PLANETARY SUNSHADE FOUNDATION

STATE OF SPACE-BASED SOLAR RADIATION MANAGEMENT

March, 2023

www.planetarysunshade.org

INTRODUCTION

This report is an introduction to the concept of space-based geoengineering, or a planetary sunshade. A sunshade could complement existing efforts to mitigate the climate crisis. It is intended for policy makers who are discussing climate overshoot scenarios.

The Planetary Sunshade Foundation was founded in 2021 because current decarbonization strategies are insufficient for a livable planet. We develop and advance the concept of space-based solar radiation management.

The Planetary Sunshade Foundation believes that solar radiation management is a necessary part of the global warming solution, complementing the transition away from fossil fuels and the removal of excess greenhouse gases from the atmosphere.

PLANETARY SUNSHADE FOUNDATION

RECOMMENDATIONS

- The United States should understand the opportunity of combining climate strategy and space strategy. Discussion of geoengineering should include a space-based option.
- Congress should fully fund modeling of possible climate interventions as recommended by the National Academy of Sciences and include research of space-based options.
- The White House should initiate legal research to allow structures like the sunshade to be constructed, as well as to manage the sunshade as a geoengineering tool.
- Congress should fully fund and launch NASA's Solar Cruiser mission to further study solar sailing.
- NASA and the United States Space Force should plan for and support robust in-space logistics and commercial services.
- NASA should continue scenario planning for lunar resource extraction and in-space assembly.

PREAMBLE

THE CLIMATE CRISIS IS HERE, AND IT IS GETTING WORSE FAST. Earth will exceed the threshold for 1.5°C of warming sometime in the 2030s, and there are credible scenarios for catastrophic warming of 4.5° by the end of the century. While transitioning away from fossil fuel use is imperative, net-zero emissions will not solve the problem of elevated carbon levels already present in the atmosphere. As the effects of global warming worsen, world leaders are more seriously considering climate intervention, or geoengineering.

The Earth is a thermodynamic system. Greenhouse gas emissions have caused the Earth to retain more energy than it emits, which results in global warming. Geoengineering proposals focus on correcting that energy imbalance. There are two main types of geoengineering. The first is removing carbon from the environment to restore pre-Industrial levels. While carbon removal is necessary, it will take over a century to remove and sequester the carbon already present in the atmosphere and oceans. The second type is solar radiation management (SRM), which reduces the amount of solar energy that impacts Earth.

The most well-known SRM technology is stratospheric aerosol injection (SAI). SAI involves dispersing millions of tons of tiny particles, called aerosols, into the stratosphere each year to reflect a small percentage of incoming solar energy. Though the technology to deploy SAI does not currently exist, it could be developed within the next decade. SAI could be deployed relatively cheaply and would be rapidly effective at cooling the Earth. However, it has significant drawbacks, such as increased pollution, damage to the ozone layer, and a milky appearance to the sky.

Now that it is impossible to limit Earth to a 1.5°C temperature rise without geoengineering, the eventual deployment of SRM is increasingly discussed. Because of the downsides of SAI, any credible discussion of stratospheric aerosol injection should also include the only other global method of solar radiation management: the planetary sunshade.

Placing a physical structure, a planetary sunshade, between the Sun and the Earth can reduce solar energy and provide a long-term, sustainable wind-down from SAI. SAI and space based SRM complement each other. While SAI can be deployed quickly and inexpensively, it must be replenished constantly and maintained until carbon is removed from the atmosphere. On the other hand, deploying the sunshade will take longer and cost more, but it is a cleaner, more sustainable proposal. The planetary sunshade should be considered a wind-down strategy for SAI. The sunshade also has many positive benefits beyond addressing climate change that should be understood by policy makers.

For more detailed analysis of the relevant aspects of the greenhouse effect, see **Appendix A**.
For a more detailed overview of geoengineering and SAI, see **Appendix B**.

REPORT ORGANIZATION

PREAMBLE

Current efforts to combat catastrophic climate change are insufficient. Geoengineering could be deployed to buy time to restore Earth's atmosphere. Stratospheric aerosol injection is fast and cheap but has drawbacks. A planetary sunshade could be a clean, sustainable, long-term complement to terrestrial geoengineering.

THE PLANETARY SUNSHADE

A structure in space that blocks enough solar radiation to offset all or part of anthropogenic global warming

ECONOMIC BENEFITS OF SUNSHADE LEADERSHIP

The many positive aspects of a cislunar economy

POLICY RECOMMENDATIONS

Build on existing initiatives and new policy recommendations

SUMMARY

The sunshade should be considered a key part of a comprehensive response to the climate crisis, focusing emerging space capabilities on the defining issue of our time

APPENDIX A: The Climate Crisis and Earth as a Thermodynamic System
APPENDIX B: Geoengineering and Stratospheric Aerosol Injection

THE PLANETARY SUNSHADE

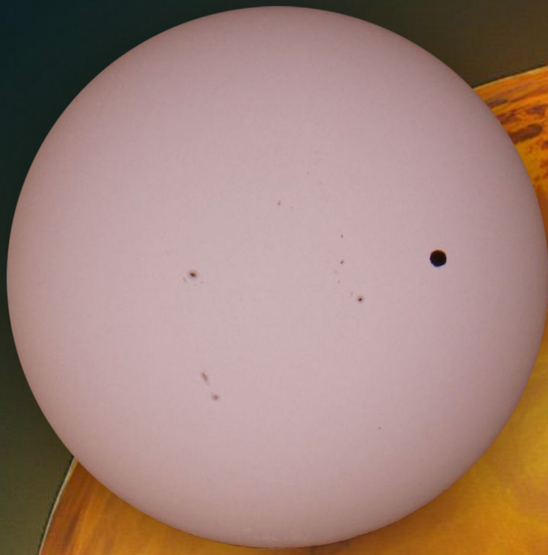
THE CONCEPT OF A PLANETARY SUNSHADE IS RELATIVELY SIMPLE. Like an umbrella on a sunny day, an object placed between the Earth and the Sun will reduce the amount of incoming solar energy and, therefore, the temperature of Earth. A planetary sunshade is a scalable intervention: larger sunshades would be able to block more solar energy. Preliminary calculations show that, to counteract about 1°C of anthropogenic warming, a sunshade would need to block approximately 0.5% of incoming solar energy[1].

1 Fix, S. (2021). Feasibility study of a sunshade in the vicinity of the Sun Earth L1 Lagrange Point (Issue February). University of Stuttgart. https://www.planetarysunshade.org/publications

A real-world example of this concept was the transit of Venus between the Earth and the Sun in June of 2012.

Although the transit was much too short to have a measurable effect on Earth's temperature, the transit reduced incoming solar radiation by 0.35 W/m^2.[2] Figure 1 shows how the transit of Venus appeared from Earth. A planetary sunshade would be made from many smaller elements, achieving similar radiation blocking while being far less visible than Venus or even the sunspots in this image. Since Venus is much farther away from Earth than the sunshade would be, the cross-sectional area of Venus is many times larger than the planetary sunshade.

Figure 1: 2012 transit of Venus (large spot), as observed from Tempe, Arizona (smaller dots are sunspots)[3]



Because the distance from the Earth is great, and the relative size of the sunshade elements is tiny, a sunshade would cast a diffuse but not an acute shadow on the earth. The 'umbra', or acute part of the shadow, does not reach Earth, and therefore no part of the Earth would experience direct shading. Instead, the sunshade's penumbra, or diffuse shadow, is what covers the entire Earth (see Figure 2). The penumbra's diffuse shading ensures that the cooling is spread evenly across the globe, minimizing regional impacts.

2 Observations of the Venus Transit – Total Irradiance (2012). Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder. https://lasp.colorado.edu/home/sorce/2012/06/10/observations-of-the-venus-transit-total-irradiance/

3 Wikipedia. 2012 transit of Venus. Stephen Rector. https://en.wikipedia.org/wiki/2012_transit_of_Venus.

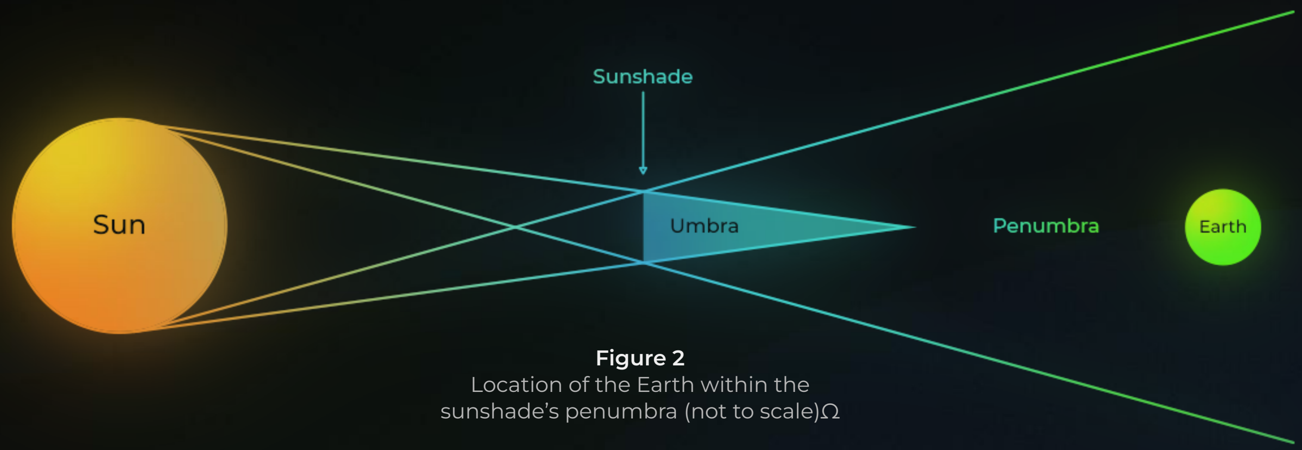


Figure 2
Location of the Earth within the
sunshade's penumbra (not to scale)Ω

Due to the realities of gravitational physics, the most feasible location for a planetary sunshade is near the Sun-Earth Lagrange point 1 (L-1)[4] (see Figure 3). Lagrange points are equilibrium points where the gravity of two large bodies (in this case, the Sun and the Earth) and the centrifugal orbital forces balance. Objects located at L-1 remain on the line between the Earth and the Sun and require relatively minor stationkeeping to maintain their orbital location. Without orbital maintenance in the long term, objects will naturally drift away from the shading position. The sunshade optimal location is about 2.4 million km from Earth, or about 5 times further away than our Moon's orbit.

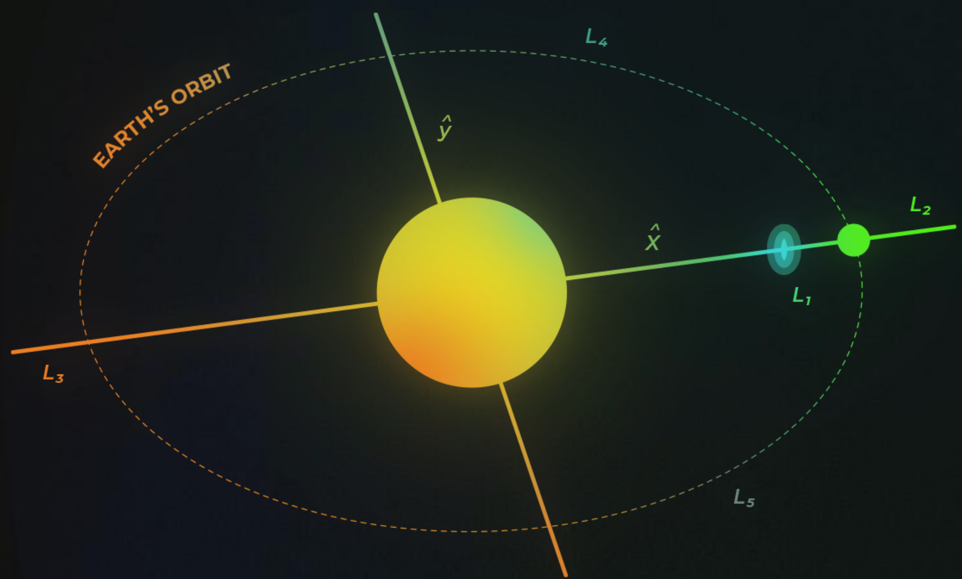


Figure 3
Planetary sunshade location at
Sun-Earth Lagrange point 1[5]

4 Jehle, A., Scott, E., Centers, R. (2020) A Planetary Sunshade Built from Space Resources. AIAA ASCEND Conference, November 16-18, 2020, Virtual, https://doi.org/10.2514/6.2020-4077.
5 Sánchez, J. P., McInnes, C. R., & Marchis, F. (2015). Optimal sunshade configurations for space-based geoengineering near the Sun-Earth L1 point. PLoS ONE, 10(8), 1–25. https://doi.org/10.1371/journal.pone.0136648.

Calculations using an empirically derived climate sensitivity parameter and geometrically defined radiative forcing demonstrate that the sunshade would be effective in reducing global temperatures. A larger sunshade results in more cooling, while a smaller sunshade causes less.

For reference purposes, achieving 1°C of cooling would require blocking 0.5% of the sun's energy. A 1.7 million km^2 sunshade, massing about 74M tons of material, would achieve this result.[6]

To construct such a sunshade, a variety of methods could be used to maximize surface area while minimizing mass and without needing to deploy a monolithic structure. Individual sunshade elements of 20 km^2 could be constructed of thin aluminum foil stretched over circular frames. Technical components would be manufactured on Earth, while the bulk of minerals to manufacture a simple aluminum foil would be sourced from a mining operation on the lunar surface. The Moon's significantly lower gravity offers an opportunity to minimize the cost of the sunshade in terms of both money and launches, and aligns with US policy on commercializing space technology developed by Artemis Accord nations.

Launching mass to low Earth orbit from Earth will always require a 70 to 1 fuel-to-payload ratio, whereas the Moon's low gravity results in a 3-1 fuel-to-payload ratio.

The planetary sunshade is a large project, but achievable with commitment from the world's richest nations. Construction of the sunshade would afford its creators significant prestige and economic opportunities, in addition to climate stability.

HISTORICAL ANALOGIES

Civil engineering projects of this scale have been undertaken successfully before:

- In 1805, Lewis and Clark stood on the shores of the Pacific, as emissaries from the United States. 64 years later, the Golden Spike connected the Pacific to the east with train service. While the federal government's payments to construct the railroad were seen as very substantial at the time, they pale in hindsight compared to the benefit to the country's well-being and financial growth.
- Dwight Eisenhower passed the Interstate Highway System Act in 1956, launching a decades-long construction project which was completed in 1992.
- From 1941-1945, the US produced more than 300,000 aircraft after starting at approximately zero. After the war, the industry transformed into a commercial public service that continues to this day.
- In the 1960s, just 60 years after the first flight of an airplane, NASA's budget was over 4% of the federal government's spending, effectively winning the Space Race and establishing NASA as one of the most beloved brands in the world.
- Denmark is currently building an 18km road and rail tunnel under the Baltic Sea to connect Denmark and Germany. Once completed, it will be the longest immersed tunnel in the world.
- The International Space Station, built by a coalition of partnering nations, has been in continuous operation for over 20 years.

6 H.R.2262 – U.S Commercial Space Launch Competitiveness Act. 114th Congress. https://www.congress.gov/bill/114th-congress/house-bill/2262

ECONOMIC BENEFITS OF PLANETARY SUNSHADE LEADERSHIP

The economic potential of an industrial economy on and around the Moon is massive, and the leaders who develop this economy will benefit the most. Construction of a sunshade will kickstart the next frontier of human industrial activity.

The aerospace industry and the US government are fast developing the capabilities necessary to construct a sunshade. The United States sees itself as entering a second Space Race, confronting China's ambitious space vision.[7, 8] Private industry and commercial services give this Space Race a very different economic profile than the last Space Race.

NASA and the US Space Force convene an annual workshop on the State of the Space Industrial Base, and produce a report based on the workshop attendees' contributions. While the proposals in this report are not official policy, they offer helpful insight. The annual report gives an overview of the space industry, the evolving national security considerations of space, and the opportunities for the United States to lead in this arena. In the 2022 report, the authors recommend:[9]

- Establish "Space Development and Settlement" as our National "North Star" Space Vision - The United States still requires a whole-of-nation vision and strategy for the economic and industrial development of space, to unite all elements of national power, and to attract like-minded allies and partners to a common wealth-creation framework.
- "Make Space a Central Part of Climate Action Plans - The space industrial base is capable of immense and diverse contributions to tackling climate change. But it must be deliberately mobilized by White House policy."

7 Mark Whittington, opinion contributor. "The New Race to the Moon: The Artemis Alliance vs. the Sino-Russian Axis." The Hill, The Hill, 28 Mar. 2021, https://thehill.com/opinion/technology/545280-the-new-race-to-the-moon-the-artemis-alliance-vs-the-sino-russian-axis/.
8 L.D. Hanlon, Michelle. "Lunar Mining, Moon Land Claims, and Avoiding Conflict and Damage to Spacecraft." The Space Review: Lunar Mining, Moon Land Claims, and Avoiding Conflict and Damage to Spacecraft, https://www.thespacereview.com/article/4446/1.
9 Olson, J., et al. Edited by Peter Garretson, 2022, State of the Space Industrial Base 2022, https://www.diu.mil/latest/state-of-the-space-industrial-base-2022.

One of the ways this leadership is emerging is the Artemis Accords, a series of over 20 bilateral agreements between the United States and other space-faring nations. The Accords set up a framework for the commercial use and industrial development of the Moon, where the majority of sunshade resources would be extracted. Construction of a sunshade is in line with, and could be the centerpiece of, the Artemis Accords efforts.

A driving force in the rapid expansion of space activity is the plummeting cost of launch (see Figure 4). It was only as recently as 2015 that SpaceX first succeeded in landing a Falcon 9 rocket for reuse, transforming the launch industry. In the years since, 'flight-proven' rockets have become the norm, with individual boosters flying over 15 times and counting. The next generation of heavy lift launch vehicles will push this trend much further. SpaceX's Starship is the most promising, with NASA's Space Launch System and Blue Origin's New Glenn also entering the game. China has scrapped plans to develop any new rockets which are not reusable, choosing to focus entirely on re-use. The cost savings of reusing rockets are enormous, and the space industry is responding quickly to the new opportunities these lower costs make possible.

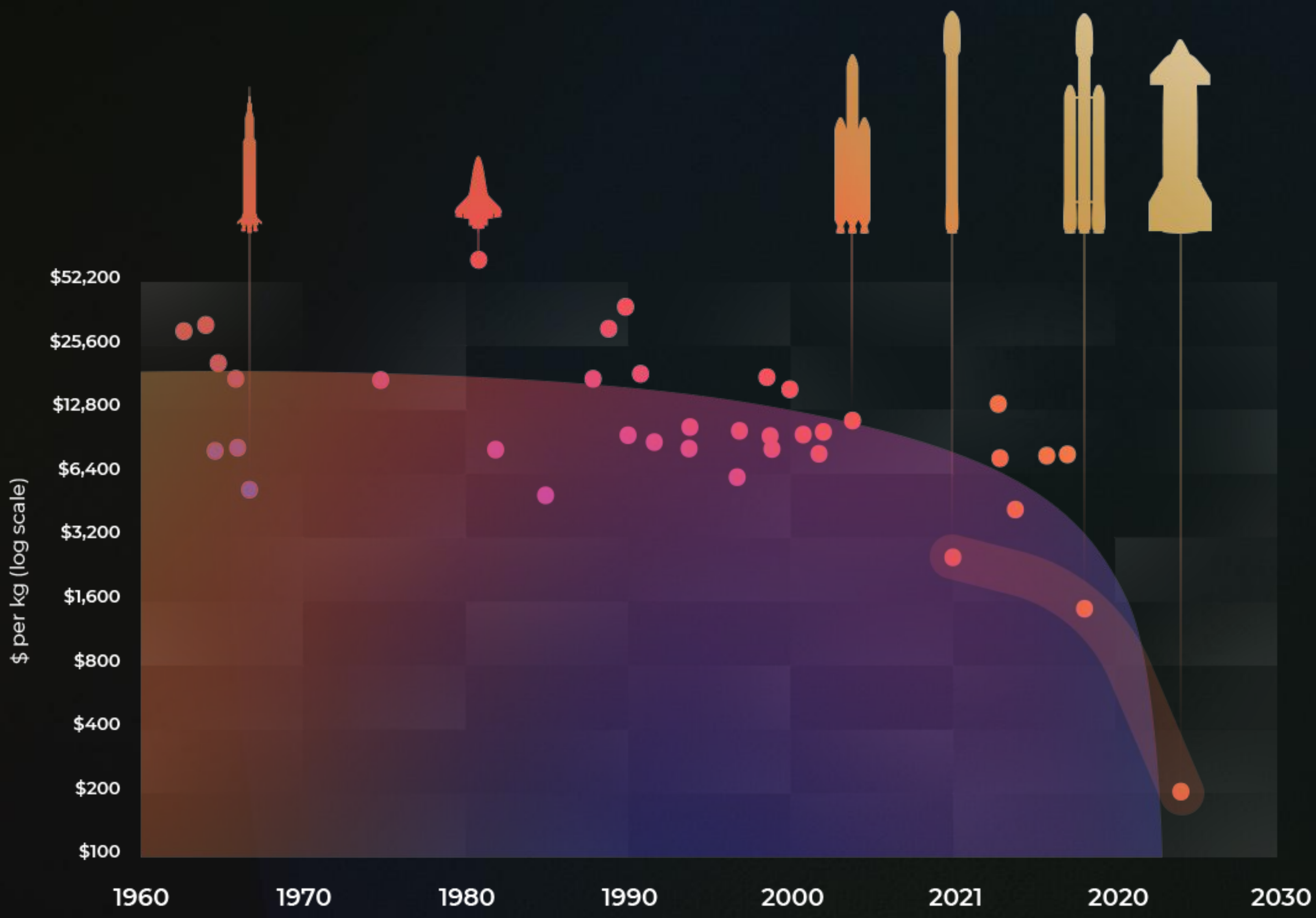


Figure 4: The cost of launch is falling rapidly. Note the exponential scale of this chart [10]

10 Olson, J., et al. Edited by Peter Garretson, 2021. State of the Space Industrial Base 2021, https://www.diu.mil/latest/state-of-the-space-industrial-base-2021

The falling cost of launch enables a sunshade to be built, and construction could begin by building and launching sunshade elements from the Earth until lunar infrastructure is mature enough.[11] However, lunar industrial development has many advantages and the bulk of the resources needed for sunshade construction should still be extracted from the Moon.

Mining and manufacturing equipment would be constructed on Earth, while raw material extraction, refining and ultimately deployment into sunshade form would all happen outside of Earth's atmosphere. While the greenhouse gas emissions from launching rockets from Earth are measurable, they are tiny compared to other sectors. However, construction with lunar resources would eliminate the majority of Earth launch emissions.

A cislunar economy capable of building a planetary sunshade from space resources would be beneficial to a variety of stakeholders.
The space resources economy encompasses:

- Resource prospecting
- Extraction and processing
- Manufacturing and assembly
- Logistics
- Eventually, millions of people living and working in space to support these endeavors.

The technologies needed to extract and process materials from space are being researched by universities, civil space agencies, and companies across America and around the world. The economic development and human settlement of space is the recommended 'North Star Vision' in NASA and Space Force's 2022 report.[12] Many science initiatives, led by NASA and other civil space agencies, have dual use as prospecting missions. The Lunar Surface Innovation Consortium, a collaborative organization led by NASA and Johns Hopkins Applied Physics Laboratory, brings together industry, academia, and government to develop key technologies for lunar surface exploration. There is also a vibrant space resources startup ecosystem in the US, with companies such as Orbit Fab, Redwire, Lunar Outpost, iSpace, and Blue Origin receiving hundreds of millions of dollars in grants and venture capital funding. Legacy aerospace companies such as Northrop Grumman and Lockheed Martin are all looking to space resources for the future. There is at least one company, Ethos Space, actively developing a planetary sunshade architecture. The US Air and Space Forces, supported by the White House, also have a key role; the US military is partnering with NASA and commercial entities to provide space domain awareness[13] and the "Space Superhighway" infrastructure[14] to support growing economic activity around the Earth and Moon. The technologies and infrastructure to build a planetary sunshade would not develop in a vacuum; rather, it will ride a tide of investment and activity that is already rising.

It is hard to overstate the economic potential of a cislunar economy capable of building a planetary sunshade from space resources. Expanding the sphere of human economic activity into space would rival the Industrial Revolution in scope and scale. Trillions of dollars of industrial economic growth outside of Earth's ecosystem are available for the nations who lead the way in the cislunar economy.

11 Fuglesang, C., García de Herreros Miciano, M. (2021) Realistic sunshade system at L1 for global temperature control. Acta Astronautica 186, 269-279. https://doi.org/10.1016/j.actaastro.2021.04.035
12 National Science and Technology Council (2022). National Cislunar Science and Technology Strategy. https://www.whitehouse.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf
13 Cislunar Highway Patrol System (CHPS). Air Force Research Laboratory. https://afresearchlab.com/technology/cislunar-highway-patrol-system-chps/

CONSTRUCTION OF A PLANETARY SUNSHADE WOULD CATALYZE AN ECONOMIC REVOLUTION FOR HUMANITY

POLICY RECOMMENDATIONS

US leadership at the intersection of space and climate can create a more stable and sustainable world.

BUILD ON EXISTING INITIATIVES

Congress should appropriate funds for NASA to launch its already-developed Solar Cruiser solar sailing mission to the L1 point. The sunshade is a series of large solar sails, and the more we learn about building and operating this technology the more accurately we can plan for construction of a sunshade. NASA has developed the Solar Cruiser mission to study solar sailing at L1. Fully funding Solar Cruiser is an achievable and constructive action to advance the sunshade and is a demonstration that can be conducted rapidly, with launch as soon as FY27 or FY28.

NASA and the US Space Force should continue to plan for and support the development of in-space logistics systems. In-space logistics such as satellite refueling, fuel production, and cargo delivery are essential functions of any space-based industrial project. A well-developed private logistics industry would make a sunshade far cheaper to develop and support.[15]

NASA should continue scenario planning for the lunar resource extraction, processing, and manufacturing systems that will enable the sunshade. NASA's Artemis program emphasizes a sustainable return to the Moon, including the use of space resources. NASA's long-term lunar development planning should consider the manufacturing commercialization, scale, production, and launch of sunshade elements.

14 Tomek, D., et al. (2022) The Space Superhighway: Space Infrastructure for the 21st Century. 73rd International Astronautical Congress (IAC 2022), Paris, France. https://ntrs.nasa.gov/citations/20220012880

15 National Science and Technology Council (2022). National In-Space Servicing, Assembly, and Manufacturing Implementation Plan. https://www.whitehouse.gov/wp-content/uploads/2022/12/NATIONAL-ISAM-IMPLEMENTATION-PLAN.pdf

NEW POLICY RECOMMENDATIONS

Congress should allocate money to expand climate modeling with regard to geoengineering. The National Academy of Sciences 2021 report says “the U.S. Global Change Research Program (USGCRP) should lead the effort to establish and coordinate a solar geoengineering research program across federal agencies and scientific disciplines, with funding in the range of $100 million-$200 million over the first five years”.[16] This scale of investment would be transformative for the climate modeling community. In addition to SAI, the modeling work done via this funding should fully consider space-based solar radiation management to deepen our understanding of climate impacts.

The US Federal government should align space and climate policy. White House climate policy should explore the possibility of a space-based strategy for solar radiation management. The White House should also adopt the North Star Vision for “Economic Development and Human Settlement” of space as proposed in the 2022 State of the US Space Industrial Base report. The report goes on to note that “Space development also enables concepts (such as the Sun-Earth-Lagrange 1 Sunshade) which could responsibly and reversibly conduct solar radiation management”.

The White House should create a policy for space-based climate leadership. This policy would align relevant parts of the executive branch, the aerospace industry, and the scientific research community. Such a policy could call for the necessary research into climate models, lunar resource development, and in-space construction.

NASA, the US State Department, and legal scholars should explore the international legal framework that would allow for a sunshade to be constructed. Building on the Outer Space Treaty and the Artemis Accords, more work is needed to establish a legal framework sufficient to support the logistics and resource needs of a sunshade.

The White House should engage with the development of legal frameworks to manage the sunshade as a geoengineering tool. While the sunshade has many benefits as a relatively neutral intervention,[17] a trusted governance structure will be necessary before beginning construction. The American Geophysical Union is developing an ethical framework for climate intervention. The Climate Overshoot Commission is considering forms of geoengineering, including governance considerations.[18] The White House should take an active role in these conversations and propose a governance structure that gives the world a chance to secure a stable climate.

16 National Academies of Sciences, Engineering, and Medicine. 2021. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. https://doi.org/10.17226/25762.
17 American Geophysical Union, 2022. AGU Climate Intervention Engagement: Leading the Development of an Ethical Framework. https://www.agu.org/-/media/Files/Learn-About-AGU/AGU-Climate-Intervention-Ethical-Framework.pdf
18 Climate Overshoot Commission. https://www.overshootcommission.org/

SUMMARY

The planetary sunshade should be considered a key part of a comprehensive response to the climate crisis. The sunshade concept complements greenhouse gas reduction efforts such as the phase out of fossil fuels and buys Earth time to remove the extra carbon from the atmosphere. It also complements stratospheric aerosol injection as a sustainable wind-down pathway. While the sunshade concept does not address all the impacts of climate change, it greatly increases our ability to manage a wide array of impacts associated with rising temperatures.

Construction of a planetary sunshade is possible. The fundamental physics and engineering are understood. Civil engineering projects of this magnitude have been built before and have proven to be transformative. Because of the second Space Race and rapid technological progress on space launch systems, the cost of sending materials and people into space is dropping fast, changing the scope of what is possible.

Climate change is here, and each additional bit of warming has a horrific human cost. The Earth will cross 1.5 C° in the next decade, a threshold that world's nations unanimously decided was unacceptable. Every year, the destruction caused by extreme weather, sea level rise, and fires will increase, as will political pressure to respond to the crisis. Melted ice caps and methane released from permafrost cannot be undone. The existence of this civilization is at stake, and all options should be under consideration to mitigate the climate crisis. The planetary sunshade should be considered a valuable tool in the effort to ensure a livable climate.

APPENDIX A

The Earth as a Thermodynamic System

Climate change is here, and it is getting worse fast. Despite decades of international climate talks, the trajectory of emissions under best-case scenarios still points toward unacceptable warming.

In order to limit global warming to 1.5°C, the Intergovernmental Panel on Climate Change (IPCC) estimates that the remaining carbon emissions budget is around 500 million tons of carbon dioxide.[19] The cumulative net CO2 emissions between 2010 and 2019 was 410 million tons which means, on the current emissions trajectory, we will exceed the threshold for 1.5°C of warming sometime in the early 2030s. There are credible scenarios, driven by continued greenhouse gas emissions and exacerbated by feedbacks in the climate cycle and potential ecological tipping points, for warming of 4.5°C or more by 2100; warming at that level would have catastrophic consequences for the environment and human health and society.[20]

Transitioning away from fossil fuel use is imperative and must be accomplished as quickly as possible. Although progress has been made on international commitments to reduce greenhouse gas (GHG) emissions, proposed emissions cuts are insufficient to reach the goal of limiting global warming to 1.5°C (see Figure 5).

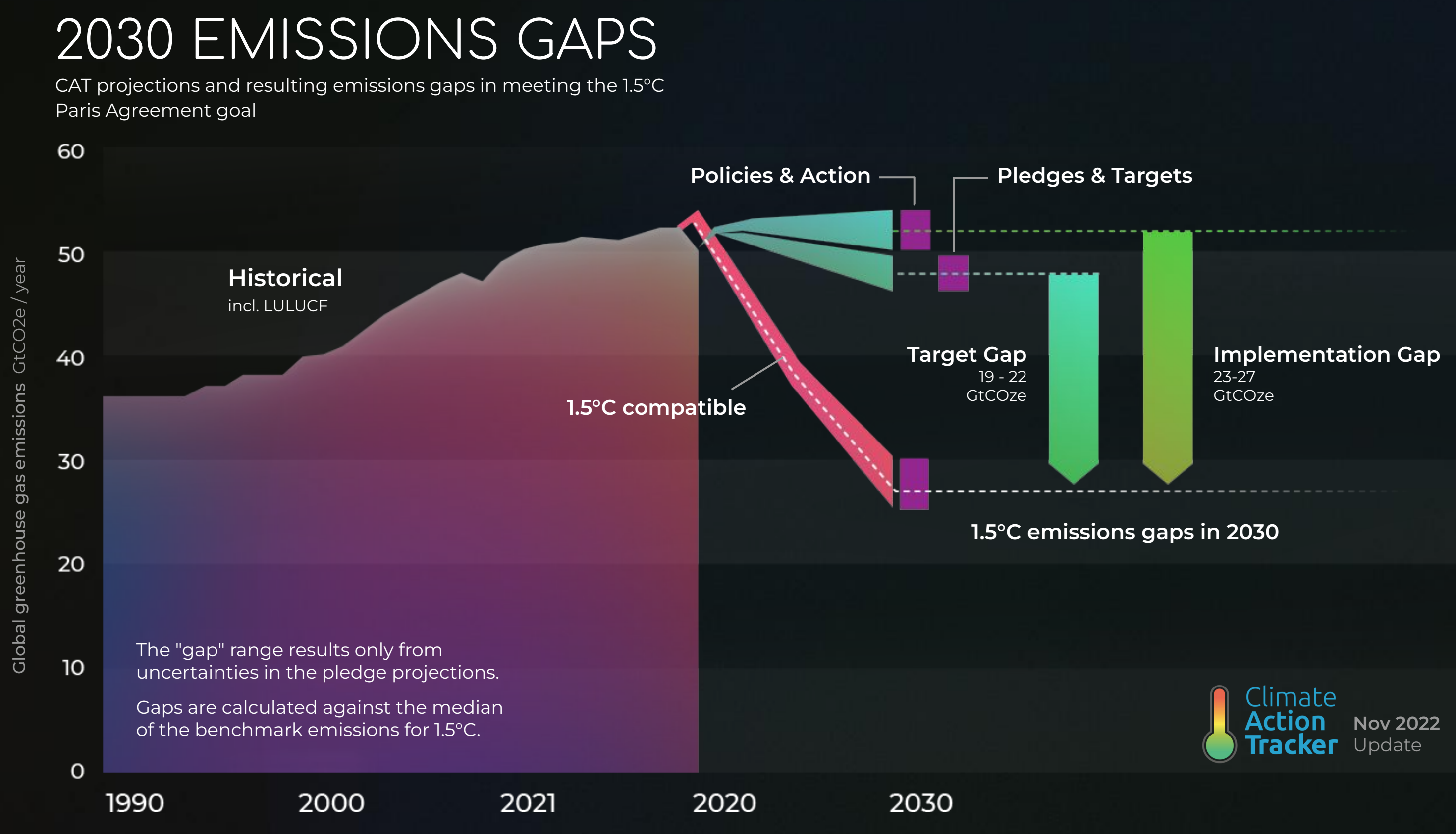


Figure 5: 2030 emissions gap, showing the difference between international emissions reduction pledges and targets and the emissions trajectory required to limit global warming to 1.5°C. (LULUCF: land use, land use change, and forestry).[21]

19 IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. doi: 10.1017/9781009157896.
20 Kemp, L, et al. (2022) Climate Endgame: Exploring catastrophic climate change scenarios. PNAS Vol 119, No, 34. https://doi.org/10.1073/pnas.2108146119
21 Climate Action Tracker, https://climateactiontracker.org/global/cat-emissions-gaps/.

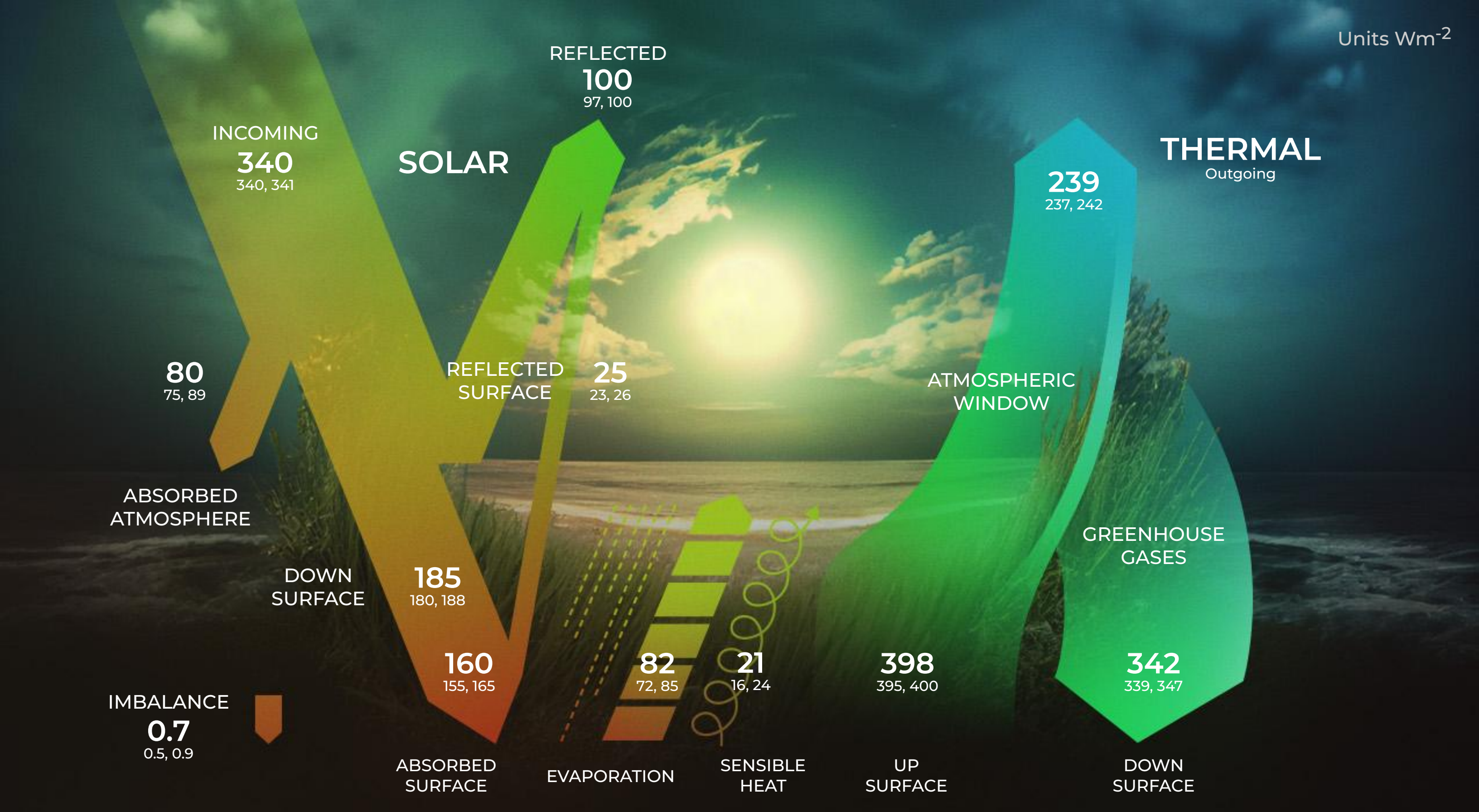


Figure 6: Global mean energy budget of the Earth according to the IPCC (values expressed in W/m2, uncertainty ranges shown in parentheses).[22]

However, achieving net-zero emissions will not solve the problem of the high carbon concentration already present in the atmosphere. Carbon dioxide can last for hundreds or thousands of years in the atmosphere, and even if we reached net-zero emissions today, global temperatures could continue to rise for decades before stabilizing. Because every bit of warming increases the risk of climate tipping points and causes more destruction, world leaders are more seriously considering active climate interventions, known as geoengineering.

Geoengineering proposals all focus on correcting the energy imbalance of the greenhouse effect. When the system is in equilibrium, global temperatures are relatively stable. However, carbon dioxide and other greenhouse gases (GHG) have accumulated in the atmosphere, causing it to absorb thermal energy that would have otherwise radiated back out into space. This energy imbalance is approximately 0.7 W/m^2 (see Figure 6), and results in global warming.

22 IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner, H.O., et al (eds.)] Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi: 10.1017/9781009325844.

APPENDIX B

Geoengineering and Stratospheric
Aerosol Injection

“Geoengineering is the deliberate large-scale intervention in the Earth’s natural systems to counteract climate change.”

Oxford Geoengineering Programme

Geoengineering, also known as climate intervention, is being discussed by many decision makers to address the imbalance in the Earth’s energy budget. Here we briefly review the two most discussed methods: Carbon Dioxide Removal and Stratospheric Aerosol Injection.

Carbon Dioxide Removal, or CDR, focuses on increasing the amount of energy Earth emits out to space by restoring the atmosphere to pre-industrial conditions through removal of heat trapping GHG already present in the environment. There are many forms of CDR in various stages of readiness, but they all remove and sequester carbon from the atmosphere.

CDR is necessary to fully undo the effects of climate change. It is the only solution that will address global warming as well as other side effects, such as ocean acidification and altered weather patterns. However, removing hundreds of billions of tons of excess carbon from the atmosphere will be slow and expensive. CDR cannot begin at scale until enough excess clean energy is available to power direct air capture systems. Even after net-zero emissions are reached, removing excess carbon from the atmosphere will be a generational effort, and is unlikely to be profitable, requiring substantial public subsidy. But until enough carbon is removed to reach pre-industrial levels, the Earth will continue to be too warm.

The other way to restore the balance between energy entering and energy leaving the Earth system is to block incoming solar energy. This set of proposals is referred to as solar radiation management (SRM). Unlike CDR, SRM does not solve the underlying imbalance of the atmosphere’s chemistry (too much carbon in the atmosphere). Instead, SRM addresses one of climate change’s most severe consequences - global warming - to buy time for emissions reductions and carbon removal while minimizing the ecological, economic, and human impacts of climate change.

Many regional forms of SRM have been proposed and studied in models, including modifying land to increase its reflectivity, preserving highly reflective ice sheets, brightening marine clouds by seeding them with saltwater, and thinning cirrus clouds, which trap heat in the atmosphere. The most viable SRM method, and the one that has garnered the most credible attention, is Stratospheric Aerosol Injection (SAI).

STRATOSPHERIC AEROSOL INJECTION

In stratospheric aerosol injection (SAI), tiny particles, called aerosols, are injected into the stratosphere to reflect a small percentage of incoming solar energy. The stratosphere is high in the atmosphere, where the air is thin and relatively stable; aerosols injected at this altitude can last for around two years before migrating to the poles and falling back to the surface. The motion of currents in the stratosphere is primarily horizontal, so injections made at one longitude will distribute relatively evenly around the globe at that latitude. To cool the Earth enough to offset 0.5-1.0°C of global warming, several million metric tons of aerosols must be injected into the atmosphere each year.[23]

Various aerosols have been proposed, but sulfur dioxide (SO2) has received the most study. In addition to being plentiful and cheap, sulfur dioxide is naturally present in the stratosphere as a result of powerful volcanoes. Volcanic eruptions, Mount Pinatubo in 1991 (see Figure 7), sent millions of tons of sulfur dioxide into the stratosphere and had marked impacts on Earth's temperature. Mount Pinatubo's eruption reduced temperatures by 0.5°C[24] with effects lasting one to two years. Powerful volcanic events are a natural proof of concept of SAI.

23 Keith, D. (2013) A Case for Climate Engineering, MIT Press https://keith.seas.harvard.edu/a-case-climate-engineering

24 Parker, D. E, et al. (1996). The Impact of Mount Pinatubo on World-Wide Temperatures. International Journal of Climatology. 16 (5): 487–497. Bibcode:1996IJCli..16..487P. doi:10.1002/(SICI)1097-0088(199605)16:5<487::AID-JOC39>3.0.CO;2-J

Figure 7
Eruption of Mt. Pinatubo
June 12, 1991[24]

There are several crucial benefits to SAI

First, it is effective very rapidly. As demonstrated by volcanoes, injecting aerosols into the stratosphere can result in dramatic temperature reductions within a year or two. SAI also provides flexibility in desired temperature. More aerosol injection could fully return Earth to pre-Industrial temperatures; less SAI could shave a few tenths of a degree off global temperatures to avoid the worst temperature-related outcomes of climate change. The third benefit of SAI is that the cost is relatively low. A fleet of one hundred purpose-built high-altitude aircraft (see Figure 8), plus the infrastructure to support deployment, could cost several tens of billions of dollars: vastly less than the trillions of dollars needed for CDR or to adapt to unmitigated climate change. The technical capabilities to deploy SAI at scale are not available today but could be developed with existing technology if a decision was made to pursue SAI.[26]

25 Dave Harlow, USGS. https://volcano.si.edu
26 Smith, Wake. *Pandora's Toolbox: The Hopes and Hazards of Climate Intervention*. Cambridge University Press, 2022.

Figure 8

Stratospheric Aerosol Injection Lofter (SAIL) aerosol deployment aircraft

Despite its benefits, SAI is not a perfect solution. Sulfur dioxide is a precursor to sulfuric acid, which causes acid rain. While the amount of SO2 needed to counteract anthropogenic warming is an order of magnitude less than the SO2 currently emitted by the world's industry, it would still have a measurable impact. Deployment at the level needed to significantly mitigate global warming will result in a cloudy or milky appearance of the sky. SAI may have undesirable impacts on the hydrological cycle, and more modeling is needed. Injecting sulfur into the atmosphere will also cause some damage to Earth's ozone layer, as sulfur reacts with ozone to become sulfuric acid, although ozone damage from SAI is also an order of magnitude less than that caused by current pollution. Decision makers will need to weigh these factors against climate change impacts when making a decision to implement this technology.

SAI, like all SRM, sets up the conditions for termination shock. If an intervention is implemented and is successful in reducing temperatures, and is then rapidly halted, the climate would suffer a temperature snap-back, where the full effects of global warming would return over the course of 1-2 years. The speed of this rapid snap-back could be more damaging than gradual global warming. Once SAI begins, it must be maintained until carbon is removed from the atmosphere: since CDR is expected to take generations, SAI must be maintained at some level until that task is completed.

Optimistic estimates for removing hundreds of gigatons of carbon from the atmosphere guess at over 100 years[27] of expensive 'waste removal' style work, funded by governments with little room for economic upside.

GEOENGINEERING:
MORE RESEARCH NEEDED

Impacts of geoengineering require a greater level of understanding, but unfortunately the research is woefully underfunded. SRM, and geoengineering in general, have long been the third rail of climate discussions, although this is changing fast.

The opposition to geoengineering research centers on two key arguments: **1)** the moral hazard, and **2)** the unintended consequences. The moral hazard argument says that geoengineering interventions will reduce our commitment to decarbonization. The Planetary Sunshade Foundation supports the urgent phase-out of all fossil fuel use and does not accept money from the fossil fuel industry. Furthermore, we believe that current efforts to decarbonize are already far too weak, and thus more effort fighting the climate crisis generally is far better than a purist argument around only one 'right' way. The unintended consequences will always be a concern, as are the unintended consequences of burning all available fossil fuels. We should study this as much as we can and weigh our best knowledge against the catastrophic consequences of unmitigated warming.

Now that limiting Earth to a 1.5°C temperature rise is no longer achievable and, in the absence of geoengineering, a global temperature rise of well over 2.0°C is likely, the eventual deployment of SRM is increasingly discussed. However, once SRM is deployed, we are committed to maintaining it for as long as it takes to remove carbon from the atmosphere and restore Earth's climate.

Any credible discussion of stratospheric aerosol injection should also include the only other global method of solar radiation management: the planetary sunshade.

27 UNEP (2017). The Emissions Gap Report 2017. United Nations Environment Programme (UNEP), Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf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