REPORT IN BRIEF

NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING
INSTITUTE OF MEDICINE
NATIONAL RESEARCH COUNCIL

Board on Atmospheric Sciences and Climate, Ocean Studies Board

Climate Intervention

Carbon Dioxide Removal and Reliable Sequestration
Reflecting Sunlight to Cool Earth

CLIMATE INTERVENTION IS NO SUBSTITUTE for reductions in carbon dioxide emissions and adaptation efforts aimed at reducing the negative consequences of climate change. However, as our planet enters a period of changing climate never before experienced in recorded human history, interest is growing in the potential for deliberate intervention in the climate system to counter climate change. This study assesses the potential impacts, benefits, and costs of two different proposed classes of climate intervention: (1) carbon dioxide removal and (2) albedo modification (reflecting sunlight). Carbon dioxide removal strategies address a key driver of climate change, but research is needed to fully assess if any of these technologies could be appropriate for large-scale deployment. Albedo modification strategies could rapidly cool the planet's surface but pose environmental and other risks that are not well understood and therefore should not be deployed at climate-altering scales; more research is needed to determine if albedo modification approaches could be viable in the future.

To date, most research on countering the impacts of climate change has focused on mitigating climate change by reducing greenhouse gas emissions or on adapting human and natural systems to make them more resilient to the effects of a changing climate. In contrast, climate intervention—purposeful intervention in the climate system to counter climate change—has received little attention. Despite growing interest in climate intervention (also called geoengineering) over recent years, there is a lack of information on the impacts, benefits, and costs of these technologies. These reports provide a scientific assessment to help inform the technological, ethical, legal, economic, and political discussions surrounding the topic of climate intervention.

CLIMATE INTERVENTION AS PART OF A PORTFOLIO OF CLIMATE RESPONSES

Even if human-caused carbon dioxide emissions were to cease today, it would take millennia for natural processes to return Earth's atmosphere to pre-industrial carbon dioxide concentrations. To stabilize or reduce atmospheric concentrations of greenhouse gases, and thus avoid the worst impacts of warming, present-day global greenhouse gas emissions must be reduced by at least 90 percent.

There is no substitute for dramatic reductions in emissions of carbon dioxide and other greenhouse gases to mitigate the negative consequences of climate change. Although emissions reductions are technologically feasible, they have been difficult to implement for political, economic, and social reasons that may persist well into the future. Efforts at climate adaptation are ongoing, but both human systems and natural ecosystems face substantial challenges in adapting to the varied impacts of climate change over coming years, decades, and centuries.

***Albedo** is the technical term for the proportion of sunlight that Earth's surface and atmosphere reflect back to space.*

Box 1. *Proposed Climate Intervention Strategies*

This study considers two proposed classes of climate intervention:

– Carbon dioxide removal strategies would actively remove carbon dioxide from the atmosphere and sequester it reliably.

– Albedo modification strategies would reduce the amount of sunlight absorbed by Earth in order to cool the planet's surface.

As the Committee analyzed specific carbon dioxide removal and albedo modification strategies, it became apparent that there are vast differences in the research needs, and the extent of the environmental and social risks associated with the two classes of approaches. This led the Committee to separate the climate intervention topics considered in this study into two separate reports.

It is thus prudent to also examine other options for countering the impacts of climate change. Climate intervention strategies could one day become part of a portfolio of climate response strategies, but currently these technologies are at a very early stage of development. Many questions remain about the potential for unintended consequences, effectiveness, and economic costs.

Recommendation 1: Efforts to address climate change should continue to focus most heavily on mitigating greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and poorly quantified risks and are at a greater state of technological readiness.

CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

Carbon dioxide removal strategies could address a major cause of climate change, but they are inherently slow and require further research to become effective at slowing the rate of global warming.

Some forms of carbon dioxide removal carry environmental risks—for example, ocean iron fertilization could cause changes in ocean ecology—and would require further investigation prior to serious consideration. For some other approaches the risks are relatively low and well-understood.

However, cost and lack of technical maturity are limiting implementation, and current carbon dioxide removal technologies would work slowly to reduce global temperatures. Absent some unforeseen technological innovation, large-scale carbon dioxide removal techniques may have costs comparable to or exceeding those of replacing high-carbon fossil fuels with low-carbon energy, such as solar or wind power.

If carbon dioxide removal techniques are to be widely deployed in the near term, it is critical to embark on a research program to address these challenges and lower the technical barriers to developing techniques that are both efficient and affordable.

Box 2. *Carbon Dioxide Removal Strategies Considered in This Study*

- Changes in land use management to enhance natural carbon sinks such as forests and agricultural lands
- Accelerated weathering in the ocean and on land to enhance natural processes that remove carbon dioxide from the atmosphere
- Bioenergy with carbon capture and sequestration
- Direct air capture and sequestration of carbon dioxide
- Ocean iron fertilization to boost phytoplankton growth and enhance take-up of carbon dioxide

Recommendation 2: The Committee recommends research and development investment to improve methods of carbon dioxide removal and disposal at scales that would have a global impact on reducing greenhouse warming, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.

ALBEDO MODIFICATION POSES POORLY UNDERSTOOD RISKS

Theoretical and observational data indicate albedo modification has the potential to offset some of the consequences of global warming within years and at a relatively low direct cost. However, deploying albedo modification techniques at climatically important scales would bring an array of environmental, social, legal, economic, ethical, and political risks.

The observed side effects from volcanic eruptions—a natural source of sunlight-reflecting aerosols—provide some indication of the environmental risks associated

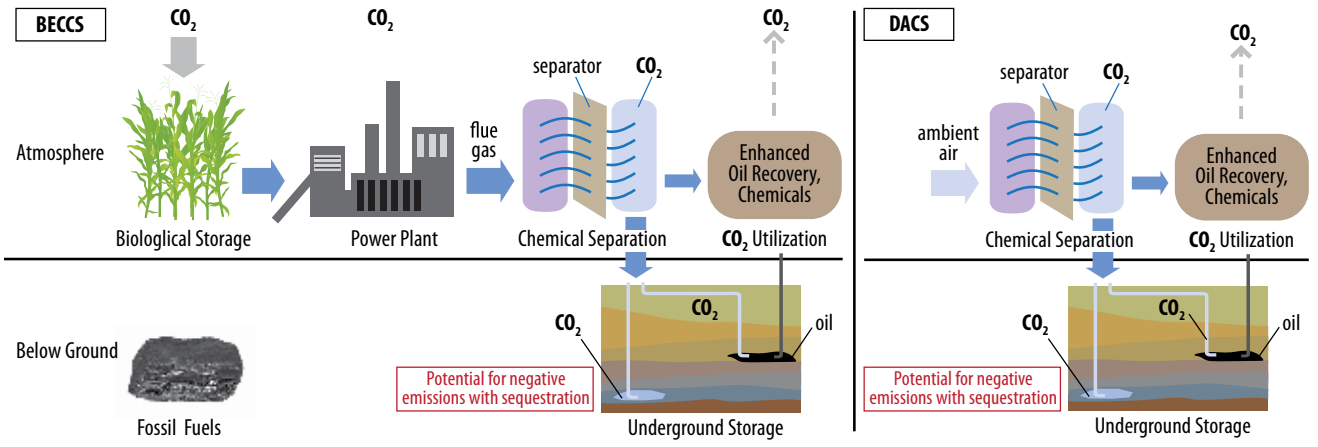

Figure 1. *In Bioenergy with Carbon Capture and Sequestration (BECCS, shown on left), crops such as corn or switchgrass take up carbon dioxide from the atmosphere as they grow. The crops can be burned in power plants to produce electricity, and the carbon dioxide generated is captured and sequestered underground. In Direct Air Capture and Sequestration (DACS, shown on right), carbon dioxide can be removed from the atmosphere as air passes through air filtering structures and is sequestered underground. Block arrows represent fluxes of carbon (as fuel or as carbon dioxide); dashed arrows indicate residual carbon dioxide emissions.*

with albedo modification. These include decreases in stratospheric ozone and changes in the amount and patterns of precipitation.

Furthermore, albedo modification does not counteract impacts of elevated concentrations of carbon dioxide in the atmosphere, such as ocean acidification. Without reductions in atmospheric carbon dioxide levels, the amount of albedo modification required to offset greenhouse warming would continue to escalate for millennia, generating greater risks of negative consequences if it is terminated for any reason.

Many of the processes most relevant to albedo modification—such as those that control the formation of clouds and aerosols—are among the most difficult components of the climate system to model and monitor. Present-day observational capabilities lack sufficient capacity to monitor the environmental effects of an albedo modification deployment on weather, climate, or the greater Earth system.

Given the enormous uncertainties associated with albedo modification, the current level of understanding of the climate system, and the alternatives available to slow or reverse the build-up of greenhouse gases, the Committee does not recommend climate-altering deployment of albedo modification at this time.

Recommendation 3: Albedo modification at scales sufficient to alter climate should not be deployed at this time.

MORE RESEARCH NEEDED ON ALBEDO MODIFICATION

Until now, there has been limited research into albedo modification strategies. However, it is becoming clear that research is needed to determine if albedo modification could be a viable climate response in the future. For example, political or social pressure to deploy albedo modification could arise in the event of a climate emergency, such as global warming that causes massive crop failures. In another hypothetical scenario, a single nation, a large corporation, or a group of individuals with sufficient means could potentially deploy albedo modification without international coordination, spurring the need to detect, quantify, and understand the consequences of this act. Research is also needed on the social, ethical, political, and economic impacts of albedo modification.

Much of the required research on albedo modification overlaps with the basic research needed to further understanding of the climate system and human-caused climate change. Most notably, research on clouds and aerosols would advance climate research while also contributing to understanding albedo modification.

Research may also be needed that is specific to learning about albedo modification, for instance, to better understand mechanisms for delivering materials that form aerosols in the stratosphere. This work is unlikely to be supported without a research program focused on climate intervention. Research topics specific to albedo modification should be identified, prioritized, and tasked to the relevant federal agencies for possible support within existing or expanded programs.

Box 3. *Albedo Modification Strategies Considered in This Study*

- Stratospheric aerosols that help reflect sunlight back into space
- Marine cloud brightening to enhance reflection of sunlight

Small-scale field experiments with controlled emissions may, in some cases, help reduce model uncertainties, validate theory, and verify model simulations in different conditions. Such experiments—which may include the injection of gases or particles into the atmosphere, followed by observations—should be conducted at the smallest practical scales, designed so as to pose no significant risk, and planned subject to the deliberative process outlined in Recommendation 6.

Recommendation 4: The Committee recommends an albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers both basic understanding of the climate system and its human dimensions.

Recommendation 5: The Committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate.

GOVERNANCE CONSIDERATIONS

Albedo modification research is not specifically addressed by any federal laws or regulations beyond those that apply broadly to scientific research and its

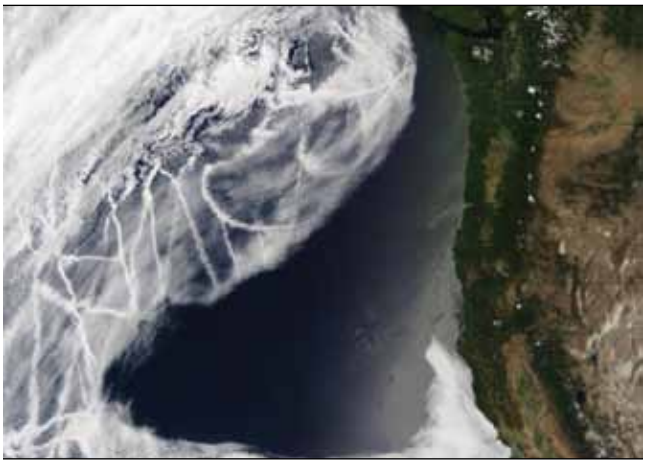

Figure 2. *Ship tracks—bright areas of clouds produced by aerosol particles in the exhaust emissions of ships—are an example of albedo modification similar to that produced by deliberate marine cloud brightening. This satellite image shows ship tracks produced by commercial cargo ships off the coast of California. Source: Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC*

impacts on worker safety, the environment, and human and animal welfare. However, planning for any deployment of albedo modification would bring unique legal, ethical, social, political, and economic considerations.

Open conversations about the governance of albedo modification research could help build civil society trust in research in this area. If new governance is needed, it should be developed in a deliberative process with input from a broad set of stakeholders. If an expanded program of albedo modification research includes controlled-emission experiments, it should be accompanied by sufficient governance to define the scale of experiment at which oversight begins.

Recommendation 6: The Committee recommends the initiation of a serious deliberative process to examine:

(a) What types of research governance, beyond those that already exist, may be needed for albedo modification research;

(b) The types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations.

Carbon Dioxide Removal proposals...	Albedo Modification proposals...
… address the cause of human-induced climate change (high atmospheric GHG concentrations).	…do not address cause of human-induced climate change (high atmospheric GHG concentrations).
…do not introduce novel global risks.	… introduce novel global risks.
…are currently expensive (or comparable to the cost of emission reduction).	…are inexpensive to deploy (relative to cost of emissions reduction).
…may produce only modest climate effects within decades.	…can produce substantial climate effects within years.
…raise fewer and less difficult issues with respect to global governance.	…raise difficult issues with respect to global governance.
…will be judged largely on questions related to cost.	…will be judged largely on questions related to risk.
…may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth.	…could be implemented suddenly, with large-scale impacts before enough research is available to understand their risks relative to inaction.
…require cooperation by major carbon emitters to have a significant effect.	…could be done unilaterally.
…for likely future emissions scenarios, abrupt termination would have limited consequences.	…for likely future emissions scenarios, abrupt termination would produce significant consequences.

Figure 3. *Overview of general differences between carbon dioxide removal proposals and albedo modification proposals. Each statement may not be true of some proposals within each category.*

CONCLUSION

Climate change is a global challenge, and addressing it will require a portfolio of responses with varying degrees of risk and efficacy. There is no substitute for dramatic reductions in greenhouse gas emissions to mitigate the negative consequences of climate change, together with adaptation of human and natural systems to make them more resilient to changing climate. However, if society ultimately decides to intervene in Earth's climate, the Committee most strongly recommends any such actions be informed by a far more substantive body of scientific research—encompassing climate science and economic, political, ethical, and other dimensions—than is available at present.

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The National Academies appointed the above committee of experts to address the specific task requested by the National Academy of Sciences, U.S. intelligence community, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Department of Energy. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report. For more information, contact the Board on Atmospheric Sciences and Climate at 202-334-3512 or visit http://dels.nas.edu/basc. Copies of *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* and *Climate Intervention: Reflecting Sunlight to Cool Earth* are available from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; (800) 624-6242; www.nap.edu.