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The Risk of Termination Shock From Solar Geoengineering

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Key Points::

- We found no reason to dismiss the threat of termination shock. Managing this risk should be a key concern if solar radiation management (SRM) is ever considered for use
- But if current projections about stratospheric aerosols injection characteristics prove accurate, it should be easy to build an SRM system that is resilient and robust
- The motivation to avoid termination shock would be strong. Where many parties can maintain SRM, it cannot be terminated unilaterally

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Abstract If solar geoengineering were to be deployed so as to mask a high level of global warming, and then stopped suddenly, there would be a rapid and damaging rise in temperatures. This effect is often referred to as termination shock, and it is an influential concept. Based on studies of its potential impacts, commentators often cite termination shock as one of the greatest risks of solar geoengineering. However, there has been little consideration of the likelihood of termination shock, so that conclusions about its risk are premature. This paper explores the physical characteristics of termination shock, then uses simple scenario analysis to plot out the pathways by which different driver events (such as terrorist attacks, natural disasters, or political action) could lead to termination. It then considers where timely policies could intervene to avert termination shock. We conclude that some relatively simple policies could protect a solar geoengineering system against most of the plausible drivers. If backup deployment hardware were maintained and if solar geoengineering were implemented by agreement among just a few powerful countries, then the system should be resilient against all but the most extreme catastrophes. If this analysis is correct, then termination shock should be much less likely, and therefore much less of a risk, than has previously been assumed. Much more sophisticated scenario analysis—going beyond simulations purely of worst-case scenarios—will be needed to allow for more insightful policy conclusions.

1. Introduction

Solar geoengineering (also known as solar radiation management or SRM) is a proposal for slowing the rise in global temperatures, or even reversing it, by reflecting a small fraction of inbound solar energy back into space. It has been proposed as a potential method for reducing the climate risks to which the planet is committed from past greenhouse gas (GHG) emissions. The SRM technique currently receiving the most attention is stratospheric aerosol injection, which would work by spraying reflective aerosol particles into the stratosphere to reduce the amount of solar energy reaching the Earth (Rasch et al., 2008); (Crutzen, 2006).

SRM only masks the warming effects of GHGs and is not designed to reduce their concentrations in the atmosphere. Therefore, if SRM were ever used to mask a high level of warming and its deployment were terminated suddenly, temperature would rebound toward the levels they would have reached without the geoengineering (Brovkin et al., 2009; Irvine et al., 2012; Jones et al., 2013; Llanillo et al., 2010; Matthews & Caldeira, 2007; McCusker et al., 2012, 2014). This effect is referred to as "termination shock" or "termination effect." Termination shock could be very damaging for natural and human systems as the rate of warming would probably be much higher than that otherwise expected under anthropogenic climate change (Irvine et al., 2012; Llanillo et al., 2010; Matthews & Caldeira, 2007; McCusker et al., 2014), meaning that both ecosystems and human societies would have less time to adapt to the rapidly changing new conditions (McCormack et al., 2016; Trisos et al., 2018).

1.1. An Influential Concept

Termination shock has been a very influential concept in both academic and popular commentary, and is often cited as one of the most serious threats from the development and deployment of SRM (Hamilton, 2013). The idea has also informed a range of policy messages. In numerous academic papers (see, e.g., Brovkin et al., 2009; Clark et al., 2016; Pidgeon et al., 2013; Vaughan & Lenton, 2012) and high-profile commentary pieces (Appell, 2013; Dean, 2010; Klein, 2014; Pierrehumbert, 2015; Plumer, 2014), it is claimed that once deployed, SRM would need to be maintained for centuries or even millennia to avoid the risk of termination shock. It has also been argued that due to the risk of termination shock, SRM should only be considered an option of last resort for emergency use (Llanillo et al., 2010) or that the cooling from any deployment of SRM should be limited to a level that would not cause a dangerous temperature rebound in the event of termination (Kosugi, 2013). Aggressive mitigation would need to be a prerequisite of SRM deployment in the opinion of McCusker et al. (2014), while Kruger (2015) takes this idea one stage further, arguing not only that SRM should not be deployed without an "exit plan" in the form of very large-scale carbon dioxide removal technologies but also that those costs should be seen as an integral component of the costs of SRM.

Most model studies of SRM have simulated the same general scenario: SRM is deployed to entirely halt future temperature increases under a scenario of very high future GHG emissions, then at a future date the deployment is terminated instantly and permanently. For example, the G2, G3, and G4 scenarios of the Geoengineering Model Intercomparison Project, which have been used as the basis for many modeling studies, all follow this approach (Berdahl et al., 2014; Jones et al., 2013; Kravitz et al., 2011). This modeling convention shows termination shock in its starkest relief, as a large degree of SRM cooling, stopped suddenly and permanently, produces the clearest climate response. However, this is the most extreme termination scenario and there are many other possibilities. SRM need not be deployed either at a large magnitude or indefinitely to usefully reduce the risks of climate change (Kosugi, 2013; MacMartin et al., 2014). Furthermore, large-magnitude SRM deployment could be phased out gradually (Irvine et al., 2012), or it could be interrupted for a time and later restored.

Almost all research papers to date have focused on the impacts of termination shock, ignoring how or why termination might occur, or how likely it might be (with notable exceptions of Barrett, 2014; Baum et al., 2013; Goes et al., 2011). Typically, analysis and commentary either proceed on the basis that some undefined eventuality could cause the sudden and permanent cessation of SRM (Boucher et al., 2013; Plumer, 2014; Rayner et al., 2013; Specter, 2012; Zürn & Schäfer, 2013) or speculate in general terms that termination could be caused by events such as terrorist attacks or natural disasters (Appell, 2013; Bellamy & Lezaun, 2017; Hamilton, 2013; Olson, 2011; Pierrehumbert, 2015).

1.2. Aims and Structure of This Paper

This study aims to address two critical gaps in the literature on termination shock: first, providing some definitions and boundaries for what would and would not constitute a termination shock and second, exploring the factors that would affect the likelihood of the occurrence of a termination shock.

The paper is structured as follows. Section 2 defines termination shock and describes the conditions that must be met for a termination shock to occur. Section 3 plots out the steps by which a range of proposed driver events (such as terrorism, economic collapse, natural disasters, or the discovery of damaging side effects) could lead to a termination shock, and considers where appropriate policy responses might increase the robustness and the resilience of an SRM system against disruptions. In Sections 4 and 5, we draw out some implications of our analysis.

1.3. Assumptions About Deployment Methods and Costs

For the sake of simplicity, we focus on stratospheric aerosols injection (SAI), delivered by high-flying jets, as the method of SRM deployment. SAI would involve releasing aerosols, or aerosol precursors, into the stratosphere, where they would have an e-folding time of about one year and particles would circulate to form a global aerosol cloud (Robock et al., 2008). A number of proposals for delivering aerosols to the stratosphere have been assessed, and high-flying jets have been judged feasible in part as they would require little technical innovation (McClellan et al., 2012; Moriyama et al., 2016; Robock et al., 2009). In line with the highest current estimates for a very large-scale deployment, we assume it would cost an initial outlay of about $50 billion for the hardware needed for SAI and $12.5 billion per year for deployment.

2. Defining Termination Shock

We define a termination shock as a rapid and substantial rise in global temperatures following a cessation of SRM deployment.

There are thus three criteria that need to be met for termination shock to occur: the amount of SRM cooling would need to be large, it would need to be terminated suddenly, and it would need to stay off for a substantial period. To better determine what would constitute a termination shock, it is therefore necessary to provide answers to the following questions:

- How large must the SRM cooling effect be before termination shock becomes possible?
- How slowly would large-scale SRM need to be phased out to avoid causing a rapid and substantial warming?
- How long would a disruption to large-scale SRM have to persist to cause a substantial warming?

2.1. How Large Must the Cooling Effect of Solar Geoengineering Be for There to Be the Potential for a Rapid and Substantial Warming?

If SRM of any scale were to be terminated suddenly, a rapid warming would follow. The magnitude of this warming would depend on the amount of cooling that was being exerted at the time of termination. Most of the modeling studies to date have simulated quite dramatic termination scenarios, where SRM is offsetting the warming effect of many decades of GHG emissions at the time of termination so that a rapid, substantial rise in global temperature follows. At the other end of the spectrum, it is also clear that a very small magnitude deployment of SRM poses very little risk as there would not be a substantial rise in temperatures if it were terminated. Whether or not solar geoengineering could be deployed at such a scale that it would have an appreciable effect on global temperatures without carrying a risk of a rapid and substantial warming if it were to be terminated is therefore an important question (Kosugi, 2013).

There is no widely accepted definition of what would constitute a substantial or dangerous rate of warming—what therefore would constitute termination "shock." However, useful benchmarks can be found in recent climate trends and the temperature response to the representative concentration pathways (RCPs), the scenarios of future GHG emissions used by the climate modeling community to simulate the impacts of climate change. The change in temperature between the last two decades (1997–2006 and 2007–2016) was approximately 0.1°C (Morice et al., 2012). This decadal rate of change is low compared to other periods in the recent past due to the strong el-Nino event of 1997–1998 and the so-called global warming hiatus (1998–2013). The RCP 2.6 scenario represents an optimistic scenario of emissions cuts with implementation of substantial negative emissions before 2100 that reaches a radiative forcing of 2.6 W m^{-2} by 2100 and keeps temperatures below 2°C above the preindustrial in most models. In this "best case" scenario, the peak rate of warming is around 0.2°C per decade. At the other end of the spectrum, in the RCP 8.5 scenario, models project a rise in temperature of more than 4°C by 2100 and a peak rate of warming of around 0.5°C per decade (Knutti & Sedlacek, 2013). On the basis of these examples, we suggest that a substantial rate of additional warming for our purposes is of the order a few tenths of a degree Celsius per decade. This is in line with the threshold for a termination shock of 0.2°C per decade for a termination suggested by Kosugi (2013).

If a threshold for termination shock is defined in this manner, then it is also possible to define a cooling threshold below which an instantaneous cessation of SRM would lead to less than this threshold rate of additional warming. It is possible to estimate this threshold magnitude of cooling forcing by evaluating the response of global temperatures to an instantaneous change in forcing. Simulations by a range of Earth system models project that in response to an instantaneous quadrupling of CO_2 concentrations (an instant change in radiative forcing of about 7.4 W m^{-2}) around one half of the equilibrium temperature response occurs within a decade, with around three quarters occurring within 100 years (Caldeira & Myhrvold, 2013). Therefore, the cooling threshold would be roughly double the threshold decadal rate of warming. Adopting the suggestion of Kosugi (2013) of a maximum acceptable rate of warming of 0.2°C implies a cooling threshold of 0.4°C. Modest deployments of SRM, at or below this threshold, could still have appreciable benefits, see Kosugi (2013) and MacMartin et al. (2014). Furthermore, it follows that if SRM were exerting less cooling than this threshold, there would not be a risk of a substantial rapid additional warming. Note that the warming effects of termination would be in addition to the ongoing climate response to other anthropogenic forcings and the total rate of warming could therefore be higher.

Therefore, for the purposes of defining termination shock, we suggest that a cooling of order a few tenths of a degree Celsius, equivalent to roughly a decade of warming, defines the approximate magnitude of SRM deployment for which the risk of termination shock could become appreciable. For larger deployments of solar geoengineering that offset many decades of warming there would be a clear risk of a rapid and substantial global warming, whereas for a smaller deployment that offset less than a tenth of a degree Celsius, there would not. This suggests that if SRM forcing were ramped up slowly, there would be a certain period of time before the cooling were large enough to pose a potential risk of termination shock.

2.2. How Quickly Could Substantial SRM Forcing Be Phased Out Without Causing a Substantial and Rapid Warming?

If a larger SRM deployment were phased out sufficiently slowly, the rate of warming could be limited, and termination shock avoided, even where it exerted a very large cooling effect. As we argued in the previous section, guidance can be found from the simulated climate response to the RCP emissions scenarios. Limiting the rate of warming to that expected in the extreme RCP 8.5 scenario would imply phasing out SRM at a rate of 0.5°C per decade, but this is generally regarded as likely to be dangerously rapid. Limiting the rate of warming to the maximum expected in the optimistic RCP 2.6 scenario, 0.2°C per decade, would imply a phase out of 50 years per degree Celsius of cooling.

2.3. How Long Would a Disruption to Large-Scale SRM Have to Persist to Cause a Substantial Warming?

If something disrupted large-forcing SRM deployment activities and they were not resumed, then a rapid warming would follow. However, if SRM deployment were restarted before a substantial increase in temperatures had been realized, then the impacts of the disruption would be much less than for a full termination shock. The length of this "buffer period" during which forcing can be restored would be determined by three factors: the timescale on which the radiative forcing from deployment activities decays, the timescale on which global temperatures respond to changes in the radiative forcing, and the magnitude of the forcing.

First, instantly halting deployment would not stop the aerosols which had been released up until that point from scattering light and so exerting a radiative forcing on the climate. From observations of the stratospheric aerosol burden following large volcanic eruptions, an e-folding time of roughly one year has been calculated (Robock et al., 2008; Stenchikov et al., 1998). This means that the cooling effect of stratospheric aerosol geoengineering would persist for many months after termination. It follows that with an e-folding time of one year, 98% of the aerosol burden would remain after a week, 92% after a month, and that it would take over eight months for the burden, and hence the forcing, to fall to under half of what it was at the time of termination. However, this timescale would only be a matter of days for marine cloud brightening and cirrus cloud thinning, as tropospheric aerosols only have a lifetime of days before they are rained out or fall to the ground (Latham, 1990; Mitchell & Finnegan, 2009).

Second, it takes some time for surface air temperature to adjust to a change in radiative forcing because it takes time for the Earth's atmosphere and its oceans to warm. The process is not well described by a simple e-folding time, but as we noted before, Caldeira and Myhrvold (2013) reported that around one quarter of the equilibrium warming response to an instantaneous change in forcing occurs within a year, half within a decade, and three quarters within 100 years. Cao et al. (2012) extend this analysis to shorter timescales, finding that global temperature would rise to around 7% of its equilibrium value within a month.

Third, the smaller the magnitude of forcing at the time of termination, the longer it will take to cross a given threshold of warming. However, the effect of disruptions to very large-scale deployments which would lead to substantial, rapid warming will still take some time to do so for the reasons given above.

We do not attempt to precisely define the length of disruption required to produce a substantial warming, but we do provide a rough estimate of the timescale based on the results described above. The timescale of about one year for the decay of forcing following a cessation of stratospheric aerosol geoengineering and the delayed response of temperature to a change in radiative forcing means that it would take several years for the temperature to rise by an appreciable fraction of the eventual response following a cessation of stratospheric aerosol geoengineering. This means that if large-scale stratospheric aerosol geoengineering were redeployed at the original level within a few months of a disruption, then there would not have been time for an appreciable rise in temperatures to occur. However, for marine cloud brightening and cirrus cloud thinning, the days-long lifetime of the forcing effect implies the timescale during which they can be safely restored would be shorter. However, it would still take weeks before a substantial rise in global temperature could occur due to the thermal inertia of the land and surface ocean. Therefore, there would be, at minimum, a buffer period of the order of weeks or months, depending on the form and magnitude of SRM deployed, during which forcing could be restored in order to avert a substantial increase in temperatures.

In Section 4, we consider the broader impacts of interruptions to SRM and make suggestions for future research on this topic.

3. Pathways to Termination

An interruption to the political, economic, or technical capabilities to maintain SRM could result in an interruption to the SRM deployment. In this section, we plot out the pathways by which different events (referred to here as drivers) could cause such interruptions and lead to termination, and we identify the points at which timely policy intervention could avert termination shock.

By sketching out the pathways from driver events to termination, we attempt to provide a foundation for analysis of this neglected issue. The reader can see the factors that we consider to be influential in determining whether termination shock occurs and can easily identify points of disagreement, or indeed, more accurately target their praise.

We have divided the pathways to termination into two classes: (1) where external drivers *force* termination even where humanity wants SRM to continue and (2) where termination would be an *elective* political decision, taken when continuation of SRM were still possible.

3.1. Forced Termination of SRM

Drivers in this class would entail external events forcing termination even where there was a desire for SRM to continue. Forced termination might be caused by destruction of the SRM delivery infrastructure, or interruptions to the economic or political capacity to maintain deployment.

3.1.1. Forced Termination Pathway 1: Destruction of Deployment Infrastructure

It has been suggested that destruction of the SRM deployment infrastructure, for instance by terrorist attack, could cause termination shock (Bellamy & Lezaun, 2017; Olson, 2011; Pierrehumbert, 2015). By plotting out the pathway, it becomes clear that a number of conditions would have to be met for destruction of infrastructure to lead to termination shock (see Figure 1).

First, an attack must overcome any defensive systems and disable a large fraction of the deployment capability. Achieving more than 1 W m^{-2} of cooling through stratospheric aerosol injection would require fleets of hundreds of aircrafts, most likely operating out of numerous air fields around the world, so a physical attack would have to be extremely well planned, coordinated, and supported to be effective. A cyberattack might conceivably be able to disable an entire system at once, however.

Second, even if defenses failed, a termination shock would still not be automatic. There would still be a buffer period of months (at least) during which the system could be repaired or a backup system deployed before the global temperature rise became significant. If no replacement SRM system were deployed during this time, termination shock would occur.

It should be relatively simple to greatly increase the robustness of an SRM system against destruction of deployment infrastructure. Basic defenses of the delivery equipment, such as those that guard nuclear power plants or military bases, are an obvious precaution. Also, the more geographically distributed the aerosol delivery system, the harder it would be to disable a large fraction of it.

Even if a terrorist attack were successful in stopping SRM globally, relatively easy and cheap policy choices would allow operations to restart soon after disruption. If any capable party, anywhere around the world,

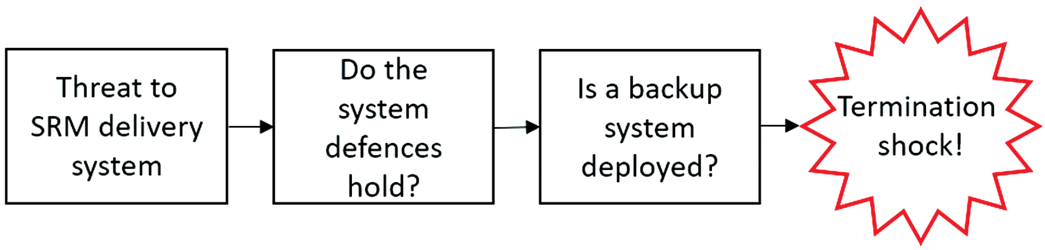

Figure 1. The pathway to termination shock from a terrorist attack on the delivery system.

kept backup SRM delivery hardware, it could be redeployed to maintain the SRM cooling before temperatures started to rise rapidly.

3.1.2. Forced Termination Pathway 2: Catastrophe, or the Destruction of Economic or Political Capacity to Maintain SRM

Beyond the destruction of the SRM deployment infrastructure, termination could be forced if a large catastrophe (such as a natural disaster, an economic collapse, or a war) were to interrupt the economic or political ability to maintain an SRM program. Figure 2 outlines this pathway. First, the deployer(s) would have to suffer an event that destroyed their economic and/or political capacity to maintain SRM. Second, there would need to be no other actors capable of redeploying before temperatures rose rapidly. If neither the original deployer nor any other party were capable of redeploying an SRM system in the months after a catastrophe, then termination shock would occur.

The same measures that would increase the resilience of SRM against terrorist attacks would also increase resilience against disasters that were local or regional in scope. If spare deployment capacity were maintained or numerous nations were capable of deployment, then the SRM system would be resilient against catastrophes that were confined to one country or one region.

Not all catastrophes are regional though, and various global calamities (such as nuclear war, a global pandemic, or an economic collapse) have been suggested as possible drivers of termination (Barrett, 2014; Hamilton, 2013; Olson, 2011). Amidst a true global catastrophe, one that destroyed the capacity of all competent actors to maintain deployment, backup delivery equipment would not help.

While there should be no doubt that a global catastrophe could destroy global capacity to maintain SRM, it is worth noting quite how destructive such an event would have to be. For example, consider how large the economic damage would have to be before maintaining SRM became unaffordable. If nations were to cooperate to maintain SRM—a proposition that we find reasonable given the projected damages of termination shock—then global gross domestic product (GDP) would still need to drop by over 90% before maintaining SRM would cost more than 1% of the collective postcatastrophe GDP of the world's top 20 economies.[1] Even assuming no international cooperation, the catastrophe would still have to be colossal to force SRM termination based on economic factors. Even if a disaster wiped off 70% of their GDPs, China or the United States alone could still deploy SRM for less than 1% of their postcatastrophe GDPs (IMF, 2014). To put these figures in context, arguably the greatest international calamities of the last century, World War I and Spanish influenza combined, the Great Depression, and World War II caused GDP in Europe to fall by 13%, 8%, and 21%, respectively (The Maddison-Project, 2013).

Therefore, if spare deployment capacity were maintained, or could be brought online quickly, a catastrophe would have to be on a scale unprecedented in modern history to force termination shock. Such events are not inconceivable though, and an asteroid strike, global nuclear war, or catastrophic pandemic could force an end to SRM even where there was a desire to maintain it. In this instance, few policies could prevent termination. We reflect on this possibility in Section 4.3.

3.2. Elective Termination of SRM

So far, the paper has only considered factors that could force cessation of SRM where there was a continuing commitment to maintaining it. It is also possible that termination would be a political choice. We assume that it would be widely understood how damaging a termination shock would be, such that no party would bring on termination shock out of ignorance. However, politicians vehemently opposed to geoengineering could come to power, there could be a revolution, or a coalition of countries might decide that they were suffering unacceptable harms from SRM and push for it to be stopped.

Figure 3 outlines the pathway from political opposition to SRM through to termination shock. First, actors opposed to SRM would need to gain sufficient power to force an end to deployment within their own jurisdictions. It would also need to be the case that they preferred termination shock to other forms of SRM

[1] Assuming that SRM deployment cost $50 billion in its first year (which is above the highest current cost projection), and if the global economy did not grow any larger than it is today, global GDP would need to drop from nearly $62 trillion down to $5 trillion (IMF, 2014).

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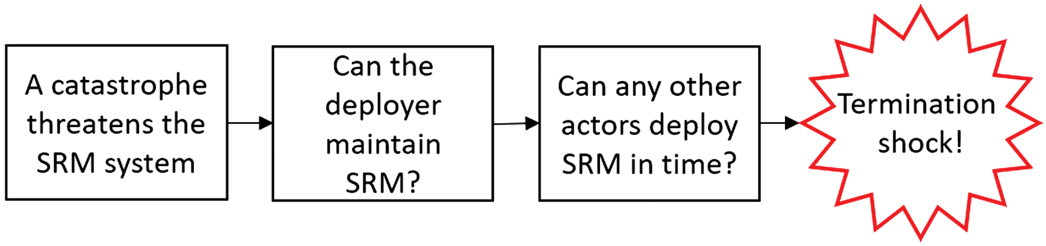

Figure 2. The pathway to termination from a catastrophe.

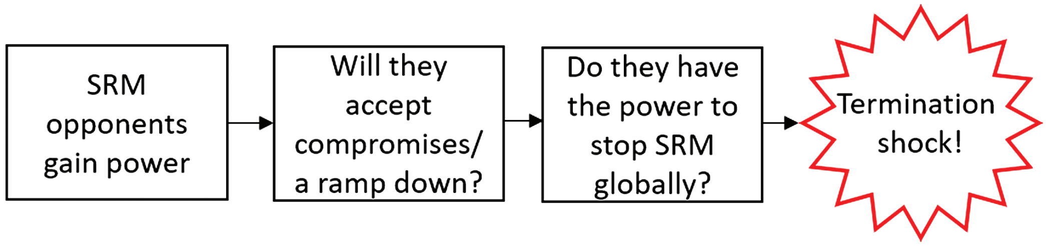

Figure 3. The pathway to elective termination of SRM.

deployment (such as a different technique, different aerosol spraying locations, or different aerosol type), or to any form of slower phasing out of deployment. Finally, they would need to have the power to impose their will for termination on all other parties, all around the world, even those who wanted to maintain SRM.

A number of different policies might be able to reduce the drivers of elective termination. In particular, decision-making mechanisms that reduced possible grievances over the impacts of SRM, or over the decision to deploy it in the first place, would reduce the level of antipathy to an ongoing geoengineering deployment. Making sure that deployment was agreed as widely as possible and was supported by strong support for adaptation and compensation regimes could help reduce injustices and perceptions of injustice. Slowly ramping up the SRM cooling, with extensive environmental monitoring before and after deployment, could reduce the risks of damaging environmental effects being discovered only after the point where termination shock had become possible. The development of alternative SRM techniques or deployment methods, which might maintain cooling while avoiding given environmental drawbacks, could allow the SRM system to be modified to reduce undesired impacts. Finally, stopping SRM need not involve termination shock, as parties pushing for an end to SRM might be open to a gradual phase out of deployment, reducing the rate of temperature change and hence the impacts of termination (Irvine et al., 2012).

4. Discussion

Most analysis of termination shock to date has addressed two issues. Modeling studies have mostly sought to quantify the climate response to a sudden and permanent cessation of large-scale SRM deployment, while commentaries have discussed the policy implications of this worst-case possibility. Here, we have addressed a number of key gaps in that analysis. We have looked beyond the extreme cases of termination shock to create a more nuanced picture of the implications of stopping SRM deployment, and we have suggested boundaries on what would constitute a termination shock. We have also made a first attempt to methodically analyze the pathways that could lead to a cessation of SRM deployment, from terrorist attacks and natural disasters to political decisions, considering also policy options that might be employed to reduce the likelihood of termination shock.

4.1. The Physical Characteristics of Termination Shock

Clarifying the physical dimensions of what would constitute a termination shock leads us to conclude that three conditions must be met for termination shock to occur:

1. SRM deployment would have to be exerting a substantial cooling.
2. Deployment would have to be terminated suddenly.

3. Disruptions to SRM deployment would have to persist for many months or longer.

From this, we conclude that the common claim "once you start SRM it cannot be stopped" is just not accurate. Even if SRM were used to offset a large amount of GHG warming, it could be stopped without incurring termination shock if it were phased out slowly. Additionally, it would be possible to suddenly terminate a low level of SRM cooling (we tentatively suggest an upper limit of few tenths of a degree Celsius), without risking impacts worthy of the name of termination shock (Kosugi, 2013; MacMartin et al., 2014). Some might question whether using SRM to exert a few tenths of a degree of cooling would have any benefits, but studies investigating the climatic differences between global warming of 1.5°C and 2°C—the two temperature goals cited in the Paris climate agreement—indicate that the extra 0.5°C of warming could mean significantly larger impacts on sea level rise, coral bleaching, agriculture in the tropics, and heat waves (Schleussner et al., 2016).

Knowing that SRM cooling could be ramped up to a few tenths of a degree without fear of termination shock also has implications for research. Scientists could explore the environmental impacts of global SRM deployment knowing that the system could be safely turned off if any unacceptable impacts were discovered. Such research could inform decisions as to whether to deploy SRM at greater intensities, past the point at which termination shock becomes a concern. Future modeling work could help to quantify the level of cooling required for a termination of SRM to be reliably detectable against natural variability.

Another important finding is that the years-long residence time of stratospheric aerosols and the substantial thermal inertia in the climate system imply that it would take months for a disruption to SRM deployment to result in a substantial change in global temperatures. This is crucial for analyzing the risks of termination shock, as it means that humanity would have a period of several months in which to resume deployment of SRM in the event of a disruption. Future modeling work should address the potential impacts of months- or years-long interruptions to SRM deployment, and to evaluate how long such interruptions would have to persist to be detectable.

4.2. The Motivation to Avoid Termination Shock

Reflecting on the physical characteristics of termination shock and our analysis of scenarios by which driver events could lead to termination, we make two broad arguments:

1. There would be a strong motivation to maintain an SRM system and avoid termination shock.
2. The projected technical characteristics of SRM mean that it should be relatively easy to make a system that would be highly robust and resilient against most proposed drivers of termination.

Regarding the motivation to avoid termination shock, once SRM is deployed to a level at which its termination would produce large damages, it seems self-evident that there would be a strong and widely held incentive to maintain the system. The threat of termination shock is already a central concern about SRM development, and we expect that this concern would only increase if the use of SRM ever appeared to be a realistic prospect.

We draw parallels to the level of societal effort that goes toward protecting and maintaining critical infrastructure. Where damage to infrastructure would present immediate dangers, there is often a high level of security (as with nuclear power plants or airports). Where prolonged interruption of the infrastructure service would be dangerous, there is often investment in backup systems. For example, to ensure reliable electricity supplies, countries maintain spare power stations while hospitals have backup generators. Looking internationally, the European Union, China, and Russia have developed their own independent satellite navigation systems to parallel the original US global positioning system, even though they are able to use the American system.

While there would be opposition to SRM use under any deployment scenario, we believe that even where people or states were initially opposed to the deployment of SRM, this would be unlikely to carry over to support for sudden termination in the majority of cases. To argue by analogy we believe that few people who opposed the construction of a nuclear power plant near their homes would want it to be shut down by removing the cooling rods and allowing a meltdown. Instead, we contend opponents would lambast the original decision to build the plant while agitating for it to be decommissioned as quickly and safely as possible. Similarly, we believe that regardless of initial antipathy to the use of SRM, most in favour of ending deployment would prefer to see it phased out carefully rather than terminated suddenly.

Note that we are not arguing that actors must behave with perfect rationality in order to guard against termination. It is more that they must just avoid wanton *irrationality*. We think that it would be absurdly reckless for capable nations to ignore the risk of termination shock and to fail to make simple security and capacity investments to avoid it. However, there are instances where sufficient precautions are not taken to avoid damages from failing systems (such as the engineering failures that led to the flooding of New Orleans caused by Hurricane Katrina (Van Heerden, 2007), or that the Fukushima nuclear plant might be compromised in the event of a tsunami (Synolakis & Kânoğlu, 2015). It would be useful to research where and how societies protect against damage from interruption to important infrastructure—and crucially where they do not.

4.2.1. Would Discovered Damages Overwhelm the Motivation to Maintain SRM?

Some have argued that the motivation to maintain SRM could be trumped by states aggrieved that they were suffering damages from SRM use (Burns quoted in Kahn, 2018; Robock, 2018). What if a nuclear-armed nation decided that it wanted SRM deployment stopped, the argument goes, and seemed prepared to act to get its wish? What if countries experienced damaging droughts and demanded that geoengineering be terminate immediately? While obviously possible, we argue that there would be strong factors working against this, meaning it might be much less likely than it superficially appears.

First, it would have to be the case that the discovered impacts of SRM were so damaging that they were perceived to be more dangerous than termination shock, and that they were not discovered during any research or ramp-up period. We believe that ceteris paribus these facts work against each other, and that environmental impacts more damaging than termination shock would likely be discoverable when SRM were being tested and ramped up. This is a strong reason for any SRM to be studied in depth before being considered for use, then, if ever deployed, to be ramped up slowly and accompanied by careful monitoring and evaluation.

Second, termination due to discovered damages would be like any other form of elective termination (Section 3.2). Those pushing for an end to SRM would need to have the power to force the entire planet to suffer termination shock in spite of the projected global damages. Therefore, where the capability to deploy SRM is distributed around the world, SRM cannot be terminated unilaterally—a key finding of this paper.

4.2.2. Implications for Justice and Lock In

It must be noted that the fact that SRM could not be terminated unilaterally is a double-edged sword. While we believe it means that termination shock is much less likely, it might have significant justice implications. If a minority of people or regions (even conceivably a majority) were to suffer serious adverse effects of SRM, they might not be able to force an end to it. This effect could be particularly pronounced if those suffering were poor and vulnerable, without power or a strong political voice.

In turn, this could have implications for "lock-in." It has been noted elsewhere that the threat of termination shock could end up locking humanity into continued use of SRM, even if damaging impacts are discovered (Burns, 2011; Ott, 2012). Our analysis adds some weight to this idea, as once SRM were being used to the point where termination shock became possible, there would be an increased incentive to maintain it, and it could prove very difficult to stop deployment unless the most powerful states agreed.

4.3. The Capacity to Avoid Termination Shock

Where societal systems are affordable, distributed, and flexible, and where interruptions take considerable time to result in harms, they should be quite robust and resilient against disruptions caused by external shocks. We think that this is evident from systems like global food production or electricity generation. Prolonged termination of either would cause significant damage, but there is little societal worry about this, in part because it is reasonable to surmise that persistent termination would not happen in all but the most calamitous of disasters. Our analysis in Section 3.1 leads us to believe that it would be relatively simple to build an SRM system that fit these criteria:

- Geographically distributed, with deployment from many sites.

- Affordable enough for multiple actors to maintain independent systems or backup deployment hardware.
- Slow to lead to damages following disruption, with months between termination and the onset of the effects of termination shock.

Therefore, if a few nations separately or collectively invested in excess deployment capacity, and the capability to redeploy SRM were distributed, then the system should be resilient in the face of anything but a sustained global calamity, such as a global nuclear war or an unprecedented pandemic.

However, major global catastrophes may occur, which could conceivably cripple the global capacity to maintain SRM. Some have questioned how much additional suffering would be caused by SRM termination shock in the wake of a global nuclear war, for instance (Barrett, 2014). However, Baum et al. (2013) explore this possibility in compelling depth, and argues that a termination shock could compound the risks of an initial catastrophe, conceivably turning a disaster into an extinction-level event if a rapidly warming climate made it even harder for humans to survive. While noting the potential for termination shock to cause a “double catastrophe,” we suggest that SRM is not unique in this regard. Global society is reliant on a number of other advanced sociotechnical systems (such as farming or healthcare) whose disruption would compound human suffering following a global calamity. Future research on such “double catastrophes” is warranted in the context of ongoing research into existential risks (Bostrom, 2013). It is important to understand the potential impacts of such high-impact low-probability events, and consider how the risks might be managed, or whether they could be great enough to preclude SRM use beyond a certain magnitude.

5. Conclusion

This study has made a first attempt to rigorously analyze the concept of SRM termination shock. It has characterized the physical dimensions and has explored the potential pathways by which a range of drivers could lead to termination, as well as the potential policy responses that might reduce its risk. We have found, as others have before, that starting SRM does not mean that it cannot be stopped, as it should be possible to exert a few tenths of a degree of geoengineered cooling before reaching a point where termination shock even became a possibility. We believe that beyond that point, there would a strong motivation to maintain an SRM system, and we note that if the assumptions in this paper prove reasonable, it should be feasible to build an SRM system that would be robust and resilient against all but the most destructive of global calamities, and therefore secure against termination shock, except in extremis.

Protecting SRM infrastructure from attack should not be any harder than protecting existing critical infrastructure such as power plants or airports, making it hard for an act either of God or man to destroy enough of the infrastructure to severely disrupt deployment. There would be a buffer period of (at least) several months after SRM were terminated before global temperatures started to rise dangerously, giving time for redeployment. Furthermore, if the technology and knowledge required to implement SRM were widely available, numerous states could maintain SRM cooling if the original deployer proved unable or unwilling to continue. This means that a distributed deployment system would be resilient against local or regional catastrophes, be they economic, political, or physical. We have outlined how vast a global catastrophe would need to be before it forced the termination of SRM on economic grounds. While some have argued that political pressure could easily force termination shock, we disagree with this simplistic characterization. In a world where multiple parties were capable of deployment, SRM could not be terminated unilaterally. Those wishing to stop SRM cooling would need to be able to force their preference—and the damages of termination shock—on all other actors around the world.

We therefore conclude that termination shock is much less likely than previous work seems to assume, because we think we have demonstrated that it should be much easier to avoid than has been previously been recognized. As such, this paper challenges the common and unhelpful framing in which evaluation of termination shock had become mired, where only the most dramatic termination scenarios are modeled and discussed, and where the risks of termination shock are evaluated by considering only the magnitude of impacts without exploration of their likelihood. We believe that this warrants a change to the way in which termination shock scenarios are both modeled and discussed in popular and academic literature. It is not possible to reach useful policy conclusions based on analysis of the worst-case scenarios, such as those modeled in the G2 and G3 scenarios from the Geoengineering Model Intercomparison Project. Similarly, it is not justifiable to draw insights about the risk of termination shock by reporting the magnitude of the worst possible impacts, while leaving aside consideration of the likelihood of events that could cause or prevent termination. Risk analysis must address both likelihood and impacts, and a range of more sophisticated SRM deployment and termination scenarios is needed to build up an evidence base that allows for more informed policy messages.

This paper has found no reasons to dismiss the threat of termination shock, however, and if SRM is ever developed to the point where deployment appears a realistic possibility, management of the risk of termination shock should be a central concern. We have outlined ways that an SRM system could be made robust and resilient, but this does not mean that a robust and resilient system would be implemented in real life.

Also, our analysis is founded on a set of assumptions that we believe reflect the current understanding of the costs and characteristics of an SRM system, but different assumptions might produce different conclusions. For instance, if SRM proves much costlier than currently projected, or much more difficult to realize technically, then fewer nations would be able to build SRM systems and the capacity to maintain SRM would be less distributed, and therefore less resilient against external threats.

Our final conclusion is the most obvious and important. The best way to avoid termination shock would be to avoid a situation where a large amount of SRM would be needed to reduce committed climate risks. Strong action on mitigation would reduce the amount of SRM necessary to maintain a stable global temperature. The development of safe and scalable carbon dioxide removal techniques could reduce the cooling needed from SRM after deployment, and strong adaptation investment would reduce the suffering from the residual climate impacts to which Earth is already committed.

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