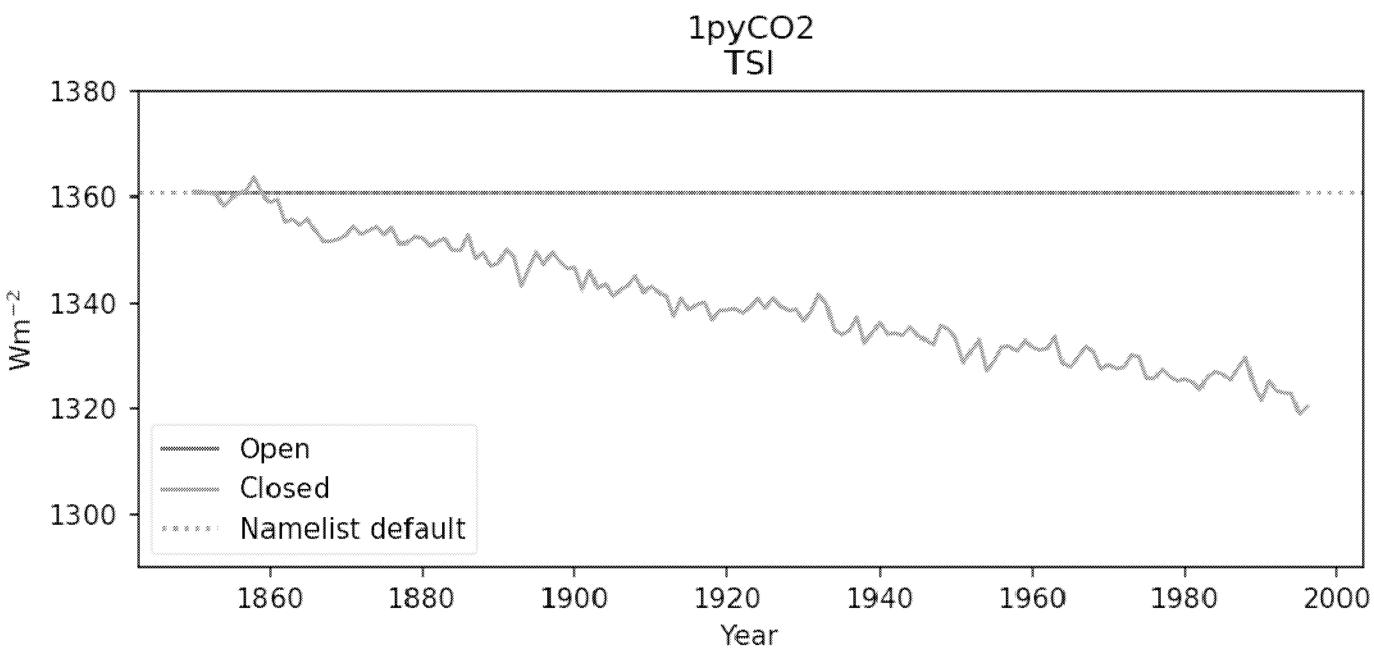
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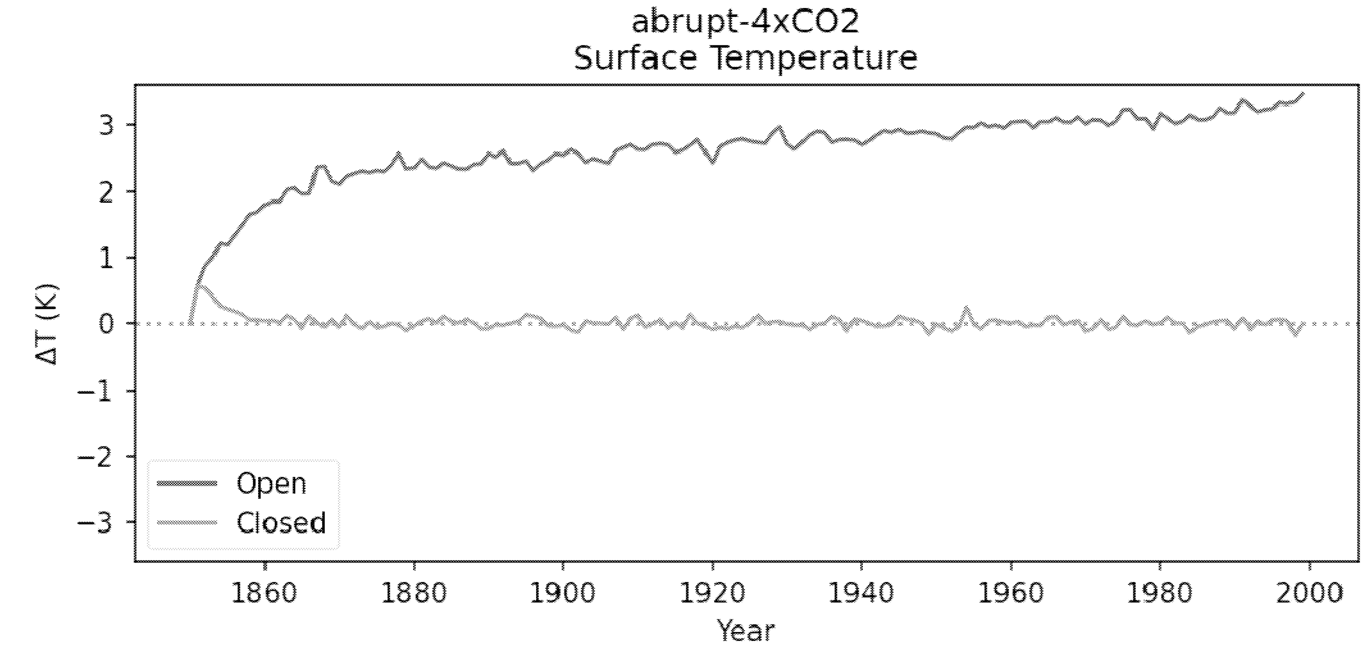
abrupt-4xCO2
Surface Temperature
ΔT (K)
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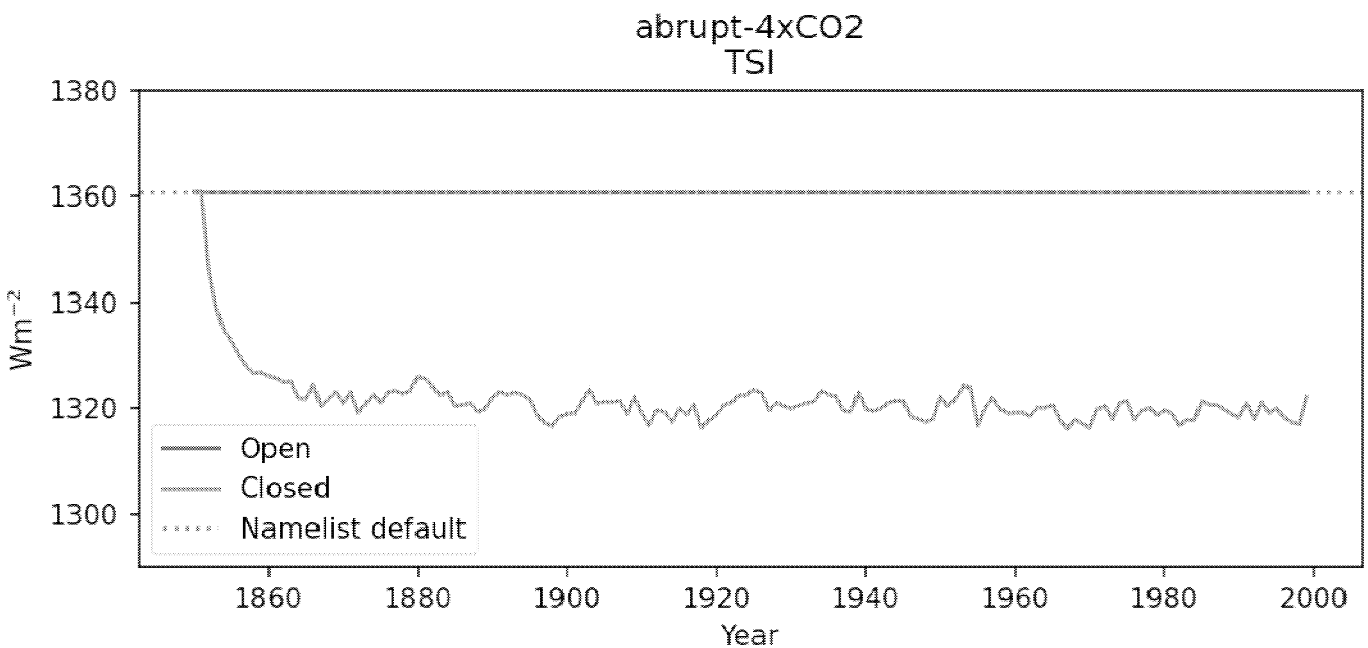
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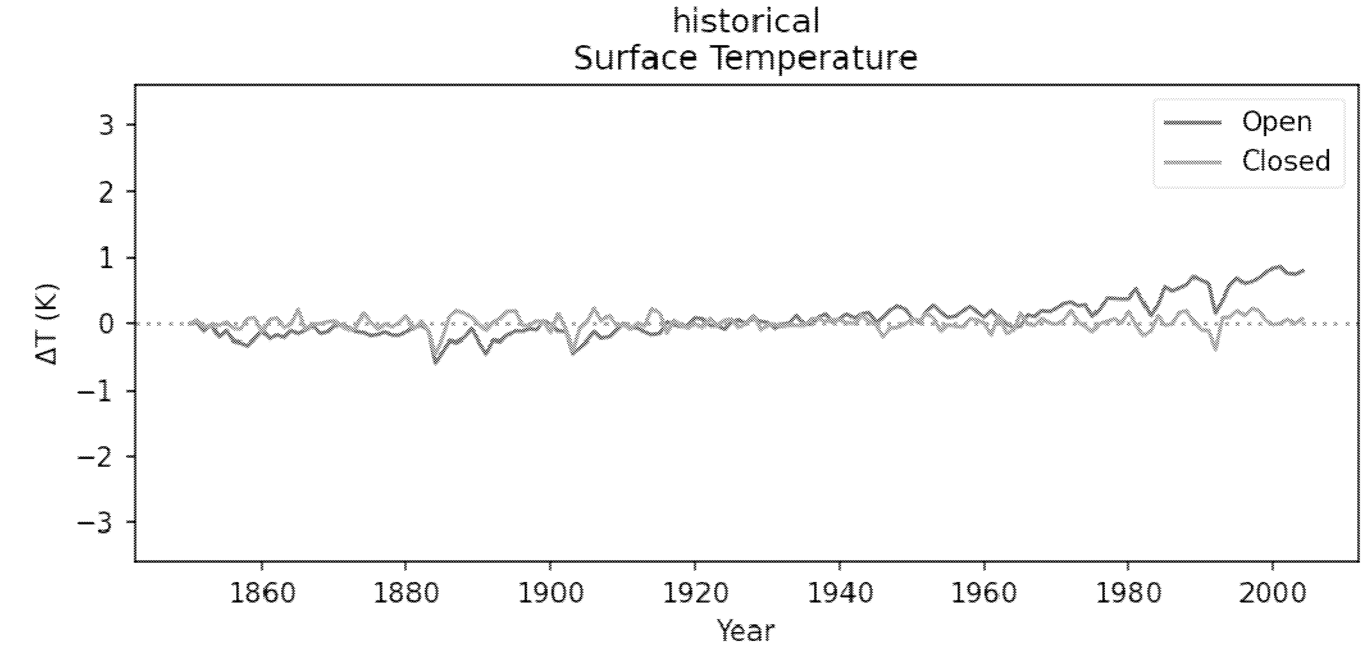
historical
Surface Temperature
ΔT (K)
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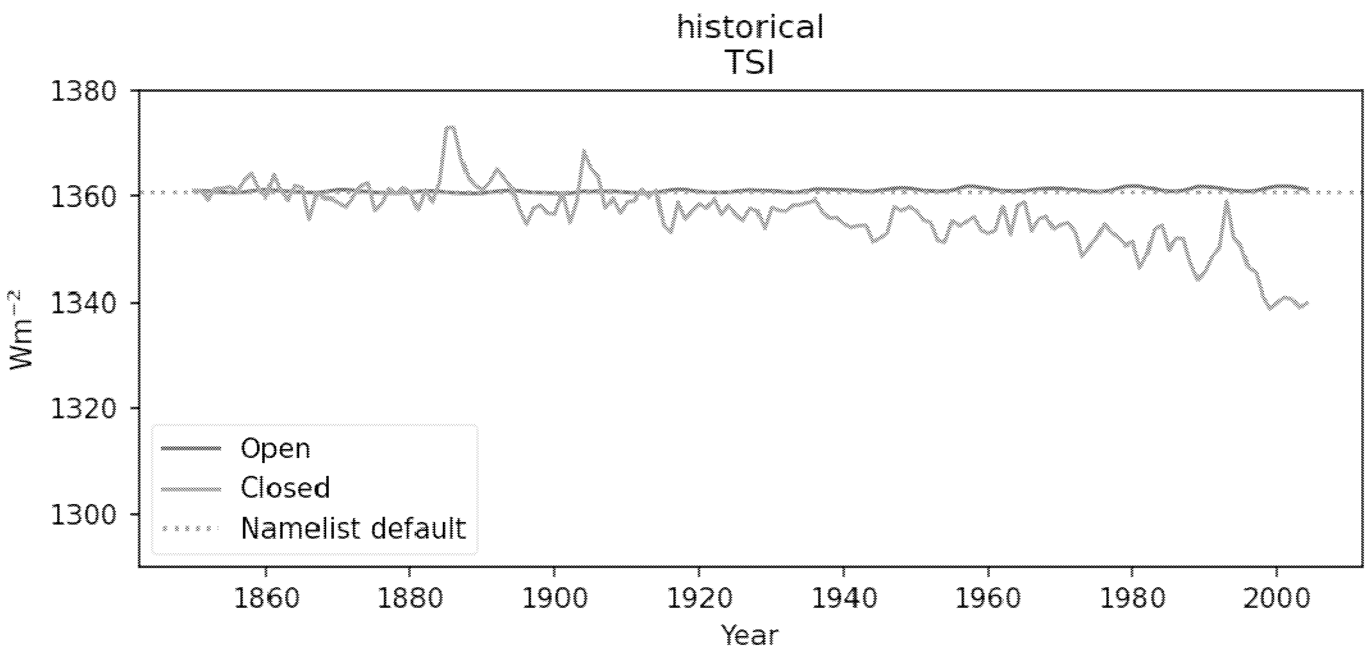
historical
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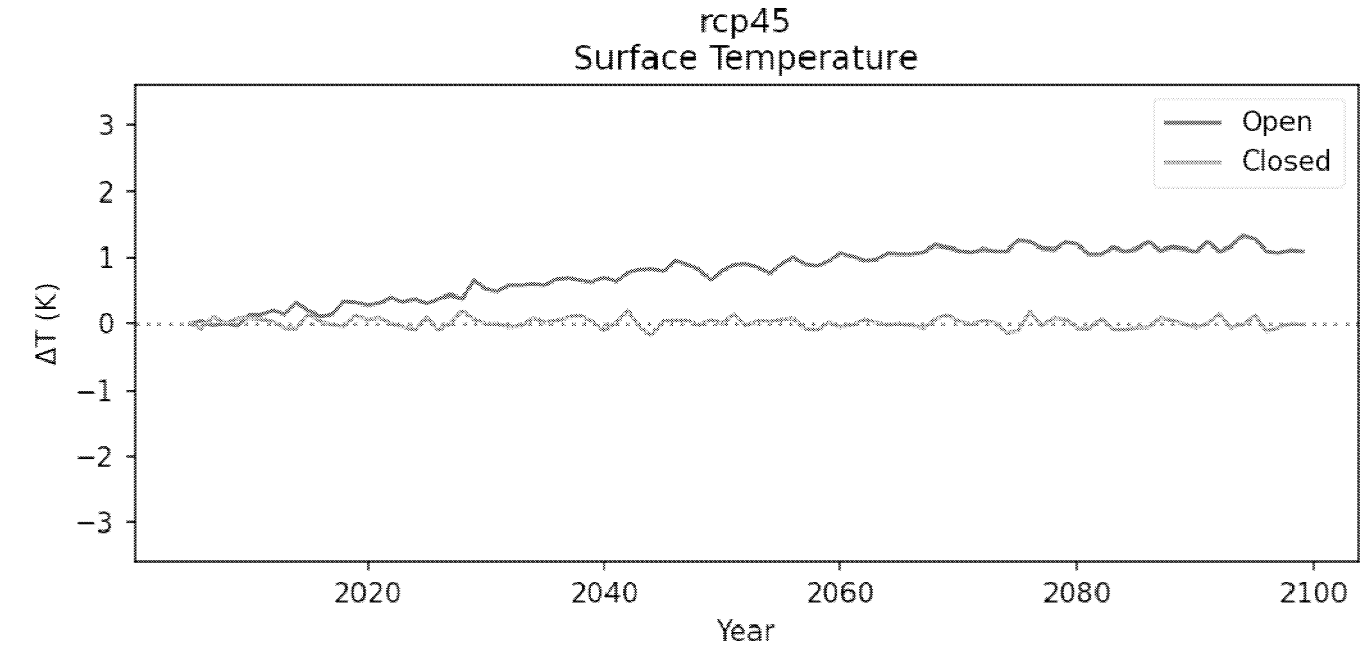
rcp45
Surface Temperature
ΔT (K)
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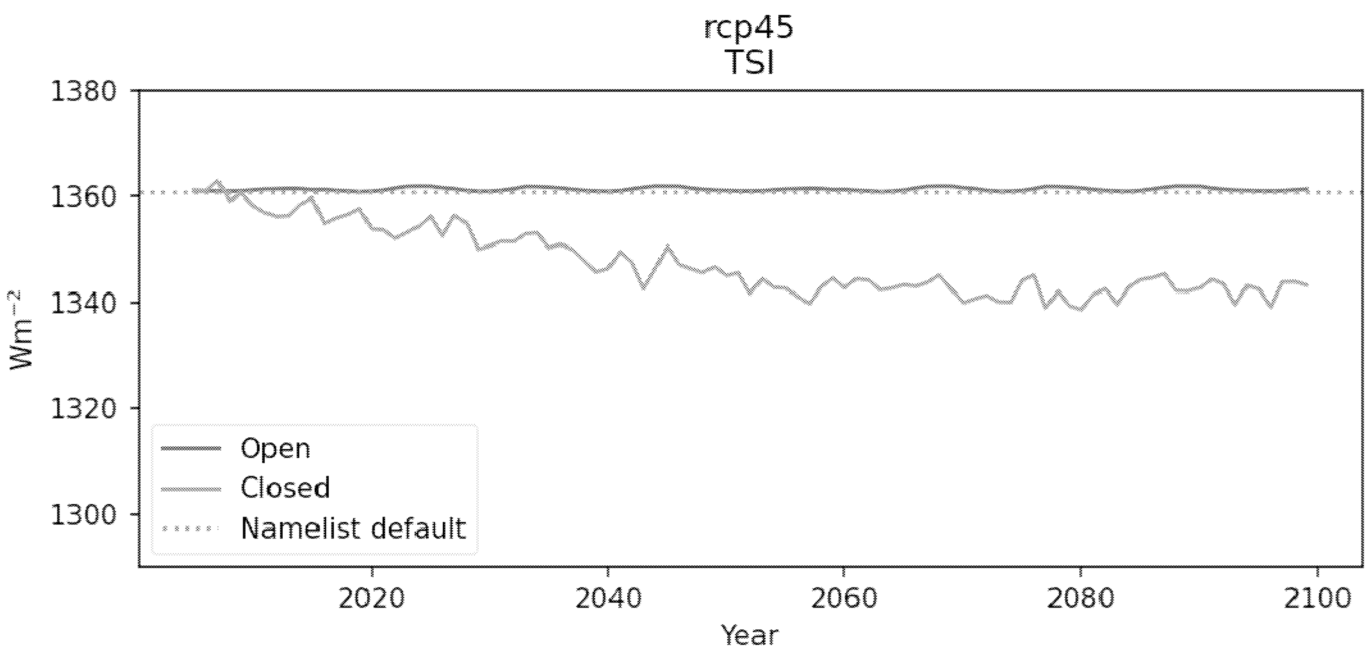
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TSI
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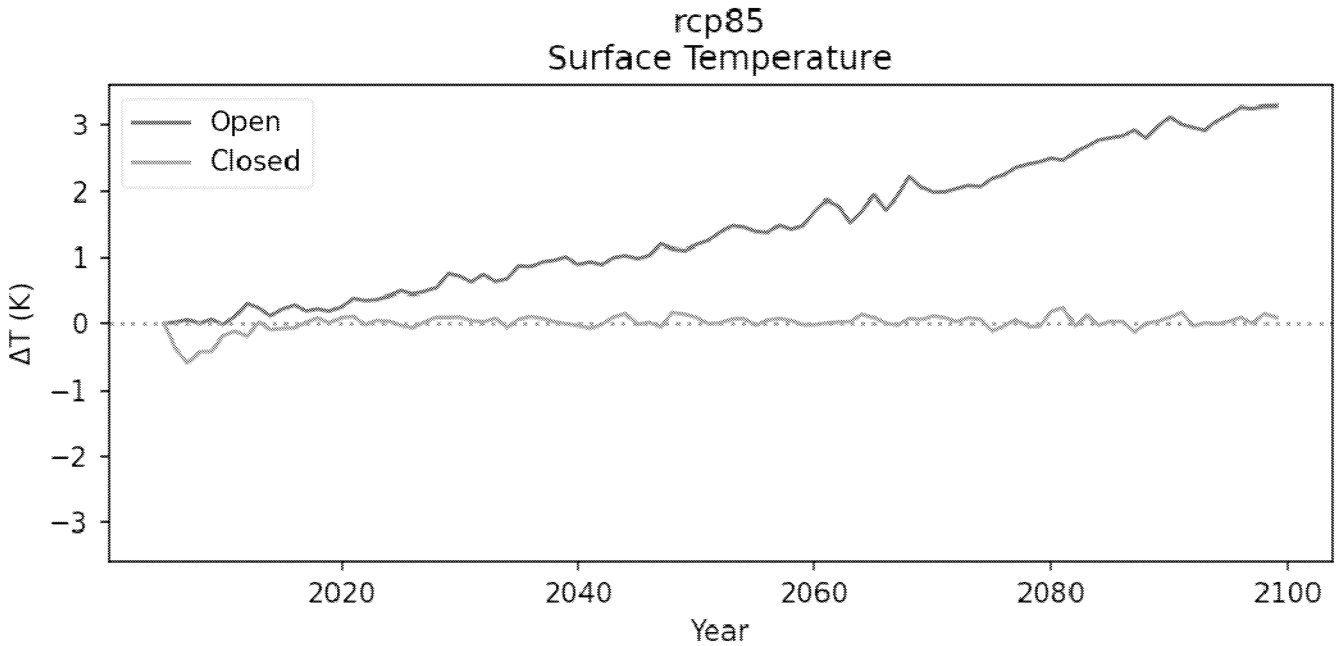
rcp85
Surface Temperature
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Closed
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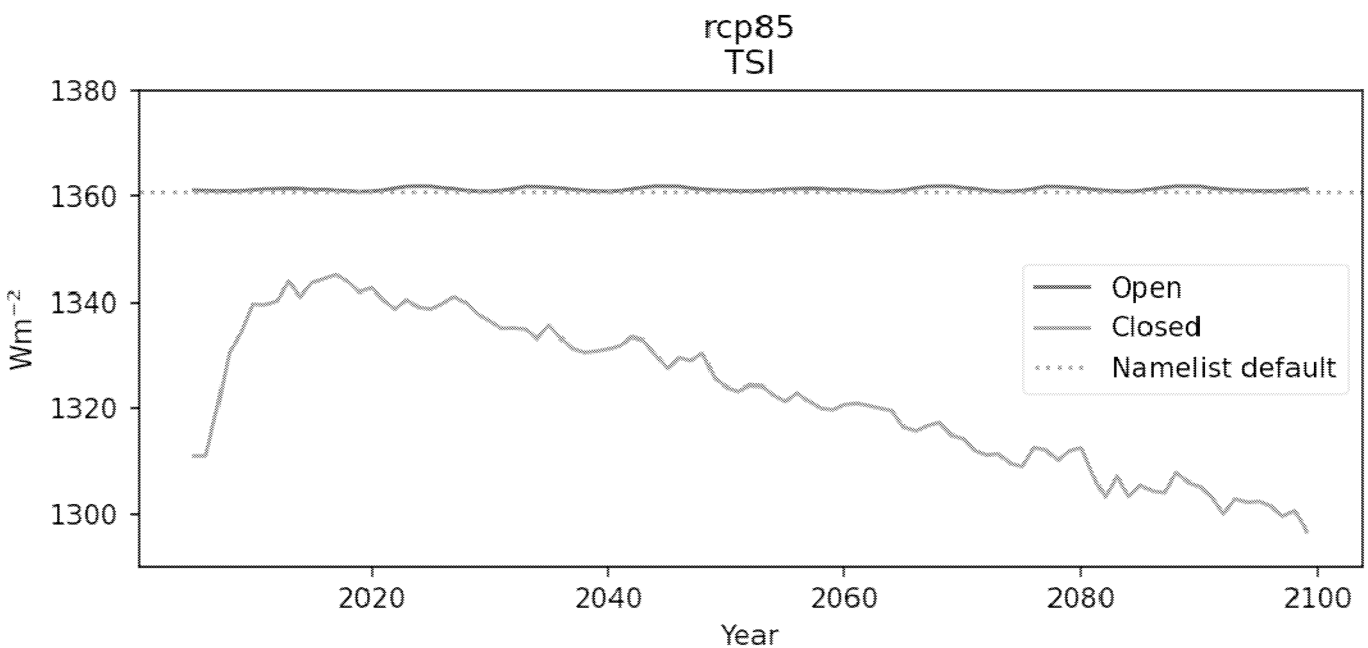
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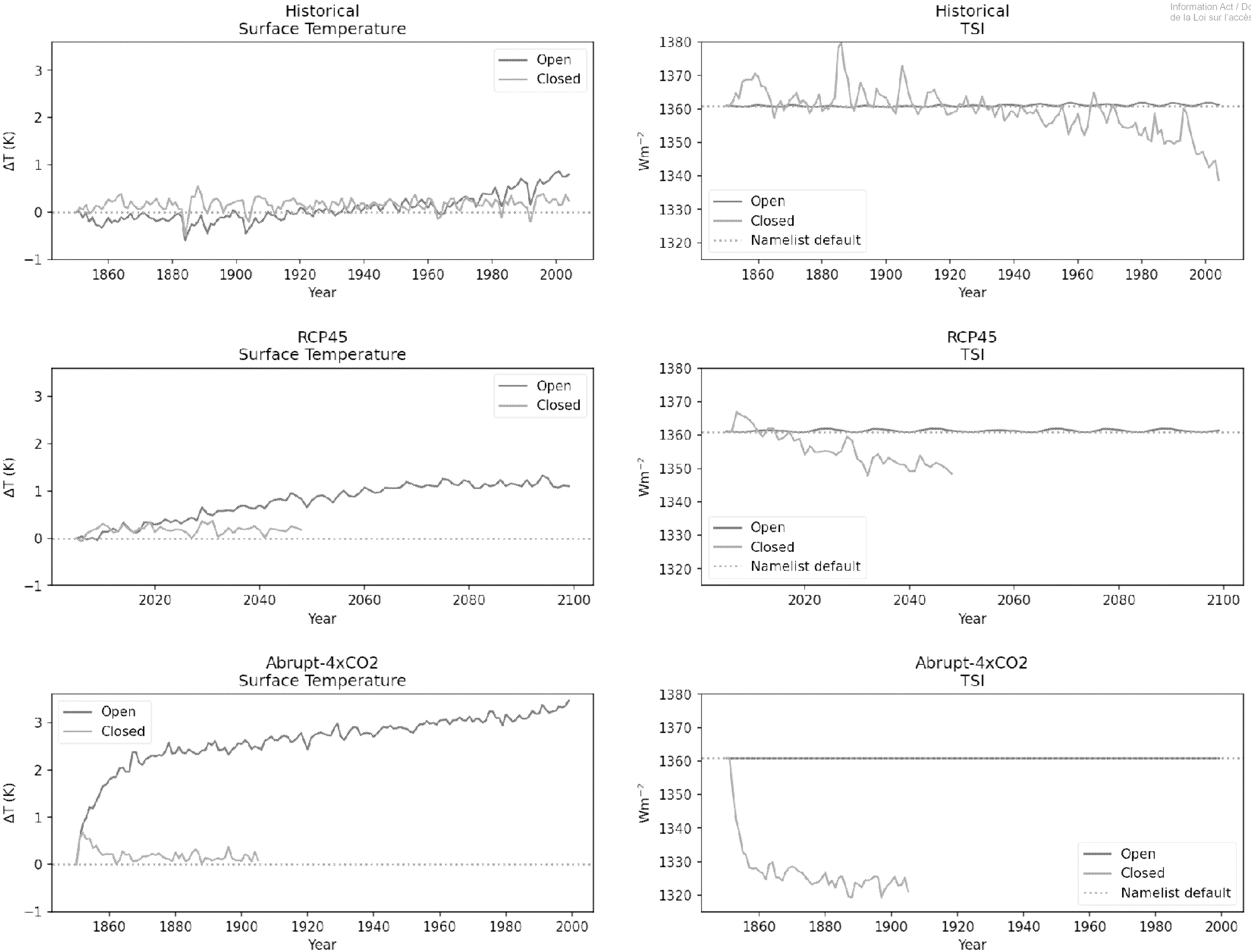

Historical
Surface Temperature
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Closed
Historical
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Wm^{-2}
Year
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Namelist default
RCP45
Surface Temperature
ΔT (K)
Year
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Closed
RCP45
TSI
Wm^{-2}
Year
Open
Closed
Namelist default
Abrupt-4xCO2
Surface Temperature
ΔT (K)
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Abrupt-4xCO2
TSI
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Year
Open
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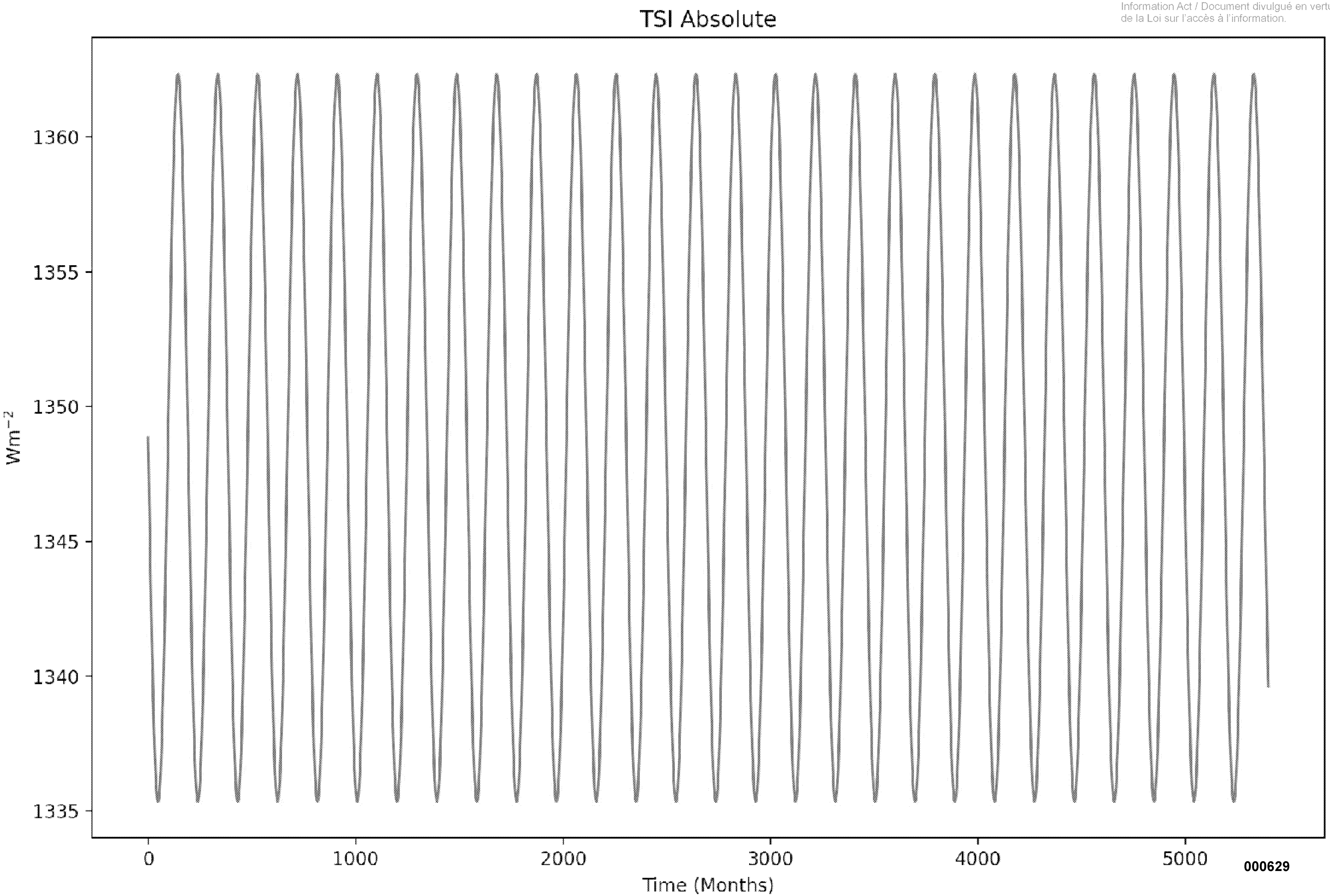
Namelist default


TSI Absolute
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4000
5000
Time (Months)

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: January 2, 2020 10:54 AM
To: Kravitz, Ben
Subject: Re: GeoMIP paper on storm tracks

Excellent. Having the GeoMIP meeting within the Gordon Conference will make it much easier for me to justify my attendance.

Jason

From: Kravitz, Ben <bkravitz@iu.edu>
Sent: Thursday, January 2, 2020 10:52 AM
To: Cole, Jason (EC)
Subject: Re: GeoMIP paper on storm tracks

Hi Jason -

Thanks for letting me know about the paper. And I'm glad to hear about your progress with the new experiments. I'm running behind too (I think GISS still hasn't finalized their SSP input files).

The next GeoMIP meeting will be held at the Gordon Conference this coming June/July. It will be a quick meeting (on a lunch break) because we won't have to do all of the science updates - that's what the GRC is for. It would be great to see you at the conference and to work more closely with you when you reconnect.

Best,

Ben

Ben Kravitz
Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
http://pages.iu.edu/~bkravitz/
Pronouns: he/him/his

From: "Cole, Jason (EC)" <jason.cole@canada.ca>
Date: Thursday, January 2, 2020 at 10:48 AM
To: "Kravitz, Ben" <bkravitz@iu.edu>
Subject: Re: GeoMIP paper on storm tracks

Hi Ben,

Thanks for the interesting paper and for the offer of co-authorship but I think I will not take the offer for this particular paper. The G1 data has been out for a while and the analysis is a bit outside of my area so I don't think I can contribute much to the paper.

While I am emailing you, a couple of GeoMIP related questions. FYI, we'll be doing the remaining GeoMIP experiments soon. I've had little time to work on the transient experiments and we had to deal with a supercomputer change so I decided to push them off until the switch.

Do you know where the next GeoMIP workshop will be held? Do you know of any other particularly useful meeting being held next year with respect to climate engineering? I see there is a Gordon Conference which I think might be useful plus I've enjoyed every one of them I've attended in the Radiation and Climate series. There is some increased interest in the climate engineering within my department and I want to try to reconnect a bit more after being focused more on other topics the last couple of years.

Jason

From: Kravitz, Ben <bkravitz@iu.edu>
Sent: Monday, December 30, 2019 11:29 AM
To: Shingo Watanabe; Olivier Boucher; Haywood, Jim; Jones, Andy; Andrew Lenton; steven.phipps@utas.edu.au; Cole, Jason (EC); John Moore; Duoying Ji
Cc: Charles Gertler; Paul O'Gorman
Subject: GeoMIP paper on storm tracks

Hi folks -

I've been involved with a paper led by Charles Gertler and Paul O'Gorman (CCed), looking at circulation changes in G1. We wanted to continue the GeoMIP tradition of offering coauthorship to the modeling groups that contributed output to this analysis.

I've attached a draft of the manuscript as it stands. There's still a little bit of analysis left to do, but it's mostly complete. We're aiming to have a submission date of January 13, which is two weeks from today. If you'd like to be involved, please let us know before then, and also please let us know if that date is too soon. I know that people may still be away from email for the holidays, so if you don't get a chance to respond before submission, please get in touch and we'll figure it out.

Best,

Ben

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Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
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bkravitz@iu.edu
http://pages.iu.edu/~bkravitz/

Pronouns: he/him/his

s.19(1)

Subject: Re: Dear GeoMIP group, Here's a link to our work on surface albedo modification of Arctic ice.
From: "Swart, Neil (EC)" <neil.swart@canada.ca>
Date: 7/2/20, 16:38
To: "Cole, Jason (EC)" <jason.cole@canada.ca>, "Sigmond, Michael (EC)" <michael.sigmond@canada.ca>

Yes, this does sound relevant. It would be good to learn more.

Neil

From: Cole, Jason (EC)
Sent: June 29, 2020 9:21 AM
To: Swart, Neil (EC); Sigmond, Michael (EC)
Subject: Fw: Dear GeoMIP group, Here's a link to our work on surface albedo modification of Arctic ice.

HI guys,

GeoMIP is holding a "virtual" meeting where one of the presentations is from ICE911. I've heard of them but not many details. Any interest in participating? The short description is they seem to be looking for simulations in which an ensemble of of simulations are performed: control, Arctic-wide sea-ice albedo modification and Fram Strait only sea-ice albedo modification. In theory this sounds fairly straight-forward. If there is interest, I'll ask for information about the experiment proposal they are preparing.

By the way, the technology they are proposing is hollow glass sphere on the sea-ice to increase its reflectivity (they have already done small field tests!). It might work to adjust the sea-ice albedo (unless the spheres get covered by snow?) but it seems like that this would have consequences (when the sea-ice melts will the spheres get into the ocean and eaten by sea creatures).

Jason

From: geomip-meeting-2020@googlegroups.com <geomip-meeting-2020@googlegroups.com> on behalf of Leslie Field ·
Sent: Monday, June 29, 2020 11:51 AM
To: GeoMIP Meeting 2020
Subject: Dear GeoMIP group, Here's a link to our work on surface albedo modification of Arctic ice.

https://drive.google.com/file/d/1TGVKHslt0pWmZUMRAy2q_8hXpy2dUaue/view?usp=sharing

We are preparing a GeoMIP proposal, and we are actively seeking collaborations.

--

Subject: Re: GeoMIP6 models table
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 6/10/20, 15:01
To: "Cole, Jason (EC)" <jason.cole@canada.ca>

Hi Jason -

Prescribing the G4 aerosols with an input field didn't work terribly well. MIROC-ESM did that, and when looking at the results, it was pretty clear that model was doing something totally different from the others. I think you could still do it, and it would be a welcome contribution, but if you want to go with the less work option, I wouldn't blame you.

Glad to hear about your progress on G6solar.

I think all of the fixed SST simulations are Tier 2. We included them in the sea spray round of GeoMIP as kind of an experiment to see who would do them and who would use them. The answer was "not too many people". So you're welcome to do them, but I wouldn't call them high priority.

Best,

Ben

Ben Kravitz
Assistant Professor
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Indiana University
1001 East 10th Street
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Tel: (812) 855-4334
bkravitz@iu.edu
http://pages.iu.edu/~bkravitz/
Pronouns: he/him/his

From: "Cole, Jason (EC)" <jason.cole@canada.ca>
Date: Wednesday, June 10, 2020 at 10:57 AM
To: "Kravitz, Ben" <bkravitz@iu.edu>
Subject: Re: GeoMIP6 models table

Hi Ben,

A couple of questions about the G6 experiments as I'm finally working on them.

1. The G6sulfur is only for models that can do sulfur injections? I recall that the G4 had the option to perform calculations using prescribed stratospheric aerosols but if that does not make sense for G6sulfur that is fine (less work for me).

2. I'm doing some trial simulations for G6solar to get the forcing correct for the

entire 2015-2100 period as the suggested protocol of rerunning decades is difficult due to how we run our model. Luckily I did transient ERF simulations for both scenarios so I'm pretty close with the forcing right off the bat, maximum decadal difference within 0.5 K. One or two more iterations should have the forcing correct and I can do the official G6solar simulations. If all goes well, these simulations will be done by end of June.

3. I should be able to perform the G6SST and piSST-4xCO2-solar with little effort since I've already done most of the similar RFMIP simulations. Are any of these a particular priority? If so I can do them first.

Jason

From: Kravitz, Ben <bkravitz@iu.edu>
Sent: Thursday, May 7, 2020 4:47 PM
To: Cole, Jason (EC); Simone Tilmes; mmills@ucar.edu; Roland Séférian; Olivier Boucher; Olivier Boucher; Helene Muri; Jones, Andy; Ulrike Niemeier
Subject: GeoMIP6 models table

Hi folks -

Now that people are starting to write papers, I'd appreciate your help in updating the models table:

https://docs.google.com/spreadsheets/d/1vFQdnCZwVCmD1CDUBlzfx-SoqDm4bnw4iVqdz6bBI70/edit#gid=0

Best,

Ben

Ben Kravitz
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Subject: [GeoMIP_list] G7cirrus status
From: "Kravitz, Ben" <Ben.Kravitz@pnnl.gov>
Date: 7/12/18, 15:06
To: "geomip_list@email.rutgers.edu" <geomip_list@email.rutgers.edu>

Hello everyone -

I have recently made a request to the CMIP6 working group to "demote" G7cirrus from Tier 1 to Tier 2. This is based on several discussions we have had at a few meetings regarding how well Earth System Models can simulate upper tropospheric ice water path and cirrus. The experiment will still be interesting for model intercomparisons to help understand how process changes can lead to changes on larger scales, which is why it will not be eliminated from the protocol entirely. I know CMIP6 is getting underway, so please feel free to spread the word to the relevant modeling teams.

Best,

Ben

Ben Kravitz
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GeoMIP_list mailing list
GeoMIP_list@email.rutgers.edu
https://email.rutgers.edu/mailman/listinfo/geomip_list

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Subject: [GeoMIP_list] G6solar/G6sulfur
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 5/31/19, 00:25
To: "geomip_list@email.rutgers.edu" <geomip_list@email.rutgers.edu>

Hi folks -

I'm getting a couple of inquiries about G6solar and G6sulfur. The specifications document that I sent around a few months ago is now online:

http://climate.envsci.rutgers.edu/GeoMIP/doc/G6specs.docx

If you feel like any necessary information is missing from that document, please let me know.

Best,

Ben

Ben Kravitz
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Tel: (812) 855-4334
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http://pages.iu.edu/~bkravitz/
Pronouns: he/him

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: January 6, 2020 11:21 AM
To: Bush, Elizabeth (EC)
Subject: Re: Geoengineering Modeling Research Consortium meeting synthesis

I should try to do more of that this year given that this topic is undoubtedly going to get more attention going forward.

Probably a good idea. I'm not sure if it has come up on your radar but CCCma (Knut, me and Vivek leading) development of a geoengineering request for Budget 2021. If you are around this week, I can stop by and summarize its current state. It would be good to get your thoughts since you've seen the interdisciplinary side of geoengineering more than us (certainly me).

Jason

From: Bush, Elizabeth (EC)
Sent: Monday, January 6, 2020 11:10 AM
To: Cole, Jason (EC)
Subject: RE: Geoengineering Modeling Research Consortium meeting synthesis

I signed up for Silver Linings newsletter. I haven't heard of them before but I really haven't been tracking climate engineering discussions recently. I should try to do more of that this year given that this topic is undoubtedly going to get more attention going forward. Looks like they've assembled an experienced well connected team of scientists.

Re CEC2020 – it is well targeted at people like me. I really like the interdisciplinary approach of the CEC conference. I'd love to go again, but I already do a lot of international travel for IPCC and UNFCCC so getting permission to go might be tough. I'll sound out Heather…….i expect I will be told that travel budgets are limited for 'nice to go' vs 'invited to go' conferences.
E

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: January 6, 2020 10:56 AM
To: Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>
Subject: Re: Geoengineering Modeling Research Consortium meeting synthesis

I'll let you know if I see anything about the bill. The Silver Lining NGO might be useful to keep an eye on as well. They seem fairly active in the US.

I didn't include it in the email but I also saw that there is the CEC20 Conference (https://www.ce-conference.org/). I think we discussed this conference when it was CEC17. Looks interesting but a bit too broad in scope for me to be effective at the conference (relative to the Gordon Conference).

Jason

From: Bush, Elizabeth (EC)
Sent: Monday, January 6, 2020 10:43 AM

To: Cole, Jason (EC)
Subject: RE: Geoengineering Modeling Research Consortium meeting synthesis

Hi Jason:

Thanks for keeping me in the loop on this topic. Interesting about Bill H.R. 5519……..if you hear about progress as it moves through the system, pls let me know. I'll try to keep a watching scan for updates (I didn't both to register directly for alerts on this bill).
I'll take a look at the synthesis report.
Cheers,
Elizabeth

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: January 3, 2020 1:10 PM
To: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>
Cc: Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; VonSalzen, Knut (EC) <knut.vonsalzen@canada.ca>
Subject: Geoengineering Modeling Research Consortium meeting synthesis

Hi all,

The synthesis document for the GMRC meeting I attended last September is now available: http://www.cgd.ucar.edu/projects/gmrc/files/2nd_GMRC_Meeting_Synthesis-FINAL.pdf.

A few related items.

1. It seems that a bill was introduced in the US to fund research and observations needed for climate engineering (https://www.silverlining.ngo/hr5519)

2. In a previous email chain we discussed the Community Climate Interventions Strategies (CCIS) Workshop and potential attendance from CCCma. I would suggest remote attendance at this workshop is sufficient. It looks like they presented the plenary talks remotely for the first workshop. I will plan to attend the GMRC meeting remotely.

3. Instead of the NCAR meeting I think, from the solar radiation management side of things, a more useful meeting is the Climate Engineering Gordon Research Conference (https://www.grc.org/climate-engineering-conference/2020/). I plan to submit a request to attend as the next GeoMIP meeting will be held at the conference (I just found out yesterday).

Jason

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: July 6, 2020 1:00 PM
To: Morrison2, Heather (EC)
Cc: Farahani, Ellie (EC)
Subject: Re: Harvard Geoengineering project

Hi Heather,

No, their focus is solar/thermal radiation management although the name of the consortium (Geoengineering Modeling Research Consortium) does not clearly convey this.

Here is their website: http://www.cgd.ucar.edu/projects/gmrc/ and mission statement,

"The mission of the Geoengineering Modeling Research Consortium (GMRC) is to identify and prioritize critical research gaps in climate modeling with specific significance to solar geoengineering, otherwise known as solar radiation modification (SRM), and to coordinate among U.S. researchers to close those gaps through collaborative model assessment and development efforts."

Jason

From: Morrison2, Heather (EC)
Sent: Monday, July 6, 2020 12:50 PM
To: Cole, Jason (EC)
Cc: Farahani, Ellie (EC)
Subject: Harvard Geoengineering project

Hi Jason,

Does that Harvard-led geoengineering science forum that you participated in (the one with the meeting in Boston) include CDR?

Thanks,

Heather

Heather Morrison, Ph.D.

A/Director Climate Research Division, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
heather.morrison2@canada.ca / Tel: 416-739-4761 / Cel. : 416-669-8592

Directrice Intérimaire Division de la recherche sur le climat / Direction générale des sciences et de la technologie
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heather.morrison2@canada.ca / Tél. : 416-739-4761 / Tél. cell. : 416-669-8592

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From:
s.19(1)

Sent: February 5, 2022 8:00 PM
To: Cole,Jason (ECCC)
Subject: RAP Proposal Draft
Attachments: CCCma_RAP_Proposal.pdf

Hi & Jason,

Attached is a draft of the RAP proposal document. I say draft because currently the methods are quite broad, but I hope the motivation is clear.

P.S. Jason, not sure if this is going to effect anything timeline wise but I'm currently having some trouble getting fingerprinting done for ECCC. Hopefully I can get it sorted by the end of next week. Another roadblock is that I'm required to prove citizenship using either a passport or original birth certificate.

Allison told me there might be a workaround but nothing has been confirmed yet.

UNIVERSITY OF WATERLOO
Mobile:
Email:

Website: https://
Skype:

000641

s.19(1)

Project

Examining a priori and a posteriori methods of modeling Solar Geoengineering comparatively using two Earth System Models.

Motivation

Modelling solar geoengineering using Earth System Models (ESMs) has evolved significantly since the first Geoengineering Model Inter-comparison Project (GeoMIP) (Kravitz et al., 2011a, 2013, 2015). Conventional approaches for idealized experiments, which in this case refer to guidelines in extra resources provided by GeoMIP, can be considered a priori (Kravitz et al., 2011b). For example, the G1 experiment aims reduce the solar constant such that it offsets the radiative forcing from an abrupt quadrupling of CO_2. The solar constant offset is obtained beforehand using a heuristic equation. The same solar constant offset obtained via these methods is used for the G2 experiment, which gradually reduces the solar constant against a 1% per yer increase of CO_2. Methodologies for carrying out more complex geoengineering experiments (e.g. stratospheric aerosol injections) become more disparate across modelling groups depending on structural differences between ESMs. For example, certain models may be required to specify variables such as aerosol distribution and/or distributions of aerosol optical depth (e.g. CNRM-ESM2-1), whereas others with fully prognostic aerosol treatment may only need to specify the injection point for an aerosol precursor (e.g. CESM2-WACCM) (Visioni et al., 2021).

Recently, studies proposing novel approaches of geoengineering execution have adopted a feedback algorithm with set geoengineering oriented temperature and precipitation goals (Kravitz, MacMartin, Wang, & Rasch, 2016; MacMartin, Kravitz, Keith, & Jarvis, 2014). Rather than approximating some level of "geoengineering", be it a globally averaged solar constant reduction or the location/magnitude of SO_2 injection a priori, the feedback is calculated based off of the preceding time window's deviation away from a given target (e.g. maintaining the present day historical equator-to-pole surface temperature gradient (Tilmes et al., 2018). The feedback is constantly adjusted relative to the distance away from the target with a predetermined time lag and as such this method can be considered a posteriori. A consequence of this approach being novel is its lack of widespread adoption across modelling centres, where most studies implementing a feedback approach have primarily done so with a version of the Whole Atmosphere Community Earth System Model (WACCM) (Tilmes et al., 2018; Kravitz et al., 2016, 2017; MacMartin et al., 2017; Zhang, MacMartin, Visioni, & Kravitz, 2021; Visioni et al., 2020). In particular for GeoMIP6, CESM2-WACCM was the only ESM that contributed simulations produced using such an approach (Visioni et al., 2021).

With this project, I propose expanding this approach to a multi-model framework whilst returning to an idealized experiment design in order to promote parity across models. A multi-model comparison of the same idealized solar geoengineering experiment using both a priori and a posteriori approaches would elucidate the both the effectiveness of each method from a modelling standpoint, as well as the inter-model uncertainty in residual climate response. In the context of the a posteriori approach, residual climate response refers to the climate response relative to present day excluding the desired geoengineering target goal.

Methods

I propose running the G6solar experiment as per GeoMIP guidelines using both CanESM5 and CESM2. Specifically, this involves gradually reducing the solar constant in a Shared Socioeconomic pathway (SSP) 5-8.5 simulation such that the global mean radiative forcing is reduced to its equivalent in SSP2-4.5 (O'Neill et al., 2016; Kravitz et al., 2015). Each experiment will be run using both methods outlined

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above. Particularly with regards to the a posteriori approach, the experiments will follow the Single Input-Single Output (SISO) feedback algorithm approach where the input is the solar constant reduction and the output is the effective radiative forcing from SSP2-4.5.

Expected Outcomes

Execution of the series of simulations outlined above will provide the first multi-model comparison the posteriori design approach as outlined in (MacMartin et al., 2014). In turn, this will explore the uncertainty of the approach across ESMs with the same inputs and output goals. Here, uncertainty can be measured via comparison of both feedback gain and time delay between CESM2 and CanESM5. Furthermore, such a comparison could illustrate the difference in residual climate response between both models. For the Centre for Climate Change Modeling and Analysis (CCCma), this work will provide the G6solar submission to GeoMIP6, as well as the validation and implementation of the SISO feedback algorithm framework for use with CanESM5.

References

Kravitz, B., Caldeira, K., Boucher, O., Robock, A., Rasch, P. J., Alterskjær, K., ... others (2013). Climate model response from the geoengineering model intercomparison project (geomip). *Journal of Geophysical Research: Atmospheres*, *118*(15), 8320 8332.

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Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Farahani,Ellie (ECCC)
Sent: February 20, 2022 10:37 PM
To: Cole,Jason (ECCC)
Subject: RE: Proposed work for Jack Virgin's RAP

Hi Jason,

Thank you very much! The project you defined seems well aligned with the climate engineering proposal which is part of the AdRen package and CCCma strategic priorities. Hopefully this will help us to get a head start with climate engineering simulations.

Ellie

Dr Ellie Farahani
(she, her, elle)

Acting Director, Climate Research Division, Science and Technology Branch
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ellie.farahani@ec.gc.ca | Tel: N/A during covid | Cell: +1-236-464-1175

Directrice intérimaire, Division de la recherche climatique, Direction générale de la science et de la technologie
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From: Cole,Jason (ECCC) <Jason.Cole@ec.gc.ca>
Sent: Sunday, February 20, 2022 6:51 AM
To: Farahani,Ellie (ECCC) <Ellie.Farahani@ec.gc.ca>
Subject: Proposed work for Jack Virgin's RAP

Hi Ellie,

Sorry for the delay getting this to you. It is Jack's proposed work for the RAP.

In short, he will be using the control system developed by Ben Kravitz and colleagues. He will perform and analyse climate engineering simulations of increasing complexity in which global reductions in incoming total solar radiation will be used to offset changes in the global mean temperature (single input/single output control system). He will do this with the NCAR CESM model and CanESM.

This will benefit CCCma by,

1. Submit a G6Solar simulation to GeoMIP. This was a simulation for CMIP6/GeoMIP that I was unable to complete due to challenges completing the simulation (it is complicated) and lack of time.

2. Testing the control system with CanESM. This will provide a basis going forward for climate engineering simulations including using it for multiple input/multiple output control systems.

3. A detailed analysis of GeoMIP simulations performed with CanESM with CESM.

Jason

Subject: RE: Climate Engineering
From: "Bolina2, Amandeep (EC)" <amandeep.bolina2@canada.ca>
Date: 9/30/19, 16:14
To: "Flato, Greg (EC)" <greg.flato@canada.ca>, "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>
CC: "Edwards, Patti (EC)" <patti.edwards@canada.ca>, "Anderson2, Kevin (EC)" <kevin.anderson2@canada.ca>, "Walker, Anne (EC)" <anne.walker@canada.ca>, "Carou, Silvina (EC)" <silvina.carou@canada.ca>, "Farahani, Ellie (EC)" <ellie.farahani@canada.ca>

Hi all,

Should you have any comments on the climate engineering paper, may kindly ask that you submit them by **3PM today**. Our consolidated comments will need to go to DGO by COB today.

Jason – I received your comments, thanks!

Thanks,
Amandeep

From: Bolina2, Amandeep (EC)
Sent: September 27, 2019 9:54 AM
To: Flato, Greg (EC) <greg.flato@canada.ca>; Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>; Cole, Jason (EC) <jason.cole@canada.ca>
Cc: Edwards, Patti (EC) <patti.edwards@canada.ca>; Anderson2, Kevin (EC) <kevin.anderson2@canada.ca>; Walker, Anne (EC) <anne.walker@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Subject: FW: Climate Engineering

Hi all,

Attached is the latest version of the Climate Engineering paper developed for the medium-term planning process. It is being shared with us again for comments/input. Please provide any comments you may have on the attached document by **COB Sept 30**.

Thanks,
Amandeep

From: Shepherd, Marjorie (EC) <marjorie.shepherd@canada.ca>
Sent: September 27, 2019 9:20 AM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Mullins, David (EC) <david.mullins@canada.ca>; Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>; Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
Subject: FW: Climate Engineering

Looping in Heather for CRD review. I will also review and we should provide integrated comments from myself, AQRD and CRD.
Mj

From: Moncrieff, Don (EC) <don.moncrieff@canada.ca>
Sent: September 27, 2019 8:27 AM
To: Shepherd, Marjorie (EC) <marjorie.shepherd@canada.ca>; Mullins, David (EC) <david.mullins@canada.ca>
Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>

Subject: FW: Climate Engineering

Hi,

Please see request below from the ADMO….is there anyone else you think should be looped in to provide comments on the attached document? Note the deadline of Oct 1st.

Don

Don Moncrieff

Bureau du Directeur général, Direction de Sciences et technologie atmosphériques
Environnement et Changement climatique Canada / Gouvernement du Canada
Don.Moncrieff@canada.ca / Tél: 613-998-7346

Director General's Office, Atmospheric Science & Technology Directorate
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Government of Canada Gouvernement du Canada Canada

From: Hayne, Shari (EC) <shari.hayne@canada.ca>
Sent: September 26, 2019 5:11 PM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Monforton, Amanda (EC) <amanda.monforton@canada.ca>; Vien, Julie (EC) <julie.vien@canada.ca>
Cc: Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hello,

Attached is the Climate Engineering paper developed for the medium-term planning process. Hilary Geller indicated that we don't have a government policy and inquired if it should be included in the National Climate Change Science and Knowledge plan.

Please provide input and comments on the paper and note ongoing discussions in the department and observations from the ECCC geoengineering working group to date (I believe Marjorie Shepherd and David Mullins were the STB representatives).

Due in ADMO Oct 1 COB

Thanks,
Shari

From: Goon, Amy (EC) <amy.goon@canada.ca>
Sent: September 20, 2019 9:56 AM
To: Hamzawi, Nancy (EC) <nancy.hamzawi@canada.ca>
Cc: Huddleston, Jeanne-Marie (EC) <jeanne-marie.huddleston@canada.ca>; Hayne, Shari (EC) <shari.hayne@canada.ca>; Chandler, Janina (EC) <janina.chandler@canada.ca>; Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hi Nancy,

Understand that you are looking for the Climate Engineering paper that was developed for the mitigation medium-term planning process. Please find it attached. It was a led by IAB, and has been DG approved. Input from the ECCC geoengineering working group (comprised of officials from STB, IAB, EPB, PCFIO) was sought.

Happy Friday!
Amy

-------- Original message --------
From: "Geller, Hilary (EC)" <hilary.geller@canada.ca>
Date: 2019-09-20 9:36 AM (GMT-05:00)
To: "Huddleston, Jeanne-Marie (EC)" <jeanne-marie.huddleston@canada.ca>
Cc: "Jones, Matt (EC)" <matt.jones@canada.ca>, "Hamzawi, Nancy (EC)" <nancy.hamzawi@canada.ca>
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Hilary.geller@canada.ca / Téléphone : 819 938-3782

EA/AE: Cheryl Devine (819) 938-3783

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Date: 9/30/19, 18:11
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Due in ADMO Oct 1 COB

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Hi Amandeep:

Sorry for coming in late with comments. I hope you can still pass these comments on.
Elizabeth

Introduction:

Editorial: Para three – first sentence – a word is missing after 'carried' I think. (carried out? Or replace with 'contained in"?)
Para three, second sentence: the statement of what is covered in the State of Climate Change Science transition doc on climate engineering is misleading.

- *In addition, a separate transition document on the state of science for climate change includes information on climate engineering as possible measures to counter global warming ~~addresses the current understanding of climate engineering~~ in the context of the gap between current mitigation efforts and the Paris agreement global temperature goal. ~~climate system response.~~*

Why Climate Engineering:
First sentence: the goal of the Paris Agreement is to hold the increase in global temp to well below 2C, and pursue efforts to hold it to 1.5C. While in the past, we sometimes used 1.5-2C to describe the Paris Agrt goals, this isn't really correct. So I'd suggest rephrasing the text here to simply say well below 2C. or, 1.5 – well below 2C.

- "There is currently a significant gap between national pledges under the Paris Agreement, and the emissions reductions required to hold the increase in global temperatures to ~~1.5 to~~ well below 2°C above pre-industrial levels.

Second sentence: it may be worthwhile being clear up front here that climate engineering may be proposed to slow down the rate of warming while enhanced mitigation is also pursued, just to be very clear that proponents are not positioning climate engineering as an alternative to more aggressive mitigation. Also, referring to research in this sentence doesn't make much sense as the research will not itself slow down the rate of global warming. Since the need for research is covered in the next sentence, I think the reference to research could be deleted here.

- "Pressure may grow to ~~research and~~ deploy climate engineering technologies to slow down the rate of global warming, in parallel with ongoing efforts to enhance mitigation action.

Gaps in Research, Global Governance and National Governance
Title: The text for this section doesn't address gaps in research **on** climate engineering. Rather it mentions a gap in governance **of** research on climate engineering. Suggest the title should be revised to reflect this, maybe just by striking out "Research" from the title.

First sentence: Another reason for the difficulties in getting consensus on climate engineering governance is the wide range of potential climate engineering methods. Governance requirements would be very different depending on the method, and certainly different for CDR vs SRM.

- "Consensus on climate engineering governance has been difficult to achieve in international fora,

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particularly due to the wide range of potential methods, and due to limited understanding of the science and risks associated with some of these ~~this issue."~~

Climate Engineering Methods – CDR section
Under 'natural' – shouldn't afforestation be included?

Under marine geoengineering: I think the various methods (ocean fertilization, ocean pumping to bring more nutrients to the surface, artificial downwelling (I'm not familiar with the latter but after a brief google search, it seems the objective is the same – to enhance CO2 uptake from the atmosphere and transport to the deep ocean) are all methods aimed at enhancing ocean carbon uptake and storage. Suggest editing this sentence to make that clearer. And I would suggest avoiding the term 'ocean carbon capture and storage' as the phrase 'carbon capture and storage' is used to refer to capturing Co2 from an emission source and not for removing additional CO2 from the atmosphere.

- **Marine geoengineering,** including ocean fertilization (i.e., spreading/distributing iron or other micronutrients to promote marine algal growth) and ocean pumping (i.e., artificial upwelling, downwelling) to enhance carbon uptake and storage in the deep ocean.

Under negative emission technologies: after direct air capture, should add "and storage or use". Capturing the CO2 from the air is just the first helf of the solution. They you have to store the CO2 permanently (or use it in an industrial application of some kind).

The para on page 3 about adverse effects seems to be missing a couple of things:

1. No mention of the big issue of potential land use conflicts if CDR is implemented at large scale (e.g. with land for agriculture)
2. The risk of leakage of CO2 from land storage deep underground was assessed by the IPCC to be very small, if I remember correctly. And leakages from land storage would not cause ocean acidification.

Page 4-8 (didn't have time to review. Sorry.)

Page 8 ; Scientific Research:
This sentence: "While research previously focused almost exclusively on theoretical and climate modelling of SRM technologies, researchers are conducting a growing number of real-world experiments." Makes it sound as though a number of real-world experiments have already been conducted and yet the text that follows only describes one cancelled experiments and a bunch of proposed experiments. Suggest being clear about the extent to which real-world experiments have already been carried out vs are being proposed, pending necessary approvals/governance?

Page 9 under Ethical Considerations:
SRM does not reduce the drivers of climate change. Edit needed:

- "It is important to acknowledge that while SRM can reduce/offset ~~the drivers of~~ anthropogenic climate change, it is not a "silver bullet" solution to the challenges of climate change.

Page 9 Main take aways:
It seems to me the first bullet could also say what climate engineering COULD be in addition to what it is not. Red text is a suggestion – you may find better words to convey the same thing.

- "Even with lower-risk forms of climate engineering, climate engineering should not be considered a substitute for mitigation and adaptation." Climate engineering might prove useful to help achieve climate targets if aggressive mitigation and adaptation measures fall short.

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Hi Amandeep,
Apologies for being late on this. In addition to Greg and Elizabeth's comments, I would propose the edits below.

Cheers,

Nathan

Why Climate Engineering?
Replace 'So far, Canada's position in international fora has been that the deployment of climate engineering technologies should not occur without adequate governance structures, or before more research is available' with 'Canada's position in international fora has been that the deployment of climate engineering technologies should not occur without adequate governance structures, or before more research is available'. (Including 'So far' makes it sound as though Canada may change its position to support deployment of geoengineering without adequate governance or further research.)

Carbon Dioxide Removal
Replace 'For example, Squamish, British Columbia's Carbon Engineering, formed in 2009' with 'For example, Climate Engineering, formed in 2009 in Squamish, British Columbia,'

Solar radiation management
After 'In doing so, these technologies could offset temperature increases associated with high concentrations of atmospheric CO2.' insert:
However, stabilising global mean temperature in the presence of ongoing CO2 emissions would require progressively strengthening SRM, and even stabilising warming at a lower level after CO2 emissions are reduced to zero would require a constant level of SRM to be continued indefinitely. SRM over a limited period of time would only potentially be useful in limiting peak warming under scenarios with strong mitigation to reduce CO2 emissions to zero, followed by CDR to remove CO2 from the atmosphere.
(I think there would be value in including some text here to indicate that if we are interested in limiting peak warming, and if we don't want to continue SRM for ever, then it's only in these peak and decline scenarios with negative emissions, that SRM could potentially make sense).

Scientific Research
First line replace 'in the field' to 'on this topic'. 'in the field' could be read as referring to field experiments, which is not what is meant here, as the next sentence discusses GEOMIP modelling experiments.

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Looping in Heather for CRD review. I will also review and we should provide integrated comments from myself, AQRD and CRD.
Mj

From: Moncrieff, Don (EC) <don.moncrieff@canada.ca>
Sent: September 27, 2019 8:27 AM
To: Shepherd, Marjorie (EC) <marjorie.shepherd@canada.ca>; Mullins, David (EC) <david.mullins@canada.ca>
Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>
Subject: FW: Climate Engineering

Hi,

Please see request below from the ADMO….is there anyone else you think should be looped in to provide comments on the attached document? Note the deadline of Oct 1st.

Don

Don Moncrieff

Bureau du Directeur général, Direction de Sciences et technologie atmosphériques
Environnement et Changement climatique Canada / Gouvernement du Canada
Don.Moncrieff@canada.ca / Tél: 613-998-7346

Director General's Office, Atmospheric Science & Technology Directorate
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Don.Moncrieff@canada.ca / Tél: 613-998-7346

Government of Canada Gouvernement du Canada Canada

From: Hayne, Shari (EC) <shari.hayne@canada.ca>
Sent: September 26, 2019 5:11 PM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Monforton, Amanda (EC) <amanda.monforton@canada.ca>; Vien, Julie (EC) <julie.vien@canada.ca>
Cc: Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hello,

Attached is the Climate Engineering paper developed for the medium-term planning process. Hilary Geller indicated that we don't have a government policy and inquired if it should be included in the National Climate Change Science and Knowledge plan.

Please provide input and comments on the paper and note ongoing discussions in the department and observations from the ECCC geoengineering working group to date (I believe Marjorie Shepherd and David Mullins were the STB representatives).

Due in ADMO Oct 1 COB

Thanks,
Shari

From: Goon, Amy (EC) <amy.goon@canada.ca>
Sent: September 20, 2019 9:56 AM
To: Hamzawi, Nancy (EC) <nancy.hamzawi@canada.ca>
Cc: Huddleston, Jeanne-Marie (EC) <jeanne-marie.huddleston@canada.ca>; Hayne, Shari (EC) <shari.hayne@canada.ca>; Chandler, Janina (EC) <janina.chandler@canada.ca>; Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hi Nancy,

Understand that you are looking for the Climate Engineering paper that was developed for the mitigation medium-term planning process. Please find it attached. It was a led by IAB, and has been DG approved. Input from the ECCC geoengineering working group (comprised of officials from STB, IAB, EPB, PCFIO) was sought.

Happy Friday!
Amy

-------- Original message --------
From: "Geller, Hilary (EC)" <hilary.geller@canada.ca>
Date: 2019-09-20 9:36 AM (GMT-05:00)
To: "Huddleston, Jeanne-Marie (EC)" <jeanne-marie.huddleston@canada.ca>
Cc: "Jones, Matt (EC)" <matt.jones@canada.ca>, "Hamzawi, Nancy (EC)" <nancy.hamzawi@canada.ca>
Subject: Climate Engineering

Hi JM,

There is a paper called "Climate Engineering" that is part of the suite of mitigation papers done over the summer

Could you please flip it to Nancy electronically

Thanks,
Hilary

Hilary Geller
Assistant Deputy Minister / Sous-ministre adjointe
Strategic Policy Branch / Direction générale de la politique stratégique
Environment and Climate Change Canada / Environnement et Changement climatique Canada
Hilary.geller@canada.ca / Téléphone : 819 938-3782

EA/AE: Cheryl Devine (819) 938-3783

s.19(1)

Subject: RE: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction
From: "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>
Date: 11/3/20, 15:13
To: "Cole, Jason (EC)" <jason.cole@canada.ca>, "Morrison2, Heather (EC)" <heather.morrison2@canada.ca>

tipped me off to a NOVA special called Can we Cool the Planet that aired this past weekend on PBS. I missed it and haven't yet tried to find it on demand. But I'm hoping I can find a way to watch it still.

The public conversation on climate engineering is mounting!

I have been trying to watch some of the C2G webinars on CDR and SRM. I have found them to be a good resource. Thanks for the link to the more technical info, Jason.
Elizabeth

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: November 3, 2020 9:07 AM
To: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Anderson2, Kevin (EC) <kevin.anderson2@canada.ca>; Walker, Anne (EC) <anne.walker@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>; Edwards, Patti (EC) <patti.edwards@canada.ca>; Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; Tam, Benita (EC) <benita.tam@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>; Luce, Sarah (EC) <sarah.luce@canada.ca>; Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
Subject: Re: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction

Thanks Heather. I saw this article but it was previously paywalled, at least for me.

Since many of the people mentioned in the article were at the NCAR CCIS workshop last week, here is a link to that effort: https://www.ccis.ucar.edu/. There should be a workshop summary in the near future, although one useful living document already up is a list of existing initiatives: https://docs.google.com/document/d/1E0Y-sz7vE8f-54v-WRSjFBj88fIHL-G_AaeC5zPkNJ0/edit.

My understanding is that there should be a new SRM report from the US National Academy of Sciences in the very near future. It was noted in the workshop, and the initiative list, that SRM will be addressed in the next WMO assessment about the Montreal Protocol.

I also see that geoengineering even was the topic of a video by Kurzgesagt this week: https://youtu.be/dSu5sXmsur4. My kids introduced me to this channel so it is at least being seen by some teens.

Jason

From: Morrison2, Heather (EC)
Sent: Tuesday, November 3, 2020 8:05 AM
To: Farahani, Ellie (EC); Cole, Jason (EC); Anderson2, Kevin (EC); Walker, Anne (EC); Carou, Silvina (EC); Edwards, Patti (EC); Bush, Elizabeth (EC); Tam, Benita (EC); Gillett, Nathan (EC); Luce, Sarah (EC); Bolina2, Amandeep (EC)
Subject: FW: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction

FYI -

As Climate Disasters Pile Up, a Radical Proposal Gains Traction https://www.nytimes.com/2020/10/28/climate/climate-change-geoengineering.html?referringSource=articleShare

Heather

Heather Morrison, Ph.D.

A/Director Climate Research Division, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
heather.morrison2@canada.ca / Tel: 416-739-4761 / Cel. : 416-669-8592

Directrice Intérimaire Division de la recherche sur le climat / Direction générale des sciences et de la technologie
Environnement et changement climatique Canada / Gouvernement du Canada
heather.morrison2@canada.ca / Tél. : 416-739-4761 / Tél. cell. : 416-669-8592

Subject: RE: Climate engineering modelling session
From: "Flato, Greg (EC)" <greg.flato@canada.ca>
Date: 9/5/19, 20:39
To: "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>

Hi folks,

I also thought this was a useful discussion. One thing I'm not so clear on is the extent to which a plume-resolving model or Lagrangian transport is really essential to modelling many of the things of interest related to SRM (David seemed to suggest this was the highest priority). I can see it for volcanoes and for aviation, but unless one is really interested in the details involving flight paths of delivery vehicles, for most of the physics related to SRM efficacy, radiative forcing, impacts and unintended consequences … more conventional transport modelling and parameterization schemes would seem very appropriate. Am I missing something fundamental?

Gregory M Flato, PhD

Senior Research Scientist
Canadian Centre for Climate Modelling and Analysis, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
greg.flato@canada.ca / Tel: 1-250-363-8233 / Cell: 1-250-514-5044

Chercheur Principal
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Environnement et changement climatique Canada / Gouvernement du Canada
greg.flato@canada.ca / Tél. : 1-250-363-8233 / Tél. Cell. : 1-250-514-5044

From: Gillett, Nathan (EC) <nathan.gillett@canada.ca>
Sent: September 5, 2019 12:33 PM
To: Cole, Jason (EC) <jason.cole@canada.ca>; Flato, Greg (EC) <greg.flato@canada.ca>
Subject: RE: Climate engineering modelling session

Hi Jason, Greg,
This all makes sense to me. By the way, regarding the plume modelling this was something that EPB were keen for us to do, because they want to get good estimates of climate impacts of aviation, including the effects of possible mitigation options – there was even an offer of support for this a couple of years ago. Their argument is that aviation is projected to account for an increasingly large fraction of global emissions, and it is a hard-to-mitigate sector, so modelling its climate effects will become increasingly important. To properly model the effects you need an embedded plume model. In the end after consultation we decided not to do this at that point, because it was orthogonal to our main model development plans. But something to keep in mind….

Cheers,

Nathan

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: September 5, 2019 8:48 AM
To: Flato, Greg (EC) <greg.flato@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>
Subject: Climate engineering modelling session

000664

Hi Greg and Nathan,

That was an interesting discussion. In case you are missed the modelling consortium that was mentioned (Geoengineering Modeling Research Consortium) it can be found here: http://www.cgd.ucar.edu/projects/gmrc/.

Greg: I liked your point about ECCC potentially indicating priorities with collaborators.

With respect to radiation management I'd suggest stratospheric aerosols, clouds (low and high cloud processes) and aerosol interactions with clouds are probably the main atmospheric processes (as was mentioned in the meeting). These are also areas I'd suggest are useful for our general modelling and predication capabilities. For example, Landon's work, in collaboration with USask, to have out stratospheric aerosols move toward a prognostic model is useful for the volcanic eruptions and would be a first step the complexity mentioned in the meeting.

Jason

s.19(1)

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Farahani,Ellie (ECCC)
Sent: November 25, 2021 7:08 PM
To: Cole,Jason (ECCC)
Cc: Petersen,Tiffany (ECCC)
Subject: RE: Proposal for FSWEP student

Hi Jason,

First and foremost, please let me know if [redacted] has been previously employed under one of the student programs (FSWEP, Co-op, or RAP) or if he is registered in a PSC approved Co-op program.

Also I need the following information from you:
- Your project description (<1500 words)
- Keywords for your project
- [redacted] CV

We can use 'Software Engineer' but it would be helpful to add some relevant keywords of the project to his title.

Thanks,
Ellie

Dr Ellie Farahani (she, her, elle)

Manager, Canadian Centre for Climate Modelling and Analysis (CCCma)
Science and Technology Branch | Environment and Climate Change Canada
ellie.farahani@ec.gc.ca | +1-236-464-1175

Gestionnaire, Centre canadien de la modélisation et de l'analyse climatique (CCmaC)
Direction générale des sciences et de la technologie | Environnement et Changement Climatique Canada
ellie.farahani@ec.gc.ca | +1-236-464-1175

Government of Canada Gouvernement du Canada Canada

From: Cole,Jason (ECCC) <Jason.Cole@ec.gc.ca>
Sent: Wednesday, November 10, 2021 8:51 AM
To: Farahani,Ellie (ECCC) <Ellie.Farahani@ec.gc.ca>
Cc: Petersen,Tiffany (ECCC) <Tiffany.Petersen@ec.gc.ca>
Subject: RE: Proposal for FSWEP student

Hi Ellie and Tiffany,

I'll get back to you about the candidate. I currently have a list of 5 students that are potentially interested but they only have been given a high level description of the project. I'll now share a more detailed description with the students and if I have more than one still interested, I'll hold interviews. Once I have a candidate, I'll let you know. I'll try to complete this by the middle of next week.

Tiffany, is this an acceptable way to proceed?

Jason

From: Farahani,Ellie (ECCC) <Ellie.Farahani@ec.gc.ca>
Sent: November 10, 2021 11:45 AM
To: Cole,Jason (ECCC) <Jason.Cole@ec.gc.ca>
Cc: Petersen,Tiffany (ECCC) <Tiffany.Petersen@ec.gc.ca>
Subject: RE: Proposal for FSWEP student

Hi Jason and Tiffany,

Jason, what you propose sounds good. You can ask your candidate to apply to FSWEP and then sharing the name of applicant so we can ask the program to pull that applicant for us.

Tiffany, can you update our student budget adding this one?

Thanks,
Ellie

Ellie Farahani, PhD, MBA
(she, her, elle)

Manager, Canadian Centre for Climate Modelling and Analysis (CCCma)
ellie.farahani@ec.gc.ca | Tel: N/A during covid | Cell: +1-236-464-1175

Gestionnaire, Centre canadien de la modélisation et de l'analyse climatique (CCmaC)
ellie.farahani@ec.gc.ca | Tél. : N/A pendant covid | Portable: +1-236-464-1175

From: Cole,Jason (ECCC) <Jason.Cole@ec.gc.ca>
Sent: Wednesday, November 10, 2021 8:16 AM
To: Farahani,Ellie (ECCC) <Ellie.Farahani@ec.gc.ca>
Subject: Proposal for FSWEP student

Hi Ellie,

Following up on your comments at the management meeting about funds being available for students in the remainder of this fiscal year.

If it is possible I'd like to hire an upper year undergraduate student through FSWEP for a part-time (half time) position for January-March 2022. Rather than pull randomly from FSWEP, I made contact with a faculty member at York University who has identified a few students that would be suitable. I believe I can make targeted request of a student that is in the FSWEP database.

I would like to have the student work with me so I can make progress on the work item I have to support climate engineering,

"Review forcing feedback methodology for solar radiation management which will be needed for more complex scenarios. Report on potential application in CanESM"

I have identified a potential approach which is clearly laid out in a paper by Ben Kravitz and I believe is the same method used at NCAR. The student would work with me to test application of the approach in CanESM. While the student would working with me on first steps, we would be working toward a goal of reproducing the results in the Kravitz paper using CanESM5 and reproducing previous CanESM5 GeoMIP simulations using the methodology. Once that is in hand we would look at expanded application of the approach for climate engineering.

The benefit of this project would allow us to use CanESM for more complex climate engineering, in particular SRM, scenarios. It should also significantly reduce the need for me to manually adjust SRM forcings in CanESM simulation to meet particular targets which will become more difficult and time consuming as the targets become more complex. This will be very beneficial for future climate engineering research using CanESM.

I also think that the forcing feedback methodology might have benefits beyond climate engineering applications, although that is to be explored.

Thanks,

Jason

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Kravitz, Ben <bkravitz@iu.edu>
Sent: November 20, 2021 4:06 PM
To: Cole,Jason (ECCC)
Subject: Re: Feedback control for CanESM5 climate engineering simulations

Perfect! I'll get in touch with you in about a week.

Best wishes,

Ben

Ben Kravitz (he/him/his)
Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
https://climatemodeling.earth.indiana.edu

From: "Cole,Jason (ECCC)" <Jason.Cole@ec.gc.ca>
Date: Saturday, November 20, 2021 at 4:05 PM
To: "Kravitz, Ben" <bkravitz@iu.edu>
Subject: RE: Feedback control for CanESM5 climate engineering simulations

Hi Ben,

I forgot it was US Thanksgiving this week until I saw your away message. No rush on my side. I was given the green light to hire an undergraduate student to help me with this starting in January so if you had time at some point before mid-December that would be great. I know this is a busy time of the year for professors. The week of Nov. 29th should be possible, I just have a few meetings I need to attend during the week but I'm free otherwise.

Jason

From: Kravitz, Ben <bkravitz@iu.edu>
Sent: November 20, 2021 3:12 PM
To: Cole,Jason (ECCC) <Jason.Cole@ec.gc.ca>
Subject: Re: Feedback control for CanESM5 climate engineering simulations

Hi Jason -

Great to hear from you! I agree with you - manual adjustments aren't the most fun. I'd be happy to chat about the best way to do this. Thanksgiving week is here, and I was hoping to take some time off, so would you be okay with setting up something the week of November 29th? Or were you looking forward to getting started earlier?

Best,

Ben

Ben Kravitz (he/him/his)
Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
https://climatemodeling.earth.indiana.edu

From: "Cole,Jason (ECCC)" <Jason.Cole@ec.gc.ca>
Date: Friday, November 19, 2021 at 2:46 PM
To: "Kravitz, Ben" <bkravitz@iu.edu>
Subject: Feedback control for CanESM5 climate engineering simulations

Hi Ben,

I hope you are doing well. As the subject line indicates, I am looking at starting a, hopefully small, project to implement feedback control in CanESM5. My experience trying to do the last round of GeoMIP simulations, e.g., G6Solar, with CanESM5 highlighted to me that I need a better approach than manual adjustments. I can see the manual approach becoming less and less tractable as the complexity of the targets and forcing increase.

I've read through your nice 2016 paper in ESD and that seems like a very good place to start. Since a few years have passed since you published the paper, I wanted to touch base with you to see if you have done any improvements to approach or any experiences about things one should watch out for. Any input would be appreciated.

Thanks,

Jason

s.19(1)

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From:
Sent: December 3, 2020 4:30 PM
To: Cole, Jason (EC)
Subject: Re: AGU presentation link

Excellent, thanks.

After this last set of AEW calls, I'm very interested to see how the final selection shakes down. Let me know if anything interesting happens during the SALT discussions. I do feel ALI and SHOW have some positive momentum right now, and the teams are realizing the value of the enhancements from the instruments. Fingers crossed.

We did manage to pull off a letter from 7 university VPRs to the new CSA president to push for support of A-CCP Canadian activities. It was delivered on Monday night.

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: December 3, 2020 2:27 PM
To:
Subject: Re: AGU presentation link

Thanks. It seems to be accessible outside of the AGU meeting. I shared it with management and so far it has been well received both in terms of a summary of HAWC, content and presentation. I'll let you know if anything interesting comes back down the pipe.

Jason

From:
Sent: Thursday, December 3, 2020 12:01 PM
To: Cole, Jason (EC)
Subject: Re: AGU presentation link

Hi Jason,

Sure, this should be it. I think you have to be registered for the meeting and logged in to see it.

https://agu2020fallmeeting-agu.ipostersessions.com/?s=04-0B-96-28-B7-D9-C5-D3-32-D3-3C-32-04-69-90-B4

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s.19(1)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: December 3, 2020 10:46 AM
To:
Subject: AGU presentation link

CAUTION: External to USask. Verify sender and use caution with links and attachments. Forward suspicious emails to phishing@usask.ca

Hi

Could you point me to a non-editable link for the AGU presentation for HAWC in the geoengineering session? I'd like to send it to my manager.

Jason

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: December 10, 2020 11:28 AM
To: Farahani, Ellie (EC)
Cc: Von Salzen, Knut (EC)
Subject: Re: HAWC mission description in AGU geoengineering session

Hi Ellie,

Based on the text in red below, there seems to be an action on us to get in contact with Lisa-Marie.

Is this something we want to begin profiling through the SBEO channels? [I think so. I'm going to share your comments with Jason and Ellie and ask them to touch base with your re: example of what this could look like.]

I think it would be worth profiling this as well, especially given that the CS2050 document was recently made publicly available and it included climate engineering. From the CSA side, I know Thomas Piekutowski has been suggesting these instruments would have value for stratospheric aerosol observation, monitoring and potential dectection.

Would you like me to reach out to Lisa-Marie?

Jason

From: Morrison2, Heather (EC)
Sent: Thursday, December 3, 2020 2:34 PM
To: Cole, Jason (EC); Farahani, Ellie (EC); Von Salzen, Knut (EC)
Subject: FW: HAWC mission description in AGU geoengineering session

See below...

From: Morrison2, Heather (EC)
Sent: December 3, 2020 2:33 PM
To: Vaccaro, Lisa Marie (EC) <lisamarie.vaccaro@canada.ca>; Henry, David (EC) <david.henry@canada.ca>
Subject: RE: HAWC mission description in AGU geoengineering session

Hi LMV – See below...

From: Vaccaro, Lisa Marie (EC) <lisamarie.vaccaro@canada.ca>
Sent: December 3, 2020 2:02 PM
To: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Henry, David (EC) <david.henry@canada.ca>
Subject: RE: HAWC mission description in AGU geoengineering session

Cool! Thank you for sharing these findings Heather. I have two comments/observations:

1. I see climate engineering as a topical science piece to help inform ASTD priorities and/or the "to be developed" strategic plan, particularly in relation to informing (future) policies and regulations and/or response actions

[Agreed. It is one of the CRD priorities and is highlighted as such in our CRD ESM Strategic Plan, which we'll be ready to share shortly.]

2. Is this something we want to begin profiling through the SBEO channels? [I think so. I'm going to share your comments with Jason and Ellie and ask them to touch base with your re: example of what this could look like.]

    a. In my call out to the Branch seeking 'SBEO science in action" highlights, from CRD I received a highlight on FTS technology for improving GHG measurements, linked to a potential AOM. In sharing the inventory of 'highlights' that I pulled together, the SBEO Strategic Plan pen-holders recently expressed interest in using this example in the Plan (and David for your benefit, the EOLakeWatch is another example likely to be incorporated into the Strategic Plan). Not only did I communicate to CSA that the 'highlights' provided could be considered in the Strategic Plan, but it is a useful inventory, preliminary albeit, to dip into for other various SBEO products and communications. Let me know what you think.

3. This is one of the neatest websites I've visited to illustrate scientific information ☺ Totally agree. Very cool. I think this is how the conferences are now handling the virtual posters.

LMV

From: Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Sent: December 3, 2020 1:33 PM
To: Vaccaro, Lisa Marie (EC) <lisamarie.vaccaro@canada.ca>; Henry, David (EC) <david.henry@canada.ca>
Subject: FW: HAWC mission description in AGU geoengineering session

Fyi... In case you haven't seen this already, this is an excellent summary of the proposed Canadian contribution to ACCP.

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: December 3, 2020 12:48 PM
To: Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Cc: Von Salzen, Knut (EC) <knut.vonsalzen@canada.ca>
Subject: HAWC mission description in AGU geoengineering session

Hi Ellie and Heather,

Just wanted to give you a heads up about a poster being presented at the AGU next week on which I am a co-author: https://agu2020fallmeeting-agu.ipostersessions.com/?s=04-0B-96-28-B7-D9-C5-D3-32-D3-3C-32-04-69-90-B4.

It will be in the geoengineering session but it is not a modelling poster. Rather it highlights the ability of the TICFIRE, ALI and SHOW instruments to observe aerosols, clouds and radiation in the UTLS to baseline current conditions as well as its potential to detect and observe intentional injection of aerosols for climate engineering purposes. The three instruments are currently under consideration for the ACCP mission being lead by NASA with a launch around 2030.

This (home-grown) observation system nicely parallels the work we proposed for the climate engineering modelling.

Jason

s.19(1)

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: November 19, 2020 9:47 AM
To:
Cc:
Subject: Re: AGU poster in geoengineering session

Hi /

Unfortunately, I don't have anything substantive I could add from the modelling side beyond the typical point that these observations would be useful to inform the evaluation and guidance for model development. Our internal proposal to support model development and application to understand the impacts of climate engineering has been put forward but no decisions made.

I think the advertisement of HAWC and Landon's analysis is useful, especially in that session. Could you maybe indicate on the poster that HAWC also provides the ability to observe the current state of the UTLS? This will make it possible to put any observations of intentional aerosol injection into context.

I'd like to share this poster internally. I'm still hopeful that HAWC will be included in ACCP but if it is not, letting people know that the observations taken by HAWC would be useful for observing and monitoring the UTLS would be good. It nicely complements the modelling and application work we are proposing and the observations are in line with the efforts funded in the US.

Jason

From:
Sent: Wednesday, November 18, 2020 4:57 PM
To: Cole, Jason (EC)
Cc:
Subject: AGU poster in geoengineering session

Hi Jason,

You might remember that Landon and I put together an abstract for an AGU poster on the Canadian A-CCP instrument suite (see below).

The deadline of Nov 20 for the e-posters caught me off guard so I am essentially out of time to put anything detailed together. But I thought I might try to still put something together to advertise the three instruments, and show one of the limb+lidar cases from the Raikoke eruption that Landon has been analyzing as a sample scenario.

Do you want to add anything from the ECCC/modelling perspective?

Thanks,

Monitoring high altitude aerosol injections and climate impacts from a new Canadian instrument suite concept (HAWC)

Adam Bourassa, Landon Rieger, Doug Degenstein, Jason Cole, Jeff Langille, Jean-Pierre Blanchet, Yann Blanchard

As interest in solar radiation management geoengineering through intentional injection of stratospheric aerosols continues to develop so does the necessity to monitor high-altitude aerosol emissions and their climatic impact. Although potential emission scenarios often require significant amounts (Tg) of aerosols, initial regional tests are unlikely to be at this scale, requiring measurement systems capable of early detection, and understanding of feedbacks on climate. A system capable of making these high-sensitivity and high-precision measurements is the High altitude Aerosols, Water vapour and Clouds (HAWC) system which is a suite of three Canadian instruments designed for space-based Earth observations, and proposed by Canada as part of the NASA A-CCP mission study. HAWC is composed of the Aerosol Limb Imager (ALI), Spatial Heterodyne Observation of Water (SHOW) and Thin Ice Clouds and Fire Infrared Emissions (TICFIRE). ALI and SHOW measure limb scattered sunlight, with vertical resolution of 500m, and long path lengths that provide excellent sensitivity to levels of aerosol and water vapour not possible from nadir mappers. Combined with the upwelling thermal radiation measurements from TICFIRE, the combination of instruments will allow for early detection of aerosol formation as well as important feedback mechanisms through water vapor and ice clouds. This work investigates the capability of the ALI instrument and retrievals to measure small amounts of aerosol injected in the UTLS. Further explored are the synergistic capabilities that HAWC provide in measuring and understanding aerosol-water-cloud interactions produced by small-to-moderate stratospheric injection geoengineering scenarios.

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Hi folks -

Here's a revised version of the new G1 comparison paper. There are a couple of things in here that are flagged for me to do, but I don't see that as a reason to delay sending this to you. I'd love to get comments back within the next two weeks if possible. At that point, we'll re-evaluate whether there is anything major or whether this is ready for submission.

Best,

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Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP)

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Abstract

Solar geoengineering has been receiving increased attention in recent years as a potential temporary solution to offset global warming. One method of approximating global-scale solar geoengineering in climate models is via solar reduction experiments. Two generations of models in the Geoengineering Model Intercomparison Project (GeoMIP) have now simulated offsetting a quadrupling of the CO_2 concentration with solar reduction. Here we show that energetics, temperature, and hydrological cycle changes in this experiment are statistically indistinguishable between the two ensembles. Of the variables analyzed here, the only major differences involve highly parameterized and uncertain processes, such as cloud forcing or net primary productivity. We conclude that despite numerous structural differences and uncertainties in models over the past 20 years, broad conclusions about the climate response to global solar dimming remain robust.

Keywords: geoengineering, climate engineering, solar radiation management, climate modeling

Three main points

1. Two solar dimming model ensembles are statistically indistinguishable for many variables
2. Largest ensemble differences are in highly parameterized and uncertain processes
3. Past results about solar dimming are robust to some structural model differences and uncertainties

Suggested reviewers

- Piers Forster
- Don Wuebbles
- Peter Irvine
- Long Cao
- Ken Caldeira
- Govindasamy Bala

1. Introduction

Solar geoengineering describes a set of technologies designed to (ideally) temporarily, deliberately reduce some of the effects of climate change by changing the radiative balance of the planet, often by reflecting sunlight back to space (NRC, 2015). Numerous methods have been proposed, but arguably the most studied is stratospheric sulfate aerosol injection (Budyko, 1977; Crutzen, 2006). This method involves creating large amounts of highly reflective sulfate aerosols in the stratosphere, replicating the mechanisms that cause cooling after large volcanic eruptions (Robock, 2000). In model simulations of solar geoengineering, solar reduction is often used as a proxy for actual stratospheric sulfate aerosols, as it captures many of the broad radiative effects of stratospheric aerosol geoengineering as well as some of the important climate effects (Niemeier et al., 2013; Kalidindi et al., 2015). Any implementation of stratospheric geoengineering with sulfate aerosols would produce additional effects, such as changing atmospheric circulation in response to stratospheric heating and heating gradients (e.g., Simpson et al., 2019; Jones et al., 2020), ozone depletion (e.g., Pitari et al., 2014), and resultant changes in ultraviolet radiation flux, and enhanced diffuse radiation at the surface, but here we consider the major, large-scale effect of reflecting sunlight to cool Earth.

Simulations of solar geoengineering with solar reduction have long shown that solar geoengineering would cool the planet, offsetting global warming (e.g., Govindasamy and Caldeira, 2000; NRC, 2015; Irvine et al., 2016). Idealized simulations of solar reduction have also been simulated in a multi-model context under the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2011), to understand the robust model responses to various standardized solar geoengineering simulation designs. Multi-model conclusions from these studies indicate that solar geoengineering would be effective at partially offsetting greenhouse gas-induced temperature changes (Kravitz et al., 2013a), as well as changes in the hydrological cycle (Tilmes et al., 2013), the cryosphere (Moore et al., 2014), extreme events (Curry et al., 2014; Aswathy et al., 2015), vegetation (Glienke et al., 2015), circulation (Guo et al., 2018; Gertler et al., 2020), agriculture (Xia et al., 2014), and numerous other areas. However, the offset is not perfect (Moreno-Cruz et al., 2012), particularly on a regional basis or when considering multiple simultaneous metrics of climate change (Kravitz et al., 2014; Irvine et al., 2019; Jones et al., 2020), leading to concerns about winners and losers from geoengineering (Ricke et al., 2010). To some extent, the effects of solar geoengineering may be tailored or designed (MacMartin et al., 2013; Kravitz et al., 2016, 2017, 2019), but solar geoengineering will still not be able to perfectly offset climate change from greenhouse gases.

The previous phase of GeoMIP was associated with the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), an international collaboration of climate models to attempt to understand robust model responses to various forcings. GeoMIP has now entered a new phase, concurrent with the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016), and with it are new solar geoengineering simulations with new and updated versions of Earth System Models (Kravitz et al., 2015). As such, this is an opportunity to revisit some central questions in solar geoengineering. Many of the CMIP5 results regarding solar geoengineering showed substantial agreement across the participating GeoMIP models. In this newest iteration of GeoMIP, do the same science conclusions still hold, and do the models still generally agree on the resulting climate effects? Here we address these questions by evaluating and comparing general climate model response to GeoMIP experiment G1 (described in the next section) from both CMIP5 and CMIP6.

2. Simulations and Participating Models

In this study, we evaluate GeoMIP experiment G1, in which, starting from a preindustrial control (piControl) baseline, the atmospheric CO_2 concentration is instantaneously quadrupled (the standard CMIP experiment abrupt4xCO2), and insolation is simultaneously reduced such that net top-of-atmosphere (TOA) radiative flux is approximately unchanged from the baseline in the first decade of simulation (Kravitz et al., 2011, 2015). This experiment was part of the original suite of GeoMIP experiments and was repeated in the newest suite in an effort to understand the role of model structural uncertainty in broad conclusions about solar geoengineering. Participating models are listed in Table 1. We include 13 models from CMIP5 and 7 models from CMIP6.

Because the main focus of this paper is a comparison between the CMIP5 and CMIP6 eras of model results, we have opted for the following to aid comparisons:

- The original G1 experiment was 50 years in length, whereas the CMIP6 version is 100 years in length to allow for better analyses of rare events or to capture very slow responses. Since we are not evaluating any features that require 100 years of statistics, and the results do not show any appreciable time evolution of behavior after the first couple of years (see Supplemental Section 2 and Supplemental Figures 1 and 2), we only evaluate the first 50 years of all simulations. All maps show changes over years 11-50, removing the initial transient period.
- We do not compare previous versions of individual models with current ones, instead only examining ensembles. Even though models may share similar development histories (e.g., atmosphere and ocean dynamical cores, convective parameterizations, radiative transfer modules, terrestrial biosphere and cryosphere, etc.; Knutti et al., 2013; Zelinka et al., 2020), there have been numerous developments in models in these areas (and others) between CMIP5 and CMIP6 such that in most cases a direct comparison would not be meaningful.
- We focus extensively on the G1 results and, with few exceptions, do not focus on the corresponding abrupt4xCO2 simulations. It has been well documented that the CMIP6 models tend to have higher climate sensitivities than the CMIP5 models (Flynn and Mauritsen, 2020; Meehl et al., 2020; Zelinka et al., 2020), so we do not wish to make conclusions that might be based on a form of selection bias.
- All lack of stippling on map plots, as in previous GeoMIP studies (e.g., Kravitz et al., 2013a), indicates agreement on the sign of the response in at least 75% of models. Because $G1_{CMIP5}$ has more participating models than $G1_{CMIP6}$, this threshold provides some consistency across analyses of the ensembles. When plotting differences between the ensembles ($G1_{CMIP6}$-$G1_{CMIP5}$), there is no stippling, as it is difficult to meaningfully represent such differences between ranges. Aggregate differences between the two

ensembles, as calculated using Welch's *t*-test or differences in stippled area, are discussed in Supplemental Table 1.

3. Results

3.1. Energetics

Ensemble mean radiative and turbulent flux quantities are plotted in Figure 1, and the ensemble ranges are plotted in Supplemental Figure 3. An immediate observation is that, in both ensembles, the models were successful at limiting net TOA radiative flux change to within approximately ±0.1 W m^{-2} of the models' respective preindustrial values. Accomplishing this required an average solar reduction of 4.14% (models range in 3.20–5.00%) in CMIP5 and 4.14% (3.72–4.91%) in CMIP6. As such, despite numerous structural changes between the two generations of models, there is no appreciable change in solar efficacy (Hansen et al., 2005).

None of the radiative flux quantities indicate large transients over 50 years of simulation of G1, other than the initial flux change within the first year or so of simulation, which is consistent with the "perpetual fast response" found by Kravitz et al. (2013b). Ensemble mean fluxes show few differences (<1 W m^{-2} in magnitude) with the exception of shortwave cloud forcing, defined as all-sky minus clear-sky shortwave flux at the surface. On average, the CMIP6 ensemble has 3–4 W m^{-2} less shortwave cloud forcing than CMIP5. Neglecting some outliers, for each flux except shortwave (and hence total) cloud forcing, the median model in one ensemble is within the inter-quartile range of the other ensemble. This indicates that there are no major differences between the ensembles in how the models handle energy balance and energetics, with the exception of clouds, which is consistent with findings about CMIP5 (Zelinka et al., 2020). Moreover, it appears that most of the major differences in shortwave cloud forcing are due to outliers in each ensemble, positive for CMIP5 and negative for CMIP6.

To further explore these potential differences, Supplemental Figure 4 provides maps of the ensemble means for cloud forcing. In G1, the CMIP5 ensemble showed more positive shortwave cloud forcing and more negative longwave cloud forcing (i.e., more cancellation) than the CMIP6 ensemble. Overall, the CMIP6 ensemble has greatly reduced (in some places by over 10 W m^{-2}) shortwave cloud forcing as compared to CMIP5 under the G1 experiment. This is a widespread result, but the most prominent features are in the tropics, especially over the Amazon, Africa, and the Maritime Continent. The reasons behind these forcing changes are difficult to diagnose, as they could be due to changes in cloud thickness, cloud cover, or cloud level between CMIP5 and CMIP6 models (e.g., Vignesh et al., 2020), differences in how solar geoengineering affects clouds (Russotto and Ackerman, 2018), or artifacts of the analyses (e.g., cloud masking; Andrews et al., 2009; Kravitz et al., 2013b). Moreover, based on the results in Supplemental Figure 3, it is likely that many of these features are exaggerated by outlier models (also see Vignesh et al., 2020). As such, we reserve such detailed investigations for future work.

3.2. Temperature

These small flux changes also lead to few G1 temperature changes between the two ensembles. Figure 2 shows global, land, and ocean-averaged temperatures for the CMIP5 and CMIP6 ensembles. In general, the abrupt4xCO2 simulation in CMIP6 has higher temperatures than in CMIP5, consistent with the noted increase in climate sensitivity (Flynn and Mauritsen, 2020; Meehl et al., 2020; Zelinka et al., 2020). In both ensembles, G1 is effective at offsetting global mean temperature change, in some cases with a slight positive residual temperature change over land. Supplemental Figure 5 shows three aggregate temperature metrics: global mean temperature, the interhemispheric temperature gradient, and the equator-to-pole temperature gradient (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016). As for the fluxes, the median model in one ensemble is within the inter-quartile range of the other ensemble. This indicates that no ensemble is on average warmer than another, has a substantially warmer Northern or Southern Hemisphere than the other, or has warmer tropics or poles than the other. We can conclude that spatial patterns of temperature change from G1 are robust across a wide range of structural uncertainty.

The spatial structure of temperature change (Figure 3) does have small differences between the two ensembles. G1 in CMIP6 has multiple locations that are warmer than G1 in CMIP5, despite both ensembles achieving net energy balance at TOA and the surface (Figure 1). The majority of the differences are over land and in the tropics, where CMIP6 is slightly warmer than CMIP5 (up to a degree in some places). Nevertheless, both ensembles show the well noted feature that offsetting a CO_2 increase with solar reduction overcools the tropics and undercools the poles (Govindasamy and Caldeira, 2000; Kravitz et al., 2013a). CMIP6 shows slightly less high latitude warming than CMIP5, but temperature differences between the two ensembles are largely negligible. However, the warmer temperatures in CMIP6 near Greenland have important implications for ice sheet melt and consequent sea level rise, as well as bottom water formation. We reserve such analyses for future investigations, particularly since the models used here are not capable of simulating the eustatic component of sea level rise. In any case, these ensemble mean differences between CMIP5 and CMIP6 cannot be deemed statistically significant (Supplemental Table 1 and Supplemental Figure 4).

3.3. Hydrological and Other Integrative Changes

Figure 4 shows ensemble mean changes in precipitation (P), evaporation (E), and P–E for $G1_{CMIP5}$ and $G1_{CMIP6}$. Qualitatively, patterns are similar between both ensembles. Precipitation is slightly (<0.3 mm/day in magnitude) different in the tropics between the two ensembles. The majority of those features can be summarized as a more southward ITCZ, more precipitation in the South Pacific Convergence Zone, and less precipitation over Southeast Asia and the Maritime Continent in CMIP6. Evaporation in the two ensembles is nearly identical except for more evaporation in Amazonia and Australia in CMIP6. As such, the net P–E change between the two ensembles strongly resembles the precipitation changes. Supplemental Figure 6 shows that, like previous evaluations of ensemble ranges, the median model in one ensemble falls well within the interquartile range of the other ensemble for P, E, and P–E. As such, we cannot conclude any robust hydrological cycle changes between the two ensembles.

Figure 5 shows average (years 11–50) temperature change (with respect to piControl) plotted against average precipitation change for each model, as in Tilmes et al. (2013). Other than a potentially greater climate sensitivity of some CMIP6 models, there is no distinguishable difference in aggregate behavior between the two ensembles. The same conclusion discovered by Tilmes et al. (2013) holds: solar reduction cannot simultaneously offset CO_2-induced changes in both global mean temperature and global mean precipitation.

As an integrator of CO_2, temperature, and precipitation effects over land, Figure 6 shows changes in terrestrial net primary productivity (NPP). Numerous land regions, mostly aligned with those showing reduced precipitation in Figure 4, have lower NPP in CMIP6 than in CMIP5. The ensemble average global NPP change (G1–piControl) is 50.9 (4.1–120.9) Pg [C] y^{-1} in CMIP5 and 41.1 (23.0–77.2) Pg [C] y^{-1} in CMIP6, representing a 19.3% difference in means. Jones et al. (2013) used NPP to highlight the importance of understanding the influence of structural land model differences on climate results related to geoengineering. While it is beyond the scope of this study to perform a detailed diagnosis of which uncertainties or processes are responsible for this inter-ensemble difference, we point out that the ensemble spread of total terrestrial NPP is smaller in CMIP6 than in CMIP5, perhaps due to selection bias or perhaps due to some of these uncertainties being addressed in this newest generation of models.

4. Discussion and Conclusions

Based on the results presented here, model response to G1 has not changed substantially between CMIP5 and CMIP6. The sign of residual climate impacts (for example in temperature) are in better agreement in CMIP5 than CMIP6 (see Supplemental Table 1), but this could be a function of the smaller ensemble size in CMIP6. Energetics, temperature, and the hydrological cycle are qualitatively and quantitatively similar in both ensemble means and ensemble ranges, although these variables are somewhat related, so we might expect them to all portray a similar picture. Notable differences do exist in shortwave cloud forcing and NPP, particularly in Amazonia, Africa, and Australia, which are also regions of inter-ensemble difference in precipitation.

From these findings, we can conclude that results obtained over the past 20 years of study have not been overturned by the latest round of simulations. All of the major ensemble differences highlighted above deal with clouds and land surface modeling, both of which are difficult to model and are necessarily highly parameterized. The conclusions that are based on more fundamental knowledge, such as column energetics (in the case of the hydrological cycle), are relatively robust to structural uncertainty, in so far as this study adequately captures representative variations in structural uncertainty. This lends confidence to our conclusions, especially regarding robustness to uncertainty, about the broad climate effects from solar geoengineering methods that can be accurately represented via solar dimming.

We also conclude that the models used in CMIP5 are not obviously biased or inferior as compared to CMIP6. While improvements have been made in the CMIP6 generation of models, and those models are likely better for representing numerous features of the present-day climate that may be important for studies of geoengineering, there are many aspects of climate that are well represented by earlier models. In some cases, more robust analyses may be enabled by augmenting ensemble sizes with archived output from earlier generations of CMIP models.

There are numerous aspects of physical climate that we did not evaluate, nor did we pursue analyses beyond physical climate, including many other aspects of natural science, social science, the humanities, governance, justice, or ethics (to name a few important areas). A holistic assessment of the consequences of geoengineering would certainly need to take these numerous aspects into account. Nevertheless, based on the results presented here, results for geoengineering across several important metrics appear to be robust to some amount of structural uncertainty. This lends confidence to some conclusions regarding solar geoengineering.

Many of the broad features of solar geoengineering with sulfate aerosols can be represented by a reduction in solar constant (e.g., Kalidindi et al., 2015). However, the more subtle changes that derive from complex response to stratospheric aerosol heating (for example, the positive wintertime North Atlantic Oscillation; Jones et al., 2020) require detailed assessments with state-of-the-art aerosol microphysical schemes. This is particularly important for understanding regional and seasonal solar geoengineering (Kravitz et al., 2017; Visioni et al., 2019). Such detailed microphysical calculations can only be simulated in a small number of models; in the case of Jones et al. (2020), only two models were available. While simple G1-style experiments enable a robust multi-model ensemble analysis, they cannot capture details that depend on microphysics. We emphasize the importance of a variety of modeling approaches to understand solar geoengineering, particularly the role of model uncertainty in conclusions about solar geoengineering.

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Data Availability. All CMIP5 and CMIP6 output, including the respective GeoMIP simulations, is available via the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/esgf-llnl/) or by contacting the respective modeling groups responsible for the output.

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#	Model	Gen.	Reference	G1 Solar reduction (%)	Notes
1	BNU-ESM	CMIP5	Ji et al. (2014)	3.80	Cloud forcing not available
2	CanESM2	CMIP5	Arora et al. (2011)	4.00	
3	CCSM4	CMIP5	Gent et al. (2011)	4.25	NPP not available
4	CESM-CAM5.1-FV	CMIP5	Neale et al. (2010) Hurrell et al. (2013)	4.70	
5	CSIRO-Mk3L-1.2	CMIP5	Phipps et al. (2011, 2012)	3.20	Cloud forcing and NPP not available
6	EC-EARTH	CMIP5	Hazeleger et al. (2011)	4.12	Cloud forcing and NPP not available
7	GISS-E2-R	CMIP5	Schmidt et al. (2006)	4.47	
8	HadCM3	CMIP5	Gordon et al. (2000)	4.16	Cloud forcing and NPP not available
9	HadGEM2-ES	CMIP5	Collins et al. (2011)	3.88	
10	IPSL-CM5A-LR	CMIP5	Dufresne et al. (2013) Hourdin et al.(2011)	3.50	NPP not available
11	MIROC-ESM	CMIP5	Watanabe et al. (2008,2011)	5.00	
12	MPI-ESM-LR	CMIP5	Giorgetta et al. (2012) Stevens et al. (2012)	4.68	
13	NorESM1-M	CMIP5	Alterskjær et al. (2012) Kirkevåg et al. (2012)	4.03	
14	CanESM5	CMIP6	Swart et al. (2019)	3.72	
15	CESM2-WACCM	CMIP6	Gettelman et al. (2019)	4.91	
16	CNRM-ESM2.1	CMIP6	Séférian et al. (2019)	3.72	
17	GISS-E2.1-G	CMIP6	Kelley et al. (in revision)	4.13	
18	IPSL-CM6A-LR	CMIP6	Boucher et al. (2020) Lurton et al. (2020)	4.10	
19	MPI-ESM1.2-LR	CMIP6	Mauritsen et al. (2019)	4.57	NPP not available
20	UKESM1.0-LL	CMIP6	Sellar et al. (2019)	3.80	

Table 1. All participating models in both the CMIP5 and CMIP6 eras of GeoMIP, including references. For G1 solar reduction, the percentage is calculated as the percent change in incident solar irradiance at the top-of-atmosphere between G1 and its respective piControl run. Numbers in the first column correspond to the model numbers in Figure 5.

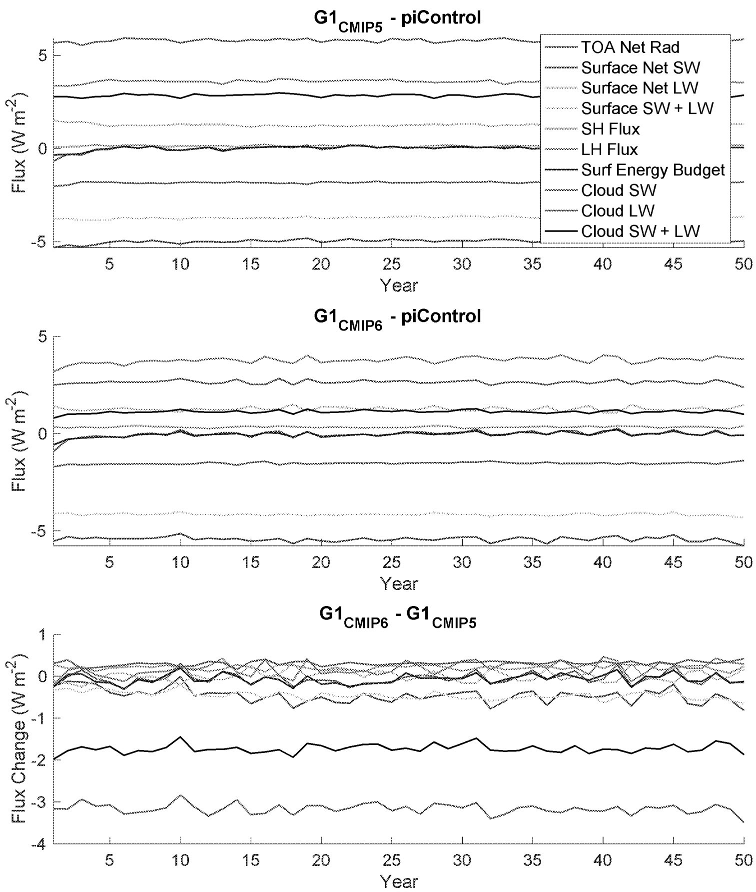

Figure 1. Ensemble mean energetics (W m^{-2}) for various flux quantities in $G1_{CMIP5}$ (top), $G1_{CMIP6}$ (middle), and the difference (bottom). All fluxes are positive downward, which is counterintuitive for sensible heat (SH) and latent heat (LH). Surf Energy Budget indicates the sum of surface shortwave (SW), surface longwave (LW), SH, and LH. Cloud forcing is calculated as all-sky minus clear-sky.

Commenté [KB1]: Comment from Alan: Do you want to add some indication of the variance between the models with whiskers or shading on each line?

Commenté [KB2R1]: I tried, and it ended up looking more confusing (too much ink).

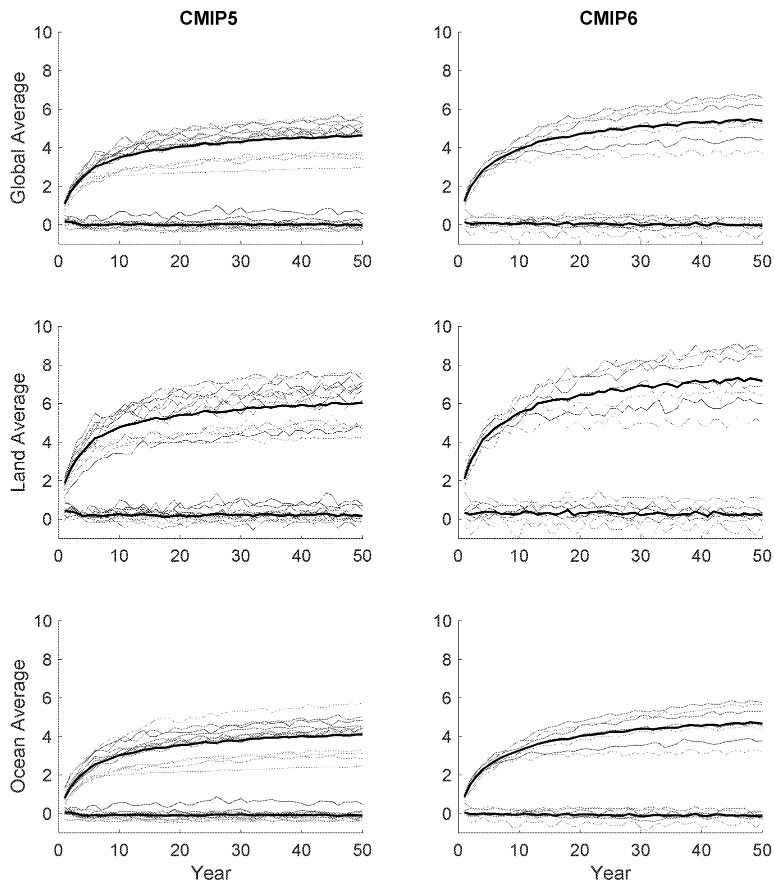

Figure 2. Global mean (top), land mean (middle), and ocean mean (bottom) temperature change (K) for the CMIP5 (left) and CMIP6 (ensembles). Thin colored lines are individual models, and thick black lines are model means. In all panels, the upper cluster of lines is the abrupt4xCO2 simulation, and the lower cluster of lines (approximately zero temperature change for the entire simulation) is experiment G1.

Commenté [KB3]: Still working on how to identify the different models in this figure. I also need to add temperature and units to the y-axes.

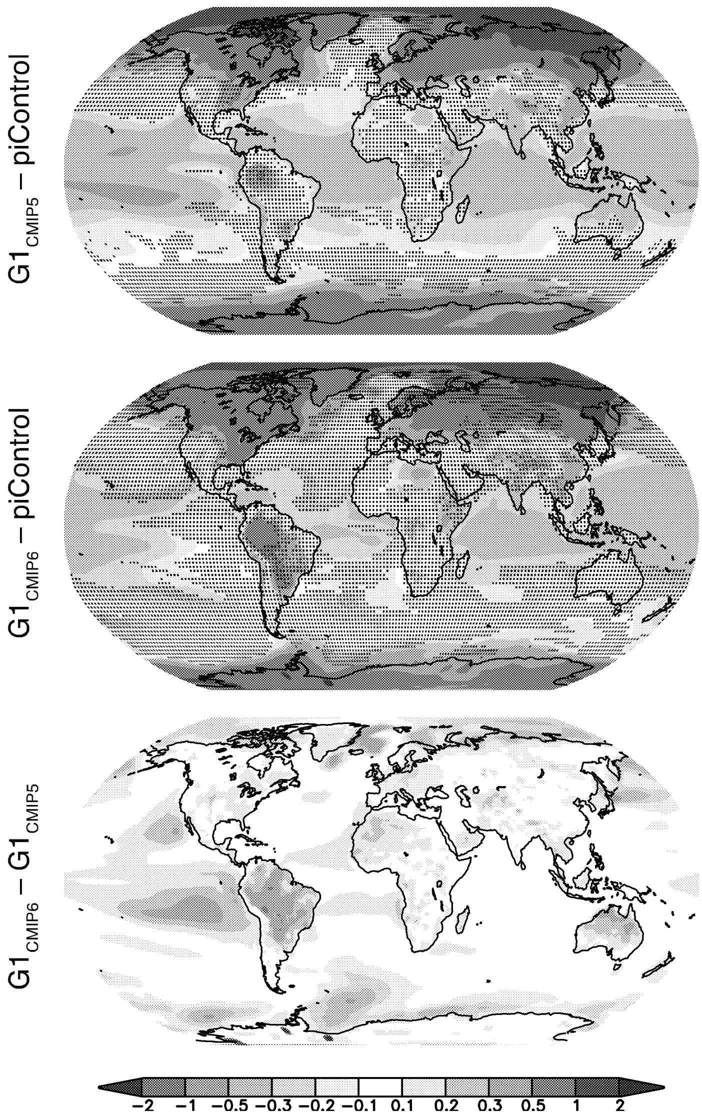

Figure 3. Ensemble average temperature changes (K) for G1 (as compared to the preindustrial control) for CMIP5 (top) and CMIP6 (middle), as well as the difference ($G1_{CMIP6}$ minus $G1_{CMIP5}$, bottom panel). In the top two panels, stippling indicates regions where fewer than 75% of the models in their respective ensembles agree on the sign of the response.

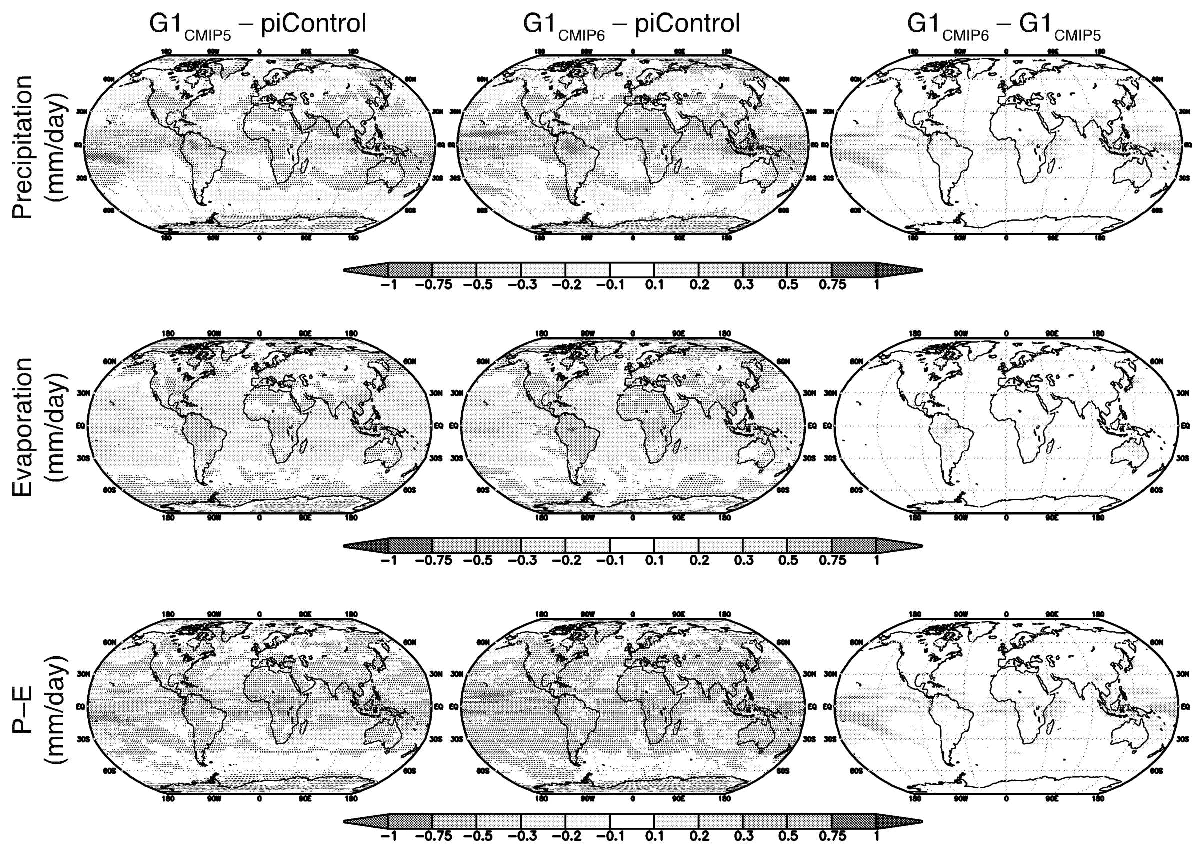

Figure 4. Precipitation (top), evaporation (middle), and precipitation minus evaporation (P-E; bottom) change from preindustrial for the CMIP5 (left) and CMIP6 (middle) ensembles, as well as the ensemble differences (right). All shaded values are ensemble means. Lack of stippling in the left and middle panels indicates agreement on the sign of the values across at least 75% of the models.

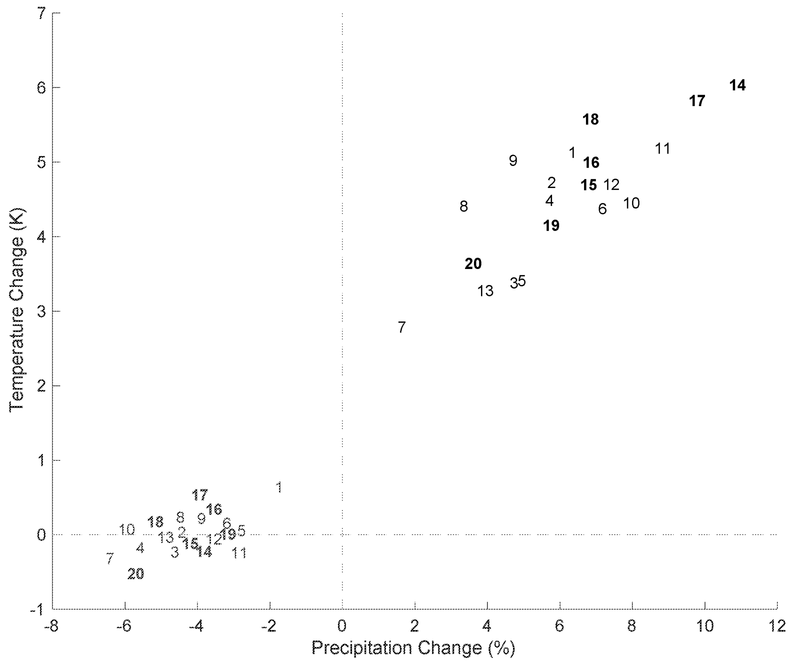

Figure 5. Average (years 11–50) temperature (y-axis; K) and precipitation (x-axis; %) change for each model in this study. Numbers indicate the model number (listed in Table 1, first column). Black numbers are for abrupt4xCO2, and red numbers are for G1. Bolded numbers are for CMIP6.

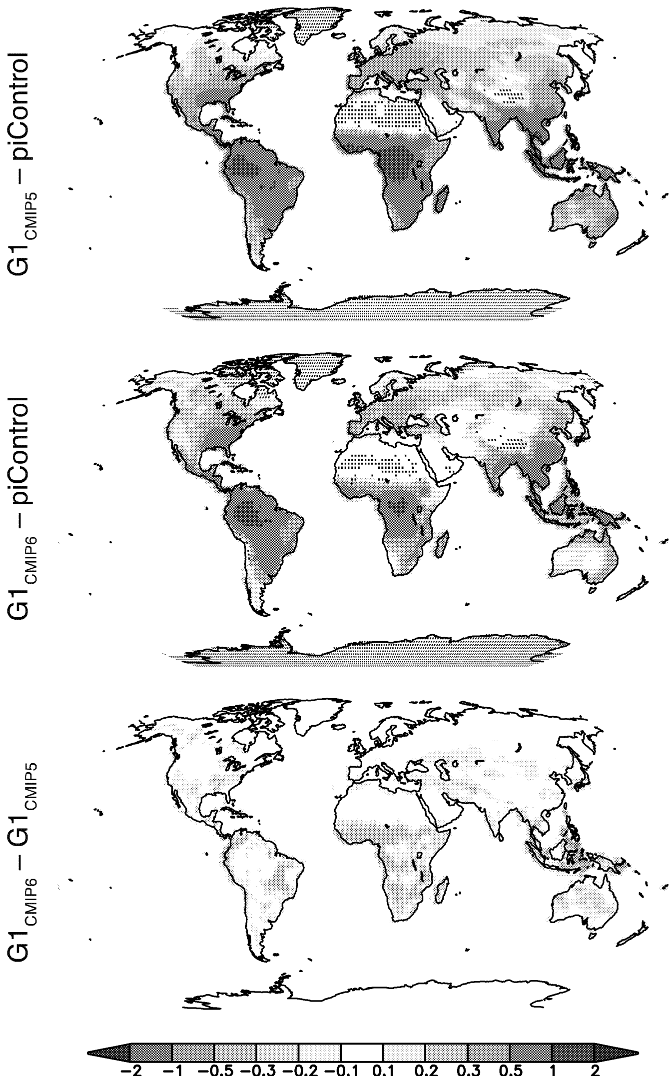

Figure 6. Terrestrial net primary productivity (kg C m^{-2} y^{-1}) for the CMIP5 (top) and CMIP6 (middle) ensembles, as well as the ensemble differences (bottom). All shaded values are ensemble means. Lack of stippling indicates agreement on the sign of the values across at least 75% of the models.

Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP)

Supplemental Online Material

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S1. Global-scale Temperature Metrics

Supplemental Figure 3 and its associated discussion in Section 3.2 include three temperature metrics (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016): global mean temperature (T_0), the interhemispheric temperature gradient (T_1), and the equator-to-pole temperature gradient (T_2). We define these in terms of the projection of the first three Legendre polynomials onto the temperature field:

$$T_0 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\, dA$$

$$T_1 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\ \sin\psi\ dA$$

$$T_2 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\ (3\sin^2\psi - 1)\, dA$$

where *T* is temperature, ψ is latitude, and *A* is area.

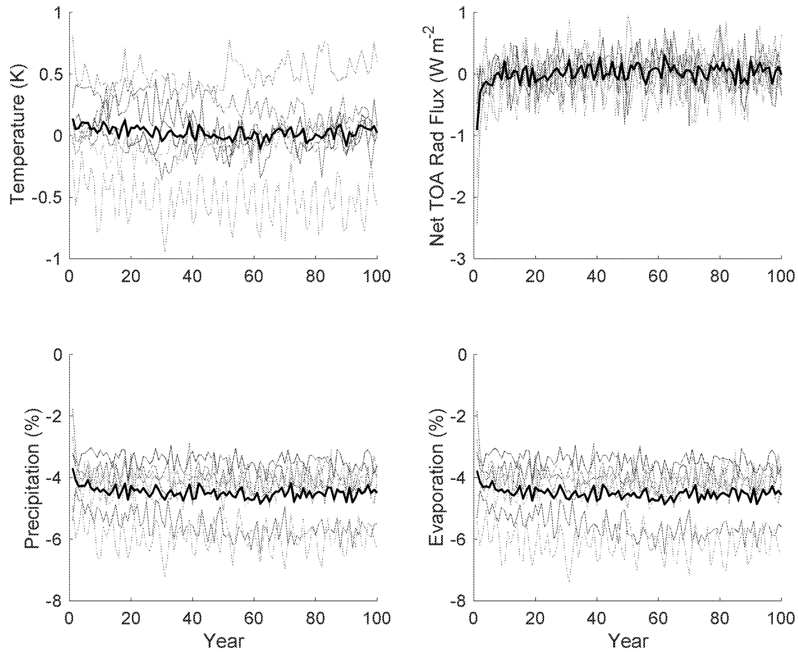
S2. Longer-Term Model Behavior

Supplemental Figures 1 and 2 look at G1 behavior over the entire 100-year period of simulation to determine whether there is any drift or trend that would not be revealed by only analyzing 50 years. With the exception of IPSL-CM6A-LR, no model shows any long-term behavior in temperature. Two models (Model X and Model Y) show a slight trend in precipitation and evaporation, with a change of <1% over the first 50 years of simulation. As such, we conclude that our choice to focus on the first 50 years of simulation does not appreciably affect our results.

Supplemental Figure 2 indicates that the temperature trend in IPSL-CM6A-LR is due to temperature changes north of 30°N, possibly related to a slight trend in sea ice coverage (Boucher et al., 2020). This model is also known to have a bicentennial oscillation, which could affect G1–piControl differences, depending on the baseline period used for subtraction. To verify that this oscillation is not impacting our results, we divided the 1200-year piControl run into 50-year chunks and computed the surface air temperature average for each of those chunks. The largest temperature found was 286.0339 K, and the smallest was 285.6384 K. The average over the entire ensemble was 285.8604 K. As such, using the mean of the entire ensemble versus matching the appropriate period in the bicentennial oscillation would have an impact on G1–piControl temperature by at most 0.22 K. Only averaging the first 100 years of the piControl run (which may be the best match to the period covered by G1) yields a temperature of 285.9084 K, which is 0.048 K different from the mean of the entire piControl run. As such, we conclude that this bicentennial oscillation is unlikely to have substantially influenced our findings.

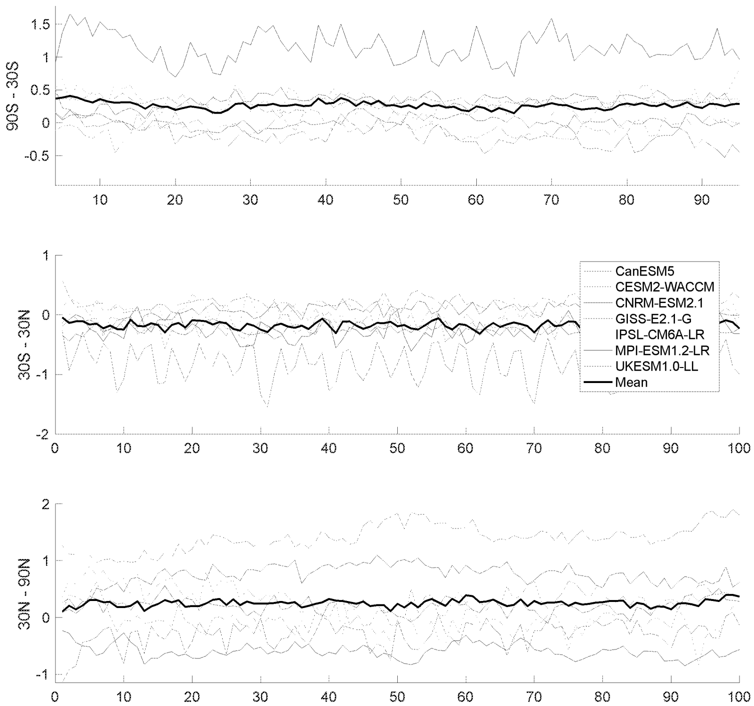
Supplemental Table 1. Ensemble differences between the CMIP5 and CMIP6 ensembles for each variable evaluated in this study (left column). Column 2 indicates the difference between the ensembles in how much of the Earth's surface is not stippled (more than 75% of models agree on the sign of the response; positive values indicate that CMIP6 has more unstippled area than CMIP5). Column 3 indicates the fraction of the Earth's surface for which the CMIP5 ensemble is statistically different from the CMIP6 ensemble, based on 95th percentile confidence intervals from Welch's *t*-test.

Variable	**Stippling (%)**	**Welch's *t*-test (%)**	**Notes**
Surf. air temperature	-25.77	0.87	
Precipitation	-3.56	11.17	
Evaporation	-2.33	6.47	
Precip minus Evap	-15.23	1.13	
SW Cloud Forcing	-8.02	9.65	
LW Cloud Forcing	11.99	6.57	
Net Primary Prod.	-1.42	1.15	Land surface only

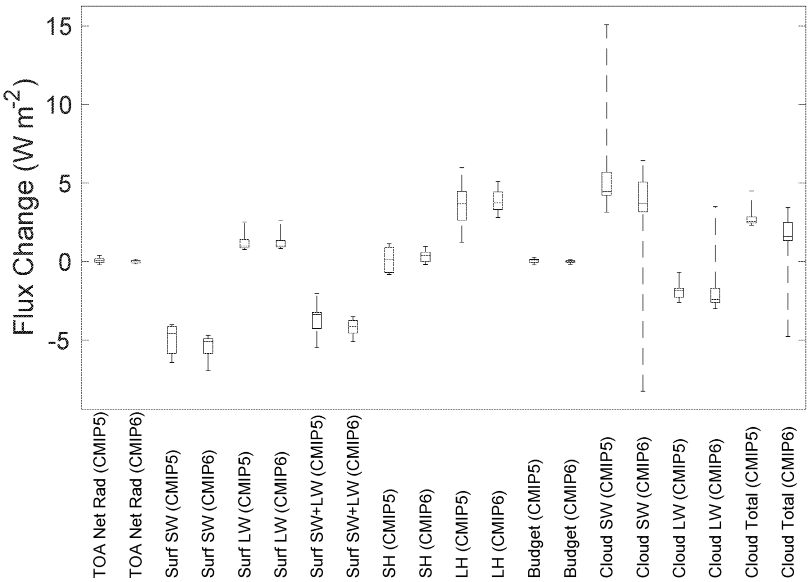


Supplemental Figure 1. Temperature (top left; K), net top-of-atmosphere radiative flux (top right; W m^{-2}), precipitation (bottom left; %), and evaporation (bottom right; %) change in G1$_{CMIP6}$ compared to piControl over 100 years of simulation. Thin colored lines are individual models, and thick black lines are ensemble means.

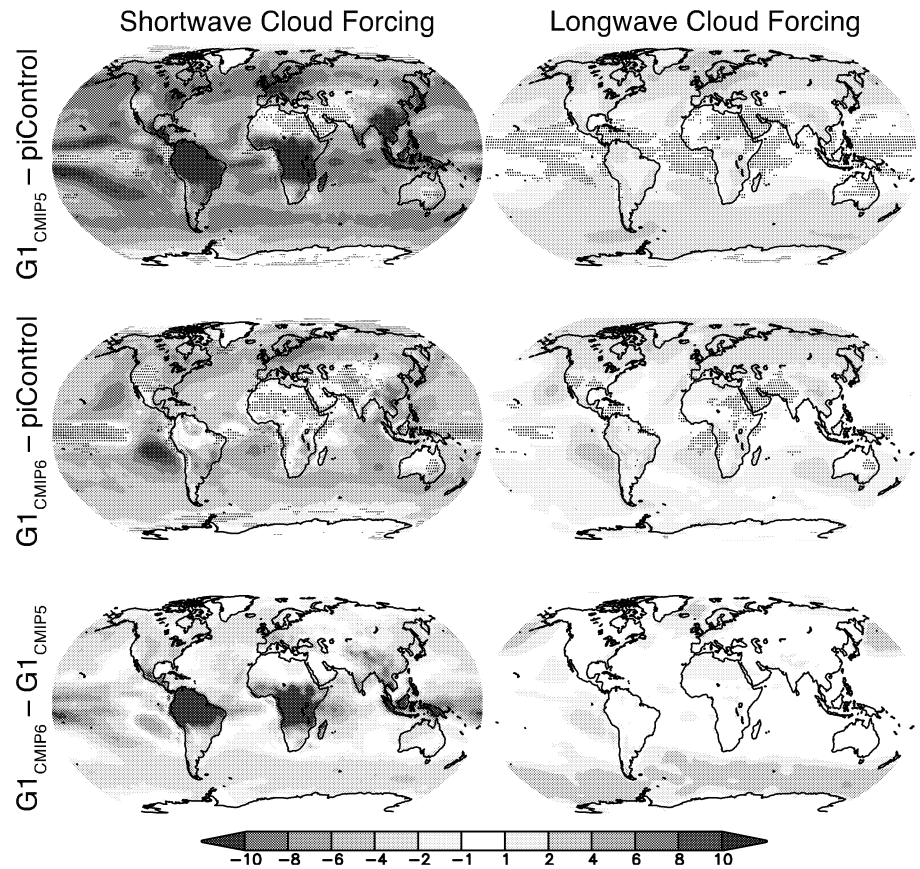
Commenté [KB4]: Needs a legend



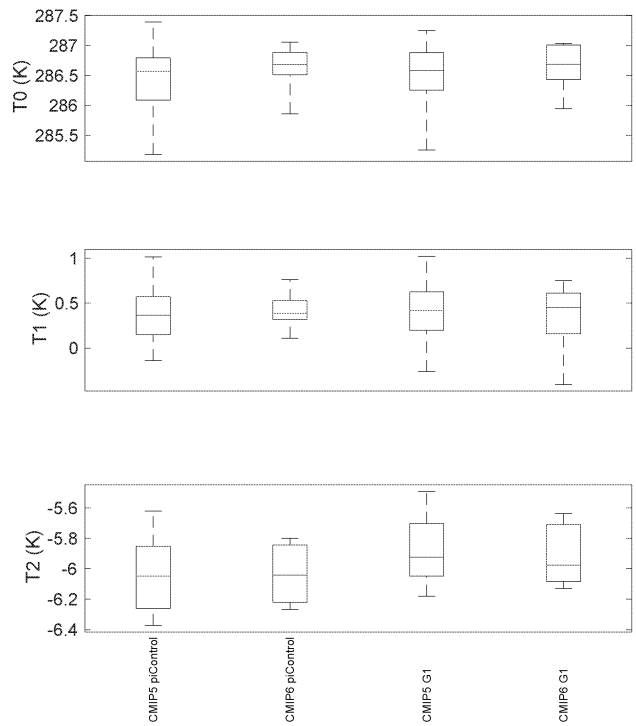
Supplemental Figure 2. Annual mean surface temperature (K) in each model averaged over 90°S-30°S (top), 30°S-30°N (middle), and 30°N-90°N (bottom). The ensemble mean is plotted as thick black lines.



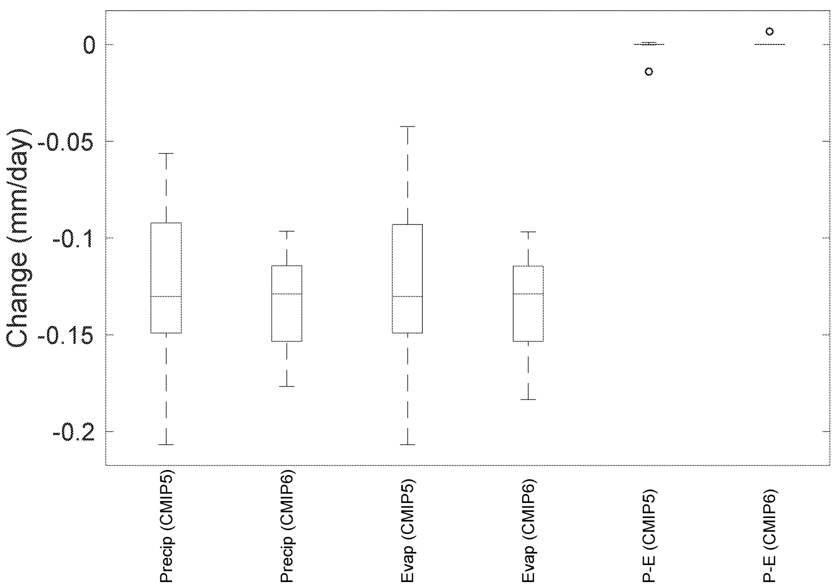
Supplemental Figure 3. Ensemble median (red lines), inter-quartile (blue boxes), and ranges (black whiskers) for the same global mean energetics quantities as in Figure 1 (G1 minus piControl) for both the CMIP5 and CMIP6 ensembles.



Supplemental Figure 4. Surface shortwave (left) and longwave (right) cloud forcing (W m^{-2}) change from preindustrial for the CMIP5 (top) and CMIP6 (middle) ensembles, as well as the ensemble differences (bottom). Cloud forcing is measured as all-sky minus clear-sky radiative flux. All shaded values are ensemble means. Lack of stippling indicates agreement on the sign of the values across at least 75% of the models.



Supplemental Figure 5. Ensemble ranges for global mean temperature (T_0), the interhemispheric temperature gradient (T_1), and the equator-to-pole temperature gradient (T_2), as defined in Supplemental Section 1 (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016). Red lines indicate ensemble medians, blue boxes are the inter-quartile ranges, and black whiskers indicate total ranges.



Supplemental Figure 6. Global mean ensemble median (red lines), inter-quartile (blue boxes), and ranges (black whiskers or, for P-E one blue circle indicating an extreme outlier) for the hydrological quantities shown in Figure 4 for both the CMIP5 and CMIP6 ensembles.

s.19(1)

Subject: G1 CMIP6 paper
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Hi folks -

I've attached a draft of the G1 paper comparing the results of the experiment in CMIP5 and CMIP6. It ended up being not so long, so I think ERL might be a good target. Supplemental information is in the same file at the end. There are two versions of Figure 5, so please let me know which one you like the best.

I'd love to get all of your comments by the end of the month. If you think that's not going to be possible, please let me know, and we can work with your availability.

You are welcome to send your comments to the group or to me privately. I don't mind integrating changes manually.

Best,

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Attachments:

GeoMIP6_G1_v1.docx 526 bytes

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Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP)

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Abstract

One method of approximating global-scale solar geoengineering is via solar reduction. Two generations of models in the Geoengineering Model Intercomparison Project (GeoMIP) have now simulated offsetting a quadrupling of the CO_2 concentration with solar reduction. Here we show that energetics, temperature, and hydrological cycle changes in this experiment are statistically indistinguishable between the two ensembles. Of the variables analyzed here, the only major differences involve highly parameterized and uncertain processes, such as cloud forcing or net primary productivity. We conclude that despite numerous structural differences and uncertainties in models over the past 20 years, broad conclusions about global solar dimming remain robust.

Keywords: geoengineering, climate engineering, solar radiation management, climate modeling

Three main points

1. Two solar dimming model ensembles are statistically indistinguishable for many variables
2. Largest ensemble differences are in highly parameterized and uncertain processes
3. Past results about solar dimming are robust to some structural differences and uncertainties

Suggested reviewers

- Piers Forster
- Don Wuebbles
- Peter Irvine
- Long Cao
- Gerald Meehl
- Ken Caldeira
- Govindasamy Bala

1. Introduction

Solar geoengineering describes a set of technologies designed to temporarily, deliberately reduce some of the effects of climate change by changing the radiative balance of the planet, often by reflecting sunlight back to space (NRC, 2015). Numerous methods have been proposed, but arguably the most studied is stratospheric sulfate aerosol injection (Budyko, 1977; Crutzen, 2006). This method involves creating large amounts of highly reflective sulfate aerosols in the stratosphere, replicating the mechanisms that cause cooling after large volcanic eruptions (Robock, 2000). In model simulations of solar geoengineering, solar reduction is often used as a proxy for actual stratospheric sulfate aerosols, as it captures many of the broad radiative effects of stratospheric aerosol geoengineering as well as some of the important climate effects (Niemeier et al., 2013; Kalidindi et al., 2015).

Simulations of solar geoengineering with solar reduction have long shown that solar geoengineering would cool the planet, offsetting global warming (e.g., Govindasamy and Caldeira, 2000; NRC, 2015; Irvine et al., 2016). Idealized simulations of solar reduction have also been simulated in a multi-model context under the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2011), to understand what robust model responses are to various standardized solar geoengineering simulation designs. Multi-model conclusions from these studies indicate that solar geoengineering would likely not only offset greenhouse gas-induced temperature changes (Kravitz et al., 2013a), but also changes in the hydrological cycle (Tilmes et al., 2013), the cryosphere (Moore et al., 2014), extreme events (Curry et al., 2014), vegetation (Glienke et al., 2015), circulation (Guo et al., 2018; Gertler et al., 2020), agriculture (Xia et al., 2014), and numerous other areas. However, the offset is not perfect (Moreno-Cruz et al., 2012), particularly on a regional basis or when considering multiple simultaneous metrics of climate change (Kravitz et al., 2014; Irvine et al., 2019), leading to concerns about winners and losers from geoengineering (Ricke et al., 2010). To some extent, the effects of solar geoengineering may be tailored or designed (MacMartin et al., 2013; Kravitz et al., 2016, 2017, 2019), but solar geoengineering will still not be able to perfectly offset climate change from greenhouse gases.

The previous phase of GeoMIP was associated with the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), an international collaboration of climate models to attempt to understand robust model responses to various forcings. GeoMIP has now entered a new phase, concurrent with the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016), and with it are new solar geoengineering simulations with new and updated versions of Earth System Models (Kravitz et al., 2015). As such, this is an opportunity to revisit some central questions in solar geoengineering. Many of the CMIP5 results regarding solar geoengineering showed substantial agreement across the participating GeoMIP models. In this newest iteration of GeoMIP, do the same science conclusions still hold, and do the models still generally agree on the resulting climate effects? Here we address these questions by evaluating and comparing general climate model response to GeoMIP experiment G1 (described in the next section) from both CMIP5 and CMIP6.

2. Simulations and Participating Models

In this study, we evaluate GeoMIP experiment G1, in which, starting from a preindustrial control (piControl) baseline, the atmospheric CO_2 concentration is instantaneously quadrupled (the standard CMIP experiment abrupt4xCO2), and insolation is simultaneously reduced such that net top-of-atmosphere (TOA) radiative flux is approximately unchanged from the baseline (Kravitz et al., 2011, 2015). This experiment was part of the original suite of GeoMIP experiments and was repeated in the newest suite in an effort to understand the role of model structural uncertainty in broad conclusions about solar geoengineering. Participating models are listed in Table 1. We include 13 models from CMIP5 and 6 models from CMIP6.

Because the main focus of this paper is a comparison between the CMIP5 and CMIP6 eras of model results, we have opted for the following to aid comparisons:

- The original G1 experiment was 50 years in length, whereas the CMIP6 version is 100 years in length to allow for better analyses of rare events or to capture very slow responses. Since we are not evaluating any features that require 100 years of statistics, and the results do not show any appreciable time evolution of behavior after the first couple of years (see Supplemental Figure 1), we only evaluate the first 50 years of all simulations. All maps show changes over years 11-50, removing the initial transient period.
- We do not compare previous versions of models with current ones, instead only treating ensembles. Even though models may share similar development histories (Knutti et al., 2013; Zelinka et al., 2020), there have been numerous developments in models between CMIP5 and CMIP6 such that in most cases a direct comparison would not be meaningful.
- We focus extensively on the G1 results and, with few exceptions, do not focus on the corresponding abrupt4xCO2 simulations. It has been well documented that the CMIP6 models tend to have higher climate sensitivities than the CMIP5 models (Flynn and Mauritsen, 2020; Zelinka et al., 2020), so we do not wish to make conclusions that might be based on a form of selection bias.
- All stippling on map plots, as in previous GeoMIP studies (e.g., Kravitz et al., 2013a), indicates agreement on the sign of the response in at least 75% of models. Because $G1_{CMIP5}$ has more participating models than $G1_{CMIP6}$, this threshold provides some consistency across analyses of the ensembles. When plotting differences between the ensembles ($G1_{CMIP6}$-$G1_{CMIP5}$), there is no stippling, as it is difficult to meaningfully represent such differences between ranges. Aggregate differences between the two ensembles, as calculated using Welch's t-test, are discussed in Supplemental Table 1.

3. Results

3.1. Energetics

Ensemble mean radiative and turbulent flux quantities are plotted in Figure 1, and the ensemble ranges are plotted in Supplemental Figure 2. An immediate observation is that, in both ensembles, the models were successful at limiting net TOA radiative flux change to within approximately ±0.1 W m^{-2} of the models' respective preindustrial values. Accomplishing this required an average solar reduction of 4.14% (models range in 3.20–5.00%) in CMIP5 and 4.05% (3.72–4.91%) in CMIP6. As such, despite numerous structural changes between the two generations of models, there is no appreciable change in solar efficacy (Hansen et al., 2005).

None of the radiative flux quantities indicate large transients over 50 years of simulation of G1, other than the initial flux change within the first year or so of simulation, which is consistent with the "perpetual fast response" found by Kravitz et al. (2013b). Ensemble mean fluxes show few differences (<1 W m^{-2} in magnitude) with the exception of shortwave cloud forcing, defined as all-sky minus clear-sky shortwave flux at the surface. CMIP6 has 3–4 W m^{-2} less shortwave cloud forcing than CMIP5. Neglecting some outliers, for each flux except shortwave cloud forcing, the median model in one ensemble is within the inter-quartile range of the other ensemble. This indicates that there are no major differences between the ensembles in how the models handle energy balance and energetics, with the exception of clouds. Moreover, it appears that most of the major differences in shortwave cloud forcing are due to outliers in each ensemble, positive for CMIP5 and negative for CMIP6.

To further explore these potential differences, Supplemental Figure 3 provides maps of the ensemble means for cloud forcing. In G1, the CMIP5 ensemble showed more positive shortwave cloud forcing and more negative longwave cloud forcing (i.e., more cancellation) than the CMIP6 ensemble. Overall, the CMIP6 ensemble has greatly reduced (in some places by over 10 W m^{-2}) shortwave cloud forcing as compared to CMIP5 under the G1 experiment. This is a widespread result, but the most prominent features are in the tropics, especially over the Amazon, Africa, and the Maritime Continent. The reasons behind these forcing changes are difficult to diagnose, as they could be due to changes in cloud thickness, cloud cover, or cloud level between CMIP5 and CMIP6 models (e.g., Vignesh et al., 2020), differences in how solar geoengineering affects clouds (Russotto and Ackerman, 2018), or they could be artifacts of the analyses (e.g., cloud masking; Andrews et al., 2009; Kravitz et al., 2013b). Moreover, based on the results in Supplemental Figure 2, it is likely that many of these features are exaggerated by outlier models (also see Vignesh et al., 2020). As such, we reserve such detailed investigations for future work.

3.2. Temperature

These small flux changes also lead to few G1 temperature changes between the two ensembles. Figure 2 shows global, land, and ocean-averaged temperatures for the CMIP5 and CMIP6 ensembles. In general, the abrupt4xCO_2 simulation in CMIP6 has higher temperatures than in CMIP5, consistent with the noted increase in climate sensitivity (Flynn and Mauritsen, 2020; Zelinka et al., 2020). In both ensembles, G1 is effective at offsetting global mean temperature change, in some cases with a slight positive residual temperature change over land. Supplemental Figure 4 shows three aggregate temperature metrics: global mean temperature, the interhemispheric temperature gradient, and the equator-to-pole temperature gradient (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016). As for the fluxes, the median model in one ensemble is within the inter-quartile range of the other ensemble. This indicates that no ensemble is on average warmer than another, has a substantially warmer northern or southern hemisphere than the other, or has warmer tropics or poles than the other. We can conclude that spatial patterns of temperature change from G1 are robust across a wide range of structural uncertainty.

The spatial structure of temperature change (Figure 3) does differ somewhat between the two ensembles. In general, G1 in CMIP6 is slightly warmer than G1 in CMIP5, despite both ensembles achieving net energy balance at TOA and the surface (Figure 1). The majority of the differences are over land and in the tropics, where CMIP6 is slightly warmer than CMIP5 (up to a degree in some places). Nevertheless, both ensembles show the well noted feature that offsetting a CO_2 increase with solar reduction overcools the tropics and undercools the poles (Govindasamy and Caldeira, 2000; Kravitz et al., 2013a). CMIP6 shows slightly less high latitude warming than CMIP5, but temperature differences between the two ensembles are largely negligible. However, the warmer temperatures in CMIP6 near Greenland have important implications for ice sheet melt and consequent sea level rise, as well as bottom water formation. We reserve such analyses for future investigations, particularly since the models used here are not capable of simulating sea level rise. In any case, these ensemble mean differences between CMIP5 and CMIP6 cannot be deemed statistically significant (Supplemental Table 1 and Supplemental Figure 3).

3.3. Hydrological and Other Integrative Changes

Figure 4 shows ensemble mean changes in precipitation (P), evaporation (E), and P–E for $G1_{CMIP5}$ and $G1_{CMIP6}$. Qualitatively, patterns are similar between both ensembles. Precipitation is slightly (<0.3 mm/day in magnitude) different in the tropics between the two ensembles. The majority of those features can be summarized as a more southward ITCZ, more precipitation in the South Pacific Convergence Zone, and less precipitation over Southeast Asia and the Maritime Continent in CMIP6. Evaporation in the two ensembles is nearly identical except for more evaporation in Amazonia and Australia in CMIP6. As such, the net P–E change between the two ensembles strongly resembles the precipitation changes. Supplemental Figure 5 shows that, like previous evaluations of ensemble ranges, the median model in one ensemble falls well within the interquartile range of the other ensemble for P, E, and P–E. As such, we cannot conclude any robust hydrological cycle changes between the two ensembles.

Figure 5 shows average (years 11–50) temperature change (with respect to piControl) plotted against average precipitation change for each model, as in Tilmes et al. (2013). Other than a potentially greater climate sensitivity of some CMIP6 models, there is no distinguishable difference in aggregate behavior between the two ensembles. The same previously discovered conclusion holds: solar reduction cannot simultaneously offset CO_2-induced changes in both global mean temperature and global mean precipitation (Tilmes et al., 2013).

As an integrator of CO_2, temperature, and precipitation effects over land, Supplemental Figure 6 shows changes in terrestrial net primary productivity (NPP). Numerous land regions, mostly aligned with those showing reduced precipitation in Figure 4, have lower NPP in CMIP6 than in

CMIP5. The ensemble average global NPP change (G1–piControl) is 50.88 (4.12–120.93) Pg [C] y^{-1} in CMIP5 and 41.05 (23.01–77.22) Pg [C] y^{-1} in CMIP6, representing a 19.3% difference in means. Jones et al. (2013) used NPP to highlight the importance of understanding the influence of structural land model differences on climate results related to geoengineering. While it is beyond the scope of this study to perform a detailed diagnosis of which uncertainties or processes are responsible for this inter-ensemble difference, we point out that the ensemble spread of total terrestrial NPP is smaller in CMIP6 than in CMIP5, perhaps due to selection bias or perhaps due to some of these uncertainties being addressed in this newest generation of models.

4. Discussion and Conclusions

Based on the results presented here, model response to G1 has not changed substantially between CMIP5 and CMIP6. (See Supplemental Table 1 for quantification supporting this point.) Energetics, temperature, and the hydrological cycle are qualitatively and quantitatively similar in both ensemble means and ensemble ranges, although these variables are somewhat related, so we might expect them to all portray a similar picture. Notable differences do exist in shortwave cloud forcing and NPP, particularly in Amazonia, Africa, and Australia, which are also regions of inter-ensemble difference in precipitation.

From these findings, we can conclude that results obtained over the past 20 years of study have not been overturned by the latest round of simulations. All of the major ensemble differences highlighted above deal with clouds and land surface modeling, both of which are difficult to model and are necessarily highly parameterized. The conclusions that are based on more fundamental knowledge, such as column energetics (in the case of the hydrological cycle), are relatively robust to structural uncertainty, in so far as this study adequately captures representative variations in structural uncertainty. This lends confidence to our conclusions, especially regarding robustness to uncertainty, about the broad climate effects from solar geoengineering methods that can be accurately represented via solar dimming. We acknowledge that solar dimming is a better analogue for stratospheric aerosols in some cases than in others (Kalidindi et al., 2015; Simpson et al., 2019).

We also conclude that the models used in CMIP5 are not obviously biased or inferior as compared to CMIP6. While improvements have been made in the CMIP6 generation of models, and those models are likely better for representing numerous features that may be important for studies of geoengineering, there are many aspects of climate that are well represented by earlier models. In some cases, more robust analyses may be enabled by augmenting ensemble sizes with earlier generations of CMIP models.

There are numerous aspects of physical climate that we did not evaluate, nor did we pursue analyses beyond physical climate, including many other aspects of natural science, social science, the humanities, governance, justice, or ethics (to name a few important areas). A holistic assessment of the consequences of geoengineering would certainly need to take these numerous aspects into account. Nevertheless, based on the results presented here, results for geoengineering across several important metrics appear to be robust to some amount of structural uncertainty. This lends confidence to some conclusions regarding solar geoengineering.

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Data Availability. All CMIP5 and CMIP6 output, including the respective GeoMIP simulations, is available via the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/esgf-llnl/) or by contacting the respective modeling groups responsible for the output.

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Model	Gen.	Reference	G1 Solar reduction (%)	Notes
BNU-ESM	CMIP5	Ji et al. (2014)	3.80	Cloud forcing not available
CanESM2	CMIP5	Arora et al. (2011)	4.00	
CCSM4	CMIP5	Gent et al. (2011)	4.25	NPP not available
CESM-CAM5.1-FV	CMIP5	Neale et al. (2010) Hurrell et al. (2013)	4.70	
CSIRO-Mk3L-1.2	CMIP5	Phipps et al. (2011, 2012)	3.20	Cloud forcing and NPP not available
EC-EARTH	CMIP5	Hazeleger et al. (2011)	4.12	Cloud forcing and NPP not available
GISS-E2-R	CMIP5	Schmidt et al. (2006)	4.47	
HadCM3	CMIP5	Gordon et al. (2000)	4.16	Cloud forcing and NPP not available
HadGEM2-ES	CMIP5	Collins et al. (2011)	3.88	
IPSL-CM5A-LR	CMIP5	Dufresne et al. (2013) Hourdin et al.(2011)	3.50	NPP not available
MIROC-ESM	CMIP5	Watanabe et al. (2008,2011)	5.00	
MPI-ESM-LR	CMIP5	Giorgetta et al. (2012) Stevens et al. (2012)	4.68	
NorESM1-M	CMIP5	Alterskjær et al. (2012) Kirkevåg et al. (2012)	4.03	
CanESM5	CMIP6	Swart et al. (2019)	3.72	
CESM2-WACCM	CMIP6	Gettelman et al. (2019)	4.91	
CNRM-ESM2.1	CMIP6	Séférian et al. (2019)	3.72	
GISS-E2.1-G	CMIP6	Kelley et al. (in revision)	4.13	
IPSL-CM6A-LR	CMIP6	Boucher et al. (2020) Lurton et al. (2020)	4.10	
UKESM1.0-LL	CMIP6	Sellar et al. (2019)	3.80	

Table 1. All participating models in both the CMIP5 and CMIP6 eras of GeoMIP, including references. For G1 solar reduction, the percentage is calculated as the percent change in incident solar irradiance at the top-of-atmosphere between G1 and its respective piControl run.

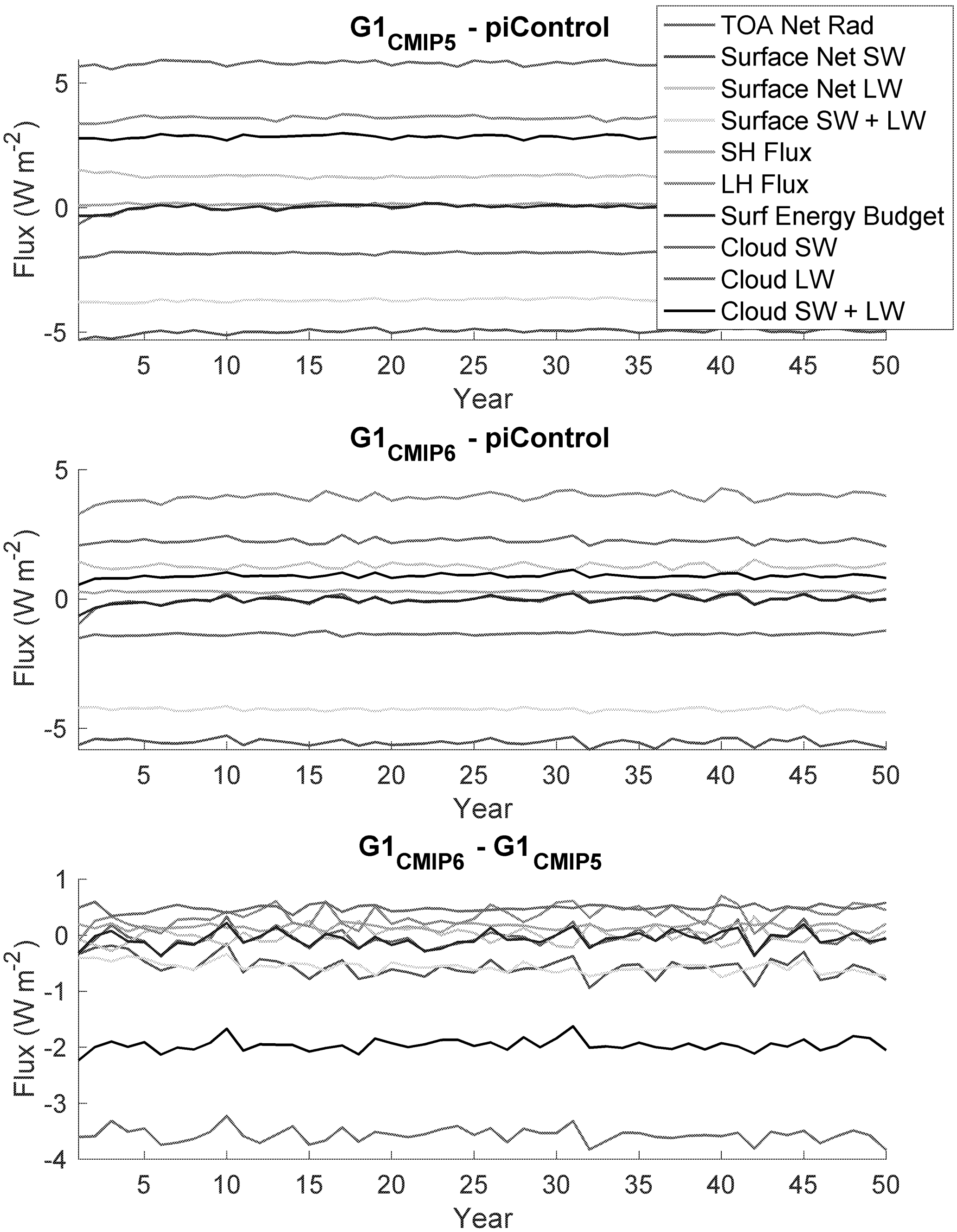


Figure 1. Ensemble mean energetics (W m^{-2}) for various flux quantities in $G1_{CMIP5}$ (top), $G1_{CMIP6}$ (middle), and the difference (bottom). All fluxes are positive downward, which is counterintuitive for sensible heat (SH) and latent heat (LH). Surf Energy Budget indicates the sum of surface shortwave (SW), surface longwave (LW), SH, and LH. Cloud forcing is calculated as all-sky minus clear-sky.

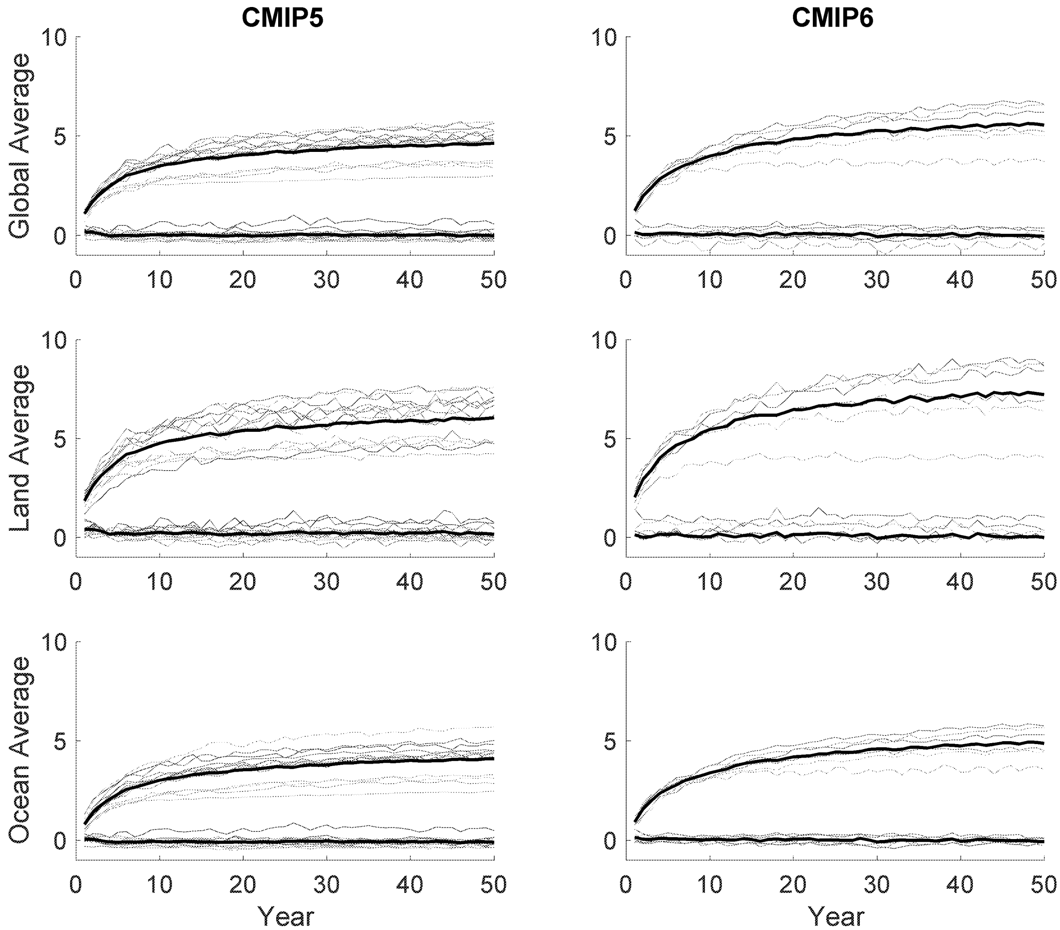


Figure 2. Global mean (top), land mean (middle), and ocean mean (bottom) temperature change (K) for the CMIP5 (left) and CMIP6 (ensembles). Thin colored lines are individual models, and thick black lines are model means. In all panels, the upper cluster of lines is the abrupt4xCO2 simulation, and the lower cluster of lines (approximately zero temperature change for the entire simulation) is experiment G1.

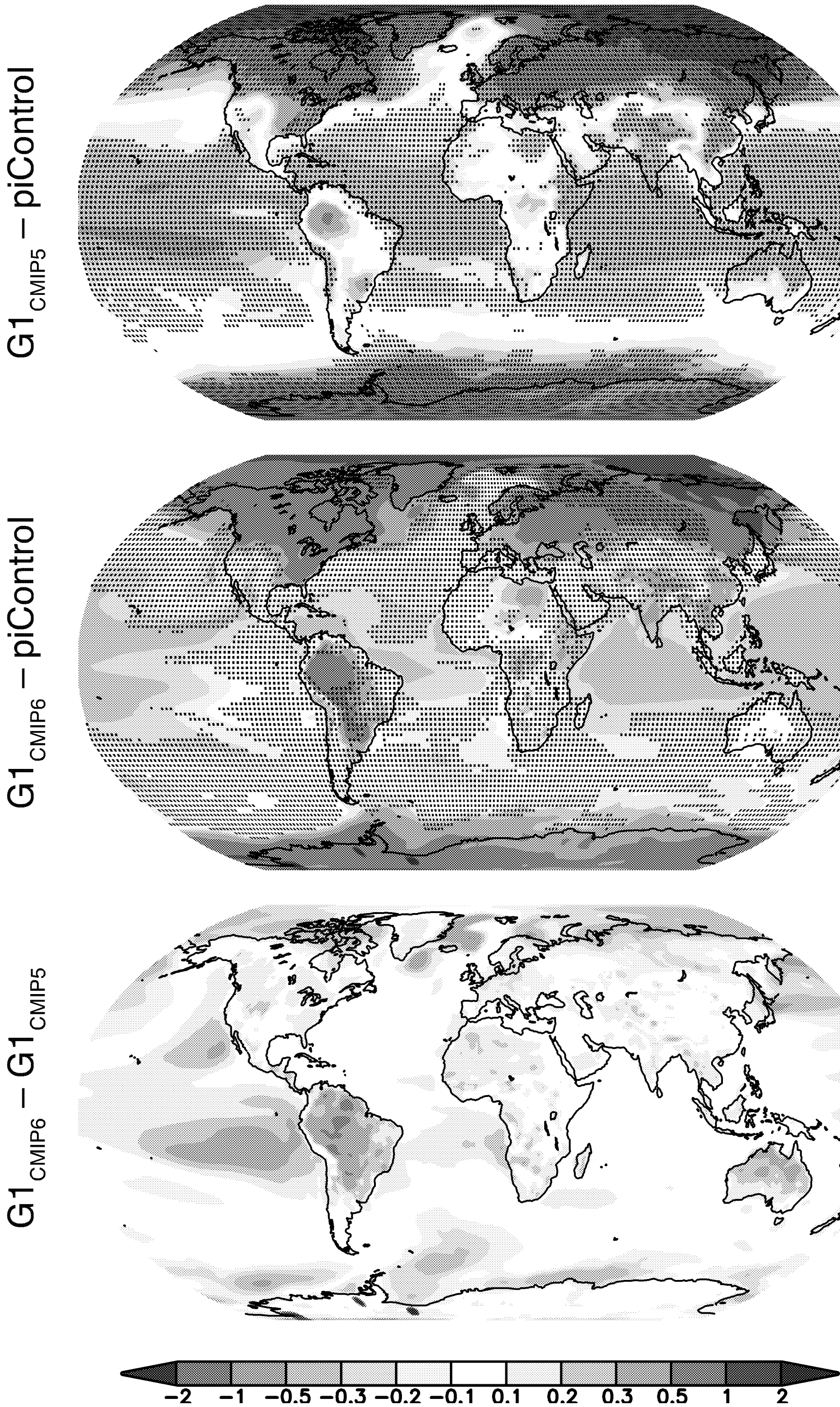


Figure 3. Ensemble average temperature changes (K) for G1 (as compared to the preindustrial control) for CMIP5 (top) and CMIP6 (middle), as well as the difference ($G1_{CMIP6}$ minus $G1_{CMIP5}$, bottom panel). In the top two panels, stippling indicates regions where at least 75% of the models in their respective ensembles do not agree on the sign of the response.

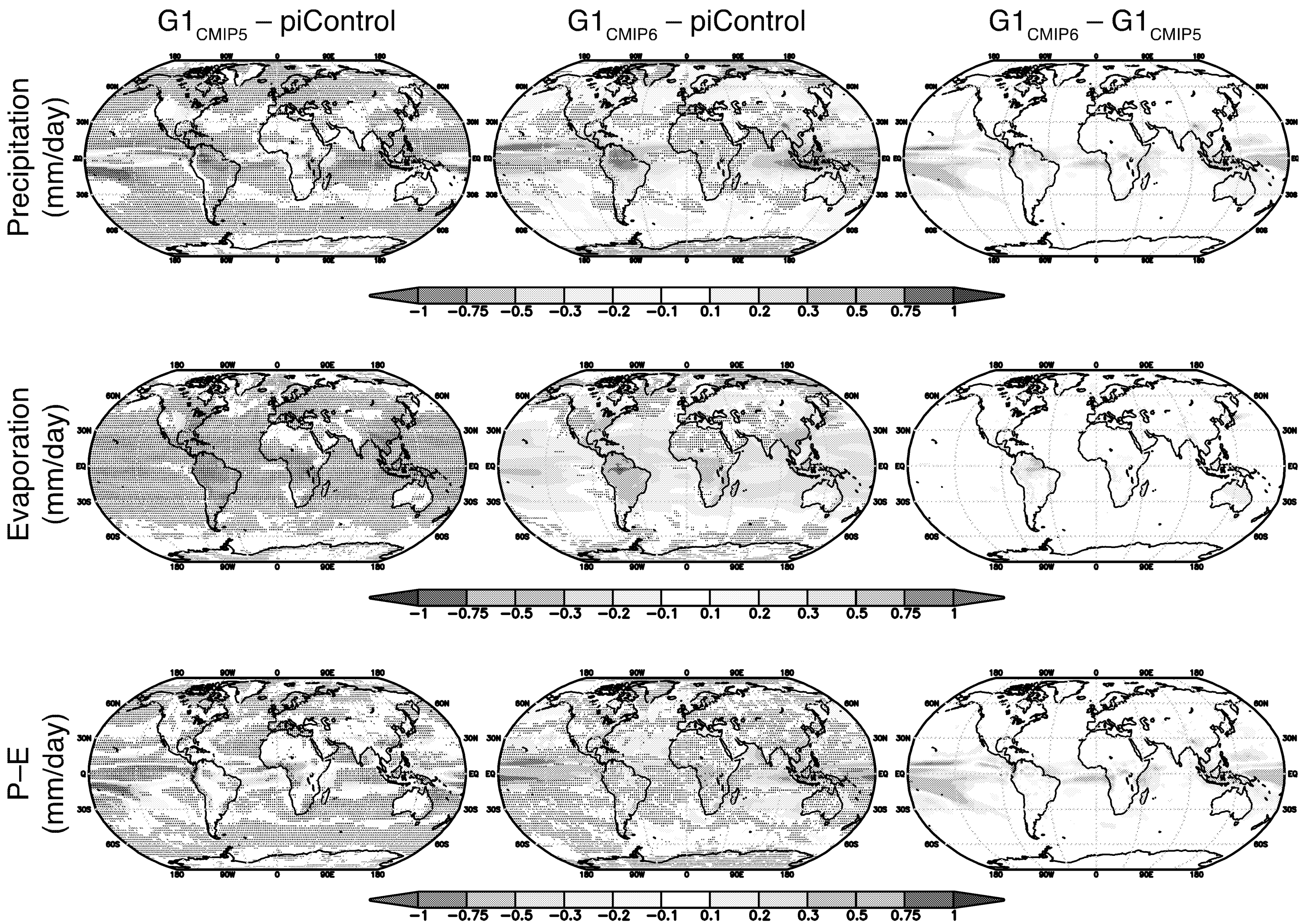


Figure 4. Precipitation (top), evaporation (middle), and precipitation minus evaporation (P-E; bottom) change from preindustrial for the CMIP5 (left) and CMIP6 (middle) ensembles, as well as the ensemble differences (right). All shaded values are ensemble means. Stippling indicates agreement on the sign of the values across at least 75% of the models.

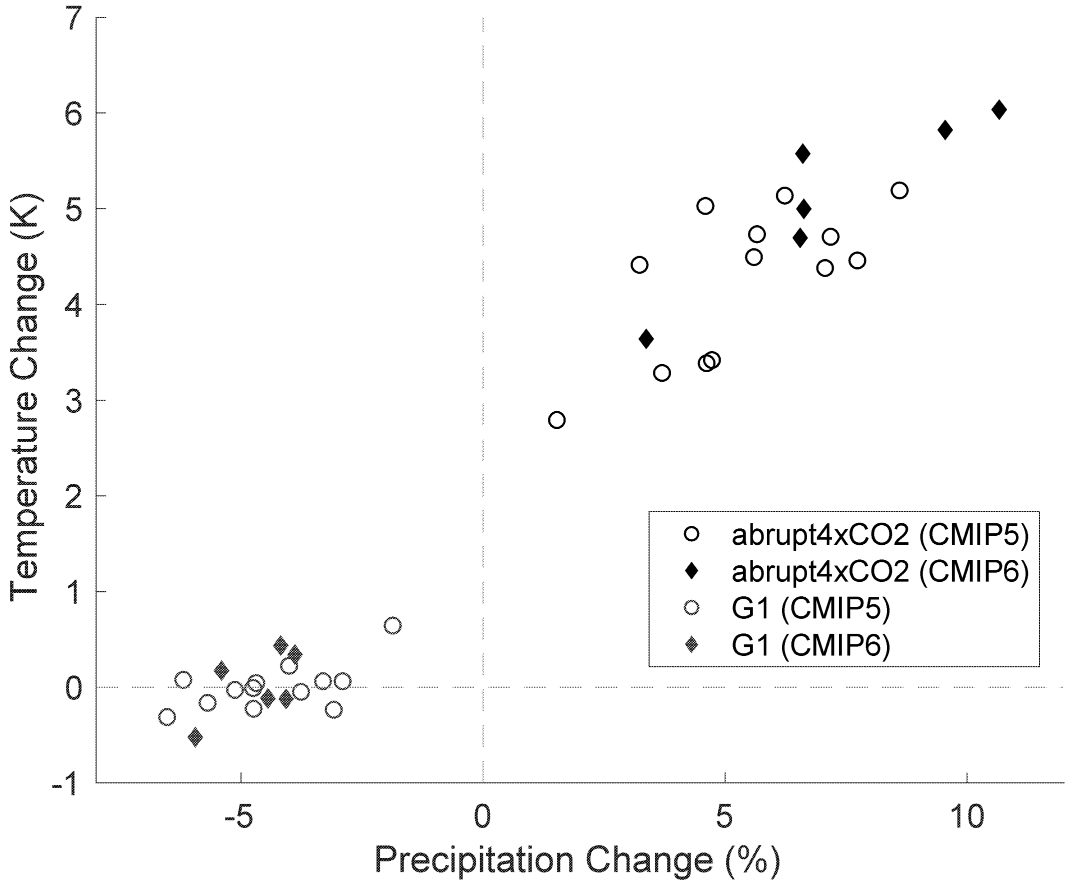
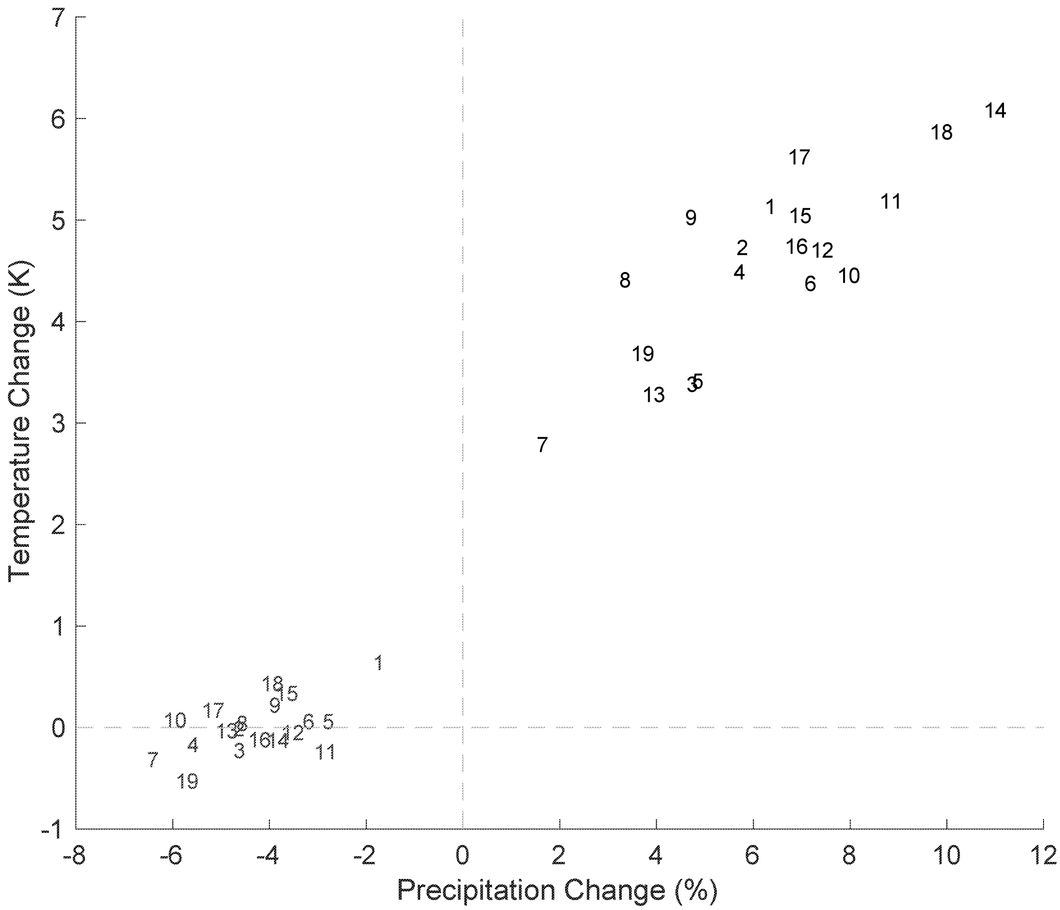


Figure 5. Average (years 11–50) temperature (y-axis; K) and precipitation (x-axis; %) change for each model in this study.



Alternate Figure 5. Average (years 11–50) temperature (y-axis; K) and precipitation (x-axis; %) change for each model in this study. Numbers indicate the model number (listed in Table 1, in order). Black numbers are for abrupt4xCO2, and red numbers are for G1.

Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP)

Supplemental Online Material

Ben Kravitz,[1,2,*] Douglas G. MacMartin,[3] Daniele Visioni,[3] Olivier Boucher,[4] Jason N. S. Cole,[5] Jim Haywood,[6,7] Andy Jones,[7] Thibaut Lurton,[4] Martine Michou,[8] Michael J. Mills,[9] Pierre Nabat,[8] Alan Robock,[10] Roland Séférian,[8] and Simone Tilmes[9]

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Submission to *Environmental Research Letters*

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S1. Global-scale Temperature Metrics

Supplemental Figure 3 and its associated discussion in Section 3.2 include three temperature metrics (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016): global mean temperature (T_0), the interhemispheric temperature gradient (T_1), and the equator-to-pole temperature gradient (T_2). We define these in terms of the projection of the first three Legendre polynomials onto the temperature field:

$$T_0 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\, dA$$

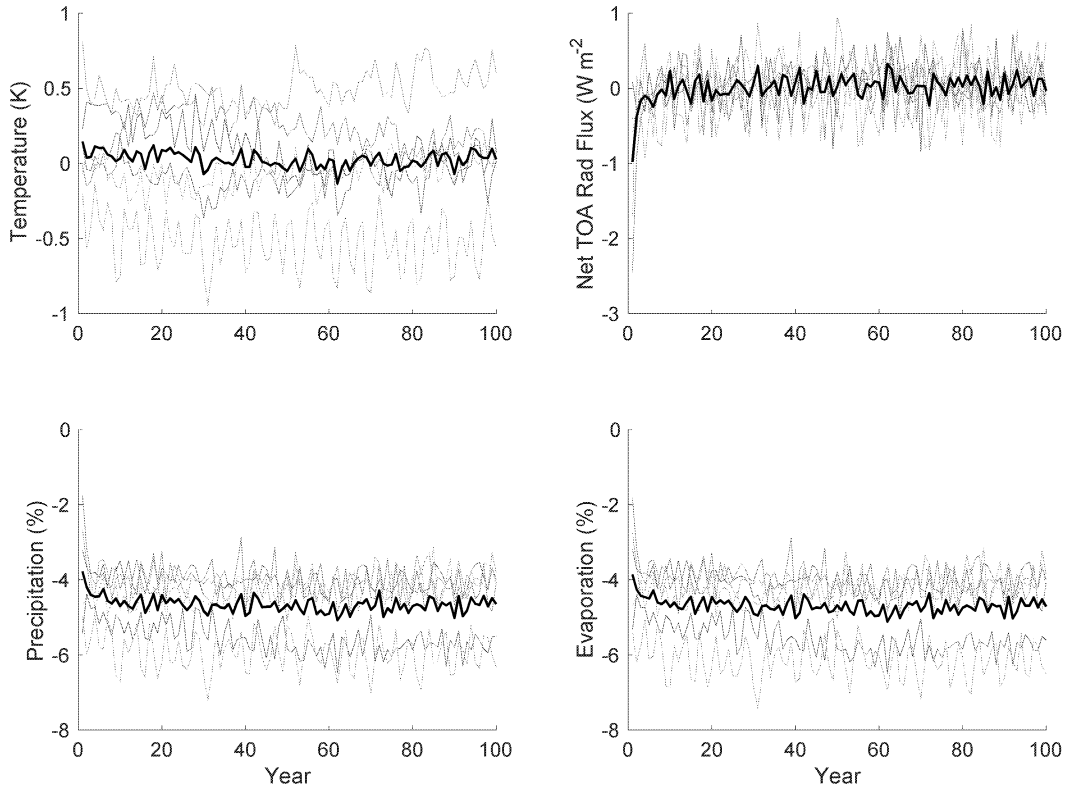
$$T_1 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\, \sin\psi\, dA$$

$$T_2 = \frac{1}{A} \int_{-\pi/2}^{\pi/2} T(\psi)\, (3\sin^2\psi - 1)\, dA$$

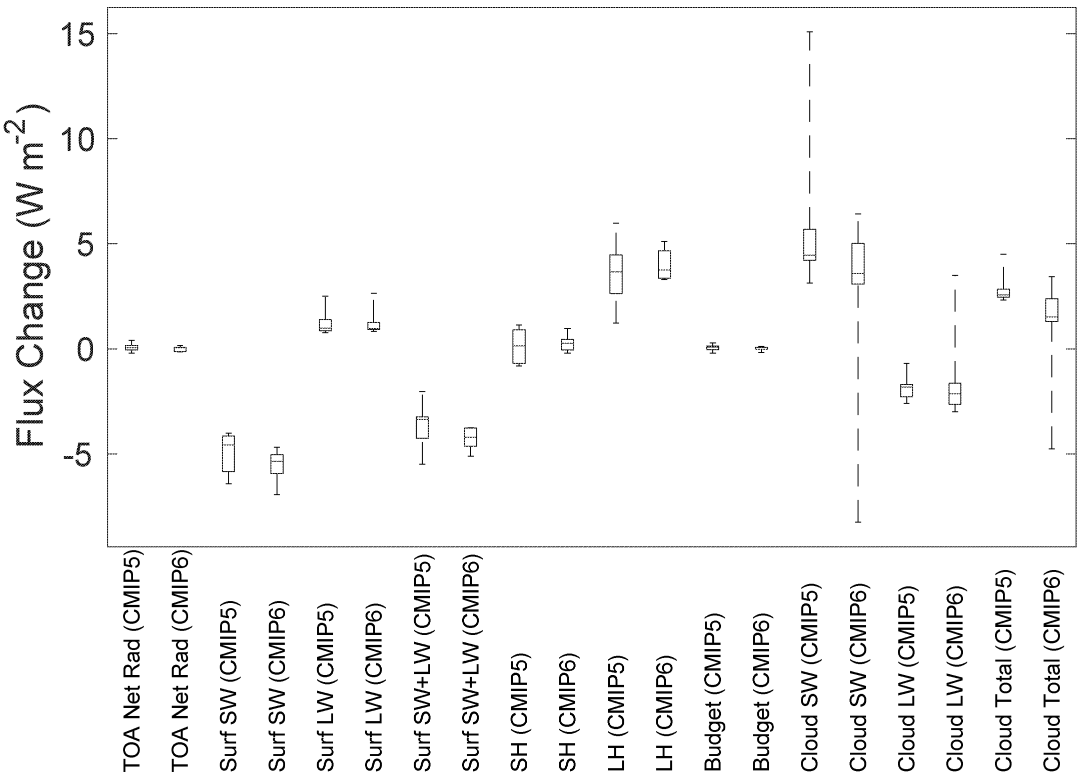
where *T* is temperature, ψ is latitude, and *A* is area.

Supplemental Table 1. Fraction of the Earth's surface for which the CMIP5 ensemble is statistically different from the CMIP6 ensemble. Results are based on 95th percentile confidence intervals from Welch's t-test.

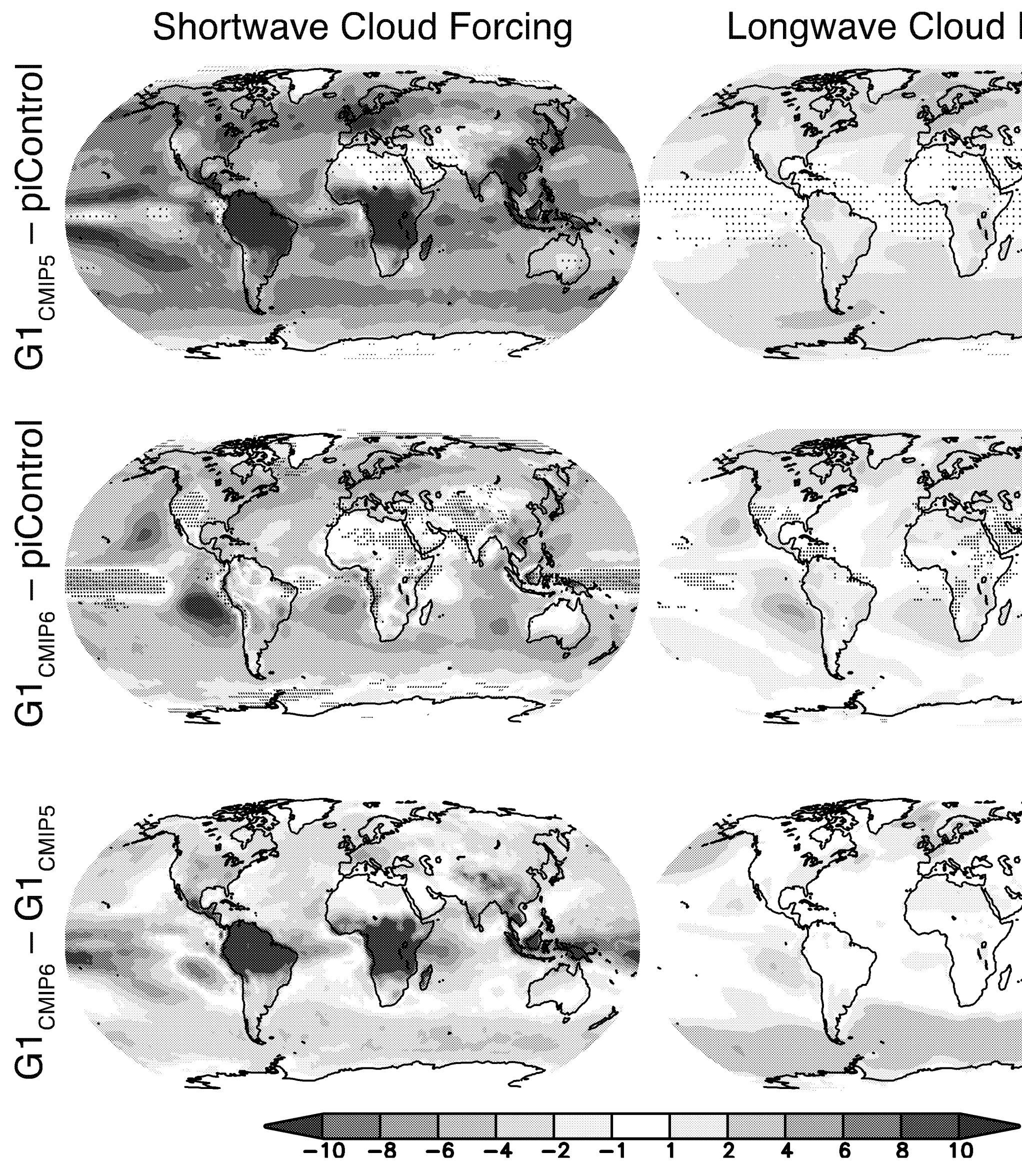
Variable	Percent	Notes
Surface air temperature	0.65	
Precipitation	11.51	
Evaporation	7.66	
Precip minus Evap	9.15	
SW Cloud Forcing	13.53	
LW Cloud Forcing	4.86	
Net Primary Productivity	4.31	Land surface only



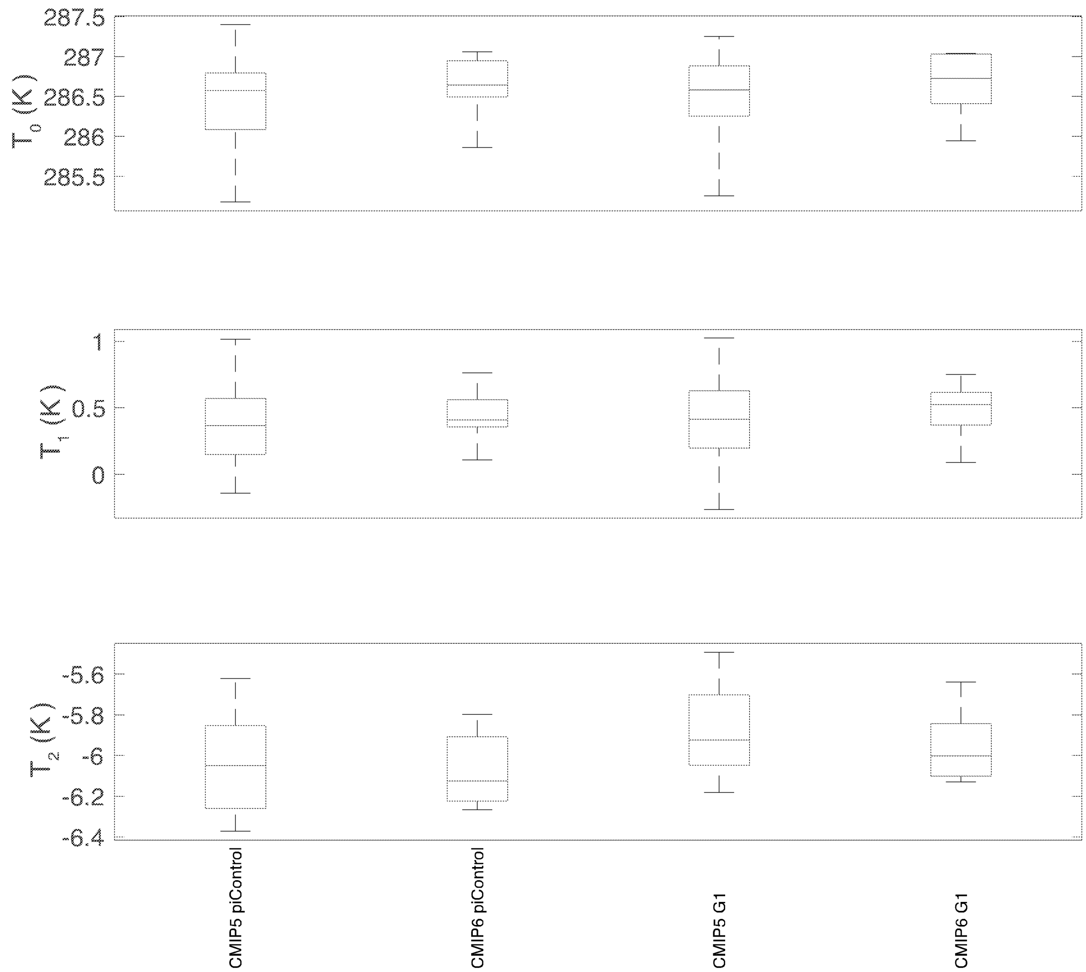
Supplemental Figure 1. Temperature (top left; K), net top-of-atmosphere radiative flux (top right; W m^{-2}), precipitation (bottom left; %), and evaporation (bottom right; %) change in $G1_{CMIP6}$ compared to piControl over 100 years of simulation. Thin colored lines are individual models, and thick black lines are ensemble means.



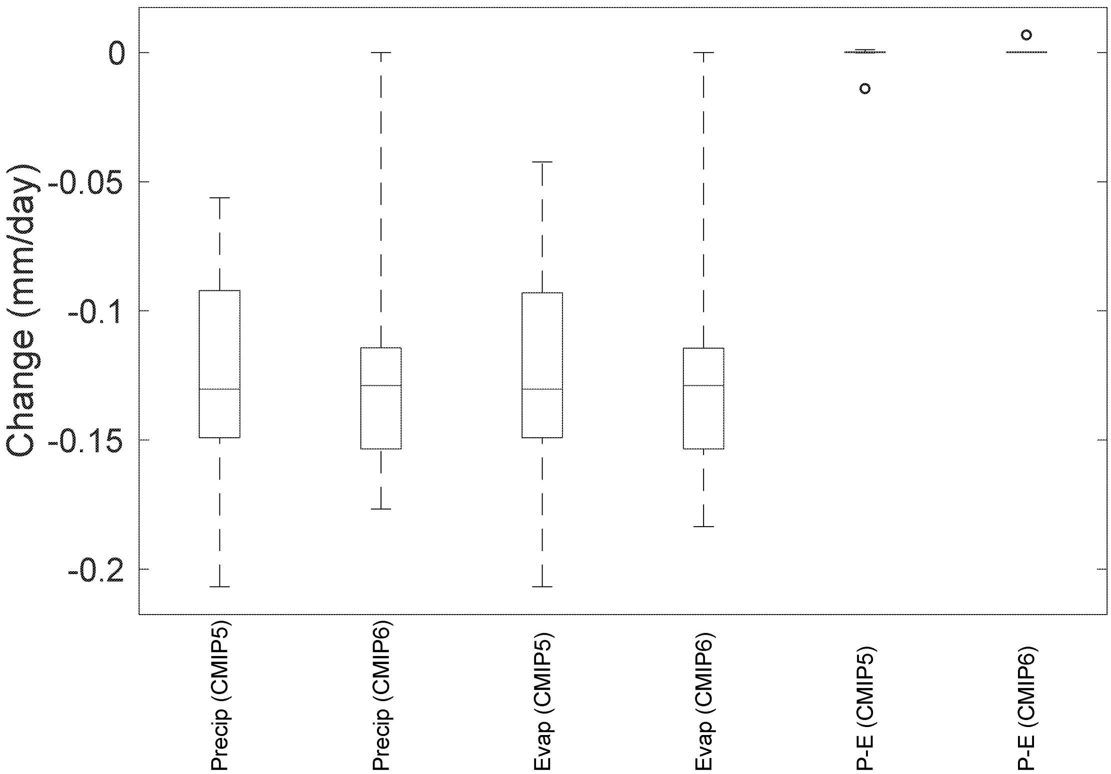
Supplemental Figure 2. Ensemble median (red lines), inter-quartile (blue boxes), and ranges (black whiskers) for the same global mean energetics quantities as in Figure 1 (G1 minus piControl) for both the CMIP5 and CMIP6 ensembles.



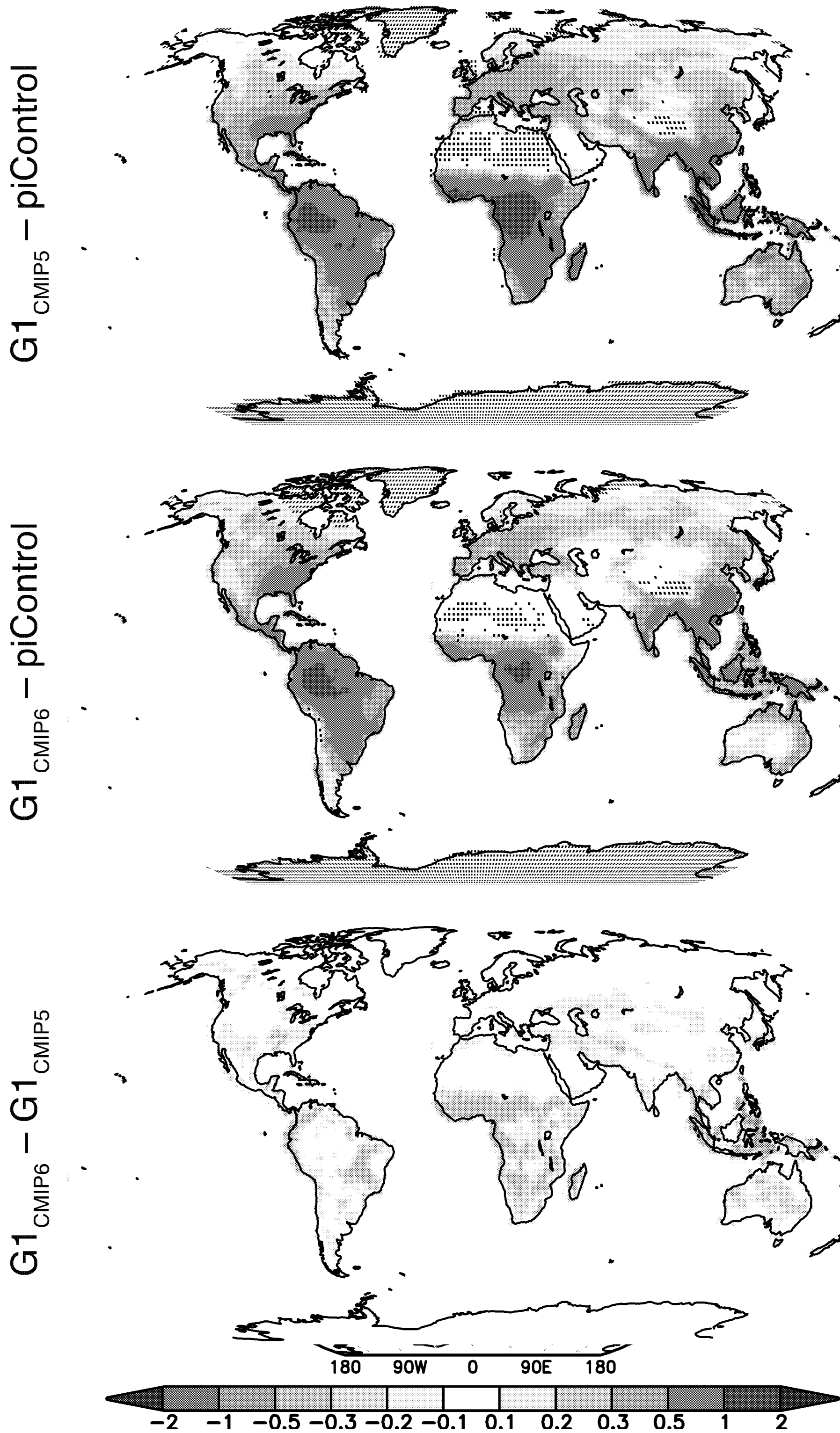
Supplemental Figure 3. Surface shortwave (left) and longwave (right) cloud forcing (W m^{-2}) change from preindustrial for the CMIP5 (top) and CMIP6 (middle) ensembles, as well as the ensemble differences (bottom). Cloud forcing is measured as all-sky minus clear-sky radiative flux. All shaded values are ensemble means. Stippling indicates agreement on the sign of the values across at least 75% of the models.



Supplemental Figure 4. Ensemble ranges for global mean temperature (T_0), the interhemispheric temperature gradient (T_1), and the equator-to-pole temperature gradient (T_2), as defined in Supplemental Section 1 (Ban Weiss and Caldeira, 2010; Kravitz et al., 2016). Red lines indicate ensemble medians, blue boxes are the inter-quartile ranges, and black whiskers indicate total ranges.



Supplemental Figure 5. Global mean ensemble median (red lines), inter-quartile (blue boxes), and ranges (black whiskers or, for P-E one blue circle indicating an extreme outlier) for the hydrological quantities shown in Figure 4 for both the CMIP5 and CMIP6 ensembles.



Supplemental Figure 6. Terrestrial net primary productivity (kg C m^{-2} y^{-1}) for the CMIP5 (top) and CMIP6 (middle) ensembles, as well as the ensemble differences (bottom). All shaded values are ensemble means. Stippling indicates agreement on the sign of the values across at least 75% of the models.

s.19(1)

Subject: G1 paper, version 3
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 7/15/20, 18:46
To: "Haywood, Jim" [redacted], Alan Robock ☮ <robock@envsci.rutgers.edu>, "Douglas MacMartin" <dgm224@cornell.edu>, Daniele Visioni <dv224@cornell.edu>, "olivier.boucher@lmd.jussieu.fr" <olivier.boucher@lmd.jussieu.fr>, "Cole, Jason (EC)" <jason.cole@canada.ca>, "Haywood, James" <J.M.Haywood@exeter.ac.uk>, "Jones, Andy" [redacted], "thibaut.lurton@ipsl.fr" <thibaut.lurton@ipsl.fr>, "mmills@ucar.edu" <mmills@ucar.edu>, NABAT Pierre <pierre.nabat@meteo.fr>, Ulrike Niemeier <ulrike.niemeier@mpimet.mpg.de>, Roland Séférian [redacted]>, Simone Tilmes <tilmes@ucar.edu>

Hi folks -

Here's an updated version of the G1 paper. Based on everyone's comments, I think this is in decent shape. I'll plan on submitting this Friday, sometime after I've had my coffee. If that's too soon, please let me know, and I will push the submission back.

https://www.dropbox.com/s/wxr2f68i8jig7ry/GeoMIP6_G1_v3.docx?dl=0
(Placed on dropbox because some of you have a 10 MB email attachment limit)

One question before I do that. In the GeoMIP meeting, we had discussed a special issue of ACP/ESD/something else. Any opinions as to whether I should submit to ACP instead of ERL? If we did that, I would probably move everything out of the supplemental material and into the main text.

Best,

Ben

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Pronouns: he/him/his

000740

 9/23/22, 13:31

Subject: Revised G1 paper
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 12/16/20, 22:51
To: Olivier Boucher <olivier.boucher@ipsl.fr>, Alan Robock ☮ <robock@envsci.rutgers.edu>, "Haywood, Jim" ,
Douglas MacMartin <dgm224@cornell.edu>, Daniele Visioni <dv224@cornell.edu>, "olivier.boucher@lmd.jussieu.fr" <olivier.boucher@lmd.jussieu.fr>, "Cole, Jason (EC)" <jason.cole@canada.ca>, "Haywood, James" <J.M.Haywood@exeter.ac.uk>, "Jones, Andy" . "thibaut.lurton@ipsl.fr" <thibaut.lurton@ipsl.fr>, NABAT Pierre <pierre.nabat@meteo.fr>, "Ulrike Niemeier" <ulrike.niemeier@mpimet.mpg.de>, Roland Séférian
"Simone Tilmes" <tilmes@ucar.edu>

Hi folks -

The reviews for the G1 paper came in a couple of days ago, and (shock of shocks) they were pretty easy to address. I've attached a revised version of the manuscript, a tracked changes version, and a response to reviewers. Please let me know if you have any comments.

I didn't see anything terribly controversial in here, so I'll plan on uploading the responses to reviewers on the 23rd (Wednesday of next week), just on the off chance that someone over at the journal is paying attention.

Best,

Ben

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Attachments:

diff.pdf	438 bytes
GeoMIP6_G1_v4_revised.pdf	489 bytes
Response to Reviews.docx	541 bytes

Key messages related to carbon dioxide (CO_2) removal (CDR) and solar radiation modification (SRM)

1. Key messages related to carbon dioxide (CO_2) removal (CDR) and solar radiation modification (SRM) from IPCC AR6 WG1 report and special report on 1.5C.

    a. Anthropogenic CDR has the potential to remove CO_2 from the atmosphere and help achieve net zero emissions.

    b. CDR would lower the atmospheric CO_2 concentration and reverse surface ocean acidification.

    c. While CDR can help gradually reverse the global CO_2-induced surface temperature increase other climate changes would continue in their current direction for decades to millennia (e.g. sea level rise).

    d. Anthropogenic CO_2 emissions are partially compensated by CO_2 uptake by land and ocean carbon pools, and similarly anthropogenic CO_2 removals are partially compensated by CO_2 release from land and ocean carbon pools.

    e. CDR methods can have potentially wide-ranging effects on biogeochemical cycles and climate, which can either weaken or strengthen the potential of these methods to remove CO_2 and reduce warming, and can also influence water availability and quality, food production and biodiversity.

    f. SRM can offset some warming but there would be substantial residual and overcompensating climate change at the regional scale and seasonal timescale.

    g. SRM would not stop CO_2 from rising in the atmosphere and ocean acidification will continue.

    h. The sudden and sustained termination of SRM would rapidly increase global warming.

    i. Uncertainties surrounding SRM methods constrain their potential deployment. These include knowledge gaps, as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development.

2. ECCC's Earth System Modelling framework developed by the Climate Research Division is capable of projecting the climate and terrestrial/oceanic ecosystem effects of both CDR and SRM.

    a. The Canadian Earth System Model (CanESM) includes representation of both land and ocean carbon cycles. The model is capable of simulating effects of afforestation, reforestation, ocean fertilization, increasing ocean alkalinity, and direct removal of CO2 from the atmosphere.

b. While CanESM is currently capable of examining idealized effects of SRM on climate, through changes to clouds, stratospheric aerosols, and surface albedo, ongoing improvement to model physics is needed to better simulate more realistic SRM scenarios.

c. Future model development to support SRM research and its effect on climate includes interactive stratospheric aerosols and more sophisticated cloud microphysics.

d. Progress on these model improvements, especially interactive stratospheric aerosols, depend on additional resources for aerosol model development and evaluation. This would also improve simulation of volcanic aerosols and their effect on climate and potentially weather forecasting.

3. Impact, policy, and governance of CDR and SRM in upcoming IPCC WGII and WGIII AR6

a. Assessment on impacts and policy issues associated with CDR and SRM will be included in the upcoming IPCC WGII and WGIII reports, due to be released in 2022.

b. A comprehensive assessment of the effects of CDR on food production, water availability, and biodiversity will be included in WGII (Chapters 2 and 5) and WGIII (Chapters 7 and 12).

c. SRM risks and its impacts on human and natural systems will be assessed in the AR6 WGII report (Chapter 16), and the international governance issues related to SRM and CDR will be assessed in the AR6 WGIII report (Chapter 14).

s.19(1)

Cole,Jason (il, le, lui | he, him, his) (ECCC)

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: March 23, 2021 11:01 AM
To:
Subject: RE: ALI/SHOW/TICFIRE and Geoengineering

Hi

Could we use Teams (link below)? I have issues with Webex on my Linux machine and I don't want to commandeer my daughter's laptop.

Thanks,

Jason

https://teams.microsoft.com/l/meetup-join/19%3ameeting_ZGUzZWE2YWMtMzc0ZS00MmMwLWE2MDktZTI1MDQyMDJhN2E4%40thread.v2/0?context=%7b%22Tid%22%3a%22740c5fd3-6e8b-4176-9cc9-454dbe4e62c4%22%2c%22Oid%22%3a%2258880a89-b590-4e0b-91cc-ea3d6edc4075%22%7d

From:
Sent: March 22, 2021 6:00 PM
To: Cole, Jason (EC) <jason.cole@canada.ca>
Subject: Re: ALI/SHOW/TICFIRE and Geoengineering

That'd be great, how about 12:00 noon Eastern tomorrow?

mentioned the VolMIP scenarios. These look great; as you know I've been thinking about an OSSE study like this for a while.

Thanks,
Adam

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: March 22, 2021 9:38 AM
To:
Subject: Re: ALI/SHOW/TICFIRE and Geoengineering

CAUTION: External to USask. Verify sender and use caution with links and attachments. Forward suspicious emails to phishing@usask.ca

Hi

A discussion about this would be good. Any time or day that works best for you?

s.19(1)

It is not Keith's group but David started the ball rolling on discussions among interested people in Canada. It seems to be going sporadically, or I'm not in the core group trying to push it forward. If they get organized, I do think they might help the case for the Canadian instruments, maybe not directly to A-CCP but at least strengthen the discussion in Canada. I'm not sure what will be in the report but the US NAS is releasing a report on SRM climate engineering this Thursday. There might be something in there that could be useful. I'll forward an email about it to you.

A couple of weeks ago, I was talking to about VolMIP stuff and suggested an application of the HAWC simulators they have developed. There are some interesting aerosol injection simulations from the WACCM model (https://www.cesm.ucar.edu/projects/community-projects/GLENS/) with relatively high frequency output available (6-hourly), although the model is lower resolution (~1 degree). If it possible to use the simulators on this output, I was thinking it would be a nice demonstration of the instrument capability. For example, early in the injection (detection of stratospheric changes), some mid-points (show capability to detect properties), later points (the signal might be saturated?). It could be neat. In my mind, it would also be a useful methodology to show the capability of the instruments (and perhaps orbits) for other injection scenarios.

Jason

From:
Sent: Friday, March 19, 2021 4:32 PM
To: Cole, Jason (EC)
Subject: ALI/SHOW/TICFIRE and Geoengineering

Hi Jason,

You mentioned a while back about some interest from David Keith's group in the Usask stratospheric aerosol algorithms and the potential for the Canadian A-CCP instruments in a geoengineering scenario.

I think we should connect with them. They might be able to help in an interesting way with the case for the Canadian instruments as part of A-CCP. Can we chat about this sometime next week?

s.19(1)

Subject: FW: Fostering research on solar geoengineering in Canada
From: "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>
Date: 12/16/20, 22:10
To: "Farahani, Ellie (EC)" <ellie.farahani@canada.ca>
CC: "Fyfe, John (EC)" <john.fyfe@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>

Hi Ellie,
Just letting you know that Shawn Marshall has put us in touch with David Keith for a science discussion about geoengineering research.

Cheers,

Nathan

Sent from my Bell Samsung device over Canada's largest network.

-------- Original message --------
From: "Marshall, Shawn (EC)" <shawn.marshall@canada.ca>
Date: 2020-11-03 6:39 p.m. (GMT-08:00)
To: "Fyfe, John (EC)" <john.fyfe@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, @harvard.edu
Subject: FW: Fostering research on solar geoengineering in Canada

Hi John, Nathan:

I am writing to e-introduce you to David Keith, whom you may know of.

David is at Harvard where he works on a wide range of things, among them solar geoengineering. See here for a bit of background on this question and some of David's work:

https://keith.seas.harvard.edu/geoengineering-resources
https://www.bostonglobe.com/2020/10/19/opinion/world-needs-explore-solar-geoengineering-tool-fight-climate-change/

. He is looking to engage with the national atmospheric science community and ECCC on SRM and climate science. I suspect you will have lot of mutual interests.

David has some ideas to advance but I will pass over to him know - happy to stay in the loop as this is interesting to me and, I think, really important.

Hope all is well at CCCmA, despite these strange times.

All best,
Shawn

Call Regarding Next Steps for a Potential Intergovernmental / International CDR Forum – May 26
Hosted by Carnegie Climate Governance Institute (C2G)

Purpose of meeting: discuss next steps regarding formal or informal Cdn participation in a proposed the a potential international Carbon Dioxide Removal (CDR) Forum proposed by C2G. This Forum would bring together governments and the private sector to fill the international governance gap with respect to CDR through international collaboration and information sharing.

Context

- CDR is considered included in emission scenarios consistent with different levels of global warming presented in the recent IPCC reports. Based on its analysis of these scenarios, large-scale use of CDR as well as significant efforts to reducereductions in emissions will be needed in every scenario to limit warming to 1.5°C (and in most scenarios to limit global warming to 2°C).
- Net zero global carbon emissions are a requirement for stabilizing global temperature at any level. This means that any positive carbon emissions exceeding the allowable carbon emission budget for a given global temperature target need to be compensated by negative emissions – that is, by carbon dioxide removal from the atmosphere and long term storage in suitable reservoirs. Given that the carbon emissions budget for limiting global warming to 1.5C is small, all emission scenarios envision some level of overshoot of the temperature target followed by returning to 1.5C through large scale CDR.
- Suggest briefly note the two forms of CDR – enhanced terrestrial/marine sinks or technology – direct air capture. (Possible text to use: There are two main forms of CDR: 1. Enhancement of biological carbon sinks, 2. Technological approaches. In all cases, long term storage of carbon in biomass or geological formations is required to ensure 'permanent' removal of the carbon from the atmosphere. Large scale afforestation / reforestation, biochar and biomass energy systems combined with carbon capture and storage (BECCS) are examples of biological CDR. Direct air capture and carbon storage (DACCS) is an example of technological CDR.
- (Given that this note later refers to 'climate engineering' I think you need a sentence here under Context that explains that CDR has traditionally been considered as a form of climate engineering. Possible text is: "CDR has traditionally been considered one of two main approaches to climate engineering (the other being Solar Radiation Management). Climate engineering refers to the deliberate, large-scale intervention in the climate system to offset global warming. For CDR, the boundary between climate engineering and mitigation is unclear but generally relates to the scale and impact of the intervention.[1]
- Switzerland tabled a resolution calling for an expert review by the UN Environment Programme (UNEP) of climate engineering technologies, processes, risks, and governance. Opposition from the United States, Saudi Arabia, and Brazil stalled the proposal and led to its eventual withdrawal. While these states argued that a UNEP assessment would be duplicative of the IPCC work, the Sixth Assessment Report (due in 4 volumes over the period 2021-2022[2]) is not expected to address comprehensively all the relevant aspects of climate engineering such as linkages to biodiversity and the broad suite of sustainable development goals generally or governance.
- Canada saw merit in the Swiss resolution and was prepared to support the concept, but chose not to vocalize support to avoid risk of politicizing the issue, especially with the US.

[1] See for example the discussion in Minx et al., 2018. Negative emissions – Part 1: Research landscape and synthesis. Environmental Research Letters 13 (2018) 063001.
[2] IPCC timelines for the Sixth Assessment Report are being affected by the current global pandemic and may be delayed.

Commenté [B[1]]: Do we know which of these two C2G is proposing?

Commenté [S[2]]: Scope and intent not clear. Is this about Cdn engagement or participation in the C2G hosted forum – presumably it will proceed w/o us.

Commenté [B[3R2]]: The original email from Xin Gao had a Concept Note that explained C2G is proposing the establishment of an international forum on (perhaps) the margins of the UNFCCC to discuss governance of CDR. So not a CG2 hosted forum – they are hosting the call.

Commenté [B[4]]: I don't think this is correct. The meeting on May 26 is an international meeting the purpose of which is to discuss the feasibility and desirability of creating an international or intergovernmental forum on CDR. It is not to discuss Cdn participation.

Commenté [G[5]]: Reductions in CO2 emissions to close to zero. I think 'significant reductions in emissions' understates this.

Commenté [G[6]]: Classification of BECCS as 'Enhancement of biological carbon sinks' seems wrong to me. This approach requires storage of captured carbon underground in geological reservoirs – this isn't just an enhancement of carbon sinks.

Commenté [S[7]]: STB Climate Research Division can confirm / elaborate,.

Commenté [B[8R7]]: We don't know for sure what WGIII will cover but I expect it will cover governance aspects of CDR to some extent.

Commenté [S[9]]: Suggest just say why Canada saw value in it

Mis en forme : Anglais (États-Unis)

- Despite the withdrawal of the resolution, C2G viewed it as a success because it brought governments together to discuss these issues for the first time.
- According to G2G, governance of CDR could be undertaken by UNFCC and would:
  - Support accounting and verification of emissions reductions using CDR at the international level
  - Manage politics, such as between developed countries who can afford the technology and developing countries who can't; as well as possible unilateral large scale deployment by states causing unknown impacts
- Provide guidance to states on the relationship between CDR and issues such as biodiversity, food security and the Sustainable Development Goals. The IPCC Special Report on Climate Change and Land (2019) drew particular attention to how such interactions depended on the scale of CDR. xx

Canada's position

- (It might be worth starting with a general position that there is no 'silver bullet' for mitigating global warming. Modelled emission pathways include a large suite of mitigation options to reduce emissions from existing sources, avoid new emissions, and enhance carbon removal from the atmosphere.)
- (Could state that as a Party to the UNFCCC, Canada's position already includes support for enhancement of natural carbon sinks and Canada's domestic action plan, the Pan Canadian Framework on Clean Growth and Climate Change, continues to support such activities.)
- Canada has supported companies developing CDR direct air capture technologies.
  - Canada's Carbon Engineering has the world's most advanced direct-air capture technology, with headquarters and pilot facility in Squamish, BC
  - Canada has provided $25M to Carbon Engineering through the Strategic Innovation Fund in 2019
- In Canada, there are no ~~is no comprehensive legislative~~ formal or informal science, regulatory or legislative frameworks to govern climate engineering research, scale-up or large-scale deployment activities ~~at the federal or provincial levels~~. Clear regulations and a carbon price are the most effective ways for governments to support the scaling up of CDR technologies.
- A variety of CDR methods exist with a wide range of costs, possible scales, and potential impacts. More research is needed on the efficacy of different CDR approaches and of their possible environmental impacts (unintended consequences), especially at larger scales. Efforts must also be made to ensure the public understands these technologies and that CDR does not weaken resolve for essential mitigation or adaptation efforts.
- International fora discussing CDR governance provide opportunity for Canada to learn from other countries to inform domestic research and policy.

Commenté [G[10]: Would 'through the' or 'under the' be better? The UNFCCC is a convention – doesn't seem that it could directly govern C2G.

Commenté [B[11]: This seems a very categorical statement. Is it supported with evidence? Developing countries have natural carbon sinks and are already engaged in natural carbon sink enhancement under the UNFCCC.

Commenté [S[12]: Be explicit about the co-benefits and trade-offs, noting trade-=offs could have negative impact on achieving SDGs.

Commenté [S[13]: Are their any other for a that are being proposed vis-a-vs governance of CDR? Is this the only mechanism that exists for Canada to engage in this conversation?

Commenté [S[14]: Confirm details w NRCan – subsidized R&D presumably, pre-scale-up?

Commenté [S[15]: Suggest avoid adjectives

Commenté [S[16]: What is this based on? Suggest cite source for such a substantive statement.

Commenté [S[17]: What are the risks of being left out of C2G forum? Or not being a C2G member?? Are their ways to engageinformally??

Subject: [GeoMIP_list] Additional runs from BNU-ESM
From: "Kravitz, Ben" <Ben.Kravitz@pnnl.gov>
Date: 2/19/18, 04:36
To: "geomip_list@email.rutgers.edu" <geomip_list@email.rutgers.edu>

Hello again -

Please see the following information about some new runs from BNU (please contact Duoying Ji and John Moore for further details):

We recently finished three new extended G1 simulations of 100yr and second ensemble of G4 with our CMIP5 version model. Especially the new G1 runs adequately restore the global mean temperature to its preindustrial level. These new runs are published at the following sites:

http://globalchange.bnu.edu.cn/duoyingji/G1.html
http://globalchange.bnu.edu.cn/duoyingji/G4.html
http://climatemodeling.bnu.edu.cn/G1.html
http://climatemodeling.bnu.edu.cn/G4.html

The old GeoMIP and CMIP5 runs could be reached at our local data node: http://esg.bnu.edu.cn

----

Best,

Ben

Ben Kravitz
Climate Scientist
Atmospheric Sciences and Global Change Division
Pacific Northwest National Laboratory
P.O. Box 999, MSIN K9-30
Richland, WA 99352
Tel: (509) 372-6846 Fax: (509) 375-6448
ben.kravitz@pnnl.gov

____
GeoMIP_list mailing list
GeoMIP_list@email.rutgers.edu
https://email.rutgers.edu/mailman/listinfo/geomip_list

Subject: [GeoMIP_list] G7cirrus status
From: "Kravitz, Ben" <Ben.Kravitz@pnnl.gov>
Date: 7/12/18, 15:06
To: "geomip_list@email.rutgers.edu" <geomip_list@email.rutgers.edu>

Hello everyone -

I have recently made a request to the CMIP6 working group to "demote" G7cirrus from Tier 1 to Tier 2. This is based on several discussions we have had at a few meetings regarding how well Earth System Models can simulate upper tropospheric ice water path and cirrus. The experiment will still be interesting for model intercomparisons to help understand how process changes can lead to changes on larger scales, which is why it will not be eliminated from the protocol entirely. I know CMIP6 is getting underway, so please feel free to spread the word to the relevant modeling teams.

Best,

Ben

Ben Kravitz
Climate Scientist
Atmospheric Sciences and Global Change Division
Pacific Northwest National Laboratory
P.O. Box 999, MSIN K9-30
Richland, WA 99352
Tel: (509) 372-6846 Fax: (509) 375-6448
ben.kravitz@pnnl.gov

Subject: [GeoMIP_list] G6solar/G6sulfur
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 5/31/19, 00:25
To: "geomip_list@email.rutgers.edu" <geomip_list@email.rutgers.edu>

Hi folks -

I'm getting a couple of inquiries about G6solar and G6sulfur. The specifications document that I sent around a few months ago is now online:

http://climate.envsci.rutgers.edu/GeoMIP/doc/G6specs.docx

If you feel like any necessary information is missing from that document, please let me know.

Best,

Ben

Ben Kravitz
Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
http://pages.iu.edu/~bkravitz/
Pronouns: he/him

Subject: RE: Climate Engineering
From: "Bolina2, Amandeep (EC)" <amandeep.bolina2@canada.ca>
Date: 9/30/19, 16:14
To: "Flato, Greg (EC)" <greg.flato@canada.ca>, "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>
CC: "Edwards, Patti (EC)" <patti.edwards@canada.ca>, "Anderson2, Kevin (EC)" <kevin.anderson2@canada.ca>, "Walker, Anne (EC)" <anne.walker@canada.ca>, "Carou, Silvina (EC)" <silvina.carou@canada.ca>, "Farahani, Ellie (EC)" <ellie.farahani@canada.ca>

Hi all,

Should you have any comments on the climate engineering paper, may kindly ask that you submit them by **3PM today**. Our consolidated comments will need to go to DGO by COB today.

Jason – I received your comments, thanks!

Thanks,
Amandeep

From: Bolina2, Amandeep (EC)
Sent: September 27, 2019 9:54 AM
To: Flato, Greg (EC) <greg.flato@canada.ca>; Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>; Cole, Jason (EC) <jason.cole@canada.ca>
Cc: Edwards, Patti (EC) <patti.edwards@canada.ca>; Anderson2, Kevin (EC) <kevin.anderson2@canada.ca>; Walker, Anne (EC) <anne.walker@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Subject: FW: Climate Engineering

Hi all,

Attached is the latest version of the Climate Engineering paper developed for the medium-term planning process. It is being shared with us again for comments/input. Please provide any comments you may have on the attached document by **COB Sept 30**.

Thanks,
Amandeep

From: Shepherd, Marjorie (EC) <marjorie.shepherd@canada.ca>
Sent: September 27, 2019 9:20 AM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Mullins, David (EC) <david.mullins@canada.ca>; Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>; Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
Subject: FW: Climate Engineering

Looping in Heather for CRD review. I will also review and we should provide integrated comments from myself, AQRD and CRD.
Mj

From: Moncrieff, Don (EC) <don.moncrieff@canada.ca>
Sent: September 27, 2019 8:27 AM
To: Shepherd, Marjorie (EC) <marjorie.shepherd@canada.ca>; Mullins, David (EC) <david.mullins@canada.ca>
Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>

Subject: FW: Climate Engineering

Hi,

Please see request below from the ADMO….is there anyone else you think should be looped in to provide comments on the attached document? Note the deadline of Oct 1st.

Don

Don Moncrieff

Bureau du Directeur général, Direction de Sciences et technologie atmosphériques
Environnement et Changement climatique Canada / Gouvernement du Canada
Don.Moncrieff@canada.ca / Tél: 613-998-7346

Director General's Office, Atmospheric Science & Technology Directorate
Environment and Climate Change Canada/Government of Canada
Don.Moncrieff@canada.ca / Tél: 613-998-7346

Government of Canada Gouvernement du Canada Canada

From: Hayne, Shari (EC) <shari.hayne@canada.ca>
Sent: September 26, 2019 5:11 PM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Monforton, Amanda (EC) <amanda.monforton@canada.ca>; Vien, Julie (EC) <julie.vien@canada.ca>
Cc: Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hello,

Attached is the Climate Engineering paper developed for the medium-term planning process. Hilary Geller indicated that we don't have a government policy and inquired if it should be included in the National Climate Change Science and Knowledge plan.

Please provide input and comments on the paper and note ongoing discussions in the department and observations from the ECCC geoengineering working group to date (I believe Marjorie Shepherd and David Mullins were the STB representatives).

Due in ADMO Oct 1 COB

Thanks,
Shari

From: Goon, Amy (EC) <amy.goon@canada.ca>
Sent: September 20, 2019 9:56 AM
To: Hamzawi, Nancy (EC) <nancy.hamzawi@canada.ca>
Cc: Huddleston, Jeanne-Marie (EC) <jeanne-marie.huddleston@canada.ca>; Hayne, Shari (EC) <shari.hayne@canada.ca>; Chandler, Janina (EC) <janina.chandler@canada.ca>; Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
Subject: FW: Climate Engineering

Hi Nancy,

Understand that you are looking for the Climate Engineering paper that was developed for the mitigation medium-term planning process. Please find it attached. It was a led by IAB, and has been DG approved. Input from the ECCC geoengineering working group (comprised of officials from STB, IAB, EPB, PCFIO) was sought.

Happy Friday!
Amy

-------- Original message --------
From: "Geller, Hilary (EC)" <hilary.geller@canada.ca>
Date: 2019-09-20 9:36 AM (GMT-05:00)
To: "Huddleston, Jeanne-Marie (EC)" <jeanne-marie.huddleston@canada.ca>
Cc: "Jones, Matt (EC)" <matt.jones@canada.ca>, "Hamzawi, Nancy (EC)" <nancy.hamzawi@canada.ca>
Subject: Climate Engineering

Hi JM,

There is a paper called "Climate Engineering" that is part of the suite of mitigation papers done over the summer

Could you please flip it to Nancy electronically

Thanks,
Hilary

Hilary Geller
Assistant Deputy Minister / Sous-ministre adjointe
Strategic Policy Branch / Direction générale de la politique stratégique
Environment and Climate Change Canada / Environnement et Changement climatique Canada
Hilary.geller@canada.ca / Téléphone : 819 938-3782

EA/AE: Cheryl Devine (819) 938-3783

Subject: RE: Climate Engineering
From: "Flato, Greg (EC)" <greg.flato@canada.ca>
Date: 9/30/19, 18:11
To: "Bolina2, Amandeep (EC)" <amandeep.bolina2@canada.ca>, "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>
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Hi folks,

A couple comments.

1st sentence. I would replace "reduce" to "offset", or alternatively "reduce or offset". The reason is that SRM does not really 'reduce' anthropogenic climate change, but rather it reduces incoming solar radiation so as to offset some or all of the warming that would have otherwise occurred.

Pg. 2. Under the heading of Climate Engineering Methods, I would change the sentence that begins "SRM has the potential …" to "SRM has the potential to slow or even reverse global temperature change, but it does not address the underlying drivers of climate change, notably increasing carbon dioxide concentration in the atmosphere, the way that CDR does."

Pg. 2. I would change "**Natural**" to "**Enhanced Natural**"

Pg 5. I had commented on an earlier draft about how misleading the WMO statement about air pollution deaths is. This has not been corrected. In my view it really must be.

Greg

Gregory M Flato, PhD

Senior Research Scientist
Canadian Centre for Climate Modelling and Analysis, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
greg.flato@canada.ca / Tel: 1-250-363-8233 / Cell: 1-250-514-5044

Chercheur Principal
Centre canadien de la modélisation et de l'analyse climatique, Direction générale de la science et de la technologie
Environnement et changement climatique Canada / Gouvernement du Canada
greg.flato@canada.ca / Tél. : 1-250-363-8233 / Tél. Cell. : 1-250-514-5044

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Government of Canada Gouvernement du Canada Canada

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Subject: Climate Engineering

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Hilary Geller
Assistant Deputy Minister / Sous-ministre adjointe
Strategic Policy Branch / Direction générale de la politique stratégique
Environment and Climate Change Canada / Environnement et Changement climatique Canada
Hilary.geller@canada.ca / Téléphone : 819 938-3782

EA/AE: Cheryl Devine (819) 938-3783

Subject: RE: Climate Engineering
From: "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>
Date: 9/30/19, 20:47
To: "Flato, Greg (EC)" <greg.flato@canada.ca>, "Bolina2, Amandeep (EC)" <amandeep.bolina2@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>
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Hi Amandeep:

Sorry for coming in late with comments. I hope you can still pass these comments on.
Elizabeth

Introduction:

Editorial: Para three – first sentence – a word is missing after 'carried' I think. (carried out? Or replace with 'contained in"?)
Para three, second sentence: the statement of what is covered in the State of Climate Change Science transition doc on climate engineering is misleading.

- *In addition, a separate transition document on the state of science for climate change includes information on climate engineering as possible measures to counter global warming ~~addresses the current understanding of climate engineering~~ in the context of the gap between current mitigation efforts and the Paris agreement global temperature goal. ~~climate system response.~~*

Why Climate Engineering:
First sentence: the goal of the Paris Agreement is to hold the increase in global temp to well below 2C, and pursue efforts to hold it to 1.5C. While in the past, we sometimes used 1.5-2C to describe the Paris Agrt goals, this isn't really correct. So I'd suggest rephrasing the text here to simply say well below 2C. or, 1.5 – well below 2C.

- "There is currently a significant gap between national pledges under the Paris Agreement, and the emissions reductions required to hold the increase in global temperatures to ~~1.5 to~~ well below 2°C above pre-industrial levels.

Second sentence: it may be worthwhile being clear up front here that climate engineering may be proposed to slow down the rate of warming while enhanced mitigation is also pursued, just to be very clear that proponents are not positioning climate engineering as an alternative to more aggressive mitigation. Also, referring to research in this sentence doesn't make much sense as the research will not itself slow down the rate of global warming. Since the need for research is covered in the next sentence, I think the reference to research could be deleted here.

- "Pressure may grow to ~~research and~~ deploy climate engineering technologies to slow down the rate of global warming, in parallel with ongoing efforts to enhance mitigation action.

Gaps in Research, Global Governance and National Governance
Title: The text for this section doesn't address gaps in research **on** climate engineering. Rather it mentions a gap in governance **of** research on climate engineering. Suggest the title should be revised to reflect this, maybe just by striking out "Research" from the title.

First sentence: Another reason for the difficulties in getting consensus on climate engineering governance is the wide range of potential climate engineering methods. Governance requirements would be very different depending on the method, and certainly different for CDR vs SRM.

- "Consensus on climate engineering governance has been difficult to achieve in international fora, particularly due to the wide range of potential methods, and due to limited understanding of the science and risks associated with some of these ~~this issue."~~

Climate Engineering Methods – CDR section
Under 'natural' – shouldn't afforestation be included?

Under marine geoengineering: I think the various methods (ocean fertilization, ocean pumping to bring more nutrients to the surface, artificial downwelling (I'm not familiar with the latter but after a brief google search, it seems the objective is the same – to enhance CO2 uptake from the atmosphere and transport to the deep ocean) are all methods aimed at enhancing ocean carbon uptake and storage. Suggest editing this sentence to make that clearer. And I would suggest avoiding the term 'ocean carbon capture and storage' as the phrase 'carbon capture and storage' is used to refer to capturing Co2 from an emission source and not for removing additional CO2 from the atmosphere.

- **Marine geoengineering,** including ocean fertilization (i.e., spreading/distributing iron or other micronutrients to promote marine algal growth) and ocean pumping (i.e., artificial upwelling, downwelling) to enhance carbon uptake and storage in the deep ocean.

Under negative emission technologies: after direct air capture, should add "and storage or use". Capturing the CO2 from the air is just the first helf of the solution. They you have to store the CO2 permanently (or use it in an industrial application of some kind).

The para on page 3 about adverse effects seems to be missing a couple of things:

1. No mention of the big issue of potential land use conflicts if CDR is implemented at large scale (e.g. with land for agriculture)
2. The risk of leakage of CO2 from land storage deep underground was assessed by the IPCC to be very small, if I remember correctly. And leakages from land storage would not cause ocean acidification.

Page 4-8 (didn't have time to review. Sorry.)

Page 8 ; Scientific Research:
This sentence: "While research previously focused almost exclusively on theoretical and climate modelling of SRM technologies, researchers are conducting a growing number of real-world experiments." Makes it sound as though a number of real-world experiments have already been conducted and yet the text that follows only describes one cancelled experiments and a bunch of proposed experiments. Suggest being clear about the extent to which real-world experiments have already been carried out vs are being proposed, pending necessary approvals/governance?

Page 9 under Ethical Considerations:
SRM does not reduce the drivers of climate change. Edit needed:

- "It is important to acknowledge that while SRM can reduce/offset ~~the drivers of~~ anthropogenic climate change, it is not a "silver bullet" solution to the challenges of climate change.

Page 9 Main take aways:
It seems to me the first bullet could also say what climate engineering COULD be in addition to what it is not. Red text is a suggestion – you may find better words to convey the same thing.

- "Even with lower-risk forms of climate engineering, climate engineering should not be considered a substitute for mitigation and adaptation." Climate engineering might prove useful to help achieve climate targets if aggressive mitigation and adaptation measures fall short.

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Sent: September 30, 2019 2:12 PM
To: Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>; Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>; Cole, Jason (EC) <jason.cole@canada.ca>
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Pg 5. I had commented on an earlier draft about how misleading the WMO statement about air pollution deaths is. This has not been corrected. In my view it really must be.

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Cc: Fox, Carolyn (EC) <carolyn.fox@canada.ca>; Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
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Mj

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Please see request below from the ADMO….is there anyone else you think should be looped in to provide comments on the attached document? Note the deadline of Oct 1st.

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Government of Canada Gouvernement du Canada Canada

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Sent: September 26, 2019 5:11 PM
To: Moncrieff, Don (EC) <don.moncrieff@canada.ca>; Monforton, Amanda (EC) <amanda.monforton@canada.ca>; Vien, Julie (EC) <julie.vien@canada.ca>
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Please provide input and comments on the paper and note ongoing discussions in the department and observations from the ECCC geoengineering working group to date (I believe Marjorie Shepherd and David Mullins were the STB representatives).

Due in ADMO Oct 1 COB

Thanks,
Shari

From: Goon, Amy (EC) <amy.goon@canada.ca>
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To: Hamzawi, Nancy (EC) <nancy.hamzawi@canada.ca>
Cc: Huddleston, Jeanne-Marie (EC) <jeanne-marie.huddleston@canada.ca>; Hayne, Shari (EC) <shari.hayne@canada.ca>; Chandler, Janina (EC) <janina.chandler@canada.ca>; Lajeunesse, Stephanie (EC) <stephanie.lajeunesse@canada.ca>
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Happy Friday!
Amy

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From: "Geller, Hilary (EC)" <hilary.geller@canada.ca>
Date: 2019-09-20 9:36 AM (GMT-05:00)
To: "Huddleston, Jeanne-Marie (EC)" <jeanne-marie.huddleston@canada.ca>
Cc: "Jones, Matt (EC)" <matt.jones@canada.ca>, "Hamzawi, Nancy (EC)" <nancy.hamzawi@canada.ca>
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Subject: RE: Climate Engineering
From: "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>
Date: 9/30/19, 21:35
To: "Flato, Greg (EC)" <greg.flato@canada.ca>, "Bolina2, Amandeep (EC)" <amandeep.bolina2@canada.ca>, "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>
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Hi Amandeep,
Apologies for being late on this. In addition to Greg and Elizabeth's comments, I would propose the edits below.

Cheers,

Nathan

Why Climate Engineering?
Replace 'So far, Canada's position in international fora has been that the deployment of climate engineering technologies should not occur without adequate governance structures, or before more research is available' with 'Canada's position in international fora has been that the deployment of climate engineering technologies should not occur without adequate governance structures, or before more research is available'. (Including 'So far' makes it sound as though Canada may change its position to support deployment of geoengineering without adequate governance or further research.)

Carbon Dioxide Removal
Replace 'For example, Squamish, British Columbia's Carbon Engineering, formed in 2009' with 'For example, Climate Engineering, formed in 2009 in Squamish, British Columbia,'

Solar radiation management
After 'In doing so, these technologies could offset temperature increases associated with high concentrations of atmospheric CO_2.' insert:
However, stabilising global mean temperature in the presence of ongoing CO_2 emissions would require progressively strengthening SRM, and even stabilising warming at a lower level after CO_2 emissions are reduced to zero would require a constant level of SRM to be continued indefinitely. SRM over a limited period of time would only potentially be useful in limiting peak warming under scenarios with strong mitigation to reduce CO_2 emissions to zero, followed by CDR to remove CO_2 from the atmosphere.
(I think there would be value in including some text here to indicate that if we are interested in limiting peak warming, and if we don't want to continue SRM for ever, then it's only in these peak and decline scenarios with negative emissions, that SRM could potentially make sense).

Scientific Research
First line replace 'in the field' to 'on this topic'. 'in the field' could be read as referring to field experiments, which is not what is meant here, as the next sentence discusses GEOMIP modelling experiments.

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EA/AE: Cheryl Devine (819) 938-3783

s.19(1)

Subject: RE: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction
From: "Bush, Elizabeth (EC)" <elizabeth.bush@canada.ca>
Date: 11/3/20, 15:13
To: "Cole, Jason (EC)" <jason.cole@canada.ca>, "Morrison2, Heather (EC)" <heather.morrison2@canada.ca>

[redacted] tipped me off to a NOVA special called Can we Cool the Planet that aired this past weekend on PBS. I missed it and haven't yet tried to find it on demand. But I'm hoping I can find a way to watch it still.

The public conversation on climate engineering is mounting!

I have been trying to watch some of the C2G webinars on CDR and SRM. I have found them to be a good resource. Thanks for the link to the more technical info, Jason.
Elizabeth

From: Cole, Jason (EC) <jason.cole@canada.ca>
Sent: November 3, 2020 9:07 AM
To: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Anderson2, Kevin (EC) <kevin.anderson2@canada.ca>; Walker, Anne (EC) <anne.walker@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>; Edwards, Patti (EC) <patti.edwards@canada.ca>; Bush, Elizabeth (EC) <elizabeth.bush@canada.ca>; Tam, Benita (EC) <benita.tam@canada.ca>; Gillett, Nathan (EC) <nathan.gillett@canada.ca>; Luce, Sarah (EC) <sarah.luce@canada.ca>; Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
Subject: Re: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction

Thanks Heather. I saw this article but it was previously paywalled, at least for me.

Since many of the people mentioned in the article were at the NCAR CCIS workshop last week, here is a link to that effort: https://www.ccis.ucar.edu/. There should be a workshop summary in the near future, although one useful living document already up is a list of existing initiatives: https://docs.google.com/document/d/1E0Y-sz7vE8f-54v-WRSjFBj88fIHL-G_AaeC5zPkNJ0/edit.

My understanding is that there should be a new SRM report from the US National Academy of Sciences in the very near future. It was noted in the workshop, and the initiative list, that SRM will be addressed in the next WMO assessment about the Montreal Protocol.

I also see that geoengineering even was the topic of a video by Kurzgesagt this week: https://youtu.be/dSu5sXmsur4. My kids introduced me to this channel so it is at least being seen by some teens.

Jason

From: Morrison2, Heather (EC)
Sent: Tuesday, November 3, 2020 8:05 AM
To: Farahani, Ellie (EC); Cole, Jason (EC); Anderson2, Kevin (EC); Walker, Anne (EC); Carou, Silvina (EC); Edwards, Patti (EC); Bush, Elizabeth (EC); Tam, Benita (EC); Gillett, Nathan (EC); Luce, Sarah (EC); Bolina2, Amandeep (EC)
Subject: FW: NYTimes: As Climate Disasters Pile Up, a Radical Proposal Gains Traction

FYI -

As Climate Disasters Pile Up, a Radical Proposal Gains Traction https://www.nytimes.com/2020/10/28/climate/climate-change-geoengineering.html?referringSource=articleShare

Heather

Heather Morrison, Ph.D.

A/Director Climate Research Division, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
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heather.morrison2@canada.ca / Tél. : 416-739-4761 / Tél. cell. : 416-669-8592

s.19(1)

Subject: G1 paper, version 3
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 7/15/20, 18:46
To: "Haywood, Jim" [redacted], Alan Robock ☮ <robock@envsci.rutgers.edu>, "Douglas MacMartin" <dgm224@cornell.edu>, Daniele Visioni <dv224@cornell.edu>, "olivier.boucher@lmd.jussieu.fr" <olivier.boucher@lmd.jussieu.fr>, "Cole, Jason (EC)" <jason.cole@canada.ca>, "Haywood, James" <J.M.Haywood@exeter.ac.uk>, "Jones, Andy" [redacted] "thibaut.lurton@ipsl.fr" <thibaut.lurton@ipsl.fr>, "mmills@ucar.edu" <mmills@ucar.edu>, NABAT Pierre <pierre.nabat@meteo.fr>, Ulrike Niemeier <ulrike.niemeier@mpimet.mpg.de>, Roland Séférian [redacted], Simone Tilmes <tilmes@ucar.edu>

Hi folks -

Here's an updated version of the G1 paper. Based on everyone's comments, I think this is in decent shape. I'll plan on submitting this Friday, sometime after I've had my coffee. If that's too soon, please let me know, and I will push the submission back.

https://www.dropbox.com/s/wxr2f68i8jig7ry/GeoMIP6_G1_v3.docx?dl=0
(Placed on dropbox because some of you have a 10 MB email attachment limit)

One question before I do that. In the GeoMIP meeting, we had discussed a special issue of ACP/ESD/something else. Any opinions as to whether I should submit to ACP instead of ERL? If we did that, I would probably move everything out of the supplemental material and into the main text.

Best,

Ben

Ben Kravitz
Assistant Professor
Department of Earth and Atmospheric Sciences
Indiana University
1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
http://pages.iu.edu/~bkravitz/
Pronouns: he/him/his

000770

Subject: Revised G1 paper
From: "Kravitz, Ben" <bkravitz@iu.edu>
Date: 12/16/20, 22:51
To: Olivier Boucher <olivier.boucher@ipsl.fr>, Alan Robock ☮ <robock@envsci.rutgers.edu>, "Haywood, Jim" [redacted] Douglas MacMartin <dgm224@cornell.edu>, Daniele Visioni <dv224@cornell.edu>, "olivier.boucher@lmd.jussieu.fr" <olivier.boucher@lmd.jussieu.fr>, "Cole, Jason (EC)" <jason.cole@canada.ca>, "Haywood, James" <J.M.Haywood@exeter.ac.uk>, "Jones, Andy" [redacted], "thibaut.lurton@ipsl.fr" <thibaut.lurton@ipsl.fr>, NABAT Pierre <pierre.nabat@meteo.fr>, "Ulrike Niemeier" <ulrike.niemeier@mpimet.mpg.de>, Roland Séférian [redacted] "Simone Tilmes" <tilmes@ucar.edu>

Hi folks -

The reviews for the G1 paper came in a couple of days ago, and (shock of shocks) they were pretty easy to address. I've attached a revised version of the manuscript, a tracked changes version, and a response to reviewers. Please let me know if you have any comments.

I didn't see anything terribly controversial in here, so I'll plan on uploading the responses to reviewers on the 23rd (Wednesday of next week), just on the off chance that someone over at the journal is paying attention.

Best,

Ben

Ben Kravitz (he/him/his)
Assistant Professor
Department of Earth and Atmospheric Sciences
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1001 East 10th Street
Bloomington, IN 47405-1405
Tel: (812) 855-4334
bkravitz@iu.edu
https://climatemodeling.earth.indiana.edu

Attachments:

diff.pdf	438 bytes
GeoMIP6_G1_v4_revised.pdf	489 bytes
Response to Reviews.docx	541 bytes

Subject: Re: Internal review
From: "Li, Jiangnan (EC)" <jiangnan.li@canada.ca>
Date: 4/13/18, 17:52
To: "Cole, Jason (EC)" <jason.cole@canada.ca>

Jason

Sure, please send it.

Jiangnan

From: Cole, Jason (EC)
Sent: April 13, 2018 10:46 AM
To: Li, Jiangnan (EC)
Subject: Internal review

Jiangnan,

Could you perform an internal review for me? It is for a geoengineering paper in which they artificially increase the albedo of open ocean to offset increased CO2.

Here is the title and abstract.

The climate effects of increasing ocean albedo: An idealized representation of solar geoengineering

Marine cloud brightening has been proposed as a means of geoengineering/climate intervention, or deliberately altering the climate system to offset anthropogenic climate change. As an idealized representation of marine cloud brightening, this paper discusses experiment G1ocean-albedo of the Geoengineering Model Intercomparison Project (GeoMIP), involving an abrupt quadrupling of the CO2 concentration and an instantaneous increase in ocean albedo to maintain approximate net top-of-atmosphere radiative flux balance. Eleven Earth System Models are relatively consistent in their temperature, radiative flux, and hydrological cycle responses to this experiment. Due to the imposed forcing, air over the land surface warms by a model average of 1.14 K, while air over most of the ocean cools. Some parts of the near-surface air temperature over ocean warm due to heat transport from land to ocean. These changes generally resolve within a few years, indicating that changes in ocean heat content play at most a small role in the warming over the oceans. The hydrological cycle response is a general slowing down, with high heterogeneity in the response, particularly in the tropics. While idealized, these results have important implications for marine cloud brightening, or other methods of geoengineering involving spatially heterogeneous forcing, or other general forcings with a strong land/ocean contrast. It also reinforces previous findings that keeping top-of-atmosphere net radiative flux constant is not sufficient for preventing changes in global mean temperature.

Jason

000772

Subject: FW: acp-2018-340 (author) - manuscript accepted for final publication
From: "Kravitz, Ben" <Ben.Kravitz@pnnl.gov>
Date: 8/28/18, 14:58
To: "Rasch, Philip J" <Philip.Rasch@pnnl.gov>, "Wang, Hailong" <Hailong.Wang@pnnl.gov>, "<robock@envsci.rutgers.edu>" <robock@envsci.rutgers.edu>, Corey Gabriel <cjgabriel7@gmail.com>, "Corey Gabriel" <cjgabriel@ucsd.edu>, Olivier Boucher <olivier.boucher@lmd.jussieu.fr>, "Jason.Cole@ec.gc.ca" <Jason.Cole@ec.gc.ca>, Jim Haywood <jim.haywood@metoffice.gov.uk>, Duoying Ji <duoyingji@bnu.edu.cn>, Duoying Ji <duoyingji@gmail.com>, "Jones, Andy" <andy.jones@metoffice.gov.uk>, "Andrew.Lenton@csiro.au" <Andrew.Lenton@csiro.au>, John Moore <john.moore.bnu@gmail.com>, Helene Muri <helene.muri@geo.uio.no>, Helene Muri <helene.muri@ntnu.no>, "Niemeier, Ulrike" <ulrike.niemeier@mpimet.mpg.de>, Steven J Phipps <s.phipps@unsw.edu.au>, "wnabe@jamstec.go.jp" <wnabe@jamstec.go.jp>, Shuting Yang <shuting@dmi.dk>, JINHO YOON <yjinho@gist.ac.kr>, "Schmidt, Hauke" <hauke.schmidt@mpimet.mpg.de>, "Haywood, James" <J.M.Haywood@exeter.ac.uk>

Hi folks -

I think you may have already received this notification, but in case you didn't, the G1ocean-albedo paper is now accepted for publication. Congratulations and thanks to all of you for your hard work on this paper! And based on the discussions we had throughout, there's still plenty more to look at in this experiment. If anyone is interested in pursuing further analysis, please let me know - I'd be happy to help.

Best,

Ben

____

Ben Kravitz
Climate Scientist
Atmospheric Sciences and Global Change Division
Pacific Northwest National Laboratory
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Tel: (509) 372-6846 Fax: (509) 375-6448
ben.kravitz@pnnl.gov

On 8/28/18, 06:32, "editorial@copernicus.org" <editorial@copernicus.org> wrote:

Dear Ben Kravitz,

We are pleased to inform you that your following manuscript was accepted for final publication in ACP:

Title: The climate effects of increasing ocean albedo: An idealized representation of solar geoengineering
Author(s): Ben Kravitz et al.
MS No.: acp-2018-340
MS Type: Research article
Iteration: Revised Submission
Special Issue: The Geoengineering Model Intercomparison Project (GeoMIP): Simulations of solar radiation reduction methods (ACP/GMD inter-journal SI)

Presently, your manuscript is being transferred to the Copernicus Publications Production Office for typesetting and publication. To proceed, please upload all files that are required for production no later than 07 Sep 2018 at https://editor.copernicus.org/ACP/production_file_upload/acp-2018-340. For further information on files and formats we kindly refer you to the submission guidelines: https://www.atmospheric-chemistry-and-

000773

physics.net/for_authors/submit_your_manuscript.html

In your manuscript, please use full first names for all authors. Although references are still based on initials, we will use full first names on the title page of your paper.

Before file upload, please consider submitting data sets, model code, or video supplements to reliable repositories, receive DOIs, and cite these assets in your manuscript including entries in the reference list.

To log in, please use your Copernicus Office user ID 162934.

You are invited to monitor the processing of your manuscript via your MS Overview: https://editor.copernicus.org/ACP/my_manuscript_overview

In case any questions arise, please contact me.

Kind regards,

Natascha Töpfer
Copernicus Publications
Editorial Support
editorial@copernicus.org

on behalf of the ACP Editorial Board

Subject: FW: Fostering research on solar geoengineering in Canada
From: "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>
Date: 12/16/20, 22:10
To: "Farahani, Ellie (EC)" <ellie.farahani@canada.ca>
CC: "Fyfe, John (EC)" <john.fyfe@canada.ca>, "Cole, Jason (EC)" <jason.cole@canada.ca>

Hi Ellie,
Just letting you know that Shawn Marshall has put us in touch with David Keith for a science discussion about geoengineering research.

Cheers,

Nathan

Sent from my Bell Samsung device over Canada's largest network.

-------- Original message --------
From: "Marshall, Shawn (EC)" <shawn.marshall@canada.ca>
Date: 2020-11-03 6:39 p.m. (GMT-08:00)
To: "Fyfe, John (EC)" <john.fyfe@canada.ca>, "Gillett, Nathan (EC)" <nathan.gillett@canada.ca>, _ @harvard.edu
Subject: FW: Fostering research on solar geoengineering in Canada

Hi John, Nathan:

I am writing to e-introduce you to David Keith, whom you may know of.

David is at Harvard where he works on a wide range of things, among them solar geoengineering. See here for a bit of background on this question and some of David's work:

https://keith.seas.harvard.edu/geoengineering-resources
https://www.bostonglobe.com/2020/10/19/opinion/world-needs-explore-solar-geoengineering-tool-fight-climate-change/

David is a Canadian and is settled part-time (well, maybe full-time these days) into Canmore, AB. He is looking to engage with the national atmospheric science community and ECCC on SRM and climate science. I suspect you will have lot of mutual interests.

David has some ideas to advance but I will pass over to him know - happy to stay in the loop as this is interesting to me and, I think, really important. Plus David is good guy and an exceptional, creative thinker, that you may have read about online.

Hope all is well at CCCmA, despite these strange times.

All best,
Shawn

Farahani,Ellie (elle, la, lui | she, her, hers) (ECCC)

From: Farahani, Ellie (EC) <ellie.farahani@canada.ca>
Sent: Tuesday, March 2, 2021 3:32 PM
To: Carou, Silvina (EC); Walker, Anne (EC); Luce, Sarah (EC)
Cc: Morrison2, Heather (EC); Edwards, Patti (EC)
Subject: RE: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Hi Sarah,

To add to what Anne and Silvina provided, if you want to also include some information on seasonal to decadal predictions and floodplain mapping, considering the timeline mentioned on the slides, I put together the following bullets:

- Year 1 onward: Detailed seasonal and annual predictions, consisting of interactive forecast maps for temperature, precipitation, snow water equivalent, sea surface temperature, downward solar radiation and cloudiness for Canada to inform wildfire, water management, public health and agricultural decision making (e.g., ECCC's seasonal predictions, along with the NRCan's Canadian Wildland Fire Information System, provide the basis for NRCan's monthly and seasonal forecasts of fire weather severity reported).
- Year 3: Quantification of uncertainty in hydrological parameters of climate projections to inform analyses of potential future flooding risk, ultimately leading to construction of specialized future scenarios for forward-looking floodplain mapping in Canada.

I hope my two cents help,
Ellie

From: Carou, Silvina (EC) <silvina.carou@canada.ca>
Sent: March 2, 2021 2:24 PM
To: Walker, Anne (EC) <anne.walker@canada.ca>; Luce, Sarah (EC) <sarah.luce@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>
Cc: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Edwards, Patti (EC) <patti.edwards@canada.ca>
Subject: RE: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Hi Sarah

I revised the second and third bullet that Anne dug up to describe the work that would support the NSRA goals in general.

- Event attribution analyses for high-impact Canadian events in order to determine the change in the likelihood of such events attributed to anthropogenic climate change.
- Development of downscaled climate projections in order to assess how terrestrial and marine extremes and associated impacts may change under a future climate

In general, risk assessments for various natural hazards will need to draw on CRD's data, models and expertise related to weather and climate extremes.

There could be potential implications related to the Impact Assessment process. For instance, NRPs for different disasters could in the long-term be integrated in Impact Assessment decisions/mitigation measures in regional assessments (e.g.

Ring of Fire or offshore oil development). This would be for the Impact Assessment Agency to consider though. It may result in a need to revise existing federal guidelines on risk assessment/evaluation (e.g. Climate Lense, the SACC/TG on Climate Change Resilience) for consistency.

Hope this is useful.

Silvina

From: Walker, Anne (EC) <anne.walker@canada.ca>
Sent: March 2, 2021 11:26 AM
To: Luce, Sarah (EC) <sarah.luce@canada.ca>; Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>
Cc: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Edwards, Patti (EC) <patti.edwards@canada.ca>
Subject: RE: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Last August we provided the following climate science activities towards an ECCC contribution to the development of National Risk Profiles for Wildfires led by PSC and NRCan. MSC was the ECCC lead on this file. If these activities were submitted, then there may be an expectation to deliver on these.

- Developing a fire module for ECCC's CLASSIC land surface model, which simulates historical and future area burned and emissions of primary trace gases and aerosols under a changing climate. On-going development of modelling capabilities (aerosols and gas-phase chemistry) to use projected fire emissions from the CLASSIC land surface model to assess impacts on air quality
- Conducting event attribution analyses for high-impact Canadian events, including for wildfire conditions, in order to determine the change in the likelihood of such events attributed to anthropogenic climate change.
- Provided recommendations and downscaled climate model data (CanLEAD) for a CCCS/CFS project to create a web application that describes fire risk under a changing climate (MOU with NRCan)
- Ongoing development of GHG (carbon and methane) modelling and data assimilation capacity (ECCC Carbon Assimilation System) to quantify anthropogenic and natural emissions and source/sinks over Canada

You can probably summarize the above into one bullet that reflects climate science contributions as a whole from CRD. The third bullet looks like something that is already completed....but I assume that provision of downscaled climate model output will be an important contribution to several hazard risk assessments falls under NSRA as a whole.

Anne

Anne Walker

Manager, Climate Processes Section, Science and Technology Branch
Environment and Climate Change Canada / Government of Canada
Anne.Walker@canada.ca / Tel: 416-739-4357 / Cel. : 416-452-4120

Gestionnaire, Section des processus climatiques, Direction générale de la science et de la technologie
Environnement et Changement climatique Canada / Gouvernement du Canada
anne.walker@canada.ca / Tél. : 416-739-4357 / Tél. cell. : 416-452-4120

1871 | 2021
1971 | 2021

50e anniversaire d'Environnement et Changement climatique Canada
Environment and Climate Change Canada's 50th anniversary

150e anniversaire du Service météorologique du Canada
Meteorological Service of Canada's 150th anniversary

From: Luce, Sarah (EC) <sarah.luce@canada.ca>
Sent: March 1, 2021 5:35 PM
To: Farahani, Ellie (EC) <ellie.farahani@canada.ca>; Carou, Silvina (EC) <silvina.carou@canada.ca>; Walker, Anne (EC) <anne.walker@canada.ca>
Cc: Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Subject: FW: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Hi Silvina, Ellie and Anne,

We have been asked to provide a few bullets on the demands/implications to our program from the expanding scope of the National Risk Profiles (NRP) National Strategic Risk Assessment (NSRA), which is being led by Public Safety Canada. As noted in the attached deck, *the goal of the NSRA is to address the disjointed nature of risk assessments across the federal landscape through the development of a single, coherent, national picture of risk, as well as structured, integrated risk assessment. It is intended as a knowledge product that may influence policy-making, by identifying, comparing, and prioritizing which hazards require immediate attention. Reports to be presented to Cabinet on a yearly basis, and to be made public every other year, starting in 2022.*

Background from DGO:
The DG of Emergency Management Committee is developing a deck (draft attached), which will be presented to the ADM/DG Science and Policy Committee. The deck presents the context for emergency management in Canada, and an outline of GoC efforts (historical to present) in this area. Over time, the NSRA will have an expanded focus, which may result in varying demands and implications for various parts of ECCC (see slide 9).

At this time Branches are being asked to input to the deck, **identifying how the branch may be implicated/impacted as the NSRA evolves.** STSD is leading for STB and will provide the overarching text with respect to the Branch role in Emergency management. They are looking for input specific to any potential implications/priorities with respect to the expanding scope of the NSRA in years 1, 2, and 3 (see slide 9 for scope per year, and slide 10 – example slide from MSC).

I have gone through the deck and am reaching out to the three of you as I believe this program will implicate your sections' work, especially regarding seasonal to decadal predictions, flood mapping, wildfire risk, projected severe weather overall etc., (slides 6-10). And possibly our environmental assessments work.

- It may still be worth mentioning future work that can contribute to future NSRAs that won't be available in years 1-3 (i.e. collaborations with MSC on coastal flooding prediction work – if this applies to our canSIPS/coastal modelling development? *I may not be remembering correctly*)

If you could please provide a high-level bullet on how your program may be implicated by the expanding scope of NSRA through years 1-3 **by COB Tomorrow, Tuesday March 2nd**, that would be helpful.

For reference, the discussion questions below (slide 13) will be used to help navigate the DG EMC/ADM/DG Science and Policy Committee discussion.

- **What are the potential implications of the NSRA for ECCC?**
    - **Will they change moving forward?**

- **What key opportunities are there to leverage the NRP and its associated activities/ structures as a platform to support other ECCC priorities?**
- **What key risks should be considered in our involvement in this file?**

Thank you,

Sarah

From: Morrison2, Heather (EC) <heather.morrison2@canada.ca>
Sent: March 1, 2021 2:04 PM
To: Luce, Sarah (EC) <sarah.luce@canada.ca>
Subject: FW: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Hi Sarah – I'll leave this one to you to look into. Off the top of my head, only the EA work we do will likely apply.

Heather Morrison, Ph.D.
A/Director, Climate Research Division / Directrice/I, Division de la recherche sur le climat
416-669-8592

From: Bolina2, Amandeep (EC) <amandeep.bolina2@canada.ca>
Sent: March 1, 2021 1:17 PM
To: Mullins, David (EC) <david.mullins@canada.ca>; Luce, Sarah (EC) <sarah.luce@canada.ca>; Markovic, Marko (EC) <marko.markovic@canada.ca>
Cc: Morrison2, Heather (EC) <heather.morrison2@canada.ca>; Bernier, Natacha (EC) <natacha.bernier@canada.ca>; Jatar, Muriel (EC) <muriel.jatar@canada.ca>
Subject: FW: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Hi all,

ECCC is working to support the development of National Risk Profiles (NRP) National Strategic Risk Assessment (NSRA) that is being led by Public Safety Canada. As noted in the attached deck, *the goal of the NSRA is to address the disjointed nature of risk assessments across the federal landscape through the development of a single, coherent, national picture of risk, as well as structured, integrated risk assessment. It is intended as a knowledge product that may influence policy-making, by identifying, comparing, and prioritizing which hazards require immediate attention. Reports to be presented to Cabinet on a yearly basis, and to be made public every other year, starting in 2022.*

The DG of Emergency Management Committee is developing a deck (draft attached), which will be presented to the ADM/DG Science and Policy Committee. The deck presents the context for emergency management in Canada, and an outline of GoC efforts (historical to present) in this area. Over time, the NSRA will have an expanded focus, which may result in varying demands and implications for various parts of ECCC (see slide 9). In year 1 (2020-21) the initial focus is on earthquakes, wildfires, floods and pandemics; Year 2 (2021-22) expanded focus to all natural disasters; Year 3 (2022-23), further expanded focus to all hazards (natural and human induced).

At this time Branches are being asked to input to the deck, **identifying how the branch may be implicated/impacted as the NSRA evolves.** STSD is leading for STB and will provide the overarching text with respect to the Branch role in Emergency management. They are looking for input specific to any potential implications/priorities with respect to the expanding scope of the NSRA in years 1, 2, and 3. (see slide 10 – example slide from MSC).

Can I ask that divisions please provide a bullet or two on demands/implications for your programs to the expanding scope of the NSRA through years 1-3 by **noon on March 3**?

Please let me know should you have any questions.

Thanks,
Amandeep

From: Volk, Joanne (EC) <joanne.volk@canada.ca>
Sent: February 26, 2021 9:42 AM
To: Cash, Kevin (EC) <kevin.cash@canada.ca>; Henry, David (EC) <david.henry@canada.ca>; Simon, Patrice (EC) <patrice.simon@canada.ca>; Goncalves, Jacqueline (EC) <jacqueline.goncalves@canada.ca>; Dawson, Jaime (EC) <jaime.dawson@canada.ca>
Cc: D'Iorio, Marc (EC) <marc.diorio@canada.ca>; Fox, Carolyn (EC) <carolyn.fox@canada.ca>; Monforton, Amanda (EC) <amanda.monforton@canada.ca>; Petz, Karie (EC) <karie.petz@canada.ca>; Miller, Sancha (EC) <sancha.miller@canada.ca>; Whelan, Josee (EC) <josee.whelan@canada.ca>; Lalonde-Robert, Carole (EC) <carole.lalonde-robert@canada.ca>
Subject: Input Requested: Suivis rencontre du 22 février 2021 Comité des DG de la gestion des urgences d'ECCC | Do-outs Feb 22 2021 meeting of the ECCC DG Emergency Management Committee

Colleagues,

As mentioned at yesterday's SitRep, ECCC is actively working to support the development of National Risk Profile's (NRP) National Strategic Risk Assessment (NSRA) that is being led by Public Safety Canada. As noted in the attached deck, *the goal of the NSRA is to address the disjointed nature of risk assessments across the federal landscape through the development of a single, coherent, national picture of risk, as well as structured, integrated risk assessment. It is intended as a knowledge product that may influence policy-making. Reports to be presented to Cabinet on a yearly basis, and to be made public every other year, starting in 2022.*

The DG EMC is developing a deck (draft attached), which will be presented to the ADM/DG Science and Policy Committee. The deck presents the context for emergency management in Canada, and an outline of the GoC efforts (historical to present) in this area. The NSRA will evolve over time (see slide 9), which may result in varying demands and implications for various parts of ECCC.

At this time, Branches are asked to input to this deck (one slide per Branch) identifying how the Branch may be implicated/impacted as the NSRA evolves. Slide 10 is the slide from the MSC and is an example of the information sought.

To develop the slide for STB, I would appreciate if you could send me your Directorate (DG approved) input by COB March 3. Please focus on input for years 1, 2, 3; STSD will provide the overarching text.

This timeline will allow time for questions as needed, consolidation, and ADM approval to meet the deadline of March 8. I am available to talk to whomever in your team will complete this task. Please tell them they can contact me directly.

Thanks.
jo

Joanne Volk
Directrice générale intérimaire, Stratégies en sciences et technologie | Acting Director General, Science and Technology Strategies
Direction générale des sciences et de la technologie | Science & Technology Branch

Environnement et changement climatique Canada | Environment and Climate Change Canada

50e anniversaire d'Environnement et Changement climatique Canada
Environment and Climate Change Canada's 50th anniversary
150e anniversaire du Service météorologique du Canada
Meteorological Service of Canada's 150th anniversary

Subject: Re: Internal review
From: "Li, Jiangnan (EC)" <jiangnan.li@canada.ca>
Date: 4/13/18, 17:52
To: "Cole, Jason (EC)" <jason.cole@canada.ca>

Jason

Sure, please send it.

Jiangnan

From: Cole, Jason (EC)
Sent: April 13, 2018 10:46 AM
To: Li, Jiangnan (EC)
Subject: Internal review

Jiangnan,

Could you perform an internal review for me? It is for a geoengineering paper in which they artificially increase the albedo of open ocean to offset increased CO2.

Here is the title and abstract.

The climate effects of increasing ocean albedo: An idealized representation of solar geoengineering

Marine cloud brightening has been proposed as a means of geoengineering/climate intervention, or deliberately altering the climate system to offset anthropogenic climate change. As an idealized representation of marine cloud brightening, this paper discusses experiment G1ocean-albedo of the Geoengineering Model Intercomparison Project (GeoMIP), involving an abrupt quadrupling of the CO2 concentration and an instantaneous increase in ocean albedo to maintain approximate net top-of-atmosphere radiative flux balance. Eleven Earth System Models are relatively consistent in their temperature, radiative flux, and hydrological cycle responses to this experiment. Due to the imposed forcing, air over the land surface warms by a model average of 1.14 K, while air over most of the ocean cools. Some parts of the near-surface air temperature over ocean warm due to heat transport from land to ocean. These changes generally resolve within a few years, indicating that changes in ocean heat content play at most a small role in the warming over the oceans. The hydrological cycle response is a general slowing down, with high heterogeneity in the response, particularly in the tropics. While idealized, these results have important implications for marine cloud brightening, or other methods of geoengineering involving spatially heterogeneous forcing, or other general forcings with a strong land/ocean contrast. It also reinforces previous findings that keeping top-of-atmosphere net radiative flux constant is not sufficient for preventing changes in global mean temperature.

Jason

Environnement et Changement climatique Canada | Environment and Climate Change Canada

MIN-267149

MEMORANDUM TO MINISTER

OVERVIEW AND DRAFT COPY OF CLIMATE SCIENCE 2050 REPORT

(For Information)

PURPOSE

To provide you with an overview and draft copy of Climate Science 2050: advancing science and knowledge on climate change.

SUMMARY

- Climate Science 2050 report is a national endeavour to identify gaps in climate change science and knowledge and to improve coordination to address issues with respect to natural, health, and social sciences.
- The Department led the development of the Climate Science 2050 project and convened a broad range of stakeholders using a variety of mechanisms (survey, workshops, targeted engagement) to identify gaps and priorities across five main themes.
- The Climate Science 2050 project aligns with and supports broader federal climate commitments, including achieving net zero by 2050, building a more resilient Canada, implementing nature-based climate solutions, and advancing clean technology.
- It is anticipated that the report (see the attached draft) (**Annex I**) will be released in **early fall 2020**. A targeted communications approach is recommended, since the main key audiences are the scientific/academic communities.
- Stakeholder reaction is expected to be largely positive, given the feedback received during targeted engagement on the draft document.
- The Climate Science 2050 report is an opportunity to continue and formalize an interdisciplinary, coordinated dialogue on climate change science, targeting science and policy communities.

Canada

CONTEXT AND CURRENT STATUS

In collaboration with other federal departments and agencies, the Department has led the development of the Climate Science 2050 project, which is nearing completion. Early fall 2020 release of the report is targeted. The Climate Science 2050 report is intended to identify gaps in climate change science and knowledge. This information could be used to guide strategic investments in science to support climate action. It represents an important step in bringing more cohesion to the Canadian climate change science landscape, which, despite its importance in making well-informed adaptation and mitigation decisions, remains relatively uncoordinated. The Climate Science 2050 project is a nationally scoped perspective on climate change science and knowledge needs that was developed with broad stakeholder engagement. It goes beyond the federal government, encompassing science and knowledge producers, holders, and funders from across all sectors involved in climate change science and knowledge activities (e.g., government, private sector, academia, Indigenous organizations, non-governmental organizations).

CONSIDERATIONS

The Climate Science 2050 project spans the natural, health, and social sciences, and it also recognizes the importance of supporting the mobilization of Indigenous leadership and participation in climate change science and knowledge. It emphasizes the value of collaboration and interdisciplinary work in making progress on multiple fronts and maximizing co-benefits.

The Climate Science 2050 report highlights many science and knowledge needs, but it is explicit in stating that climate action must continue in parallel with research activities, drawing on existing knowledge and incorporating new insights as they become available. The Climate Science 2050 report places knowledge synthesis and mobilization on a par with knowledge generation to ensure that decision makers have the best available knowledge to inform their efforts.

The science and knowledge needs outlined in the Climate Science 2050 report fall into five main themes:

1) earth system climate science
2) healthy and resilient Canadians, communities, and built environments
3) carbon neutral society
4) resilient terrestrial and aquatic ecosystems
5) sustainable natural resources

The Climate Science 2050 report also outlines three areas of foundational capacity that are critical to support work across all science and knowledge needs identified. These are:

1) monitoring and observation, which are key in providing situational awareness, assessing change, and measuring progress;
2) digital infrastructure, such as data storage and high-performance computing; and
3) open science, which will contribute to transparency and accelerate progress.

For greater detail, please refer to **Annexes II and III** (attached).

The Climate Science 2050 report is aligned with the goals of the Pan-Canadian Framework on Clean Growth and Climate Change and can be positioned as a complementary science pillar. However, recognizing current work to update the Pan-Canadian Framework, the climate science 2050 report has intentionally been framed to be flexible. It is positioned to encourage science to inform federal climate commitments in the near term, the medium term, and long term, including resilient infrastructure, disaster risk reduction, nature-based climate solutions, the pathway to net zero (including emission reduction milestones), and advances in clean technology. The research needs it outlines would also contribute to government objectives that are not strictly climate related, such as the circular economy, sustainable development, and the nature agenda.

A range of partners and stakeholders were engaged over the course of the development of the climate science 2050 report to ensure that it reflects the diverse perspectives of the Canadian climate change science community. This includes national Indigenous organizations, provinces and territories, academia, the private sector, non-governmental organizations, and the federal family. Partners and stakeholders were engaged using a variety of mechanisms, including a scoping survey, a national workshop to identify strategic gaps and priorities, targeted expert workshops on permafrost and the carbon cycle, and bilateral discussions.

Implementation of the work outlined in the climate science 2050 report

There is a continuing need for the Department to play a strong convening and coordinating role to lead the implementation of the work outlined in the climate science 2050 report within the federal government and beyond. Federal implementation of this will be guided by the interdepartmental Deputy Ministers Science Coordination Group on Climate Change, which is co-chaired by the Deputy Minister of Environment and Climate Change and Canada's Chief Science Advisor. Federal departments and agencies will seek to balance work across all themes and foundational capacity needs. Federal implementation of the work outlined in the climate science 2050 report will be tightly coupled with climate policy and program priorities, and it will balance federal capacity and extramural funding.

Implementation of the work outlined in the climate science 2050 report is an opportunity to advance dialogue on climate change science, targeting science and policy communities to foster interdisciplinary collaboration and knowledge exchange and mobilization. The dialogue will actively make space for Indigenous voices, will include engagement opportunities for youth, and will be used opportunistically to highlight new or timely climate change science topics for Canadians. This aligns with the Department's proposed science communication objectives, and it will require the participation of federal departments engaged in climate change science, including federal scientists and departmental science advisors.

NEXT STEPS

- The communications approach for the release of the climate science 2050 report will be informed by the broader landscape of federal climate change activities and announcements, as well as the coronavirus (COVID-19) context.
- For an early fall 2020 release timeline, officials will:
  - complete targeted engagement with national Indigenous organizations;
  - provide the final draft to the Deputy Minister of Environment and Climate Change and Canada's Chief Science Advisor, for their concurrence to present to the interdepartmental Deputy Ministers Science Coordination Group on Climate Change, in order to seek broad federal approval prior to release; and
  - finalize the communications strategy and products.
- Develop options for federal implementation of the work outlined in the climate science 2050 report, including a dialogue on climate change science.

Officials are available to brief you or your Office at your convenience.

T. Christine Hogan Deputy Minister c.c.: Martine Dubuc	Martine Dubuc Associate Deputy Minister c.c.: T. Christine Hogan

Attachments (3):

- *Annex I Climate Science 2050 : advancing science and knowledge on climate change (draft of June 24, 2020)*
- *Annex II Climate Science 2050 executive summary*
- *Annex III Climate Science 2050 placemat*

WORKING DRAFT **Last updated: June 24 – 15h**

Climate Science 2050: Advancing Science and Knowledge on Climate Change

NOTE: This document is a working draft. Work is ongoing to engage key partners.

EXECUTIVE SUMMARY

Science and knowledge are critical in guiding the swift and ambitious action needed to build a resilient, carbon-neutral Canada. The breadth and complexity of the science and knowledge needed to meet this challenge require collaboration across disciplines, sectors, communities, and research bodies. *Climate Science 2050: Advancing Science and Knowledge on Climate Change* (CS2050) is intended to guide science and knowledge generators, holders, and funders as they advance the collaborative and interdisciplinary efforts needed to inform climate action. CS2050 encompasses the natural, social, and health sciences and recognizes the need to mobilize the full spectrum of Indigenous leadership, participation, and knowledge systems. While climate change science has traditionally focused on the natural sciences, CS2050 recognizes the need to elevate the role of social and behavioural sciences, as they have important contributions to make in informing the transformation needed in Canadian society.

While CS2050 highlights many science and knowledge needs, there is already a strong knowledge base on which to build. The urgency of the climate change challenge means that decision-makers should not and cannot wait for all the science to be in before taking action. Climate action must continue in parallel with research activities, drawing on existing knowledge and incorporating new insights as they become available. As such, knowledge synthesis and mobilization—including the dialogue they establish between knowledge producers, holders, and users—are key elements of CS2050. They will ensure decision-makers have the best-available knowledge and will keep research efforts aligned with user needs. These efforts could include science and risk assessments, knowledge portals, and case studies, and will benefit from increasing climate change science literacy and professional competencies.

Given the scale and urgency of the challenge, and ubiquitous nature of climate change impacts, addressing the science and knowledge needs outlined in CS2050 will require an increasingly integrated approach to advance multiple priorities in parallel. It will also benefit from embracing new and participatory approaches to research and knowledge development (e.g., experimentation, learning by doing, co-production) and from the respectful consideration of Indigenous Knowledge. The science and knowledge needs covered by CS2050 are organized into four outcomes, with a fifth area of work—Earth system climate science—providing a key foundation.

Earth system climate science – Work is needed to reduce uncertainties related to the magnitude, timing, and impacts of future change and the prediction of climate extremes, floods, droughts, and wildfires. This research will enable a better understanding of the influence of climate change on permafrost, glaciers, oceans, ice (sea, river, lake), and freshwater. It is also central to providing more detailed and tailored sector-based information. Research is also needed to evaluate the effectiveness of mitigation efforts (e.g., short-lived climate forcers, climate engineering).

Healthy and resilient Canadians, communities, and built environments – Developing a nuanced understanding of vulnerability, resilience, and empowerment—and how these vary across regions and groups—will help ensure efforts to build health and resilience are effective. Work is also needed to protect and improve the health and well-being of

Canadians and increase the resilience of health systems, including a better understanding of climate-related health risks, intersections with action in other sectors (e.g., transportation, urban planning), and innovative and scalable interventions that maximize resilience and empower behavioural change. Building climate-resilient communities and infrastructure will benefit from research into natural infrastructure, community design, the value and co-benefits of resilient infrastructure solutions, and essential infrastructure systems (e.g., energy, water, transportation). There is also a need to understand the climate impacts on governance, trade, global migration patterns, and development and international assistance.

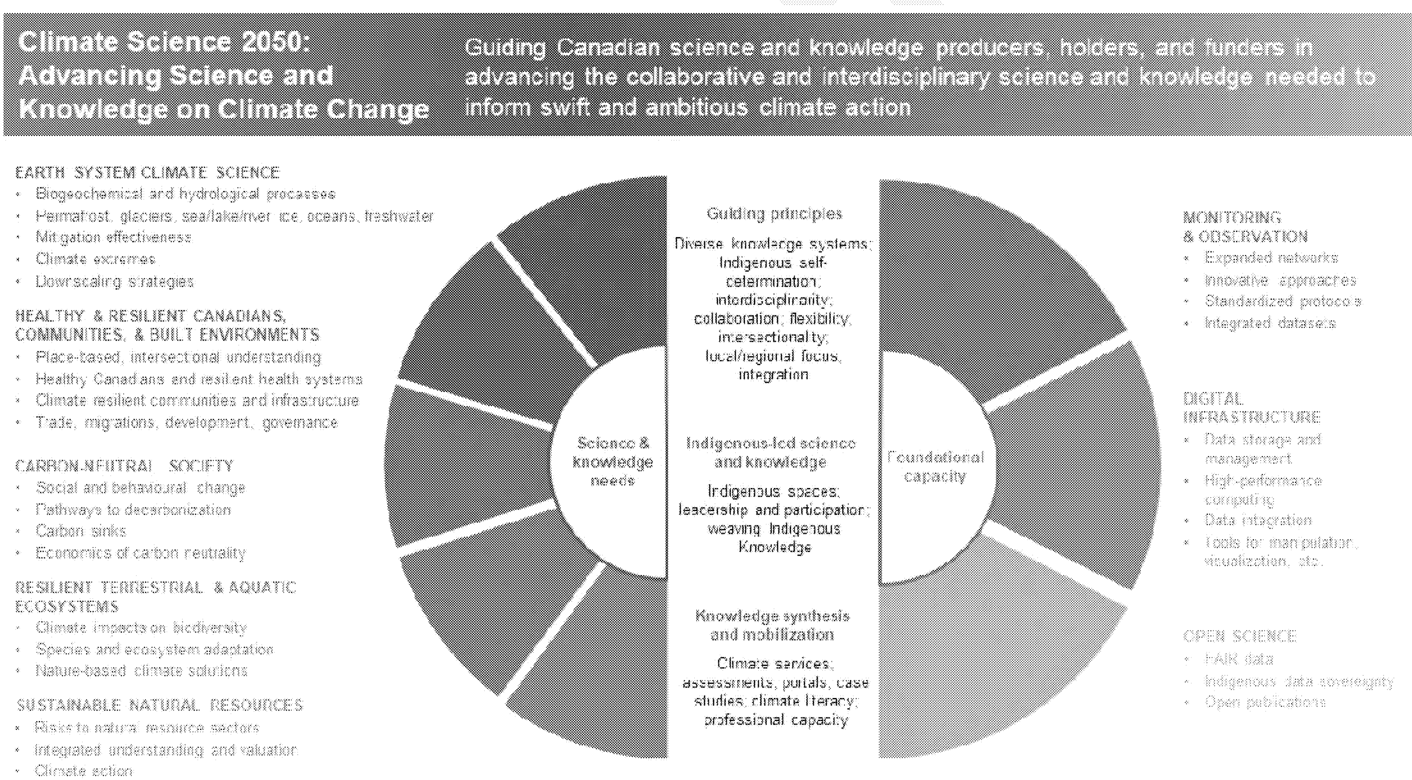
A carbon-neutral society – Accelerating the transformational change needed to meet and exceed Canada's 2030 greenhouse gas (GHG) emissions reduction goal under the Paris Agreement and achieve net-zero emissions by 2050 will require a deeper understanding of the social and behavioural side of decarbonization. Research to understand decarbonization pathways will be valuable, including work related to a just transition and the economic aspects of carbon neutrality. Energy decarbonization is a key research area, as is work to understand the mitigation potential of infrastructure construction and management approaches. In moving toward net-zero emissions, research is needed to help protect and enhance terrestrial and aquatic carbon sinks, from fundamental carbon cycle science to research aimed at developing socio-economic levers and best practices.

Resilient terrestrial and aquatic ecosystems – To ensure Canada's ecosystems remain healthy and resilient, research is needed to improve our foundational understanding of the impacts of climate change on the processes that underpin healthy ecosystems, the sensitivity, resilience, and adaptive capacity of species and ecosystems, and the effects of changing stressors and their cumulative impact on biodiversity and ecosystems. Work will also be needed to anticipate and minimize the threats to vulnerable species and ecosystems, as well as efforts to develop and test adaptation measures. Nature can also be a powerful ally in addressing climate change, and work is needed to address knowledge gaps related to identifying and deploying nature-based solutions, such as research into potential negative effects, socio-economic and cultural valuations and trade-offs, and the impact of extreme events on these solutions when implemented.

Sustainable natural resources – Helping the agricultural, forestry, fisheries, water management, mining, and energy sectors—and the traditional lifestyles connected to these industries—remain resilient and productive in the face of climate change requires a better understanding of the risks climate change poses (e.g., extreme events, water availability, pests, disease, invasive species). Meanwhile, as some resource-based communities navigate a just transition, social science research can help to understand the social, cultural, and economic impacts of this transformation. Furthermore, an integrated understanding of natural resource and land/water goals and opportunities will help maximize co-benefits (e.g., advancing carbon sequestration, health, energy, and food security simultaneously). Canada's natural resource sectors will also benefit from research to inform climate-smart, sustainable practices.

Three key areas of foundational capacity are essential in supporting work across all science and knowledge needs identified in CS2050. Whether carried out on the ground or via satellites, monitoring and surveillance efforts continue to be key in providing situational awareness, assessing change, informing action, and measuring progress. The magnitude and diversity of climate change data and knowledge will require advances in digital infrastructure (e.g., data storage and management, high-performance computing), including tools for data management, extraction, manipulation, visualization, standardization, and interoperability. Finally, ensuring climate change science is open and accessible will increase transparency, maximize investments, and accelerate progress.

CS2050 represents an opportunity to make deliberate decisions about climate change science and knowledge activities and funding in Canada, which will be pivotal in guiding the way to a resilient, carbon-neutral society.



INTRODUCTION

Climate change is real; we are seeing evidence for it across Canada, and some additional warming and further changes in climate are unavoidable.[1]

The magnitude and urgency of the climate change challenge cannot be understated. Canada's economy, infrastructure, environment, health, and social and cultural well-being are already feeling its consequences, though these impacts are not experienced to the same degree by all Canadians. In response, Canada's House of Commons declared a national climate emergency in June 2019. Many of these impacts will continue even if the temperature goal set out in the Paris Agreement[2] is achieved, and current emission reduction commitments under the agreement have been collectively assessed as being insufficient to meet this goal. This emphasizes not only the need for a concerted effort to adapt to these impacts, reduce risks and vulnerabilities, and build resilience, but also the need for Canada and other countries to increase their level of ambition in achieving net-zero emissions and stabilizing temperature to avoid further harm.

As we increase the speed and ambition of our climate action, science and knowledge will play an essential role in helping us navigate the complex intersections, synergies, and trade-offs inherent in building a thriving, climate-resilient, carbon-neutral Canada that is just and equitable. The scientific consensus around anthropogenic climate change does not signal the end of the need for climate change science. Far from it. Sustained, synthesized, and inclusive science and knowledge will allow us to understand what is in store for Canada and the world, assess the risks, take informed and ambitious action, and track our progress against set milestones. This includes a deeper understanding of both the climate system and the social systems underpinning action. It also includes the science and innovation needed to continue developing the approaches that will be pivotal in addressing climate change—from clean technology to nature-based climate solutions to resilient, low-carbon infrastructure—and to ensure they are applied, monitored, and evaluated in the most effective way.

No single discipline, sector, order of government, community, or research body can undertake the breadth or complexity of the science and knowledge required to meet the climate change challenge. The skills, knowledge, experience, and resources needed are substantial and diverse. Broad interdisciplinary collaboration is crucial, especially in advancing the science and knowledge to inform integrated and coordinated mitigation and adaptation efforts. Further, the inclusion of First Nations, Métis, and Inuit leadership and knowledge, while respecting their sovereignty and ownership over their knowledge and data, will be a crucial part of a more resilient and adaptive response to a warming climate.

Climate Science 2050: Advancing Science and Knowledge on Climate Change (CS2050) is designed to support and guide these collaborative and interdisciplinary efforts. It encompasses the natural, social (including economics), and health sciences. There is already an extensive foundation of scientific work to build on, as demonstrated in *Canada's Changing Climate Report*,

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[1] Bush, E. and Lemmen, D.S., editors (2019): *Canada's Changing Climate Report*; Government of Canada, Ottawa, ON.

[2] Holding the increase in average global temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C.

the Canadian Council of the Academies' report on *Canada's Top Climate Change Risks*, and the work of the Intergovernmental Panel on Climate Change (IPCC), to name just a few. (For an overview of the state of climate change science in Canada, see Annex 1.) CS2050 is a forward-looking endeavour, building on this knowledge and aligning with ongoing mitigation and adaptation efforts and priorities. While CS2050 highlights a wide array of science and knowledge needs to be addressed, climate action can and must proceed in parallel, drawing on the existing body of knowledge and incorporating new insights as they emerge.

CS2050's primary objective is to guide planning, investment, and implementation across the full range of Canadian climate change science and knowledge producers, holders, and funders. This includes governments of all levels, Indigenous Nations, communities, and organizations, a wide range of academic disciplines, the private sector, non-governmental organizations, and civil society. An additional objective is to facilitate the mainstreaming of climate change science and knowledge so that these considerations are integrated by default into decision making in all sectors and communities, as well as into research planning. Knowledge synthesis and mobilization will facilitate this mainstreaming, making these efforts just as important as knowledge generation. While decision making and action (e.g., decision-support systems, services, policies, regulations) are crucial and are informed by the knowledge generated under CS2050, they fall outside its scope.

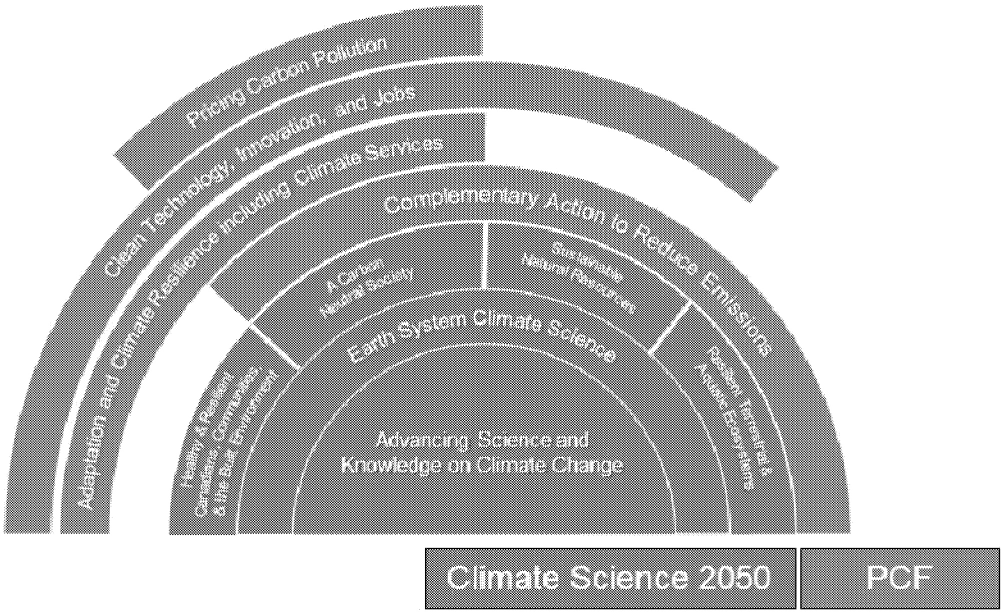
Overall, the science and knowledge needs highlighted in CS2050 are organized according to four broad outcomes that they support, all of which are enabled by advances in a fifth area of work: Earth system climate science. These outcomes are:

- healthy and resilient Canadians, communities, and built environments;
- a carbon-neutral society;
- resilient terrestrial and aquatic ecosystems; and
- sustainable natural resources.

Several of the science and knowledge needs identified across these outcome areas demonstrate the necessity of interdisciplinarity in advancing work on multiple fronts simultaneously and, in doing so, helping address the intersecting knowledge gaps decision makers must navigate. In addition to emphasizing interdisciplinarity, bringing the social and behavioural sciences into the climate change science dialogue more fully will be essential in advancing work across all outcome areas and empowering action.

The outcomes that provide the organizing structure for CS2050 are consistent with the goals of many of the foundational climate change strategies and plans that form the policy backdrop of CS2050. Federally, this includes the *Pan-Canadian Framework on Clean Growth and Climate Change* (PCF), and CS2050 can be positioned as a complementary science pillar for the PCF. However, the policy landscape is much broader. CS2050 is intended to support the objectives of other government, Indigenous, and sector-based climate change plans and strategies, informing the ongoing implementation of existing plans and serving as a building block for future climate plans and action from the near term to mid-century and beyond. It also supports Canada's obligations—for instance, under the *Canadian Environmental Protection Act, 1999* and the

United Nations Framework Convention on Climate Change—to undertake climate change research, monitoring, and reporting.



While CS2050 will help focus collective efforts in Canada, it is important to recognize that climate change is a global phenomenon that will require collaboration and activity beyond Canada's borders. The work CS2050 advances will enable continued Canadian leadership and participation in international climate change science efforts. This will allow us to leverage international science to enhance Canadian research capacity and to contribute to advancing science and knowledge in a way that reflects the global nature of climate change.

Box 1. Canadian participation and leadership in international climate change science

Government of Canada climate change science is embedded in and contributes to a wide range of international efforts. Canadian scientists make significant contributions to IPCC reports, as well as other international syntheses, such as those of the Arctic Council. Canadian climate modelling and data analysis research undertaken as part of the multi-national World Climate Research Program and the World Meteorological Organization's climate program, allows Canada to contribute to and access the leading-edge understanding of our climate system.

Canadian scientists play leadership roles in international research efforts to monitor and model a wide variety of aspects of the global climate system, such as Arctic sea ice and freshwater fluxes, snow cover, and short-lived climate pollutants. Canada is a member of the international Group on Earth Observations (GEO) network, which has a mandate to collect Earth Observations (EO) and provide open EO data in support of the United Nations (UN) Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction, the UN System of Environmental and Economic Accounts, and the UN Framework Convention on Climate Change (UNFCCC). Observations collected and curated from Canadian networks feed into international databases, such as the global snow dataset of the European Space Agency climate change initiative and the Global Runoff Data Centre for river flows. Canada also serves as one of three global intercomparison programs to ensure consistent global monitoring of atmospheric GHGs.

THE PATH TO CS2050

In developing CS2050, Environment and Climate Change Canada convened discussions with a range of partners and stakeholders to ensure that the climate change knowledge synthesis, mobilization, and research needs identified here reflect the diversity of perspectives represented by Canadian climate change science and knowledge producers, holders, funders, and users. Engagement efforts included a scoping survey (November 2018) sent to approximately 200 science and knowledge producers and users to identify short- and medium-term gaps and a national workshop (February 2019) that brought together more than 100 experts from a range of sectors and disciplines to discuss science and knowledge priorities and opportunities for collaboration and knowledge mobilization. In addition, two targeted expert workshops informed this work, which were focused on permafrost and on carbon cycle science and policy (both June 2019). These efforts were complemented by a series of bilateral discussions with key partners and stakeholders.

CS2050's publication does not signal the end of these conversations; in fact, it is meant to be a springboard to an ongoing national dialogue around climate change science. This dialogue will evolve with advances in our understanding of our warming world and as new questions, challenges, and opportunities emerge. Ongoing work to address and implement the needs and activities outlined here, in tandem with the national dialogue, will contribute to shaping future research directions and priorities.

GUIDING PRINCIPLES

Several principles will guide CS2050's implementation, given that it will be an ongoing process involving of a range of actors and disciplines. While CS2050 provides guidance on *what* should be prioritized, the principles below offer guidance on *how* knowledge synthesis, mobilization, and research efforts can build on existing knowledge and understanding in a respectful, inclusive, and interdisciplinary way that benefits all Canadians.

- Ensure **equity of diverse knowledge systems**, making space for Indigenous leadership and innovation, and recognizing that Indigenous Knowledge is a distinct network of knowledge systems that cannot be integrated into western science but that there are spaces where the two can co-exist and co-create knowledge.
- Further **Indigenous self-determination in research** to support an approach to climate change research that is holistic, place-based, and responsive, and that respects Indigenous sovereignty and ownership of data and Indigenous Knowledge.
- Embrace **interdisciplinarity** to produce science and knowledge that reflect the complexity and interconnections inherent in climate change and that encompass different kinship systems and relationships with the land.

- Emphasize **collaboration** across generations, disciplines, sectors, orders of government, organizations, and regions to bring together a range of experiences, perspectives, and areas of expertise.
- Adopt a **flexible, adaptive approach** in science and knowledge activities to be responsive to emerging priorities, challenges, and opportunities.
- Apply an **intersectional** lens that considers how climate change intersects with various identity factors (e.g., race, class, gender) to develop solutions that tackle both climate change and inequity, removing systematic barriers and promoting well-being.
- Respond to **local and regional** contexts, needs, priorities, protocols, cultures, and ways of knowing, involving communities affected by the research to produce tailored and effective adaptation and mitigation efforts.
- Consider climate change **mitigation, adaptation, and sustainable development** in an integrated way to maximize co-benefits and avoid maladaptive actions.

Box 2. Synergies between climate change and sustainable development

Climate change poses a significant threat to sustainable development. In 2015, the United Nations adopted three multilateral frameworks that, together, reflect the important linkages between climate change and other environmental, social, and economic issues:

- the 2030 Agenda for Sustainable Development, which outlines 17 Sustainable Development Goals (SDGs),
- the Sendai Framework for Disaster Risk Reduction, which developed seven targets to better deal with disasters (including "building back better"), and
- the Paris Agreement, which aims to strengthen the global response to climate change, taking into consideration equity and sustainable development.

The Intergovernmental Panel on Climate Change Special Report on 1.5°C notes that mitigation and adaptation pathways consistent with limiting warming to 1.5°C are associated with multiple synergies and trade-offs across the SDGs. The net response, however, is determined by the pace and magnitude of the changes, the choice of climate action pathway, and how societies manage the transition. Currently, the most robust synergies on a global scale are associated with SDGs for health, clean energy, cities and communities, economic growth, and infrastructure. Conversely, the likely trade-offs of climate action have implications with SDGs for poverty, hunger, clean water, and life on land and life below water. Research is needed to understand the net impact of climate action on SDGs and develop strategies to promote synergies and mitigate trade-offs.

Importantly, there is a lack of recognition of how climate action impacts the poor and most vulnerable populations. A key commitment of sustainable development is the concept of Leaving No One Behind, which extends across several SDGs. Canadian climate action must consider its impacts on all people and adhere to the principles of equity, fairness, and just transition.

Overall, climate change action and sustainable development are intricately linked: action on one can help advance achievement of the other, and likewise, inaction on one can jeopardize achievement of the other. There is strong alignment between climate change research priorities and the SDGs. Situating climate change research in the broader socio-economic context of sustainable development can advance both agendas and help facilitate the mainstreaming of climate change science and knowledge.

INDIGENOUS-LED CLIMATE CHANGE SCIENCE AND KNOWLEDGE

The importance of Indigenous spaces in climate change science

There is a need to ensure that there are both physical and conceptual spaces in climate change research and knowledge generation that support the inclusion and leadership of Indigenous Peoples, researchers, and Elders and Indigenous Knowledge systems. Since time immemorial, Indigenous Peoples have led as stewards of the lands, waters, and ice. Indigenous Knowledge systems, built upon generations of relating to, observing, understanding, and living off of the land, are not static, and they continue to evolve and be developed. These knowledge systems are critical for identifying and adapting to changing environmental conditions. While First Nations, Métis, and Inuit are disproportionately affected by the impacts of climate change, they are leading crucial contributions to climate change science and knowledge.

Despite their long-standing relationships to the land, water, and ice, Indigenous Peoples have experienced ongoing marginalization by western scientific research practices and colonial policies. First Nations, Métis, and Inuit have unique relationships with lands, waters, and ice, distinct from other Canadians. The recognition and affirmation of Aboriginal and treaty rights in Section 35 of the *Constitution Act, 1982*, reflects this. As such, it is critical that their voices, worldviews, and knowledge are given space to lead in climate change science and knowledge decisions. Mobilizing Indigenous Knowledge systems in climate change research and decision making allows Canada to better respond to climate change and contributes to the maintenance and revitalization of culture, food and water security, resource co-management, healthy lands and waters, economic development, community infrastructure, and health and well-being. Indigenous-led research generates crucial and relevant data and evidence for decision making at various scales. This is an important step to reconciliation, Indigenous sovereignty, self-determination, and implementing the United Nations Declaration on the Rights of Indigenous Peoples in Canada.

The equal and respectful co-development of climate change research and knowledge involving multiple knowledge systems can also serve as a mechanism through which long-term, meaningful partnerships can be fostered between researchers and Indigenous partners. This enables Canadian research to better respond to the unique and distinct research needs and interests of First Nations, Métis, and Inuit communities. Enhancing the inclusion of Indigenous Knowledge—while respecting Indigenous Peoples' ownership and control over their knowledge, data, and information—and innovation through these partnerships can support the inherent rights and interests of Indigenous Peoples.

Box 3. Creating space: Promoting the participation, knowledge, and rights of Indigenous Peoples in international climate discussions

Taking direction from Indigenous leaders, Canada worked in full partnership to advance rights-based language into the text of the Paris Agreement. Due to this shared advocacy, a direct reference to the "rights of Indigenous Peoples" can be found in the preamble of the Agreement, creating the foundation for further decisions on amplifying the rights, voices, and knowledge of Indigenous Peoples in the UNFCCC. Over the last several years, Canada, in partnership with leaders from the National Indigenous Organizations, championed the creation of the Local Communities and Indigenous Peoples Platform, and the creation of the Facilitative Working Group (FWG)—the first Constituted Body with equal representation between Indigenous Peoples and State representatives. The platform is an important space for the direct and meaningful participation of Indigenous Peoples in the UNFCCC process, and enables international collaboration of Indigenous networks. Its purpose is to strengthen the knowledge, technologies, practices, and efforts of Indigenous Peoples related to addressing and responding to climate change and enhancing their engagement in the UNFCCC process. The first Work Plan—co-created by the FWG—was adopted in Madrid.

Canadian delegations to the UNFCCC and the IPCC also include representatives from National Indigenous Organizations, ensuring that Indigenous Peoples can provide input into Canada's positions, that Government officials can benefit from their perspectives and knowledge, and that the important role Indigenous Knowledge plays in understanding climate change is recognized. References to the value and importance of Indigenous Knowledge were most recently included in the IPCC Special Report on Oceans and Cryosphere in a Changing Climate, which recognized that Indigenous Knowledge underpins successful adaptation efforts and enables public awareness and social learning.

Mobilizing Indigenous leadership and participation in climate change science and knowledge

Supporting capacity building within Indigenous communities, organizations, and governments is essential for sustainable, self-determined knowledge generation. Research by and with Indigenous Peoples must consider how projects can increase research capacity and leadership in communities beyond the lifespan of the project. This includes supporting Indigenous researchers as Principal Investigators, training community members to undertake research themselves, providing employment opportunities, contributing to community research infrastructure, and supporting the research needs and priorities of the community.

Research by and with Indigenous Peoples should also respect their protocols, policies, governance structures, and Aboriginal or treaty rights.[3] In many cases, Indigenous Peoples of Canada have protocols and policies guiding consultation, research, or the inclusion of Indigenous Knowledge. Further, when Indigenous communities partner with external researchers, results should be communicated in culturally appropriate and accessible ways, linking to existing information resources where possible.

The capacity to enable the full spectrum of involvement in research—from participation to co-development to support for Indigenous-led initiatives—needs to be incorporated within non-Indigenous governments and research institutions. Critically, non-Indigenous individuals involved in science and knowledge production should be trained on the diverse contexts of Indigenous Peoples. Other essential actions include consensual data management practices (e.g., the First Nations principles of OCAP®: ownership, control, access, and possession of knowledge and data originating in Indigenous communities[4]), Indigenous leadership in research

[3] The *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* provides a framework for the ethical conduct of research involving Indigenous Peoples.
[4] OCAP® is a registered trademark of the First Nations Information Governance Centre (FNIGC) www.FNIGC.ca/OCAP.

governance, the recruitment and retention of Indigenous researchers, community members, and youth, adequate funding of projects led and co-led by Indigenous Peoples, and equity participation in research, development, and demonstration (RD&D).

There is a spectrum of ways to improve the meaningful involvement of Indigenous Peoples in climate research and knowledge synthesis, mobilization, and generation. Indigenous participation and leadership in climate change science will differ greatly on a case-by-case basis, as community contexts, research priorities, and capacities vary. Actions towards the advancement of Indigenous-led climate change science and knowledge in Canada can include, but are not limited to:

- elevating opportunities for Indigenous leadership and participation in community-based monitoring;
- aligning resources with research and climate change strategies and priorities of First Nations, Métis, and Inuit organizations, governments, and communities, for example, the *National Inuit Climate Change Strategy* (2019) and future plans as they are developed;
- co-developing projects in which Indigenous Peoples are involved at all stages of RD&D, that respond to Indigenous priorities, and that respect a distinctions-based approach;
- seeking review and approval from the appropriate Indigenous leadership bodies prior to conducting research on Indigenous lands, waters, and ice; and
- formalizing partnerships with research agreements.

Science in action: Applying Indigenous Knowledge Systems in climate monitoring and research

The Indigenous Community-Based Climate Monitoring Program at Crown-Indigenous Relations and Northern Affairs Canada supports projects that weave together multiple ways of knowing. Indigenous communities across the country leading these projects co-apply Indigenous Knowledge Systems and science to answer climate questions relevant to their context, as they self-determine. Indigenous Knowledge Systems often inform which climate indicators are monitored, where, and how often, and may be used to create monitoring methodologies consistent with cultural protocols. Interviews with Elders and knowledge holders are used to gather information on historical trends and changes over time and inform broader climate change strategies. Elders and knowledge holders are often integral to training youth and on-the-land monitoring activities, facilitating intergenerational knowledge transfer. As an example, as part of their Climate Monitoring Program, Dene Tha' First Nation has formed an Elders and Youth Advisory Group to advise the project team and incorporate Dene Tha' value systems and traditional practices into monitoring protocols, data collection methodologies, and study area maps. Through their program, this project team aims to maintain strong cultural identity and language, traditional ways of living, and spiritual relationships with the land.

It is important that Indigenous Knowledge and worldviews lead decision making related to climate change science and knowledge. Fostering productive and respectful spaces for Indigenous leadership and representation ensures that Canada's approach to climate change is more holistic and responsive.

A new lens: Weaving Indigenous Knowledge into CS2050's implementation

Other sections in this document contain references to some of the climate change science and knowledge priorities of Indigenous Peoples. For example, infrastructure, extreme weather events, food and water security, and human health are all influenced by climate change and are currently of research interest to many Indigenous communities in Canada. However, references to Indigenous research priorities in CS2050 are by no means exhaustive, and it is important for researchers to identify national, regional, and local climate science and knowledge priorities. Besides learning of priorities directly from individuals, these can be found in Indigenous research and climate strategies, and explored through early engagement and co-development with Indigenous partners. Directing research and funding towards the distinct climate change science and knowledge priorities of First Nations, Métis, and Inuit, will contribute to resilient communities and ecosystems in Canada for generations to come.

Excerpt from the Inuit Tapiriit Kanatami's National Inuit Climate Change Strategy[5]

PRIORITY AREA 1: Advance Inuit capacity and knowledge in climate decision making

Inuit have largely been excluded from participation in federal, provincial, and territorial climate decision making. In order to ensure that Inuit can meaningfully contribute to climate decisions, and to improve local Inuit access to the best available climate data and services, we must have the opportunity and capacity to become fully engaged. Increased capacity, coordination and information sharing are necessary to benefit climate decision making both within and beyond Inuit Nunangat by improving climate research and educational goals, and enabling more effective use of Inuit knowledge.

Objectives

- 1.1 Strengthen Inuit self-determination in climate change decisions, policy-making and assessment processes
- 1.2 Facilitate and support regional Inuit climate change strategies
- 1.3 Promote Inuit-driven climate change research and monitoring

Actions

- 1.1.1 Influence policy and practice to ensure Inuit knowledge is equitably used in climate change decision making
- 1.2.1 Ensure regional climate strategies are in place and linked to the adoption of the national Inuit climate change strategy
- 1.3.1 Ensure climate information is available to all Inuit to inform evidence-based decision making
- 1.3.2 Establish two-way climate change information sharing best practices among Inuit from the local to the international level
- 1.3.3 Build Inuit regional and circumpolar climate change exchange opportunities
- 1.3.4 Develop a mechanism for effective in-house sharing of emerging Inuit climate change initiatives and corresponding data among Inuit representational organizations
- 1.3.5 Promote Inuit-led and co-produced climate change research and monitoring

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[5] Inuit Tapiriit Kanatami (2019): *National Inuit Climate Change Strategy*, Ottawa, ON.

Long-term outcomes

- Inuit have meaningful roles at climate change decision making tables
- Culturally appropriate, Inuktut educational initiatives linked to on-the-land Inuit knowledge transfer are sustainably and widely available across Inuit Nunangat, and internationally across Inuit Nunaat to Inuit in other circumpolar countries
- Best available knowledge, both Indigenous and scientific, is accessible and used in climate decision making across Inuit Nunangat and Inuit Nunaat

KNOWLEDGE SYNTHESIS AND MOBILIZATION

Integrating and contextualizing findings from individual studies (knowledge synthesis) and translating research outcomes into useful knowledge for practitioners (knowledge mobilization) are key activities in mainstreaming climate change science and knowledge into planning and decision making. While a great deal of knowledge has been developed, only a portion reaches decision-makers in a timely or accessible fashion, and a lack of capacity among decision-makers can also hamper their ability to use the information. Placing importance on knowledge synthesis and mobilization, in addition to knowledge generation, will allow Canada to reap the full benefit of its investments in climate change science and knowledge. Knowledge synthesis and mobilization also serve to establish a dialogue between knowledge producers and users, keeping research aligned with user needs and maximizing its utility and relevance. Opportunities for knowledge synthesis and mobilization for a range of topics (e.g., infrastructure, ecosystems, Arctic and North) are identified in Annex 2.

Broad national assessments, such as the reports produced under the Canada in a Changing Climate process (e.g., *Canada's Changing Climate Report*, *Canada's Marine Coasts in a Changing Climate*, and *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation*) and expert panel reports, such as the Canadian Council of Academies' *Canada's Top Climate Change Risks* and the *Final Report of the Expert Panel on Sustainable Finance*, have helped raise general awareness and guide Canada's response to climate change. Beyond national-level reports, it is also important to produce knowledge syntheses tailored to the specific priority needs of various target users.

Increasingly, government departments, the private sector, Indigenous groups, and academic networks are preparing targeted climate science information (e.g., local-level assessment studies), drawing together results from surveillance, observation, and monitoring programs, model outputs, interdisciplinary analyses, and science and risk assessments. However, there are limitations to how accessible and understandable these targeted **science and risk assessments** are for individuals, communities, businesses, governments, and other organizations developing climate action plans. Knowledge mobilization efforts can increase the accessibility and use of these reports, as well as datasets and other scientific findings, in advancing resilience and decarbonization efforts. This includes improved Indigenous outreach, translation, and access to science and risk assessments. Further, creating targeted **knowledge portals** for communities, regions, or key sectors (e.g., energy, infrastructure, health, agriculture, fisheries, tourism)—and building on and promoting those that already exist—can also help move this knowledge to action.

National and regional **climate services** organizations (e.g., the Canadian Centre for Climate Services) are another useful mechanism for synthesizing and disseminating data and information from long-term monitoring, research, and analysis about climate impacts and vulnerabilities. Expanding existing climate services and/or integrating climate-oriented data portals with a broader array of geographical, ecological, health, and socio-economic data centres will generate additional knowledge and insights. It is also important to continue climate literacy efforts and communication related to the limitations of local and regional data and scenarios.

Case studies and lessons learned are another useful tool for mobilizing knowledge. This could include, for example, accounts of projects and promising practices related to community- and sector-level adaptation and mitigation, technology demonstration, health and well-being, climate-smart conservation, nature-based solutions, and beneficial land management techniques. Doing so can support the application of these approaches and tools in other contexts and locations, thus promoting the scaling up and out of promising solutions. These case studies also need to be translated into actionable, relevant information and tools to inform individual decision making, including information about efforts individuals can take to reduce emissions and/or protect themselves and their communities from climate change impacts.

As knowledge synthesis and mobilization efforts continue and are enhanced, targeted, audience-specific approaches for communicating climate change science and uncertainties to decision-makers and community members will be helpful. Continued social science research into effective climate change communications and strategies for bridging the science-policy gap will be helpful in this respect. **Climate change science and data literacy** efforts at all levels should complement this work, as should efforts to develop **professional climate-related competencies** in all sectors. Scientists and boundary organizations have an important role to play in the delivery of knowledge through the various knowledge mobilization mechanisms outlined above, and through outreach and public engagement to expand both trust and climate literacy.

SCIENCE AND KNOWLEDGE NEEDS

The science and knowledge needs identified here would benefit from the collective focused attention of the Canadian climate change research community. The needs outlined in this section are organized according to four outcomes that are central to building a healthy, resilient, and carbon-neutral Canada. A strong foundational understanding of Earth system climate science underpins work across all outcomes.

The outcomes and the allocation of various needs within them are imperfect and do not adequately represent the integrated nature of research that will be required. A narrow approach that explores issues individually is insufficient. Climate change research must increasingly take a holistic approach that considers the synergies and trade-offs between mitigation, adaptation, the stewardship of nature, sustainable development, and equity and justice, in order to find comprehensive solutions that advance multiple priorities at once. Quantifying these co-benefits and developing metrics to evaluate the transformative potential of climate solutions will be important areas of work as integrated action advances.

The scale and urgency of the climate challenge do not afford the science community the luxury of time, making it necessary to do research in new and different ways. Experimentation and iteratively learning by doing and by observing will be increasingly important. The use of, for example, living laboratories, pilot studies, emerging technology demonstration projects, on-the-land observations, and the co-production of knowledge with practitioners, Indigenous Peoples, and community partners can be powerful research approaches to support transformative climate action. It is crucial to develop participatory research processes that involve deep engagement with non-academic partners, including participants from civil society and Indigenous communities, to transition away from extractive research approaches toward co-developed ones. Monitoring and evaluation of climate change interventions, particularly using an equity approach, will be key in ensuring effectiveness and avoiding inadvertently creating barriers or adverse impacts for some individuals and communities.

Throughout this section, there are icons showing the specific sectors or areas of interest that are covered under each topic. The list below is not exhaustive, and is meant to help readers identify content that is applicable to their specific area of expertise, interest, or focus. A detailed list of research needs organized by these areas of interest can be found in Annex 4. These icons also serve a second purpose: to demonstrate opportunities for interdisciplinary work.

Accelerating transformational change	Economics	Health and well-being
Aquatic systems	Ecosystems (terrestrial and aquatic)	Infrastructure
Communities and social structures	Energy	Land systems
Earth system climate science	Extreme events	

Advancing Earth system climate science

Understanding the complexities of the physical climate system, which includes the atmosphere, ocean, freshwater, land surface, and cryosphere (glaciers, permafrost, sea and lake ice, snow) is fundamental to advancing a wide range of climate change science and knowledge. This includes better understanding the ecological, hydrological, and biogeochemical aspects that influence climate through changes in GHG emissions, land use, atmosphere/ocean processes (including clouds, precipitation, sea level, ocean waves, turbulence circulation, weather and storm processes), surface albedo, the water cycle, and heat storage in the ocean. Given the global nature of climate change, Canada's science capabilities will benefit from continued international engagement.

Canada's Earth system model (CanESM) is an integral part of the international ensemble of climate models being used to make projections under a range of future GHG emission scenarios and includes carbon, sulphur, and, increasingly, nitrogen cycle feedbacks. Downscaling techniques provide more detailed information for the various models needed to assess climate impacts (e.g., crop simulations, basin-scale hydrological models, regional and basin-scale ocean models). Satellite observation data is an important input to Earth system modelling, providing observations of climate change trends and aiding in understanding the processes that drive climate change.

An increased level of effort is needed to improve the representation of the physical and biogeochemical processes and feedbacks, including ecosystem-level processes (e.g., forests, permafrost, tundra, wetlands), that are particularly relevant to Canada and that contribute to uncertainties around the magnitude and timing of future change. The assessment of feedbacks and related processes rests on a broad range of essential activities, from *in situ* and remote observations (aerial and satellite) and monitoring, focused field studies, surveillance, and laboratory work through to global and regional modelling and data archiving and analysis. Indigenous, national, and international scientists and partners are important in advancing these activities.

Work is also needed to better assess and simulate the influence of climate change on permafrost thaw and glacial melt, including their implications for carbon cycling, sea-level change, and feedbacks, as well as their direct effects on infrastructure and operations, natural resource sector productivity, habitat degradation, climate-driven infectious diseases, aquatic biodiversity, and water quality and availability. This work will depend on improved observations and simulations of the land and ocean surface and subsurface, higher horizontal resolution, and strengthened interdisciplinary research, including in collaboration with Northern and Indigenous communities.

Freshwater supply is subject to variability and change in key stores and fluxes of the water cycle, including extreme events such as droughts and floods. Given the importance of freshwater to some ecosystems, the economy, and the health and well-being of Canadians, research is needed to connect observed and projected climate change impacts on water supply to anticipated water demand across Canada.

Targeted interdisciplinary research is also needed to evaluate the effectiveness of different mitigation strategies and their trade-offs and interactions. One area in need of further research is our understanding of the role of short-lived climate forcers (e.g., methane, black carbon) in meeting near-term climate targets. Research to provide a more comprehensive scientific assessment of climate engineering (or geo-engineering, including Carbon Dioxide Removal and Solar Radiation Management) and its potential consequences would also be of value, including an analysis of

Science in action: Increasing climate resiliency for buildings and infrastructure

Potential extreme weather events can cause severe damage to residential and commercial buildings, as well as to other core public infrastructures (e.g., bridges, roads, wharves, municipal water systems, rail transit). To help prepare communities and private building owners, Infrastructure Canada and the National Research Council are collaborating with Environment and Climate Change Canada and others on research to inform the planning of new buildings and the rehabilitation of existing ones, with the ultimate result of integrating climate resiliency into building and infrastructure design, guides, and building codes. These guidelines and codes (e.g., wildland fire urban interface, flood resiliency of buildings, adaptation of existing stormwater management systems) will enable easy adoption and enforcement by provinces and municipalities.

the Canadian implications of climate engineering undertaken elsewhere.

A targeted and comprehensive research effort is also required to improve the prediction of climate extremes (e.g., heat waves, cold snaps, extreme precipitation, flooding, wildfires), including in the ocean (e.g., acidification, deoxygenation, hypoxia, marine heat waves, high salinity). This includes work on flooding, erosion, and exacerbated landslide occurrence caused by extreme precipitation. On the coastline, flooding, storm surges, and erosion are increasing from local sea-level rise and the reduction of sea ice duration and extent. More work is also needed to better understand convective events leading to thunderstorms, extreme winds, and localized rain and hail, to inform resilience measures in the built environment (including natural infrastructure) and better emergency preparedness. Such work will inform improved predictive capabilities to ensure Canadians are able to better prepare for individual climate events with sufficient advanced warning.

The development of downscaling techniques must continue in order to provide more spatial detail and information tailored to specific sectors or regions. This will improve the utility of climate projections for communities, biodiversity, agriculture, fisheries and aquaculture, infrastructure, transportation, ocean and coastal impacts, natural resources, health, and other domains. Downscaling efforts would benefit from the improved use of existing, emerging, and novel approaches for observing the Earth system, including space-based observations (particularly for Canada's data-sparse Arctic and North) and from data analytics and synthesis techniques that leverage shared data and research infrastructure (e.g., ships, aircraft). Further developing techniques to assimilate satellite and surface observations efficiently and enhance the spatial detail in model and downscaling outputs will enable better prediction of climate extremes and help extend the range of climate variables covered by the seasonal to decadal predictions used in climate services.

Box 4. Event attribution

Increasingly, there is a desire to identify the extent to which extreme events and their impacts can be attributed to anthropogenic climate change. That is, to quantify the extent to which human activities (GHG emissions, aerosols, land-use change) have made certain events more intense and/or frequent. By being explicit about the role of human activities in changes in extremes and extreme events, attribution strengthens the business case for and acceptance of climate action. It also helps facilitate the development of cross-jurisdictional governance, multi-stakeholder decision-making frameworks, emergency management plans for disaster risk reduction, and financial assistance related to extremes (e.g., disaster relief, insurable risks).

Extreme events are associated with substantial physical and mental health issues and economic costs. Increasingly, government and non-government actors are seeking to understand attribution in the context of investment risk disclosure, insurance payouts, culpability related to due diligence in implementing climate action, and financing for infrastructure renewal. There are, however, very few studies that have attributed trends in Canadian extremes and specific extreme events in Canada to anthropogenic climate change. Additionally, there are challenges in defining which extremes or extreme events are relevant, as this can differ between sectors.

The spatial and temporal resolution of both observed and simulated Canadian climate extremes datasets (e.g., extreme heavy precipitation) are currently insufficient to support *regional* detection and attribution studies and additional capabilities are needed for the routine attribution of individual extreme events as they occur. A better understanding of the processes that drive extreme events is also integral to their improved prediction on timescales of days through decades. Comprehensive attribution of extreme events in Canada requires the study of the full range of climate, weather, and environmental variables and processes. This includes consideration of compound extreme events, when extremes occur concurrently or consecutively (e.g., extreme hot temperatures alongside very low precipitation).

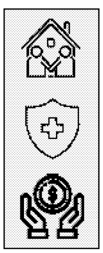
Extending the analysis through to the attribution of the impacts and related socio-economic costs requires even broader data on how a sector or community is affected. Evaluating individual, community, corporate, and government impacts and responses relies on an understanding of historical event attribution and improved prediction of extremes, and is constrained by the limited availability of socio-economic data at an appropriate scale.

Healthy and resilient Canadians, communities, and built environments

The impacts of climate change put the health and well-being of Canadians, communities, and infrastructure at risk, and increased resilience is needed on all levels (e.g., individual, local, regional, national, global). To ensure that efforts to build resilience are effective, a nuanced and thorough understanding of vulnerabilities, strengths, and risks is needed, given that these are not distributed uniformly across all regions and social, cultural, and economic groups. Strengthening our understanding of the similarities between climate change adaptation and disaster risk reduction—two areas with similar objectives—will also help build resilience by contributing to a more integrated and efficient use of resources.

Overall, research to quantify the costs and benefits of impacts and adaptation action in Canada is needed, including how these costs would evolve in different scenarios (e.g., in the case of delayed mitigation action, abrupt non-linear changes). This research and analysis is key to understanding the value of investments in adaptation and resilience, and full lifecycle analyses will be critical here, supported by robust data and curated databases. Research on methods and governance for financing adaptation would be helpful, including insights related to balancing and mobilizing both private and public financing.

Developing a place-based, intersectional understanding of vulnerability and resilience



Climate change impacts and actions are not experienced in the same way by all Canadians, with the already marginalized and economically vulnerable often being disproportionately affected. In many cases, the quality of determinants of health and other social characteristics drive vulnerability to climate change and influence individual and community adaptive capacity. Research is needed on these drivers (e.g., sex, gender, race, sexuality, age, language, ability, income, education, location) and how they shape experiences of climate change impacts, vulnerability, strengths, and the ability to adapt. Work to explore how individual and community assets and resources can contribute to adaptation efforts would complement this research.

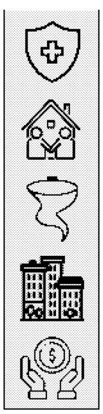
Understanding the impacts that climate change policy, programs, and legislation have from an equity and gender perspective is needed, as is work to understand the exclusion some groups face in adaptation and mitigation efforts. Identifying opportunities to use climate actions to address broader social and health inequities (e.g., poverty, unemployment, colonialism, language barriers, and lack of access to healthcare and public health services, education, energy, and housing) will also be useful. Given the heterogeneous experiences of climate change, place-based perspectives that enhance and leverage the agency of communities to act are essential, especially for vulnerable communities (e.g., coastal, forest, agricultural, rural, remote, Arctic and Northern, and on- and off-reserve Indigenous communities) and those facing climate change-induced displacement.

Longer-term economic studies of the differing effects on key demographic groups and geographic regions—including intergenerational effects—are needed, and could explore the job market, food prices/cost of living, energy accessibility and security, and food security. Work to develop costed options for minimizing impacts, to understand the consequences of cost shifting (e.g., between groups, regions, generations, etc.), and to identify options for minimizing undesirable impacts of climate action on different groups will be beneficial.

Developing partnerships between researchers, knowledge holders, cities, Indigenous Peoples, and communities will help advance knowledge related to the process of transformative climate action. Examining how novel approaches are implemented, understanding their transferable lessons, and studying how communities can motivate local governments to take action can all directly inform climate action at the local level. Better understanding the mechanisms of inclusion, transparency, and collaboration when building political legitimacy will help minimize the disruptive effects of transformative change, especially for marginalized communities and community members, and can help expand the positive impacts of climate change interventions.

Research is also needed to develop an integrated understanding of risk that takes into account social, cultural, ecological, health, and economic factors. Qualitative methods can make an important contribution to developing a nuanced understanding how communities feel about the risks and stresses they are facing and the decisions being made to address them. This work will contribute to understanding the broad impact of extreme events, as well as the more gradual (slow-onset) impacts of climate change—including exposure, vulnerability, and risk management—and their effects on individuals, communities, and the interconnected systems on which they rely.

Supporting healthy Canadians and resilient health systems



Climate change poses significant direct and indirect risks to the physical and mental health and well-being of Canadians. It also affects health systems, for example through extreme weather events that damage health infrastructure and lead to hospital evacuations, disrupted delivery and supply chains, and increased health costs and pressure on the public health system. Continued research is needed to assess climate-driven risks and vulnerabilities across the health system (e.g., workforce, information systems, infrastructure, service delivery), and identify adaptation actions.

To reduce these risks, Canadians and communities, health and public health professionals and authorities, allied professionals, and decision-makers in other sectors all require relevant and actionable research, laboratory diagnostics, knowledge, and evidence. Public health can play a critical role by providing climate change and health information, influencing and empowering behavioural change among Canadians, and supporting decision making to mobilize action. Understanding the impacts, risks, and opportunities for human health will require investigating climate impacts across the health research spectrum—bio-medical, clinical, health system services, population health—as well as research into understanding interactions with other sectors and disciplines. Addressing challenges related to the availability and accessibility of high-quality, timely data and the interoperability of environmental and climate data with health data will allow the measurement of climate change health impacts.

In particular, there is a need to better understand climate-related risks to the health of Canadians, such as those associated with extreme weather events (e.g., heat waves), natural hazards, emerging climate-driven infectious diseases, impacts to mental health and well-being, and changes in air quality. For example, research is required to support an integrated understanding of how climate change will affect air quality (including outdoor air pollution, wildfire smoke, aeroallergens, and indoor air quality) and the associated health and economic impacts, as well as how climate action can lead to air quality health and economic co-benefits. Innovative and collaborative actions are needed to support novel, integrated, and multi-disciplinary surveillance and monitoring, and to enhance prediction and modelling capabilities for greater foresight. This includes new or advanced approaches for data collection and analysis, early warning systems, community science, novel laboratory diagnostics, meta-genomics, and geospatial mapping in partnership with other sectors, disciplines, academia, Indigenous Peoples, and all levels of government.

Climate-related health risks are experienced differently across populations (e.g., Indigenous Peoples, seniors, children, the socially and economically disadvantaged, people with chronic illnesses or mobility challenges, women, immigrants) and communities (e.g., urban, rural, remote, Indigenous, Northern, coastal). Research is needed to understand these differential impacts, strengths, and vulnerabilities, and their implications for population health and health equity. This work should include considerations of the intersection of climate change and colonialism on Indigenous mental health.

The health of humans, plants, animals, and entire ecosystems is connected, necessitating a multidisciplinary 'One Health' approach to understanding the complex interactions between human, environmental, and animal health. This includes understanding how this interrelation is driving changes in the geographic distribution, seasonality, and/or transmission of infectious diseases, pests, and related food security implications. This also provides a critical opportunity to build on the experiences and learning of other disciplines and sectors. For example, there is a need to identify where and when climate-driven infectious diseases may emerge or re-emerge in Canada, such as the climate impacts on zoonotic, food-borne, and water-borne diseases.

Understanding how climate change will impact the systems that support health, such as water, sanitation, and food and nutrition (e.g., through impacts on fisheries, aquaculture, and agriculture) is an important area of interdisciplinary work, as is work to understand how the actions of non-health decision-makers influence the health impacts of climate change (e.g., transport, water, urban planning, energy, agriculture, conservation). Health co-benefits and risks can be associated with climate change measures taken in other sectors. For instance, investments in active transportation infrastructure can increase physical activity and air quality, landscape management actions to lessen urban heat or infectious disease risks can provide carbon sequestration or flood protection, and the deployment of nuclear generation can also provide medical radioisotopes. Research into these kinds of no-regrets solutions will be beneficial in identifying and designing climate solutions that also have positive spillover effects in terms of mental and physical health and well-being, health equity, community health, and climate resilience.

Science in action: Bringing partners together in a One Health approach

'One Health' is a multi-sectoral approach that brings together human, animal, plant, and environmental health disciplines to integrate data, science, and research and work collaboratively to achieve better public health outcomes. The ECO2 Prototype is a One Health pilot collaboration between the Public Health Agency of Canada, Environment and Climate Change Canada, Agriculture and Agri-Food Canada, and the Canadian Food Inspection Agency in the South Nation Watershed in Eastern Ontario. It monitors infectious disease emergence, environmental change, and biodiversity, while supporting the development of regional partnerships with individual citizens (farmers, landowners/managers, communities), local universities, and local and provincial government scientists and officials within human, livestock, wildlife, and environmental health fields. By working collaboratively, the prototype enables the collection of field, laboratory, climate science, and Earth observation data needed to understand how climate/environmental changes influence infectious diseases. This science and knowledge generated is used to forecast disease outbreaks and support early warning systems that inform decision making and action at the local level.

Supporting healthy communities will require more than just research to understand impacts. It will also require research on how to design and test interventions that could provide long-term, scalable, and impactful solutions. Interdisciplinary intervention research and implementation science focused on maximizing health and resilience outcomes will be key. Given that the health sector plays an important role in supporting a stable society and economy, there is a need to understand how climate change related-health issues may affect other aspects of society, such as economic performance and productivity, and social cohesion and functioning.

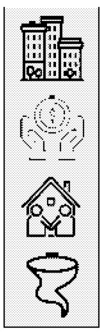
Box 5. Understanding the mental health consequences of climate change

The need to understand the mental health effects of climate change has increased in response to a growing number of Canadians experiencing climate-related grief, traumas, and anxieties. Health decision-makers and those in other sectors (e.g., emergency management, occupational health) need tools and capacity to measure and monitor the mental health effects related to specific climate hazards (e.g., traumas related to experiencing wildfires or flooding; violence, aggression, and suicide related to extreme heat) and the mental health effects of experiencing climate change more broadly (e.g., eco-anxiety, ecological/climate grief). Further, there is a need for research to understand and support psychosocial adaptation to a changing climate.

This field of study is growing, and there is a need to better understand successful upstream interventions that build resilience, tools, and coping skills that enable positive mental health and wellness before, during, and after a climate-driven event. In addition, empirical evidence is needed that explores the long-term effects of climate change-related hazards, as well as longitudinal studies that examine the mental health consequences of slow-onset hazards (e.g., sea-level rise, pervasive drought). Future adaptation efforts will benefit from a greater understanding of the mental health impacts of climate change on specific population groups, for example, the effects on children and youth who appear to be experiencing eco-anxiety or eco-grief, as well as impacts from more frequent exposures to climate-related hazards. Effectively planning for climate change impacts on health will also benefit from greater knowledge of affirmative mental health outcomes, like psychosocial resilience, altruism, and compassion after experiencing climate hazards. Finally, there is a need to understand the best ways of communicating about climate hazards in a way that does not induce more anxiety or overwhelm Canadians, but rather motivates action and supports individual and social well-being.

Advancing knowledge in these areas is limited by a lack of population-level data on mental health that is interoperable with ecological and environmental data. Expanded surveillance of mental health in a changing climate is necessary to understand the health effects of climate change.

Building climate-resilient communities and infrastructure



Adapting to climate change will require significant changes to where and how our communities are planned and built, from their overall design to their individual infrastructure assets. Infrastructure (e.g., buildings, transportation, energy) is one of the sectors most at risk from climate impacts, and those impacts can have negative effects on ecosystems, health and well-being, cultural resources, and the economy. It is also one of the sectors with the greatest potential to reduce vulnerability and GHG emissions.

To inform efforts to increase community and infrastructure resilience, there is fundamental work needed to better understand risk. An integrated approach to risk assessments that examines climate risks, vulnerabilities, system interdependencies, and cascading impacts will support a deeper understanding of current and future climate risks and their associated costs at a variety of scales. An improved understanding of risk will also benefit from continued work on natural hazards, extreme weather events, and slow-onset climate change impacts, such as how changes in frequency and intensity will affect the resilience and reliability of infrastructure (e.g., increased loads, accelerated aging of materials, increased energy demand) and which impacts are likely to have the greatest consequences both now and in the future. In the rapidly changing context of the Arctic and North, it is particularly important to better quantify climate impacts over time (e.g., precipitation, temperature, wind, permafrost thaw, sea-level change, sea ice, waves, storm surges) and determine their effects on already-vulnerable infrastructure, including for Indigenous communities, and mechanisms for mitigation and adaptation. Economics work on non-linear change and tipping points as they relate to vulnerable infrastructures, including questions of loss and damages, liability, and compensation, will inform a more integrated understanding of risk.

In addition to understanding climate-related risks to Canadian communities and infrastructure, there is a need to understand the value of resilience measures and their co-benefits. This includes better evaluation of the cost-benefit or return on investment of both design-phase and retrofit traditional, hybrid, and natural infrastructure solutions, as well as analyses of how energy efficiency measures and construction and maintenance quality affect emissions from built infrastructure, including from heritage assets. Furthermore, a more integrated understanding of the economic, social, health, ecological, cultural, and reconciliation implications and co-benefits of different resilient infrastructure solutions is needed across all scales, as this will be crucial in developing resilient, equitable, and culturally appropriate infrastructure in Canada. For example, it would inform the development of housing, energy and transportation systems, and coastal infrastructure in Arctic and Northern and Indigenous communities.

Developing and implementing infrastructure solutions will require knowledge mobilization and increased professional capacity. Qualitative methods can help researchers and practitioners to understand the challenges different professionals are facing in building climate-resilient communities and infrastructure (e.g., urban planners, engineers, economic development directors, emergency managers, park directors, utility managers).

At the asset level, the location, design, repair, and replacement of built assets will benefit from data and analyses on the types and condition of existing assets, as well as from greater coverage of information related to the impacts of climate change on geological materials and processes (e.g., erosion, permafrost, landslides). Asset management is a promising point of entry for adaptation efforts, and work is needed to develop better asset monitoring, identify best practices for building resilience, and better understand the intersection of adaptation and mitigation (e.g., lifecycle assessments of costs and GHGs).

In terms of infrastructure solutions at the broader landscape and community levels, work is needed in two areas: natural infrastructure and community design / the built form. Natural infrastructure solutions, landscape naturalization, and nature in general (including networks of protected areas) can make important contributions to building resilience, in addition to offering multiple co-benefits. Work is needed to help decision makers understand how and where to apply them. Research related to resilient community design and the built form is also needed to determine how to implement transformational community design changes in ways that are practical and actionable, that respect the environment, and that maximize health co-benefits. This research is needed for a range of contexts (e.g., urban, rural, remote, Arctic, Northern, Indigenous). Pilot projects could play an important role in engaging communities in co-developing, testing, and evaluating context-specific interventions (e.g., increasing densification).

Resilient communities rely on a range of systems (e.g., health facilities, water, energy, transportation) that need to remain operational during extreme events or come back online quickly following these events. Research is needed to advance the resilience of these systems and their various intersections, including through the development of revised codes and standards. This includes focused work related to critical infrastructure (e.g., hospitals and health facilities) and the community infrastructure needed to support it (e.g., roads, water and sanitation). A deeper understanding of the attributes of resilience (e.g., redundancy, diversity, modularity) and how they can be incorporated into Canadian communities and the systems they rely on will also be beneficial.

Enhanced capacity to project future water availability and quality will ensure that municipalities can make informed decisions in planning for and responding to climate change impacts on their water supply, and will also contribute to planning, preparedness, and responses to water-related disasters. This should be complemented with research on inclusive governance for integrated water management at the local and regional scales.

Canadian society depends on diverse energy inputs, and increasing the resilience of the processes and infrastructure through which that energy is produced, delivered, and consumed is crucial. Research is needed to develop communication strategies, control algorithms, modernized monitoring, and appropriate and adapted technologies to reduce reliance on diesel. In addition, implementing modular, multi-application (e.g., co-generation), scalable, and resilient non-emitting energy systems will require a holistic approach to research to find synergies and advance multiple priorities at once. Planning for these solutions, particularly in Arctic, Northern, Indigenous, and remote communities, will require insights into how to balance energy infrastructure needs with energy security, the maintenance of ecological integrity, and the ability to provide nature-based climate solutions.

Box 6. Floods: Understanding risk and resiliency

Many parts of Canada are anticipated to experience increased flood risk resulting from climate change, owing largely to more intense rainfalls, local sea-level rise, changing sea-, river- and lake-ice conditions, storm surges, increasing wave heights, and other environmental changes. These impacts sometimes intersect with land-use planning decisions that do not account for climate and flood risks.

Flooding across Canada causes over $1 billion in damages annually, with certain populations (e.g., First Nations on reserves and Métis communities, coastal communities) having a higher risk for evacuation and longer recovery periods. Flooding events exacerbated by climate change can increase the risk to public health and safety, damage infrastructure, impact landscape stability, disrupt municipal drinking, storm, and waste water systems, and cause sudden contaminant or nutrient releases from agricultural, industrial, and urban areas with significant public health and ecosystem impacts.

Climate change and human activities (e.g., clearing vegetation, diverting water, paving) have impacted many surface landscape features, including forests and wetlands, which can affect a region's hydrology and associated flood risk. However, there is a limited understanding of how these changes will impact future flooding and what interventions can be used to reduce flood risk (e.g., ecosystem restoration).

There is a growing amount of quantitative information about flood risks and impacts (including economic and property damages), as well as qualitative information from Indigenous communities based on teachings of adaptation to past land changes and recent stories of flood events. However, continued work involving many ways of knowing is required to better understand future flood regimes. This includes a better understanding of future flood risk due to extreme precipitation events, as well as the more complex spring floods driven by factors like changing winter snowpacks, earlier spring runoff, river ice-jams, and prevailing ground conditions. For coastal regions, improved knowledge about long-term changes in local sea level and reductions of sea ice is critical, since this will result in more frequent damage to coastal infrastructure and ecosystems supporting the fisheries and tourism sectors.

In terms of implementing risk reduction efforts, there is the perception that healthy and resilient ecosystems, such as forested watersheds, peatlands, and wetlands, have an essential role to play in buffering communities from flooding. The extent to which these ecosystems ameliorate flood risks is site specific and not always well quantified, nor are the impacts of a warming climate on these ecosystems in flood-prone regions.

Reducing flood risk is a key element of emergency management planning. Beyond the critical step of updating flood maps, the science must continue to evolve by integrating climate, weather, and hydrological modelling tools with enhanced land-cover information to improve planning and engineering design through detailed analysis of the accelerating hydrological cycle. Enhanced operational flood predictions for inland, riverine, and coastal communities and regions are required, which rely on improved predictions of the changing intensity and frequency of extreme precipitation. Coastal communities will be even more prone to increased flooding due to sea-level rise, increased storm occurrence and severity, and increased storm surges.

Developing a better understanding of inclusive governance mechanisms for integrated water management, including managing flood risk, at local and regional scales will inform risk reduction measures. Work is also needed to understand how flood risk and disaster risk reduction interventions (e.g., enhanced spillways, wetland retention, community relocation, zoning changes, adjustments to disaster relief financing and flood insurance) could affect vulnerable communities, in order to avoid exacerbating social and health inequities. This work should draw on the lessons learned from Indigenous and non-Indigenous communities that have experienced flooding.

Research is also required to better understand the mental health and community impacts of flooding. Additionally, work to understand the societal response to flood risk will provide insights into how to encourage adaptation at many levels, including the implementation of climate-resilient building codes, standards, and guidelines. Finally, given the broad range of impacts (public health, multiple economic sectors, ecosystems, infrastructure), research into economic valuation or avoided costs of adaptation and resilience is important to inform action, including economic analyses that compare long-term flood mitigation costs against relocation costs.

Understanding climate impacts on trade, migrations, development, and governance

Climate change will impact socio-economic systems, such as trade, migration, and international cooperation. It also has the potential to worsen geopolitical tensions and social conflicts, trigger humanitarian crises and the displacement of people, and affect global trade systems. Research is needed to assess the scope and likelihood of these risks and the role of adaptation in reducing them.

Work to understand the potential of climate change to act as a threat multiplier and magnifier in the international and global security context should examine potential impacts on domestic and international trade (e.g., climate policy impacts on trade disputes, impacts on trade-related transportation infrastructure), as well as its impact on domestic and international treaties, boundaries, and agreements. Work to assess the effectiveness of existing environmental provisions in Canada's trade agreements in reducing the negative impacts of trade on climate and the environment is also needed, as is research to advance international collaboration on climate-friendly trade. Strengthening our understanding of the resilience of trade routes, the potential impacts of climate change and extreme events on them, and ways to address vulnerabilities and build resilience will also be helpful.

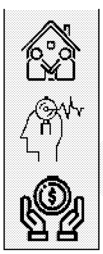
Climate change threatens to reverse the significant development gains achieved globally over the past decades, and could push many people in developing countries below the poverty line. Research on the effects of climate change and climate-related policies on the poorest and most vulnerable could help improve the adaptation results of international assistance in developing countries. Work is also needed to understand the impacts of climate change on global migration patterns and Canada's immigration and resettlement programs, and strategies for preparing to meet those needs, for example with respect to the provision of health and social services.

Moving from the global to the local governance level, more research is needed to understand the degree to which municipalities are autonomous, how this affects their implementation of climate policy (especially policy set at the federal and provincial levels), and ways to develop and increase the flexibility of municipal governance tools to ensure implementation reflects local realities. Given the movement of people and products, research to support more effective multi-jurisdictional governance and regional coordination on climate action will be beneficial, as will work to better understand governance fragmentation and regionalization and its impact on effective action.

A carbon-neutral society

Exceeding Canada's 2030 GHG emissions reduction goal under the Paris Agreement and achieving net-zero emissions in Canada by 2050 will require transformational change across society and the economy. It will mean substantial decarbonization in all sectors, particularly in the energy sector, which accounts for the majority of emissions. This will require significantly changing how we produce and use energy, as well as protecting and enhancing our carbon sinks. A range of economic and policy instruments will be needed to drive this change and support emerging technologies that could contribute to decarbonization. While technology and economics are important parts of the solution, decarbonization is also a behavioural challenge, and social science work will be critical in understanding what limits or inspires action.

Accelerating social and behavioural change



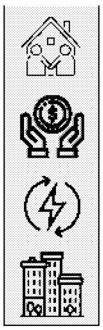
Engaging the public on policy responses and motivating action is the foundation of ambitious and successful mitigation efforts. Economic and behavioural shifts may be challenging to maintain in the long-term through policy design without strong and continued social license. Understanding Canadians' perceptions of evolving climate policy (e.g., through the Canadian Surveys on Energy and Environment) and their attitudes towards behavioural shifts over prolonged time series will help shape policy design that is consistent with climate science and that increases the level of stringency in socially acceptable ways that move Canadian society towards positive tipping points that result in rapid changes. This understanding could also be key in leveraging buy-in from communities that have relied on carbon-intensive industries for their livelihood and economic prosperity over many decades.

Similar work is required to better understand behaviours that lead to climate resilience, and it will be important to explore adaptation and mitigation jointly where appropriate in order to maximize co-benefits. Beyond approaches focussed on individual behaviour change, insights are needed for the systemic normalization of sustainability across society. Understanding how to structure education to strengthen environmental sustainability and climate action will play an important role here, as will social research on processes of environmental education and social learning.

Research related to the effective communication and appropriate framing of messaging is needed in order to encourage awareness and action, address complacency and/or the tendency to respond to urgent rather than slow-developing risk, and build support for proposed measures. This is especially important given that this messaging is dynamic, evolving as individuals shift their values and behaviours.

Continued psychological, economic, and social science research into behavioural change will be beneficial, as will better integration of existing knowledge from these fields into decision making and planning. This includes work to understand the factors that motivate or prevent action at the individual and collective levels, including the positive reinforcement between behavioural change and structural change. Understanding the possible future states of our systems and structures (e.g., social, economic, political) is key to identifying policy mixes that support environmentally sustainable behaviours that reinforce climate-related goals. Finally, insights into where individual and social behaviour can play the greatest role in creating change will help accelerate progress to reduce emissions and build resilience.

Identifying pathways to decarbonization



As Canada pursues decarbonization efforts on the path to reaching net-zero in 2050, a significant amount of research will be required to understand the process of decarbonization, the various levers that can be used, and potential barriers. The process of decarbonization will not be linear. In fact, attempts to measure early progress may not even reveal that changes are underway. As such, research is needed to develop measurable indicators of transformative change.

Foresight practices will be useful in identifying pathways to transformational change, while applied decarbonization pathway research and analyses that model the impact of various mixes of policy instruments will support the development of detailed mitigation strategies. This work should aim to improve understanding of the technological, social, health, political, and economic perspectives related to these pathways. Given that policy instruments can lead to large-scale, long-term change and increased public support, work to evaluate the transformative potential of the various interventions will be a useful complement.

Integrated assessment models (IAMs) can deliver a synthesis of knowledge across multiple social, economic, and future climate contexts. In a climate context, IAMs link social and economic drivers with Earth system climate models. IAM results are interdisciplinary by nature and can illustrate the potential risks and benefits across multiple simultaneously changing pathways. However, there is limited IAM capacity in Canada.

Nurturing analytical and modelling capacity in Canada is a prerequisite for understanding the inherent trade-offs and synergies in climate policy and regulations. Doing so will support the development of emission mitigation pathways and adaptation priorities that respond to diverse societal, cultural, health, economic, and environmental priorities and values in Canada. Greater collaboration and capacity in academia, government, and Indigenous communities will foster future enhancement and extensions of IAMs that are attuned to Canadian contexts. Areas of priority in IAM development could include damages and feedbacks (e.g., effects of permafrost thaw, impacts on and effects of air pollutants), technological learning and transitions for mitigation options, the costs and benefits of mitigation and adaptation, the integrated inclusion of nature-based climate solutions, and the effects of socio-economic transformations (e.g., circular economy).

As work to decarbonize progresses, advances in economics and social sciences will be needed to inform a just transition. Social science research can help communities plan for new energy futures and navigate any unintended social impacts during the transition. Analyses are needed of alternative employment and economic strategies that are both creative and ambitious enough to address the necessary shifts in the Canadian economy. Specific labour market-related questions include how workers from different sectors will be affected by climate change and Canada's response to it, as well as the gender breakdown of employment in fields designed to mitigate climate change, such as clean energy or sustainable transport. In addition, studies of structural changes are needed to ensure that the burden of this transition does not fall on those who can least afford it, as is work to understand issues of clean energy affordability and reliability. Finally, decarbonization strategies may have implications and unintended consequences (positive or negative) on, for example, human health and well-being. Understanding these impacts, ways to navigate trade-offs, conflict, and resistance, and opportunities to maximize co-benefits and build climate resiliency, will be required.

Advances in socio-technological systems can contribute to sustainability transitions, and energy is one area where this will be key. Decarbonizing the energy supply will play a critical role, and there is a broad need for science related to full lifecycle assessment of clean (e.g., solar, wind, nuclear, water, geothermal, hydrogen, biomass) and fossil energy sources and pathways, energy efficiency, and electrification. Advances in artificial intelligence, big data, non-technical and social barriers, and advanced materials will be essential. In terms of energy efficiency, research is needed to help foster next-generation technologies and infrastructure to improve the efficiency of vehicles and related infrastructure, industrial processes (e.g., via energy management systems), and buildings (e.g., smart appliances, net-zero design, space heating and cooling). It will also be critical to understand the role of carbon capture, utilization, and storage technologies and to develop marketable products out of carbon dioxide to render these technologies economically viable in order to reduce emissions from sources that are more difficult to replace with lower-emitting alternatives.

For electrification, advances in innovative technologies are needed, including smart and distributed energy technologies and systems, integrated technologies for cleaner energy, and clean heat and combined heat and power. Research to develop small modular reactor and energy storage technologies to be applied at the community level will help address the variability of some renewable technologies. Electrifying transportation will require work to develop more advanced zero-emission technology where practical solutions for reducing emissions are not available. Key gaps here include those related to medium- and heavy-duty vehicles, off-road equipment, marine, and rail. Research to address barriers to infrastructure installation, operation, and management will also contribute to electrifying transportation.

The development of cleaner future fuels requires an improved understanding of their full lifecycle impacts, and insight into how existing systems and infrastructure must be adapted to enable their use. Effectively supporting the integrated assessment modelling of potential risks and benefits of future fuels requires science-based lifecycle analyses (LCAs) that accurately establish the emissions of short-lived climate pollutants, criteria air contaminants, and toxics across multiple simultaneously changing renewable and non-renewable fuel pathways. Effective policy development will require that new LCA science provide highly resolved spatial and temporal differentiation of the health and environmental risks and benefits of future renewable and non-renewable fuels across all production and consumption pathways. For instance, the design of future energy systems requires research into resilience, reliability, economic cost, energy security, and land-use minimization, while renewable fuels policies must be informed by research to ensure that biofuel development does not endanger food security. The development and integration of cleaner fuels will require community engagement to foster leadership and ownership of these initiatives.

Science in action: Reducing aviation-related GHG emissions through biofuel blends

A collaborative research project between several partners, including Chevron Lummus, Agrisoma Bioscience, the National Research Council (NRC), and the Green Aviation Research and Development Network, led to the world's first civil jet flight powered by 100% biofuel in 2012. The work to advance sustainable aviation is continuing. For instance, the partners in the Civil Aviation Alternate Fuel Contrail and Emissions Research project gather data to test the environmental benefits of biofuel use in commercial flights. Advanced sensing equipment mounted on an NRC research jet is measuring the impact of biofuel blends on contrail formation from an aircraft in commercial operation. Results of this work have shown that the emissions of a commercial airplane in cruise mode are considerably reduced when using a biofuel blend compared to conventional jet fuel.

From an infrastructure standpoint, the choices made today regarding the construction and management of built infrastructure and natural assets will have long-term consequences for decarbonization in Canada. It is essential to better understand the mitigation potential of infrastructure, as well as the co-benefits of joint mitigation and adaptation action. Accurate, transparent, and trusted LCA tools, methods, and data are needed to support infrastructure decision making and should incorporate future climate projections and resilience considerations. A better understanding of when and where to apply natural and hybrid infrastructure solutions and the ability to quantify potential reductions and co-benefits associated with them is also needed, including a standardized methodology for measuring emissions and embodied carbon in natural and engineered materials and assets. In terms of energy efficiency retrofits, estimates of the capacity to cost-effectively retrofit building stock and heritage sites will be beneficial. The challenges for Canadian heritage buildings and sites are unique for both mitigation and adaptation, and research is needed to provide guidance on retrofitting these sites.

Protecting and enhancing our carbon sinks

Net carbon removals in land and aquatic systems will be an important tool in achieving net-zero emissions. Action on this front will require an improved fundamental understanding of carbon stocks and GHG fluxes and transfers. Special emphasis is required in northern ecosystems, given the complex interactions between the landscape and permafrost systems and the atmosphere-sea ice-ocean system. There is an opportunity here to partner with Indigenous Peoples in the North to build capacity, collect consistent and accurate data, and leverage synergies with Indigenous Knowledge, ensuring Northern participation in research for the North.

Currently about one quarter of the CO_2 entering the atmosphere through human activities is taken up by the oceans. However, there are uncertainties surrounding the capacity of the oceans to absorb carbon in the context of a changing climate that will require further research (e.g., ocean warming, changes in primary production, retreating sea ice). Research is also needed to better understand carbon movement in aquatic systems, as well as between terrestrial and aquatic environments. An integrated framework could enable collaboration and address interactions and linkages across land and aquatic systems (e.g., wetlands, forests, grasslands, croplands, inland and coastal aquatic systems).

Given the asymmetry of risk that exists between the slow natural uptake of carbon and the potential for its fast release in the event of a disturbance, work is needed to better understand and estimate the impacts of climate change and human activity on carbon stocks and GHG fluxes, particularly at a regional scale. There are specific knowledge gaps here related to wetlands, lakes, rivers, permafrost, and northern soils and peatlands. Improving how disturbances (e.g., agricultural drainage, resource extraction) and management actions (e.g., related to forests, silviculture, and soils) are observed, quantified, and modelled will reduce uncertainty with respect to the mitigation potential of these systems.

In examining mitigation strategies, the full environment-economy system should be considered, including net GHG and other climate-forcing impacts across ecosystems and human use of them (e.g., for wood products, food, energy). Additionally, as climate change causes shifts in land suitability, agricultural zones may shift at the expense of forests or wetlands, and work is required to assess the impact of these shifts on carbon and GHG fluxes, and other environmental and socio-economic consequences.

The need for rapid and deep emission reductions means that work to better understand carbon stocks and GHG fluxes must be paired with applied research aimed at understanding and developing regional and local mitigation best practices and actions in the land and aquatic sectors. For instance, this could include the conservation of carbon-rich areas, facilitated through the use of perennial crops in agriculture, macroalgal crops in the ocean, the protection of natural kelp and eelgrass beds, and the creation of protected areas and Indigenous protected and conserved areas. This would also contribute to achieving the goal of protecting 25% of Canada's land and 25% of our oceans by 2025. Decision-makers need research results relevant to their specific land type or aquatic zone, the management options available to them, and the expected impacts and risks. Monitoring the results of management interventions will encourage learning from experience.

Understanding the economic aspects of carbon neutrality

There are still important knowledge gaps related to the economics of mitigation options, including the cost effectiveness of various technologies and practices, and this work will help identify trade-offs associated with different pathways to carbon neutrality. This includes research aimed at developing the social cost of carbon, marginal abatement costs, and measures of technological innovation. Further research and modelling is also needed on the design and impact of carbon pricing instruments, options for revenue recycling, and complementary policies, particularly as they relate to the Canadian context, which should be undertaken with an intersectional lens. Research on the impact these pricing instruments and complementary policies have on competitiveness will also be valuable. In addition, research into the economic valuation of health and environmental co-benefits of mitigation is required, as these can yield large immediate societal benefits and help offset the costs of emissions reductions.

Economic research related to infrastructure is needed on two fronts: (1) measuring the economic value of infrastructure solutions (natural, hybrid, and built) that sequester carbon and (2) measuring the economic value of potential housing stock retrofits in northern and remote contexts, where this work is especially complex. Research here will need to incorporate interdependencies between social, well-being, and reconciliation aspects to ensure equity. In the North, this work could inform immediate decision making to address acute housing needs while making informed short-, medium-, and long-term choices related to low-carbon development pathways.

Finally, there are knowledge gaps to fill related to the financial implications of climate change (e.g., sustainable finance, climate finance, insurance, international markets), including mobilizing private financing for a just transition, incorporating climate risks into financial decisions, and ensuring development aid is consistent with climate goals.

Box 7. Clean technology for climate solutions

Clean technology—any process, product, or service that reduces environmental impacts—is critical for the transition to low-carbon growth in all sectors. The emerging green economy represents a significant economic opportunity. Meeting Canada's emission reduction targets will require developments in net-zero emission technologies (e.g., renewable energy, zero-emission vehicles, smart grids and storage, small modular reactors, carbon capture, storage, and use), as well as broader deployment of existing clean technologies.

Technology can provide alternative approaches for producing the goods and services we rely on in ways that are low-carbon, resilient, and aligned with the principles of a circular economy. However, it is likely that the time required to scale up and deploy new technologies means that their contributions to reducing emissions would take some time, as there are still barriers to implementing these technologies that need to be understood.

Priorities in clean technology research that will contribute to achieving climate goals and that will position Canada as a global leader in clean technology include:

- Developing strategies for the research, development, demonstration, and deployment of clean technology, considering its unique risk profiles and the economic, environmental, social, technical, and non-technical barriers to large-scale deployment in different sectors (e.g., drinking water and wastewater, smart grids, smart modular reactors, nature-based solutions, carbon capture technologies).

- Undertaking analyses to identify Canadian clean technology strengths and opportunities, including in global markets, to prioritize further investment and anchor intellectual property in Canada.
- Developing holistic methodologies to identify non-emitting technologies with multiple applications (e.g., heat and power co-generation, hydrogen production, water desalination), synergies with other technologies (e.g., hybrid energy systems), and co-benefits for other sectors (e.g., health and sanitation, transportation).
- Improving methodologies (top-down and bottom-up) for comprehensive measurement of GHG emissions to identify mitigation opportunities and verify the validity of clean technology claims.
- Understanding the broad range of health, environmental, and social implications of a given technology through prediction tools and integrated analyses in order to understand its unintended and intended consequences (e.g., on air, water, soil quality, biodiversity, land use, health).
- Developing a full lifecycle understanding of the health and environmental impacts of goods and services on energy use, GHG emissions, air and water pollution, site decommissioning, and waste disposal to avoid the selection of lower-cost available technologies that may have longer-term negative impacts.
- Developing methods and good practices for scaling up and deploying new technologies.
- Developing pilot projects to study and demonstrate the potential of low-carbon and non-emitting technologies and systems, hence reducing financial, regulatory, and technical risks and attracting investors.
- Understanding the social, cultural, and psychological barriers to the adoption of existing and new clean or alternative fuel technologies, including potential conflict or resistance stemming from unintended impacts or trade-offs of their implementation.

Resilient terrestrial and aquatic ecosystems

Climate change is threatening Canada's landscapes and seascapes, the valuable ecosystem goods and services they provide, and the spiritual, cultural, and traditional significance they hold. Already species ranges are shifting, predator-prey relationships and seasonal patterns are changing, and new pests—including insects, pathogens, and invasive species—are emerging. A warming ocean is becoming more acidic and losing oxygen, resulting in multiple stressors for marine ecosystems, and coastal ecosystems are facing additional threats from sea-level rise and erosion.

Healthy, thriving, and resilient ecosystems have an essential role to play in addressing climate change. They provide a buffer against flood and drought, cool cities, sequester carbon, provide food and materials for communities, and contribute to the health and well-being of Canadians, in addition to providing many other climate- and non-climate-related ecosystem services. The research needed to ensure that Canada's ecosystem resilience is restored, maintained, and enhanced will be based on a foundational understanding of how climate change is impacting and will impact Canada's biodiversity and ecosystems. It will also need to explore ways we can help Canada's species and ecosystems adapt to the challenges of climate change and the ways that nature can help us build resilience, including by exploring and drawing on the synergies between western science and Indigenous stewardship in maintaining resilient ecosystems.

Understanding how climate change will impact biodiversity and ecosystems

Understanding how climate change is impacting and will continue to impact Canada's terrestrial, freshwater, sea-ice, and marine ecosystems and ecosystem services will set the stage for subsequent research and action. There is a need to better understand the impacts of climate change on the various components of aquatic and terrestrial systems, as well as the biophysical and biogeochemical processes that underpin the functioning of healthy ecosystems (e.g., nutrient cycling; vegetation dynamics; aquifer recharge; water storage and movement; ocean-ice-atmosphere, ocean-land-seafloor, surface water-groundwater interactions).

In addition, a more robust understanding of ecosystem and species sensitivity, resilience, and adaptive capacity is needed at all levels of biological organization (e.g., gene, species, population, community). This must include a better understanding of how climate change will affect species' life histories, ecosystem composition and function, and the interactions among species and between species and their environments. The co-application of Indigenous Knowledge and science, as well as a variety of tools and approaches (e.g., genomics, environmental DNA, trait-based approaches, on-the-land observations), will be important in advancing this work.

Science in action: Collaboration and capacity building through the Inuit Field Training Program

Canada's Arctic is warming faster than the rest of Canada. Carrying out research in this vast region is a challenge, and Inuit—who are experiencing firsthand the impacts of climate change—have a crucial role to play in the future of climate monitoring and research. Environment and Climate Change Canada's Inuit Field Training Program introduces Inuit youth to the skills and techniques required to work in a northern research camp. Delivered in collaboration with Inuit communities, and with training delivered by a team of Inuit mentors and scientists, this hands-on experience is designed to build confidence and enthusiasm, and act as a stepping stone towards further training or employment opportunities in environmental research or monitoring. The program builds capacity, so that Inuit can play a leading role in the future of Arctic climate change research.

Even if species and ecosystems are resilient enough to adapt to one aspect of a changing climate, the cumulative impacts from a wide range of other stressors could override this resilience. Thus there is a need to develop a better understanding of changing stressors and their influence on species and ecosystem response. This includes how climate-related stressors (e.g., temperature, precipitation, ocean acidification, hypoxia, extreme events) are changing, how natural and anthropogenic non-climate stressors are changing as a result of climate change and other factors (e.g., algal blooms, emerging pests, contaminants, shifts in land cover/use, resource use), and the cumulative effect these stressors have on the adaptive capacity of species and ecosystems. Arctic ecosystems are particularly vulnerable and warrant a specific research focus in collaboration with Indigenous partners.

Helping species and ecosystems adapt to a changing climate

Proactive adaptation measures are required to minimize threats to vulnerable species and ecosystems. These measures will require improved predictions and projections of impacts and responses, including an improved ability to forecast emerging and novel ecosystems, sensitivity, resilience, and adaptive capacity, as well as changes in key relationships (e.g., predator-prey, plant-pest, physical-biological). Models are important assets in this endeavour. Work is needed to better integrate physical, ecological, biogeochemical, and social processes into models. In addition, it will be useful to better understand when, where, and for which species and ecosystems different kinds of models can be used. It will be important to understand how results from these various approaches align or differ, and how multiple sources of uncertainty affect outcomes and, by extension, action.

There are also research needs related to developing and testing adaptation measures and identifying barriers (e.g., behavioural, economic, regulatory) to the proactive implementation of these measures. This includes work on pest management, assisted migration, conservation of genetic diversity, habitat restoration, and species protection and recovery, as well as the design and use of a variety of landscapes and seascapes—from human-modified systems to protected areas—to promote adaptation, ensure connectivity, and provide refugia. Decision-makers will benefit from work aimed at testing and improving existing prioritization tools and developing new ones where needed. Multiple lines of evidence will be needed to advance this work, including predictive modelling and laboratory and field experiments. Field-based landscape- and seascape-level studies will be important in assessing the effectiveness of and full ecosystem response to these interventions, and identifying possible unintended consequences.

Working with nature to advance climate action

Nature-based solutions (NbS) and related terms (e.g., natural infrastructure) are actions that protect, enhance, manage, and restore ecosystems while simultaneously addressing environmental, social, and economic needs and challenges. NbS can potentially play a role in addressing the interrelated challenges of climate change and biodiversity loss, while also providing a range of other co-benefits (e.g., for human health). In a climate change context, NbS can be used to increase carbon storage and/or build resilience, and could include, for example, planting trees in degraded habitats, urban areas, and agricultural landscapes, implementing appropriate agriculture practices, adjusting forest management practices, and restoring wetland, grassland, macroalgal, and eelgrass ecosystems. Expanding terrestrial and marine protected area networks also contributes to NbS, in addition to helping improve the adaptive capacity of species, ecosystems, and landscapes (e.g., by providing climate refugia, landscape connectivity), though must be done in a way that protects Indigenous rights and is integrated with work on Indigenous protected and conserved areas.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services *Global Assessment of Biodiversity and Ecosystem Services* identifies climate change as one of five principal drivers of biodiversity loss. The report also anticipates that its effects are likely to become more significant as climate change accelerates and interacts with and amplifies other drivers of change. This can result in unexpected non-linear change, with possible irreversible impacts on biodiversity and the benefits nature provides to people and to society. One of the report's key messages is the need to address biodiversity loss and climate change simultaneously, identifying synergies and acknowledging trade-offs. Climate change interventions can pose risks to or have negative impacts on nature, and there is a need to study and consider the potential impact of climate change interventions on biodiversity and ecosystems. This includes NbS to climate change, which have the potential to both support nature and biodiversity and harm biodiversity and ecosystem function. Given that not all NbS have conservation value, research to evaluate the effectiveness of NbS approaches for conservation priorities (e.g., addressing biodiversity loss) is an important knowledge need. There is also a need to better understand the climate change mitigation values of ecosystems. Developing, testing, monitoring, and evaluating NbS solutions will help understand the trade-offs and opportunities to maximize co-benefits.

Work to address knowledge gaps related to resilient ecosystems, land and aquatic management practices, the carbon cycle, and carbon sinks will benefit the understanding and application of NbS; however, there are some research needs specific to these interventions, both generally and in the context of a changing climate. These include better understanding and quantifying the potential of these actions to impact radiative forcing, reduce/avoid emissions, and build resilience, avoiding unexpected negative effects (e.g., increasing the spread of pests or exposure to infectious disease risks, including the introduction of invasive species or habitat for infectious disease pathogens and vectors), and generally understanding how and where to deploy them in the most effective way. It will also be important to develop a deeper understanding of how climate extremes and extreme events will influence NbS. Given the potential of wetlands, grasslands, forests, and macroalgal/eelgrass beds as a nature-based solution, work will be required to identify and address knowledge gaps related to the impacts that climate change will have on them.

NbS and natural infrastructure can provide a wide range of benefits when deployed alone or in tandem with traditional built infrastructure. Developing a greater understanding of these benefits and a standardized way to measure their economic value will be helpful, and should take into consideration the costs associated with their initial construction and ongoing maintenance. In a similar vein, research on payments for ecosystem services and natural assets management may benefit the implementation of NbS. There are specific knowledge needs related to valuing these goods and services (economically, socially, culturally), navigating the environmental and economic trade-offs inherent in managing an ecosystem for a particular good or service, and eliminating barriers and concerns related to accounting and financing.

Finally, while interest in these approaches has been growing, implementation has been slow and relatively small scale. Interdisciplinary research that integrates different knowledge systems to understand and minimize the barriers to implementation would be beneficial, particularly given that Indigenous Peoples have been practicing NbS since time immemorial. Efforts to include land managers (e.g., agricultural producers) in NbS research would also be of value, particularly in connecting knowledge to action.

Box 8. Informing urgent action on climate change and biodiversity loss

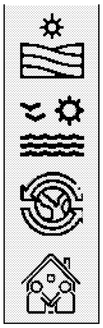
Biodiversity is declining at a rate unprecedented in human history, and climate change and biodiversity loss are twin threats. It is becoming increasingly urgent to address them both, particularly in areas where these two crises intersect. Nature plays a critical role in regulating the climate. The impacts of climate change on biodiversity and ecosystem services are expected to accelerate, and the loss of nature and natural carbon sinks further contributes to climate change. Climate change poses a threat to some species, and could exacerbate the decline of populations already at risk. In working to address the biodiversity and climate crises, deepening our understanding of the impacts of climate change on biodiversity is essential. This will help us identify which species and ecosystems are most vulnerable and where, develop more accurate predictions of the impacts they could face, and understand how healthy and resilient ecosystems can buffer these impacts on biodiversity and ecosystem services. Understanding the full complexity of impacts is necessary. For instance, one knowledge gap that is often overlooked is the effect of human responses to climate change, and how these may have cascading effects on species, ecosystems, and ecosystem services.

A deeper understanding of impacts is essential in identifying effective and efficient climate-smart conservation and adaptation strategies, especially ones that integrate a dynamic view of climate change and the variability of its effects over space and time at both the ecosystem and species levels. Protected area networks are a cornerstone conservation strategy and are increasingly important in a changing climate. There are important knowledge gaps related to protected and conserved areas, including understanding their long-term viability in a changing climate, as well as the gaps in the current network in order to provide refugia and corridors. While many research needs remain, delaying conservation and management action can accelerate loss. Adaptive management can provide a way to iteratively learn by doing, advancing knowledge while protecting Canada's biodiversity and upholding our international obligations related to conservation (e.g., under the Convention on Biological Diversity, the Ramsar Convention, and the North American Bird Conservation Initiative).

Sustainable natural resources

Ensuring Canada's natural resource sectors remain resilient and productive in the face of climate change is a key factor in Canada's continued prosperity, and research to inform climate-smart, sustainable practices is needed. The agricultural, forestry, fisheries, aquaculture, water management, mining, and energy sectors are already facing threats from climate change, including extreme events, existing and emerging pests, shifting water availability and quality, and ocean acidification, among others. Building resilience across many of the natural resource sectors will rely on work to ensure the resilience of Canada's ecosystems. Overall, resilient natural resource sectors will benefit from a deeper understanding of the place-based risks they face, as well as a more integrated understanding of how to advance multiple natural resource and land/aquatic-use goals. Applied research to inform on-the-ground action will also be necessary to help ensure action is evidence-based, efficient, and effective.

Understanding risks to natural resource sectors



A better understanding of and ability to predict changes and risks to natural resource sectors will help ensure that they remain competitive in a changing climate and are positioned to contribute to mitigation and adaptation efforts. In addition, new and innovative tools to assess the threats facing resource systems are needed.

Improving information about the frequency, potential severity, and location of extreme events will help resource sectors manage their operations to reduce the effects of these events and build resilience into their operations. In all sectors, short-term/seasonal predictions of extremes are required, as is longer-term modelling to predict changes and risks.

There is also a need to better understand how multiple stressors and compound conditions affect natural resource sectors (e.g., combinations of temperature, soil quality, pest and disease viability on land, or combinations of acidification, increased temperature, and deoxygenation in the ocean). For fisheries and aquaculture, an improved understanding of ecosystems and fishery responses to extremes is needed. More broadly, a better understanding of the climatological sensitivity of pests, disease, and invasive species that affect crop, forest, and fishery health will be beneficial. Additionally, science-based information about current and future freshwater availability will inform the development of protection targets for freshwater areas.

A large number of communities were settled and developed around the operations of natural resource sectors and are vulnerable to the impacts of climate change, and research is needed on decommissioning and cleaning up infrastructure from these industries as these communities transition. Social science can play a strong role in helping envision, plan, and implement community transformation. It can also help to better understand the long-term local impacts of economic transformation and transition and the corresponding social and cultural issues and changes.

Box 9. Ensuring food and water security and safety for Canadians

Climate-related disruptions in food and water systems impact human health and well-being by diminishing food and water security. These disruptions include direct impacts (e.g., drought, pests, shifting species distributions, marine heatwaves, ocean acidification), impacts on food transportation and storage, and indirect impacts, such as shifts in job opportunities and cost of living increases (including food costs). Lack of access to safe drinking water and disruptions to the food system will disproportionately affect marginalized and vulnerable communities, as well as those who depend on the land and oceans. They also make eliminating hunger and poverty and preventing certain diseases—among other sustainable development objectives—more difficult.

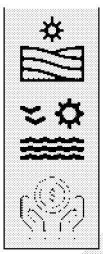
There are many knowledge gaps related to sustaining a robust, nutritious, and accessible food supply for all Canadians, from production (agriculture, fisheries, aquaculture, country foods) and imports to harvesting, processing, and distribution. These gaps include:

- the food system components most vulnerable to climate change (slow-onset change and extremes);

- ecosystem capacity to sustain biodiversity, freshwater supplies (surface and groundwater), and soil health;
- use of land and water for food and non-food production (e.g., renewable energy, carbon sequestration, conservation of biodiversity and ecosystem services);
- strategies to ensure sufficient staples can be produced for and delivered to all Canadians;
- the risk of food- and water-borne disease;
- climate risks and pressures to Indigenous Peoples and coastal, remote, and Northern communities;
- climate vulnerabilities of country and market food systems;
- the potential for economic transition to exacerbate existing food insecurity among vulnerable populations and regions; and
- behavioural insights to inform sustainability in dietary choices.

Advancing knowledge in these areas is limited by a lack of demographic and socio-economic data and monitoring, particularly in formats that allow interoperability with ecological and environmental data. Expanded surveillance of food security-related indicators is necessary to understand the complex relationships among the factors noted above and to develop quantitative projections of food and water availability and quality.

Advancing an integrated understanding and valuation of natural resources



Given the importance of advancing climate actions that maximize co-benefits, it is important to develop an integrated understanding of natural resource and land/water goals and opportunities. This work will support integrated planning and management, and will benefit from research to develop effective and inclusive governance structures for decision making in the context of a changing climate.

Fundamental work related to water resources management, land-/aquatic-use planning (including ecological restoration in areas disturbed by industrial activity), traditional food security, resource sector productivity and profitability, carbon sequestration, and ecosystem carrying capacity will be key to developing an integrated understanding. Specific areas of integrated understanding to explore could include:

- ensuring food, water, and energy security while also considering cultural practices, human health, carbon sequestration, and climate resilience;
- advancing clean energy production (e.g., bioenergy, hydroelectricity, solar, wind, nuclear, hydrogen, geothermics) in ways that also advance food and fibre production, carbon sequestration, and Indigenous self-determination in resource production;
- managing forest, agriculture, fisheries, and aquaculture systems in the context of climate-induced geographic shifts, while minimizing development pressures and protecting biodiversity; and
- conserving terrestrial and aquatic areas and biodiversity while advancing NbS and protecting ecocultural landscapes and seascapes.

Research related to the valuation of natural resources and land use is required, from both an economic and a more holistic perspective. Enhanced economic and societal analyses of climate change impacts on natural resource sectors, particularly for food and fibre, are needed from local to global scales. In addition, research is required into how the socio-economic value of land and aquatic systems is determined and how this influences land/aquatic-use choices for natural resource sectors, energy production, ecosystem conservation, and urban/industrial development.

Beyond this, it will be important to develop an integrated understanding of the economic, social, environmental, health, cultural, and place-based value of land and aquatic systems to inform the integration of multiple uses that respect the broad range of benefits and impacts. For instance, the lands and oceans used by Indigenous and Northern communities for harvesting, hunting, and gathering traditional foods and medicines for subsistence and cultural revitalization hold greater overall value as climate change exacerbates already-high rates of food insecurity in these communities. Other examples of the diverse values of multiple land/aquatic uses include the joint consideration of adaptation and mitigation in natural resource sectors, the development of renewable energy systems, the study of the potential for carbon sequestration and geothermal energy, and the resilience of natural ecosystems.

Enabling climate action in Canada's natural resource sectors

Effective climate mitigation and adaptation in natural resource sectors requires regionally- and locally-relevant technical information to inform risk assessments, ensure continued productivity, and enable any necessary transitions in response to the implementation of climate action. This includes research to inform the development of resilient, climate-smart / low-GHG practices (e.g., clean energy technologies), and assess their costs and benefits, as well as research to inform sector resilience to variability and extremes. Knowledge mobilization efforts, along with monitoring, measurement, and evaluation of the measures put in place, will be important. In addition, improved monitoring—for instance, for soil conservation, fresh water availability, enhanced carbon storage, ocean acidification and deoxygenation—and access to telemetry in regions where access is difficult will also be of value.

For the oceans, fisheries, and aquaculture sectors, there is a need for blue-carbon technology and actions to address ocean acidification and deoxygenation, as well as research on science-based decision tools that can detect climate impacts (and related uncertainty) for resources and their management. There is also a need for greater understanding and assessment of cumulative impacts of multiple stressors (e.g., temperature, pH, oxygen). Work to better reflect changes in aquatic ecosystem/resource services, activities, and human well-being in the prioritization of actions aimed at increasing the sustainability of aquatic systems in the context of a changing climate is also needed.

In agriculture, there is a need for continued research into regionally appropriate resilient crops and livestock that can withstand seasonal variability and extreme weather events. There is also a need to continue developing and incentivizing low-emission-intensity crops and accelerating the adoption of climate-smart management practices that increase carbon sequestration, reduce GHG emissions, and contribute to on-farm resilience (e.g., natural infrastructure like wetlands and agroforestry, integrated cropping systems, precision application of nutrients). The participation and active involvement of agricultural producers in this research will ultimately benefit its uptake. Improved definition and monitoring of soil health will be essential in advancing soil conservation, restoration, and enhanced carbon storage, and facilitating access to new or expanding agricultural regions.

For forestry, research is required to develop management practices that increase resilience, community safety and well-being, economic opportunity, and carbon sequestration, taking into account both forest management and how wood is used. This should extend to an examination of forest policy and opportunities to harmonize with other sector-based policies in order to enable more effective and coordinated climate action. There is also a need to understand forest management decisions for a range of future climate conditions, including management options that could support both mitigation and adaptation (e.g., Indigenous traditional forest management practices) in the context of increasing wildfire risk.

In the energy sector, research is needed into the social, political, economic, and technological factors that would raise the environmental performance of the oil and gas sector. This includes, for example, understanding how to accelerate and facilitate the use of non-emitting technologies (e.g., small modular reactors, hydrogen-powered trucks, electric vehicles) in resource extraction operations. There is also a need for additional work to demonstrate and deploy emerging renewable energy technologies (e.g., tidal, geothermal), and inform the resilience of energy-related natural resource operations (e.g., freshwater availability and hydropower; extreme events and energy security, accessibility, and infrastructure).

With respect to the mining industry, there are several adaptation research and development gaps related to assessing and reducing risks surrounding mine waste management (e.g., sulphide oxidation, tailings management, the effect of permafrost thaw on impoundment structures). Research on waste management reclamation in a changing climate would support this work. There is also a need to assess and reduce risks associated with water/effluent management and changes in the water balance. In addition, research on ecosystem risk, including species diversity and tolerance to mining impacts in the context of a changing climate, is required. Finally, an assessment of the impact of seasonal variability and extreme weather events will help understand and address climate change-related mining infrastructure risks.

Science in action: Using cattle diets to reduce emissions

Cattle in Canada can contribute up to 25 million tonnes of CO_2 equivalent annually from the methane generated during digestion. Researchers from Agriculture and Agri-Food Canada and Australia collaborated to find the best feeding practices for addressing this problem, and evaluate them for their efficiency, safety, and long-term sustainability, as well as the potential synergies between them. They found that feeding cows a rapidly digested starch like wheat has been shown to reduce methane emissions by up to 50% compared with slowly digested starches (e.g., corn, barley). They also examined an experimental feed additive that blocks methane formation in the cow's stomach (shown to lower methane emissions by up to 60%) and a nitrate product that provides an alternative pathway to the formation of methane (shown to reduce methane by up to 20%). By working to address one mitigation challenge, this research is helping develop options for producers that are practical and cost-effective for a range of market conditions, farm management practices, and types of cattle.

Box 10. Arctic and Northern considerations

The Arctic and North's[6] climate and environment are changing more rapidly and unpredictably than anywhere else on Earth. The region is warming at about three times the global rate, and the widespread and wide-ranging environmental impacts of this warming will continue. In addition, the Arctic Ocean suffers from the highest rate of acidification on the planet. The region's unique and culturally significant environments and species are disproportionately vulnerable to anthropogenic and natural stressors. Changes in wildlife behaviour and habitat use pose a threat to the viability of traditional subsistence activities, health and well-being, and cultural practices, while impacts to physical infrastructure jeopardize community safety, security, and resilience. The Arctic and North are critical to Canada's sovereignty and natural resource potential, and interest in the region is intensifying as the loss of sea ice makes the region more accessible to economic growth, resource extraction, and transportation.

Climate change knowledge creation, synthesis, and mobilization in the Arctic and North should be centred on meaningful and respectful collaboration, working with Arctic and Northern stakeholders, rights holders, and decision-makers and moving towards increased agency, self-determination, and leadership of Indigenous Peoples. There are foundational documents, such as the *National Inuit Climate Change Strategy* and the *National Inuit Strategy on Research*, that can guide this meaningful and respectful collaboration. *Canada's Arctic and Northern Policy Framework* also provides a co-developed roadmap for collaboratively achieving progress on a range of priorities, including science, knowledge, and research that are meaningful for communities.

Conducting climate change research in the region can be logistically challenging and costly, and it requires a large and varied inventory of infrastructure. There is a need to work in partnership to maintain, enhance, and augment monitoring networks in key areas to ensure adequate regional coverage, especially in more remote and sensitive areas, including those of value to Indigenous Peoples or with high potential for resource development. This physical monitoring infrastructure must be complemented by enhanced capacity for community-based monitoring, as well as digital infrastructure and data and knowledge management approaches that are appropriate for the region and its communities in order to effectively share relevant data between Arctic and Northern stakeholders and rights holders.

It is essential to fill data gaps and to develop a more complete baseline understanding of the biophysical environment and how it may change over time. The protected area network of the Canadian Arctic and North can provide excellent locations and logistical support for benchmark monitoring for global ecosystem change. Improved data collection using consistent methods (e.g., *in situ*, space-based Earth observation) and involving Indigenous Knowledge holders is key in building a better understanding of priority areas and climate-sensitive ecosystem components of cultural, traditional, conservation, and commercial value.

Benchmark and trend data will contribute to a better understanding of the state of Arctic and Northern ecosystems, how they will change, and their adaptive capacity, which are all crucial for identifying tipping points and assessing their potential impacts. This data, as well as the integration of existing datasets and their interpretation, is critical for contextualizing, understanding, and improving the prediction of the impacts of climate change across the breadth and complexity of the Arctic and Northern environment. Enhanced datasets can support research aimed at developing solutions to increase food, water, and energy security in the region, including through the provision of clean and renewable energy.

[6] While there are numerous definitions of Arctic and North, this document adopts the one used in Canada's Arctic and Northern Policy Framework, which "includes the entirety of Inuit Nunangat—the Inuvialuit Settlement Region in the Northwest Territories, Labrador's Nunatsiavut region, the territory of Nunavik in Quebec, and Nunavut—the Inuit homeland in Canada."

FOUNDATIONAL CAPACITY

Addressing the gaps and priorities outlined above will require a solid foundation of monitoring and digital infrastructure, as well as a strong commitment to making all stages of the climate change research process more open and accessible, while respecting Indigenous data sovereignty and ownership of Indigenous Knowledge. Strengthening this foundation will be key in supporting Canada's contribution to, and leveraging of, international climate change science. Enhanced coordination among partners, networks, and programs will be critical, as will sustained efforts to attract and train the highly qualified personnel needed to undertake all aspects of climate change research.

Monitoring and observations

As the climate changes, ongoing integrated monitoring and surveillance systems will be key assets in providing situational awareness (e.g., in the context of extreme events), assessing change, informing action, and measuring progress. They will also help identify unanticipated responses to climate change (e.g., disorderly socio-economic responses) and to climate action (e.g., broad-scale implementation of NbS).

Additional effort and investment is needed to maintain and strategically fill spatial and temporal gaps monitoring networks across all atmospheric, terrestrial, freshwater, and marine systems, deploy novel and innovative approaches, integrate socio-economic indicators, adopt standardized monitoring and reporting protocols, and integrate datasets from multiple sources and disciplines. Satellite technology is progressing rapidly, enabling improved surveillance, especially in the high Arctic region.

Increasing collaboration with Indigenous communities and organizations in monitoring projects will improve the quality and quantity of data collected, especially given the critical and unique nature of the knowledge held by Indigenous Peoples regarding their local environment and climate change impacts. Community-based science activities can also provide surveillance data while increasing education, awareness, and engagement to empower individuals in acting on climate change.

Canadian monitoring reflects, for the most part, the international guidance and data quality objectives identified for Essential Climate Variables. Future monitoring should build on and strengthen existing efforts, partnerships, programs, and infrastructure (e.g., research vessels, multi-disciplinary monitoring sites, buoy networks, satellite observing systems) and draw on a range of surveillance and monitoring designs, including community science. Critical considerations for sustaining and strengthening monitoring and observations include:

- Enhanced monitoring (spatially and temporally) to capture benchmark conditions and to improve projected trends, impacts, and extremes in climate, cryosphere, marine, freshwater, terrestrial, and landscape variables, particularly in the Arctic and North.
- Adequate and high-quality observations of extreme precipitation, solid precipitation (snow, ice), soil moisture, evapotranspiration, surface and groundwater levels, and other variables related to understanding freshwater availability, flood, and drought.

- Sustained monitoring of ocean physics (e.g., marine heatwaves), chemistry, and biology, with increased effort in the Arctic and North and in nearshore zones.
- Freshwater monitoring of rivers and lakes for water quality, distribution, and availability, as well as groundwater quality and quantity.
- A national, long-term, holistic network to collect consistent and interoperable data across a range of disciplines, scales, ecosystems, and environmental gradients using both professional and community science.
- Monitoring of biodiversity and ecosystem integrity to inform conservation and valuation of ecosystem services, and to improve understanding of the impact and possible unintended consequences of NbS.
- *In situ* and remote sensing-based measurement networks to quantify climate change impacts on land and aquatic systems and validate carbon stocks, stock change, and GHG flux estimates.
- A national, long-term vision for space-based Earth observation systems and access to international and commercial datasets to populate a central hub of satellite data.
- Novel, integrated, and multi-disciplinary surveillance systems for emerging zoonotic, food-borne, and water-borne diseases and plant pests, particularly in the health, forestry, aquaculture, fisheries, and agricultural sectors.
- Sector- and community-level monitoring that brings together socio-economic, infrastructure, health, and environmental monitoring activities, including monitoring of the effectiveness of adaptation measures and differential impacts and outcomes for various populations (e.g., urban/rural, seniors, women, children, Indigenous Peoples).
- Building capacity for sustained monitoring networks at various scales, including building Indigenous leadership in monitoring while supporting Indigenous self-determination in research.
- Adoption of new technologies, such as space-based monitoring, drones, and low- or medium-precision / lower-cost *in situ* sensors where they can be integrated in the long-established and international networks to maintain and complement multi-decadal records.

Box 11. The role of space-based Earth observation for climate knowledge

Canada's vast geography makes collecting national environmental intelligence a challenge. Our dynamic environment requires systematic monitoring, but it is not feasible to do so entirely from the ground. Satellites are an efficient and effective observational tool and have become a cornerstone of multiple services to Canadians (e.g., weather forecasting, agricultural monitoring, ice mapping, atmospheric and ocean monitoring, disaster response). Satellite data, combined with data from the ground, helps Canadians deal with the impacts of climate change on a daily basis, from crop forecasting tools for agricultural producers to web applications for information on ice location for northern communities.

The space-based Earth observation (SBEO) landscape is evolving, with a focus on open data, international collaboration, and long-term visioning to address key climate challenges, and Canada's

SBEO capabilities must keep pace. Advances in SBEO technology can provide faster, more accurate, and cost-effective ways to address Canada's climate challenges. A sustained, long-term vision for data acquisition and distribution from national, international, and commercial satellites is vital to the future of Canadian climate knowledge.

Digital infrastructure

The magnitude and diversity of climate change data and knowledge requires unprecedented advances and capacity in data storage and management, high-performance computing, and methods and algorithms. Sharing, re-use, and integration of data are currently limited by the fact that data is managed according to discipline and producer/custodian. There is a critical need to implement data and computing systems, standards, and analytical tools that enable the integration of and common access to climate, ocean, ecological, environmental, social, health, and economic data. This digital infrastructure is an intrinsic part of monitoring, analysis, and modelling efforts, and should include tools for data management, extraction, manipulation, visualization, standardization, and interoperability. Artificial intelligence could play an important role in helping identify trends and relationships in large complex datasets, in forecasting, and in optimizing solutions. As digital infrastructure advances, a deeper understanding of jurisdictional and environmental (e.g., energy consumption) issues related to cloud-based high-performance computing, large data storage, and computational/data facilities will be required. Access to affordable and reliable high-speed internet will also enable broader participation in research activities that rely on this digital infrastructure.

Targeted effort, complemented by local/regional capacity building, is needed in the following areas:

- Dedicated data centres to facilitate access to and integration of data.
- Digital infrastructure, platforms, and tools for Indigenous Peoples to manage their knowledge and data and contribute to Indigenous research capacity, data sovereignty, and self-determination in research.
- Enhanced participation in the development of data standards and governance to support interoperability, facilitate sharing across domains and jurisdictions, and enable access to international data.
- High-performance computing environments to better use and augment observations through synthetic observations, re-analysis methods, data assimilation, and Earth system and numerical modelling.
- Methodologies and protocols for addressing privacy concerns related to socio-economic, health, and demographic data to enhance its use in metrics and indices for impacts and evaluating action.
- Enhanced capacity for the submission of open data from Canadian sources to international data centres and vice versa.

Open science

Ensuring that climate change science is open and accessible at each stage of the research process is crucial for advancing the evidence base needed for ambitious action. Open climate change science and knowledge will increase transparency, maximize investments, accelerate progress, and lead to new and unexpected insights. It can also connect decision-makers with the information they need and, more generally, improve science literacy. Canada's Chief Science Advisor 's *Roadmap for Open Science* provides a series of recommendations and overarching principles to guide open science activities in Canada, which could be helpful in advancing the openness of climate change science and knowledge.

Open science principles can be applied from the outset of the research process. Being open when identifying research questions—for example, through community engagement, open proposals, and innovation challenges—can enhance collaboration and integrate multiple ways of knowing. It can also bring knowledge users and communities implicated by the research into the process early on to ensure the research aligns with their needs, and to increase their understanding of potential climate change solutions that emerge from the research.

When data is open, it is easier to access, re-use, and integrate. While there is no one-size-fits-all solution to open data, making data FAIR (Findable, Accessible, Interoperable, and Reusable) is one established best practice. Ensuring that data is fit for use by unanticipated users for novel purposes will accelerate climate change science across disciplines. FAIR data can also be seamlessly incorporated into big data workflows or used as input to artificial intelligence. However, despite the benefits of making data open, not all data should be open by default.

Open climate change science and knowledge should respect Indigenous Peoples' sovereignty of the data, information, knowledge, and traditional cultural expressions of their communities. Indigenous communities and knowledge holders own their knowledge and information, and their consent and validation should be obtained for its collection, use, application, or interpretation in open science, including through formal agreements. These agreements could be specific to data and should respect the rights, self-determination, self-governance, and data sovereignty of Indigenous Peoples as they relate to their data and knowledge (e.g., the OCAP® principles).

As a general practice, researchers and data users should clearly identify whose knowledge is being opened by whom, and for whose benefit and/or risk. If data is managed with respect for privacy and data sovereignty, openness can contribute to the democratization of knowledge and a restructuring of institutionalized power structures and values.

Continued effort is needed to bring climate change-related publications out from behind paywalls, as this is an integral part of making climate change science and knowledge more accessible and usable by both researchers and practitioners. This can be accomplished by publishing in open access journals, archiving a copy in a repository after embargo periods have elapsed, or publishing a preprint on public archive systems to make results available more quickly. In addition, research outcomes should be communicated to decision-makers and implicated communities in a clear and accessible manner.

MOVING FORWARD

Science and knowledge are essential in guiding the development and implementation of climate policy and actions to limit warming and future risk. By providing a common and transparent foundation for evidence-based action, science and knowledge can contribute to depolarizing the public discourse around climate action. In order to accelerate the transformational changes necessary to build a resilient, net-zero Canada, both climate change research and action must move quickly towards more holistic approaches that integrate mitigation, adaptation, and sustainable development.

Each community, discipline, and sector has its own particular expertise and perspective to bring to the table in order to work together to solve the climate change challenge. CS2050 profiles a broad spectrum of work, and recognizes that much of it must proceed in parallel. The urgency of the challenge means that decision-makers should not and cannot wait for all the science to be in before taking action. As such, knowledge synthesis efforts must also occur while research continues to unfold, ensuring that decision-makers can integrate the latest results and insights into their ongoing efforts.

While the focus of climate change science efforts has traditionally been on the natural and health sciences, there is a pressing need to support and integrate the social sciences, as these will be essential in motivating the human behaviours that are ultimately at the heart of taking swift, ambitious action on climate change.

Given the broad impact of climate change across all regions, sectors, and communities, decision-makers must navigate multiple knowledge gaps simultaneously. This is particularly clear when it comes to highly interdisciplinary areas of work, such as:

- understanding and predicting the national, regional, and local impacts of climate extremes and extreme events across economic sectors and communities, which will inform disaster risk reduction responses, economic and non-economic valuation of climate impacts, energy security, resilient infrastructure, and community-level health and socio-economic risk reduction;
- increasing the understanding, monitoring, and forecasting of climate change impacts on the health of Canadians and health systems, including maximizing the health co-benefits of climate actions in other sectors, as well as integrating environmental, human, animal health, and socio-economic information;
- developing and understanding the socio-economic and climate implications of Canadian pathways to net-zero, as this work requires an integrated understanding of climate behaviour, carbon sinks (including feedbacks), NbS, alternative energy pathways, economic transitions for emissions-intensive sectors, and community-level implications;
- improving the economic valuation of the costs, benefits, avoided costs, and externalities associated with climate action and ecological services, which includes developing methodologies for and applying various global emission pathways or climate scenarios, as well as options for Canadian pathways that integrate the full range of science and knowledge;

- enabling and accelerating a just transition, recognizing and exploring implementation challenges and developing effective climate change communications that empower action and enable constructive engagement opportunities; and
- applying our understanding of climate change to advancing sustainable development, as the intersection of climate change and sustainable development research objectives has the potential to identify multiple benefits and advance implementation for each.

Science infrastructure is a critical enabler for advancing climate change science and knowledge. There is already a solid foundation of infrastructure on which to build. Going forward, it will be necessary to not only maintain this capacity, but also strengthen and diversify it in a way that fully addresses the complexities of the climate emergency and that expands efforts into areas where little work has been done so far. The respectful and meaningful inclusion of information from all knowledge systems, and a committment to collaborative approaches, will be crucial.

CS2050 represents an opportunity to make deliberate decisions about climate change science and knowledge funding and activities where Canadian climate change research can make a difference and can develop knowledge specific to the Canadian context. As Canadians continue mobilizing to build a resilient, carbon-neutral society, science and knowledge will be pivotal in guiding the way.

ANNEX 1 – THE STATE OF CLIMATE SCIENCE

Warming of the Earth's climate, and Canada's climate, is unequivocal and is being driven primarily by global emissions of carbon dioxide from human activity. Some additional warming is inevitable; therefore, adaptation is imperative to build climate resilience among communities and ecosystems in Canada. Global efforts to mitigate emissions will determine how much future warming occurs globally, and in Canada.

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels. Parties to the Paris Agreement have committed to limiting global warming to well below 2°C above pre-industrial levels recognizing that this would significantly reduce the risks and impacts of climate change in all regions. Both past and future warming in Canada is about double the magnitude of global warming. Northern Canada has warmed and will continue to warm at more than double the global rate.

To stabilize global temperature at any level, global carbon emissions from human activity must become net zero (that is, remaining emissions must be offset by withdrawals of carbon from the atmosphere). In other words, to stabilize temperature at any level there is a total amount of carbon dioxide (CO_2) that can be emitted; this is referred to as a carbon emissions budget. To stabilize global temperature at well below 2°C above pre-industrial levels, global carbon emissions must become net zero early in the second half of the century. If global emissions exceed the carbon emissions budget for limiting global warming to well below 2°C, then net negative global carbon emissions will be required later in the second half of the century. Deep emission reductions in non-CO_2 emissions affecting climate are also required. The scale of mitigation required to meet the Paris Agreement global temperature target is understood to be extremely challenging, requiring major transitions in all aspects of society.

To realize the Paris Agreement global temperature goal, Canada and all countries need to shift towards carbon neutrality within a few decades. Canada's National Greenhouse Gas Inventory is prepared and submitted annually to the United Nations Framework Convention on Climate Change (UNFCCC). Under the Paris Agreement, Canada has committed to reducing GHG emissions by 30% below 2005 levels by 2030. Canada's and other Parties' commitments have collectively been assessed as broadly consistent with cost-effective pathways that result in warming of about 3ºC by 2100. Science is needed to improve understanding of Canadian emission sources across all sectors, including the land sector, and of the capacity for enhanced removal of atmospheric carbon by sinks (primarily on land).

Between 1948 and 2018, Canada has warmed by 1.8°C, while northern Canada has warmed by 2.4°C. The effects of widespread warming are evident in many parts of Canada and are projected to intensify in the future with additional warming. These effects include more extreme heat, less extreme cold, longer growing seasons, shorter snow and ice seasons, earlier spring peak streamflow, thinning glaciers, thawing permafrost, warmer and more acidic oceans, and rising sea level. The projected increase in extreme hot temperatures will increase the severity of heatwaves and contribute to increased drought and wildfire risks. More intense rainfalls are projected for the future, and these will increase urban flood risks. Coastal flooding is expected to increase in many areas of Canada due to local sea level rise. Ocean acidification is expected to intensify, especially in Arctic regions, due to increased CO_2 uptake. Changes in climate are increasingly affecting Canada's natural environment, economic sectors, and the health of Canadians, and climate change is increasingly exacerbating the impact of other stressors on natural ecosystems in Canada and on the well-being of Canadians.

While global mitigation efforts will determine how much future warming occurs, some additional warming and consequent impacts are unavoidable. Canadians need to understand how climate change is already impacting them and what further impacts are anticipated, in order to plan and prepare for the challenges that climate change brings, and to empower their engagement and support for ambitious mitigation. Adaptation is a necessary response to climate change, in addition to mitigation; it enhances the economic and social resilience of Canadians to climate change impacts. Northern and coastal communities and Indigenous Peoples are among the most exposed to changes in climate in Canada. Indigenous Knowledge and science, including social science, can provide a more holistic perspective on climate change action.

The Government of Canada has capacity and the mandate to undertake science to inform effective climate action. Obligations to do this work are part of commitments under the *Canadian Environmental Protection Act, 1999*, the Federal Sustainable Development Strategy, and the United Nations Framework Convention on Climate Change. Provinces, territories and Indigenous governments also have a wealth of capacity to undertake scientific work and build knowledge systems within their jurisdictions and in cooperation with others. Climate change science activities generate and disseminate new knowledge and data to improve our understanding of climate system behaviour, the human influence on climate, future climate changes globally and in Canada, and associated impacts on natural and human systems. Climate change science activities are undertaken jointly through core government programs (mainly federal), academic institutions, and collaborative research networks. These activities involve federal, provincial, municipal, academic, and private sector partners.

The federal government provides most of the essential science infrastructure for climate system research and modelling, and long-term systematic observations programs for monitoring the state of the climate system and atmospheric concentrations of greenhouse gases. This work is complemented primarily by research and observation activities undertaken by the Canadian academic community, whose focus is on enquiry driven science. Productive partnerships have been established between the two communities and both continue to make substantial and essential collaborative contributions to Canadian and international programs. The federal programs then play a major role in the provision of scientific findings (knowledge synthesis and translation) and services to inform decision making on climate change mitigation and adaptation domestically, as well as internationally.

Numerous scientific disciplines from a range of government and academic institutions are involved in research on the climate system and climate change in Canada. Much foundational climate research in Canada is coordinated with international research efforts through the World Climate Research Programme and other international fora. Such strong international coordination has the dual benefits of supporting international climate policy and research obligations under the UNFCCC, thereby allowing Canada to take a credible and constructive role at domestic and international climate negotiations, while also leveraging international research, observations and modelling of the global climate system to ensure climate projections for Canada are based on the best available science.

ANNEX 2 – KNOWLEDGE SYNTHESIS AND MOBILIZATION OPPORTUNITIES

Themes	Knowledge synthesis and mobilization opportunities
Communities and social structures	Synthesis of existing knowledge on social, cultural, economic, and mental health impacts of climate change on communities to better identify the needs specific to communities, especially in the Arctic.
	Assessment of synergies between mitigation, adaptation, and sustainable development actions, including strategies adopted across sectors (particularly the forestry, fisheries, aquaculture, and agriculture sectors, and in protected areas, related to carbon sequestration).
Economics	Analyses of market and non-market goods and services for varying emission scenarios, including second-order impacts, such as anchoring Canadian intellectual property and impacts on the financial system (e.g., high insurance payouts, stranded assets, divestment).
	Analyses of mitigation approaches, including decarbonization pathways aligned with domestic and international targets, to help assess the level and distribution of domestic and international efforts.
	Analyses of costs and benefits, including direct and indirect health and social costs and benefits, associated with climate change impacts and adaptation actions to transition to a climate-resilient economy, including macro-economic models.
	Analyses of the impacts of large-scale non-marginal changes associated with climate change (e.g., domestic and international perspectives on issues that could inform consideration of loss and damage caused by climate change).
Ecosystems	An assessment of climate change impacts on biodiversity and ecosystem services for Canada's terrestrial and aquatic ecosystems.
	Synthesis of trends in agro- and ecosystem land indicators to report on the status and trends of land indicators across the full range of ecozones of the Canadian landmass.
	Assessment of land and aquatic system-based mitigation options, including risks and socio-economic feedbacks considering net GHG and other climate-forcing impacts across ecosystems and human use of those ecosystems (e.g., wood products, macroalgae, food, energy), with international considerations related to the export of bioenergy feedstocks and the possible impact of foreign investments in land or mitigation activities in Canada.
	Assessment of synergies between mitigation and adaptation options in the forestry, fisheries, aquaculture, and agriculture sectors, as well as in parks and protected areas, to identify options that maximize co-benefits and synergies and minimize trade-offs for adaptation and mitigation actions.
	Integrated assessment of freshwater quality, quantity, and availability including sector and municipal implications, leveraging publications, public databases, and recent compilations of historical source and drinking water quality and cryosphere data in order to assess freshwater security.

Themes	Knowledge synthesis and mobilization opportunities
Energy	Synthesis of the scale and current and future potential of non-emitting generation, emerging technologies (e.g., small modular reactors), and alternative energy systems required to meet net-zero (or low-carbon) targets across municipal, provincial, and national climate action plans.
	Better data availability to adequately understand and model local and regional energy supply and demand across all sectors, as this data is not universally accessible across Canada.
	Synthesis of existing knowledge on social, economic, ecological, and health impacts of current and future energy assets to better identify the needs specific to communities and sectors.
	Integrated energy infrastructure risk assessments at the national, provincial, regional, community, or asset levels, that examine vulnerabilities, system interdependencies, cascading impacts, and associated social and economic implications.
Extreme events	National syntheses of risks from changes in extremes (e.g., extreme temperatures, precipitation, winds, floods, wildfires, sea-level rise, storm surges and waves, and combinations of those) and the impacts on human health, ecosystems, forestry, fisheries, aquaculture, and agriculture.
	Science assessment to integrate understanding of climate trends and extremes in the context of natural disasters to inform disaster risk reduction efforts, mechanisms to reduce public health impacts, health system resilience, and relief programming, including financial assistance, and reconstruction planning and implementation.
Health and well-being	Synthesis and mobilization of knowledge of direct and indirect climate change impacts on physical and mental health of Canadians and health systems, including in relation to actions taken in other sectors to mitigate or adapt to climate change.
	Integration and analysis of environmental, human, and animal health, and social data to better understand current and emerging climate change impacts on human health, and to monitor, including in real-time (e.g., syndromic surveillance, novel laboratory diagnostics) and forecast health impacts and outcomes (e.g., Earth observation, risk assessment).
	Integrated assessment of air quality impacts under multiple climate and/or emission pathways.
Infrastructure	Integrated infrastructure risk assessments at the national, provincial, regional, community, or asset levels that examine vulnerabilities, systems interdependencies, cascading impacts, and associated ecological, social, economic, and cultural implications.
	Tools to understand the value of climate resilience and mainstream incorporation of climate considerations in infrastructure and community decision making.
	Efforts to foster the understanding and implementation of climate-informed building codes, standards, guidelines, and best practices in new and retrofit building

Themes	Knowledge synthesis and mobilization opportunities
	projects, aided by regional infrastructure asset management tools and guidelines, including the scalability and implementation of natural infrastructure.
	Building capacity to use climate knowledge, data, and tools in infrastructure decision making, including community-level adaptation strategies, risk assessments, and asset management plans. For example, mobilizing knowledge and expertise and developing technical professional competencies related to northern infrastructure, especially on coastal and ground conditions (including permafrost) for planning major infrastructure and resource development and informing adaptation strategies in the Arctic and North.
	Mobilize existing knowledge about the synergies between mitigation and adaptation measures in the built environment (e.g., insulation material selection that also contributes to thermal resilience, fire resilience, passive survivability in prolonged power outages), which will help prioritize investments.
Arctic and Northern	Synthesis of baseline and future climate and environmental knowledge and data characterize the state and variation of biophysical environments and strengthen the capacity of Arctic and Northern communities and Indigenous Peoples to acquire and apply available data and research, specifically: (1) current state of sampling to identify and address gaps in key datasets, and (2) integration and analysis of information on natural ecosystems to facilitate improved understanding of the complex linkages and cumulative effects.
	Synthesis of existing knowledge of social, cultural, economic, and mental health impacts of climate change in communities to better identify their specific needs.

ANNEX 3 – SCIENCE AND KNOWLEDGE NEEDS

Themes	Science and knowledge needs
Accelerating transformational change	Understand what affects youth and other populations most, how to cope with grief, and how to develop behaviours that lead to resilience and greater literacy related to environmental sustainability.
	Understand how socio-economic and technological systems may evolve through foresight and disruptor prediction to identify individual and structural changes that are positively reinforcing (e.g., aligning self-interest with the public good).
	Develop alternative metrics to evaluate progress based on catalytic and transformative potential, so that reporting becomes an agent of change and equips individuals to adopt environmental policy and/or sustainable development actions.
	Understand and develop communication strategies and messaging that motivates and enhances behavioural change (rather than changes attitudes) that break barriers to adoption (e.g., SHIFT: Social norms, Habit, Individual self, Feelings and cognition, and Tangibility) and utilizes choice architecture.
	Develop and deploy emerging technologies that enable the assessment of, and response to, threats to natural resource-based sector productivity, vector-borne disease, novel agriculture/aquaculture production systems, and nature-based solutions to achieve multiple objectives (e.g., conservation of protected areas, carbon storage, migration corridors).
	Quantify co-benefits associated with climate policy and develop ways to measure progress.
	Understand the synergies and opportunities for integrated adaptation and mitigation to achieve better climate outcomes.
Aquatic systems	Improve fundamental understanding of the processes and impacts of warming, deoxygenation, hypoxia, and acidification in marine and freshwater environments. Expand monitoring of key variables (e.g., temperature, alkalinity, salinity, pH, CO_2, water levels, stream flows, oxygen) both spatially and temporally. Key ecosystems of concern are the Arctic and nearshore areas, where little data is available.
	Identify related place-based vulnerabilities, risks, and impacts on ecosystems and resources, including on species of concern, ocean and fisheries management, aquaculture, and infrastructure.
	Examine impacts of key variables and their interaction on growth, survival, behaviour, productivity, and physiology of a variety of species and socio-economic variables to understand impacts on aquatic resources and coastal communities.
	Improve understanding of aquatic system components of the carbon cycle, including relationships between terrestrial carbon input, mineralization, and sediment mobilization. Improve understanding of carbon capture and storage and ability to quantify carbon sink potential in coastal areas (i.e., blue carbon). Identify impacts of wetland, macroalgal/eelgrass beds, and permafrost changes on carbon reservoirs and transfers of carbon between aquatic, land, cryosphere, and atmospheric systems to quantify carbon cycles and budgets.
	Improve basin-scale physical and biogeochemical ocean circulation models to enhance climate downscaling capability and improve regional climate projections and seasonal to decadal predictions of aquatic ecosystem variables. Improve

Themes	Science and knowledge needs
	projections of freshwater quality, quantity, and availability and study their related impacts on human well-being and activities.
	Examine response of rivers, lakes, wetlands, marshes, and coastal areas to changing temperature, salinity, oxygen, acidification, and seasonality effects to inform climate feedbacks.
	Study climate change impacts of nutrient release, contaminant distribution and transport, and metals toxicity in aquatic systems related to a warming climate, changing precipitation patterns, and ocean changes.
	Develop science-based adaptation tools for current climate-change impacted management issues.
Communities and social structures	Understand how climate change mitigation and adaptation will each and collectively impact diverse groups of people within communities, the extent to which such groups have been engaged in developing climate action, and the impact of these interventions on drivers of vulnerability.
	Develop place-based or local perspectives on risk and vulnerability in coastal, forest, rural, remote, urban, Indigenous, and Arctic and Northern communities to leverage the agency of these communities to mitigate and adapt to climate change.
	Improve understanding of the extent to which municipalities are autonomous from other levels of government, and the implications for climate policy and action. This should extend to understanding how local efforts can feed into regional efforts, and methods for effective coordination. Improve understanding of how local governments can be empowered to increase the flexibility of their governance tools.
	Develop a better understanding of how conditions and mechanisms of inclusion, transparency, and collaboration contribute to building political legitimacy to minimize the disruptive (positive and negative) effects of transformative change, especially for marginalized communities and community members. This includes going beyond a focus on individuals to the broad normalization of sustainability.
	Develop "living labs" or approaches to "learn by doing" in partnership with cities and communities to understand successes and opportunities related to climate change communications, citizen and political mobilization, climate services, technological innovations, and funding and governance models.
	Understand how to measure progress towards decarbonization and develop indicators for measuring transformative change.
	Understand the implications of sector, gender, and occupational health and safety in the context of the labour force in response to climate change and economic and sector transformation (e.g., energy, transportation, long-term care services).
	Understand the potential of climate change to act as a risk multiplier in the international and global security context, such as domestic and international trade; treaties, boundaries, and agreements; immigration and resettlement infrastructure; sovereignty and national security; and socio-economic outcomes, including physical and mental health of communities.
	Develop methodologies and approaches for climate change science communication and the development of professional capacity and competencies

Themes	Science and knowledge needs
	in climate change science, knowledge, and action across public and private sector enterprises.
Earth system climate science	Improve understanding and representation of climate-ecosystem feedbacks in models across the physical climate components (atmosphere-ocean-land-cryosphere) and ecosystems (terrestrial, inland freshwater, marine). Within this, a focus on landscape/hydrology and carbon cycle processes, including the response of permafrost and glaciers, to improve understanding of feedbacks and freshwater availability.
	Improve understanding of the behaviour of aquatic components and their interactions with the atmosphere, cryosphere, terrestrial, and aquifer systems and the seafloor, and improve their representation and integration in models.
	Explore the climate response to the mitigation of short-lived climate forcers (methane, black carbon, ozone, sulphates, ozone-depleting substances) and climate engineering (Carbon Dioxide Removal and Solar Radiation Management).
	Develop and evaluate more skillful climate predictions on seasonal to inter-annual and decadal scales, including initialization techniques and use of observations.
	Further develop climate projection downscaling techniques, including better use of observational data.
Economics	Explore distributional and differential impacts of climate change on the economy and society (e.g., employment, cost of living, urban infrastructure investments, Emission-Intensive Trade-Exposed industries) and ways to minimize these impacts, including developing methodologies to account for vulnerabilities, responsibility, capacity to adapt, and income levels.
	Improve the design, selection, and implementation of climate policy instruments, including decarbonization pathways analysis, carbon pricing instrument design, enablers of non-emitting technologies, incentives for zero-carbon energy generation, and estimates of payments for ecosystem services to preserve non-market benefits.
	Explore costs and benefits of climate action, including Integrated Assessment Model analyses and Social Cost of Carbon estimation; monetization of the disruption of public services, social services, and health services; costs of inaction; avoided costs; economic valuation of resilience/adaptation actions; competitiveness and mitigation; adaptation costs in scenarios of delayed global mitigation efforts or abrupt non-linear changes; and technological innovation opportunities (e.g., small modular reactors).
	Understand the finance implications of incentives and financing models targeting municipalities and remote communities, infrastructure asset management, the health sector, and urban planning and design within the broad categories of physical risks (e.g., extreme events) and transition risks (e.g., climate-related risk financial disclosure). This work would capture potential economic opportunities (currently not well defined), including the dynamics of clean technology, sustainable finance, and climate finance.
	Conduct a holistic cost-benefit analysis of current and new non-emitting technologies by considering the full spectrum of techno-economic, environmental, and energy requirements and drivers (e.g., lifecycle GHG emissions, ecosystem impacts, land use, reliability, flexibility, scalability, co-generation applications,

Themes	Science and knowledge needs
	Canadian intellectual property, and global trade potential). This work would create a methodology to appraise and select technologies best suited to decarbonize the Canadian economy at national, provincial, and regional levels.
	Continue research on behavioural economics as it relates to understanding and support for climate policy.
	Explore the economic implications of, and policy options for, enabling a just transition for workers, sectors, and communities impacted by the transition to a low-carbon, resilient economy.
	Identify how climate change will influence socio-economic drivers, such as population growth, globalization, urbanization, governance, and social structures.
	Understand how to enable better uptake of publicly funded adaptation measures and remove barriers to adaptation.
Ecosystems	Understand the impact of climate change on the biophysical processes fundamental to healthy ecosystems (e.g., nutrient and carbon cycling, permafrost, vegetation dynamics, aquifer recharge and water storage, natural disturbances such as pests and wildfires) and the subsequent impact on ecosystem function and productivity.
	Advance understanding of ecological community and species interactions (e.g., pests, invasive species, migration, range expansion) and how these relationships will respond to climate and non-climate stressors (including contaminant behaviour and re-release/distribution in water, sediments, air), and various climate scenarios, which will inform understanding of cumulative ecosystem effects.
	Develop process models and integrate species adaptive capacity into predictive models to understand how ecosystems will respond under various climate scenarios, forecast emerging and novel ecosystems, and understand and project how changes will affect wildlife. This includes developing alternative statistical or ecological niche approaches and genomic analyses.
	Develop measures and indices to enable species and ecosystem adaptation and advance management approaches to conserve habitats and biodiversity. These measures should integrate as many issues as possible to provide simple (and ideally single) measures to multiple concerns (e.g., biodiversity conservation, carbon sequestration, species at risk, productivity).
	Investigate NbS for mitigation and adaptation to understand their implications for carbon sequestration, biodiversity, wildfires, pests, invasive species, freshwater, food and fibre, the bioeconomy, and communities.
	Develop new surveillance and monitoring tools for emerging zoonotic diseases and plant/animal pests in natural and managed ecosystems.
Energy	Enhance the safe, affordable, accessible, and reliable development, demonstration, and deployment of non- and low-carbon emitting energy and energy technologies, including biomass gasification, large-scale hydrogen production from renewable energy, hydrogen energy and small modular reactor technologies, renewable natural gas, and hydrogen distribution, while providing economic benefits.

Themes	Science and knowledge needs
	Develop carbon capture, utilization, and storage technologies (CCUS) and related marketable products, as well as understand the potential scalability and deployment of direct air capture technologies (Carbon Dioxide Removal).
	Improve energy efficiency across sectors, including in buildings, transportation, and industry to reduce energy demand and optimize thermal energy generation, transmission, and storage; and support the use of low-carbon energy sources, feedstocks, and non-emitting technologies (e.g., renewables).
	Develop smart technologies to optimize the supply and use of energy, and to support high-efficiency and net-zero design energy systems, including modular, regional (i.e., district), and resilient energy systems.
	Advance electrification-focussed research in key sub-sectors (e.g., on-grid, off-grid, resource extraction, transportation), including generation (blended systems: renewable, nuclear, thermal), storage, smart technologies, and barriers to implementation (e.g., for electric vehicles).
	Advance understanding of the infrastructure, economic, and technological requirements of the energy transformation needed to achieve net-zero emissions by 2050.
	Advance understanding on the opportunities and barriers associated with next-generation clean technologies, such as net-zero energy ready homes, hydrogen energy, small modular reactors, and smart grids and devices.
	Develop an integrated and discrete energy dispatch model for the supply-demand balancing of the Canadian power grid, including GHG emission assessment, at the national and provincial levels.
	Develop scientific knowledge, including on the role of minerals, nature-based solutions, and technology on clean growth, to inform the transformation needed in the energy sector to achieve net-zero emissions by 2050.
	Advance understanding of wood and pellet heating solutions, particularly in northern, rural, and remote areas on climate change, land-use change, and environmental and health concerns, such as air pollution and habitat loss. Consideration should be given to recent energy efficiency advances in technologies, economic opportunities, and GBA+ considerations.
Extreme events	Improve prediction and projection of climate extremes, extreme events, and storms, including quantitative predictions to inform disaster risk reduction.
	Improve attribution of historical and contemporary extreme events to anthropogenic climate change.
	Understand risk posed by extremes and develop methods for integrating climate risks with changes in exposure and vulnerability for social/cultural systems, forestry, wildlife, health systems, infrastructure, fisheries, aquaculture, and agriculture. This includes understanding compound or simultaneously occurring extreme events and developing indices and sector-specific thresholds.
	Investigate how climate extremes and extreme events will influence the efficacy of mitigation and adaptation measures, including nature-based solutions and energy systems.
Health and well-being	Identify where and when climate-driven infectious diseases will emerge or re-emerge in Canada, including understanding the climate impacts on zoonotic, food-

Themes	Science and knowledge needs
	borne, and water-borne diseases, both exotic and endemic, related to surveillance and monitoring, modelling, laboratory diagnostics, and public health prevention and promotion efforts.
	Understand health risks and drivers of vulnerability to climate-related extreme weather events (e.g., extreme heat), including effective adaptation actions to protect health.
	Understand mental health and psycho-social impacts of acute climate impacts and longer-term impacts on mental health and well-being, including impacts to children and youth, knowledge of affirmative mental health outcomes, and ways of communicating about climate hazards in such a way that does not induce or exacerbate mental health issues.
	Improve understanding and models of the impact of multiple climate change projections on air quality (anthropogenic air pollution, wildfire smoke, aeroallergens, indoor air quality) and associated health and economic impacts.
	Understand how climate-related impacts may affect different populations, the implications for health equity, and effective and culturally appropriate adaptation measures for these populations.
	Understand the climate-related risks, vulnerabilities, costs, and effective adaptations for health systems and services, including on health policies, programs, services, and infrastructure; health human resources planning, management and training; and supply chains critical for health.
	Improve understanding of needs, methods, and novel approaches for health, social, and environmental data collection, integration, analysis, and dissemination to support timely and accurate information for health sector decision making.
	Understand the health impacts of climate change on food safety and security, including impacts on supply chains and prices; as well as pests, pathogens, and bio-toxins that can infect plants, animals, fish and seafood, including species traditionally harvested by Indigenous Peoples.
	Understand direct and indirect health co-benefits and risks of climate actions taken by other sectors (e.g., transportation, energy, urban planning), and the economic and social returns of investing in climate-resilient health systems.
Infrastructure	Continue research to understand current and future extreme weather, natural hazards, and other climate change impacts (e.g., floods, storms, wildfire, urban heat islands, local sea-level rise, permafrost thaw, erosion) and the related impact on current and planned infrastructure (e.g., built, natural, energy, transportation). This includes developing seasonal to decadal prediction of how extremes will change (intensity and frequency).
	Increase climate data in coastal communities, Indigenous communities, the North, and remote areas. Quantify climate impacts over time in the North (e.g., precipitation, wind, permafrost, sea ice, sea level, waves, storm surges) and determine their effects on Northern infrastructure, including for Indigenous communities.
	Develop standardized methodologies to predict and measure emissions from engineered and nature-based construction materials, structures, retrofits, and hybrid approaches.

Themes	Science and knowledge needs
	Develop technical and behavioural solutions to developing low-carbon, resilient infrastructure and communities, including economic implications (avoided costs, return on investment) of new and retrofit approaches, managed retreat and re-location options, associated economic impacts and implications for social equity in an inclusive systems-wide approach. Links to disaster risk reduction are key.
	Understand implications of low-carbon and resilient infrastructure development and energy retrofits for Northern and remote community housing stock.
	Investigate the economic, social, ecological, and cultural implications of infrastructure resilience and adaptation solutions at national, provincial, regional, local, and asset-specific scales. This includes research to understand the full range of benefits of natural infrastructure solutions.
	Develop tools that ascribe value (economic and non-economic) to hybrid and natural infrastructure solutions that sequester carbon.
Land systems	Improve our understanding of terrestrial carbon stocks and links with landscape features and hydrology, GHG fluxes, and associated processes driving transfers among ecosystems, across landscapes, and to and from the atmosphere. This requires more accurate measurement of above- and below-ground living biomass, dead organic matter, and soil carbon using *in situ*, airborne, and space-based observations. Special attention is required for northern and permafrost regions.
	Produce accurate estimates of the impact of current and historic human activities on carbon stocks and GHG fluxes, including quantification and mapping of carbon and nitrogen transfers between managed and natural environments.
	Understand current and projected impacts of climate change on terrestrial carbon stocks and GHG fluxes, such as vulnerability of carbon stocks, impacts of disturbances including fires, inter-annual variability, and impacts of shifts in land use in response to climate change.
	Understand land-based mitigation and adaptation actions to identify synergies and to enable the development of tools, best practices, and actions that integrate mitigation and adaptation objectives for regional and local implementation while addressing ecological, economic, and social objectives under a range of future climate scenarios.
Arctic and Northern	Develop digital infrastructure, monitoring, and data strategies that enable the participation of Northerners in research, and access to Canadian and international research results and observations.
	Develop Arctic-appropriate and adapted technologies to reduce reliance on diesel related to renewable energy systems and storage, heat recovery, and energy efficiency.
	Include and encourage leadership and self-determination of Inuit and Northerners in the continued development of climate research and monitoring to address the significant existing gaps in knowledge across the Arctic and North at all scales.
	Include and encourage leadership of Arctic and Northerners in multidisciplinary research to understand the economic and health impacts of climate change at the community level, and the resulting needs of these communities. This includes research to support community-led clean energy projects.

Themes	Science and knowledge needs
	Understand the physical, landscape, and community impacts of the scientific priorities identified above in an Arctic and Northern context.

ANNEX 4 – SCIENCE IN ACTION VIGNETTES

Below are examples of climate change science in action to supplement those found in the main body of this document.

Tracking greenhouse gases at our doorstep

Urban areas have many sources of GHG emissions. Tracking emission changes and identifying mitigation opportunities is key to reducing the carbon footprint of urban residents and businesses. Environment and Climate Change Canada (ECCC) researchers are using measurements of local atmospheric GHG enhancements to quantify the impact of industrial and urban emissions. They have combined socio-economic and atmospheric data to generate maps of GHG emissions for Southern Ontario, and have analyzed the relative importance of different sectors (e.g., on-road transportation, residential, commercial) and shown that understanding the contribution of natural sources is crucial. Furthermore, they did over 10,000 km of mobile surveys in the greater Toronto and Montreal areas to find mitigation opportunities related to methane, which showed that the waste sector is a major contributor, while natural gas infrastructure is a smaller source than in other North American cities. These techniques can be expanded to other urban areas in Canada and used by academic and private sector partners.

Tuktoyaktuk Community Climate Resilience Project

The Tuktoyaktuk Community Corporation has developed innovative partnerships with researchers and institutions in the Inuvialuit Settlement Region to build climate monitoring capacity and research skills. Trained monitors track permafrost variables, ice thickness, ice thaw dates, snow depth, and water quality at monitoring locations informed by Traditional Knowledge. Climate monitoring and time-lapse photo monitoring is generating timely weather information, supporting improved decisions about whether it is safe to go out on the land. This is particularly important as Inuit Elders have indicated difficulty in predicting weather due to the rapidly changing climate.

International collaboration on satellite data and applications through the Polar View project

The Polar View project uses operational satellite data to establish services for Arctic communities. The Community Ice Service project provides one of these critical services to several northern Inuit communities. Due to climate change, the location and extent of ice and seasonal ice edges is rapidly evolving and additional information is valued greatly to complement Indigenous Knowledge. Through a collaboration between scientists at the European Space Agency and the Canadian Space Agency, routine ice data is provided and used by Inuit communities to inform daily activities. Other Polar View services related to iceberg monitoring and glacial observation have become an integral part of northern tourism and transportation, in which natural features act as both attraction and hazard. Using these services, tourism operators can identify areas for recreational viewing, while keeping vessels at a safe distance from sensitive ecosystems or hazards. Overall, the project has successfully transformed and applied satellite-derived data to the daily lives of Canadians.

Coastal infrastructure

Many of Canada's coastal areas are of great economic, social, historical, or environmental significance. Climate change is resulting in rising sea levels and water temperatures, increasing ocean acidity, and decreasing sea ice and permafrost, all of which pose considerable challenges for vulnerable coastal communities. Coastal infrastructure damage represents a high risk for these regions. For example, Fisheries and Oceans Canada's Small Craft Harbours program manages more than 750 core commercial fishing harbours with approximately 7,000 structures and a replacement value of $5.2 billion. In response to the risks associated with climate change, Fisheries and Oceans Canada invested in scientific research that has resulted in the development and implementation of decision-making tools to provide engineers and managers with science-based advice on where best to invest in adaptation projects.

Which oilseeds make good biofuel?

Biofuels are a promising way to reduce the carbon footprint of air travel. It is estimated that using a fuel mixture containing 50% biofuel would cut flight emissions by 50-70%. Currently, biofuels account for a small part of the fuel mix, but Agriculture and Agri-Food Canada (AAFC) scientists are working to change that. Although biofuels can be made from a variety of feedstocks, their cost compared to fossil fuels makes their widespread use a challenge. To find a way to make biomass feedstock more efficient and less expensive, AAFC scientists studied five different oilseeds grown on the Canadian Prairies. They found that, overall, canola appeared to be the most efficient biomass feedstock for biofuel, given that it had the highest growth rate, highest seed yield, and was the most efficient at using water. While it may be a few more years before flights are predominantly fuelled by plants, AAFC's research is helping advance this work and grow the aviation industry of the future.

Reducing transportation-related GHG emissions through zero-emission vehicles

Using a hydrogen fuel cell to power an electric motor allows for a zero-emission vehicle, with the advantage of a relatively short refuelling time (3-5 minutes) and a range of over 500 km on one single tank. But cost, durability, and the availability of hydrogen refuelling infrastructure are still challenges to the commercialization of fuel cell electric vehicles (FCEV). Work is ongoing to understand and optimize cost-effective processes for the technology used in fuel cell electric vehicles, as well as to assess the economics of scaling up the production of this technology and the feasibility of commercialization. Combining the techno-economic analysis results and the engineering and production knowledge shows that zero-emission vehicles must not be overlooked as a technology that enables the reduction of transportation-related GHG emissions.

Accelerating the clean energy transition through small modular reactors (SMRs)

In our effort to achieve a resilient, carbon-neutral society, SMRs can contribute to decarbonizing the Canadian economy by serving as a reliable, flexible, and clean energy solution. More than just electricity generation, SMRs could be the key to building an overall low-carbon energy system with other non-emitting technologies, providing high temperature heat for applications such as district heating, resource extraction, desalination, hydrogen production, and remote off-grid applications. SMR innovators are collaborating with laboratories, universities, and operators on R&D work to make them simpler in design and capable of factory fabrication, while incorporating enhanced safety features and reducing waste volumes, with some even capable of recycling waste as fuel. To advance these technologies toward demonstration and commercialization by the late 2020s, current areas of scientific focus include reactor physics, thermalhydraulics, fuel fabrication, and plant safety. Governments, together with researchers, industry stakeholders, and international partners, are working to assess technologies, reduce costs, mobilize private finance, and establish policy and regulatory frameworks to pave the way to deployment.

Impacts of the 2013-2015 marine heat wave on Canada's west coast

A warming event of record magnitude started offshore of the west coast of British Columbia in 2013. It became evident in British Columbia coastal waters by summer 2015, with an increase in water temperatures of 3˚C above normal. This warming of coastal waters was accompanied by harmful algal blooms, record high levels of large gelatinous zooplankton, and invasion of warm water species.

The event had cascading ecosystem consequences, such as the extraordinary bloom of a colonial waterborne tunicate (an animal with no backbone that is rarely found north of California) observed along the whole west coast of North America in 2017. This bloom had substantial negative impacts on commercial and recreational fishing operations due to fouling of fishing gear, illustrating that anomalous events can have unforeseen impacts on coastal fisheries. This Marine Heat Wave was unprecedented and DFO stock assessment and resource management included observations of this extreme event in the 2016 forecasts of Pacific salmon returns to British Columbia river systems. The linkages of warm ocean conditions to poor quality prey items for Pacific salmon informed the pre-season outlook for salmon returns and fishing opportunities, with expected variability across salmon stocks and general below average abundance.

Accelerating the co-development and adoption of solutions through living laboratories

All too often, one-dimensional solutions are applied to individual components of the climate change problem, overlooking the complexity between them and impeding broad-scale success or sufficient adoption rates. Through Agriculture and Agri-Food Canada's Living Laboratories Initiative, farmers, scientists, and other partners are working together to co-develop, test, and monitor new practices and technologies in a real-life context. This nationwide network of living laboratories provides an integrated approach to agricultural innovation that can address complex relationships in the development of agricultural climate change adaptation and mitigation actions. This initiative will accelerate the adoption of new technologies and beneficial management practices to build greater resilience in agricultural landscapes, including adaptation to climate change, improving agri-environmental performance (including greenhouse gas mitigation), and achieving sustainable intensification of agricultural production.

Predicting extreme weather

The Extreme Weather Indices are a suite of interactive maps showing short-term forecasts throughout the agricultural season, which will help agricultural producers assess the risks of extreme weather to their operations. They are a result of nearly a decade of scientific collaboration between Agriculture and Agri-Food Canada and Environment and Climate Change Canada, drawing on shared climate data, high-performance computers, complex models, and large datasets. The information in the indices is tailored to agriculture, with maps showing where extreme weather is forecast and the magnitude and the probability of its occurrence. Users can choose to view and explore maps from categories such as temperature, heat, wind, and precipitation prediction up to a month ahead. Having access to this information helps farmers assess the spread of pests, plan when to spray their crops, assess the risk from frost, and plan when to harvest.

A national crop yield forecasting tool to help Canada's agricultural sector adapt and thrive in a changing climate

Through a collaboration between Agriculture and Agri-Food Canada and Statistics Canada, satellite and land management data are combined to provide early warning information for crop conditions under current and future climate scenarios. The Integrated Canadian Crop Yield Forecaster (CCYF) tool was created by integrating critical satellite-derived information (e.g., soil moisture, plant health) with complex agro-climate data. The tool provides predictive lead times of two to three months for crop growth rate. As a result, the agricultural value chain is better able to anticipate, mitigate, and respond to climate risks while maintaining sustainable food production. As more detailed and frequent data become available from satellite platforms such as the RADARSAT Constellation Mission, crop yield predictions are expected to become even more accurate.

Environnement et Changement climatique Canada   Environment and Climate Change Canada

ANNEX II

CLIMATE SCIENCE 2050 EXECUTIVE SUMMARY

Science and knowledge are critical in guiding the swift and ambitious action needed to build a resilient, carbon-neutral Canada. The breadth and complexity of the science and knowledge needed to meet this challenge require collaboration across disciplines, sectors, communities, and research bodies. *Climate Science 2050: Advancing Science and Knowledge on Climate Change* (CS2050) is intended to guide science and knowledge generators, holders, and funders as they advance the collaborative and interdisciplinary efforts needed to inform climate action. CS2050 encompasses the natural, social, and health sciences and recognizes the need to mobilize the full spectrum of Indigenous leadership, participation, and knowledge systems. While climate change science has traditionally focused on the natural sciences, CS2050 recognizes the need to elevate the role of social and behavioural sciences, as they have important contributions to make in informing the transformation needed in Canadian society.

While CS2050 highlights many science and knowledge needs, there is already a strong knowledge base on which to build. The urgency of the climate change challenge means that decision-makers should not and cannot wait for all the science to be in before taking action. Climate action must continue in parallel with research activities, drawing on existing knowledge and incorporating new insights as they become available. As such, knowledge synthesis and mobilization   including the dialogue they establish between knowledge producers, holders, and users   are key elements of CS2050. They will ensure decision-makers have the best-available knowledge and will keep research efforts aligned with user needs. These efforts could include science and risk assessments, knowledge portals, and case studies, and will benefit from increasing climate change science literacy and professional competencies.

Given the scale and urgency of the challenge, and ubiquitous nature of climate change impacts, addressing the science and knowledge needs outlined in CS2050 will require an increasingly integrated approach to advance multiple priorities in parallel. It will also benefit from embracing new and participatory approaches to research and knowledge development (e.g., experimentation, learning by doing, co-production) and from the respectful consideration of Indigenous Knowledge. The science and knowledge needs covered by CS2050 are organized into four outcomes, with a fifth area of work   Earth system climate science   providing a key foundation.

Earth system climate science   Work is needed to reduce uncertainties related to the magnitude, timing, and impacts of future change and the prediction of climate extremes, floods, droughts, and wildfires. This research will enable a better understanding of the influence of climate change on permafrost, glaciers, oceans, ice (sea, river, lake), and freshwater. It is also central to providing more detailed and tailored sector-based information. Research is also needed to evaluate the effectiveness of mitigation efforts (e.g., short-lived climate forcers, climate engineering).

Canada

Healthy and resilient Canadians, communities, and built environments Developing a nuanced understanding of vulnerability, resilience, and empowerment and how these vary across regions and groups will help ensure efforts to build health and resilience are effective. Work is also needed to protect and improve the health and well-being of Canadians and increase the resilience of health systems, including a better understanding of climate-related health risks, intersections with action in other sectors (e.g., transportation, urban planning), and innovative and scalable interventions that maximize resilience and empower behavioural change. Building climate-resilient communities and infrastructure will benefit from research into natural infrastructure, community design, the value and co-benefits of resilient infrastructure solutions, and essential infrastructure systems (e.g., energy, water, transportation). There is also a need to understand the climate impacts on governance, trade, global migration patterns, and development and international assistance.

A carbon-neutral society Accelerating the transformational change needed to meet and exceed Canada's 2030 greenhouse gas (GHG) emissions reduction goal under the Paris Agreement and achieve net-zero emissions by 2050 will require a deeper understanding of the social and behavioural side of decarbonization. Research to understand decarbonization pathways will be valuable, including work related to a just transition and the economic aspects of carbon neutrality. Energy decarbonization is a key research area, as is work to understand the mitigation potential of infrastructure construction and management approaches. In moving toward net-zero emissions, research is needed to help protect and enhance terrestrial and aquatic carbon sinks, from fundamental carbon cycle science to research aimed at developing socio-economic levers and best practices.

Resilient terrestrial and aquatic ecosystems To ensure Canada's ecosystems remain healthy and resilient, research is needed to improve our foundational understanding of the impacts of climate change on the processes that underpin healthy ecosystems, the sensitivity, resilience, and adaptive capacity of species and ecosystems, and the effects of changing stressors and their cumulative impact on biodiversity and ecosystems. Work will also be needed to anticipate and minimize the threats to vulnerable species and ecosystems, as well as efforts to develop and test adaptation measures. Nature can also be a powerful ally in addressing climate change, and work is needed to address knowledge gaps related to identifying and deploying nature-based solutions, such as research into potential negative effects, socio-economic and cultural valuations and trade-offs, and the impact of extreme events on these solutions when implemented.

Sustainable natural resources Helping the agricultural, forestry, fisheries, water management, mining, and energy sectors remain resilient and productive in the face of climate change requires a better understanding of the risks climate change poses (e.g., extreme events, water availability, pests, disease, invasive species). Meanwhile, as some resource-based communities navigate a just transition, social science research can help to understand the social, cultural, and economic impacts of this transformation. Furthermore, an integrated understanding of natural resource and land/water goals and opportunities will help maximize co-benefits (e.g., advancing carbon sequestration, health, energy, and food security simultaneously). Canada's natural resource sectors will also benefit from research to inform climate-smart, sustainable practices.

Three key areas of foundational capacity are essential in supporting work across all science and knowledge needs identified in CS2050. Whether carried out on the ground or via satellites, monitoring and surveillance efforts continue to be key in providing situational awareness, assessing change, informing action, and measuring progress. The magnitude and diversity of climate change data and knowledge will require advances in digital infrastructure (e.g., data storage and management, high-performance computing), including tools for data management, extraction, manipulation, visualization, standardization, and interoperability. Finally, ensuring climate change science is open and accessible will increase transparency, maximize investments, and accelerate progress.

CS2050 represents an opportunity to make deliberate decisions about climate change science and knowledge activities and funding in Canada, which will be pivotal in guiding the way to a resilient, carbon-neutral society.

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ANNEX III

CLIMATE SCIENCE 2050 PLACEMAT

Guiding Canadian science and knowledge producers, holders, and funders in advancing the collaborative and interdisciplinary science and knowledge needed to inform swift and ambitious climate action

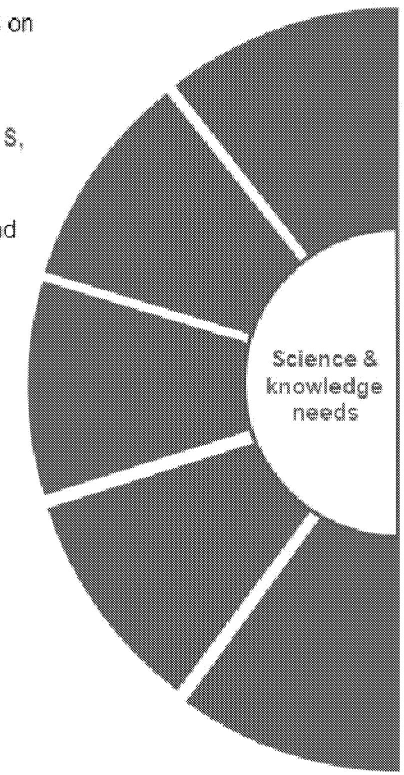
EARTH SYSTEM CLIMATE SCIENCE
Future change and extremes; impacts on permafrost, glaciers, oceans, etc.; mitigation effectiveness

HEALTHY & RESILIENT CANADIANS, COMMUNITIES, & BUILT ENVIRONMENTS
Intersectionality; health (individuals and the health system); communities and infrastructure; trade, migrations, governance

CARBON-NEUTRAL SOCIETY
Social and behavioural change; decarbonization pathways and economics; carbon sinks

RESILIENT TERRESTRIAL & AQUATIC ECOSYSTEMS
Climate impacts; adaptation; nature-based climate solutions

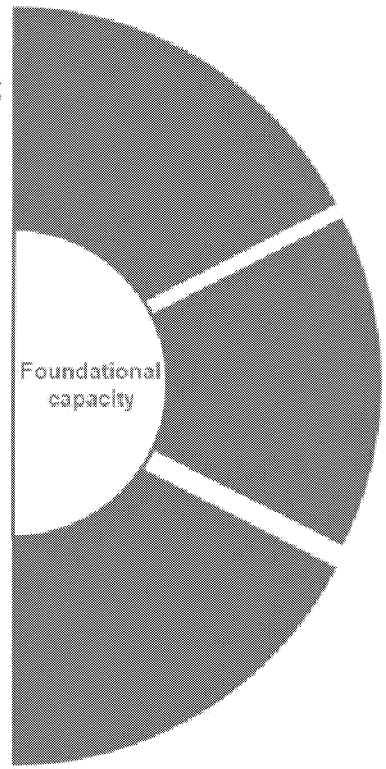
SUSTAINABLE NATURAL RESOURCES
Climate risks and action; integrated valuation (economic, social, cultural, ecological)



Guiding principles
Diverse knowledge systems; Indigenous self-determination; interdisciplinarity; collaboration; flexibility; intersectionality; local/regional focus; integration

Indigenous-led science and knowledge
Indigenous spaces; leadership and participation; weaving Indigenous Knowledge

Knowledge synthesis and mobilization
Climate services; assessments; portals; case studies; climate literacy; professional capacity



MONITORING & OBSERVATION
Expansion; innovation; standardization; integration

DIGITAL INFRASTRUCTURE
Data (storage, management, tools); high-performance computing

OPEN SCIENCE
FAIR data; Indigenous data sovereignty; open publications

Canada

INFO 231641-For the Office of an MP
[Content of response based on previous M.P Response formats: INFO 220697 and 205683 and Weather Modification standard reply: MIN 195575; and previously approved text]

REQUEST:
Summary: Questions regarding aerial spraying/ geoengineering (climate engineering) and weather modification via cloud seeding

Regarding contrails/chemtrails - MSC has indicated 'nil'

STB (ASTD) input:
Please consider the following points:

Climate engineering/ climate *geoengineering – definition*

- Climate engineering, which is also known as geoengineering, refers to the deliberate large-scale manipulation of the planetary environment to counteract human-made (anthropogenic) causes of climate change.

Climate engineering/ climate *geoengineering- national/global scale*

- Environment and Climate Change Canada (ECCC) does not conduct any real-world climate engineering activity, whether stratospheric aerosol injection, albedo enhancement or any other deliberate atmospheric or land-based intervention for the purpose of modifying the atmosphere or counteracting climate change.

- Environment and Climate Change Canada uses climate models to improve understanding of changes in the atmosphere due to natural and human activities, including aerosol loading from volcanic eruptions and theoretical solar radiation management approaches, but it does not conduct real-world climate engineering activities.

- Environment Canada is not involved in, or aware of, any government projects that inject chemicals into, or alter, the atmosphere for the purposes of controlling the weather.

Weather modification – *definition*

- Whereas, climate engineering is focused on the global scale, weather modification is focused on bio-regional or local scales.

- Weather modification includes any activity designed or intended to produce, by physical or chemical means, changes in the composition of dynamics of the atmosphere for the purpose of increasing, decreasing or redistributing precipitation, decreasing or supressing hail or lightning or dissipating fog or cloud.

Weather modification – *History of Canadian federal government involvement*

- Starting in 1948, the federal government was involved in weather modification experiments. Most of these activities took place in the 1960s and 1970s. The conclusions were that there was no statistical or physical evidence demonstrating that the weather modification activities were effective. The research programs declined in the second half of the 1970s and ended in the early 1980s.

- Environment and Climate Change Canada (ECCC) does not conduct any weather modification activities or experiments.

The Weather Modification Information Act

- At the federal level, there is no permitting process, nor are permits issued for weather modification activities.

- Weather modification activities in Canada follow the guidelines outlined under the *Weather Modification Information Act* (http://laws-lois.justice.gc.ca/eng/acts/W-5/FullText.html). The Act requires any person (or organization) seeking to engage in weather modification activities over Canada to inform the Administrator of the Act, in writing, of his/her intent. The person (or organization) must identify his/her name and address and include information about the purpose and method of the activity, such as dates, times, equipment, materials and geographic area.

- Under the Act, any person (or organization) that carries out any weather modification activity must maintain a daily record of the activity. This includes detailed information relating to the location and operation of any equipment used; any meteorological observations made; and the chemical nature, physical properties, and quantities of any substances emitted into the atmosphere for the purposes of weather modification. Any person (or organization) that carries out any weather modification activity must also submit to the Administrator a report specifying details about the nature and scope of his/her activities, including the dates and any meteorological observations that were made.

Weather Modification Inc.

- Weather Modification Inc., as the only company undertaking weather modification activities in Canada, uses silver iodide as a cloud seeding agent in an attempt to reduce damage caused by hail.

- Weather Modification Inc. is the sole organization conducting weather modification activities over Canada. It provides the necessary reports to Environment and Climate Change Canada on a yearly basis. The attached *2016 Annual Report* and *2017 Notification of Intent* contain summaries of its weather modification activities in Alberta.

- ECCC (as per World Meteorological Organization [WMO] guidelines) receives notification and annual reporting of all cloud seeding activities using silver iodide; this has occurred since 1986 – see *Weather Modification Act*.

Environmental and human health impacts

- The emissions produced by silver iodide, as a seeding agent, are considered to have negligible environmental or human health impacts.

- Material Safety Data Sheets (M.S.D.S.) for silver iodide, which include information about ecological and human health impacts, are readily available online. M.S.D.S. hazard categorizations are related to occupational health and safety guidelines on the handling of substances and exposure risks at associated high concentrations, not atmospheric concentrations.

- According to the most recent report from Weather Modification Inc., the episodic emissions of silver iodide as a seeding agent are not expected to have environmental or human health impacts given the considerable small quantities used.

- Moreover, measurements of silver iodide concentrations in regions where weather modification activities using this compound have occurred have not found concentrations above natural background concentrations.

International relations

- For long term, larger scale weather modification operations, Environment and Climate Change supports the position of the World Meteorological Organization (WMO) outlined in the draft WMO Weather Modification Statement and Guidelines (2016): https://www.wmo.int/pages/prog/arep/wwrp/new/weathermod_new.html

Human health impacts: cloud-seeding/ weather modification

- It is recommended that the Office of the MP, also consult Health Canada (The Honourable Ginette Petitpas Taylor, Minster of Health) regarding any questions and concerns related to human health impacts of the uses of silver iodide as a cloud seeding agent

Archived: Tuesday, September 20, 2022 1:06:09 PM
From:
To:
Cc:
Subject: INFO-287598: (info Request) - {Responsive info re: NRC Guideline document inquiry}
Sensitivity: Normal
Attachments:
INFO 287598_STB Response_v2.docx

Hi Franco,

Please find STB's ADM approved response including MSC's input.

INPUT/APPROVAL FROM:

Alex Cannon, Research Scientist, ASTD-CRD, STB

Megan Hartwell, A/Program Coordinator, ASTD-CRD, STB

David Henry, DG, ASTD, STB

Diane Campbell ADM, MSC

Jacqueline Gonçalves, A/ADM, STB

Merci,

Karine Régimbald

Agent de breffage | Briefing officer

Unité des opérations et du breffage ministériel | Operations and Departmental Briefing Unit,

Secrétariat Ministériel | Corporate Secretariat

200 Sacré-Coeur– 2e étage office 274

Environnement et Changement climatique Canada (ECCC) | Environment and Climate Change Canada (ECCC)

Tel: (819) 938-9064

Courriel | Email :karine.regimbald@canada.ca

From: Bianco,Franco (ECCC) <Franco.Bianco@ec.gc.ca>
Sent: Friday, April 1, 2022 9:55 AM
To: EC.F Demandes Min / Min Requests F.EC <F.DemandesMin-MinRequests.F@ec.gc.ca>
Cc: Christopher,Lynn (ECCC) <Lynn.Christopher@ec.gc.ca>; Crowe,Deeva (ECCC) <Deeva.Crowe@ec.gc.ca>; Pyne,Meghan (ECCC) <Meghan.Pyne@ec.gc.ca>; Rondeau,Stephane (ECCC) <stephane.rondeau3@ec.gc.ca>
Subject: (info Request) - {Responsive info re: NRC Guideline document inquiry}

Hi,

MinO was hoping the dept. would be able to send them some responsive information for the inquiry below that they received from an individual:

\cbpat5The NRC guideline documents trends in extreme rainfall per Environment and Climate Change Canada's Engineering Climate Dataset and refutes the statement I had inquired about (i.e., that "powerful storms are becoming more frequent"). I'll share some excerpts for rain intensity trends across Canada (see Appendix E page 16):

\cbpat5

INFO 287598: (MINO INFO REQUEST) – Responsive Info re: NRC Guideline Document Inquiry

Response Lines:

- The table referenced shows the changes in Intensity-Duration-Frequency (IDF) values when using a longer and more up-to-date observational data set. These small and statistically insignificant differences are a result of recalculation with a larger sample size. This is simply a more robust estimate of the past average climatological rainfall statistics. It cannot be interpreted as providing evidence for a lack of climate change.

- The evidence and cause of climate change is evaluated by a systematic investigation of global trends across different climate variables and the theoretical understanding of climate systems modelling, not through the analysis of individual stations.

- The IPCC Sixth Assessment Report was released in August of 2021 (Sixth Assessment Report (ipcc.ch). It assessed the large body of scientific evidence on this topic, specifically addressed in A.3.2 and B.2.4 of the Working Group I Summary for Policymakers:
    - "The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis, and human-induced climate change is likely the main driver."
    - "It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming."

Additional Info:

- There is abundant evidence that extreme precipitation has increased globally and that we can attribute such changes to human-induced warming. One recent example is the significant rainfall that led to flooding in the British Columbia lower mainland in November 2021.

- A lack of significant trends in extreme precipitation at individual stations in Canada is not confirmation of no historical change. These trends might be explained by the detectability of natural climate variation, especially when assessed at the station level with short records.

- Scientific research results from Shephard et al., (2014) indicate that at least two-thirds of the regions across Canada have increasing trends in short duration extreme rainfall amounts, with up to 33% being significant (depending on location and duration).

- The Engineering Climate Datasets, found on the Historical Climate Data website, provide historical climatic design data for engineering applications. In order to design safe, reliable, and durable infrastructure, engineers and designers require up-to-date specialized climate data, including snow and rain loads, wind loads, ice loads, IDF curves for short-term extreme rainfall amounts, and solar radiation for modelling building energy loading. Climatic design data provide a starting point from which designers apply the factors provided by Environment and Climate Change Canada. The three datasets available for download are:

- **IDF Files:** Short-duration rainfall IDF statistics in the form of tables and graphs with accompanying documentation for various locations across Canada.
- **Canadian Weather Energy and Engineering Datasets (CWEEDS):** Hourly weather conditions occurring at various locations across Canada (564 locations with at least 10 years of data for the period between 1998 and 2017, and 145 locations with at least 48 years of record, starting as early as 1953). The primary purpose of these files is to provide long term weather records for use in urban planning, siting and design of wind and solar renewable energy systems, and design of energy efficient buildings. The files are also applicable to any sector that is weather-sensitive, such as transportation, air quality, agriculture, forestry, tourism, structural design, or general interest.
- **Canadian Weather Year for Energy Calculation (CWEC):** The CWEC files have been developed under the auspices of the National Research Council of Canada. They are derived using statistical criteria from long-term series of up to 30 years of CWEEDS hourly data.

Drafted by: Megan Hartwell, ASTD-CRD, STB
Input from: MSC
Approved by: David Henry, DG, ASTD; Marc D'Iorio, ADM, STB
Date: April 7, 2022

Trends in IDF data rainfall intensities reflect changes in observed annual maximum rainfall observations described in Section 2.2. These may be estimated by comparing previous design intensity values with current ones to show the influence of recent observation on values. A total of 226 climate stations across Canada that had IDF data updated in the Engineering Climate Datasets Version 3.10 also had Version 2.00 data for comparison. The average Version 3.10 data series record length was 37.8 years, compared to 29.1 years for the Version 2.00 data. The median changes in design intensity across all durations and return periods that results from adding 8.7 more years of data are shown in table.

Table 17: Average Trends in Design Rainfall Intensities in Canada – Engineering Climate Datasets Version 2.00 to 3.10

Duration	Return Period						
	2 Year	5 Year	10 Year	25Year	50 Year	100 Year	Average
5 Minute	0.4%	-0.6%	-0.9%	-1.2%	-1.4%	-1.6%	**-0.9%**
10 Minute	0.7%	0.1%	0.0%	-0.2%	-0.3%	-0.3%	**0.0%**
15 Minute	0.8%	-0.2%	-0.4%	-0.4%	-0.4%	0.8%	**0.0%**
30 Minute	0.8%	0.1%	-0.2%	-0.2%	-0.3%	-0.4%	**-0.1%**
1 Hour	0.8%	0.4%	0.0%	-0.6%	-0.7%	-0.7%	**-0.1%**
2 Hour	0.7%	0.1%	-0.2%	-0.4%	-0.6%	-0.7%	**-0.2%**
6 Hour	0.3%	0.0%	-0.4%	-0.6%	-0.7%	-0.7%	**-0.3%**
12 Hour	0.4%	0.2%	0.0%	-0.2%	-0.3%	-0.4%	**0.0%**
24 Hour	0.5%	0.0%	-0.3%	-0.3%	-0.3%	-0.4%	**-0.1%**
Average	**0.6%**	**0.0%**	**-0.3%**	**-0.4%**	**-0.6%**	**-0.5%**	**-0.2%**

On average, there is a slight but insignificant decrease in extreme rainfall intensities, i.e., 10, 25-year, 50-year and 100-year return periods decrease 0.3%, 0.4%, 0.6% and 0.5%, respectively. These is a slight increase of 0.6% in more frequent 2-

\cbpat5

\cbpat5

\cbpat5The data shows a decrease in powerful storm intensities based on 226 climate stations across the country - 100-year storm intensities have decreased 0.5% on average based on the last update of federal data. Major population regions like southern Ontario show no change in extreme rainfall at long term climate stations since 1990, as shown in the new NRC guidelines (appendix E page 17):

\cbpat5

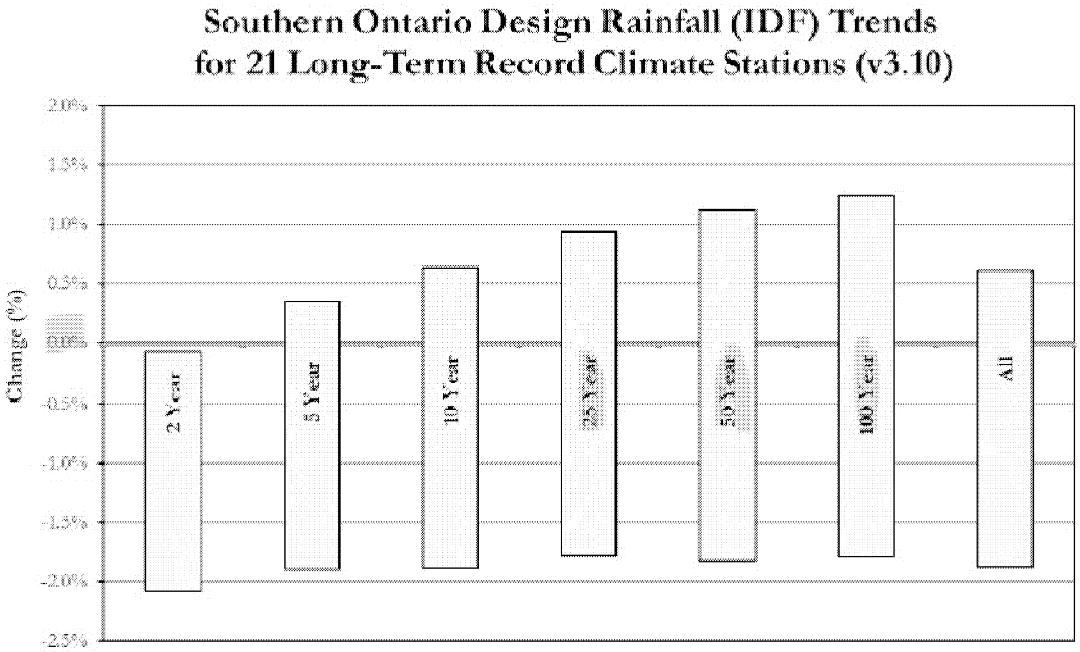


Figure 2: Range in Average Change in Southern Ontario IDF Values for Engineering Design by Return Period – Record-Length Weighted Changes Between 1990 (pre-Version 1) and Version 3.10 Datasets for 21 Climate Stations with Long-Term Records

The City of Saskatoon study *Flood Mapping with Updated Intensity Duration Frequency Curves Incorporating Climate Change Risk 2020* (City of Saskatoon, 2020) was completed in partnership with University of Saskatchewan and Cocordia University to to assess both how rainfall intensities in Saskatoon have changed, and the risks of increased rainfall intensities in the future as a result of climate change. Historical data from 1892 to 2018 was analyzed. Results indicated increasing and decreasing rainfall trends that are mostly statistically insignificant and that vary based on rain gauge location, duration of rainfall, time period, and the methodology used to assess the trend (e.g., a linear trend or a moving average trend).

IDF curves have been updated for use in the Greater Vancouver Sewerage and Drainage District (GHD, 2018). Regional IDF curves previously updated in 2009 were updated in 2018 including data up to 2016 using the QA/QC methods applied by the ECCC. IDF curve data were separated into warm and cool phases of the Pacific Decadal Oscillation, given that intensities genrally decreased in the warm phase and increased in the cool phase, however, all data were used to update IDF curves. It was recommended that in five years the rainfall at representative stations be reviewed to determine if there is a statistically significant trend in observed rainfall. If there is a statistically significant trend, and IDF curve update is recommend, while if there is no trend the IDF curve update can be delayed for five more years. Figure 3 illustrates increases and decreases in IDF data in one zone, depending on duration. It also illustrates appreciable increases in 2-year return period values (i.e., 4% increase) and negligible change in 50 to 200-year return period values. Two zones (Zones 1

\cbpat5

\cbpat5

\cbpat5Please advise how you will be following up on this significant discrepancy between the data and (what appear to be unsupported) statements like in the 2021 budget document. My concern is that policies and program priorities need to informed by data. Currently, it does not appear that any data is being relied upon. What is worse is there is no opportunity to explore what data those writing the budget were relying upon or will rely on in the future

\cbpat5

Lead: MSC

Due Date: April 8

Thanks,

Franco