Double Catastrophe: Intermittent Stratospheric Geoengineering Induced By Societal Collapse

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Environment, Systems and Decisions 33(1):168-180. This version: 23 March 2013

Abstract

Perceived failure to reduce greenhouse gas emissions has prompted interest in avoiding the harms of climate change via geoengineering, that is, the intentional manipulation of Earth system processes. Perhaps the most promising geoengineering technique is stratospheric aerosol injection (SAI), which reflects incoming solar radiation, thereby lowering surface temperatures. This paper analyzes a scenario in which SAI brings great harm on its own. The scenario is based on the issue of SAI intermittency, in which aerosol injection is halted, sending temperatures rapidly back toward where they would have been without SAI. The rapid temperature increase could be quite damaging, which in turn creates a strong incentive to avoid intermittency. In the scenario, a catastrophic societal collapse eliminates society's ability to continue SAI, despite the incentive. The collapse could be caused by a pandemic, nuclear war, or other global catastrophe. The ensuing intermittency hits a population that is already vulnerable from the initial collapse, making for a double catastrophe. While the outcomes of the double catastrophe are difficult to predict, plausible worst-case scenarios include human extinction. The decision to implement SAI is found to depend on whether global catastrophe is more likely from double catastrophe or from climate change alone. The SAI double catastrophe scenario also strengthens arguments for greenhouse gas emissions reductions and against SAI, as well as for building communities that could be self-sufficient during global catastrophes. Finally, the paper demonstrates the value of integrative, systems-based global catastrophic risk analysis.

Keywords: geoengineering, societal collapse, global catastrophic risk, scenario analysis, climate change

1. Introduction

Perceptions that humanity is failing to reduce greenhouse gas emissions adequately have prompted attention to the possibility of counteracting the effects of emissions through geoengineering, which we define as the intentional manipulation of global-scale Earth system processes (Crutzen 2006; Wigley 2006). Perhaps the most promising geoengineering proposal is stratospheric aerosol injection (SAI). Aerosol particles injected into the stratosphere would reflect sunlight away from Earth, thereby cooling the surface. SAI is estimated to be several orders of magnitude easier and less expensive per unit temperature decrease than reducing emissions (Barrett 2008; Robock et al. 2009; Schelling 1996). But SAI also raises several important concerns (Robock 2008; Tuana et al. 2012).

This paper analyzes a scenario involving one of the most important concerns about SAI: intermittency. If aerosol injection is intermittent, that is, if particles are not continuously injected into the stratosphere, then temperatures rapidly increase as the existing particles circulate toward the poles and fall out of the atmosphere. The rapid temperature increase could be highly damaging to human and ecological systems. Our scenario involves a catastrophic societal collapse during SAI that causes intermittency. The rapid temperature increase is then a second catastrophe disrupting an already-vulnerable population. The effects of this double catastrophe could be quite severe, possibly even causing human extinction. While the possibility of this scenario is insufficient to conclude that SAI should not be pursued, it does strengthen the argument against SAI by showing how SAI could contribute to a global catastrophe.

The SAI double catastrophe scenario could play an important role in the economics of climate change risk. Recent literature on the economics of climate change suggests that the risk analysis is driven by the possibility of global catastrophe from large temperature increase (Weitzman 2009). But SAI (and other geoengineering) could keep temperatures stable. Other research has found that SAI may not pass a cost-benefit test due to the risk of intermittency (Goes et al. 2011). But this research does not consider what would cause the intermittency. As long as the capacity to continue SAI exists, intermittency may be unlikely due to the strong incentive to avoid it.[1] A societal collapse could cause intermittency despite the incentive and could make the damages even more severe due to there being two catastrophes together. The worst-cases for SAI double catastrophe could even include human extinction. Thus, the specifics of the SAI double catastrophe scenario could play a large role – perhaps even a dominant role – in analysis of the risk from greenhouse gas emissions and from SAI.

The paper is organized as follows. Section 2 provides background on global catastrophic risk and scenario analysis. Section 3 develops the SAI double catastrophe scenario in detail, including the initial climate change that occurs before SAI is implemented (Sect. 3.1), the implementation of SAI (Sect. 3.2), the societal collapse that causes intermittency (Sect. 3.3), and the SAI intermittency and double catastrophe (Sect. 3.4). Section 4 discusses implications of the scenario for SAI decision making. Section 5 concludes.

2. Background

Our discussion of the SAI double catastrophe scenario is motivated by considerations from global catastrophic risk and scenario analysis. In short, our focus on SAI double catastrophe is motivated by the global catastrophic risk issue, and our use of scenario analysis to study SAI double catastrophe is motivated by aspects of scenario analysis methodology. Some background on both of these topics will be helpful before going into detail on the scenario.

2.1. Global Catastrophic Risk

Global catastrophic risks are risks of events that would significantly harm or even destroy humanity at the global scale. As such, they are risks of the highest magnitude, regardless of probability. Global catastrophic risk has received considerable research interest over recent years.[2] Global catastrophic risk is similar to the concept of existential risk, which refers more narrowly to risks to the existence of humanity (i.e. human extinction) or related events (Bostrom 2002; 2012). Another related concept is that of global survival, which refers to efforts to prevent or endure global catastrophes (Seidel 2003).

A core reason for focusing on global catastrophic risk is because of its significance for expected value maximization. The moral foundations of risk analysis, cost-benefit analysis, and related

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[1] Intermittency without societal collapse is plausible, for example if a group opposed to SAI on moral grounds gains control of the SAI.

[2] Some major recent publications on global catastrophic risk and related concepts include Bostrom and Ćirković (2008); Martin (2007); Matheny (2007); Posner (2004); Rees (2003); Rockström et al. (2009); Smil (2008); Sunstein (2007); and Tonn and MacGregor (2009a). An extensive global catastrophic risks bibliography can be found at http://sethbaum.com/research/gcr/bibliography.pdf.

paradigms are all rooted in some form of expected value maximization, in which the best actions are those that result in the largest expected value given uncertainty about the consequences of the possible actions. A global catastrophe would result in a large decline in value, with the largest declines coming from catastrophes that result in the permanent destruction of advanced technological civilization. Human extinction events are included here (Matheny 2007; Ng 1991). Also included are civilization collapses in which some humans are still alive but unable to ever rebuild civilization. Such a population would likely be smaller and more vulnerable to extinction by subsequent catastrophes. If nothing else, the population would go extinct when changes in the Sun render Earth uninhabitable in about five billion years, whereas a civilization with advanced technology could colonize space and survive for many orders of magnitude longer (Baum 2010; Tonn 2002). The scenario in Sect. 3 and decision analysis in Sect. 4 are heavily oriented toward the possibility of SAI double catastrophe causing permanent destruction of advanced technological civilization.

Many discussions of global catastrophic risk treat specific risks in isolation. These discussions are limited because they neglect the various ways in which possible catastrophic events and risk reduction measures can interact with each other. One global catastrophe could cause another, such as climate change causing biodiversity loss (Fischlin et al. 2007). The net effects of multiple global catastrophes could be more severe if they occur simultaneously than if they occur at separate times, such as the “singular chain of events” described in Tonn and MacGregor (2009b), in which several smaller events combine to cause human extinction. Or the net effects could be less severe, such as nuclear winter arriving during a period of intense global warming, thereby resulting in a more moderate average global temperature. Measures taken to reduce some risks could exacerbate others, resulting in risk–risk tradeoffs (Graham and Weiner 1995), such as nuclear electricity reducing greenhouse gas emissions but increasing nuclear weapons proliferation. Other measures could reduce multiple risks at once, such as stockpiling food, creating isolated refuges for humans (Hanson 2008) or agricultural seeds (Charles 2006; Hopkin 2008), or colonizing space (Burrows 2006; Mautner 1996; Shapiro 2009). For these reasons, a systems approach to global catastrophic risk analysis should be employed (Haimes 2008).

The SAI double catastrophe scenario involves two separate global catastrophes that become intertwined via SAI. The impacts and risks of climate change prompt humanity to perform SAI. A catastrophic societal collapse then causes a second catastrophe in the form of SAI intermittency. The result is a double catastrophe similar to the Tonn and MacGregor (2009b) singular chain of events. Likewise, the options for reducing the risk of this double catastrophe depend on both of the two catastrophes and their interactions. For these reasons, the double catastrophe cannot be analyzed if specific risks are to be considered in isolation: A systems approach is necessary. Figure 1 presents a system diagram of the SAI double catastrophe.

2.2. Scenario Analysis

Scenario analysis is an effective method for studying systems of global catastrophic risk. A scenario involves one particular sequence of events that could potentially unfold into the future. It is a claim on what plausibly could happen, and not on what is likely to happen or what should happen (though a scenario may also be likely or desirable). Because the focus is on the sequence of events, there is no restriction of focus on specific types of events. One scenario can readily include multiple catastrophes and any interactions between them, as in the SAI double catastrophe scenario.

Scenario analysis can be helpful for training our minds to understand and respond to events as they unfold. By “training our minds,” we mean that our minds become familiar with and expert at thinking about, identifying, and analyzing specific scenarios and variations of the scenarios. Likewise, the training process involves studying and reflecting on the scenarios and the patterns found in them. The patterns of an actual sequence of events may have some similarities with the analyzed scenarios even if the specifics differ from the scenario details.

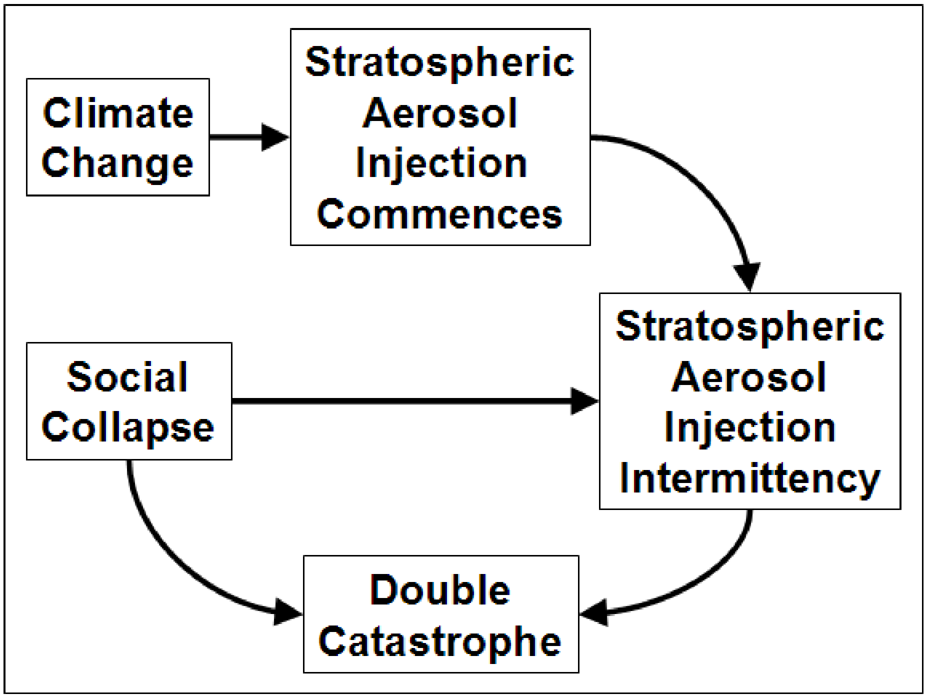

Fig. 1 System diagram showing the SAI double catastrophe

Scenario analysis also can inform decisions made via risk analysis, cost-benefit analysis, and similar paradigms. Here, the scenario analysis would be input to the risk analysis or cost-benefit analysis. Scenario analysis can be especially useful when results of a risk analysis or cost-benefit analysis are dominated by a small number of scenarios. In this case, the risk analysis or cost-benefit analysis would benefit from detailed analysis of these scenarios. A high level of detail for these scenarios will lead to a more accurate overall risk analysis or cost-benefit analysis even if there is less detail on the other possible scenarios.

A risk analysis or cost-benefit analysis of decisions involving global catastrophic risks will in general be dominated by scenarios involving global catastrophe. Thus, understanding global catastrophe scenarios can be of particularly great value to a risk analysis or cost-benefit analysis. Indeed, this paper's detailed discussion of the SAI double catastrophe is largely motivated by needs of risk/cost-benefit analysis of climate change. Recent climate change cost-benefit analysis by Weitzman (2009) finds emissions reduction decisions to be driven by the (unlikely) possibility that emissions will lead to global catastrophe. This study and related studies of the economics of catastrophic climate change[3] focus on the possibility of a high climate sensitivity, that is, that a given amount of greenhouse emissions will cause a large temperature increase. While a large temperature increase could well be catastrophic (see in particular Sherwood and Huber 2010), such scenarios can be avoided via geoengineering. Thus, an accurate cost-benefit analysis of climate change must take geoengineering scenarios into consideration.

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[3] See Ackerman et al. (2010), Costello et al. (2010), Dietz (2011), Nordhaus (2011), and Pindyck (2011).

It should be noted that SAI double catastrophe can be conceptualized as a family of scenarios and not one specific scenario. The double catastrophe could occur in a variety of ways. Greenhouse gas emissions could follow different trajectories, resulting in different amounts of temperature increase. The SAI implementation could be done by different institutional arrangements and with varying degrees of technical sophistication. The societal collapse could be caused by many different factors, with many different effects on humanity. The intermittency could occur at many different times and for a variety of different reasons. Variations in each of these factors result in different scenarios and potentially different outcomes for humanity. In particular, some scenarios may be more catastrophic for humanity than others. In what follows, we explore a portion of the plausible SAI double catastrophe scenarios; readers should be advised that other scenarios may be plausible as well.

3. The Double Catastrophe Scenario

We now proceed step-by-step through the double catastrophe scenario (or family of scenarios): initial climate change, SAI implementation, initial catastrophe, and SAI intermittency. The intent is to show how major scenario variants could unfold, including some indication of how likely they are and how damaging they would be. There is considerable uncertainty throughout the scenario. The impacts of the double catastrophe are particularly uncertain due to the situation's complex and unprecedented nature and because it has not received prior research attention, but some initial statements can nonetheless be made.

3.1. Initial Climate Change

The severity of the SAI double catastrophe scenario depends on the temperature increase that results from adding greenhouse gases to the atmosphere. The temperature increase in turn depends on how much greenhouse gas has been emitted (emissions trajectories) and how sensitive the climate system is to these emissions (climate sensitivity). Both emissions trajectories and climate sensitivity are uncertain. Emissions trajectories depend on the size and carbon intensity of the global industrial economy, which is influenced by such factors as global emissions reduction policy (or lack thereof) and technological breakthroughs. Climate sensitivity depends on feedback mechanisms within the climate system, for which uncertainties remain (Knutti and Hegerl 2008). The SAI double catastrophe scenario is compatible with any emissions trajectory and climate sensitivity associated with increasing average global temperatures. Increasing average global temperatures is very likely; perhaps the only way to avoid increasing average global temperatures would be via a major technological breakthrough.[4]

Climate change is expected to cause a variety of disruptions to ecological and human systems (Parry et al. 2007). While any of these disruptions could play a role in an SAI double catastrophe scenario, two aspects of climate change are of particular interest. The first is extreme weather events, which often generate substantial public and political will for action on climate change. For example, Hurricane Katrina prompted increased attention to climate change in the United States (Kluger 2005); the 2010 Russian heat wave and wildfires prompted Russians to increase support for climate change policies (Weir 2010). As climate change makes extreme weather events more frequent and more severe, calls for geoengineering could intensify. The second is the possibility of the climate system crossing certain thresholds or tipping points (Lenton et al. 2008), such as permafrost melt (Shakhova et al. 2010), ice sheet collapse (Bamber et al. 2001, 2009), and Atlantic thermohaline circulation shutdown (Bryden et al. 2005; Kuhlbrodt et al. 2007). Crossing these thresholds could result in large

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[4] For example, molecular nanotechnology has been hypothesized to be able to make it profitable to mine CO_2 from the atmosphere (Toth-Fejel 2009).

and irreversible damages. For this reason, if scientists are able to detect imminent threshold crossings, there could be heightened interest in geoengineering in order to avoid crossing the thresholds. As discussed below, the possibility of imminent threshold crossing makes SAI particularly attractive relative to emissions reductions and other geoengineering options.

3.2. SAI Implementation

Increasing average global temperatures and the correspondingly increasing damages from climate change will likely prompt increasing interest in some form of geoengineering. Many different geoengineering schemes have been proposed (Keith 2000), though each has certain limitations. For example:

- Removing CO_2 from the atmosphere through chemical engineering mechanisms ("direct air capture"; Boucher et al. 2011; Keith 2009; Vaughan and Lenton 2011) is energy-intensive and thus would only be a viable geoengineering option if low-carbon energy sources become more widely available (Socolow et al. 2011).
- Increasing oceanic carbon sequestration by using iron fertilization to stimulate phytoplankton growth ("ocean fertilization"; Buesseler et al. 2008; Fuhrman and Capone 1991; Gnanadesikan et al. 2003; Martin 1990; Strong et al. 2009) would disrupt ocean ecosystems and may not even result in net decreases in atmospheric CO_2.
- Placing shades, mirrors, or other reflecting bodies into orbit between Earth and the Sun ("space reflectors"; Angel 2006; Early 1989) shares some of SAI's advantages and is also not prone to intermittency, but would be very expensive and may not even be feasible with available technology.

Because it does not share these limitations, SAI has emerged as the most promising geoengineering scheme. SAI involves injecting aerosol particles into the stratosphere. The particles reflect incoming solar radiation, rapidly cooling Earth's surface in a process similar to that of space reflectors (Boucher et al. 2011; Crutzen 2006; Kravitz et al. 2011; Matthews and Caldeira 2007; Vaughan and Lenton 2011; Wigley 2006). On average, global crop yields would largely benefit from increased CO_2 availability without the additional stress of temperature increases (Pongratz et al. 2012), even while global precipitation (Bala et al. 2008) and solar radiation available for photosynthesis would have both decreased. The climatic benefits of SAI are similar to those of space reflectors, but at much more advantageous monetary cost and technological feasibility. Full global implementation is estimated to potentially cost as little as several billion US dollars per year (Robock et al. 2009), vs. a total cost of several trillion US dollars for space reflectors (Angel 2006). SAI could also be developed and deployed within a fairly brief period of time, roughly 10 years (Vaughan and Lenton 2011). The short deployment time combined with the quick temperature response to SAI could enable SAI to be used to prevent the climate system from crossing specific thresholds (Lenton et al. 2008), thereby preventing a "dangerous climate emergency" (Blackstock et al. 2009; Matthews and Caldeira 2007). For example, if scientists observe that a major ice sheet collapse may be imminent, SAI potentially could be used to cool temperatures enough to prevent the collapse. The ability for SAI to be cool temperatures rapidly is another advantage of SAI over other geoengineering options. Because of these advantages, SAI is perhaps the most promising geoengineering option.

However, SAI does have several drawbacks (Robock 2008). Long-term high concentrations of stratospheric aerosol would contribute to an increase in ozone depletion (Tilmes et al. 2008), leading to higher rates of skin cancers (Norval et al. 2011) and ecological stress (Haqq-Misra 2012). Increased concentrations of stratospheric aerosol would also contribute to brighter and "whiter" skies as seen from the ground, due to a higher proportion of increased forward scattering from longer versus shorter wavelengths (Kravitz et al. 2012). Regional climates and hydrological cycles could shift drastically (Ricke et al. 2010), realigning geopolitical relations around securing sufficient water sources, which would also affect global food trade and distribution. The artificially low temperature would cause global carbon sinks to increase the amount of carbon that they could store, masking much of the effect of CO_2 emissions on atmospheric concentrations of CO_2, which would in turn cause ocean acidification to increase more than it would have without the implementation of SAI (Matthews and Caldeira 2007). Ocean acidification is causing significant disruptions to ocean ecosystems including species extinctions (Veron 2008).

One of the largest drawbacks with SAI is the issue of intermittency. Aerosol in the stratosphere has a short lifetime: It travels toward the poles and then falls to the surface within about five years of entering the stratosphere. Because of this, in order for SAI to keep surface temperatures approximately constant, aerosol particles would need to be continuously replenished. Otherwise—if SAI is intermittent—the particles will leave the stratosphere, causing temperatures to rise. The temperature rise would be very rapid, with computer simulations finding increases on the order of 2 °C per decade, 10 times the current rate of warming, eventually reverting to the temperatures that would exist without SAI (Fig. 2; Kravitz et al. 2011; Matthews and Caldeira 2007; Robock 2008; Robock et al. 2008). Higher atmospheric CO_2 concentrations would cause more rapid temperature increases, so the severity of SAI intermittency would increase over time, assuming that CO_2 emissions continue. The rapid temperature increase could be very difficult for both ecological and human systems to adapt to, possibly resulting in global catastrophe. Global temperature increases have probably not exceeded 2–4 °C per decade for the past several glacial cycles (EPICA Community Members 2006; Matthews & Caldeira, 2007). Previous periods of rapid climate change appear to have contributed to the collapse of the Mayan (Dunning et al. 2012), Khmer (Buckley et al. 2010), and Old Kingdom Egypt societies (Butzer 2012). While modern society is quite different from these societies, it may be even more vulnerable to disruptions due to its high degree of global interconnectedness (Hanson 2008). For these reasons, intermittency is cited as a core reason to avoid SAI (Goes et al. 2011).

It should be stressed that uncertainty about SAI remains high. Implementing SAI would be an unprecedented alteration to the Earth system and thus could bring about many unintended consequences, for better or worse. Most of the empirical information regarding the cooling effect of atmospheric aerosol on the global climate comes from observations of volcanic eruptions. But volcanic eruptions release a single pulse of aerosol into the stratosphere that temporarily cool the global climate and then dissipate within a few months to a few years (Crutzen 2006; Keith 2000; Robock et al. 2008). In contrast, SAI would be an ongoing project, potentially spanning decades, centuries, or even longer. Observations of volcanic eruptions offer less insight into the impacts of long-term heightened atmospheric aerosol concentrations. Several climate modeling exercises have simulated SAI, finding a likely decline of global precipitation, increased ozone depletion, and an increase in global carbon sinks (if CO_2 emissions continue unabated), the latter of which in turn leads to increased ocean acidification (Kravitz et al. 2011; Matthews and Caldeira 2007; Robock et al. 2009). These modeling exercises reveal a lot, but much uncertainty nonetheless remains. Likewise, expressions of support for SAI are typically cautious ones, often with SAI viewed as a last resort option to be entertained only if emissions reductions are inadequate (e.g., Victor et al. 2009).

If SAI is implemented, then the institutional form of the implementation can be important. One possible SAI implementation scenario has SAI implemented by a global body such as the United Nations with broad international support (Horton 2011). Such an SAI regime may be especially durable over time, since it would have limited opposition, access to ample funding, and access to the best technological expertise. This durability would result in increasing amounts of aerosol injections as long as greenhouse gas emissions were also increasing. The durability could also mean that it would take a relatively large societal collapse to induce intermittency. Indeed, without such a collapse, intermittency may be unlikely due to the strong incentive to avoid it. Perhaps the only other way that intermittency could occur is if there is a change in power, but this may be relatively unlikely for a regime based on broad international consensus.

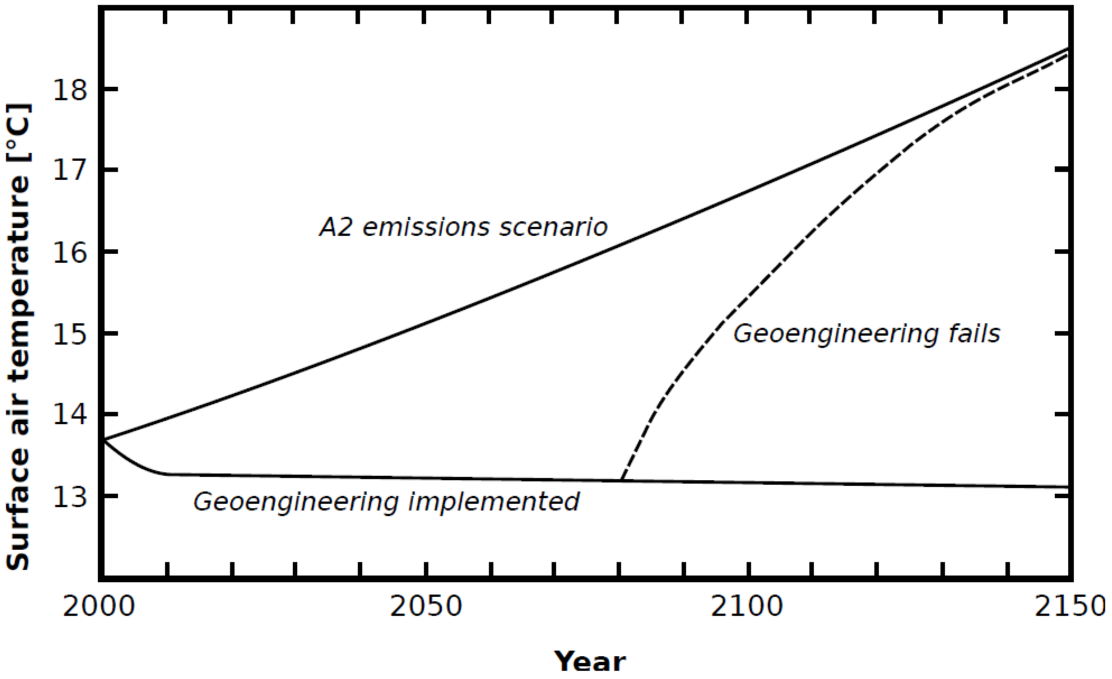

Fig 2 Temperature trajectories with no geoengineering*(top curve)*, with SAI geoengineering *(bottom curve)* and with SAI intermittency failure*(dashed curve)*, adapted from Matthews and Caldeira (2007). The trajectories use the A2 emissions scenario, considered a normal emissions trajectory (Nakicenovic et al. 2000).

Another possible SAI implementation scenario has SAI implemented by a rogue actor despite broad international opposition. The minimal cost and relative ease of SAI implementation could allow a single country or entity to initiate such a program (Barrett 2008; Schelling 1996). For example, Millard-Ball (2011) describes a scenario in which Tuvalu unilaterally implements SAI in a last-ditch effort to save its territory from sea level rise, perhaps funded by a "Greenfinger" (Victor 2008:324), a wealthy individual acting to protect the planet.[5] A unilateral SAI regime may be highly non-durable and thus prone to intermittency. Perhaps other countries would intervene to force the rogue actor to shut its operations down. Perhaps the Greenfinger would withdraw her funding or run out of funds. Perhaps the rogue actor would undergo a change in power, a change in heart, or a change in technological capability. Any of these factors could cause intermittency with much less in the way of societal collapse. The lower durability also means less opportunity for SAI with higher amounts of aerosol. Because of this, rogue SAI regimes may result in less severe double catastrophe scenarios.

The SAI implementation itself could potentially lead to societal collapse. For example, perhaps SAI would be implemented by a coalition of countries experiencing the greatest impacts from climate

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[5] Millard-Ball (2011) notes that opposition to SAI implemented by a country like Tuvalu may be diminished by international sympathy towards Tuvalu's dire predicament.

change, such as the countries of South Asia, Southeast Asia, and sub-Saharan Africa. Other states might object to SAI implementation—perhaps Russia would view warmer temperatures as beneficial for its agriculture, its Arctic shipping and oil drilling, and its overall quality of life. This dispute could increase geopolitical tensions and contribute to a major international conflict. A sufficiently severe conflict could induce a societal collapse and in turn an SAI double catastrophe.

At this time, it is difficult to predict what effect SAI implementation would have on greenhouse gas emissions. A common assumption is that SAI would cause increased greenhouse gas emissions: solving the climate change problem via geoengineering renders emissions reductions less important (Schneider 1996). However, Polborn and Tintelnot (2009) and Millard-Ball (2011) argue that SAI (or other geoengineering) could instead cause reduced greenhouse gas emissions. The logic here is that concern about the side effects of geoengineering would alarm the world into action on emissions. In the case of SAI, perhaps fear of intermittency would motivate emissions reductions. If emissions are sufficiently reduced, then less SAI is needed to achieve desirable temperatures, thereby attenuating the effects of intermittency. Thus, the most important double catastrophe cases are those in which emissions continue at a high rate. For the remainder of the discussion, we will assume that emissions remain high after SAI.

3.3. Societal Collapse

We now have a world with stabilized temperatures from SAI and increasing greenhouse gas emissions. Fear of damages from intermittency provides a strong incentive to continue SAI, even despite any reservations that some may have about it. The overall situation is thus general stable in the absence of any outside perturbations. The societal collapse provides precisely such a perturbation.

Butzer and Endfield (2012) define societal collapse as a long-term negative transformation of social, cultural, demographic, and environmental conditions. For our purposes, a simpler definition suffices. We define societal collapse as any large-scale decline in the capabilities of a society, that is, of an interconnected group of people. In defining societal collapse in terms of capabilities, we do not mean to diminish the importance of other attributes such as culture or demographics. Instead, we mean only to focus our discussion on the specific aspect of society that is most relevant to the SAI double catastrophe scenario. The specific societal collapses that are of ultimate interest in this paper are collapses that eliminate society's capacity to continue SAI.

The possibilities for the societal collapse will depend on the form of the SAI implementation. If SAI is implemented by a narrow coalition or by a single (perhaps rogue) actor, then a smaller collapse localized to the region of the coalition/actor could induce intermittency. The collapse could be caused by, among other things, a local disease outbreak, economic collapse, conflict (international or domestic), or natural disaster. One important attribute of such a localized collapse is that it would not damage societies in other regions as much. To be sure, in a globally interconnected society such as that which exists today, a collapse in one region will have at least some consequences for other regions. But other regions would not suffer as much. Groups in the other regions could even attempt to commence SAI so as to lessen the harms of intermittency; if these other groups are ultimately opposed to SAI, they could commence SAI and then gradually phase out its use, thereby avoiding the rapid temperature increases associated with an abrupt cessation of SAI. Thus, localized collapse scenarios would cause a less severe double catastrophe and thus are of less interest in the context of maximizing expected value and reducing global catastrophic risk.

If SAI is implemented by a broad international coalition, many of whose members have the capacity to implement SAI on their own, then the magnitude of the collapse may need to be very large to induce intermittency—a significant global catastrophe. For comparison, neither the combined event of World War I and the 1918 flu nor World War II would have been large enough. Both of these events still left major industrialized countries (such as the United States) with significant technological capacity. To induce intermittency, a societal collapse would need to be much larger. Unfortunately, societal collapses of this order are not out of the question (Bostrom and Ćirković 2008). A pandemic today could be more severe than that of 1918, since advances in international travel would cause the disease to spread more rapidly and be more difficult to contain. Additionally, advances in biotechnology make it increasingly easy for the design and production of novel pathogens. Another threat is nuclear war, which lingers despite the end of the Cold War. About 19,000 nuclear weapons remain, mainly in the United States and Russia (FAS 2012). One possibility is for rogue actors to incite a US–Russia nuclear war between by leading one of the countries to believe it was under nuclear attack by the other, for example, by detonating a stolen or improvised nuclear bomb (Ayson 2010; Intriligator and Brito 1990; Mosher et al. 2003).

A catastrophe large enough to knock out a broad international SAI coalition would probably kill a large portion of the human population. Some may survive in specially designed bunkers or refuges (Hanson 2008). Similar bunkers were created during the Cold War to ensure the survival of societal elites in case of nuclear war onset (McCamley 2007). But these survivors may lack the practical skills needed for post-collapse survival. A better-situated survivor group would be rural communities distant from the initial catastrophe stressor (pandemic, nuclear war, etc.). Rural communities would already be skilled in farming and other means of self-sufficiency. Today's "preppers" or "survivalists" (e.g. Rawles 2009) may have additional advantages such as food stockpiles to help endure the initial catastrophe. With basic human needs secure, civilization would have a chance to regrow, though it would meanwhile be vulnerable to additional stressors.

3.4. SAI Intermittency

The societal collapse would have two core consequences: damages from the collapse itself and damages from the ensuing SAI intermittency. The result is a double catastrophe: two distinct (but interrelated) catastrophes occurring at the same or adjacent times, providing two major stressors on human civilization. The exact severity of the double catastrophe is difficult to characterize due to its complex and unprecedented nature and due to the lack of dedicated research. Still, some initial characterizations can be made. Several factors are key: the form of the SAI implementation, the form of the societal collapse, and the ability of collapse survivors to adapt to the rapidly changing temperatures caused by intermittency.

If SAI is implemented by a small regional coalition or lone actor, and if the societal collapse is local to that region, then the effects of the intermittency would be less severe. Society across other regions would remain largely intact and thus have more capacity to adapt to the rapid temperature increases. The societies potentially could also slow the temperature increases by implementing some SAI of their own. As long as societies in other regions stay intact, the intermittency would not result in the permanent destruction of advanced technological civilization, and thus would not cause a global catastrophe of the highest value.

Alternatively, if the societal collapse is global (which would likely be necessary if SAI is implemented by a global coalition), then the effects of intermittency may be grave. Because of the complex and unprecedented nature of these scenarios, it is difficult to place bounds on the outcomes. While there is some modest understanding about the climatic consequences of SAI intermittency, there is much less understanding of how well normal society could cope with these consequences and virtually zero understanding of how well a post-collapse society could cope. What follows is a crude attempt at sketching out some of the possibilities; this should be viewed as an exploratory discussion, not a definitive conclusion.

As a starting point, consider a pandemic that kills a large portion of the human population and ends inter-regional trade. Survivors would likely be concentrated in isolated agricultural regions, with their survival depending on their ability to produce their own food. As local stockpiles of fertilizer and fuel are depleted, annual crop yields would decline as survivors are forced to switch to manual labor. But humans have survived for most of their history without heavily mechanized agriculture, and many contemporary farmers succeed with their own hands, so presumably these survivor communities could do the same—that is, without any additional stressors.

Now add to this situation, temperatures rising at rates of around several degrees Celsius per decade (Matthews and Caldeira 2007), with some regions experiencing more rapid increases than others (Ricke et al. 2010; Robock et al. 2008). Food security now becomes much more difficult. Note that a few days of high heat when crops are seeding or fruiting can decimate yields (Tubiello et al. 2007). Rising temperatures would increase the frequency, duration, and magnitude of these heat waves, harming survivors. But heat waves (or other extreme weather events) do not happen every year for any given region. Thus, regions could store up food during plentiful years to help survive leaner years. Additionally, if there is inter-regional trade, then in any given year, regions with plentiful agriculture could help regions with leaner agriculture. The bottom line is that agriculture could potentially succeed enough for survival, though it would become increasingly difficult as average global temperatures increase.

The rate of temperature increase could pose a more serious problem. Farmers might simply not know which crops to plant, since climatic conditions may be quite different from year to year. Predicting conditions might be feasible with the advanced climate science of today's pre-catastrophe society. But such scientific capacity would likely be wiped out by the initial catastrophe. Furthermore, even if farmers did know which crops to plant, they might not have the correct crops available, since every few years a different crop might become suitable for the region. In extreme cases, sufficiently rapid temperature increases could render no existing crop viable for any one growing season. With food security in question, long-term survival must be as well.

Because of the uncertain nature of this scenario, it is difficult to place bounds on its severity. Perhaps survivors would successfully adapt to the rapidly changing climatic conditions and go on to rebuild civilization. Indeed, the resulting civilization could be even stronger, with lessons learned and innovations generated from the double catastrophe experience. Or, perhaps adaptation would not succeed, given the very difficult conditions involved. Indeed, from this initial inquiry, we cannot rule out the possibility that the double catastrophe would result in permanent destruction of advanced technological civilization or even human extinction. The most obvious mechanism is a worldwide failure of food supplies, but other mechanisms could exist too.

As a twist to the SAI double catastrophe scenario, consider that some forms of societal collapse come with their own climatic effects, including nuclear warfare, supervolcano eruption, and large asteroid impact. The latter two are relatively unlikely, so we will focus on nuclear war. A nuclear weapons exchange would burn cities, sending large amounts of ash into the atmosphere, causing nuclear winter (Robock 2011). If the nuclear war occurs at the same time that SAI ceases, then the ash from burned cities could partially counteract the effect of SAI cessation. The effect would only be partial: The burning of cities would cause a rapid increase in atmospheric particulates, whereas the SAI cessation would cause a more gradual decline in stratospheric aerosol. The net effect may be to cause a rapid temperature decline from the nuclear war ash, followed by a rapid temperature increase as both the ash and the SAI particulates leave the atmosphere. Detailed climatic modeling beyond the scope of this paper could clarify the specific climatic consequences of a nuclear war/SAI intermittency double catastrophe. The bottom line is that this double catastrophe scenario would pose a different set of climatic challenges, which may be as difficult to survive as other scenarios, or even more difficult.

4. Implications For SAI Decision-Making

The SAI double catastrophe scenario (or, more generally, family of scenarios) is one way in which climate change and SAI geoengineering could contribute to a global catastrophe of the highest magnitude: an event causing the permanent end of advanced technological civilization or even human extinction. As such, the scenario has important implications for decision making about climate change in general and about geoengineering. In the context of expected value maximization, decision making can be simplified to minimizing the risk of highest-magnitude global catastrophes. Thus, the key questions here are which decisions about climate change and geoengineering would minimize the risk of highest-magnitude global catastrophes.

It will help to develop criteria for evaluating the expected value (EV) of SAI, which is the change in the value of the world (W) with SAI versus without SAI. Without consideration of other catastrophes, the value can be expressed as follows:

$$\mathrm{EV(SAI)} = \mathrm{EV(W|SAI)} - \mathrm{EV(W|N)} = [\ \mathrm{EV(S)} + \mathrm{EV(I)}\ ] - \mathrm{EV(N)} \qquad (1)$$

Here, N is no SAI (i.e. the decision to not implement SAI), S is successful SAI (i.e. SAI without intermittency), and I is intermittent SAI. EV(S) and EV(I) are weighted by the probabilities (P) of SAI success and SAI intermittency, respectively:

$$\mathrm{EV(S)} = \mathrm{P(S)}\ \mathrm{EV(W|S)} = \mathrm{P(S)} \sum_{j=1}^{J} P(j)M(j) \qquad (2a)$$

$$\mathrm{EV(I)} = \mathrm{P(I)}\ \mathrm{EV(W|I)} = \mathrm{P(I)} \sum_{k=1}^{K} P(k)M(k) \qquad (2b)$$

Here, J and K represent the total number of possible consequences of S and I, respectively; j and k are index variables for each possible consequence; and M represents the magnitude of value for each possible consequence. This notation can help us analyse SAI decisions. If EV(SAI) > 0, then SAI increases expected value and (assuming an expected value maximization framework) society should decide to implement SAI. Let us assume that EV(W|N) < EV(W|S) under the premise that successful SAI would lower average global temperatures, thereby bringing net expected benefits to humanity. This assumption implies that other drawbacks of SAI would not render SAI inferior. If EV(W|S) < EV(W|N) then there would be no reason to implement SAI. We will further assume that EV(W|I) < EV(W|N) under the premise that the rapid temperature increases of intermittency are expected to be more damaging than the gradual increases without SAI (as shown in Fig. 1). If EV(W|N) < EV(W|I) then there would be no reason to worry about intermittency.

The assumption EV(W|I) < EV(W|N) means that P(I) is a crucial parameter. If P(I) is sufficiently high, then the possibility of intermittency would be enough to recommend against SAI. But the incentive to avoid intermittency suggests that P(I) is low, unless there is an initial catastrophe to induce intermittency.[6] Factoring in the possibility of a non-climate catastrophe inducing an SAI double catastrophe gives us:

$$EV(SAI) = [\ EV(S) + EV(A) + EV(D)\ ] - [\ EV(R) + EV(C)\ ] \qquad (3)$$

Here, A is intermittency alone (i.e. without double catastrophe), D is double catastrophe, R is "regular" climate change (i.e. without SAI or catastrophe), and C is "single" catastrophe (i.e. the same catastrophe as would cause an SAI double catastrophe, except without the SAI). S is the same as in Equation 1. SAI intermittency (I) can happen either without (A) or with (D) intermittency, and so $EV(I) = EV(A) + EV(D)$. Likewise, climate change without SAI (N) can happen either without (R) or with (C) a separate catastrophe, and so $EV(N) = EV(R) + EV(C)$. Let us assume that $EV(W|D) < EV(W|A)$ under the premise that intermittency would be worse with an initial catastrophe than without. We will also assume that $EV(W|D) < EV(W|C)$ under the premise that the rapidly warming temperatures of intermittency would render double catastrophe worse than a single catastrophe. This latter assumption can be called into question. Pre-catastrophe society could be stronger in an SAI world than in a world with gradual climate change, and that strength could help it endure the catastrophe. Also, some of the harsher effects of climate change, such as ice sheet collapse, occur only after an extended period of higher temperatures; SAI intermittency might happen to quickly to trigger these effects, especially if survivors are able to eventually resume SAI. That said, $EV(W|D) < EV(W|C)$ still seems like a reasonable assumption, given the challenges of coping with the rapid temperature increases of intermittency.

Expected value calculations are dominated by the possibility of global catastrophe causing the permanent destruction (PD) of advanced technological civilization, as discussed in Sect. 2.1. Thus,

$$EV(SAI) \approx [\ 1 - P(PD|SAI)\ ]\ EV(X) - [\ 1 - P(PD|N)\ ]\ EV(X) \qquad (4)$$

Here, X is the value of PD not occurring, that is, of advanced civilization remaining intact. EV(X) hinges critically on difficult questions about such things as the moral value of future generations, the technological feasibility of space colonization, and the long-term fate of the universe. EV(X) could even be infinite, in which case decision making could require attention to the mathematics of infinity (Baum 2010). We will set aside the infinite value issue and suggest minimizing P(PD) as a decision criterion, which roughly corresponds to the "maxipok" (maximize the probability of an "OK" outcome) criterion of Bostrom (2012). Using this criterion, we define the decision value (DV) of SAI as:

$$DV(SAI) = P(PD|N) - P(PD|SAI) \qquad (5)$$

Thus, SAI should be implemented if $DV(SAI) > 0$, that is, if SAI results in a net decrease in P(PD). Combining Equations 3 and 5 gives:

$$\begin{aligned} DV(SAI) = &\ [\ P(R)P(PD|R) + P(C)P(PD|C)\ ] \\ &- [\ P(S)P(PD|S) + P(A)P(PD|A) + P(D)P(PD|D)\ ] \end{aligned} \qquad (6)$$

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[6] As noted above, intermittency without initial catastrophe is possible despite the incentives, such as if a group opposed to SAI on moral grounds gains control of the SAI. Superficially, such scenarios appear substantially less likely than initial catastrophe scenarios, though dedicated research on these scenarios could clarify this.

Overall, we would expect that $P(PD|S) < P(PD|R) < \{ P(PD|A), P(PD|C) \} < P(PD|D)$. $P(PD|S)$ could be close to zero, especially if other SAI drawbacks are insignificant. Regular climate change (R) involves great harms (as in Sherwood and Huber 2010), but these would be easier to endure than those of intermittency (A) or an additional catastrophe (C). Comparing $P(PD|A)$ and $P(PD|C)$ would require knowing details of the catastrophe in C. Finally, $P(PD|D)$ is the highest because it involves both intermittency and the additional catastrophe.

Note that $P(C) = P(D)$, since both involve the same catastrophe, just with versus without SAI. Let D^* be the catastrophes that would cause permanent destruction with a double catastrophe but not with a single catastrophe. We will assume that $C^* \approx 0$, with C^* being the catastrophes that would cause permanent destruction with a single catastrophe but not with a double catastrophe. Also, $P(A)$ appears to be low due to the incentive to avoid intermittency. Setting $P(PD|S) \approx 0$ and $P(A) \approx 0$, Equation 6 can be approximated as:

$$DV(SAI) \approx P(R)P(PD|R) - P(D^*)P(PD|D) \tag{7}$$

An important insight from Equation 7 is that SAI decision making depends critically on the probability of certain non-climate catastrophes, or $P(D^*)$.[7] If such catastrophes are sufficiently rare, then SAI is advantageous by protecting against the possibility of permanent destruction from climate change alone. But if the catastrophes are sufficiently frequent, then SAI would be counterproductive, resulting in a net increase in the probability of permanent destruction. Essentially, the decision to implement SAI reduces to the question “Which is more worrisome: climate change catastrophe or double catastrophe?”

It is quite plausible that $P(PD|R)$ is low, that is, that climate change damages on their own would be unlikely to cause permanent destruction. This is to say that human civilization would likely endure climate change, despite the harms it brings. In this case, the usual logic of SAI protecting against the damages of climate change is reversed. Instead, we can now say that not implementing SAI protects against the damages of double catastrophe. The stakes in this new logic are much higher: Humanity is asked to endure great harm in order to protect its very existence. This could make for a difficult decision, especially if $P(D^*) << P(R)$. In that case, SAI would have a large probability of significantly improving conditions for humanity and a small probability of causing permanent destruction. Is a small chance of catastrophe enough to skip SAI and sentence humanity to the damages of climate change? Strictly following the logic of expected value maximization, the answer is yes. However, in the face of increasingly harsh climate change damages, there could be strong desire to implement SAI anyways and take the chance of permanent destruction.

Today’s decisions are not about SAI implementation per se but about SAI research and development, which is often expressed as taking out insurance for possible future climate change damages (Keith 2000; Crutzen 2006; Gardiner 2010; Moreno-Cruz and Keith 2012). But the possibility of double catastrophe means that SAI could be even riskier than climate change alone. Likewise, the possible future desire to implement SAI despite the risks could mean that today’s research and development creates a harmful temptation. In this case, the correct decision would be to abstain from SAI research and development so as to deny future decision-makers the harmful temptation, much like Ulysses and the Sirens (Elster 1979).[8]

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[7] An example of the type of probability estimate we have in mind here is Hellman’s (2008) estimate of 1% for the annual probability of U.S.–Russia nuclear war.

[8] Ulysses (of Homer’s epic) ordered his crew to bind him to his ship so he could then hear the Siren’s song without killing himself. The story is of a present decision to constrain one’s future options out of expectation that the future self would make the wrong choice.

5. Conclusion

This paper has provided a detailed analysis of the SAI double catastrophe scenario, in which a catastrophic societal collapse induces SAI intermittency. The severity of this scenario depends jointly on the severity of the collapse and the severity of the intermittency. Great uncertainty exists throughout this scenario, especially regarding how effectively collapse survivors could cope with the rapidly rising temperatures of intermittency. However, it is plausible that the double catastrophe could be so severe as to cause permanent destruction of advanced technological civilization or even human extinction. For this reason in particular, avoiding the double catastrophe is an important goal for decision making about greenhouse gas emissions, geoengineering, and global catastrophic risk reduction in general.

One safe conclusion from the SAI double catastrophe scenario is that greenhouse gas emissions reductions would help reduce global catastrophic risk. In the absence of SAI or other geoengineering, emissions reductions help avoid catastrophic climate change impacts (as in Sherwood and Huber 2010). If SAI is implemented, emissions reductions reduce the severity of any possible intermittency. And in either case, emissions reductions help with ocean acidification, which lurks as another possible cause of global catastrophe. On the other hand, it is possible for emissions reductions to increase global catastrophic risk. Perhaps emissions reductions would cause economic decline, leaving society more vulnerable to other shocks. Future research is needed to clarify these possibilities. For now, it appears that emissions reductions would cause a net decrease in global catastrophic risk.

The SAI double catastrophe scenario also has implications for how to implement SAI. Certain preparations may help avoid intermittency, including in the case of societal collapse. The capacity to implement SAI could be distributed broadly across geographic regions, political structures, and other groups. In the event of disruptions to any one of these groups, the other groups could continue SAI, thereby preventing catastrophic intermittency. Another option is to implement SAI with a smaller amount of aerosol. This approach would gain some of the benefits of lower temperatures while reducing the severity of intermittency.

There are at least two important factors in SAI decisions that have not been explored in detail in this paper. First, how would greenhouse gas emissions compare with or without SAI? If SAI would prompt major emissions reductions, for example, out of fear of intermittency, then SAI could cause a net decrease in global catastrophic risk. Second, is societal collapse more or less likely to occur with SAI? If SAI reduces the probability of societal collapse, for example, by making society more resilient to pandemics, wars, and other stressors, then SAI could again cause a net decrease in global catastrophic risk. SAI decisions would benefit from future research on these topics.

Finally, the SAI double catastrophe scenario strengthens the argument for increasing society's resilience to collapse. Creating and supporting self-sufficient local communities would be more capable of surviving societal collapse and in turn SAI double catastrophe. Such communities may be most successful if located in geographically isolated areas and equipped with the ecological, technological, and human capital needed for agriculture, machine building, and other basic building blocks of civilization. In light of the double catastrophe scenario, such communities would further benefit from the capacity to endure large, rapid temperature increases with no outside assistance. Bunkers and refuges with stockpiles of food and other necessities could help, but these may be of limited value unless the people in them have the skills to support themselves and rebuild society after the stockpiles dwindle. It is of note that self-sufficient local communities would also be valuable across a range of other global catastrophe scenarios, including societal collapse scenarios that do not induce SAI intermittency.

A more general conclusion that can be reached from this paper is on the importance of considering multiple global catastrophic risks at once. Global catastrophes can have important interaction effects, such as with a catastrophic societal collapse causing SAI intermittency. More importantly, actions we can take now can impact multiple global catastrophic risks, such as efforts to build communities that could be self-sufficient during a variety of catastrophe scenarios. An integrative, systems-based approach to global catastrophic risk analysis is needed to understand these various interactions and how best to reduce the overall risk of global catastrophe.

Acknowledgments

Valuable feedback on the ideas in this paper was received from an audience at the Research Institute for Humanity and Nature, Kyoto. Helpful assistance was received from Vanessa Schweizer on greenhouse gas emissions trajectories and Anthony Barrett on nuclear war scenarios. We also thank three anonymous reviewers for helpful feedback on an earlier draft. Any shortcomings remaining in this paper are entirely the responsibility of the authors.

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