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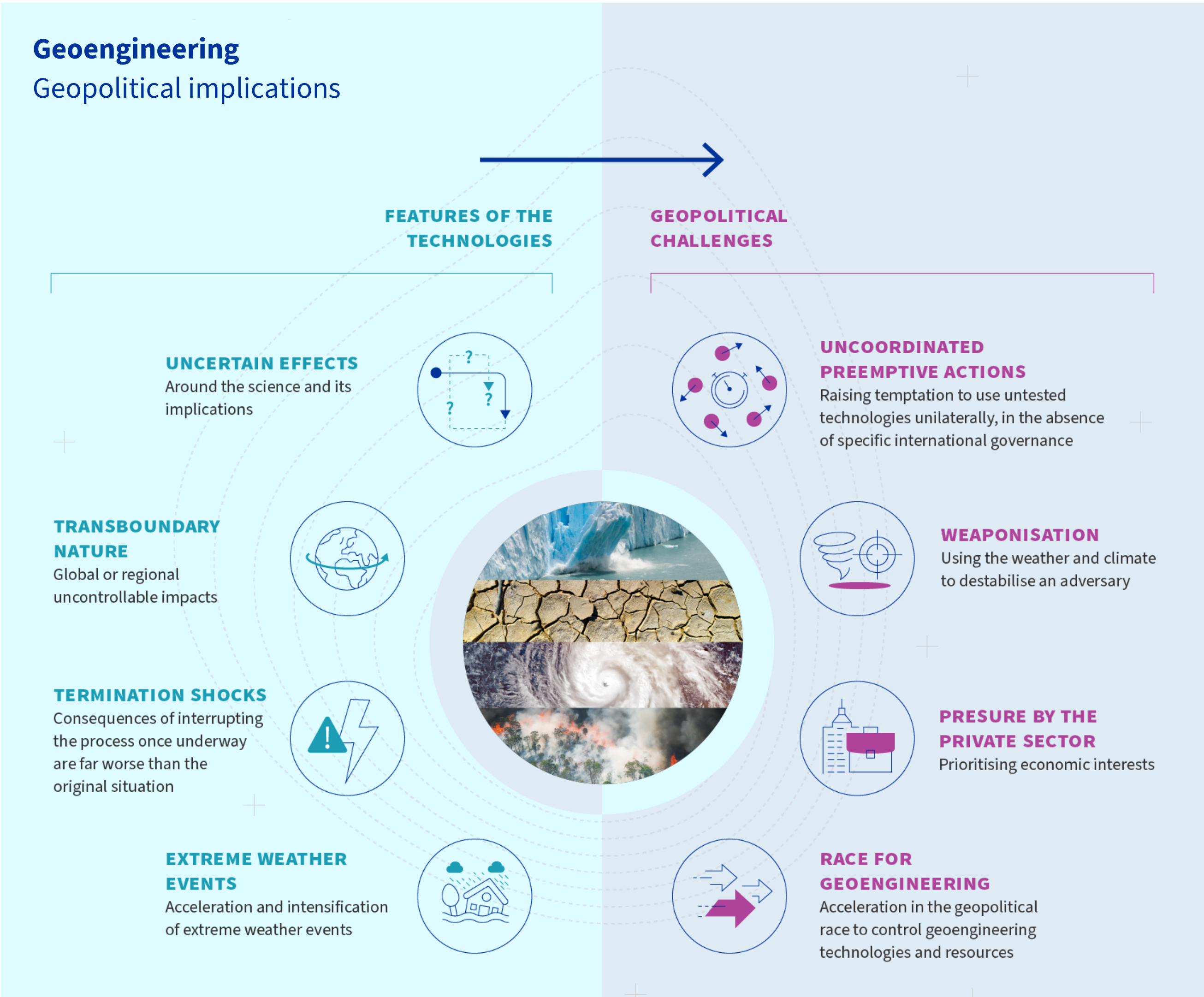
Geoengineering: playing the Sorcerer's Apprentice?

Geopolitical risks of a race to control the climate



Executive Summary

What if technology could replicate the impact on the climate of the 1991 mount Pinatubo eruption[1] in the Philippines? This event lowered the average global temperatures by about 0.5 degree Celsius over the following 15 months. At first glance this seems a promising way to mitigate some of the impacts of climate change. But it came at the cost of a massive catastrophic event injecting into the atmosphere about 15-20 million tonnes of sulphur dioxide with consequences for the environment, health and food production and no reduction in CO2 levels.

Since the second half of the 20th century, scientists, governments, the military, and researchers have been looking into how a storm or a cloud can be diverted. Humans are trying to find ways of exercising control over the planet, including by changing the energy balance on Earth. The wide range of technologies used to influence the climate and the weather are grouped under the umbrella concept of geoengineering, which ranges from carbon removal to solar radiation. These technologies are still in their infancy, with very little knowledge about their possible impact and unintended consequences. This has led to considerable controversy about their use which also limits the possibilities for carrying out research and testing. All technological innovation involves a degree of uncertainty over its long-term impact. The climate challenge is the consequences of decisions and choices made in the past.

> *“This would suggest the need for greater political oversight of future technological breakthroughs.”*

Several factors are increasing the pressure to develop and deploy technologies able to control the climate. First and foremost, the **climate emergency**, with the worsening of climate conditions, more frequent and violent extreme weather events, rising temperatures, and a rise in sea-level. Geoengineering aims to mitigate some of these impacts by reducing the amount of greenhouse gases in the atmosphere or reflecting more sunlight back into space. For some countries, solutions are urgent, and reducing CO2 emissions will not be enough to check current trends before they reach a critical threshold. They might well regard geoengineering as playing a critical role by offering solutions which go beyond the existing mitigation and adaptation strategies. Secondly, **technological and scientific advancements** could allow for geoengineering to be used more effectively and with fewer uncertainties and therefore less risk. For example, new materials have been developed that can reflect more sunlight back into space, and new methods of carbon capture and storage are also under development. **Artificial Intelligence** opens up the possibility for large scale simulation models to be developed. These are essential for understanding and managing the possible impact of geoengineering.

Whilst some see these technologies as a **silver bullet** which would allow for global temperatures to be checked in a more immediate and cost-effective way than CO2 reduction strategies, there is heated debate over the risks of geoengineering for the environment, ecosystems, and life in general. Geo-engineering could also generate **moral hazard** by reducing the commitment to more traditional methods of reducing CO2 emissions.

The risks associated with the cross-border effects of some of these technologies, national political and economic interests, the possibility of weaponization, and private sector initiatives driven by purely commercial interests to deliver solutions, are all possible **sources of global tensions or conflicts**. These factors together point to an acceleration in the **geopolitical race** to control geoengineering technologies and resources. In this context international cooperation will be needed to ensure a global consensus on the use of geoengineering technologies. Although not yet a key player in the geoengineering sector, **the EU could step up** and push for an open and inclusive debate about its use, possibly leading to the development of common rules.

Are we playing the Sorcerer's Apprentice?

1. A broad list of methods and technologies: from planting trees to space-based panels

Since the 1960s, when the concept was used for the first time, the notion of geoengineering has evolved considerably, and now covers a very wide spectrum of methods and technologies. But all aim at modifying the Earth's climate. It is an **umbrella concept,**[2] which includes such basic methods as planting trees as a way of absorbing CO2, to high-tech approaches such as the use of space-based panels to shield the earth from solar radiation.[3] Typically these are classified under two main categories: Solar Radiation Management and Carbon Dioxide Removal. These two categories are very different and give rise to very different challenges, to the extent that some do not even consider CO2 removal techniques as geoengineering. But there are two elements which are part of most definitions of geo-engineering: it is a human-led intervention which is **deliberate and planned,** and it has a **large-scale** impact, affecting whole regions if not the entire planet. Some use the term geo-engineering to refer only to technologies based on solar radiation management, which are the most controversial and potentially the most dangerous.

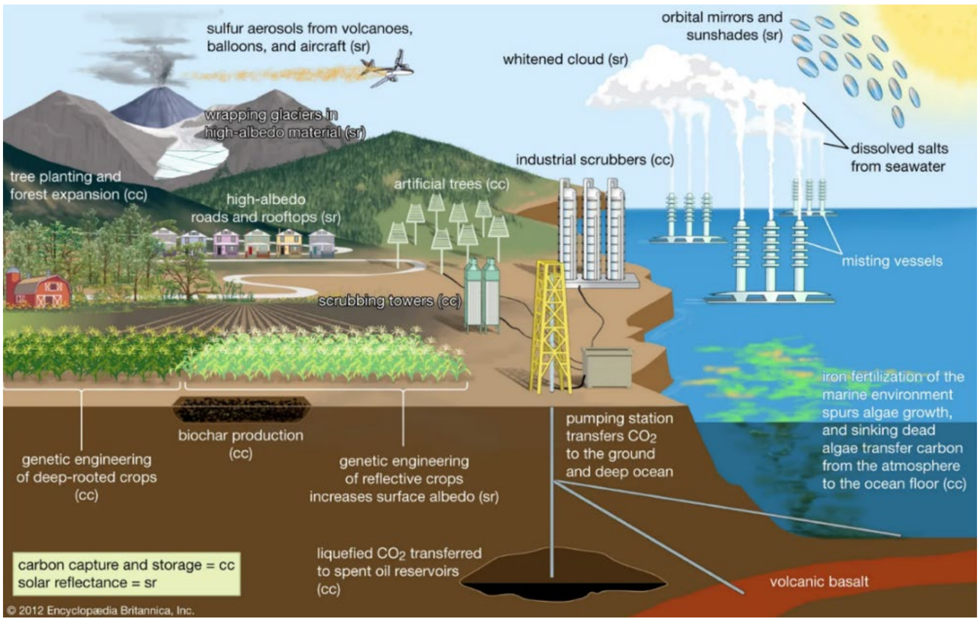
The boundaries between climate geoengineering - longer term with regional/global impact - and weather modification - shorter term with more limited effects - are often blurred, and the two concepts are sometimes used interchangeably. In some cases, weather modification is considered as a subcategory of geoengineering (which in this context is referred to as "Earth Systems Manipulation").[4]

For the purposes of this paper, geoengineering is defined as "**deliberate large-scale interventions to alter the Earth's natural systems with the aim to counteract some of the negative effects of climate change**".[5] Although there is a tendency to exclude consideration of the military uses[6] of geoengineering, this definition also covers the geopolitical dimension and its security implications. These aspects cannot be ignored given the risk of unintended spill-over effects of geoengineering (and possible responses) or that they might be used with the express aim of gaining **advantage over an adversary or accentuating regional tensions**.[7]

Geoengineering Technology/Method		Description
Solar geoengineering[8] cooling the planet by: - reflecting a portion of Solar energy back into space or- increasing the amount of Solar radiation that escapes the Earth (Earth Radiation Management)	**cloud reflectivity**	injecting particles in the lower atmosphere, thereby whitening clouds with the aim of increasing the reflection of Solar radiation
	albedo enhancement	modifying land or ocean surfaces with the aim of reflecting more Solar radiation out to space
	space based approaches	reducing the amount of Solar energy reaching the Earth
Carbon Dioxide Removal (CDR) removing carbon dioxide from the atmosphere, directly countering the increased greenhouse effect and ocean acidification	**ocean fertilisation**	enrichment of nutrients in marine environments to stimulating plant production, hence CO2 uptake from the atmosphere and the deposition of carbon in the deep ocean
	enhanced weathering	increasing the rate by which CO2 is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks
	ecosystem management	afforestation, reforestation, or measures that enhance natural carbon storage in soils and wetlands
	biological carbon capture	using harvested biomass and subsequent carbon storage: through biochar, the long-term storage of crop residues or timber, or bio-energy with carbon capture and storage
	direct chemical capture of carbon	from the atmosphere and its subsequent storage, for example, with storage as liquid CO2 in geological formations or in the deep ocean

Source: ART inspired inter alia by the Oxford Geoengineering Programme.[9]

Some of these technologies are shown in the visual below:



Source: Encyclopaedia Britannica - consulted in April 2023

None of the more advanced geoengineering methods is fully ready for deployment. None "offers an immediate solution to the problem of climate change or reduces the need for continued emissions reductions".[10]

Among the different technologies, **solar geoengineering** is the most unpredictable, with the highest risk of cross border effects and therefore the greatest potential source of geopolitical tension.

Solar Radiation Management Technologies

Geoengineering Technology	Technical Readiness	Cost Magnitude (US $)	Time Scale	Secondary Effects
 **Stratospheric aerosol injection** (SAI) involves spraying inorganic particles (e.g., sulfur dioxide) into the stratosphere to reflect sunlight	LOW/MEDIUM	Billions (for 2–5 W/m2)	Years	-generally: higher latitude warming, changes in precipitation, ozone depletion, uncertain public health impacts from food/water contaminants, ocean acidification, high risk if SAI stops suddenly; - northern hemisphere deployment: severe drought in sub-Saharan Africa and India; - southern hemisphere deployment: rain failure in northeast Brazil, more hurricanes in North Atlantic
 **Marine cloud brightening** involves spraying particles into marine clouds to make them more reflective	MEDIUM	Billions (for 0.8–5.4 W/m2)	Years	Decreased precipitation and lower temperatures, adversely affects crops; South America warmer and dryer; less rain over Amazon basin; more tropical rainfall; risk to sudden stop, need to escalate over time
 **Space mirrors** are large mirrors put into space (e.g., orbit at Lagrange point 1) to block and reflect solar radiation	MEDIUM	Trillions (for < 0.6 W/m2)	Months	Weather changes, potential decrease in biosphere, precipitation may decrease with temperature, regional shading and sunlight increase impacts agriculture

Source : RAND.[11] December 2021

2. Will geoengineering save or condemn us?

Geoengineering methods, particularly those related to solar geoengineering, are highly **controversial.**

> *"Geoengineering could negatively and permanently affect climate systems globally or regionally, with possible unintended effects across national boundaries."*

Furthermore, for some technologies, such as those based on solar radiation, stopping the process once it is already underway might generate a **termination shock** with consequences far worse than the situation it was intended to address. In any case, part or all the carbon released into the atmosphere will need to be recaptured, regardless of whether geoengineering is used or not. The risks could therefore be greater than the possible advantages.

There is also a concern that research into geoengineering technology and its implementation could divert attention and resources away from the long-standing policy of reducing CO2 emissions, which is about tackling the problem itself and not just its effects. Efforts might then end up being focussed on the idea that there is a **technological silver bullet** which will save us from the most negative impacts of climate change at limited financial cost and without a change in behaviour. The economic concept of **moral hazard** is often used to describe such an approach, which is supported by some fossil fuels interest groups.

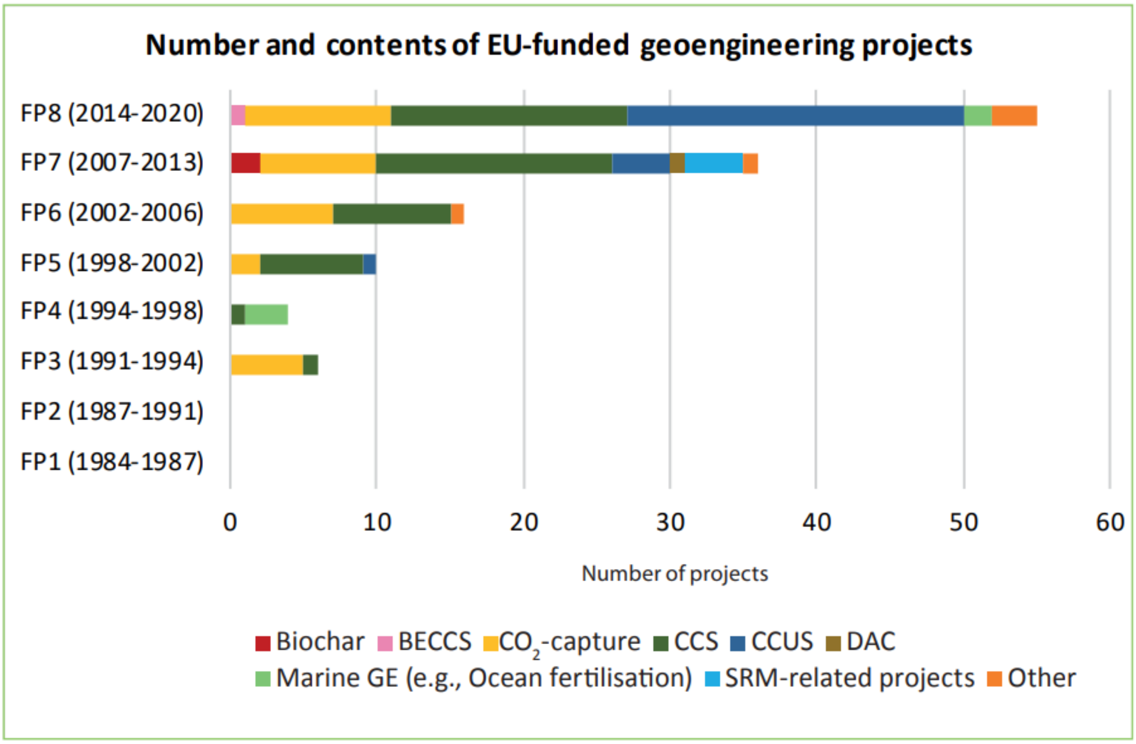
> *"We should not underestimate the potential for a politicisation of geoengineering in the public debate on zero carbon emissions, such as the Green Deal."*

Geoengineering may be driven by **political and economic interests**. Against a background of growing political **polarisation**, technological innovation may be regarded as a way of avoiding the demands of rigorous mitigation policies. Some could be tempted to resort to geo-engineering if more classical climate change mitigation strategies are seen to be failing. The point at which this might happen could vary depending on the extent of **technological risk aversion** and the level of trust of the general population in those engaged in research and application.

For as long as there are significant risks and uncertainties, one approach could be to continue to place the main emphasis on reducing CO2 emissions, whilst keeping solar geoengineering on hold as a possible **"Plan B"**. To that extent, financing research and development on geoengineering could constitute an insurance policy for humanity – an option that could be put to the test only if needed and if things do not go as planned. [12] John Holdren, speaking on a personal basis in one of his first interviews as Senior Advisor to President Obama on Science and Technology, said that "the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them because if we get desperate enough it will be considered”.[13]

A cautious EU approach

The EU is very cautious as far as solar geoengineering is concerned. Whilst it finances projects on carbon dioxide capture and supports research to improve understanding of the science behind solar geoengineering, it does not currently endorse the deployment of this technology.[14] There is a clear preference for prioritising carbon removal technology and the European Green Deal stipulation that "at least 35% of the budget of Horizon Europe will fund new solutions for climate" could accelerate these geoengineering programmes. This line was confirmed by the Commission proposal on 30 November 2022 on the "first EU-wide voluntary framework to reliably certify high-quality carbon removals"[15] which aims at boosting innovative carbon removal technologies, in line with the EU adaptation strategy.[16]



Source : Geoengineering in the EU, November 2021.[17]

Note 1: During the first four EU multi-annual Framework Programmes, research projects on geoengineering played little or no role. Especially during FP7 and FP8, the number of EU-funded geoengineering projects and the funding allocated to them increased significantly. Within FP8, with 55 known EU-funded GE projects, more than 40 field trials were conducted, including demonstration sites for CO2 capture and CCUS, CO2 injection sites, and marine offshore trial sites.

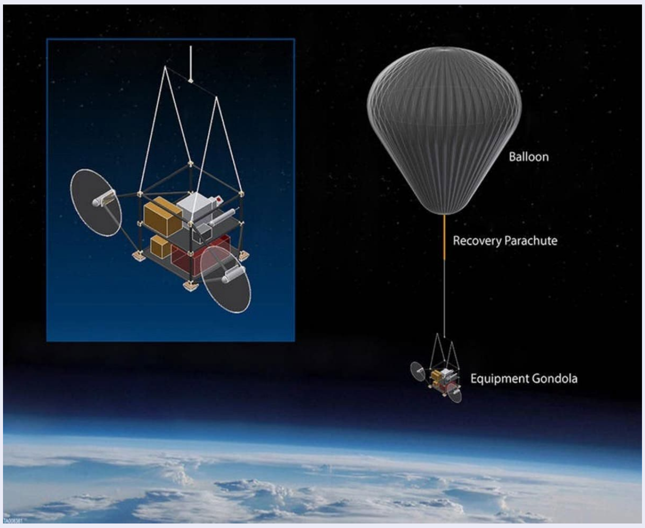
Note 2: Carbon Capture and Storage (CCS), Bioenergy with carbon capture and storage (BECCS), Carbon Capture, Usage and Storage (CCUS), Direct Air Capture (DAC), Solar radiation management (SRM).

3. Many unknowns remain

Many of the risks and vulnerabilities surrounding geoengineering arise from the **uncertainties around the science and its long-term implications**. **Computer models** can help to some extent, but it is still difficult to predict with sufficient accuracy the effects of geoengineering.[18] There are several reasons for this. First, climate and the weather are based on highly complex systems which are dependent on a set of relatively minor initial conditions (the butterfly effect). That means that even small divergences in the initial data can generate very different outcomes. Second, climate models use mathematical equations to represent physical processes. But these are far too complex to be solved with absolute accuracy, and any simplifications in the modelling can result in much higher margins of error. Thirdly, the complexity of the climate system means that vast amounts of computing power are needed to generate predictions. And the climate is subject to several feedback mechanisms which can increase or reduce the effect of changes to the overall system. Some of these feedbacks are still not fully understood, leading to a further increase in uncertainty. Finally, outdoor experimentation, which is needed to refine or validate models, has so far been rather limited given the controversy surrounding the technology (an example being the postponement of the Harvard Stratospheric Controlled Perturbation Experiment - see box below).

A contested experiment: Harvard Stratospheric Controlled Perturbation Experiment (SCoPEx).[19]

A Harvard research project that sought to conduct a small-scale open-air solar geoengineering experiment in Sweden was called off in 2021 following opposition from the country's indigenous Saami Council. They claimed that "Solar Aerosol Injection is a technology with the potential for extreme consequences, and stands out as dangerous, unpredictable, and unmanageable". The researchers are still considering other locations. The aim of the project was to provide clarity on the risks and benefits of solar geoengineering by reinforcing models with experimental results to improve the reliability of the simulations.[20]



Source: SCoPEx

4. Could Artificial Intelligence be a game changer?

Many of the limitations of geoengineering technologies are related to uncertainties over their effects. As described above, because climate is such a complex set of systems, climate modelling does not yet provide the answer to these uncertainties. AI has the potential to improve the accuracy of these models, leading to more detailed and reliable predictions. This could also allow for the development of real-time monitoring of environmental variables to optimise performance and reduce the risk of unintended consequences. AI can also encourage innovation by helping identify new solutions to complex problems by analysing large datasets and spotting patterns and correlations. This could lead to the development of new geoengineering technologies or improvements to existing ones. For example, programmes are underway in the US[21] to **explore AI-assisted models** of complex interconnected processes over the longer-term. This allows for the development of guidance on action, especially on the risks and causes of "sudden tipping-points, runaway feedback loops, and the strategic implications of potential adversarial activity".

The geopolitical implications of the deployment of geoengineering technologies

Due to their very nature, geoengineering technologies can impact on geopolitics, with the risk of increased tension, heightened suspicion and even conflict. Global tensions between the winners and losers of the race to control the climate is a function of the current limited state of scientific knowledge, the risks of termination shock, the potential for one country to influence the climate of its neighbours, whether unintentionally or deliberately (by using geoengineering as a weapon), and the pressure to act before others do.[22] In the words of Ajay K. Sood, principal scientific adviser to the Indian government, "this technology may end up concentrating power in rich countries or nonstate actors in the global north".[23] This could also apply to wealthy states in desert regions of the world that have existentialist reasons for finding climate solutions.

1. Transboundary effects fuelling existing geopolitical tensions (and possible new ones)

One of the main problems of geoengineering is the huge **uncertainty** over its long-term consequences, with the risk of unintended cascading effects[24] which could have an impact across frontiers. Some technologies, notably solar geoengineering, might affect very distant countries or regions.

> *"The desired effect in one region might be very different from what is needed in another region."*

One country might need more rain while another faces flooding. For example: if an aerosol is injected in the north hemisphere, this could cause severe droughts in sub-Saharan Africa and India. If it is injected in the southern hemisphere, it could cause rain failure in northeast Brazil and an increase in hurricanes in the North Atlantic.[25]

These uncertainties and unintended effects run the risk of exacerbating existing **geopolitical tensions** between countries and creating new disputes, not least between low carbon and high carbon emitting countries.

China's geoengineering project Tianhe: possible source of tension with India

In the past India has accused China of generating floods through dam-building activities. Such tensions could be exacerbated by China's cloud seeding geoengineering project, Tianhe (or Sky River). The aim of this project is to manage droughts in the northern parts of the county that receive less rainfall with declining water levels in its rivers.
In an extension of this project China has started to deploy tens of thousands of fuel-burning chambers across the Tibetan mountains which release silver iodide.[26] Ultimately, this will cover an area three times the size of Spain and is expected to generate 7% of China's total annual water consumption. But it could affect precipitation patterns across the whole region, including India. The project is supported by the China Aerospace Science and Technology Corporation which uses military rocket engine technology and satellite networks.[27] Links to the military apparatus further increases the level of suspicion and mistrust between two major powers.

2. The risk of uncoordinated action to tackle the impacts of climate change

The negative effects of climate change are already having a severe impact in several regions of the globe. These effects are unevenly distributed, with some regions more affected than others. As stated in the sixth IPCC report, if global warming increases by 1.5°C in the near-term this would cause unavoidable "increases in multiple climate hazards". And "ecosystems, people, settlements, and infrastructure" are already affected by an increase in the "frequency and intensity of climate and weather extremes".[28] The report estimates that "**approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change**" and that vulnerability to climate change varies substantially between and within regions.

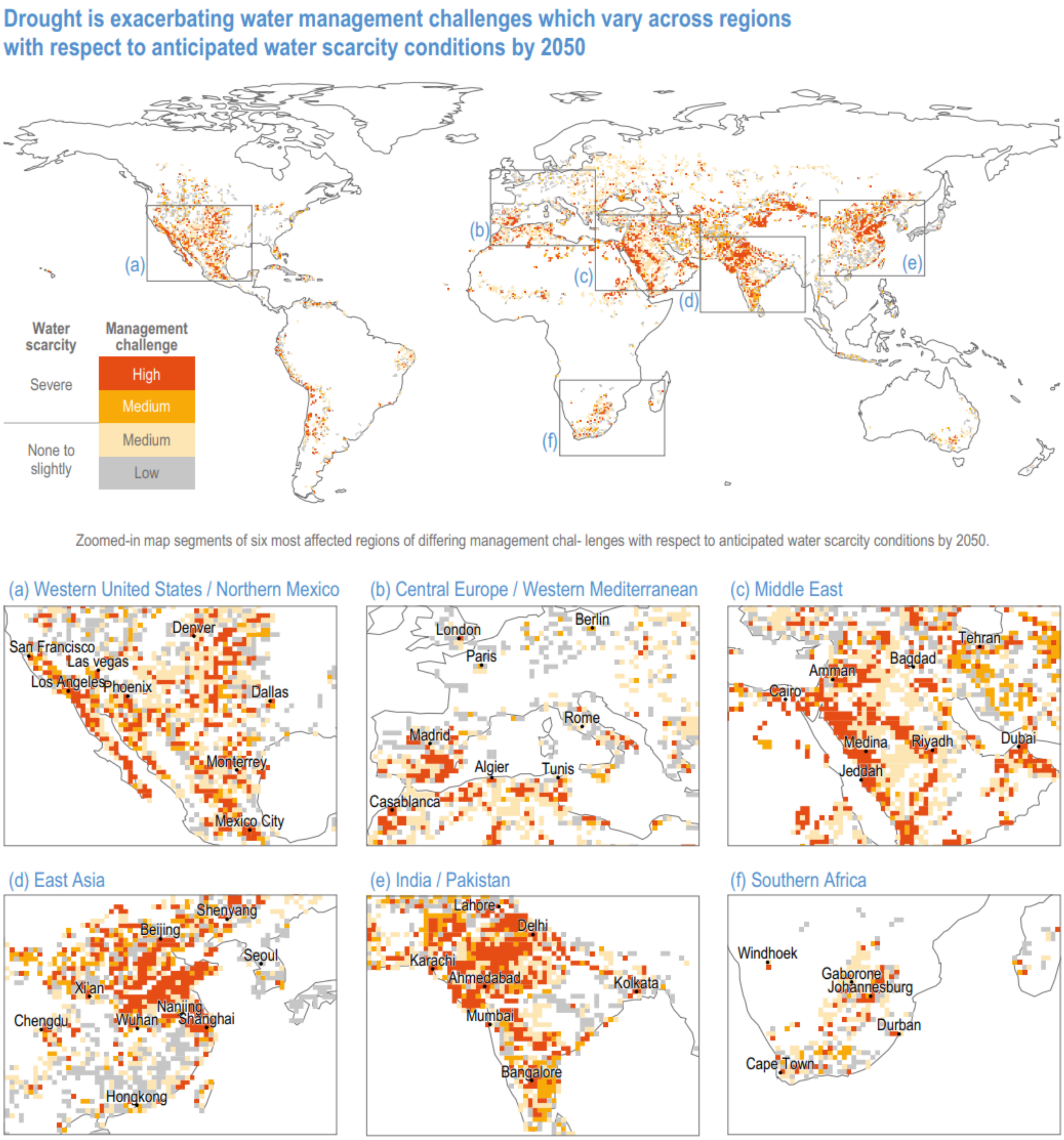


Figure AI.48 | Drought is exacerbating water management challenges which vary across regions with respect to anticipated water scarcity conditions by 2050. Local levels of policy challenges for addressing water scarcity by 2050, considering both the central estimate (median) and the changing uncertainty in projections of the Water Scarcity Index (WSI) from the present day to 2050. Projections used five Coupled Model Intercomparison Project 5 (CMIP5) climate models, three global hydrological models from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), and three Shared Socioeconomic Pathways (SSPs). Reproduced from Greve et al. (2018). {Figure Box 4.1.1; Box 4.1}

Source : Sixth IPCC report (annex I).[29]

Against this background, there are many reasons why a country might decide to deploy geoengineering technologies. Some might be affected by climate change more than others and therefore be impatient to put geoengineering to the test. They might doubt the ability and speed of the international community to address the issue. They might have domestic or economic reasons in pushing their own technology. Or all the above, with possible geopolitical tensions generated by undesired effects on other regions.

Climate Change Effects and Impacts

Climate Change Effect	Current *(at 1.1°C average warming)*	1.5°C Warming	2°C Warming	Impacts to Human Security
Heat	5 percent of global population exposed to severe heat waves once in 20 years	14 percent of global population exposed to severe heat waves once in five years	37 percent of global population exposed to severe heat waves once in five years	More intense and frequent heat waves will reduce labor productivity, increase frequency and intensity of wildfires, undermine human health, and lead to loss of life
Heavy Precipitation and Flooding	25 percent of land with significant increase in once-in-a-century floods	17 percent increased frequency of precipitation extremes over land	37 percent increased frequency of precipitation extremes over land	Increased flooding will lead to economic losses, increased calls for humanitarian assistance, and loss of life
Drought	Observed increase in frequency and intensity of droughts in southern Europe, northern Africa, and Near East	Around 132 million more people exposed to severe droughts	Around 194 million more people exposed to severe droughts	More frequent, intense, and longer droughts will undermine food security in developing countries, cause more extreme wildfires, increase political instability, and drive migration
Sea Level Rise	8 to 9 inches higher with the rate of increase doubling in the last 30 years compared to the 20th century	Total projected rise of between 11 and 32 inches, with a median of 19 inches	Total projected rise of between 11 and 38 inches, with a median of 22 inches	Rising sea levels will increasingly imperil coastal cities and exacerbate storm surges that damage infrastructure and inundate water systems
Arctic Ice Melt	13 percent decline per decade of sea ice extent since 1979 90 percent decline of at least five year old thick ice	Probability of an ice-free summer—defined as less than 15 percent ice concentration—is one every 42 years	Probability of an ice-free summer—defined as less than 15 percent ice concentration—is one every five years	Accelerated melting of Arctic ice sheets will affect ocean circulation and salinity, threaten local ecosystems, and increase competition over resources and transit route access
Tropical Cyclones	Global annual average has remained level since 1980 but geographic distribution has shifted, with more cyclones in the North Atlantic and northern Indian Oceans	Additional 2.1 category-4 hurricanes per year, compared to 2018 Additional 1.2 category-5 hurricanes per year, compared to 2018	Additional 1.4 category-4 hurricanes per year, compared to 2018 Additional 1.2 category-5 hurricanes per year, compared to 2018	More frequent, destructive, and shifting tracks of cyclones will lead to trillions of dollars in economic losses in tropical zones, increase calls for humanitarian assistance, drive population displacement and migration, and lead to loss of life
Coral Reefs	33 percent threatened with loss	Projected long-term degradation of 70-90 percent	Projected long-term degradation of more than 99 percent	The disappearance of coral reefs will eliminate an ecosystem that serves 500 million people, impacting economic and food security
Biodiversity	50 percent of terrestrial mammals and 25 percent of birds already under threat are affected by climate change	8 percent of plants, 6 percent of insects, and 4 percent of vertebrates will lose at least half of their geographic range	16 percent of plants, 18 percent of insects, and 8 percent of vertebrates will lose at least half of their geographic range	Loss of species will increase human health risks and threaten food security

Source : [National Intelligence Estimate: Climate Change and National Security 2021]

In a foresight exercise, the US National Intelligence estimated that climate change together with the national and international responses to it will generate increased security risks for democratic countries up to 2040. This is set to increase as countries respond to the growing physical effects of climate change.

None Low Medium High

Risk		2021	2030	2040
Geopolitical Tensions Over Climate Responses	Perception of Insufficient Contributions to Reduce Emissions	Low	Medium	High
	Carbon Dioxide Removal not at Scale for Countries' Net-Zero Pledges	None	Low	Medium
	Developing Country Demands for Financing and Technology Assistance	Medium	High	High
	Petro States Resisting Clean Energy Transition Away From Fossil Fuels	Low	Medium	High
	Competition With China Over Key Minerals and Clean Energy Technologies	Low	Medium	High
	Contention Over Use of Economic Tools To Advance Climate Interests	None	Low	Medium
Climate Exacerbated Geopolitical Flashpoints	Miscalculation Over Strategic Competition in the Arctic Leading to Conflict	None	Low	Medium
	Cross-Border Water Tension and Conflict	Low	Medium	High
	Cross-Border Migration Attributed to Climate Impacts	Medium	High	High
	Ungoverned Unilateral Geoengineering	None	Low	Medium
Climate Effects Impacting Country-Level Instability	Strain on Energy and Food Systems	Low	Medium	High
	Negative Health Consequences	Low	Medium	Medium
	Internal Insecurity and Conflict	Low	Low	Medium
	Greater Demand for Aid and Humanitarian Relief	Medium	High	High
	Strain on Military Readiness	None	Low	Medium

Note: This graphic does not project government and non-government actions that might mitigate risks. The IC defines the level of risk as the probability of the issue occuring multiplied by its assessed impact to US interests.

Source : National Intelligence Estimate: Climate Change and National Security 2021

3. Weaponisation and "hybrid" use

Some governments may see geoengineering technologies as a way of gaining military advantage. It could involve targeting the strategic resources of an adversary, from agriculture to water availability, for which countries compete. It could also involve destroying or damaging the critical infrastructure of an adversary by inciting extreme weather events. However, this implies having the ability to control the weather with a high degree of precision both in terms of the target area and the expected effects. This is difficult if not impossible for the time being, given the uncertainty around geoengineering technologies and the complexity of climate systems and of the weather. In other words, even the most developed **geoengineering technologies "lack the minimum level of precision**—in space, time, and effect—implicit in the concept of a weapon".[30]

Military origins

The origins of geoengineering are military. The dream of controlling the weather can be traced back to American Civil War in the 19th century. Some thought that large battles had affected the weather and developed the idea that shooting cannons, fireworks, exploding hydrogen balloons might be used to cause rain. The US Department of Agriculture carried out experiments in Texas in the 1890s. When it rained, some claimed that the experiment had been successful; but others pointed out that it was the rainy season in Texas anyway. More serious consideration of how the weather might be weaponised took off in the 1950s. There were concerns that the Soviet Union might seek to control the Earth's thermometer, and the potential effects were seen by some as being as devastating as nuclear warfare.[31] Such fears were later confirmed by Stalin's grand plan for the transformation of nature as part of which Soviet scientists were considering radical solutions to improve the climate, including detonating hydrogen bombs. This sparked a "weather race" which prefigured the space race of the 1960s. In August 1953, the US set up a President's Advisory Committee on Weather Control. During the two decades after 1945, research into the technology behind nuclear power, digital computing, chemical cloud seeding and access to space were all part of the efforts to "control and weaponize nature for dominance over a superpower rival".[32]

Operation Popeye - "*make mud, not war*": A classified cloud-seeding programme carried out by the US Air Force from 1966-1972 to try to extend the monsoon season in Vietnam and Laos so that roads would become flooded, limiting Viet Cong military movements. It did not produce any tactical advantage. The extreme secrecy surrounding the operation and the subsequent denials by the military resulted in the shutdown of the military weather modification programme.

Expanding the hybrid toolbox: as most geoengineering techniques are difficult to detect and can easily be mistaken for natural weather events, the weaponisation of the weather could offer a specific strategic advantage in that it is difficult to attribute or detect, and as such is potentially an ideal component of hybrid warfare.
The US takes this possibility very seriously. DARPA (the US Defence Advanced Research Projects Agency) has been using computer modelling and game theory[33] to look into how to react to the rogue use of geoengineering. One objective is to design an "early warning" system to detect the development of specific geoengineering techniques, in particular Solar Aerosol Injection (SAI) and their possible covert use. This system is based on information about actors with the potential to conduct SAI (several countries are likely to have such a capacity, and private companies could also be on the list), their incentive to use it and their low exposure to retaliation.

4. A "SpaceX" effect: when the private sector kicks in

There is currently nothing to prevent private companies from playing with the weather. As in the case of space exploration, this is a field where the prerogative of state action is being challenged by the private sector. Make Sunsets, a start-up, began releasing particles of sulphur dioxide into the stratosphere using two balloons over Mexico last year.[34] This was done with no public consultation or scientific oversight. Make Sunsets is planning further injections and intends to sell "cooling credits" for larger payloads. Whilst this initiative is less entrepreneurial and more an act of geoengineering activism, a number of billionaires are taking steps to support geoengineering research in line with the wider trend of "effective altruism".[35] These include George Soros, who endorsed solar geoengineering in the Arctic at the Munich Security Conference earlier this year, and Bill Gates, who in 2021 backed a project by Harvard University to test the impact of injecting calcium carbonate into the atmosphere over northern

Scandinavia. Jeff Bezos also supported geoengineering by making available Amazon's supercomputer capabilities to work on modelling the impact of plans to inject huge amounts of sulphur dioxide into the atmosphere. More recently, in February 2023, Dustin Moskovitz, a billionaire Facebook co-founder, ploughed $900,000 USD into funding for scientists in Mali, Brazil, Thailand, and other countries to study the potential effects of solar geoengineering.

These attempts by very wealthy individuals to carve out a role in solving a global problem reflect a burgeoning start-up culture which has taken off since the beginning of the century. This phenomenon puts the vast amounts of money swilling around Silicon Valley at the service of a private sector which considers it can be more effective in delivering solutions than governments. The use of technology enables the individuals concerned to sidestep many of the difficult choices around the green transition "while looking like (they) are doing good for the planet".[36] It is an approach which is a function of "long-termism" which has been adopted by some tech leaders and which in part owes its origins to an extreme libertarian ideology. They see themselves as called to be free from government oversight in order to serve the interests of individual freedom and for the benefit of future generations. Without adequate government oversight, the private sector and wealthy individuals will not be called to account. If successful they will reap enormous benefits. But failure, which might well bring with it uncontrolled side effects, will raise issues of responsibility and governance.

5. The first signs of a race for geoengineering: "clash vs cooperation"[37]

Whilst there is not yet a full-blown race over the development of solar geoengineering technologies and their deployment, there are signs that this may well be beginning. The balance of **risks and opportunities may change** rapidly if there are scientific breakthroughs, or if the pressure caused by rapidly deteriorating climate conditions pushes some countries to take pre-emptive action, prompting others to respond. The factors described in this section all seem to push in the direction of unilateral action, exacerbated by the relatively low cost of solar geoengineering. A problem known by economists as **the "free-driver" effect**, which combines relatively low-cost solutions with a lack of accountability could push a single country (or billionaire) to launch a geoengineering programme affecting the whole planet. The US National Intelligence Estimate on climate change warned in 2021 of an "**increasing chance that countries will unilaterally test and deploy large-scale solar geoengineering -** creating a new area of disputes".[38] The report also noted that several countries are already investing in these technologies.

China has a long-standing tradition of weather modification activities, both to manage rainfall for agriculture purposes and to ensure the best weather conditions for major events. The country spent $30 million shooting salt and minerals to clear skies before the 2008 Beijing Olympics,[39] as recognised in official policy documents – showing how attempts to control the weather are increasingly accepted as common practice. Already in 2002, the "Weather Modification Administrative Regulation" described the alteration of weather patterns as a method for "preventing or mitigating meteorological disasters." By the end of the decade more than 37.000 people were employed in rain-making projects across China. These efforts are supported by major government agencies.[40] China also has a solar geoengineering program at Beijing Normal University but does not seem to have implemented open-air testing yet. US sources believe that China is close to "unilaterally deploying Solar Aerosol Injection".[41]

The **US** have been involved in the development of geoengineering from the outset. In 2022, Congress mandated the White House to develop a five-year research plan on geoengineering technologies.[42] This is the first US coordinated initiative to support efforts in such a controversial field and to facilitate funding on "feasibility, benefits and risks"[43] of solar geoengineering. According to some sources, the funding could amount to USD 200 million.[44] More specifically, the 2022 Appropriations Act[45] directed the Office of Science and Technology Policy to develop an interagency working group, in coordination with NASA, the National Oceanic and Atmospheric Administration (NOAA), and the Department of Energy. This working group was mandated to "establish a research governance framework to provide guidance on transparency, engagement, and risk management for publicly funded work in solar geoengineering research".

Russia has a long-standing interest in weather and climate change which dates back to the Cold War when Stalin launched his plan for the Transformation of Nature. After the fall of the Soviet Union, scientific activity on geoengineering slowed down and only resumed in the early 21st century in the context of the climate change debate.[46] Russia has engaged in continuous efforts to find ways of controlling the weather and the climate, both by trying to influence the IPCC and through research. In 2009 Russia conducted a first solar geoengineering field trial according to the journal *Russian Meteorology and Hydrology*.[47] The test involved aerosol generators mounted on a helicopter and a car chassis which blasted out particles both at ground level and at heights of up to 200 metres.[48]

Several other countries are also active in researching and testing geoengineering technologies and methods. These include **Saudi Arabia**[49] and the **UAE,** both of which are focusing on cloud-seeding programmes to increase rainfall. **Israel** has been accused by Iran of stealing its water by using cloud seeding that reduces rainfall over its territory.[50] The **UK** has been involved in geoengineering projects since the 1950s with a project called "Project Cumulus" (also known as operation Witch Doctor). **Australia** has been actively involved in experiments on both ocean fertilisation and maritime cloud brightening.[51]

Using game theory to better understand the dynamics of geoengineering[52]

What would happen if countries could decrease the Earth's temperature at low cost? This 'free-driver' situation might push other countries who prefer higher temperatures to develop technologies to increase the temperature and deter, or if needed counter, geoengineering. The London School of Economics used game theory to explore these dynamics and their impact on the willingness of countries to collaborate.

The game was organised in two rounds. During the first round, players (impersonating countries or groups of countries) had to choose whether to collaborate and become party to a treaty or not. There were two treaty options available: a moratorium or a deployment treaty (where the coalition decides together on deployment based on common interest). The second round was about actually taking the step of modifying the global temperature based on the choices they made under step one. At first, players only had the option of increasing the Earth's temperature but could subsequently also decrease it.

The results of the game showed that, if countries have similar preferred temperatures they can choose not to enter in a treaty and benefit, as a free rider, from the temperature reduction caused by others without contributing to the costs. Efforts towards a costly transition would also be disincentivised.[53] Why go through a heavy transition if others are addressing the problem? If there are very different preferred temperatures and cooling is the only option, the country with the strongest preference for lowering the temperature will reduce temperatures as free driver. In both cases the incentives for cooperation are low.

The availability of technology which can turn the temperature back up changes the 'strategic interaction'. A 'climate clash' is now possible, with an escalation that has no winners and increasing costs. Whilst cooperation is not guaranteed, the negative outlook of such an escalation may encourage cooperation.

Conclusions

Technological advancements, the acceleration and intensification of extreme weather events, and a range of other factors are leading to a race over geoengineering.There is an **urgent need for a set of common international rules with enforcement mechanisms** that directly address geoengineering before the technology is mature and useable, and while the risks are still theoretical.

The Royal Society[54] called for the establishment of common rules in 2009, and a similar proposal was made by the US National Intelligence Council in 2021[55]. The overriding concern is how to avoid one country taking unilateral action. There are currently no legally binding international instruments that deal directly with geoengineering, although some interpret the decision adopted by the 2008 UN Convention on Biological Diversity (CBD) as constituting a moratorium.[56] This also means that there is no international governing body overseeing geoengineering efforts, including research. One of the key requirements which are seen by some as underpinning the future of geoengineering is drawn from the five so-called "Oxford principles".[57] It states that "any decisions with respect to deployment should only be taken with robust governance structures already in place"

Despite the fact that multilateralism is under pressure, recent developments, not least the UN High Seas Treaty which was agreed recently after more than a decade of negotiations, give some cause for hope that progress can be made towards the recognition of this issue as a 'global commons'. Yet an attempt led by Switzerland in 2019 to submit a resolution to the UN Environment Assembly asking for an assessment of geoengineering techniques as well as potential governance frameworks failed. Widespread resistance to such an initiative seems to have been driven by two contradictory concerns: on the one hand the fear that it could legitimise geoengineering technology, and on the other that it would open the door to stringent rules restricting their development.

Key Questions

The convergence of the climate emergency and of technological developments should serve as a call to address the challenges and potential of geoengineering. The following issues deserve attention at political level:

→ Should the EU push for an**open and inclusive debate about the use of geoengineering technologies**, including those that are the most controversial, possibly leading to the development of common international rules and ways of ensuring their enforcement?

→ If the EU develops its own capacities to **detect and even counter** possible use, including a weaponised use, of geoengineering by other powers, how would that play in terms of the dynamics of an interna-tional debate over geoengineering?

→ Should the EU **strengthen Europe's scientific knowledge and industrial capacity** to support solar geoengineering technology as a plan B to complement the green transition? Or should it consider the risks of these technologies so high as to justify a moratorium including on research?

→ As in the case of space research, geoengineering is no longer the sole prerogative of state actors. Should the EU take action to **control and oversee private initiatives** which could affect the climate of the planet?

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