OBSERVATOIRE Défense & Climat

Note

SOLAR GEOENGINEERING: GEOSTRATEGIC AND DEFENCE ISSUES

November 2023

DGRIS

IRIS INSTITUT DE RELATIONS INTERNATIONALES ET STRATÉGIQUES

The Defence and Climate Observatory, launched in December 2016, aims to study climate-related security and defence issues.

It is coordinated by IRIS under contract to the French Ministry of Defence's Directorate General for International Relations and Strategy (DGRIS). The Observatory has a multi-disciplinary and cross-disciplinary team of researchers specialising in international relations, security, defence, migration, energy, economics, climatology and health. It is directed by Julia Tasse and François Gemenne.

The Observatory has initiated numerous collaborations with European partners (Netherlands, Luxembourg) and international partners (Australia, United States, India), international NGOs and national and international public bodies. These initiatives have strengthened cooperation on climate issues and their security implications.

The Observatoire Défense et Climat produces reports and notes, organises restricted seminars and conferences open to the public, and hosts the podcast "On the climate front".

www.defenseclimat.fr/en

The Ministry of Defence regularly calls upon private research institutes for outsourced studies, using a geographical or sectoral approach to complement its external expertise. These contractual relationships are part of the development of the defence foresight approach, which, as emphasised in the latest White Paper on Defence and National Security, "*must be able to draw on independent, multidisciplinary and original strategic thinking, integrating university research as well as specialised institutes*".

Many of these studies are made public and available on the Ministry of Defence website. In the case of a study published in part, the Directorate General for International Relations and Strategy may be contacted for further information.

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In its 6th assessment report, the Intergovernmental Panel on Climate Change (IPCC) warns that it is **highly likely that the temperature threshold of +1.5°C since pre-industrial times will be exceeded by the end of the century** (IPCC, 2022, v.). The current trajectory of greenhouse gas (GHG) emissions, which should lead us to exceed this threshold before 2030, is already leading to **extremely high levels of climate insecurity.** This is borne out by the increasing number of meteorological and climate hazards which occurred around the globe in 2023, prompting UN Secretary-General Antonio Guterres to declare: "Climate collapse has begun" (*Libération*, 2023, 6 September).

The international community's failure to implement effective and tangible mitigation policies has led to renewed interest in developing "solutions", i.e. technological responses to climate change - such as **climate geoengineering: a set of techniques designed to enable large-scale intervention in the climate system, with the aim of mitigating change and/or reducing its effects.** Geoengineering can be divided into **two broad categories**, themselves comprising a variety of techniques and practices: on the one hand, **the extraction of CO_2 from the atmosphere** (*carbon dioxide removal*, or CDR) and, on the other, **modification of the radiation balance**[1], often referred to as *solar radiation management* (SRM[2]), which seeks to **compensate for the increase in global average temperature by reducing the amount of radiation absorbed by the Earth** (IPCC, 2022, 168).

While carbon extraction or capture has developed rapidly since the early 2000s, solar geoengineering techniques, which are less technologically advanced, have only seen their first field applications in recent years. Unlike less invasive techniques such as the use of white paint to increase the albedo[3] of urban surfaces, some solar geoengineering projects intend to deploy **technical and/or chemical devices in the clouds, in the atmosphere or in space**. These include *stratospheric aerosol injection (SAI)*, *marine cloud brightening* (*MCB)*, *cirrus cloud thinning (CCT*[4]) and *space sunshades*.

These techniques and their recent developments highlight the prospect of large-scale deployment of solar geoengineering over the coming decades. It therefore seems necessary to explore **the security and strategic issues raised by these techniques**, which this note sets out to do in four stages: **a presentation of the techniques studied and the associated natural and human risks** (I); **an analysis of the geostrategic and defence issues they raise** (II); **four hypotheses, and three prospective scenarios narrating the deployment of solar geoengineering techniques by 2050, together with recommendations for the Ministry of Defence** (IV).

[1] See definition in the glossary.
[2] However, we will see that some techniques do not seek to reduce the proportion of solar radiation absorbed by the Earth, but to increase the proportion of terrestrial radiation released by the Earth.
[3] See definition in the glossary.
[4] See definition in the glossary.

SOLAR GEOENGINEERING: NATURAL AND HUMAN RISKS

1. Techniques and projects

A - Local solar geoengineering through cloud modification

Two techniques for local solar geoengineering by modifying clouds have been developed: lightening marine clouds and thinning cirrus clouds. These techniques can be deployed locally as part of a strategy to cool down a specific area, but they could also be multiplied and combined with other techniques to cool down the planet as a whole.

The aim of marine cloud brightening is to increase the reflectivity and sometimes the lifespan of certain clouds. It involves injecting sea spray into low-lying marine clouds, which are ubiquitous in subtropical and mid-latitude oceans and play a fundamental role in reflecting the sun's rays back into space.

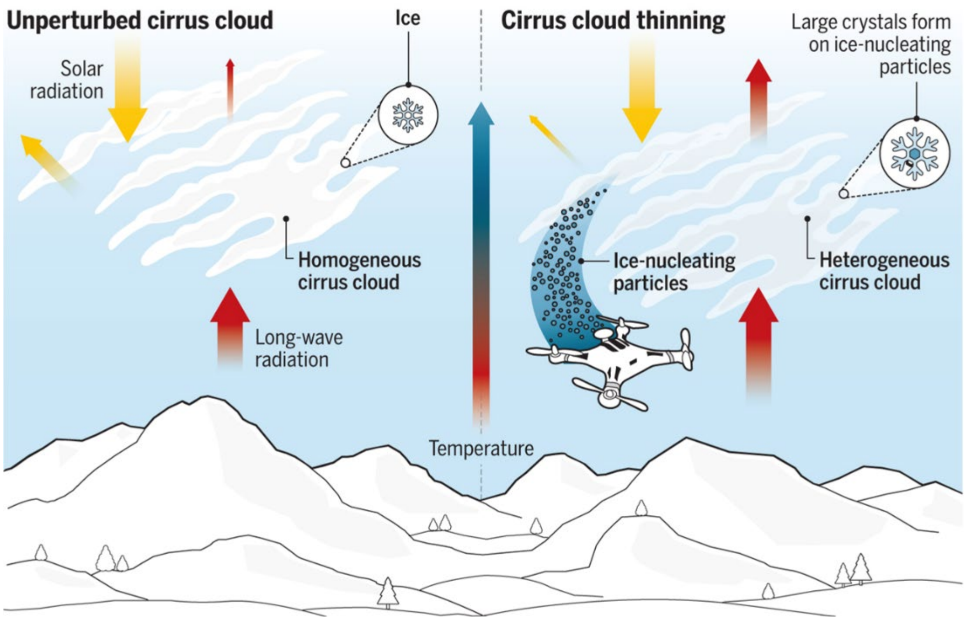
In Australia, researchers at the Sydney Institute of Marine Sciences and the Sydney School of Geosciences are proposing, through the **"*Marine cloud brightening for the Great Barrier Reef*" project** (*Great Barrier Reef Foundation*, 2023), the brightening of marine clouds over the Great Barrier Reef as a strategy for protecting the reef. Research and modelling for the project began in 2013, with deep-sea trials carried out between 2020 and 2022. Daniel Harrisson, who is in charge of the project, is planning further field trials in the coming years (Weiss, 2022). Stephen Salter, a professor at the University of Edinburgh, has been running a similar project since 2006. The process used in these two projects involves extracting salt water from a ship and then spraying it into the air *via* a turbine (Latham et al., 2012).

Photograph of a test as part of the Marine cloud brightening project (Credits: Brendan Kelaher/SCU)

The real costs associated with clearing marine clouds - and more generally, with all solar geoengineering techniques - are still uncertain, if not subject to commercial secrecy. The report published by the Royal Society in 2009 does, however, offer an estimate: **US$1.2 billion for the mobilization of 300 to 400 ships a year, plus operating costs** (Royal Society, 2009)**.**

While lightening marine clouds means increasing the amount of solar radiation[5] they reflect, thinning cirrus clouds means reducing the amount of terrestrial radiation[6] they absorb. Located in the upper troposphere[7], these thick clouds, made up of ice crystals, trap a large proportion of the Earth's radiation inside the atmosphere. Their warming effect is thus similar to that of greenhouse gases (French Embassy in the United States, 2021, 62).

When the ice crystals that make up these clouds are small and numerous, cirrus clouds are thick and allow little radiation to pass through, keeping the heat on Earth. Conversely, a thinner cirrus cloud, allowing more radiation to pass to space, is made up of larger and fewer crystals (Aslam et al., 2018). **The process of thinning cirrus clouds therefore aims to stimulate the creation of larger crystals by injecting ice nuclei such as bismuth iodide and particles of sulphuric or nitric acid into the areas where these clouds form naturally.** These injections would produce cirrus clouds with larger ice particles and a shorter lifespan, **increasing the amount of terrestrial radiation released into space.**



Behaviour of a cirrus cloud before/after intervention (Source: Lohmann & Gasparini, 2017)

[5] See definition in the glossary.
[6] See definition in the glossary.
[7] See definition in the glossary.

However, our knowledge of cirrus clouds remains speculative and uncertain, and cirrus thinning projects are still in the modelling phase throughout the world. These include American projects such as the ***Ice Cloud Size Distributions*** introduced by the Desert Research Institute in cooperation with the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin, and the ***Cirrus Cloud Thinning calculations*** project at the Swiss Federal Institute of Technology in Zurich.

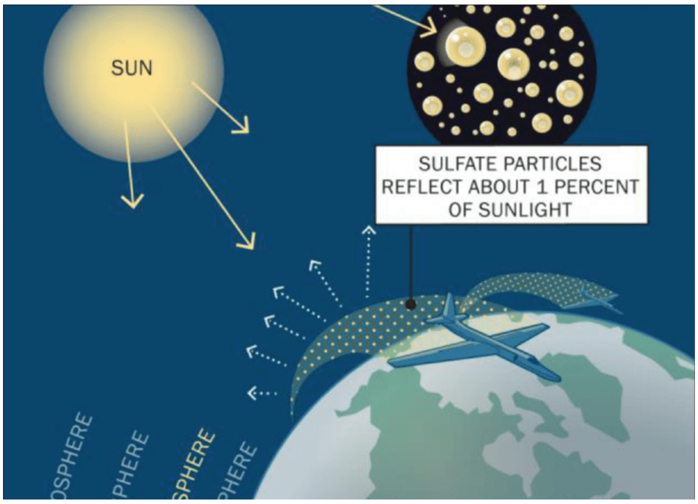
Not to be confused: solar geoengineering and weather modification

Lightening marine clouds and thinning cirrus clouds are two solar geoengineering techniques that involve cloud seeding, i.e. injecting particles into clouds. However, these techniques should not be confused with cloud seeding for weather modification, which aims to influence precipitation by stimulating the formation of water droplets or ice crystals in clouds. This method relies on the introduction of substances such as salt particles (also used in marine cloud brightening) or silver iodide into clouds, promoting the condensation or freezing of atmospheric moisture. **The main aim of cloud seeding is to provoke precipitation in dry conditions, or to reduce hail. While this technique has been used in the past for military purposes (for example, as part of Popeye Operation carried out by the US army during the Vietnam War), it is now used for economic purposes, particularly in agriculture.**

B - Planetary solar geoengineering: Injecting aerosols into the stratosphere

Unlike local geoengineering practices involving cloud modification, **the injection of aerosols into the stratosphere is a global scale technique** . This method involves **releasing reflective particles into the stratosphere by plane or balloon to create cooling conditions similar to those following major volcanic events**[8]. This is the most studied technique for modifying the radiation balance, but also the most controversial, precisely because of its global scope and the scientific uncertainty that accompanies it (Pasztor, 2023).

[8] The emission of sulphur particles and dust associated with volcanic eruptions is likely to lead to a cooling of global temperatures. After the eruption of Mount Pinatubo in the Philippines in 1991, for example, the average global temperature fell by half a degree.



Dispersion of reflective aerosols in the stratosphere (Credits: Funnel, Inc.)

To date, most modelling of this process has simulated injections at low latitudes to cool the planet relatively uniformly. However, **the injection location can vary depending on the deployment objective.** A strategy focused on preserving the Arctic (with, for example, an injection at 60°N) could cool high latitudes more efficiently and low latitudes less efficiently (Lee et al., 2022; Robock et al.2008). Because of atmospheric circulation, the **entire planet would nevertheless be affected by the dispersion of aerosols in the stratosphere.**

It is also a **complex, energy-intensive and potentially costly method**. In 2009, Alan Robock and his colleagues estimated the annual cost of injecting one teragram (10^{12} grams) of sulphur dioxide into the atmosphere. Depending on the methods used, this annual cost could range **from 225 million US dollars** (corresponding to the mobilization of 9 McDonnell Douglas KC-10 Extender aircraft, each making 3 flights per day) **to 21 billion US dollars** (corresponding to the dispatch of 37,000 stratospheric balloons per day) (Robock et al., 2009). Wake Smith and Gernot Wagner consider a scenario where aerosol injection into the stratosphere begins in 2033, with 8 aircraft making more than 4,000 flights a year. In their view, these figures would increase rapidly until 2047, when more than 60,000 flights per year would be required, at an **average cost of US$2.25 billion per year.** They also consider that no current aircraft has the technical capability to disperse aerosols in the stratosphere, which would require **new technological developments for dedicated aircraft** (Smith & Wagner, 2018).

Numerous SAI modelling and research projects have been carried out over the last ten years. However, three projects have attracted more attention because of their small-scale experiments or attempts at experimentation.

The first large-scale project is SCoPEx, led by Harvard University (Harvard University, 2023), which aims to **inject aerosols into the stratosphere using a high-altitude balloon 20 km above the Earth's**

surface. The experimental sites, initially based in Arizona and New Mexico, were moved in 2020 to the north of Sweden in order to carry out an initial technical test in the summer of 2021: a first balloon flight without dispersing aerosols. However, in March 2021, the tests were cancelled due to opposition from the Sami Council, Swedish civil society and a number of researchers.

In September 2022, *Stratospheric Aerosol Transport and Nucleation* (SATAN) balloons were released by a team of British researchers led by Andrew Lockley in partnership with European Astrotech. These balloons released 100g of sulphur into the stratosphere. This is believed to be the first time that a measured quantity of gas has been verifiably released as part of a solar geoengineering project (Temple, 2023).

Finally, the Make Sunsets start-up, founded by Luke Iseman and Andrew Song in the United States, has made a name for itself with its desire to commercialize solar geoengineering. In 2022, the company conducted experiments on Mexican territory, releasing balloons containing approximately 10g of sulphur dioxide into the stratosphere. The company's aim was to subsequently sell "cooling credits", one credit being equivalent to one gram of their balloons released into space. These experiments met with the disapproval of the Mexican government, and the project is now continuing near Reno, Nevada.

C- Space solar geoengineering using space mirrors

Some solar geoengineering projects envisage deploying reflecting devices in outer space. The **preferred strategy would be to place mirrors in orbit in space, which could reflect around 2 % of the sun's rays** (UNEP, 2023). However, this is the least advanced and least studied technique (O'Neill, 2022), mainly because of its complexity and cost. In fact, the mirrors would have to be transported by rocket and placed approximately 1,500,000 km from the Earth at Lagrange L1. At this point, the gravitational attraction of the Earth compensates for the gravitational attraction of the Sun, so that the objects can be fixed in orbit around the Earth (Siegel, 2020).

According to the report on solar geoengineering published by the United Nations in 2023, **these mirrors would have a lifespan of approximately 20 years, and an implementation cost of several billion US dollars** (UNEP, 2023). However, there could be growing commercial interest in this technique as a **potential source of renewable energy and an opportunity to open up a new market** (Baum et al., 2022). To date, only one space geoengineering project, Space Bubbles (MIT Senseable City Lab, 2023), is being carried out by a team from the Massachusetts Institute of Technology (MIT), but it remains at a very theoretical stage.

2. Natural and Human risks

A- "Moral hazard" and compromised climate policies

Solar geoengineering, by masking the effects of climate change rather than addressing them at their source, is a distraction from tangible and concrete mitigation policies (C2G Carnegie Climate Governance Initiative, 2022). A "moral hazard" (Preston, 2013) could therefore arise from the dissuasive effect of these techniques, or more precisely from their existence in the common imagination, with regard to mitigation and adaptation efforts. Since the early 2000s, this risk has been increasing as a result of the **"techno-scientific promises" made by their promoters, who spread the speculative hope of a technical solution to climate change**.

More specifically, these promises convey the idea of a **climate problem caused by a chemical or thermal malfunction that geoengineering proposes to regulate**, rather than by the inadequacy of current production and consumption patterns. **In this sense,** they **undermine climate mitigation commitments** (Asayama et al., 2019) and are supported by certain industrial sectors, particularly energy, in their quest for **alternative technical solutions to climate policies** (Low & Boettcher, 2020). In this context, moral hazard is all the more important as the effectiveness of techniques is not certain, and scientific uncertainties concerning the effects of techniques on humans and ecosystems are great.

B- Scientific uncertainties and weather, climate, food and health risks

Techniques for modifying solar radiation necessarily entail a certain number of risks for natural systems and the human societies that depend on them. However, they are at different stages of development and are not very advanced overall. As a result, there is **a high level of uncertainty about their effects on the other components of the Earth system**. Field experiments are still rare, and risk studies are based primarily on numerical modelling, reflecting **a lack of knowledge about the risks induced by solar geoengineering**. To date, studies on the subject have highlighted the following risks:

Table - Natural and human risks of solar geoengineering techniques by type

Technique	Risks to the Earth system	Risks to Human safety
Lightening of marine clouds	- **Changes in rainfall and temperature** (droughts in South America increased tropical rainfall) (Grisé et al., 2021). - **Persistence of impacts associated with rising CO_2.** - Decrease in photosynthesis impacting humidity levels, precipitation and local oxygen concentrations (Sacha, 2022). - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which ecosystems cannot adapt.	- **Reduction in agricultural yields**[9] (Sacha, 2022) - **Reduction in primary productivity in the Amazon, and a slight increase in Africa (rainfall disruption)** (Jones et al., 2009; 2011). - **Loss of ecosystem services (reduced photosynthesis).** - **Health risks linked to temperature changes**[10] (Swiss Re, 2023). - **Reduced air quality.** - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which human societies will not be able to adapt.
Thinning cirrus clouds	- **Disruption of precipitation** (intensification of rainfall in the Sahel and of the monsoon in India) (Gasparini et al., 2020). - **Amplification of global warming** if techniques are carried out in areas with low cloud cover and relatively high humidity (Peters et al., 2011) or if too many particles are injected (Gasparini et al., 2020). - **Persistence of impacts associated with rising CO_2.** - Decrease in photosynthesis impacting humidity levels, precipitation and local oxygen concentrations (Sacha, 2022). - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which ecosystems cannot adapt.	- **Health risks linked to temperature changes** (Swiss Re, 2023). - **Loss of ecosystem services (reduced photosynthesis).** - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which human societies will not be able to adapt.
Injection of stratospheric aerosols	- **Degradation of the ozone layer** (Lawrence et al., 2018). - **Deterioration in rainfall** (in particular, droughts in sub-Saharan Africa, the Mediterranean and India, torrential rains and floods in Brazil and Northern Europe) (Baughman et al., 2012; Jones et al., 2022; Grisé et al., 2021). - **More hurricanes** in the North Atlantic (Grisé et al., 2021). - **Variability of effects depending on place of injection**[11]	- **Reduced agricultural yields** (Proctor et al. 2018)[12] . - **Health risks linked to released substances** [13] - **Health risks linked to temperature changes.** - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which human societies will not be able to adapt.

[9] This is linked to a drop in photosynthesis by crops, but also in temperatures and rainfall.

[10] Changes in temperature and precipitation patterns could cause certain diseases, such as malaria, to shift geographical zones and proliferate in new areas (Carlson et al., 2022).

[11] Aerosols injected into the northern hemisphere could cause severe droughts in sub-Saharan Africa and India. Injection into the southern hemisphere could lead to a collapse of the rainfall system in Brazil and an increase in hurricanes in the North Atlantic (Grisé et al., 2021).

[12] Some studies have highlighted the risk of reduced agricultural yields following stratospheric aerosol injection in regions where productivity is strongly determined by the summer monsoon system, particularly in East Asia (Robock et al., 2008; Tilmes et al., 2013).

[13] Sulphuric acid, in particular, is extremely toxic (Lawrence et al., 2018). Sulphur could also fall back in the form of acid precipitation (Chalecki & Ferrari, 2018).

	- Interference with El Niño, the North Atlantic Oscillation, the Quasi-Benialle Oscillation, the polar vortex and the Brewer-Dubson circulation (Aquila et al., 2014; Jadwiga et al., 2018; Jones et al., 2022). - **Persistence of the impacts associated with the increase in the level of CO_2 and risk of cancelling out the benefits induced by the MRS** due to the degradation of cloud cover under the effect of GHGs (Schneider et al., 2020). - Decrease in photosynthesis impacting humidity levels, precipitation and local oxygen concentrations (Sacha, 2022). - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which ecosystems cannot adapt.	
Space mirrors	- Cascading regional variations depending on mirror positioning and shaded or unshaded regions (Sánchez & McInnes, 2015). - **Climate extreme changes in terrestrial zones with temperatures and ecosystems that are strongly impacted by solar radiation** (tropics and poles), leading to a cascade of the following effects: ➔ Rainfall disruption (United Nations, 2023) ➔ Reduction in the amplitude of the seasonal cycle (United Nations, 2023) ➔ Decrease in photosynthesis impacting humidity levels, precipitation and local oxygen concentrations (Sacha, 2022) - Objects placed at L1 are relatively stable, but risk going off their axis[10]. Without intervention (replacement or replacement), the mirrors will come off their axis after a certain time (Siegel, 2020; European Space Agency, 2023). - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which ecosystems cannot adapt.	- **Reduced agricultural yields but no chemical interference with the earth's biosphere** (Sacha, 2022). - **Health risks linked to temperature changes.** - **"Terminal shock" in the event of a halt** (cf. I, 2, b.): a sudden rise in temperature to which human societies will not be able to adapt.

C- Socio-technical lock-in: towards a "terminal shock"?

There is another significant risk in the deployment of geoengineering: **the risk of socio-technical lock-in, i.e. the irreversibility of the techniques developed**, which in fact entangle a number of economic and political interests (Cairns, 2014). By virtue of these interests, it is **possible for technical developments to be maintained and continued, even in the presence of evidence of their inefficiency or harmfulness**. This irreversibility, commonly observed in Western technological developments, is taken to its extreme in the context of solar geoengineering, due to the **'**termination shock' (Parker & Irvine, 2018).

In fact, if a solar geoengineering technique were deployed in the absence of a drastic reduction in GHG emissions, and if this technique succeeded in temporarily neutralizing global warming, it would be **impossible to put an end to its deployment without causing a sudden rise in temperatures**. This rise in temperature, which would be much faster than a warming trajectory without geoengineering, would be such that **human societies and some ecosystems would not be able to adapt to it** (Trisos et al., 2018).

In this sense, if solar geoengineering devices were to be implemented, **their vulnerability to environmental, economic and geostrategic shocks would entail considerable risks for the survival of human societies**. Space mirrors, for example, are liable to drift (Siegel, 2020) or to be the target of military confrontation, leading to an immediate rise in global temperature. This risk is also significant for geoengineering operations that require chemical intervention. For example, since aerosols in the stratosphere have a lifespan of one to three years, the injection of stratospheric aerosols would have to be repeated annually (Niemeier et al. 2011). As for marine cloud brightening operations, they would require continuous spraying of marine salts into the clouds, which have a lifespan of only ten days or so (MacDougall et al. 2020).

The irreversibility of solar geoengineering deployments and the need to renew interventions **entail two risks**: firstly, a **heavy dependence on technological developments that consume financial, energy and mineral resources**; and secondly, the risk of **brutal and devastating global warming if phenomena such as natural disasters, supply disruptions or military confrontation put an end to the deployment.**

SOLAR GEOENGINEERING:

A POLITICAL OBJECT WITH CONFLICT POTENTIAL

Due to the consequences that the deployment of solar geoengineering would have, we need to look at the dynamics of rivalries at play, as well as their strategic and security implications. The ability of a state actor to control the temperature globally or in a given territory would constitute a major technological advance. **The objective (or objectives) of deploying such a technology is therefore a central question.** While the majority of scenarios are based on the assumption that deployment will be guided by global climate objectives, the deployment of solar geoengineering could also be guided by "particular political interests" (Corry, 2023, 11 September).

The objective of this section is to dismantle the compartmentalization surrounding the discourse on solar geoengineering as an environmental technology, thereby integrating it into the broader framework of international relations and security concerns. To do this, we present players involved in the development of solar geoengineering and detail the positions of major powers. We then make an inventory of the international governance of solar geoengineering and discuss the dynamics of rivalry between powers over this technology. Finally, we explain security issues associated with solar geoengineering, firstly by presenting ways in which these technologies could be used as a political tool. We then review the involvement of defence actors in the development of solar geoengineering in the United States and discuss the technologies' potential for conflict.

1. Solar geoengineering: a developing sector

A- A diversity of players with complementary roles

States and their respective governments are contributing to the development of solar geoengineering by providing funding for research. Germany and the United Kingdom (as well as the European Union) for example, have funded research projects up to 31.3 million US dollars between 2008 and 2018 (Surprise & Sapinski, 2022, 27 October). Another example is the Australian government, which funds the Great Barrier Reef Foundation and its marine cloud whitening project at a cost of 4.7 million Australian dollars (around 3 million US dollars) (Readfearn, 2020, 14 July). **States can also play a role through their actions within international organizations**. This is particularly true of Switzerland, which is pushing for geoengineering to be put on the agenda at the United Nations[14] (Stefanini, 4 March 2019).

[14] In March 2019, Switzerland presented a resolution aimed at assessing geoengineering techniques and their governance arrangements during the United Nations Environment General Assembly. The resolution was also supported by Burkina Faso, Micronesia, Georgia, Liechtenstein, Mali, Mexico, Montenegro, New Zealand, Niger and Senegal. The resolution was blocked by the United States, Saudi Arabia and Brazil.

The scientific community is particularly active in the development of solar geoengineering. Current research programmes are hosted by universities and public research agencies. **However, the position of scientists with regard to solar geoengineering is extremely polarized.** On one side, such as David Keith[15], sees the technology as a solution to climate change (U Chicago News, 2023, 11 April). On the other, researchers like Frank Biermann[16], is opposed to this technology because of the associated risks.

Private players are also active in the development of solar geoengineering, particularly when it comes to funding, especially in the United States. Researchers Sapinski and Surprise have shown that "the majority of funding for solar geoengineering comes from foundations and individuals in the fields of *tech* and finance, many of whom are known for their environmental philanthropy" (Surprise & Sapinski, 2022, 27 October). **Private players are also active in experimenting with, and even marketing, solar geoengineering**, following the example of Californian start-up *Make Sunsets*.

Finally, international bodies and non-governmental organizations contribute to the debate on solar geoengineering. The former, like the United Nations (UNEP, 2023) and the European Commission (Abnett, 2023, 28 June), are in favour of a governance scheme for solar geoengineering. Some of the latter are in favour of solar geoengineering (SilverLining, Degrees Initiative), while others are largely opposed to its development (ETC Group, Hands Off Mother Earth campaign).

B- A definite interest on the part of the major powers, albeit tinged with opacity

United States

According to the information available from open sources and interviews conducted for this report, **the United States is considered to be the most advanced country in terms of solar geoengineering.** It dominates the sector, with several large-scale projects underway (Harvard, UCLA, Cornell). This country stands out for the **involvement of the defence sector**, which we describe in more detail in the next section. **The private sector is also extremely active in funding research,** and has granted approximately US$20 million to initiatives and projects relating to solar geoengineering between 2008 and 2018 (Surprise & Sapinski, 2022, 27 October).

[15] David Keith is Professor in the Department of Geophysical Sciences at the University of Chicago. He has directed Harvard's Solar Geoengineering Research Project.
[16] Frank Biermann is Professor and Researcher in *Global Sustainability Governance* at Utrecht University, and founder of the *Earth System Governance Project*.

The United States is considered to be a leader in the field of experimentation. The *Stratospheric Controlled Perturbation Experiment* (SCOPEX) project, housed at Harvard, was due to carry out a small-scale test in Sweden in 2021. Nevertheless, due to opposition from the Indigenous Sami people, the field tests were postponed (Cooper, 20 May 2021). As part of the *National Oceanic and Atmospheric Administration*'s new SABRE project (*Stratospheric Aerosol processes, Budget and Radiative Effects*) launched in 2023, research experiments have been carried out in Alaska and are planned for the tropics in 2024, and in the southern hemisphere in 2025 (NOAA, 2023, March 2).

Since 2022, the US has taken a public stance in favour of geoengineering research at federal level, as demonstrated by the 2022 *Federal Appropriations Act* signed by President Biden, which orders the *Office of Science and Technology Policy* to coordinate research into solar geoengineering (United States of America, 9 March 2022). In line with this mandate, a report published in June 2023 sets out recommendations for the establishment of a governance framework for publicly funded solar geoengineering research. In addition, **it proposes the creation of a federal research programme dedicated to geoengineering** and mentions international cooperation and public participation as key aspects to be established (OSTP, 2023).

China

China is active in solar geoengineering research, as shown by the existence of the publicly funded *Chinese geoengineering research project* (2015-2019), which ranged from 100,000 (Harvard Solar Geoengineering Research Program, 2019) to US$ 3 million (Temple, 2017). The latter aimed to study the climate impacts of solar geoengineering and explore the associated governance issues. **In August 2020, China conducted a local solar geoengineering experiment** on the Dagu glacier in Sichuan, covering it with a 500 m^2 of 5 to 8 mm thick textile, with the aim of reducing the melting of the glacier during the summer (Zizhu, 2020, 9 November).

For the time being, China's public statements indicate that the country is not interested in large-scale deployment of solar geoengineering. However, all the researchers interviewed for this report agree that, on the one hand, little official information is available and, on the other, it is highly unlikely that China is not interested. In addition, China's attitude to weather modification and the way in which its large-scale deployment has been conducted[17] suggests that a sudden change of position would also be possible in the case of solar geoengineering (Jayaram, 2023, 8 September).

[17] While for years China only used weather modification in agricultural areas or during major events (Beijing Olympic Games), the government suddenly announced in 2020 that the country would have a weather modification system developed by 2025 that would cover 5.5 million km^2 , equivalent to the size of India.

Russia

According to the information available from open sources, Russia does not have a solar geoengineering research programme. However, the USSR is historically the birthplace of the injection of aerosols into the stratosphere, proposed by researcher Budyko in the late 1970s (Budyko, 1977, 239). Since then, researcher Yuri Izrael has resumed this research. Izrael is considered to be a geoengineering 'enthusiast' (Mooney, 2009) in view of his numerous publications and positions (Oldfield & Poberezhskaya, 2022, 8). **In 2009, Izrael and his research team carried out a small-scale solar geoengineering experiment in Russia**, which involved injecting aerosols at an altitude of 200m (Mooney, 2009).

Moscow's official position seems to be fairly favourable to solar geoengineering. **Russia is said to be taking a close interest in the technology**, **motivated by the advances made by the other major powers (the United States and China) and the importance of the security and intelligence sectors in that country** (Corry, 2023, 11 September). The government also reportedly asked to include a paragraph on geoengineering "as a possible solution" to climate change during the preparations for the 2013 IPCC report and stated that "its scientists are developing geoengineering technologies" (Lukacs, Goldenberg and Vaughan, 19 September 2013). Even so, the researchers interviewed for this note all deplore the lack of information on Russia's progress in solar geoengineering research.

2. Solar geoengineering: a new object of governance and competition

A- International governance of solar geoengineering struggling to emerge

With the exception of a non-binding moratorium adopted by the signatory countries of the Convention on Biological Diversity in 2010 and including an exception for small-scale research (*Convention on Biological Diversity*, 2017, 23 March), **there is currently no multilateral governance framework dedicated to solar geoengineering** (*United Nations Environment Programme*, 2023, 6). Furthermore, existing international treaties are incomplete for the governance of geoengineering in that they do not explicitly cover "the intent, scope and effects of geoengineering" (Sacco et al., 2022, 24). When the 2013 amendment to the London Protocol comes into effect for example, it will only cover marine geoengineering (IMO, 2022, 10 October). Similarly, the ENMOD Convention adopted in 1977 only prohibits the use of environmental modification techniques for military or other hostile purposes (United Nations, 2023).

The need to build an international governance framework for solar geoengineering has been put forward by countries, such as Switzerland (Stefanini, 2019, 4 March), **NGOs** (Carnegie Governance Initiative) **and intergovernmental bodies such as the** European Union and the United Nations. The technologies currently being developed raise "ethical, moral, legal, equity and justice" questions (*United Nations Environment Programme*, 2023, 1) that emerge "from research, during experimentation, at the time of deployment of these techniques, but also once they have been put in place, because of their impacts on different scales" (Doumergue & Kabbej, 2021, 5-6).

The ability to build a binding, multilateral, governance framework for solar geoengineering is widely questioned (Victor, 2008), or **even considered impossible** (Biermann, 2023, September 8). The current geopolitical context, characterised by major polarization between the East and the West, and the North and the South, combined with an inability to see binding climate agreements emerge, are often cited as blocking factors. The blocking of a motion for a resolution to assess geoengineering techniques and governance arrangements during the United Nations General Assembly on the Environment by the United States, Saudi Arabia and Brazil in 2019 (Stefanini, 2019, 4 March) show that roadblocks arise as soon as discussions become official (Corry, 2023, 11 September). The blocking countries considered that the issues surrounding geoengineering should be placed under the aegis of the Intergovernmental Panel on Climate Change (IPCC).

In 2022, given the risks associated with solar geoengineering and the lack of scientific knowledge on the subject, a coalition of more than 450 researchers called for an international agreement on the non-use of solar geoengineering (*Solar geoengineering non-use agreement*, published on 17 January 2022). In addition, states or a group of states adopting a declaration of non-use of solar geoengineering would be a first step, with political effect (Biermann, 2023, 8 September). **A proposal for a moratorium "on the deployment or large-scale experimentation" of solar geoengineering was also put forward in September 2023 in a report published by the *Overshoot Commission***. However, the Commission considers that this technology "could complement other approaches" to meet the challenges associated with potentially exceeding +1.5°C of warming compared with the pre-industrial era *(Climate Overshoot Commission*, 2023, September).

As the emergence of a binding governance framework for solar geoengineering is uncertain at present, other possibilities are opening up. Firstly, **an agreement between the European Union and the countries of the so-called "Global South", based on their interests and current progress** (Jayaram, 2023, 8 September). Secondly, a governance framework that is "very permissive for those who consider themselves to be the biggest players in the field" (Corry, 2023, 11 September). Finally, a **more**

realistic governance framework could emerge "through deterrence", with bilateral negotiations between major powers, similarly to the Cold War arms race (Corry, 2023, 11 September). A parallel between the governance of solar and nuclear geoengineering has also been drawn by some researchers (Young, 2023; Scharf, 2023).

B- A sector marked by rivalry between powers

The international governance of solar geoengineering is still largely to be established, and provides a forum for the confrontation between different visions. On the one hand, the objectives of this technology and, on the other, the ways in which it should be regulated. The various players and their visions come together to influence the governance framework under consideration, or to block its emergence. The report published in June 2023 by the White House (OSTP, 2023) is a scientific exercise, but above all a political one, in that it "opened the door for the United States to unilaterally shape and advance the development of solar geoengineering" (Stephens et al., 2023, 172).

The dynamics of rivalry between powers are at the heart of the development of solar geoengineering insofar as **"research capabilities are seen by States as sources of power" and levers of influence.** Furthermore, the fact that it is impossible to assume that all states are transparent about their solar geoengineering activities indicates that this technology is a potential object of rivalry: "if some states do it, they don't necessarily want to make it public" (Corry, 2023, 11 September).

Competition between major powers is deeply rooted in the dynamics of geoengineering development, around the idea that "if others are doing it, then we must do it too" (Corry, 2023, 11 September). What's more**, the US federal government's public stance on this technology has, and will continue to have, direct consequences on the stance of other state actors** (Jayaram, 8 September). This position is also shared by Chinese researcher Chen Ying, who believes that "China has no choice but to keep up the pace with the Western powers in geoengineering research" (Moore & Freymann, 2023, 21 February). **The dynamics of rivalry between great powers also work in the opposite direction, where China's advances in solar geoengineering are motivating the United States to position itself** (Corry, 2023, 11 September).

3. Solar geoengineering: a political tool with conflict potential

A- Technology for asserting interests, protecting and negotiating

Firstly, the deployment of solar geoengineering could make it possible to ensure or prolong lifestyles that are heavily dependent on fossil fuels, and/or serve public or private interests of stakeholders dependent on the fossil fuel market. This argument that solar geoengineering could be used to protect the interests of a certain political and economic elite is put forward by Corry and McLaren (Corry & McLaren, 2023). Going even further, researchers Surprise and Sapinski develop the argument that the United States is most likely to use solar geoengineering to maintain its hegemony, which is closely linked to fossil fuels, the (petro)dollar and its military power (which is also heavily dependent on oil) (Surprise, 2020).

Secondly, solar geoengineering could make it possible to mitigate the consequences of climate change on a given territory, but also on the operational capacity of defence systems. In a context where climate change and its consequences are described as threats to national security by various countries, including the US administration (The White House, 2015), **solar geoengineering could be approached as a protective tool.** It could be deployed in extreme environments to protect military installations from melting ice (Arctic bases) or to reduce the risks associated with rising sea levels (Sovacool et al., 2023, 9).

Thirdly, solar geoengineering could be used as a negotiating tool to obtain concessions from other players. The most likely way in which geoengineering could be used would be as a political threat.
Some countries, particularly vulnerable to the impacts of climate change, could threaten rich countries with deployment. For example, if the latter do not offer them sufficient compensation, do not help them finance losses and damage linked to climate change, or do not grant them preferential trade agreements (Sovacool et al., 2023, 8). This idea is also shared by Professor Matt McDonald, for whom "the threat of deployment" would allow certain countries to be heard[18] (McDonald, 2023, 11 September).

[18] Matt McDonald is Associate Professor in the Department of Political Science and International Studies at the University of Queensland, Australia.

Involvement of the US defence sector

Historically, the defence industry was among the first to take an interest in solar geoengineering, beginning in the late 1990s, seeing the technology as a potential response to climate change (Surprise, 2023, 19 September). **Even today, solar geoengineering is being developed with the active participation of the Department of Defence and/or related institutions, including intelligence and research agencies** (Surprise, 2020). The *Central Intelligence Agency* (CIA) has been exploring the possibilities of this technology since 2011 at least, while the *Defense Advanced Research Projects Agency* (DARPA) is funding studies on the subject (Collins, 2 November 2022) and is developing models alongside the *Naval War College* to detect the unilateral deployment of geoengineering (Surprise, 2023, 19 September).

Furthermore, the involvement of the military in the development of solar geoengineering is linked to the know-how and equipment available to the defence establishment. The military have crucial knowledge of logistical operations at high altitude and in the high seas. For example, the experiment planned for 2021 as part of the *Stratospheric Controlled Perturbation Experiment* (SCOPEX) was to be carried out in partnership with *Raven Aerostar*, a long-standing Department of Defence contractor (Surprise, 2020).

B- Technology that can contribute to triggering a conflict or be used as a target

Solar geoengineering should not be seen as a trigger for conflict, but rather as a factor that complicates relations between states, and can therefore contribute to triggering a conflict, or serve as a target during a conflict.

A first source of tension between States is linked to the environmental consequences of the deployment of solar geoengineering, and the attribution of events on a territory to the intervention of a third party. The case of tensions between China and India can be put forward, with the idea that China could be accused by India of being responsible for the disruption of the monsoon phenomena on its territory (Sovacool et al., 2023, 11). Diplomatic tensions have already erupted between the two countries as a result of weather modification operations and/or the construction of hydraulic dams by China, particularly in the Tict Plateau, an already militarised area (Kishimoto & Suzuki, 2021, July 27).

The occurrence of extreme weather events could be considered the result of deliberate action by a state (or coalitions of states) that has deployed solar geoengineering[19]. This could result in claims for

[19] This type of dynamic can also be seen in the tensions between Iran and Israel, the United States and the United Arab Emirates. Tehran accuses states using weather modification techniques of being responsible for the droughts affecting its territory. More generally, the practices of environmental modification (whether weather modification or climate modification) deployed by developed states fuel an anti-Western sentiment that is likely to come to the fore whenever a major natural disaster occurs, even one of non-climatic origin. For example,

financial compensation for caused losses, for example to crops. In addition, recourse to the military route could be motivated by the environmental consequences of a deployment (e.g. modification of monsoons) on economic security or that of the population. **The inability to prove the origin of the disturbances felt in a territory would enable players to position themselves as victims and thus justify political responses, particularly military ones** (Sovacool et al., 2023, 12). If solar geoengineering were deployed, it would be difficult to know whether environmental events were the result of natural climate variations, anthropogenic climate change or climate intervention (Surprise, 2023, September 19)**.**

A second source of inter-state tensions is linked to disagreements between states on the desired effects of deploying planetary solar geoengineering, and on the methods of deployment. States' national interests, depending on economic gains and losses associated with a given temperature, diverge widely. Tensions could arise over setting the temperature objective to be achieved (limiting the rise in global average temperature to +1.5°C, +2°C, +2.5°C compared with the pre-industrial period), but also over the technology deployed[20], the location of deployment, and the way in which the technology is deployed: chemical products and/or materials used, injection altitude as part of a chemical operation, vectors used for deployment (balloons, aircraft, sprays, rockets). **In addition, inter-state tensions could arise if local geoengineering techniques are used, as geopolitical interests may diverge over a given geographical area and the consequences of a change in temperature.** The example of the Arctic is regularly cited in relation to tensions between the United States and Russia, with "divergent interests in accelerating or slowing the melting of the ice" (McLaren, 2023, September 13).

In addition to the decision to use geoengineering, the multitude of choices to be made in order to deploy it, will most likely prevent international consensus. The United Nations Environment Programme considers that differences of opinion over the use and deployment of solar geoengineering "could generate political and even military conflict" (*United Nations Environment Programme*, 2023, 19).

Turkish politicians have accused the United States of being behind the earthquake that struck Turkey and Syria in early 2023 (Wei, 2023, 14 August; i24news, 30 August; de Guglielmo, 2021).

[20] Disagreements could arise between advocates of stratospheric aerosol injection to cool the planet immediately, advocates of local geoengineering operations by modifying clouds to prevent the crossing of specific tipping points, for example by targeting the protection of poles (a position that seems to be held today by China, in particular), and finally, stakeholders who would categorically refuse to see solar geoengineering interfere in international negotiations.

Another issue is the risk of escalation, linked to the risk of inter-state tensions surrounding disagreements over deployment methods and/or the consequences of deployment. If an initial operation was carried out by a State or coalition of States without international consensus, other States could deploy "counter-geo-engineering" operations in response to the initial operation. Two forms of "counter-geo-engineering" have been theorised: a "neutralisation" *counter-geo-engineering* process, which would consist of releasing new substances to accelerate the atmospheric deposition of the first products released; and a "compensation" *counter-geo-engineering*, seeking to reverse the effects of these products by injecting warming agents (particles or greenhouse gases) (Heyen et al., 2019).

The infrastructure and devices needed to deploy solar geoengineering are further sources of tension between States, insofar as they could be subject to suspicion of surveillance. The majority of deployment scenarios involve the use of aircrafts capable of flying at high altitude, which could be used for two purposes - to disseminate chemical particles and to monitor the areas over which these particles are spread. As Professor Olaf Corry points out, "in contemporary conflicts (...) any object involving close surveillance of areas is likely to become a source of conflict" (Corry, 2023, 11 September).

Finally, the deployment of solar geoengineering could also lead to a militarization of the technology. Infrastructures (aircraft, bases, surveillance tools, etc.) required for deployment could be targeted and be the object of a physical or cyberattack. **It would** therefore **be necessary to secure all the infrastructures involved, over a long period of time and by military means in particular, insofar as these would constitute a vulnerability** (Sovacool et al., 2023, 10).

The militarization of the technology is also linked to the deployment of solar geoengineering for hostile purposes, in order to adversely affect a state's rainfall patterns, agriculture and associated crops, or the availability of water and/or fishery resources. One of the arguments put forward for this hostile use is based on the ability of certain local solar geoengineering techniques (thinning cirrus clouds and whitening marine clouds) to be deployed very quickly and at low cost, making it possible to "change the weather in a few days" (Sovacool et al., 2023, 11). However, this idea is called into question by the existing regulatory framework around the ENMOD Convention (1977), which would theoretically prevent this type of use.

In conclusion, the development and deployment of solar geoengineering will help to change the concept of power, which can be defined as "the capacity of a political unit to impose its will on other units" (Aron, 1984). On the one hand, solar geoengineering implies a new scale of intervention by states, enabling them to control living conditions on Earth by controlling temperature. On the other hand, geoengineering is a new tool of power, in addition to the military, intelligence, trade and diplomatic levers (Corry & McLaren, 2023). In this sense, the traditional security players (including the military) will have to incorporate into their strategic thinking the possibility of a third party using solar geoengineering to assert their interests.

OUTLOOK AND RECOMMENDATIONS

1. Main deployment assumptions

Several hypotheses for the deployment of solar geoengineering have been formulated in the existing literature on the subject, and by interviewed researchers. In particular, these hypotheses combine several possibilities for governance, which remains uncertain given the current state of the regulatory framework.

A- Hypothesis 1: Multilateral deployment of solar geoengineering

The deployment of solar geoengineering could take place within a **multilateral framework, where an international agreement would be reached on the temperature target and the deployment methods**. This hypothesis, according to which the international community would reach agreement on the temperature and the deployment method, is used by researchers modelling the deployment of solar geoengineering and its effects on the climate, such as the geoMIP project (geoMIP, 2023).

B- Hypothesis 2: Unilateral deployment of solar geoengineering

The deployment of solar geoengineering could be carried out **unilaterally by a state, without any consultation or international agreement**. This scenario has been developed in particular by the *National Intelligence Council*, which published a *National Intelligence Estimate* in 2021 identifying as a growing risk the "deployment of large-scale solar geoengineering technologies by one country" (National Intelligence Council, 2021, *11).* The literature also refers to the concept of *rogue state* when this scenario is presented (Sovacool et al., 2023; National Intelligence Council, 2021).

C- Scenario 3: deployment by a coalition of states

3.1 Deployment by a coalition of 10 countries at an advanced level of development and with aligned geopolitical interests solar geoengineering could be deployed **by a coalition of wealthy, industrialized states with aligned geopolitical interests**. The existing literature on the subject develops the idea that this coalition of states (Canada, Japan, Switzerland, among others) would be led to initiate deployment, because no governance framework has emerged, and in their view it is urgent to intervene on the climate (Parson & Reynolds. 2021, 133).

3.2 Deployment by a coalition of 10 countries vulnerable to climate change

In the absence of tangible and rapid results in terms of mitigation, and in view of the current and projected consequences of climate change, it is conceivable that solar geoengineering could be deployed **by a coalition of States that are particularly vulnerable to climate change** (island States, Middle Eastern countries, certain so-called "Global South" countries). Geoengineering could also be seen as a way for vulnerable states to make their voices heard on the international stage, which is dominated by developed states. This hypothesis has been formulated in several studies (Sovacool et al., 2023; Parson & Reynolds, 2021).

D- Hypothesis 4: Deployment by non-state actors

4.1 Deployment by a private player

Given the significant involvement of private players from the finance and tech sectors in the solar geoengineering sector in the United States, another hypothesis could be **deployment by a philanthropist with substantial economic and material capital**. By funding an NGO or a dedicated company, this philanthropist could implement the deployment of a geoengineering technology on a planetary scale, with a view to "saving humanity" (Sovacool et al., 2023, 7). However, the researchers interviewed for this report agree that deployment by an individual player, such as Bill Gates or Elon Musk, could not take place without the formal or informal agreement of a state.

4.2 Decentralized deployment driven by consumers

While the private sector is heavily involved in technological developments linked to solar geoengineering, it is also keen to involve consumers in the marketing of technologies. This is the case of the company *Make Sunset*, whose business model is based on private individuals financing the injection of aerosols into the stratosphere. We could thus envisage deployment **driven by consumers who, under the influence of certain public or private players, could acquire solar geoengineering devices and carry out individual operations.** This hypothesis is put forward by Gernot Wagner, who imagines a multitude of geo-engineers in Saudi Arabia buying stratospheric balloons from Alibaba to inject aerosols into the stratosphere (Wagner, 2021).

2. Scenarios for the future: solar geoengineering to 2050

Scenario 1: Unilateral deployment by the United States

In 2047, the average global temperature will be +2.5°C compared with the pre-industrial era. GHG emissions have not been reduced sufficiently, and the international community has failed to meet the targets set out in the Paris Climate Agreement. Every year, every country in the world is affected by major natural disasters, resulting in thousands of victims and displaced persons. As a result, the economic situation of all countries is weakened. In the United States, the political situation is extremely tense. Overtaken by China, the country has been relegated to the rank of second world power since 2039. Over the last ten years, social inequalities have steadily increased, virtually wiping out the middle class. The impoverishment of the American society can also be explained by the numerous climatic disasters that affect the country. Increasing in number and intensity, floods and storms destroy hundreds of civilian infrastructures every year (roads, bridges, schools, homes, hospitals, power stations, etc.). Military infrastructure is also affected, causing losses of equipment (helicopters, planes, cars) and infrastructure (runways, military buildings). In addition, droughts and the increasing scarcity of water resources are having a severe impact on the agricultural sector. Cotton and maize crops have become impossible to grow, while soya and wheat yields have fallen by almost 40% since 2025. There are now thousands of victims of natural disasters every year, while the cost of the damage is around US$230 billion a year.

Against this backdrop, the American public opinion became increasingly critical of its government, which was accused of not having sufficiently anticipated the effects of climate change and of having delayed adaptation efforts. On June 3rd, 2047, the Republican government officially announced the deployment of aerosol injection into the stratosphere, a solar geoengineering technique designed to artificially lower global temperature by reducing the amount of solar radiation entering the atmosphere. This deployment raised a lot of hopes for Americans, who were promised by their government "an effective solution that will quickly and positively affect climate conditions on its territory". The defence sector is at the heart of the deployment plan, providing financial, human and technical resources. Every day since the government's announcement, hundreds of aircrafts have taken off from military bases to spray chemical particles at high altitude. This deployment is unilateral but does not violate international law. The United States had never ratified the Convention on Solar Geoengineering adopted in 2035, which prohibited the unilateral deployment of the technology. Aware that its decision had been taken outside any multilateral framework, US diplomacy launched an advocacy effort aimed at getting the international community to accept its decision. To this end, the United States positioned itself as the defender of human conditions and the guarantor of international security.

This unilateral decision continues to polarise relations between states at a time when the United Nations is already on the verge of dissolution. Despite proposals for a resolution at the Security Council initiated by Russia, none was adopted due to the American veto. China and Russia, joined by a number of partners, launched a diplomatic campaign denouncing the "selfish" action of the United States, and threatened military intervention to destroy the deployment infrastructure if it was not stopped as soon as possible. They warn that any overflight of their territory will lead to direct retaliation and the destruction of the aircraft. In addition, discussions are taking place within the coalition about launching counter-geoengineering operations to cancel out the effects of the American deployment. Western countries, long-standing allies of the United States, are divided: some support the American decision, while others are dissociating themselves from it, denouncing it as a dangerous decision and calling for it to be stopped immediately. In France, the environmental consequences of the deployment are still uncertain, but will certainly cause a change in rainfall patterns. Tensions between the United States and the Sino-Russian coalition are rising, as is the likelihood of armed conflict.

The French government scaled up its diplomatic efforts to dissuade the US from conducting its unilateral operation, arguing that the deployment had to be halted in the absence of international agreements. It also tried, through its Armed Forces and Foreign Affairs ministers, to work towards non-escalation by initiating discussions with the Sino-Russian coalition. France's credibility as a key player in international diplomacy is being severely tested. America's isolation from the rest of the world led the government to distance itself from its historic partner. French intelligence was accused of having failed to identify and prevent the American deployment before it took place. The President of the Republic summoned the directors of the intelligence services (DRM, DGSE) and an exceptional Defence Council was organised as a matter of urgency. In addition, the American deployment plan on the one hand, and the movements of the Chinese and Russian armies on the other, forced the French armies to increase their surveillance activities in order to be prepared to the outbreak of an open conflict between the major powers. What's more, the aircraft used by the United States flew over many territories, including mainland France and the TAAF. The latter are therefore suspected of surveillance activities, leading to jamming efforts by French forces. Against this backdrop, France proposed the establishment of a joint European Union force to coordinate surveillance and jamming efforts.

Scenario 2: China and the ArcticX project

By 2050, the planet will have warmed by +2.6°C compared with the pre-industrial era. Against this backdrop, several tipping points are being exceeded, and three tipping points have been irretrievably passed: the collapse of the Greenland ice sheet, the total disappearance of winter ice in the Barents Sea, and the total melting of summer ice in the Arctic. When these tipping points were exceeded, the average sea level rose by two meters, swallowing up thousands of homes and leaving entire communities without habitable land. Several islands and archipelagos - such as the Maldives and Tuvalu - have already disappeared, and others have lost up to 50% of their habitable territory - notably French Polynesia. Biodiversity is also suffering from a cascade of extinctions. Several thousand plant and animal species have disappeared since the 2020s. The depletion of ecosystems and ecosystem services undermines human societies and creates a context of extreme climate insecurity affecting every country in the world. At the same time, conflicts over water and food resources, as well as socio-environmental conflicts, are multiplying, and citizen resistance movements to protect ecosystems are becoming increasingly virulent. Every year, several hundreds armed clashes break out in sensitive natural areas, such as the Amazon rainforest or Europe's glaciers, as well as in the capitals of the main CO2 emitters - Beijing, Washington, New Delhi, Berlin, Paris...

Against this backdrop, a coalition of states is forming in favour of deploying a solar geoengineering operation, notably involving the United States, China and India. For these countries, an operation to artificially lower the Earth's temperature is the only way to slow the effects of climate change and alleviate the growing social unrest. However, these countries are struggling to reach an international consensus on a planetary operation to inject aerosols into the stratosphere, an operation deemed too risky by the rest of the international community. Following the rejection of several deployment proposals submitted to the United Nations, China finally proposed a regional geoengineering operation to protect the Arctic, rather than a global operation, which would only require the approval of the countries in the region. As an observer member of the Arctic Council, China has strengthened its ties with the countries of the region and has stepped up bilateral and multilateral dialogue to increase its presence in the region. On 31 March 2050, China announced the deployment of its *ArcticX* solar geoengineering project, which aims to lighten marine clouds over the Arctic. This deployment was supported by all the countries in the coalition and by most of the nations in the region (Canada, Norway, Denmark and Iceland), who were determined to protect the poles at all costs.

However, this project is causing Moscow to cringe. The melting ice caps in Greenland and the Barents Sea allow Russia to use the Arctic as a commercial shipping route, far more efficient than the Panama or Suez Canal. This area also has vast deposits of oil, natural gas and minerals, as well as waters rich in fish, which are of prime interest to Russia. Russia is therefore denouncing the ArcticX project being set up without its agreement, and threatens to take military action against the ships deployed by China for its geoengineering operation. Despite growing tensions between the coalition and Moscow, *ArcticX* was deployed on May 1st, a month after China announced the project. Russia kept its promise: two of the three geoengineering ships in the Arctic were destroyed on July 15th. In a bid to ease tensions, the countries in the coalition did not retaliate immediately, but Washington and Beijing did mobilize their armies to make a show of force.

As France is not part of the coalition and has no capacity to deploy geoengineering, it remains relatively powerless in the face of diplomatic exchanges and escalating tensions. However, by virtue of its role as a permanent member of the NATO Security Council, France is supporting the coalition and preparing its armies: increasing the number of ships available for a potential operation in the Arctic, training in situations in northern Canada and Greenland. In addition, as France is an observer member of the Arctic Council and a defender of freedom of movement in international waters, it immediately decided to increase its military presence in the region by deploying more personnel and resources. At the same time, unrest emerged in Senegal, where a prolonged period of drought was blamed by the local scientific and political communities for the deployment of the first operations of the *ArcticX* project. These troubles marred relations between Senegal and China, which had become the country's main source of funds and had, over the previous decades, built dozens of transport infrastructures on its territory. These infrastructures, including a commercial port, roads and railways, are the target of targeted sabotage by armed groups, in resistance to what they call "Chinese occupation". Faced with these groups, who are taking on the Senegalese army, Senegal is asking for help from France, which is deploying forces there with two objectives: firstly, to support the fight against the armed groups by providing intelligence and training; secondly, to provide the local population with food and water resources as part of HADR support.

Scenario 3: Solar geoengineering on demand, a new consumer good

During the first half of the 21st century, the Amazon rainforest gradually became savannah, releasing increasing quantities of CO_2 into the atmosphere until it reached an irreversible tipping point. The level of carbon in the atmosphere is rising rapidly, as is the average global temperature, which in 2037 will be +3°C compared with the pre-industrial period. This warming, which is much more rapid than that modelled by the scientific community, is being felt in the form of heat waves and droughts, causing more than two million deaths a year worldwide, and agricultural losses affecting 40% of global production. However, given the ongoing release of tens of billions of tonnes of CO_2 by the Amazon, the goal of reducing carbon levels in the atmosphere seems unattainable. So, despite the growing climate insecurity in the world, mitigation objectives are considered obsolete in international negotiation arenas, and discussions tend to focus almost exclusively on adaptation policies and their financing. Technological developments in the field of atmospheric carbon extraction, meanwhile, have ended in commercial and political failure, due to the inefficiency of techniques and the many socio-environmental conflicts that have arisen around the monopolization of agricultural land for the installation of capture plants. The failure of carbon extraction, which underpinned all mitigation strategies, signals the end of the mitigation strategies themselves.

Against this backdrop, a number of countries (including the United States, the United Kingdom, the Gulf States, Russia and the Maghreb countries), backed by oil lobbies, are in favour of deploying solar geoengineering. Europe, meanwhile, is divided, with Sweden, Norway and Spain arguing against any solar geoengineering operation and in favour of implementing an emergency mitigation plan, while countries such as France, Germany and Italy stress out the need for emergency cooling measures, as mitigation policies cannot be pursued in the context of such climate insecurity. Solar geoengineering, which had already been the subject of dedicated international summits in previous years, was again the focus of international discussions at the Existential Climate Threat Summit in October 2037. On this occasion, the United States proposed the rapid deployment of an operation to inject aerosols into the stratosphere, with the aim of bringing about immediate and uniform cooling around the globe. This proposal was immediately rejected by the African Union, which denounced "the Western tendency to prefer technological innovation to questioning modes of production and consumption, even though this technological innovation is at the root of the existential threat hanging over humanity". Russia, initially in favour of deployment, and China, have followed the African Union's lead and also expressed their refusal.

Unable to obtain the approval of the international community for an operation to inject aerosols into the stratosphere, oil industry lobbying groups, supported by the United States and the Gulf States, are implementing a strategy to promote solar geoengineering to individual consumers. Through a major marketing campaign, including social networking and collaboration with of geoengineering influencers , as well as a partnership with an American company selling stratospheric balloons and diffusion torches, these lobbies are making solar geoengineering attractive and accessible to everyone. This has opened up a new commercial market by promoting a new form of climate commitment among individuals: the individual release of small quantities of aerosols into the stratosphere. It's working: several thousand people are releasing stratospheric balloons containing sulphur aerosols on a daily basis. This movement primarily, and almost exclusively, affects consumers in developed countries. A number of G77 countries, under the leadership of China, are vehemently denouncing this movement, which they believe reflects the hypocrisy of Western countries that claim to be champions of democracy but are nonetheless bypassing the arenas of international discussion in order to implement geoengineering clandestinely. France, which expressed explicit support for the US proposal at the October 2037 summit, is also seeing a large number of its citizens join this consumer movement. This is leading to a deterioration in France's relations with a number of partners, notably China, which is demanding that European countries ban these practices on their territory, and is threatening to paralyse part of the European electricity network that it has acquired. However, France, not wishing to put itself at odds with the sector and the oil and gas states, is not coming out against this move.

In diplomatic terms, this episode resulted in a major extension of China's spheres of influence, confirming its role as an international ecological power and counter-power to Western imperialism. The fight against geoengineering by injecting aerosols into the stratosphere appears, in fact, to be a direct continuation of the fight against air pollution initiated decades earlier by China. Conversely, France suffers from a loss of influence within developing countries, perceived as an environmentally irresponsible power that is blamed for a neo-colonialist desire to continue disrupting atmospheric conditions to serve Western economic interests. What's more, if this diplomatic pressure were to increase, and France were *ultimately* to take a stance against individual solar geoengineering operations, it could jeopardise its fossil fuel supplies, and by extension the operational capabilities of its armed forces, which are still heavily dependent on them. A sudden interruption in these energy supplies would be all the more paralysing for the armed forces as they are already overstretched in the context of increased climate insecurity, and as they have to cope with a rise in international tensions over the management of this insecurity. Lastly, the massive use of stratospheric balloons on French territory and on territories of interest leads to new operational problems that must be dealt with by the forces: it leads to an increase in air traffic density, which complicates airspace surveillance activities, risks of collision and, lastly, risks of an enemy using the stratospheric balloon to conceal a threat (missiles, drones, devices equipped with jamming systems).

3. Recommendations

By way of conclusion to the strategic analyses and forward-looking reflections carried out above, six recommendations for the Ministry of the Armed Forces have been drawn up:

1

Integrate into our defence strategies a reflection on solar geoengineering as a political, geostrategic and military tool, and on its geostrategic consequences.

2

Set up a scientific, technological and geostrategic watch to monitor the development of solar geoengineering projects, in particular full-scale experiments (geographical area, players involved) and anticipate the ability of various players to maintain a technological lead enabling them to deploy the technology unilaterally on a large scale.

3

Assess opportunities and risks presented by solar geoengineering for France, and develop, in close collaboration with the Ministry of Europe and Foreign Affairs, a reflection on France's geostrategic positioning on this issue in the context of international discussions.

4

Characterise the state of progress of the United States, China and Russia in terms of solar geoengineering, an exercise complicated by the lack of transparency on the subject, and justifying a dedicated dialogue with the key stakeholders.

5

Promote information sharing on solar geoengineering with allies and partners, in particular by raising the issue at strategic bilateral dialogues and setting up cooperation initiatives.

6

Strengthen partnerships with atmospheric science research institutes (like MétéoFrance) and integrate research into the consequences of climate change on natural systems with research into the possible effects of solar geoengineering, which is not the subject of any modelling work in France.

GLOSSARY

Albedo: The ability of a surface to reflect solar energy.

Cirrus cloud thinning (CCT): Stimulation of the creation of ice crystals in cirrus clouds to reduce the amount of terrestrial radiation absorbed by them.

Earth's biosphere: All living organisms on the entire planet, including all its strata and layers.

Terminal shock: Sudden rise in planetary temperature following an interruption in solar geoengineering.

Cirrus clouds: Clouds in the upper troposphere made up of ice crystals. Their special feature is that they retain part of the Earth's radiation, producing an effect similar to that of greenhouse gases.

Brewer-Dubson circulation: The Brewer-Dubson circulation refers to the meridional mean Lagrangian overturning circulation in the stratosphere. It has a two-cell structure in which the air rises in the tropics, then moves towards the poles and descends in the middle and high latitudes of both hemispheres.

Marine cloud brightening (MCB): Injection of sea spray into low-level marine clouds to increase their reflectivity.

El Niño: A warm variation of the Southern Oscillation, which alters the circulation of winds and currents on the east-west axis in the Pacific Ocean (Walker circulation) several times a decade. El Niño is the most important fluctuation in the climate system and disrupts the circulation of the atmosphere on a global scale.

Cloud seeding: The intentional modification of weather conditions by the diffusion of particles in clouds in order to reduce hail or increase rainfall.

Solar geoengineering / modification of the radiation budget: A set of technical projects designed to compensate for the increase in global average temperature caused by climate change by modifying the Earth's radiation budget (IPCC, 2022, 168). Most of these techniques aim to reduce the amount of solar radiation entering the atmosphere, such as injecting aerosols into the stratosphere, marine cloud brightening (MCB) and installing mirrors in space (space sunshades), while others aim to reduce the amount of terrestrial radiation retained by the atmosphere, such as cirrus cloud thinning (CCT).

Stratospheric aerosol injection (SAI): Diffusion by aircraft or balloon of reflective particles into the stratosphere to create cooling conditions similar to those following major volcanic events.

North Atlantic Oscillation (NOA-oNA): Movement of air masses over the Arctic and Iceland towards the Azores and the Iberian Peninsula. The NOA influences the climate of the North Atlantic, mainly Europe. The North Atlantic Oscillation can occur annually or several decades apart.

Quasi-biennial oscillation (QBO): Regular variation in the winds that blow in a belt around the planet, at an altitude of between 15 and 50 kilometers above the equator. Composed of two phases, the winds blow eastwards and then westwards approximately every fourteen months. The OQB has an impact on the strength of the polar vortex, which in turn influences surface pressure models.

Terrestrial radiation: Energy released by the Earth, made up of thermal energy and the reflection of solar radiation.

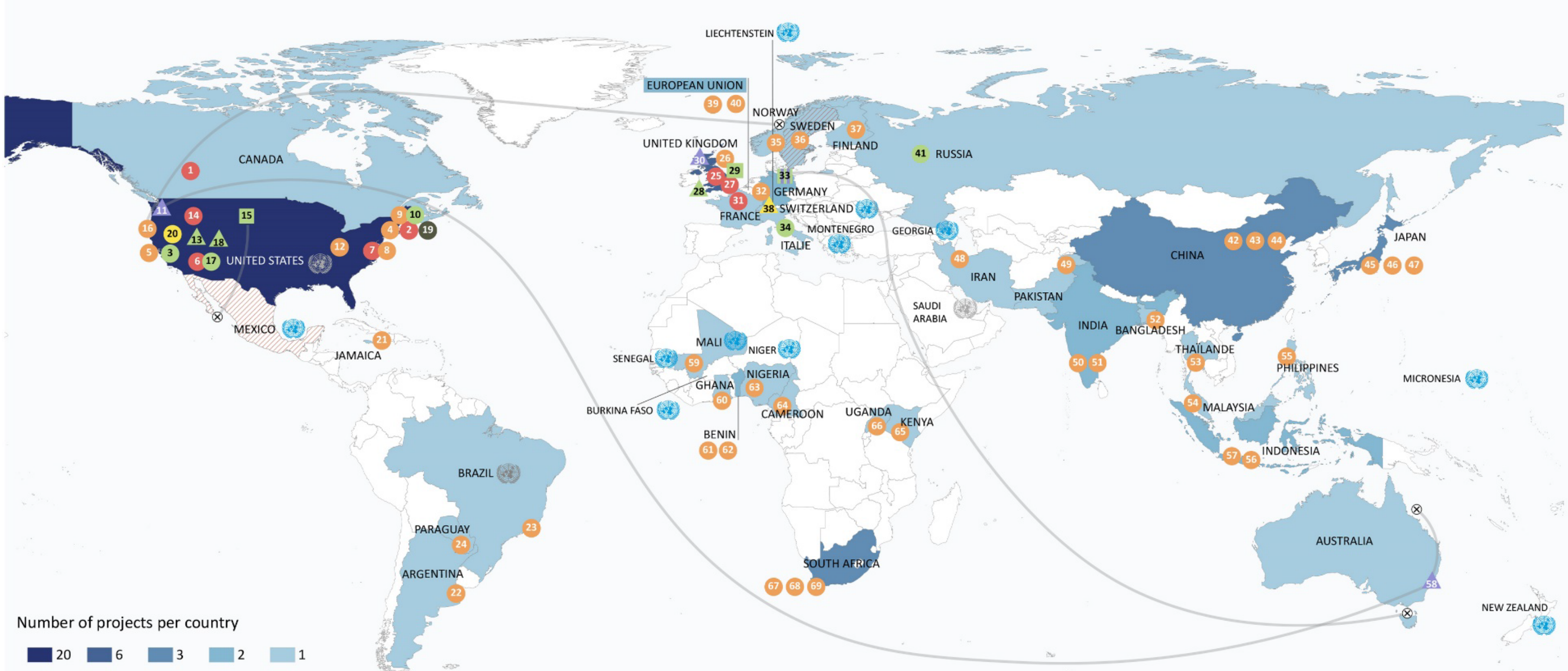
Solar radiation: Energy from the sun, mainly captured by the Earth in the form of light.

Troposphere: Part of the atmosphere between the ground and the stratosphere.

Polar vortex: A low-pressure system that settles permanently in the middle troposphere and extends into the stratosphere near one of the Earth's geographic poles. These high-altitude winds correspond to a deviation in the jet stream.

APPENDICES

Appendix 1. Map: main solar geoengineering projects worldwide



Type of project

- Multidisciplinary
- Marine Cloud Brightening (MCB)
- Stratospheric Aerosol Injection (SAI)
- Cirrus thinning
- Human and social sciences (ethical and governance issues)
- Space mirrors

Stated objective of the project

- Research
- Experimentation
- Research and experimentation
- Commercialisation

Experiments or attempted experiments

- Delocalized experiments
- Target states for experiments that have expressed opposition to deployment

2019 United Nations General Assembly Environment Resolution

Proposal for a resolution aimed at evaluating geoengineering techniques and its governance arrangements at the UNGA Environment

- States sponsoring the resolution
- States that have opposed the resolution

Sources : The Degrees Initiative; "Funding for Solar Geoengineering Research from 2008-2018" on geoengineering.environment.harvard.edu; map.geoengineeringmonitor.org, interactive map by ETC Group and the Heinrich Boell Foundation

IRIS Institut de relations internationales et stratégiques

Cartography : IRIS - A. Diacre, V. Pelpel, M. Verzeroli

Name and year of the project [1] – • *projects in progress in 2023*

Canada
- • 1 - Geoengineering Research Governance Project | 2015 - *in progress*

United States
- 2- Carnegie Climate Geoengineering Governance Initiative (C2G2) |2017-2020
- 3- Collaborative Research: Evaluation of Suggestions to Geoengineer the Climate System Using Stratospheric Aerosols and Sun Shading | 2008-2013
- 4- Cornell Climate Engineering
- 5- Emmett Institute Project | 2017-2020
- 6- Exploring Democratic Governance of Solar Geoengineering Research
- • 7- Forum for Climate Engineering Assessment | 2013 - *in progress*
- • 8- Geoengineering Model Intercomparison Project (GeoMIP) | 2008 - *in progress*
- • 9- Gordon Research Conference (GRC) | 2017 - *in progress*
- 10- Harvard's Solar Geoengineering Project (SGRP), dont Stratospheric Controlled Perturbation Experiment (SCoPEx) | 2017-2024
- • 11- Marine Cloud Brightening Project (MCB) | 2016 - *in progress*
- 12- Network for Sustainable Climate Risk Management (SCRiM) | 2012-2019
- 13- Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) | 2015-2017
- 14- The Ethics of Geoengineering: Investigating the Moral Challenges of Solar Radiation Management | 2010-2014
- • 15- Make Sunsets | 2022 - *in progress*
- • 16- Arctic Ice Project | 2018 - *in progress*
- 17- Planetary Science Institute project | 2015-2018
- 18- NOAA Earth's Radiation Budget (ERB) Initiative dont Projet SABRE
- • 19- Space Bubbles | 2021 - *in progress*
- 20- Ice Cloud Size Distributions | 2006 - 2011

Jamaica
- • 21- Caribbean agriculture under SRM: a case study in Jamaica | 2018 - *in progress* [2]

Argentina
- • 22- Impacts of SRM on the La Plata Basin's hydroclimate in South America, | 2018 - *in progress* [2]

Brazil
- • 23- Studying the response of Cyclones to SRM in the Southern Hemisphere | 2023 - *in progress* [2]

Paraguay
- • 24- Tackling the effects of climate change on the Andean glaciers | 2023 - *in progress* [2]

United Kingdom
- 25- Climate Geoengineering Governance Project | 2012-2014
- 26- Integrated Assessment of Geoengineering Proposals (IAGP) | 2010-2015
- 27- Solar Radiation Management Governance Initiative (SRMGI) | 2010-2020
- 28- Stratospheric Particle Injection for Climate Engineering (SPICE) | 2010-2014
- 29- Stratospheric Aerosol Transport and Nucleation project (SATAN) | 2021-2022
- • 30- MCB with sea water | 2006 - *in progress*

France
- 31- Systemic thinking on the issues and methods of environmental geoengineering | 2013-2014

Germany
- 32- Global Governance of Climate Engineering | 2009-2012
- • 33- ISA-Iron Salt Aerosol Method | 2019 - *in progress*

Italy
- • 34- SRM-related research at Aquila University | 2016 - *in progress*

Norway
- 35- Exploring the Potential and Side Effects of Climate Engineering (EXPECT)

Sweden
- 36- Linköping University Climate Engineering Research Programme (LUCE)

Finland
- 37- Aerosol Intervention Technologies to Cool the Climate: Costs, Benefits, Side Effects, and Governance (COOL) | 2011-2014

Switzerland
- • 38- Cirrus Cloud Thinning calculations | 2016 - *in progress*

European Union
- 39- European Transdisciplinary Assessment of Climate Engineering (EuTRACE) | 2012-2014
- 40- Implications and Risks of Engineering Solar Radiation to Limit Climate Change (IMPLICC) | 2009-2012

Russia
- 41- injection d'aérosols dans la troposphère par Yuri Izraël | 2008

China
- 42- Geoengineering: Basic Mechanisms, Impacts and Strategies | 2013-2015
- 43- Geoengineering: Integrated approaches and impacts | 2015-2019
- 44- Project by scientists from the Northwest Institute of Eco-environment and Resources, affiliated to the Chinese Academy of Sciences

Japan
- 45- Integrated Climate Assessment – Risks, Uncertainties and Society (ICARUS)
- 46- SOUSEI | 2012-2016
- 47- TOUGOU | 2017-2021

Iran
- • 48- Extreme weather events and drought in the MENA region under SRM| 2018 - *in progress* [2]

Pakistan
- • 49- The impact of climate change and SRM on malaria in South Asia| 2023 - *in progress* [2]

India
- 50- Reversing Climate Change via Geoengineering: Impacts on Developing countries like India | 2017-2020
- • 51- Investigating the Indian summer monsoon rainfall under SRM| 2023 - *in progress* [2]

Bangladesh
- • 52- Assessing the impacts of SRM on hydrology in Bangladesh| 2021 - *in progress* [2]

Thailand
- • 53- Modelling temperature and precipitation changes in lowland Thailand| 2023 - *in progress* [2]

Malaysia
- • 54- Impact of SRM on Hydro-climatic Extremes in Malaysia | 2023 - *in progress* [2]

Philippines
- • 55- Impacts of SRM on agriculture: the Southeast Asian case | 2021 - *in progress* [2]

Indonesia
- • 56- Hydro-climatic extremes in Southeast Asia under SRM| 2018 - *in progress* [2]
- • 57- Studying tropical cyclone-related extreme rainfall in Indonesia | 2023 - *in progress* [2]

Australia
- • 58- MCB for the Great Barrier Reef | 2013 - *in progress*

Mali
- • 59- Exploring whether SRM could offset droughts in West Africa| 2023 - *in progress* [2]

Ghana
- • 60- Exploring changes to the Harmattan windy season and precipitation in southern West Africa | 2023 - *in progress* [2]

Benin
- • 61- Effects of SRM on climate change in the northern Gulf of Guinea| 2018 - *in progress* [2]
- • 62- Marine biogeochemistry and sea level in the Gulf of Guinea| 2023 - *in progress* [2]

Nigeria
- • 63- Exploring whether SRM could offset droughts in West Africa| 2023 - *in progress* [2]

Cameroon
- • 64- Assessing the risks of water deficit in Central Africa | 2023 - *in progress* [2]

Kenya
- • 65- Impacts of SRM on extreme rainfall and urban floods in East Africa| 2021 - *in progress* [2]

Uganda
- • 66- The impacts of SRM on seasonal and intra-seasonal climate variability over East Africa | 2023 - *in progress* [2]

South Africa
- • 67- Agricultural production under SRM in Southern Africa| 2023 - *in progress* [2]
- • 68- Exploring whether SRM can reduce risks to biodiversity and human health | 2023 - *in progress* [2]
- • 69- Assessing the future of livestock production in Africa | 2023 - *in progress* [2]

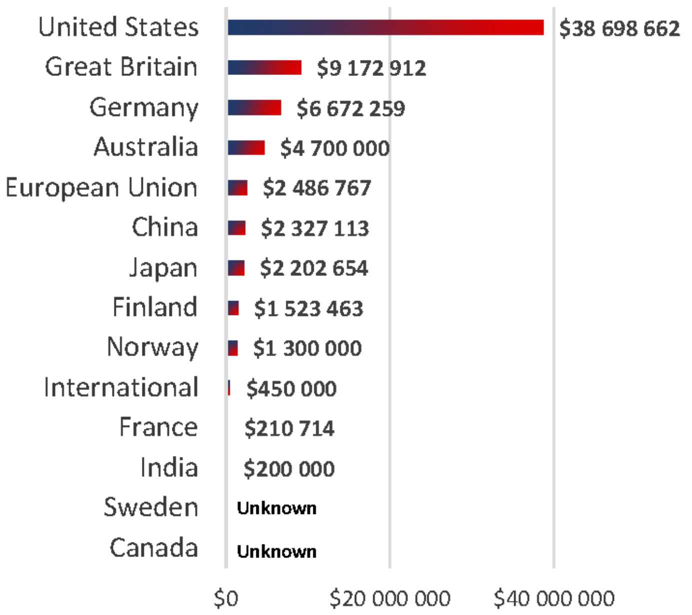
International
- 70- DECIMALS Fund | 2018-2020

(1) Project dates are indicated when available
(2) These projects are funded by the Degrees Initiative

Appendix 2. Infographics : Financial, political and security issues of geoengineering

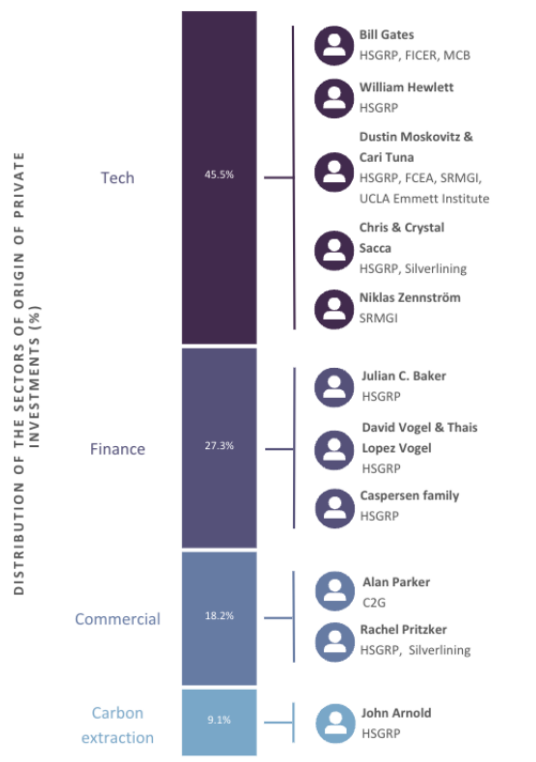
Solar geoengineering is attracting increasing attention and investment across the world. The infographic below shows the dominance of the United States in terms of investments, far ahead of Great Britain and Germany in second and third position. With investments of 210'714 and 200'000 US dollars, France and India find themselves last in the ranking. The total amount of investments from Sweden and Canada remains unknown.

a) Sum of investments in solar geoengineering by country between 2008 and 2018.



Source : Necheles et al. 2018

b) Distribution of the main private investors in solar geoengineering according to their sector of activity in the United States



Source : Necheles et al. 2019

c) Solar geoengineering as a political tool

A tool to prolong lifestyles and interests dependent on fossil fuels.

A tool to protect territories and military capabilities.

A tool for negotiating on the international scene.

Beyond the possibility of using geoengineering as a tool for adaptation to climate change, the latter could also serve strategic political interests. Furthermore, the development and possible deployment of these techniques contribute to making the issue of mitigation invisible. Thus, solar geoengineering would reduce global ambition to reduce emissions. It also has a strong conflict potential.

d) The conflictual potential of solar geoengineering

1. Tensions due to environmental consequences and their attribution to a third party.
2. Use for hostile purposes.
3. Divergences of geopolitical interests in a specific area.
4. Suspicion of surveillance.
5. Disagreements on the effects and modalities of deployment.
6. Target during a conflict.

[1] **HSGRP:** Harvard Solar Geoengineering Project; **FICER:** Fund for Innovative Climate and Energy Research; **MCB:** Marine Cloud Brightening Project; **SRMGI:** Solar Radiation Management Governance Initiative; **FCEA:** Forum for Climate Engineering Assessment; **C2G:** Carnegie Climate Geoengineering Governance Initiative.

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  - Dhanasree Jayaram is Assistant Professor in the Department of Geopolitics and International Relations, and co-coordinator of the Centre for Climate Studies at the Manipal Academy of Higher Education (MAHE), Karnataka, India.
- Olaf Corry. (2023, September 11th). Zoom interview with Sofia Kabbej.
  - Olaf Corry is Professor of Global Security Challenges at the University of Leeds.
- Matt McDonald (2023, September 13th). Zoom interview with Sofia Kabbej.
  - Matt McDonald is Professor in the Department of Political Science and International Studies at the University of Queensland, Australia.
- Duncan McLaren (2023, September 13th). Zoom interview with Sofia Kabbej.
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- Kevin Surprise. (2023, September 19th). Zoom interview with Sofia Kabbej.
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