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Partially counteracting climate change in the short- to medium-term: options globally and for Switzerland

Anthony Patt and Jean-Pierre Wolf

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Analysis conducted on behalf of the SSC Secretariat

Der Schweizerische Wissenschaftsrat

Der Schweizerische Wissenschaftsrat SWR berät den Bund in allen Fragen der Wissenschafts-, Hochschul-, Forschungs- und Innovationspolitik. Ziel seiner Arbeit ist die kontinuierliche Optimierung der Rahmenbedingungen für die gedeihliche Entwicklung der Schweizer Bildungs-, Forschungs- und Innovationslandschaft. Als unabhängiges Beratungsorgan des Bundesrates nimmt der SWR eine Langzeitperspektive auf das gesamte BFI-System ein.

Le Conseil suisse de la science

Le Conseil suisse de la science CSS est l'organe consultatif du Conseil fédéral pour les questions relevant de la politique de la science, des hautes écoles, de la recherche et de l'innovation. Le but de son travail est l'amélioration constante des conditions-cadre de l'espace suisse de la formation, de la recherche et de l'innovation en vue de son développement optimal. En tant qu'organe consultatif indépendant, le CSS prend position dans une perspective à long terme sur le système suisse de formation, de recherche et d'innovation.

Il Consiglio svizzero della scienza

Il Consiglio svizzero della scienza CSS è l'organo consultivo del Consiglio federale per le questioni riguardanti la politica in materia di scienza, scuole universitarie, ricerca e innovazione. L'obiettivo del suo lavoro è migliorare le condizioni quadro per lo spazio svizzero della formazione, della ricerca e dell'innovazione affinché possa svilupparsi in modo armonioso. In qualità di organo consultivo indipendente del Consiglio federale il CSS guarda al sistema svizzero della formazione, della ricerca e dell'innovazione in una prospettiva globale e a lungo termine.

The Swiss Science Council

The Swiss Science Council SSC is the advisory body to the Federal Council for issues related to science, higher education, research and innovation policy. The goal of the SSC, in conformity with its role as an independent consultative body, is to promote the framework for the successful development of the Swiss higher education, research and innovation system. As an independent advisory body to the Federal Council, the SSC pursues the Swiss higher education, research, and innovation landscape from a long-term perspective.

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The Secretariat supports the Swiss Science Council SSC in carrying out its legal mandate to provide consultation. In its working papers series, it conducts preliminary studies used for the Council's reports, policy papers and position statements. The author contracted by the Secretariat of the Swiss Science Council to produce the present working paper bears full responsibility for its contents.

About the authors

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Jean-Pierre Wolf is Professor of Applied Physics at the University of Geneva. His work focuses on atmospheric sensing and characterization of atmospheric aerosols. In particular, he was strongly involved in the characterization of stratospheric aerosols like PSCs and volcanic eruptions like Pinatubo. Since 2000, he pioneered laser-based methods to modulate meteorologic processes like water vapor condensation and lightning control. He was awarded the Grand Prix de Physique de l'Académie des Sciences (F), the Carl Zeiss Research Award, the Innovation Award Berlin-Brandenburg (D), the Prix La Recherche (F) and an ERC advanced Grant. He served at the CNRS direction (Comité National) and at the scientific committee of the Ministère de l'Education Nationale et de la Recherche (CNU).

Vorwort des Schweizerischen Wissenschaftsrat

2015 hat die Schweiz das Übereinkommen von Paris unterzeichnet und sich damit verpflichtet, die Bemühungen zur Begrenzung der Erderwärmung auf 1,5 Grad Celsius gegenüber vorindustriellen Werten voranzutreiben. Wird dieses Ziel verfehlt, ist mit dramatischen gesellschaftlichen und wirtschaftlichen Auswirkungen zu rechnen, wie im sechsten Sachstandsbericht des *Intergovernmental Panel on Climate Change* (IPCC) dargelegt wird. In Übereinstimmung mit den Schlussfolgerungen dieses Berichts ist der Schweizerische Wissenschaftsrat (SWR) überzeugt, dass die globale Erwärmung nur gebremst werden kann, wenn die Treibhausgasemissionen, allen voran die CO_2-Emissionen, auf Null gesenkt werden. Die gesellschaftlichen und wirtschaftlichen Veränderungen, die es zur Erreichung dieses Ziels braucht, erfordern die Umsetzung zahlreicher Massnahmen. Dazu gehören politische Massnahmen wie auch technische und soziale Innovationen. Bildung, Forschung und Innovation sind wichtige Treiber, damit die notwendigen Veränderungen gelingen.

Zur Reduktion der CO_2-Emissionen liegen umfangreiche Studien vor. Deutlich weniger gut dokumentiert sind hingegen Massnahmen, die dem Klimawandel kurz- und mittelfristig zumindest partiell entgegenwirken könnten, und wie sie sich auf die Schweiz anwenden liessen. Deshalb beauftragte der SWR zwei externe Experten, Anthony Patt von der ETH Zürich und Jean-Pierre Wolf von der Universität Genf, mit der Aufarbeitung aktueller Daten. Ihr Bericht beleuchtet die verschiedenen Dimensionen des Problems und skizziert Methoden, die relativ rasch zu einer Abschwächung der globalen und lokalen Erwärmung führen könnten; dies als Ergänzung zur weiterhin unerlässlichen Reduktion der CO_2-Emissionen. Zu den erwähnten Methoden gehören die Verringerung der Emissionen von kurzlebigen klimawirksamen Substanzen, die Kohlendioxid-Entnahme, die Modifizierung der Sonneneinstrahlung und die lokale Wetterbeeinflussung. Die vorgelegten Schätzungen zeigen, dass die Verringerung der Methanemissionen nach derzeitigem Kenntnisstand und gemäss den jüngsten Ergebnissen der COP28-Konferenz in Dubai[1] eine vielversprechende und konkrete Massnahme darstellt. Doch der SWR ist sich bewusst, dass sich die in diesem Arbeitspapier diskutierten Bereiche rasant entwickeln, zudem handelt es sich dabei nicht um einen akademischen Beitrag nach dem Peer-Review-Verfahren. Das Dokument soll der Schweizer Politik vielmehr einen Überblick über mögliche Massnahmen bieten und eine Diskussion anstossen.

Der Rat betont, dass die Optionen in diesem Arbeitspapier keine Lösung für das Problem des durch den Menschen verursachten Klimawandels darstellen. Da jedoch die Gefahr von Kipppunkten im Klimasystem weiter zunimmt, ist der SWR der Ansicht, dass jede Massnahme, die die Symptome des übermässigen Treibhausgasausstosses rasch – wenn auch nur kurz- bis mittelfristig – mildern könnte, gründlich und objektiv untersucht, geprüft und diskutiert werden sollte. Die vorliegenden Überlegungen stellen die belegte Notwendigkeit, die Treibhausgasemissionen auf Netto-Null zu senken, somit keinesfalls infrage. Hierzu sind weitere sofortige Massnahmen notwendig.

Für den SWR ist es prioritär, die Rahmenbedingungen für Bildung, Forschung und Innovation zu schaffen, die zur Bewältigung grosser gesellschaftlicher Herausforderungen wie der Klimakrise erforderlich sind. Er hat zu diesem Thema bereits Stellungnahmen und Analysen veröffentlicht, insbesondere zur Verbesserung der wissenschaftlichen Politikberatung.[2] In

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[1] An der COP28 wurde am 2. Dezember 2023 die «Oil and Gas Decarbonisation Charter» (OGDC) ins Leben gerufen, um die Klimaschutzmassnahmen in der Industrie voranzutreiben. Die Charta zur Dekarbonisierung der Öl- und Gasindustrie, der sich 50 Öl- und Gasunternehmen angeschlossen haben, beinhaltet das Ziel, die vorgelagerten Methanemissionen bis 2030 auf nahezu Null zu senken.

[2] Der SWR legte verschiedene Empfehlungen vor, um dies zu erreichen: siehe Schweizerischer Wissenschaftsrat (2022). *Wissenschaftliche Politikberatung in Krisenzeiten. Überlegungen und Empfehlungen des Schweizerischen Wissenschaftsrates SWR. Auf der Grundlage eines Expertenberichts von Caspar Hirschi, Johanna Hornung, Dylan Jaton, Céline Mavrot, Fritz Sager und Caroline Schlaufer zuhanden des SWR*. SWR: Bern. Der SWR befasste sich auch mit der Akzeptanz von Massnahmen im Zusammenhang mit der Covid-Krise (und darüber hinaus): Schweizerischer Wissenschaftsrat (2022).

seiner Stellungnahme zur BFI-Botschaft 2025–2028 plädiert der SWR für eine missionsorientierte Forschungs- und Innovationspolitik zur Lösung gesellschaftlicher Probleme; er empfiehlt die Schaffung eines Pilotprojekts bei Innosuisse und eine bessere Koordination der Ressortforschung des Bundes.[3] In diesem Zusammenhang unterstützt der SWR die Finanzierung von SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction). Das Programm wird den Zeitraum 2025–2036 abdecken und damit die mittelfristige Kontinuität der Forschungsförderung im Bereich Energie garantieren sowie eine breite Prioritätensetzung ermöglichen.[4]

Das vorliegende Arbeitspapier ist als Vorbereitungsdokument gedacht. Es soll künftige Überlegungen des Rates unterstützen bezogen auf die Rahmenbedingungen für das BFI-System, die erforderlich sind, damit der menschengemachte Klimawandel verstärkt angegangen werden kann. Bildung, Forschung und Innovation können und müssen einen wichtigen Beitrag zur Bewältigung dieser grossen Herausforderung leisten, wobei die Natur- und Ingenieurwissenschaften eng mit den Sozial- und Geisteswissenschaften zusammenarbeiten müssen.

Akzeptanz von Krisenmassnahmen durch die Bevölkerung. Die Lehren aus Covid-19. Ergebnisse von zwei Workshops und Analyse des Schweizerischen Wissenschaftsrates SWR. SWR: Bern.

[3] Die Empfehlungen und die umfassenden Überlegungen des SWR wurden veröffentlicht in: Schweizerischer Wissenschaftsrat (2023). *Missionsorientierte Forschung und Innovation in der Schweiz*. SWR: Bern.

[4] Schweizerischer Wissenschaftsrat (2023). *Verpflichtungskredit für das Forschungsförderinstrument SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction) für die Jahre 2025–2036. Stellungnahme des SWR im Rahmen des Vernehmlassungsverfahrens*. SWR: Bern.

Préface du Conseil suisse d.e la science

En 2015, la Suisse a signé l'Accord de Paris, s'engageant ainsi à prendre des mesures pour limiter la température moyenne à la surface du globe à 1,5 °C au-dessus du niveau de l'ère pré-industrielle. Un échec des efforts visant à atteindre cet objectif aurait des conséquences sociales et économiques dramatiques, comme synthétisé dans le 6e rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). En adéquation avec les conclusions de ce rapport, le Conseil suisse de la science (CSS) considère que le réchauffement planétaire ne peut être stabilisé qu'en atteignant l'objectif de zéro émission nette de gaz à effet de serre, en particulier de CO_2. Les transitions sociétales et économiques nécessaires pour atteindre cet objectif requièrent la mise en œuvre de nombreuses actions, y compris l'introduction de nouvelles lois et d'innovations techniques et sociales. La formation, la recherche et l'innovation seront des moteurs importants pour assurer le succès des transformations requises.

S'il existe une abondante documentation concernant les mesures visant à réduire les émissions de CO_2, on ne peut pas en dire autant concernant les mesures susceptibles d'infléchir partiellement le changement climatique à court ou moyen terme, et en particulier sur la façon dont ces mesures pourraient s'appliquer à la Suisse. C'est pourquoi le CSS a mandaté deux experts externes, Anthony Patt, de l'ETH Zurich, et Jean-Pierre Wolf, de l'Université de Genève, pour combler cette lacune, en s'appuyant sur les données les plus actuelles. Leur rapport explicite les différentes dimensions du problème et donne un aperçu des méthodes qui pourraient contribuer à réguler le réchauffement global et local à relativement brève échéance, en complément de la réduction des émissions de CO_2, qui reste primordiale. Les mesures envisagées comprennent la réduction des émissions de forceurs climatiques à courte durée de vie, l'élimination du dioxyde de carbone atmosphérique, la modification du rayonnement solaire et la modification locale des conditions météorologiques. Les estimations présentées ici montrent que sur la base des connaissances actuelles, et en accord avec ce qui vient d'émerger de la COP28 de Dubaï[5], la réduction des émissions de méthane apparaît comme une mesure aussi concrète que prometteuse. Néanmoins, étant donné la rapidité à laquelle évoluent les domaines traités, le CSS est conscient qu'il ne s'agit pas ici d'une contribution académique évaluée par les pairs. Il s'agit plutôt de fournir aux milieux politiques suisses une vue d'ensemble des mesures potentielles afin de lancer le débat.

Le Conseil insiste sur le fait que les options présentées dans le document de travail ne constituent pas une solution au changement climatique induit par les activités humaines. Cependant, le risque d'atteindre un point de non-retour dans le système climatique augmente continuellement. C'est pourquoi le CSS estime que toute action qui pourrait rapidement atténuer, ne serait-ce que sur le court ou moyen terme, quelques-uns des symptômes survenant à cause des émissions excessives de gaz à effet de serre mérite d'être analysée, étudiée et soumise à la discussion de façon minutieuse et impartiale. Ces considérations ne remettent aucunement en question la nécessité, amplement documentée, d'atteindre l'objectif de neutralité pour toutes les émissions nettes de gaz à effet de serre. Atteindre cet objectif requiert d'autres mesures immédiates.

L'une des priorités du CSS est d'identifier les conditions-cadres nécessaires pour permettre à la formation, la recherche et l'innovation de contribuer à la résolution des grands défis sociétaux tels que la crise climatique. Aussi a-t-il publié des prises de position et des analyses, notamment sur la manière d'améliorer le conseil scientifique dans le champ politique[6]. Dans

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[5] La «Charte de décarbonation du pétrole et du gaz» a été adoptée le 2 décembre 2023 pendant la COP28 afin d'accélérer l'action climatique au sein du secteur industriel. Signée par 50 sociétés pétrolières et gazières, elle inclut l'objectif de réduire les émissions de méthane en amont à un niveau proche de zéro d'ici à 2030.

[6] Le CSS a présenté diverses recommandations à cette fin. Voir: Conseil suisse de la science (2022). *Le conseil scientifique dans le champ politique en temps de crise. Considérations et recommandations du Conseil suisse de la science CSS. Rédigé sur la base d'un rapport d'experts par Caspar Hirschi, Johanna Hornung, Dylan Jaton, Céline Mavrot, Fritz Sager et Caroline*

sa prise de position sur le message FRI 2025–2028, il défend une politique de la recherche et de l'innovation orientées mission afin de répondre aux problèmes auxquels la société est confrontée ; il recommande de lancer un projet pilote au sein d'Innosuisse et d'améliorer la coordination de la recherche de l'administration fédérale[7]. Dans ce contexte, le CSS approuve le soutien au programme de recherche SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction). Ce programme couvrira la période de 2025 à 2036, permettant ainsi d'assurer la continuité de l'encouragement de la recherche sur le moyen terme et d'établir les priorités de façon large[8].

Ce document de travail constitue une base préparatoire. Il contribuera à alimenter les futures réflexions du CSS sur les conditions-cadres nécessaires au domaine FRI pour faciliter une approche plus exhaustive face au changement climatique induit par l'être humain. La formation, la recherche et l'innovation peuvent et doivent fournir une contribution importante à la résolution de ce défi majeur, en faisant appel à la fois aux sciences naturelles et de l'ingénierie et aux sciences sociales et humaines.

Schlaufer sur mandat du CSS. CSS, Berne. Le CSS s'est également penché sur la question de l'acceptation des mesures prises dans le contexte de la crise du Covid-19 (et au-delà): Conseil suisse de la science (2022). *L'acceptation des mesures de crise par la population. Les enseignements de la pandémie de Covid-19. Résultats de deux ateliers et analyse du Conseil suisse de la science CSS*. CSS, Berne.

[7] Les recommandations et les considérations du CSS à ce sujet sont publiées dans: Conseil suisse de la science (2023). *La recherche et l'innovation orientées mission en Suisse*. CSS, Berne.

[8] Conseil suisse de la science (*2023). Crédit d'engagement pour le programme d'encouragement de la recherche SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction) pour les années 2025 à 2036. Prise de position du CSS dans le cadre de la procédure de consultation*. CSS, Berne.

Prefazione del Consiglio svizzero della scienza

Nel 2015 la Svizzera ha firmato l'Accordo di Parigi, impegnandosi così a proseguire gli sforzi per limitare l'aumento della temperatura media globale a 1,5°C rispetto ai livelli preindustriali. Il mancato raggiungimento di questo obiettivo avrà conseguenze sociali ed economiche drammatiche, come ricorda il sesto rapporto di valutazione del Gruppo intergovernativo di esperti sul cambiamento climatico (IPCC, *Intergovernmental Panel on Climate Change*). In linea con le conclusioni di tale rapporto, il Consiglio svizzero della scienza (CSS) ritiene che la stabilizzazione del riscaldamento globale possa essere raggiunta solo azzerando le emissioni di gas serra, in particolare di CO_2. Le transizioni sociali ed economiche necessarie per raggiungere questo obiettivo richiedono l'attuazione di numerose azioni, tra cui misure politiche e innovazioni tecniche e sociali. La formazione, la ricerca e l'innovazione sono motori importanti per realizzare i cambiamenti necessari.

Esiste un'ampia documentazione sulle misure per ridurre le emissioni di CO_2. Molto meno documentate sono per contro misure che potrebbero frenare parzialmente il cambiamento climatico a breve e medio termine, in particolare in rapporto alla Svizzera. Il CSS ha pertanto incaricato due esperti esterni, Anthony Patt del Politecnico di Zurigo e Jean-Pierre Wolf dell'Università di Ginevra, di colmare questa lacuna con dati aggiornati. Il loro rapporto chiarisce le diverse dimensioni del problema e delinea i metodi che potrebbero aiutare a regolare il riscaldamento globale e locale in tempi relativamente brevi, a complemento della riduzione delle emissioni di CO_2, che rimane essenziale. I metodi qui presi in considerazione comprendono la riduzione delle emissioni di forzanti climatici a vita breve, la rimozione dell'anidride carbonica, la modifica della radiazione solare e quella del clima locale. Secondo le stime presentate, sulla base delle conoscenze attuali e in linea con quanto appena emerso dalla conferenza COP28 di Dubai[9], la riduzione delle emissioni di metano è una misura promettente e concreta. Poiché i settori qui trattati sono altamente dinamici, il CSS è consapevole che il presente documento non è il classico contributo accademico sottoposto a *peer-review*. Il suo scopo è piuttosto quello di fornire alla comunità politica svizzera una panoramica delle misure potenziali e di avviare un dibattito.

Il CSS sottolinea che le opzioni contenute nel presente documento di lavoro non rappresentano una soluzione al problema del cambiamento climatico indotto dall'uomo. Tuttavia, il rischio di raggiungere un punto di non ritorno nel sistema climatico è in continuo aumento. Per questo motivo il CSS ritiene che ogni azione che possa alleviare rapidamente i sintomi dell'eccesso di gas serra, anche se solo a breve e medio termine, meriti di essere studiata, esaminata e discussa in modo approfondito e imparziale. Queste considerazioni non inficiano assolutamente la necessità, ampiamente documentata, di azzerare tutte le emissioni nette di gas serra con ulteriori azioni immediate.

Il CSS ritiene che sia prioritario identificare le condizioni quadro necessarie affinché la formazione, la ricerca e l'innovazione permettano di affrontare grandi sfide sociali come il cambiamento climatico. Per questo ha pubblicato prese di posizione e analisi, in particolare su come migliorare la consulenza scientifica in campo politico.[10] Nella sua presa di posizione sul Messaggio ERI 2025-2028, il CSS sostiene una politica di ricerca e innovazione orientata alla missione per affrontare i problemi della società; raccomanda di avviare un progetto pilota sotto la guida di Innosuisse e di migliorare il coordinamento della ricerca nell'Amministrazione

[9] La «Carta per la decarbonizzazione del petrolio e del gas» (OGDC) è stata lanciata alla COP28, il 2 dicembre 2023, per accelerare l'azione per il clima all'interno dell'industria. La Carta, a cui hanno aderito 50 compagnie petrolifere e del gas, si prefigge di rendere "vicine allo zero" le emissioni relative al metano entro il 2030.

[10] Il CSS ha presentato diverse raccomandazioni in proposito: cfr. Consiglio svizzero della scienza (2022). *Consulenza scientifica per la politica in tempi di crisi. Considerazioni e raccomandazioni del Consiglio svizzero della scienza CSS sulla base di una perizia di Caspar Hirschi, Johanna Hornung, Dylan Jaton, Céline Mavrot, Fritz Sager e Caroline Schlaufer su richiesta del CSS.* CSS: Berna. Il CSS ha anche affrontato la questione dell'accettazione delle misure adottate nel contesto della crisi del COVID-19 (e oltre): Consiglio svizzero della scienza (2022). *Accettazione delle misure di crisi da parte della popolazione. Insegnamenti da trarre dalla pandemia di COVID-19. Risultati di due workshop e analisi del Consiglio svizzero della scienza CSS.* CSS: Berna.

federale.[11] In questo contesto il CSS appoggia il finanziamento di SWEETER (*SWiss research for the EnErgy Transition and Emissions Reduction*). Questo programma coprirà il periodo dal 2025 al 2036, garantendo così la continuità a medio termine della promozione della ricerca e permettendo di definire le priorità su larga scala.[12]

Questo documento ha carattere preparatorio. Contribuirà alle future riflessioni del Consiglio sulle condizioni quadro necessarie al sistema ERI per facilitare un approccio più completo ai cambiamenti climatici indotti dall'uomo. La formazione, la ricerca e l'innovazione possono e devono fornire un contributo importante per affrontare questa grande sfida, attingendo sia alle scienze naturali e ingegneristiche che alle scienze sociali e umanistiche.

[11] Le raccomandazioni e le considerazioni generali del CSS sono pubblicate in: Consiglio svizzero della scienza (2023). *La ricerca e l'innovazione orientate alla missione in Svizzera*. CSS: Berna.
[12] Consiglio svizzero della scienza (2023). *Credito d'impegno per il programma di promozione della ricerca SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction) per gli anni dal 2025 al 2036. Presa di posizione del CSS nell'ambito della procedura di consultazione.* CSS: Berna.

Preface by the Swiss Science Council

In 2015, Switzerland signed the Paris Agreement, thereby committing to pursuing efforts to limit the global average temperature increase to 1.5 °C above pre-industrial levels. Failing to achieve this will result in dramatic social and economic consequences, as summarised in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In line with the conclusions of that report, the Swiss Science Council (SSC) considers that stabilising global warming can only be achieved by reducing to zero the emissions of greenhouse gases, in particular CO_2. The societal and economic transitions necessary to reach this goal require the implementation of numerous actions, including policies as well as technical and societal innovations. Education, research and innovation are important drivers for the needed changes to succeed.

There is voluminous documentation of measures to reduce CO_2 emissions, but far less on measures which could partially counteract climate change in the short to medium term, and particularly how they might relate to Switzerland. Accordingly, the SSC mandated two external experts, Anthony Patt, ETH Zurich, and Jean-Pierre Wolf, University of Geneva, to fill this gap including up-to-date information. Their report clarifies the different dimensions of the problem and outlines methods which could lead to a relatively rapid modulation of global and local warming, as a complement to the essential CO_2 emission reductions. The methods include: reduction in the emissions of short-lived climate forcers, carbon dioxide removal, solar radiation modification, and local weather modification. The estimations presented show that, based on current knowledge and in agreement with what has just emerged from the COP28 conference in Dubai[13], the reduction of methane emissions is a promising and concrete measure. Nonetheless, as the fields covered in the working paper are highly dynamic, the SSC is aware that the present document is not a peer-reviewed academic contribution. Instead, it aims to provide the Swiss policy community with an overview of potentially possible measures and to launch a discussion.

The Council stresses that the options in this working paper do not represent a solution for the problem of human-induced climate change. However, as the risk of reaching tipping points in the climate system is continually increasing, the SSC considers every action that might rapidly alleviate any symptoms of the excess greenhouse gas problem, even if only in the short and medium terms, worth being thoroughly and impartially studied, examined and discussed. The considerations do not call into question the much documented need to cut all net greenhouse gas emissions to zero, which requires further immediate actions.

The SSC considers it a priority to identify the framework needed for education, research and innovation to be able to master grand societal challenges, such as the climate crisis. It has also issued position statements and analyses, notably on how to improve science policy advice.[14] In its statement on the ERI Dispatch 2025–2028, the SSC advocates a mission-oriented research and innovation policy to address societal problems; it recommends establishing a pilot project at Innosuisse and improving the coordination of the federal government's departmental research.[15] In this context, the SSC endorses the funding of SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction). This

[13] The “Oil and Gas Decarbonisation Charter” (OGDC) was launched at COP28, on December 2nd, 2023, to speed up climate action within the industry. The Charter, which was joined by 50 oil and gas companies, includes the aim for near-zero upstream methane emissions by 2030.

[14] The SSC presented various recommendations to achieve that: see Swiss Science Council (2022). *Science policy advice in times of crisis. Considerations and recommendations by the Swiss Science Council SSC. On the basis of an expert report by Caspar Hirschi, Johanna Hornung, Dylan Jaton, Céline Mavrot, Fritz Sager and Caroline Schlaufer on behalf of the SSC*. SSC: Bern. The SSC also examined the issue of acceptance in the context of the Covid crisis (and beyond): Swiss Science Council (2022). *Public acceptance of crisis measures. Learning from the Covid-19 pandemic. Results of two workshops and analysis by the Swiss Science Council SSC*. SSC: Bern.

[15] The recommendations and the comprehensive considerations of the SSC are published in: Swiss Science Council (2023). *Mission-oriented Research and Innovation in Switzerland*. SSC: Bern.

programme will cover the period from 2025 to 2036, thus ensuring the mid-term continuity of the research promotion and enabling a broad prioritisation.[16]

The working paper is a preparatory document. It will contribute to the Council's future reflection on the framework conditions necessary for the ERI system to facilitate a more extensive tackling of human-induced climate change. Education, research and innovation can and must provide an important contribution to how we face this major challenge, with the natural and engineering sciences working in tandem with the social sciences and humanities.

[16] Swiss Science Council (2023). *Guarantee credit for the research funding instrument SWEETER (SWiss research for the EnErgy Transition and Emissions Reduction) for the years 2025−2036. SSC position statement within the consultation process*. SSC: Bern.

Partially counteracting climate change in the short- to medium-term: options globally and for Switzerland

Anthony Patt and Jean-Pierre Wolf

4 October 2023

Executive Summary

1. This report presents an overview of investigated methods to cool the planet, or reduce the occurrence of extreme weather events, at short- to medium-term time scales. These interventions could, when undertaken with ambitious conventional CO_2 mitigation policies, help return the climate or some of its parameters (such as average temperature) to a state that had existed in the past, prior to the intervention. The four presented methods include rapid reductions in emissions of short-lived climate forcers, carbon dioxide removal, solar radiation modification, and local weather modification.

2. The report does not cover conventional mitigation, which comprises actions to slow or halt the accumulation of greenhouse gas concentrations in the atmosphere. It also does not cover climate adaptation, which comprises efforts to reduce losses or take advantage of opportunities associated with a changed climate.

3. There is strong consensus in the science and policy communities that the measures described in this report are not a substitute for conventional mitigation, and the possibility of their deployment in no way reduces the need to halt emissions of CO_2 and other greenhouse gases as quickly as possible. Essentially all modelling scenarios that achieve long-term temperature stabilisation well below 2°C above pre-industrial conditions include extensive deployment of carbon dioxide removal in addition to ambitious conventional mitigation, and none reach that temperature target without such conventional mitigation. None of the widely used modelling scenarios include deployment of solar radiation modification, out of concern for the risks and uncertainties associated with its deployment.

Reduction in the emissions of short-lived climate forcers

1. While CO_2 has a residence time in the atmosphere of many centuries, many greenhouse gases have much shorter residence times, and are hence known as short-lived climate forcers (SLCFs). That means that SLCFs' atmospheric concentrations respond quickly to the rate of emissions, and that reducing emissions would lead to a short-term cooling effect.

2. The most important of the SLCFs is methane, which derives both from fossil fuel production, and from the agricultural sector. Immediately eliminating all methane emissions would lead to a global cooling effect, over the next decade, of about 0.6°C.

3. Fugitive fossil methane emissions derive primarily from the oil and gas industries. It is estimated that 3.7% of the natural gas produced in North America leaks, becoming fugitive emissions. Most fugitive emissions associated with Switzerland are from gas leaks upstream of gas imports into Switzerland.

4. The second main source of methane emissions is agriculture, with two-thirds of agricultural methane emissions being associated with enteric fermentation – nearly exclusively in cattle – and the remainder coming primarily from rice cultivation. In addition to a change in people's diets, there are a number of technical options that could become available, and one that currently is available, to significantly reduce these emissions. The one now available is a feed additive that was approved for use in Europe (including Switzerland) in 2022; extensive field testing suggests that it has no adverse side effects on cattle health, meat, or milk production, reduces methane

formation during enteric fermentation by 30%, and adds costs equivalent into CHF 0.01 per litre of milk production.

5. The second major set of SLCF result from combustion of hydrocarbon fuel at the altitude of commercial aviation and are primarily associated with the formation of long-lived contrails from jet engine exhausts. Immediately eliminating these effects would lead to a global cooling effect, within days, of about 0.03°C. They could be eliminated with electric propulsion systems, although these are unlikely to be commercially viable, outside of very short flights, before 2050. Recent research suggests that they could be greatly reduced – by as much as 90% – through modifications in flight routing, primarily adjustments in altitude to avoid regions of super-saturated air. A shift to hydrogen propulsion systems would also reduce them, although the full effect is not known. Substituting synthetic aviation fuels would also lead to reduction of SCLFs, potentially by 50%. Swiss companies might benefit financially from the widespread adoption of synthetic aviation fuels.

6. There is recent evidence that hydrogen acts indirectly as a SLCF, by lengthening the atmospheric residence time of methane. While more research is needed, it is possible that fugitive emissions from green hydrogen production, transport and storage could have a large enough warming effect as to cancel out the benefits of switching from fossil fuels to green hydrogen as an energy carrier.

Carbon dioxide removal

1. There are several negative emissions technologies (NETs), which represent means of achieving carbon dioxide removal (CDR) from the atmosphere, leading to a reduction in atmospheric CO_2 concentrations. Emissions scenarios consistent with limiting global average temperature rise to 1.5°C, and assuming ambitious but nevertheless realistic declines in emissions by mid-century, suggest a likely need for NETs deployment on the order of 15 $GtCO_2$ per year.

2. These can be divided into those making use of biological CO_2 uptake, and those that involve inorganic processes. The primary biological methods relevant for Switzerland involve afforestation and improved forest management, bioenergy production combined with carbon capture and storage (BECCS), and soil carbon enhancement through the production and burial of charcoal (biochar). The primary inorganic processes are accelerated weathering of cement and basaltic stones, and direct air carbon capture and storage (DACCS).

3. The lower cost NETs are afforestation and improved forest management, and BECCS. There are tradeoffs between them, as the same grown biomass cannot contribute to both the carbon stock in the forest and to the production of energy. Assessments for Switzerland suggest that while BECCS can be sensible as an improvement on conventional biowaste management, in other cases afforestation is usually a more effective use of land than BECCS, achieving a high rate of CO_2 removal, while also serving other environmental protection goals such as biodiversity protection. Globally it is estimated that up to 1.5 $GtCO_2$ per year could be removed with afforestation at costs below USD 100 per tCO_2, while a significant fraction may come at costs close to zero. The potential for BECCS deployment, at costs below USD 100 per tCO_2, is also approximately 1.5 $GtCO_2$ per year. In Switzerland, data through 2015 suggest that afforestation had been sequestering CO_2 at that rate of 1.6 $MtCO_2$ per year. An

additional sequestration of 3 $MtCO_2$ per year could occur in Switzerland, through carbon capture and storage (CCS) deployment associated with existing waste incineration facilities, and hence not affecting forest CO_2 uptake.

4. A recently researched method of CDR is advanced weathering, which seeks to accelerate the natural process by which atmospheric CO_2 reacts with soils and rocks. One such option is to spread dust obtained from crushed volcanic rock onto agricultural soils. It has an estimated global potential of several $GtCO_2$ annually. There are large uncertainties concerning costs and risks.

5. The NET with the highest theoretical potential is DACCS. DACCS is not yet at the highest level of technological readiness, and its costs exceed USD 500 per tCO_2, although industry participants anticipate its costs falling, potentially to USD 100 per tCO_2. At such lower DACCS costs, the main cost element of DACCS facilities would be the new renewable energy needed to drive the chemical processes. For this reason, DACCS deployment is seen as most promising in world regions with high quality solar, wind, and geothermal resources, and less appropriate for countries such as Switzerland lacking these resources.

6. Both BECCS and DACCS rely on underground CO_2 storage. The most extensively tested sites are depleted oil and gas wells, where several decades of monitoring suggests little to no leakage. One such site, the Sleipnir gas field under the North Sea, has been estimated to have a potential to store 600 $GtCO_2$, likely exceeding global CO_2 storage needs. Another type of site makes use of volcanic soils, which mineralize injected CO_2 within a matter of months and thereby offer known permanence. Estimates are that such sites in Iceland and along oceanic ridges could mineralize 100,000 – 250,000 $GtCO_2$ in total, exceeding projected needs by orders of magnitude. Hence the total potential for underground storage is not an issue, but its location is. Switzerland does not have any sites that have been tested for permanent storage, and developing such sites would likely take decades, if viable at all.

7. Achieving global levels of CDR needed to limit temperature rise to 1.5°C would require multiple NETs, as the lower cost options are limited in their scalability. Almost certainly this would make DACCS required. The costs of building and operating DACCS at such a scale, including the renewable energy sources needed to operate it, would be on the order of one trillion USD annually, corresponding to roughly 1% of global GDP. The benefits deriving from such deployment, in terms of reduced damages associated with climate change, have been estimated to be far larger, exceeding 3% of global GDP by 2100.

Solar radiation modification

1. Reducing the solar radiation absorbed by the Earth by 1-2 % would counterbalance the radiative forcing due to a doubling of the atmospheric CO_2 concentration. This has motivated several geoengineering proposals and approaches, although the reduction would have to be applied globally and at least over several decades. In addition, solar radiation modification (SRM) does not counteract non-radiative issues associated to the presence of high CO_2 concentrations, like the acidification of the oceans.

2. SRM measures are mainly distributed among 3 categories: (1) Stratospheric aerosols injection (SAI), (2) Marine cloud brightening (MCB) and (3) Surface albedo

modification (SAM). Some additional approaches have also been proposed, but less investigated, like placing large reflective mirrors in space or thinning cirrus clouds to reduce their heat trapping effect.

3. Stratospheric aerosol injection was initially proposed for mimicking volcanic eruptions, like Mount Pinatubo in 1991. That eruption produced a global cooling of ~ -0.5°C over ~ 2 years by injecting SO_2 and aerosol particles (ashes) in the stratosphere. This natural experiment served as background for developing models for intentional SAI. Most models show that a forcing (~ 4 W/m^2) associated with the doubling of CO_2 concentration could be compensated by injecting yearly of the order of 10 Tg SO_2 in the stratosphere at a cost of the order of USD 10 billion/yr. While SO_2 is also associated with environmental harm and negative health effects, the ~ 10Tg envisioned is significantly smaller than annual tropospheric SO_2 emissions, which comprised roughly 150 Tg in the 1980s, and roughly 100 Tg today. Partly due to these concerns, and also because of differences in optical qualities, recent studies have focused on other types of aerosols.

4. SAI could be implemented rapidly but would need to be continually applied to maintain a constant cooling effect. It is associated with high risks and uncertainties, because of impacts on stratospheric ozone depletion and on the water cycle, such as monsoonal rains. It appears therefore unsuited for reversing warming from CO_2 in the long term. Some people have suggested it as a transient emergency measure to limit peak warming around the time that net-zero emissions are reached, until such time as NETs have had time to adequately reduce atmospheric CO_2 concentrations.

5. Marine cloud brightening aims at producing solar radiation reflecting clouds in the troposphere. Seeding the atmosphere by additional condensation nuclei can increase the cloud albedo if adequate condensing conditions are met. The associated lifetime is very short in the troposphere, of the order of days, which significantly reduces risks, but also requires permanent and large scale seeding (usually carried out with sea salt aerosols). Simulations estimate that emission rates of the order of 10^6 particles $s^{-1}m^{-2}$ over a surface area of 77,000 km^2 would be required to compensate for a doubling of atmospheric CO_2. The cost associated with such an intervention would amount to about USD 5-10 billion/yr, and the process efficiency is highly dependent on atmospheric conditions. MCB is therefore probably not the solution for global warming compensation but can be a possible adaptation measure in a local/regional context, as saving coral reefs. Very few studies have been carried out on fresh water like lakes so that further scientific studies would be required if envisaged in Switzerland.

6. Surface albedo management consists in painting roofs and other infrastructures in white and modifying agricultural practice (no-till farming, plant substitution) to increase albedo in crops. While global cooling of such measures, even massively implemented, would be negligible (e.g. -0.002 °C for white painting), local use is interesting as adaptation measure, also in Switzerland. SAM can significantly reduce temperatures inside buildings and heat island during summer heatwaves, improving human welfare and health. It can also reduce temperature (~ -2°C) and better manage drought periods in land crops. The albedo increase in cities should, however, also be evaluated in winter before being implemented, to avoid increase of heating costs.

Extreme weather events and weather engineering

1. As a consequence of the rise of extreme weather events, weather geoengineering is increasingly deployed to deal with local impacts and costs due to global warming. Most of the efforts are dedicated to rain- and snow-fall enhancement for counteracting drought and snow melt, which impact agriculture and tourism. The usual method of choice is cloud seeding with chemical agents. Other geoengineering actions are devoted to hail, fog/smog and lightning management, which induce more than USD 10 billion/yr damage costs in the USA alone.

2. Cloud seeding has been revitalized recently, with large-scale national programs. In China, the Weather Modification Office (32,000 employees) reported having conducted more than half a million weather modification operations, harvesting as much as 500 billion tons of rain. The Chinese program now covers an area equivalent to the size of India. In the USA, 922 cloud seeding projects have been registered by the National Oceanic and Atmospheric Administration (NOAA) between 2000 and 2022, for rain and snow enhancement. Precipitation enhancement is now proposed to individual customers (farmers, regions, ski resorts, etc.) at a cost as low as USD 3.50 per acre-foot (or, USD 0.003 per ton) of harvested water. Although the efficiency of cloud seeding is difficult to quantify, recent dedicated scientific campaigns have been able to provide quantitative measurements and prove causality. Most of the reported results converge on a typical value of 10-15% precipitation increase. However, more studies are required for statistical confirmation and for optimizing the process ("seedability" conditions), as well as into detrimental impacts such as soil pollution from silver compounds. There is a potential socio-economic interest (tourism, agriculture) for these technologies in Switzerland as well, but this would require a detailed assessment including of adverse effects, and an appropriate regulatory framework would be required.

3. Geoengineering measures for hail, fog and lightning protection mainly rely on seeding as well, either with chemical agents or dry ice (solid CO_2). The differences reside on the encountered atmospheric conditions themselves (thunderclouds, ground fog due to temperature gradients, etc). Main objectives are reducing lightning damages on large infrastructures, improving visibility on airport landing lanes, optical free space communications, reducing smog impacts on human health, and reducing damage costs on crops (hail).

4. Some new technologies are emerging for improving the efficiency and reducing the risks associated with cloud seeding. Among them, ion injection and laser technologies are promising, but require further scientific studies to be accurately evaluated.

Key international governance needs

1. Two factors drive the need for international cooperation on all of the methods described in this report. The first is the relative lack of effectiveness of any actions undertaken only at the scale of a single country, such as Switzerland. This is particularly the case for actions to reduce emissions of SLCFs, as well as CDR. To make a meaningful difference, these actions would have to be undertaken by a large number of countries. The second factor is the effect of actions taken by one country on other countries. This is particularly the case for SRM, with the exception of efforts to counteract local heat island effects through surface albedo modification. It can also be the case for local

weather modification efforts, which can induce regional changes in weather, affecting other countries.

2. There are currently few governance frameworks in place specifically addressing any of these measures. Many – but not all – SLCFs are covered implicitly within the Paris Agreement, equated with CO_2 emissions using the GWP100 conversion metric, which may be inappropriate to cover short-term effects. CDR is covered within the Paris Agreement, insofar as removals can offset emissions, helping countries to achieve their emission reduction targets. There is no framework, however, for assigning responsibility for undertaking CDR in order to achieve net negative emissions. With respect to SRM, there are no comprehensive governance frameworks in place that directly address the issue. Similarly, regional agreements covering weather modification are absent. Developing governance frameworks would be a key element prior to pursuing any of the actions listed in this report.

3. An additional area for international cooperation is with respect to scientific research. All of the methods described in this report require additional research, if they are to be pursued effectively and at scale. There have been calls for international research programs on them. In the case of SAI, it is also clear that there would need to be an international agreement covering any research that relies on open-air testing, as this would represent partial deployment of the technology.

Zusammenfassung

1. Dieser Bericht befasst sich mit Massnahmen zur Abkühlung des Planeten oder zur Verringerung des Auftretens extremer Wetterereignisse auf kurz- bis mittelfristigen Zeitskalen. Diese Massnahmen würden das Klima oder einige seiner Parameter (wie z.B. die Durchschnittstemperatur) in begrenztem Umfang in einen Zustand zurückversetzen, der in der Vergangenheit (also vor der Einführung der Massnahme) bestanden hat. Zu den vier Gruppen von Massnahmen gehören die rasche Verringerung der Emissionen von kurzlebigen Treibhausgasen, die Beseitigung von Kohlendioxid aus der Luft, die Modifizierung der Sonneneinstrahlung und die Veränderung des lokalen Wetters.

2. Der Bericht befasst sich nicht mit den konventionellen Klimaschutzmassnahmen, d.h. mit Massnahmen zur Verlangsamung oder zum Stoppen des Anstiegs der Treibhausgaskonzentrationen in der Atmosphäre. Er umfasst auch nicht die Anpassung an den Klimawandel, d.h. Massnahmen zur Verringerung von Verlusten oder zur Nutzung von Chancen, die mit einem veränderten Klima verbunden sind.

3. In Wissenschaft und Politik besteht ein starker Konsens darüber, dass die in diesem Bericht beschriebenen Massnahmen kein Ersatz für konventionelle Klimaschutzmassnahmen sind und dass die Möglichkeit ihres Einsatzes die Notwendigkeit, die Emissionen von CO_2 und anderen Treibhausgasen so schnell wie möglich zu stoppen, in keiner Weise verringert. Im Grunde genommen beinhalten alle Modellierungsszenarien, die eine langfristige Stabilisierung der Temperatur deutlich unter 2°C über den vorindustriellen Werten erreichen, zusätzlich zu den ehrgeizigen konventionellen Klimaschutzmassnahmen auch einen umfassenden Einsatz der Kohlendioxidbeseitigung. Kein Szenario erreicht dieses Temperaturziel ohne ehrgeizige konventionelle Klimaschutzmassnahmen. Keines der weit verbreiteten Modellierungsszenarien beinhaltet den Einsatz von Massnahmen zur Modifizierung der Sonneneinstrahlung, da die Risiken und Unsicherheiten, die mit dem Einsatz verbunden sind, zu gross scheinen.

Verringerung der Emissionen von kurzlebigen Treibhausgasen

1. Während CO_2 eine Residenzzeit in der Atmosphäre von vielen Jahrhunderten hat, haben viele Treibhausgase eine viel kürzere Residenzzeit und werden daher als kurzlebige Treibhausgase (Englisch: *short-lived climate forcers*, SLCFs) bezeichnet. Das bedeutet, dass die atmosphärischen Konzentrationen von SLCFs schnell auf die Emissionsrate reagieren und dass eine Verringerung der Emissionen zu einem kurzfristigen Kühleffekt führen würde.

2. Der wichtigste der SLCFs ist Methan (CH_4), das sowohl aus der Produktion fossiler Brennstoffe als auch aus der Landwirtschaft stammt. Die sofortige Beseitigung aller Methanemissionen würde in den nächsten zehn Jahren zu einer globalen Abkühlung von etwa 0,6°C führen.

3. Fossile Methanemissionen stammen hauptsächlich aus der Öl- und Gasindustrie. Man schätzt, dass 3,7% des in Nordamerika geförderten Erdgases entweicht und zu flüchtigen Emissionen wird. Die meisten flüchtigen Emissionen, die mit der Schweiz in Verbindung gebracht werden, stammen aus Gaslecks, die den Gasimporten in die Schweiz vorgelagert sind.

4. Die zweite Hauptquelle für Methanemissionen ist die Landwirtschaft, wobei zwei Drittel der landwirtschaftlichen Methanemissionen mit der enterischen Fermentation − fast ausschliesslich bei Rindern − in Verbindung gebracht werden und der Rest hauptsächlich aus dem Reisanbau stammt. Neben einer Änderung der Ernährungsgewohnheiten gibt es eine Reihe von technischen Optionen, die zur Verfügung stehen könnten, und eine, die bereits verfügbar ist, um diese Emissionen deutlich zu reduzieren. Es handelt sich dabei um einen Futterzusatz, der 2022 in Europa (einschliesslich der Schweiz) zugelassen wurde. Ausführliche Feldversuche deuten darauf hin, dass er keine nachteiligen Auswirkungen auf die Gesundheit der Rinder, das Fleisch oder die Milchproduktion hat, die Methanbildung während der enterischen Fermentation um 30 % reduziert und zusätzliche Kosten in Höhe von CHF 0,01 pro Liter Milchproduktion verursacht.

5. Die zweite grosse Gruppe von SLCFs resultiert aus der Verbrennung von Kohlenwasserstoff in der Höhe der kommerziellen Luftfahrt und ist in erster Linie auf die Bildung von langlebigen Kondensstreifen aus den Abgasen von Düsentriebwerken zurückzuführen. Eine sofortige Beseitigung dieser Effekte würde innerhalb weniger Tage zu einer globalen Abkühlung von etwa 0,03°C führen. Sie könnten mit elektrischen Antriebssystemen beseitigt werden, wobei diese − abgesehen von sehr kurzen Flügen − wahrscheinlich nicht vor 2050 kommerziell nutzbar sein werden. Jüngste Forschungsergebnisse deuten darauf hin, dass sie durch Änderungen der Flugroute − vor allem durch Anpassungen der Flughöhe, um Regionen mit übersättigter Luft zu vermeiden − um bis zu 90% reduziert werden könnten. Eine Umstellung auf Wasserstoffantriebe würde sie ebenfalls reduzieren, auch wenn der volle Effekt noch nicht bekannt ist. Die Substitution synthetischer Flugkraftstoffe würde ebenfalls zu einer Reduzierung der SCLFs führen, möglicherweise um 50%. Schweizer Unternehmen könnten finanziell von der breiten Einführung synthetischer Flugkraftstoffe profitieren.

6. Es gibt neue Hinweise darauf, dass Wasserstoff indirekt als SLCF wirkt, indem er die Residenzzeit von Methan in der Atmosphäre verlängert. Es sind zwar noch weitere Forschungen erforderlich, aber es ist möglich, dass die flüchtigen Emissionen aus der Produktion, dem Transport und der Lagerung von Wasserstoff einen so starken Erwärmungseffekt haben, dass die Vorteile einer Umstellung von fossilen Brennstoffen auf Wasserstoff als Energieträger zunichte gemacht werden.

Kohlendioxid-Entfernung aus der Atmosphäre

1. Es gibt eine Reihe von Negativen Emissionstechnologien (NETs), mit denen Kohlendioxid aus der Atmosphäre entfernt werden kann, was zu einer Verringerung der CO_2-Konzentration in der Atmosphäre führt. Emissionsszenarien, die mit der Begrenzung des globalen durchschnittlichen Temperaturanstiegs auf 1,5°C vereinbar sind und von ehrgeizigen, aber dennoch realistischen Emissionssenkungen bis Mitte des Jahrhunderts ausgehen, deuten auf einen wahrscheinlichen Bedarf an NETs in der Grössenordnung von 15 $GtCO_2$ pro Jahr hin.

2. Diese können unterteilt werden in solche, die die biologische CO_2-Aufnahme nutzen, und solche, die anorganische Prozesse beinhalten. Die primären biologischen Methoden, die für die Schweiz relevant sind, umfassen Aufforstung und verbesserte Waldbewirtschaftung, Bioenergieerzeugung in Kombination mit Kohlenstoffabscheidung und -speicherung (Englisch: *Bioenergy with carbon capture and storage*, BECCS) sowie die Anreicherung des Bodenkohlenstoffs durch die Herstellung und Vergrabung von Holzkohle (Biochar). Die wichtigsten anorganischen Prozesse sind

die beschleunigte Verwitterung von Zement und Basaltgestein sowie die direkte Abscheidung und Speicherung von Kohlenstoff aus der Luft (Englisch: *Direct air carbon capture and storage*, DACCS).

3. Die kostengünstigeren NETs sind Aufforstung und verbesserte Waldbewirtschaftung sowie BECCS. Allerdings kann die gleiche angebaute Biomasse nicht sowohl zum Kohlenstoffbestand im Wald als auch zur Energieerzeugung beitragen. Bewertungen für die Schweiz deuten darauf hin, dass BECCS zwar als Verbesserung der konventionellen Bioabfallbewirtschaftung sinnvoll sein kann, dass aber in anderen Fällen die Aufforstung in der Regel eine effektivere Flächennutzung darstellt als BECCS, da sie eine hohe CO_2-Bindungsrate erzielt und gleichzeitig anderen Umweltschutzzielen wie dem Schutz der biologischen Vielfalt dient. Schätzungen zufolge könnten weltweit bis zu 1,5 $GtCO_2$ pro Jahr durch Aufforstung zu Kosten von weniger als USD 100 pro tCO_2 entfernt werden, wobei ein nennenswerter Teil davon zu Kosten nahe Null erreicht werden könnte. Das Potenzial für den Einsatz von BECCS liegt bei Kosten unter USD 100 pro tCO_2 ebenfalls bei etwa 1,5 GtCO2 pro Jahr. In der Schweiz deuten die Daten bis 2015 darauf hin, dass die Aufforstung 1,6 $MtCO_2$ pro Jahr gebunden hat. Eine zusätzliche Lagerungsmöglichkeit von 3 $MtCO_2$ pro Jahr könnte in der Schweiz durch die Einführung von Kohlenstoffabscheidung und -speicherung (Englisch: *carbon capture and storage*, CCS) in Verbindung mit bestehenden Müllverbrennungsanlagen erfolgen und somit die CO_2-Aufnahme durch den Wald nicht beeinträchtigen.

4. Eine relativ neu erforschte NET ist die beschleunigte Verwitterung, bei der versucht wird, den natürlichen Prozess zu beschleunigen, durch den atmosphärisches CO_2 mit Böden und Gestein reagiert. Eine dieser Möglichkeiten ist die Ausbringung von Staub aus zerkleinertem Vulkangestein auf landwirtschaftliche Böden. Sie hat ein geschätztes globales Potenzial von mehreren $GtCO_2$ jährlich. Es bestehen grosse Unsicherheiten hinsichtlich der Kosten und Risiken.

5. Die NET mit dem höchsten theoretischen Potenzial ist DACCS. DACCS ist noch nicht vollkommen ausgereift und seine Kosten liegen bei über USD 500 pro tCO_2, wobei die Industrieteilnehmer mit sinkenden Kosten rechnen, möglicherweise bis auf USD 100 pro tCO_2. Bei solch niedrigen DACCS-Kosten wäre das Hauptkostenelement von DACCS-Anlagen die neue erneuerbare Energie, die für den Antrieb der chemischen Prozesse benötigt wird. Aus diesem Grund wird der Einsatz von DACCS in Weltregionen mit hochwertigen Solar-, Wind- und Erdwärme-Ressourcen als am vielversprechendsten angesehen und ist für Länder wie die Schweiz, die über diese Ressourcen nicht verfügen, weniger geeignet.

6. Sowohl BECCS als auch DACCS basieren auf der unterirdischen Speicherung von CO_2. Die am ausführlichsten getesteten Standorte dafür sind erschöpfte Öl- und Gasquellen, bei denen die jahrzehntelange Überwachung darauf hindeutet, dass es nur wenige bis gar keine Lecks gibt. Ein solcher Standort, das Sleipnir-Gasfeld unter der Nordsee, hat Schätzungen zufolge das Potenzial, 600 $GtCO_2$ zu speichern, was wahrscheinlich den weltweiten CO_2-Speicherbedarf übersteigt. Eine andere Art von Lagerstätten nutzt vulkanische Böden, die das eingeleitete CO_2 innerhalb weniger Monate mineralisieren und somit eine bekannte Beständigkeit aufweisen. Schätzungen zufolge könnten an solchen Standorten in Island und entlang ozeanischer Bergrücken insgesamt 100'000–250'000 $GtCO_2$ mineralisiert werden, was den prognostizierten Bedarf um Grössenordnungen übersteigt. Das Gesamtpotenzial für die unterirdische Speicherung ist also kein Problem, wohl aber ihr Standort. In der Schweiz gibt es keine Standorte, die für

eine dauerhafte Speicherung getestet wurden, und die Erschliessung solcher Standorte würde wahrscheinlich Jahrzehnte dauern, wenn sie überhaupt machbar wäre. Dies ist ein wirtschaftlicher Grund dafür, BECCS oder DACCS nicht in grossem Umfang in der Schweiz zu betreiben, sondern an Orten, an denen erneuerbare Energiequellen weniger eingeschränkt sind und die zudem näher an unterirdischen Speicherstätten liegen.

7. Um das globale Niveau der NETs zu erreichen, das zur Begrenzung des Temperaturanstiegs auf 1,5°C erforderlich ist, würden mehrere NETs benötigt, da die kostengünstigeren Optionen in ihrer Skalierbarkeit begrenzt sind. Dies würde mit ziemlicher Sicherheit dazu führen, dass DACCS benötigt wird. Die Kosten für solche Mengen von DACCS, einschliesslich der für den Betrieb erforderlichen erneuerbaren Energiequellen, würden sich in der Grössenordnung einer Billion USD jährlich bewegen, was etwa 1 % des globalen BIP entspricht. Der Nutzen, der sich aus einem solchen Einsatz ergibt, in Form von verringerten Schäden im Zusammenhang mit dem Klimawandel, ist Schätzungen zufolge weitaus grösser und übersteigt 3 % des globalen BIP bis zum Jahr 2100.

Modifizierung der Sonneneinstrahlung

1. Eine Verringerung der von der Erde absorbierten Sonnenstrahlung um 1-2 % würde den Strahlungsantrieb aufgrund einer Verdoppelung der atmosphärischen CO_2-Konzentration ausgleichen. Dies hat mehrere Vorschläge und Ansätze zum Geoengineering motiviert, obwohl die Reduzierung global und zumindest über mehrere Jahrzehnte hinweg erfolgen müsste. Darüber hinaus wirkt die Modifizierung der Sonneneinstrahlung (Englisch: *solar radiation modification*, SRM) nicht den nicht-strahlungsbedingten Problemen entgegen, die mit der Anwesenheit hoher CO_2-Konzentrationen verbunden sind, wie z.B. der Versauerung der Ozeane.

2. SRM-Massnahmen verteilen sich hauptsächlich auf 3 Kategorien: (1) Injektion von stratosphärischen Aerosolen (Englisch: *stratospheric aerosol injection*: SAI), (2) Aufhellung von Meereswolken (Englisch: *marine cloud brightening*, MCB) und (3) Veränderung der Oberflächenalbedo (Englisch: *surface albedo modification*, SAM). Es wurden auch einige zusätzliche Ansätze vorgeschlagen, die jedoch weniger erforscht sind, wie z.B. die Platzierung grosser Spiegel im Weltraum oder die Ausdünnung von Zirruswolken, um ihren Wärmeeinfangseffekt zu verringern.

3. SAI wurde ursprünglich vorgeschlagen, um Vulkanausbrüche wie den des Mount Pinatubo im Jahr 1991 zu imitieren. Dieser Ausbruch verursachte eine globale Abkühlung von ~ -0,5°C über ~ 2 Jahre, indem SO_2 in der Grössenordnung von 14-26 Tg und Aerosolpartikel in die Stratosphäre injiziert wurden. Dieses natürliche Experiment diente als Hintergrund für die Entwicklung von Modellen für absichtliche SAI. Die meisten Modelle zeigen, dass der mit der Verdoppelung der CO_2-Konzentration verbundene Treibhauseffekt (~ 4 W/m^2) durch die jährliche Injektion von etwa 10 Tg SO_2 in die Stratosphäre kompensiert werden könnte, was mit Kosten von USD 10 Mrd. pro Jahr verbunden wäre. SO_2 wird zwar auch mit Umweltschäden und negativen Auswirkungen auf die Gesundheit in Verbindung gebracht, aber die anvisierten 10 Tg sind viel geringer als die jährlichen SO_2-Emissionen in der Troposphäre, die in den 1980er Jahren etwa 150 Tg und heute etwa 100 Tg betrugen. Teilweise aufgrund dieser Bedenken, aber auch wegen der unterschiedlichen optischen Eigenschaften, haben sich die jüngsten Studien auf andere Aersole konzentriert.

4. SAI könnte schnell umgesetzt werden, müsste aber ständig angewendet werden, um einen konstanten Kühleffekt zu erzielen. Sie ist mit hohen Risiken und Unsicherheiten verbunden, da sie Auswirkungen auf den Abbau der Ozonschicht in der Stratosphäre und auf den Wasserkreislauf, z.B. die Monsunregen, hat. Sie scheint daher ungeeignet, um die Erwärmung durch CO_2 langfristig zu kompensieren. Einige haben sie als vorübergehende Notfallmassnahme vorgeschlagen, um den Erwärmungsspitzenwert zu begrenzen, und zwar zu dem Zeitpunkt, an dem die Netto-Null-Emissionen erreicht sind, bis die NETs Zeit haben, die atmosphärischen CO_2-Konzentrationen ausreichend zu reduzieren.

5. MCB zielt darauf ab, in der Troposphäre Wolken zu erzeugen, die die Sonnenstrahlung reflektieren. Das Ansäen der Atmosphäre mit zusätzlichen Kondensationskernen kann die Wolkenalbedo erhöhen, wenn geeignete Kondensationsbedingungen gegeben sind. Die damit verbundene Lebensdauer ist in der Troposphäre sehr kurz und liegt in der Grössenordnung von Tagen, was die Risiken erheblich reduziert, aber auch ein permanentes und grossflächiges Ansäen benötigt (das in der Regel mit Meersalz-Aerosolen durchgeführt wird). Simulationen gehen davon aus, dass Emissionsraten in der Grössenordnung von 106 Partikeln $s^{-1}m^{-2}$ auf einer Fläche von 77'000 km^2 benötigt würden, um eine Verdoppelung des atmosphärischen CO_2 auszugleichen. Die mit einem solchen Eingriff verbundenen Kosten würden sich auf etwa USD 5-10 Milliarden pro Jahr belaufen, und die Effizienz des Prozesses hängt stark von den atmosphärischen Bedingungen ab. MCB ist daher wahrscheinlich keine Lösung zur Kompensation der globalen Erwärmung, kann aber eine mögliche Anpassungsmassnahme in einem lokalen/regionalen Kontext sein, wie die Rettung von Korallenriffen. Es wurden bisher nur sehr wenige Studien über Süsswasser wie Seen durchgeführt, so dass weitere wissenschaftliche Studien benötigt würden, falls sie in der Schweiz in Betracht gezogen würden.

6. SAM besteht darin, Dächer und andere Infrastrukturen weiss zu streichen und die landwirtschaftliche Praxis zu ändern, um die Albedo der Pflanzen zu erhöhen. Während die globale Abkühlung durch solche Massnahmen selbst bei massiver Umsetzung vernachlässigbar wäre (z.B. -0,002°C bei weissem Anstrich), ist der lokale Einsatz als Anpassungsmassnahme interessant, auch in der Schweiz. SAM kann die Temperaturen innerhalb von Gebäuden und die Hitzeinsel während sommerlicher Hitzewellen nennenswert reduzieren und so das Wohlbefinden und die Gesundheit der Menschen verbessern. Sie kann auch die Temperatur senken (~ -2°C) und Dürreperioden bei Landkulturen besser bewältigen. Die Erhöhung der Albedo in Städten sollte jedoch auch im Winter geprüft werden, bevor sie umgesetzt wird, um einen Anstieg der Heizkosten zu vermeiden.

Extreme Wetterereignisse und Wettermodifikation

1. Als Folge der Zunahme extremer Wetterereignisse wird Wettermodifikation zunehmend eingesetzt, um die lokalen Auswirkungen und Kosten der globalen Erwärmung zu bewältigen. Die meisten Bemühungen gelten der Verstärkung von Regen- und Schneefällen, um Trockenheit und Schneeschmelze entgegenzuwirken, die die Landwirtschaft und den Tourismus beeinträchtigen. Die Methode der Wahl ist das Cloud Seeding mit chemischen Wirkstoffen. Andere Wettermodifikations-Massnahmen

betreffen Hagel, Nebel/Smog und Blitzschlag, die allein in den USA Schäden in Höhe von mehr als USD 10 Mrd. pro Jahr verursachen.

2. Das Cloud Seeding wurde in letzter Zeit mit grossen nationalen Programmen wiederbelebt. In China hat die Wettermodifikationsbehörde nach eigenen Angaben mehr als eine halbe Million wetterverändernde Massnahmen durchgeführt und dabei bis zu 500 Milliarden Tonnen Regen geerntet. Das chinesische Programm deckt inzwischen eine Fläche ab, die der Grösse Indiens entspricht. In den USA wurden 922 Cloud Seeding-Projekte zur Verstärkung von Regen und Schnee registriert. Die Verbesserung der Niederschlagsmenge wird nun einzelnen Kunden (Landwirten, Regionen, Skigebieten usw.) zu einem Preis von nur USD 3,50 pro Acre-Foot (oder USD 0,003 pro Tonne) angeboten. Obwohl die Effizienz von Cloud Seeding nur schwer zu quantifizieren ist, konnten jüngste wissenschaftliche Kampagnen quantitative Messungen durchführen und die Kausalität nachweisen. Die meisten der berichteten Ergebnisse konvergieren auf einen typischen Wert von 10-15 % Niederschlagszunahme. Es werden jedoch weitere Studien zur statistischen Bestätigung und zur Optimierung des Prozesses benötigt. Es besteht ein sozioökonomisches Interesse (Tourismus, Landwirtschaft), diese Technologien auch in der Schweiz zu erforschen.

3. Wettermodifikation zum Schutz vor Hagel, Nebel und Blitzschlag beruhen ebenfalls sehr stark auf Cloud Seeding, entweder mit chemischen Substanzen oder gefrorenem CO_2. Die Unterschiede liegen in den atmosphärischen Bedingungen selbst (Gewitterwolken, Bodennebel aufgrund von Temperaturgradienten usw.). Hauptziele sind die Verringerung von Blitzschäden an grossen Infrastrukturen, die Verbesserung der Sicht auf Landebahnen von Flughäfen, die Verbesserung der optischen Freiraumkommunikation, die Verringerung der Auswirkungen von Luftverschmutzung auf die menschliche Gesundheit und die Verringerung der Ernteschäden.

4. Es gibt neue Technologien zur Verbesserung der Effizienz und zur Verringerung der mit dem Cloud Seeding verbundenen Risiken. Unter ihnen sind Ioneninjektion und Lasertechnologien vielversprechend, benötigen aber weitere wissenschaftliche Studien, um genau bewertet zu werden.

Bedarf an internationalem Governance

1. Zwei Faktoren machen die internationale Zusammenarbeit bei allen in diesem Bericht beschriebenen Methoden notwendig. Der erste Faktor ist der relative Mangel an Wirksamkeit von Massnahmen, die nur auf der Ebene eines einzelnen Landes, wie der Schweiz, durchgeführt werden. Dies gilt insbesondere für Massnahmen zur Verringerung der SLCF-Emissionen und für CDR. Um einen bedeutenden Unterschied zu machen, müssten diese Massnahmen von einer grossen Anzahl von Ländern durchgeführt werden. Der zweite sind die Auswirkungen der Massnahmen eines Landes auf andere Länder. Dies gilt insbesondere für SRM, mit Ausnahme der Bemühungen, lokalen Wärmeinseleffekten durch Veränderung der Oberflächenalbedo entgegenzuwirken. Dies kann auch bei lokalen Bemühungen zur Veränderung des Wetters der Fall sein, die zu regionalen Veränderungen des Wetters führen können, die sich auf andere Länder auswirken.

2. Derzeit gibt es nur wenige Governance-Rahmen, die sich speziell mit einer dieser Massnahmen befassen. Viele − aber nicht alle − SLCFs sind implizit im Pariser Abkommen abgedeckt. Sie werden mit CO_2-Emissionen unter Verwendung der

GWP100-Umrechnungsmetrik gleichgesetzt, die für die Abdeckung kurzfristiger Effekte ungeeignet sein könnten. CDR ist im Pariser Abkommen insofern abgedeckt, als dass der Abbau von Emissionen ausgeglichen werden kann, was Ländern hilft, ihre Emissionsreduktionsziele zu erreichen. Es gibt jedoch keinen Rahmen für die Zuweisung der Verantwortung für die Durchführung von CDR, um negative Nettoemissionen zu erreichen. In Bezug auf SRM gibt es keine umfassenden Rahmenregelungen, die sich direkt mit diesem Thema befassen. Ebenso gibt es keine regionalen Vereinbarungen über die Veränderung des Wetters. Die Entwicklung von Governance-Rahmenwerken wäre ein Schlüsselelement, bevor eine der in diesem Bericht aufgeführten Massnahmen ergriffen wird.

3. Ein weiterer Bereich für die internationale Zusammenarbeit ist die wissenschaftliche Forschung. Alle in diesem Bericht beschriebenen Methoden benötigen zusätzliche Forschung, wenn sie effektiv und in grossem Massstab angewandt werden sollen. Es gibt Forderungen nach internationalen Forschungsprogrammen zu diesen Methoden. Im Fall von SAI ist es auch klar, dass es ein internationales Abkommen geben muss, das alle Forschungsarbeiten abdeckt, die auf Freilufttests beruhen, da diese einen teilweisen Einsatz der Technologie darstellen.

Résumé executive

1. Ce rapport présente un aperçu des méthodes permettant de refroidir la planète ou de réduire l'impact de phénomènes météorologiques extrêmes, à court et à moyen terme. Ces interventions pourraient contribuer à un retour du climat (ou certains de ses aspects comme la température moyenne) à un état qui existait dans le passé, en supplément de mesures efficaces de réduction des émissions de CO_2. Les quatre méthodes présentées comprennent la réduction rapide des émissions provocant un forçage climatique à court terme, l'élimination du dioxyde de carbone, la modification du rayonnement solaire et la modération de conditions météorologiques extrêmes.

2. Ce rapport ne couvre pas la mitigation conventionnelle, qui comprend les actions pour ralentir ou stopper l'accumulation de gaz à effet de serre dans l'atmosphère. Il ne couvre pas non plus les méthodes d'adaptation, comme la réduction des couts ou de nouvelles opportunités associées aux changements climatiques.

3. Un consensus existe aujourd'hui dans les communautés scientifique et réglementaire concernant les mesures décrites dans ce rapport : ces mesures non-conventionnelles ne constituent pas une alternative à la mitigation conventionnelle engagée. Un possible déploiement ne réduit en aucun cas la nécessité de stopper les émissions de CO_2 et des autres gaz à effet de serre, aussi vite que possible. Tous les scénarios considérés dans les modèles visant à une stabilisation de la température à long terme en dessous de 2°C d'accroissement incluent un déploiement de mesures d'élimination du CO_2 déjà présent dans l'air, en complément des mesures de mitigation conventionnelles. Aucun scénario ne permet d'atteindre cet objectif sans mitigation conventionnelle. Aucun scénario envisagé dans les modèles ne considère la modification du rayonnement solaire, à cause des risques et des incertitudes qui lui sont associés.

Réduction des émissions de gaz à effet de serre à courte durée de vie

1. Le CO_2 a un temps de résidence dans l'atmosphère de plusieurs siècles, mais de nombreux gaz à effet de serre ont des temps de résidence beaucoup plus courts, connus sous le nom de forçages climatiques à courte durée de vie (en anglais : Short-Lived Climate Forcers, ou SLCF). Les concentrations atmosphériques de ces gaz suivent rapidement l'évolution de leur taux d'émission, de sorte qu'une réduction de leurs émissions entraînerait un refroidissement rapide de l'atmosphère.

2. Le plus important des SLCF est le méthane, qui provient à la fois de la production de combustibles fossiles et du secteur agricole. L'élimination immédiate de toutes les émissions de méthane entraînerait un refroidissement global d'environ 0,6°C au cours de la prochaine décennie.

3. Les émissions fugitives de méthane proviennent principalement des industries pétrolière et gazière. On estime que 3,7 % du gaz naturel produit en Amérique du Nord est perdu sous forme de fuites. La plupart des émissions fugitives liées à la Suisse provient de fuites de gaz en amont des importations de gaz en Suisse.

4. La deuxième source principale d'émission de méthane est l'agriculture. Les deux tiers des émissions de méthane agricoles sont associés à la fermentation entérique - presque exclusivement chez les bovins - et le reste provient principalement de la culture du riz. En complément à une modification des habitudes alimentaires, il existe plusieurs options

techniques accessibles. Une de ces options consiste en l'utilisation d'additifs alimentaires pour le bétail, approuvé en Europe (y compris la Suisse) en 2022. De nombreux essais en milieu réel suggèrent qu'il n'existe aucun effet secondaire négatif sur la santé du bétail, la viande bovine et la production de lait. L'utilisation de cet additif pourrait réduire de 30% la fermentation entérique, pour un coût équivalent supplémentaire de CHF 0,01 par litre de lait produit.

5. Une autre source de SLCF identifiée provient du trafic aérien, et plus particulièrement de la formation de traînées de condensation provenant des gaz d'échappement des moteurs à réaction. L'éliminations de ces traînées de condensation pourrait permettre un refoidissement global de 0.03 °C dans l'espace de quelques jours. Ces émissions pourraient, en principe, être éliminées grâce à des systèmes de propulsion électrique, bien qu'il semble peu probable que ceux-ci soient commercialement viables avant 2050. Des études récentes suggèrent qu'il serait également possible de réduire considérablement ces nuages de condensation - jusqu'à 90 % - en modifiant les itinéraires de vol, principalement en ajustant l'altitude des couloirs de vol pour éviter les régions où l'air est sursaturé. Le passage à des systèmes de propulsion à l'hydrogène permettrait également de réduire ces émissions, bien que certaines incertitudes subsistent sur les impacts de l'utilisation de l'hydrogène. Le remplacement des carburants classiques par des carburants synthétiques pour l'aviation entraînerait également une réduction des SLCF, potentiellement de 50 %. Certaines entreprises suisses, actives dans le domaine, pourraient également bénéficier économiquement de l'adoption généralisée des carburants synthétiques pour l'aviation.

6. Il existe des preuves récentes que l'hydrogène agit indirectement comme un SLCF, en allongeant le temps de résidence du méthane dans l'atmosphère. Bien que des recherches supplémentaires soient nécessaires, il ressort que les émissions fugitives provenant de la production, du transport et du stockage de l'hydrogène vert aient un effet de réchauffement suffisamment important pour annuler les avantages du passage des combustibles fossiles à l'hydrogène vert en tant que vecteur d'énergie.

Extraction du dioxyde de carbone présent dans l'air

1. Il existe un certain nombre de technologies d'émissions négatives (Negative Emission Technologies, NET) qui permettraient de réduire les concentrations de dioxyde de carbone présentes dans l'atmosphère (en anglais : Carbon Dioxide Removal, CDR). Les scénarios visant à limiter l'augmentation de la température moyenne mondiale à 1,5 °C, incluant des baisses significatives mais réalistes des émissions d'ici le milieu du siècle, suggèrent le besoin probable d'un déploiement de NET de l'ordre de 15 $GtCO_2$ par an.

2. Ces technologies peuvent être divisées en deux catégories : celles qui font appel à l'absorption biologique du CO_2 et celles qui impliquent des processus inorganiques. Les principales méthodes biologiques pertinentes pour la Suisse concernent le boisement et l'amélioration de la gestion des forêts, la production de bioénergie combinée au piégeage et au stockage du carbone (en anglais : BioEnergy production combined with Carbon Capture and Storage, BECCS) et l'augmentation de la concentration de carbone dans le sol par la production et l'enfouissement de charbon de bois (biochar). Les principaux procédés inorganiques sont l'altération accélérée du ciment et des pierres basaltiques, et le captage et le stockage du carbone dans l'air (en anglais : Direct Air Carbon Capture and Storage, DACCS).

3. Les technologies NET les moins coûteuses sont le boisement et l'amélioration de la gestion des forêts, de même que les BECCS. Il faudra cependant faire des compromis entre eux, car la même biomasse cultivée ne peut pas contribuer à la fois au stock de carbone dans la forêt et à la production d'énergie. Les évaluations pour la Suisse suggèrent que si les BECCS peuvent être considérées comme une amélioration de la gestion conventionnelle des biodéchets, le boisement est généralement une utilisation plus efficace des terres que les BECCS. En effet, le boisement permet d'atteindre un taux élevé d'élimination du CO_2 , tout en répondant à d'autres objectifs de protection de l'environnement, tels que la protection de la biodiversité. Au niveau mondial, on estime que le boisement pourrait permettre d'éliminer jusqu'à 1,5 $GtCO_2$ par an à des coûts inférieurs à 100 dollars par tCO_2, et même qu'une part importante pourrait être obtenue à des coûts proches de zéro. Le potentiel de déploiement des BECCS, à des coûts inférieurs à USD 100 par tCO_2, est également d'environ 1,5 $GtCO_2$ par an. En Suisse, les données jusqu'à 2015 suggèrent que le boisement séquestre déjà le CO_2 à raison de 1,6 $MtCO_2$ par an. Une séquestration supplémentaire de 3 $MtCO_2$ par an pourrait avoir lieu en Suisse, grâce au déploiement de méthodes de captage et stockage du carbone (CSC) associées aux installations d'incinération des déchets existantes, et n'affectant donc pas l'absorption du CO_2 par les forêts.

4. Une méthode CDR développée récemment est l'érosion accélérée (weathering), dont l'objectif est d'accélérer les processus d'interaction du CO_2 atmosphérique avec les sols et les roches. Une possibilité est de disperser de la poussière de roche volcanique sur des sols cultivés. Ce procédé présente un potentiel global de capture de plusieurs $GtCO_2$ par an, mais des incertitudes persistent sur les couts et les risques associés.

5. Le NET présentant le potentiel théorique le plus élevé est le DACCS, bien que le DACCS n'ait pas encore atteint le niveau de maturité technologique suffisant pour être commercialement viable. Ses coûts dépassent en effet les 500 dollars par tCO_2, mais les acteurs industriels de la technologie prévoient une baisse de ces coûts, qui pourraient atteindre 100 dollars par tCO_2. Avec une telle réduction de coûts, le point critique principal des installations DACCS serait l'investissement dans l'énergie renouvelable nécessaire pour faire fonctionner l'installation. C'est pourquoi le déploiement du DACCS est considéré comme le plus prometteur dans les régions du monde dotées de ressources solaires, éoliennes et géothermiques de grande qualité, et moins approprié pour des pays tels que la Suisse, qui ne disposent pas de ces ressources.

6. Les systèmes BECCS et DACCS reposent tous deux sur le stockage souterrain du CO_2 . Les sites les plus testés sont les puits de pétrole et de gaz épuisés, pour lesquels plusieurs décennies de surveillance indiquent l'absence de fuites. L'un de ces sites, le champ gazier de Sleipnir, situé sous la mer du Nord, a été estimé capable de stocker 600 $GtCO_2$, ce qui dépasse probablement les besoins mondiaux en matière de stockage de CO_2 . Un autre type de site utilise des sols volcaniques, qui minéralisent le CO_2 injecté en l'espace de quelques mois et offrent une permanence reconnue. On estime que ces sites en Islande et le long des dorsales océaniques pourraient minéraliser entre 100 000 et 250 000 $GtCO_2$ au total, ce qui dépasserait les besoins prévus de plusieurs ordres de grandeur. Le potentiel de stockage souterrain n'est donc pas un problème, mais l'emplacement de sites adaptés peut en être un. La Suisse ne dispose d'aucun site testé pour le stockage permanent, et le développement de tels sites prendrait des décennies, s'ils étaient déclarés viables.

7. Pour atteindre les niveaux mondiaux de CDR requis pour limiter l'augmentation de la température à 1,5°C, il faudrait plusieurs NET, car les options les moins coûteuses sont limitées en termes d'expansion. Il est presque certain que cela rendrait nécessaire l'introduction de systèmes DACCS. Les coûts de construction et d'exploitation des DACCS à une telle échelle, incluant les sources d'énergie renouvelables nécessaires à son fonctionnement, seraient de l'ordre du milliard de milliards (trillions) de dollars par an, ce qui correspond à environ 1 % du PIB mondial. De plus, les bénéfices d'un tel déploiement, en termes de la réduction des dommages associés aux changement globaux, ont été estimés à plus de 3% du PIB mondial en 2100.

Modification du rayonnement solaire (SRM)

1. Une réduction du rayonnement solaire absorbé par la Terre de 1 à 2 % suffirait à contrebalancer le forçage radiatif dû à un doublement de la concentration atmosphérique de CO_2 . Cette constatation a motivé plusieurs propositions et approches de géo-ingénierie, bien que cette réduction doive être appliquée à l'échelle mondiale et pour plusieurs décennies. En outre, la modification du rayonnement solaire (SRM) ne permet pas de contrer les problèmes non radiatifs associés à la présence de fortes concentrations de CO_2 , comme l'acidification des océans.

2. Les mesures SRM se déclinent en trois catégories : (1) l'injection d'aérosols stratosphériques (SAI), (2) l'éclaircissement des nuages marins (MCB) et (3) la modification de l'albédo en surface (SAM). D'autres approches ont également été proposées, mais moins étudiées, comme la mise en place de grands miroirs réfléchissants dans l'espace ou l'amincissement optique des cirrus pour réduire leur effet de piégeage de la chaleur.

3. L'injection d'aérosols stratosphériques a été initialement proposée pour imiter les éruptions volcaniques, comme celle du Mont Pinatubo en 1991. Cette éruption a entraîné un refroidissement global d'environ -0,5°C sur environ 2 ans en injectant du SO_2 et des poussières volcaniques dans la stratosphère. Cette expérience naturelle a servi de base au développement de modèles pour des éventuelles interventions intentionnelles. La plupart des modèles montrent qu'un forçage (~ 4 W/m^2) associé au doublement de la concentration de CO_2 pourrait être compensé par l'injection annuelle de l'ordre de 10 Tg de SO_2 dans la stratosphère à un coût de l'ordre de ~ 10 milliards de dollars par an. Notons que SO_2 a été associé dans le passé à des dommages environnementaux importants sous forme de pollution troposphérique. Notons cependant que 10 Tg/an est sensiblement inférieur aux émissions troposphériques de SO_2, qui représentaient environ 150 Tg/an dans les années 80 et environ 100 Tg/an aujourd'hui. Partiellement à cause de ces inquiétudes et à cause de l'absorption optique des sulfates, les études récentes se concentrent sur d'autres aérosols.

4. SAI pourrait être implémenté rapidement mais nécessite un déploiement continu pour obtenir un refroidissement constant. Les SAI sont également associées à des risques et incertitudes élevées, en raison de leur incidence sur la déplétion de l'ozone stratosphérique et sur le cycle de l'eau, comme les moussons saisonnières. Cette méthode ne semble donc pas adaptée pour compenser le réchauffement dû au CO_2 d'une manière durable. Elle a été évoquée comme une mesure d'urgence transitoire pour compenser un éventuel emballement du système climatique ou pour limiter le pic de réchauffement pendant une période ou les émissions nettes de CO_2 ne seront pas encore nulles, et que

les NET ne seront pas encore assez déployées pour réduire les concentrations atmosphériques de CO_2.

5. L'éclaircissement des nuages marins (MCB) vise à produire des nuages réfléchissant le rayonnement solaire dans la troposphère. L'ensemencement de l'atmosphère par des noyaux de condensation supplémentaires peut augmenter l'albédo des nuages si les conditions de condensation adéquates sont réunies. La durée de vie de telles actions est très courte dans la troposphère, de l'ordre de quelques jours, ce qui réduit considérablement les risques, mais nécessite un ensemencement permanent et à grande échelle (généralement réalisé avec des aérosols de sel marin). Les simulations estiment que des taux d'émission de l'ordre de 10^6 particules s^{-1} m^{-2} sur une surface de 77 000 km^2 seraient nécessaires pour compenser un doublement du CO_2 atmosphérique. Le coût associé à une telle intervention s'élèverait à environ 5 à 10 milliards de dollars par an, et l'efficacité du processus dépendrait fortement des conditions atmosphériques. Le MCB n'est probablement pas la solution la mieux adaptée pour compenser le réchauffement climatique global à long terme, mais peut constituer une mesure d'adaptation possible dans un contexte local/régional, comme la sauvegarde des récifs coralliens. Très peu d'études ont été menées sur des eaux douces telles que les lacs, de sorte que des études scientifiques supplémentaires seraient nécessaires si ce type d'action était envisagée en Suisse.

6. La gestion de l'albédo en surface de la terre (SAM) consiste à peindre les toits et autres infrastructures en blanc et à modifier les pratiques agricoles (culture sans labour, substitution de plantes) pour augmenter l'albédo des cultures. Alors que le refroidissement global apporté par ces mesures, même mises en oeuvre massivement, resterait marginal (par exemple - 0,002 °C pour la peinture blanche), l'utilisation locale est intéressante en tant que mesure d'adaptation, y compris en Suisse. Les SAM peuvent réduire de manière significative les températures à l'intérieur des bâtiments et les îlots de chaleur pendant les vagues de chaleur estivales, améliorant ainsi le bien-être et la santé des habitants. Il permet aussi de réduire la température (~ -2°C) et mieux gérer les périodes de sécheresse dans les cultures agricoles. L'augmentation de l'albédo dans les villes devrait cependant être évaluée en hiver également avant d'être mise en oeuvre, afin d'éviter une augmentation des coûts de chauffage.

Événements météorologiques extrêmes et geo-ingénierie météorologique

1. En raison de l'augmentation des phénomènes météorologiques extrêmes, la géo-ingénierie météorologique est de plus en plus déployée pour faire face aux impacts et aux coûts dus au réchauffement climatique. La plupart des efforts est consacrée à la modification des précipitations (pluie et neige) pour contrer la sécheresse et la fonte des neiges, qui ont un impact sur l'agriculture et le tourisme. La méthode privilégiée est l'ensemencement des nuages à l'aide d'agents chimiques. D'autres actions de géo-ingénierie sont consacrées à la gestion de la grêle, du brouillard et de la foudre, qui entraînent des dommages de plus de 10 milliards de dollars par an rien qu'aux États-Unis.

2. L'ensemencement des nuages a été revitalisé récemment, avec de vastes programmes au niveau national. En Chine, le Bureau des modifications météorologiques (32 000 employés) a déclaré avoir mené plus d'un demi-million d'opérations de modifications météorologiques, récoltant jusqu'à 500 milliards de tonnes de pluie. Le programme chinois couvre désormais une superficie équivalente à celle de l'Inde. Aux États-Unis, 922 projets d'ensemencement de nuages ont été enregistrés par la National Oceanic and

Atmospheric Administration (NOAA), pour l'augmentation des précipitations de pluie et de neige. L'augmentation des précipitations est désormais proposée commercialement à des clients individuels (agriculteurs, régions, stations de ski, etc.) à un prix de l'ordre de USD 3,50 par acre-pied (soit USD 0,003 par tonne) d'eau récoltée. Bien que l'efficacité de l'ensemencement des nuages soit difficile à quantifier, des campagnes de mesure récentes ont permis de fournir des mesures quantitatives et de démontrer une causalité. La plupart des résultats publiés convergent vers une valeur typique de 10 à 15 % d'augmentation des précipitations. Toutefois, des études complémentaires seront nécessaires pour confirmer ces statistiques, optimiser le processus (conditions d'"ensemencement") et réduire les impacts négatifs associés, comme la pollution des sols par des composés d'argent. Il existe un intérêt socio-économique (tourisme, agriculture) pour ces technologies, en Suisse également, mais ces mesures nécessiteraient une évaluation précise des effets indésirables et un cadre réglementaire associé.

3. Les mesures de géo-ingénierie pour la protection contre la grêle, le brouillard et la foudre reposent principalement aussi sur l'ensemencement, soit avec des agents chimiques, soit avec de la neige carbonique. Les différences résident dans les conditions atmosphériques elles-mêmes (nuages d'orage, brouillard au sol dû aux gradients de température, etc.). Les principaux objectifs sont la réduction des dommages causés par la foudre aux grandes infrastructures, l'amélioration de la visibilité sur les pistes d'atterrissage des aéroports, les communications optiques dans l'espace libre, la réduction des effets du smog sur la santé humaine (notamment en Chine) et la réduction des dommages causés aux cultures par la grêle.

4. De nouvelles technologies émergentes apparaissent pour améliorer l'efficacité et réduire les risques liés à l'ensemencement des nuages. Parmi elles, l'injection d'ions et la technologie laser semblent prometteuses, mais nécessitent des études scientifiques supplémentaires pour être évaluées avec précision.

Principaux besoins en matière de gouvernance internationale

1. Deux facteurs expliquent la nécessité d'une coopération internationale pour toutes les méthodes décrites dans ce rapport. Le premier est le manque relatif d'efficacité des actions entreprises à l'échelle d'un seul pays, comme la Suisse. C'est particulièrement le cas pour les actions visant à réduire les émissions de SLCF, ainsi que pour la CDR. Pour faire une différence significative, ces actions devraient être entreprises par un grand nombre de pays. Le deuxième facteur est l'effet des mesures prises par un pays sur d'autres pays. C'est particulièrement le cas pour les SRM, à l'exception des efforts visant à contrer les effets d'îlots de chaleur locaux par la modification de l'albédo de surface. Cela peut également être le cas pour les efforts de modification des conditions météorologiques locales, qui peuvent induire des changements climatiques régionaux, affectant d'autres pays.

2. Il n'existe actuellement que peu de cadres de gouvernance portant spécifiquement sur l'une ou l'autre de ces mesures. De nombreux SLCF - mais pas tous - sont couverts implicitement par les accords de Paris, assimilés à des émissions de CO_2 à l'aide de la métrique de conversion GWP100, qui peut être inappropriée pour couvrir les effets à court terme. La réduction des émissions de carbone est couverte par l'accord de Paris, dans la mesure où les absorptions peuvent compenser les émissions, aidant ainsi les pays à atteindre leurs objectifs de réduction des émissions. Il n'existe toutefois pas de cadre permettant d'attribuer la responsabilité de la mise en oeuvre de la réduction des émissions

de gaz à effet de serre afin de parvenir à des émissions nettes négatives. En ce qui concerne le SRM, il n'existe aucun cadre de gouvernance traitant directement de cette question. De même, il n'existe pas d'accords régionaux portant sur la modification des conditions météorologiques. L'élaboration de cadres de gouvernance serait un élément clé de la poursuite de l'une des actions énumérées dans le présent rapport.

3. Un autre domaine de coopération internationale est celui de la recherche scientifique. Toutes les méthodes décrites dans le présent rapport nécessitent des recherches supplémentaires si l'on veut les appliquer efficacement et à grande échelle. Des appels ont été lancés en faveur de programmes de recherche internationaux sur ces méthodes. Dans le cas de SAI, il est également évident qu'un accord international devrait couvrir toute recherche reposant sur des essais en plein air, car cela représenterait un déploiement partiel de la technologie.

List of abbreviations and acronyms

3-NOP	3-nitrooxypropanol
AR6	Sixth Assessment Report
BECCS	Biomass carbon capture and storage
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CDR	Carbon dioxide removal
COP	Conference of the Parties
DAC	Direct CO_2 air capture
DACCS	Direct CO_2 air capture and storage
EOR	Enhanced oil recovery
FOLU	Forestry, agriculture, and land-use
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
MCB	Marine cloud brightening
NET	Negative emissions technology
SAF	Sustainable aviation fuel
SAI	Stratospheric aerosol injection
SLCF	Short-lived climate forcers
SMR	Steam methane reformation
SRM	Solar radiation modification
TA Swiss	Swiss Technology Assessment
TMR	Total mixed rations
UNFCCC	United Nations Framework Convention on Climate Change

Synthesis Table

In the case of options for reducing SLCFs, this table presents global potentials in terms of the maximum feasible cooling to be obtained if emissions of the SLCF were to cease. In the case of SRM, it presents the magnitude of intervention, in terms of W/m^2 and associated average cooling, that studies have explored. In the case of CDR, it suggests the maximum annual deployment that could be achieved. The magnitude of cooling to which this would lead would be contingent on the duration of the CDR intervention.

	Global Potential	Costs	Risks	Stage of development	Time frame	Key uncertainties	International cooperation
Eliminating fugitive methane emission	~ 0.36°C temperature reduction	Tied to substitutes for fossil fuels as energy source	No direct risks. Indirect risks associated with disruption of energy supply	Not clear how to implement absent the elimination of fossil fuels.	Constrained by pace of energy system transformation	Full extent of fugitive methane emissions uncertain	Not required
Eliminating methane from enteric fermentation	~ 0.24°C temperature reduction	For partial elimination with food additives, minor. Of other options, unclear.	No direct risks.	For feed additives, well developed. Laboratory meat substitutes at early development stage.	Feed additive deployment could begin immediately. Other options delayed	Societal acceptance of meat alternatives	Not required
Flight rerouting to eliminate cirrus cloud formation	~ 0.03°C temperature reduction	Unclear, likely negligible	Potential decrease in passenger comfort	Modelling studies suggesting potential from flight rerouting.	Requires additional research	Proportion of flights requiring rerouting	Essential
Substituting synthetic aviation fuels for fossil kerosine	~ 0.015°C temperature reduction	Current cost of synthetic fuels roughly five times that of fossil, could decline to less than two times.	Risks associated with scaling of biofuels production; no risk for non-biological production pathways	Synthetic fuels entering commercial production.	Constrained by pace of investment into synthetic fuels production.	Change in radiative forcing from fuel substitution uncertain	Essential

Table 1: Comparison of options (continued)

	Global Potential	**Costs**	**Risks**	**Stage of development**	**Time frame**	**Key uncertainties**	**International cooperation**
Land and forest-based CO_2 removal	Technical potential > 20 $GtCO_2$ / year, economic potential ~ 7 GtCO2 / year	Context specific, USD 0 − 400 per tCO_2	Competition with food production, nature conservation, and fresh water use	Mature technologies	Multiple decades to achieve 0.5°C cooling	Land and water availability	Likely required for CO_2 geological storage
Enhanced weathering CO_2 removal	Technical potential 4 GtCO2 / year	USD 50 – 200 per tCO_2	Potential altering of agricultural soils	Field studies pending	Multiple decades to achieve 0.5°C cooling	Effects on agricultural soils	Not required
Direct air CO_2 capture	Technical potential 40 $GtCO_2$ / year	Currently USD 500 per tCO2, cost reductions anticipated	Need for large renewable energy supply	Demonstration projects operational	Multiple decades to achieve 0.5°C cooling	Potential for cost reductions	Likely required for CO_2 geological storage

Table 1: Comparison of options (continued)

	Global Potential	Costs	Risks	Stage of development	Time frame	Key uncertainties	International cooperation
Stratospheric Aerosols Injection	~ 2 W/m^2 or more (2 W/m^2 is equivalent to ~ 0.5°C cooling)	~ USD 10 billion per year	Stratospheric ozone depletion; water cycle perturbation; rebound after stop	Evidence from natural volcanic eruption; no field experiment demonstration; possible rapid implementation	Several decades if used as a long-term measure 2 years if used as an emergency event	Impacts after multiple deployments Long term impacts of alternative aerosols than sulfur (e.g., calcite)	Broad agreement that required
Marine Cloud Brightening	~ 2 W/m^2 (equivalent to ~ 0.5°C cooling)	~ USD 5-10 billion per year	Perturbation of the water cycle; impact on marine ecosystems	Field experiment demonstrated but with considerable uncertainties	Several decades if used as a long-term measure; may be used locally for adaptation	Efficiency of the process; high dependence on weather conditions and already present nuclei	Required if used as a global cooling measure; Not required if used as local adaptation
Roof whitening **Land use / Farming**	Low	Low	Low	Adaptation measure, advantages for urban populations and crops demonstrated	Permanent	None	No

1 Introduction

This report provides an overview of options for partially reversing climate change. These have often been described as "geoengineering," although in recent years scientists have avoided using that term due to the confusion that it can generate. The two primary means of returning the climate, or at least some of its parameters, to a previous state are to lessen the concentration of greenhouse gases (GHGs) in the atmosphere, or to increase the reflectivity of the planet to incoming solar radiation. In addition, we cover efforts to locally influence weather phenomena, such as precipitation.

The perceived need to partially reverse climate change, especially with the use of negative emissions technologies, has grown in recent years. As we detail below, research on the impacts of climate change highlight that beyond 1.5°C global average warming from pre-industrial times, every additional bit of warming carries large negative consequences. Putting this in purely economic terms, the additional damages that would be experienced with 2°C warming, relative to those with 1.5°C warming, have been estimated to be equivalent to 3.5% of global GDP – several trillion dollars – by 2100 (Burke et al. 2018). At the same time, it appears very unlikely that conventional mitigation – the efforts to slow and eventually halt the rise in atmospheric GHG concentrations – will happen quickly enough to limit the rise in temperatures to 1.5°C. For that to happen, global CO_2 emissions would have to cease entirely, and emissions of other greenhouse gases would have to stabilize, by about 2030. Societal interventions to cool the planet, by reducing atmospheric GHG concentrations or increasing the planet's reflectivity, are no substitute for conventional mitigation of the highest possible level of ambition. Rather, they need to be viewed as a potential complement (Burke et al. 2018)

1.1 Basis for 1.5°C and 2°C targets

The science and policy communities have arrived an evolving set of targets for climate change. At the time of the signing of the Kyoto Protocol, in 1997, many people believed that an appropriate amount of global average warming from pre-industrial times was in the range of 3 – 4°C. This was supported by cost-benefit analyses, such as those of the economist William Nordhaus, making use of integrated assessment models (Nordhaus 1994; Nordhaus and Boyer 2000). In the early 2000s, attention started to shift towards a 2°C warming target, and indeed this was first agreed upon internationally at a Conference of the Parties (COP) of the United Nations Framework Agreement on Climate Change (UNFCCC) in 2007, held in Bali.

As a leadup to that COP, the Intergovernmental Panel on Climate Change (IPCC) had released its Fourth Assessment Report (Solomon et al. 2007; Metz et al. 2007; Parry et al. 2007), suggesting that the benefits of limiting climate change to 2°C outweighed the costs. Similarly in that year, the economist Nicholas Stern published a report of the British government reaching a similar conclusion (Stern 2007). Both the IPCC Fourth Assessment Report and the Stern Review have been interpreted as departing analytically from previous studies such as those of Nordhaus; whereas previous studies had made use of cost-benefit analysis to identify the economically optimal level of warming, the reports published in 2007 used risk-based analysis to identify a threshold (2°C) beyond which risks could be viewed as unacceptable, coupled with economic analysis to show that limiting climate change to 2°C global average warming would be economically viable (Barker 2008; Dietz and Stern 2008; Nordhaus 2007).

Achieving international consensus not just on the desirability of the 2°C target, but also on the steps needed to do so, became a goal of UNFCCC negotiators in the years between Bali and the COP scheduled to take place in Paris in 2015. At the same time, given evidence that even with 2°C warming the impacts might be severe, they requested the IPCC to begin assessing the feasibility, and desirability, of limiting warming to 1.5°C. The IPCC's Fifth Assessment Report included some preliminary analysis on this issue, although it did not make a 1.5°C target a centrepiece of its analysis (IPCC 2014). It was sufficient, however, to lead the UNFCCC negotiators to include language associated with 1.5°C in the Paris Agreement, a goal of which is holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (UNFCCC 2015).

The push towards greater consideration of the 1.5°C target came shortly thereafter, as the IPCC was requested to prepare a Special Report dedicated to this issue, which they then published in 2018 (IPCC 2018). This report suggested that indeed the marginal impacts associated with climate change between 1.5°C and 2°C were major, and that achieving a 1.5°C target was, at least theoretically, feasible; gradually, 1.5°C started to be seen as the level of ambition to which countries should strive. This was raised particularly in the context of the climate youth movement, which had profound political effects in the months and years after the IPCC 1.5°C report was published (Patt et al. 2022). To a large extent, the combined effects of the 1.5°C report and the youth protests can be seen as having triggered the wave of national net-zero emissions targets for 2050.

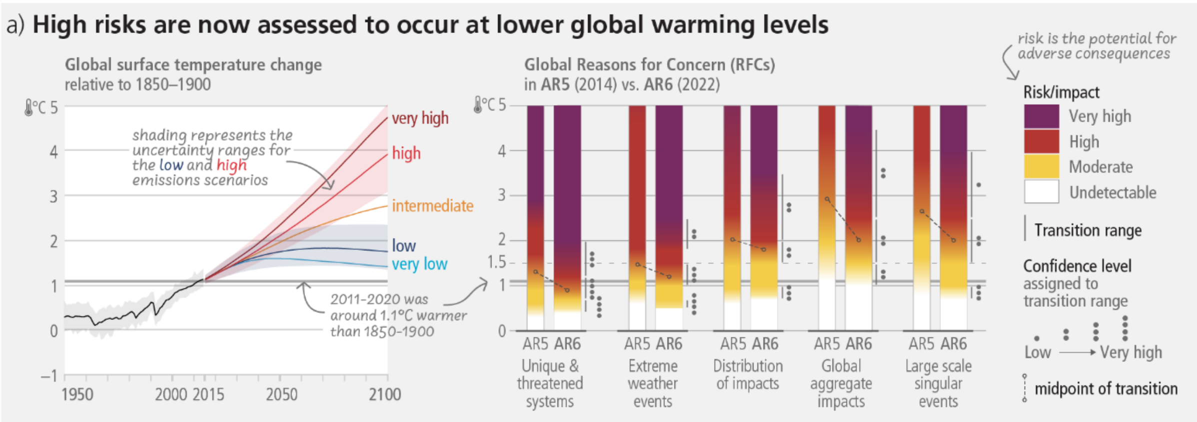


Figure 1.1: Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. Very likely ranges are shown for the low and high GHG emissions scenarios. Source: Lee et al. 2023.

The most recent IPCC assessment report suggests an even stronger basis for achieving a 1.5°C target than either the 2014 assessment report, or the 1.5°C special report (Lee et al. 2023). As Figure 1.1 shows, the most recent assessment report (AR6) estimates risk levels to be associated with a lower temperature rise than was assessed in AR5. For example, the risks to unique and threatened ecosystems were assessed in AR5 to go from "high" to "very high" in between 2 and 3°C warming; in AR6, this was projected to occur between 1.5 and 2°C warming. Or, risk levels associated with extreme weather events were assessed in AR6 to cross the line from "high" to "very high" at about 2°C warming.

1.2 1.5°C and net-zero targets

As described above, the shift towards 1.5°C as the appropriate climate target was one factor triggering the development of national net-zero emissions targets for 2050. Achieving the 2°C target, while viewed even a few years ago as likely impossible, would not have necessarily required the complete cessation of net emissions this century (Lee et al. 2023). As Figure 1.2 shows, emissions associated with the median estimate for limiting warming to 2°C remain above zero through 2100, assuming deep and rapid emissions cuts beginning in the 2020s and accelerating in the 2030s. By contrast, net emissions associated with the median estimate for 1.5°C pass through 0 around 2090, assuming even faster cuts in the 2020s. Although not shown in the figure, a somewhat slower initiation of rapid emissions cuts – in the second half of the 2020s rather than in the year 2020 – would require net emissions to cross 0 earlier, around 2050, to have a 50% chance of limiting temperature rise to 1.5°C with limited overshoot. The fact that it is already 2023, and global emissions have not yet peaked, suggest that indeed this latter scenario is closer to realistic.

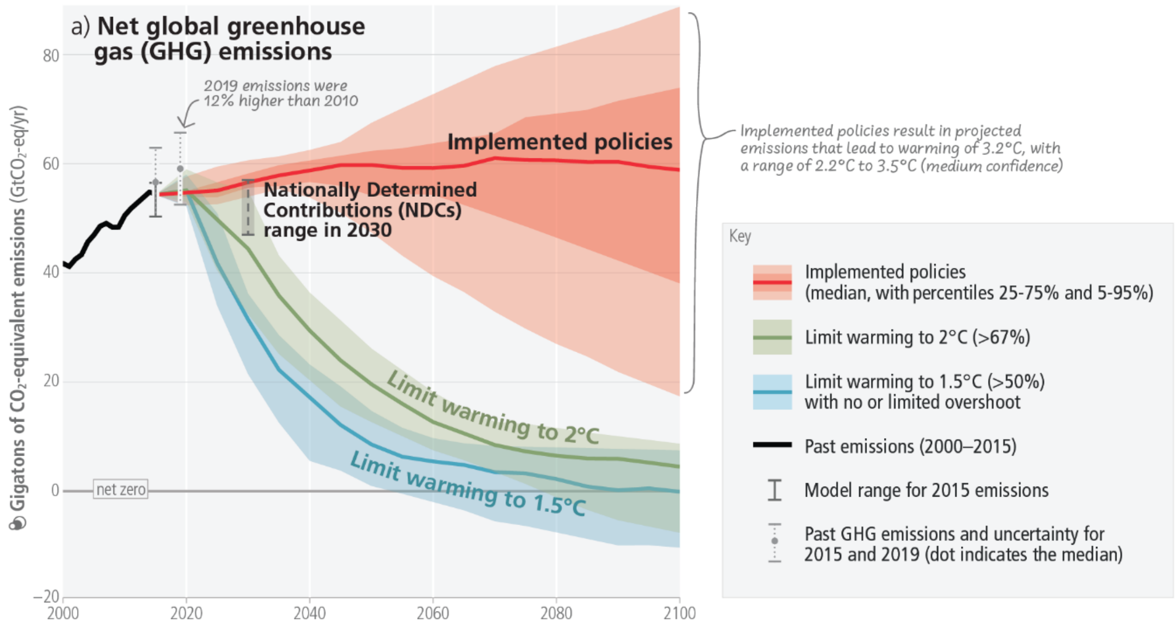


Figure 1.2: Global emissions pathways consistent with implemented policies and mitigation strategies: development of global GHG emissions in modelled pathways. Coloured ranges denote the 5th to 95th percentile across the global modelled pathways falling within a given category. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020. Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue and pathways that limit warming to 2°C (>67%) are shown in green. Global emission pathways that would limit warming to 1.5°C (>50%) with no or limited overshoot and also reach net zero GHG in the second half of the century do so between 2070–2075. Source: Lee et al. 2023.

Indeed, there are now estimates that the world may cross the 1.5°C threshold this coming year, due to rapid warming associated with the strong El Niño event in the tropical Pacific Ocean (Dale 2023). In that case, eventually limiting to 1.5°C would require net zero emissions starting essentially now. Clearly that is not going to happen. And yet it could be possible, in theory, to begin scaling up negative emissions technologies (NETs) to eventually offset all the emissions generated from today and moving forward.

1.3 Benefits of augmenting net-zero targets with additional measures

Conventional mitigation means reducing emissions of greenhouse gases (GHGs). Conventional mitigation is not likely to happen fast enough to limit temperature rise to 1.5°C. That then highlights the potential importance of augmenting conventional mitigation with additional measures, what one could call unconventional mitigation. The two main forms of unconventional mitigation are steps to actively withdraw CO_2 from the atmosphere, known as carbon dioxide removal (CDR) making use of negative emissions technologies (NETs), and steps to increase the Earth's albedo – the share of incoming shortwave solar radiation that reflects directly back out into space – through active solar radiation modification (SRM). It is essential to recognize that while CDR would lower atmospheric CO_2 concentrations, addressing the root cause of climate change, efforts to increase the Earth's albedo would only address one symptom, namely rising temperatures; it would not address other factors associated with CO_2 rise, such as ocean acidification. Together, CDR and SRM are often referred to as geoengineering, although the fact that they represent fundamentally different processes, entailing different physical pathways to global cooling, has led most people to cease bundling them together with a single term. In this report we assess these two sets of activities. We also assess the options for attaining rapid but limited global cooling through a particular form of conventional mitigation, namely the rapid phaseout of short-lived GHGs – known as short-lived climate forcers (SLCFs) such as methane. As we describe later, this form of conventional mitigation, if undertaken quickly enough, could potentially lead to an immediate reduction in global temperatures.

Especially in the case of SRM, there have been concerns that deployment of unconventional mitigation methods could crowd out the use of, or perceived need for, conventional mitigation. We describe these concerns in greater detail, below, in a section devoted to this moral hazard problem. The concerns about moral hazard have caused much of the recent analysis of SRM, and to a more limited extent CDR, to be oriented about its deployment as a complement of, rather than substitute for, rapid conventional mitigation. For example, Keith (2013) builds an argument for SRM around its limited deployment as a complement, rather than substitute. He and other researchers have increasingly been investigating the risks associated with limited deployment, such as reducing temperature rise from 2°C to 1.5°C (Patt et al. 2022). Indeed, many analyses have supposed that SRM would complement conventional mitigation over a limited period, namely until enough CDR had taken place as to stabilize atmospheric CO_2 concentrations at a level consistent with 1.5°C warming. This reflects the recognition that SRM could be deployed, to great effect, rather quickly, achieving a reduction in temperature within a period of months to years. CDR, by contrast, would be slower: NETs would have to be deployed, requiring in many cases significant investments in infrastructure, and this infrastructure would operate for multiple decades. One can imagine a scenario by which countries achieve net zero emissions in 2050, leading atmospheric CO_2 concentrations to peak, at a level that would otherwise cause temperatures to rise by 2°C. It could then take decades for CDR to then reduce atmospheric concentrations to a level consistent with 1.5°C. During those intervening decades, SRM could be used to limit temperature rise to below 2°C. This could potentially avoid some irreversible impacts associated with high temperatures, such as the rapid melting of polar ice sheets.

In this report, we concentrate on unconventional mitigation – CDR and SRM – as well as on one kind of conventional mitigation, the rapid reduction of emissions, and hence atmospheric concentrations, or short-lived GHGs. We do not discuss options for reducing CO_2 emissions quickly, although we describe how such efforts can have synergistic effects with the steps we do describe. For example, conventional mitigation in the aviation sector is likely to see the introduction of renewables-based synthetic aviation fuel; while this can allow for reductions in net CO_2 emissions from aviation, it also may lead to a reduction in immediate warming caused by the formation of contrail cirrus clouds. Similarly, the production of these fuels will require the use of direct air capture of CO_2 (DAC); this technology is also a key element of direct air carbon capture and storage (DACCS), an important NET.

We also generally do not describe methods and processes of climate adaptation, which generally means taking steps to lessen the consequences of given levels of climate change. Arguably, one could view SRM as a form of adaptation, as it lessens the consequences on the climate system (or at least on average temperatures within the climate system) of a given level of GHG concentrations in the atmosphere; nevertheless, SRM is not commonly included in the list of adaptation options. The one adaptation option that we do include here is that of local weather modification. The reason for including it is that it typically involves altering patterns of cloud formation, size, and duration. This overlaps with some methods of SRM. While local weather modification is primarily used to affect precipitation, it also has important local effects on albedo and surface-level temperatures.

1.4 An overview of measures

Climate intervention measures that have been proposed so far can be broadly classified in 3 different methodologies: (1) Carbon Capture and Sequestration/Utilization (CCS/CCU), (2) Carbon Dioxide Removal (CDR) and (3) Solar Radiation Management (SRM).

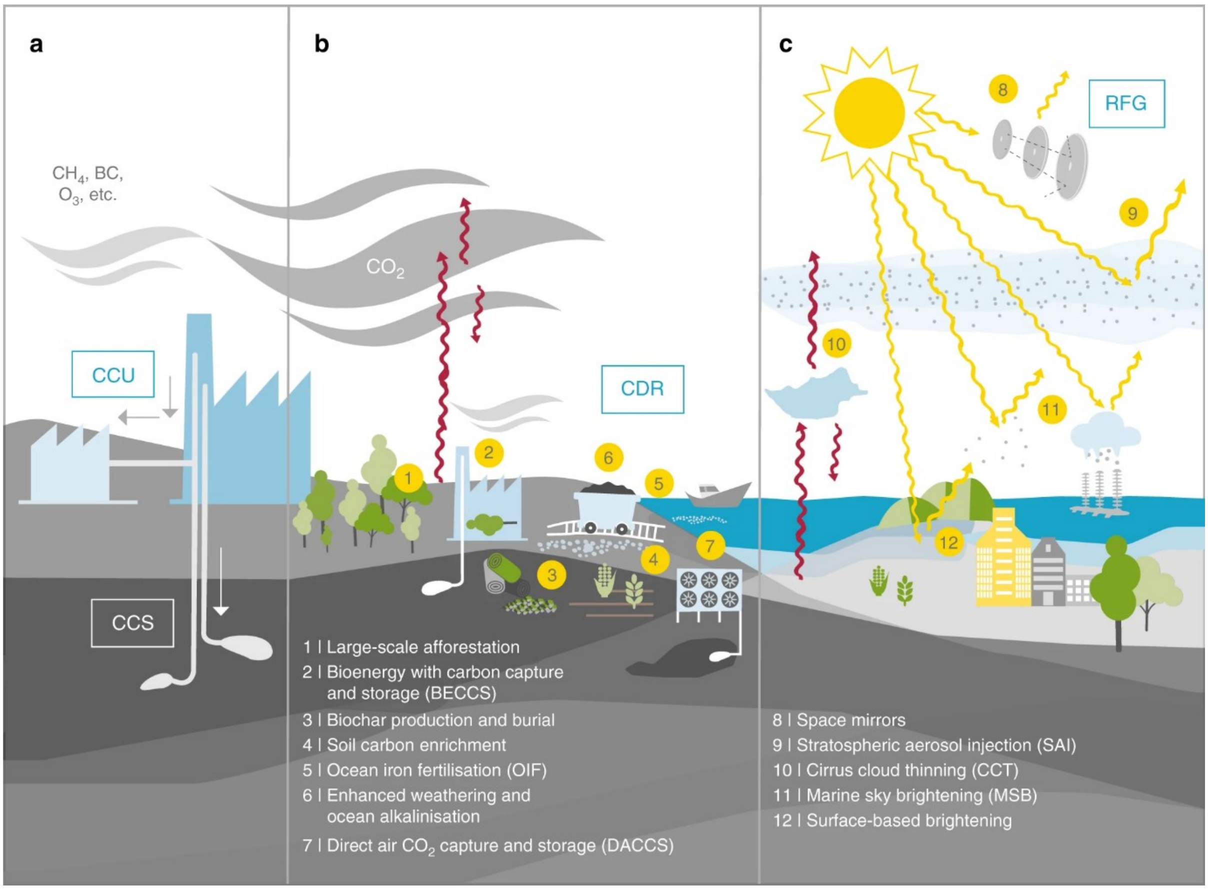


Figure 1.3: Overview of some climate intervention measures.
Source: Lawrence et al. 2018.

1.4.1 Carbon Capture and Sequestration (CCS)

Carbon Capture and Sequestration consists in extracting CO_2 emissions (filtering, chemical separation) from the exhaust of large point sources (power plants, cement plant, chemical plants), sequestrating it in rocks or concrete, or liquefying and injecting it into porous rock formations (aquifers) in geologic basins. This method of carbon storage is also sometimes part of enhanced oil recovery (EOR), because it is used later in the life of a producing oil well. Another chemical use (CCU) of CO_2 is its transformation in urea, for fertilizers production. It is essential to recognize that CCS, where the CO_2 is obtained from these point sources of fossil or chemically-produced CO_2 (e.g. in cement kilns), does not lead to a reduction in atmospheric concentration. For this to happen, the CO_2 must be removed directly from the air.

1.4.2 Carbon Dioxide Removal (CDR)

In contrast to carbon capture at industrial sources, CDR aims at reducing the CO_2 concentration that is already in ambient air, and is therefore a negative emission technology (NET). This approach is crucial for counteracting the impact of distributed CO_2 sources, like transportation.

Direct Air CO_2 Capture and Storage (DACCS) is carried out using large air extractors at the cost of high energy consumption. The extraction is relatively inefficient as compared to industrial exhausts capture (factor 3 to 5) (National Academies of Sciences and Medicine 2019) due to much lower CO_2 concentration in the ambient air. DACCS reduces ambient CO_2 concentrations in the air and can thus be considered as a NET, provided its source of energy is decarbonated. Industrial prototypes are currently tested, also from Swiss companies. Both DACCS and CCS require, however, either sufficient underground sequestration locations, as well as dedicated transport (pipelines) to suitable sequestration sites.

In addition to geological sequestration, biological sequestration in plants, trees and soils is an attractive option for long-term storing CO_2. To increase the natural ambient CO_2 removal process (photosynthesis in vegetation), **reforestation and afforestation** (planting trees on land that was not recently covered by forest) may provide a significant contribution, depending on the type of trees, geographical location and altitude. The IPCC estimated that afforestation could potentially provide CO_2 sequestration rates as high as 5 Gt/yr (IPCC 2013). There are, however, limits to the amount of carbon that can be removed from the atmosphere through reforestation and afforestation. When a forest matures, the rate of CO_2 uptake is balanced by respiration and the decay of dead organic matter. It also modifies the earth albedo and the hydrologic cycle. Massive modification of land use to accommodate new forests may also compete with agriculture and food production. However, considering the recent dramatic increase of forest fires due to drought, reforestation and afforestation, in some cases with more resilient tree species, should become a priority.

Bioenergy with Carbon Capture and Storage (BECCS) is an interesting approach as it combines biological and geological capture of CO_2 with renewable energy production. More precisely, ambient CO_2 is captured by forests of trees (or other crops and vegetation) that will be systematically replanted after harvesting. The biomass is then burned in a factory to produce energy (electricity, heating, etc.) and the CO_2 released by combustion is captured and sequestrated in bedrock (or other storage options) as for CCS.

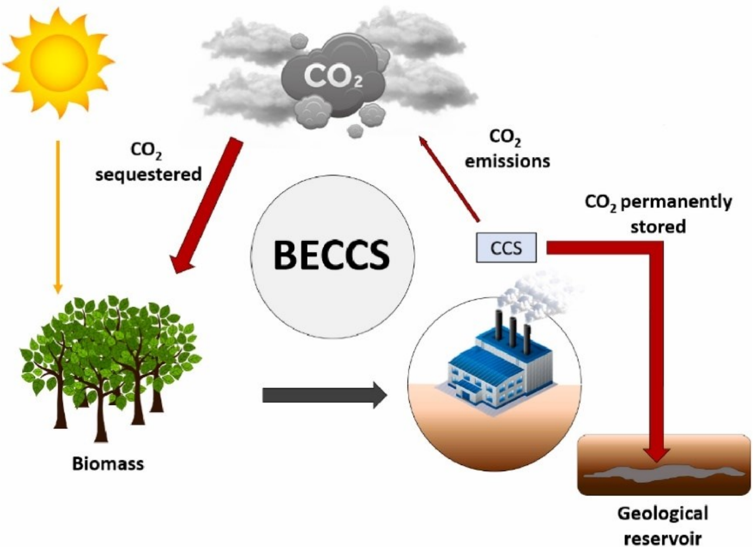


Figure 1.4 The principle of Bio-Energy with Carbon Capture and Sequestration (BECCS). Source: Almena et al. 2022.

The energetical advantages and CDR potential provided by BECCS have made it the dominating NET in the integrated assessment models of the IPCC (Almena et al. 2022). BECCS is projected to sequester 5-10 $GtCO_2$ per year by the end of the century (IPCC 2018, National Academies of Sciences and Medicine 2019). In order to be sustainable, however, BECCS should not induce a long-term net deforestation (over-harvesting as compared to growth capacity) and should carefully filter well-known toxic pollutants emitted by biomass burning (NOx, VOC, CO, particulate matter PM, heavy metals) (Yao et al. 2023), which might emerge as a significant issue.

Due to agriculture (e.g. harvesting plants and roots), soils are increasingly depleted in organic carbon. **Re-enriching soils** by CO_2 sequestration is an attractive approach and may be realized by agricultural practice and land use. Specific actions include no-tillage, erosion control, addition of cover crop, increased soil biodiversity (earthworms, fungi, bacteria), addition of compost, crop residues and manure, etc..

Instead of burning the biomass that sequestrated CO_2, it is possible to pyrolize it at low temperature and low oxygen content. The result is **biochar**, i.e. biological charcoal, which can be easily stored in soils, used in combination with fertilizers, or, as a concrete additive. Biochar has also been used in animal feed for centuries.

Weathering is the breaking down or dissolving of rocks and minerals on the Earth surface. This induces a larger surface exposed to the air, which can interact with the atmospheric CO_2 (and carbonic acid when in contact with water), and capture it by chemical reactions with calcium and magnesium. **Enhanced weathering** has thus appeared as a possible sequestration route, by grinding rocks and spreading the fine powdered minerals on farmland or forestland. The process can also be “forced” by capturing CO_2 with these minerals in autoclaves, but at the cost of energy consumption.

Enhancing CO_2 capture from the oceans is another route that is proposed. Atmospheric CO_2 is naturally converted to carbonic acid at the surface of the oceans, constituting a major carbon sink in the atmospheric system (about 7 Pg/yr = 7000 Tg/yr). The thermohaline circulation moves dissolved carbon dioxide to cooler waters where it is more soluble, increasing carbon concentrations in the ocean interior. Phytoplankton and algae use this dissolved CO_2 and carbonates to produce organic carbon by photosynthesis.

A first method of enhancing oceanic capture of CO_2 is to follow the weathering route, i.e. adding mineral powders like carbonates and silicates that **increase the oceans alkalinity** and bind CO_2 to it. These powders will ultimately precipitate and be stored on the ocean ground (National Academies of Sciences and Medicine 2022). This approach requires a sequence of actions, from mining and grinding rocks, transporting them to the coast, loading them on a ship and spraying them on the ocean.

The second method follows the biological track, by **fertilizing the ocean** to promote the photosynthetic activity. Iron is a trace element that is strongly involved in photosynthesis and often considered as the limiting nutrient for phytoplankton growth. Large algal blooms can also be artificially provoked by supplying iron to iron-deficient ocean waters.

Both ocean alkalization and ocean iron fertilization are controversial, when applied on large scales, because of possible impacts on marine ecosystems.

1.4.3 Solar Radiation Management (SRM)

In contrast to the former methods, which aim at reducing heat trapping by GHG, SRM aims at reducing the incoming solar radiation and its absorption, i.e. enhancing the albedo of the Earth. Several approaches have been proposed to this end. Some of them rely on the static deployment of high albedo surfaces, like large mirror arrays in space or whitening surfaces on the ground, while other rely on the generation or modification of clouds that scatter the incoming solar radiation (stratospheric aerosol injection, marine cloud brightening, cirrus cloud thinning).

The use of **space mirrors** is, at the present stage, not a plausible option because of the time and costs that such a technological development requires. The only experimental attempt in this direction was the Russian Znamya project in the 1990s, which launched deployable mirrors in space of a diameter of 20 m. In comparison, the required size of a space reflector able to reduce the incoming radiation by 1.5 W/m^2 is estimated to ~ 500 km (Feinberg 2022).

Increasing the albedo on the ground by **white painting roofs and infrastructures** is, on the other hand, a simple and cost-effective measure. The major advantage of such measures is a decrease of the local temperature in buildings, reduce heat waves and associated morbidity increase. Virtually no global cooling is expected from such actions, although its local impacts – such as reducing urban heat-island effects – can be major. Another approach for increasing the ground albedo targets agriculture practice, by encouraging **no-till farming or crop variants with lighter colours**.

Major SRM players for achieving global negative forcing are related to the intentional production or modification of clouds or aerosols. Among them **Stratospheric Aerosols Injection (SAI)** is the most widely studied, but also the most debated geoengineering action. The origins of SAI rely on the observation of a significant global cooling after major volcanic eruptions. For instance, in 1991, the eruption of Mount Pinatubo produced a net cooling of ~ 0.5 K over ~ 2 years. The volcano injected roughly 10-20 Tg of SO_2 in the stratosphere, which nucleated aerosols and stratospheric clouds. In turn, these stratospheric aerosols partially reflected and scattered the incoming solar radiation, inducing a radiative cooling of ~ 3W/m^2.

This event was sufficiently well documented to allow numerical simulations that qualitatively reproduced the observations. On this basis, several scientists, including the Nobel laureate Paul Crutzen (Crutzen 2006), proposed to intentionally inject SO_2 or sulphate aerosols in the stratosphere, in order to mimic volcanic eruptions. Injection may be realized by a fleet of dedicated aircrafts. The approach is still highly debated because of large uncertainties on detrimental side effects of these injections, like ozone layer depletion, tropical stratospheric heating, hydrologic perturbations, etc.. A sudden stop of SAI would also induce a significant rebound effect with an associated destabilization of the global atmospheric circulation. The use of alternative mineral or salt aerosols has been proposed, like calcite, which are less chemically active than sulphur and more transparent. There is, however, a significant need for further research on nucleation processes, stratospheric spread and circulation, aerosol-cloud interactions, and aerosol properties for better evaluating the potential and the risks associated with SAI.

Similar cloud formation induced by aerosols has also been proposed for tropospheric clouds. The idea of **Marine Cloud Brightening (MCB)** relies on the observation of long cloudy tracks induced by large ships on the ocean. Under specific weather conditions, the aerosol particles emitted by the ship engine serve as condensation nuclei, and lead to cloud formation. As a large number of small droplets scatters light more efficiently than a small quantity of large droplets, increasing the number of nuclei increases the albedo of the cloud, at least to a certain extent. These findings encouraged proposals of using sea salt aerosols as seeding particles in order to produce brighter marine clouds. The spread of salt aerosols can be realized by directly spraying small droplets of sea water that evaporate and produce sea salt particles. Key difference as compared to SAI is that effects and impacts are more local and controllable, shorter term and less polluting. However, because of this local action, continuous and large frame deployments would be required to achieve long term global cooling.

1.4.4 Extreme weather events and weather engineering

Although methodologies are often similar, there is a fundamental difference between climate and weather engineering. While climate engineering tackles long term trends over global scales (temperature rise, ice caps and glacier melt, ocean acidification, etc.), weather engineering focuses on local events, like drought, flooding, hail, thunderstorms, etc. Due to global warming, however, extreme weather is becoming normality, so that causes and consequences are now calling both for possible additional engineered measures.

A symptomatic example is severe drought, which induces a significant revival of **cloud seeding methods.** Cloud seeding aims at **triggering rain and snow fall** by injecting hygroscopic particles (salt) or spraying freezing agents like silver iodide (AgI) to generate ice crystals from supercooled droplets. Although these methods have been developed in the late 1940s and extensively tested since then without statistically significant results until recently, large-scale cloud seeding programs have been launched in the USA and China since the beginning of the 2st century. China is particularly active in this field, with a weather modification office accounting for 32,000 employees, 35 equipped planes, 7,000 canons and 5,000 rocket launchers (Qiu and Cressey 2008). The office claims having conducted more than half a million weather modification operations, resulting in 500 billion tons of rain (Chien et al. 2017). In the USA, similar actions have been carried out, as illustrated by the 922 projects about rain/snow enhancement and hail suppression, registered by the NOAA between 2000 and 2022 (NOAA 2023). As mentioned, a quantitative assessment of the cloud seeding efficiency is a difficult task, as it critically depends on very local weather conditions, the quantity of nuclei already present in the clouds, the seeding method, and the difficulty of comparing 2 identical events, one seeded and one unseeded. Recent large-scale campaigns in the USA on orographic cloud seeding were, however, able to assess the AgI seeding efficiency for inducing snowfalls and some key "cloud seedability" conditions (Friedrich et al. 2020).

The **prevention of hail** uses the same approach as cloud seeding for rain enhancement, but in thunderstorms. The idea is that by increasing the number of ice-nucleating particles, the number of hail embryos increases, depletes the supercooled water earlier and thus reduces the hailstone size. Associated damage costs due to hail amount to ca USD 10 billion per year in the USA (Allen et al. 2020). Similarly, damage costs due to **lightning** amount to ca USD 2-5 billion per year, with additional human and cattle casualties.

As highlighted for SRM, there is a crucial need for increasing scientific knowledge about nucleation, condensation, aerosol-cloud interaction, cloud dynamics and material research in order to better evaluate cloud seeding methods and their associated risks (e.g. soil pollution, effects on biotopes and biodiversity, etc.). Some new technologies, like ionization-based or laser-based methods, are also currently investigated to provide alternatives to the chemical cloud seeding method (e.g. with AgI and dry ice) demonstrated by V. Schaefer in 1946 (Schaefer 1946) and B. Vonnegut in 1947 (Vonnegut 1947).

2 Reducing atmospheric concentrations of short-lived climate forcers

Greenhouse gases (GHGs) have different residence times in the atmosphere. While the dominant anthropogenic GHG, CO_2, has a residence time of several centuries, short-lived climate forcers (SLCFs) have residence times ranging from hours to roughly a decade (Szopa et al. 2021). The result of this is that their effective radiative forcing (ERF) resulting from SLCF emissions, or emissions giving rise to SLCF formation in the atmosphere, is highest immediately following emissions, and then declines as their concentration in the atmosphere falls.

For global governance purposes, emissions of different gases are related to each other using conversion metrics related to their long-term effects on temperature; the most used of these is Global Warming Potential over 100 years (GWP100), while others are also used, such as GWP20, which measures over 20 years. These express how much radiative energy the emissions of 1 ton of a gas will absorb over a given period of time (e.g. 100 or 20 years), relative to the emissions of 1 ton of CO_2 over that same time period. Among the GWP metrics, we use the GWP20 metric in this report, as it more closely corresponds with the time horizon for Swiss net emissions. While useful, the use of such equivalency metrics can also be misleading, because it suggests that continued emissions of SLCFs will result in additional warming (Allen et al. 2018). In fact, if there were a lasting and global reduction in emissions of those SLCFs having a warming effect, that would imply a decline in aggregate ERF, and a net cooling effect.

2.1 Contribution of short-lived gases to overall warming

The IPCC lists sixteen SLCFs, classifying them according to whether they are directly emitted, or form in the atmosphere as a result of chemical interactions involving other emitted gases (Szopa et al. 2021). Of these, six have a cooling effect on the atmosphere, four have a warming effect, and six have both cooling and warming effects. The overall impact of all sixteen SLCFs is one of cooling, dominated by the effects of SO_2 and NO_x. Figure 2.1

displays the effects of SLCFs, as well as two long-lived gases (CO_2 and N_2O), on global average surface temperatures compared with their effects prior to industrialization. As can be seen, by far the largest effects are due to methane (CH_4) emissions. Not included in the figure, because the research identifying effects is too new, are SLCFs due to aviation. In this report we focus on those two: methane and aviation.

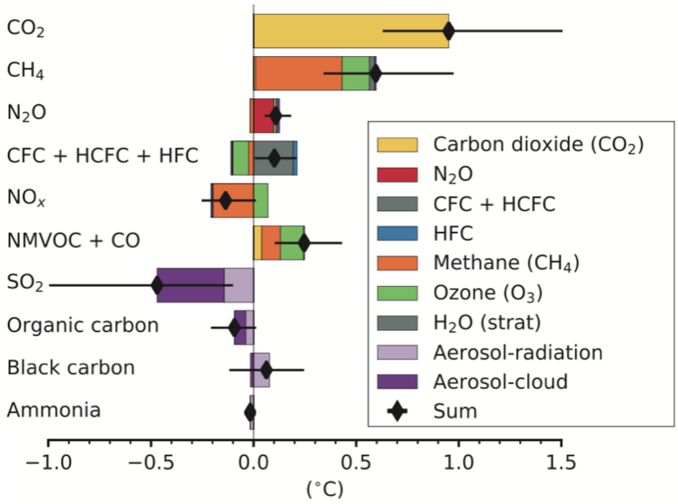


Figure 2.1: Effects of different GHGs on global surface air temperatures relative to 1750. Note that CO_2, N_2O and CFS + HCFC are long-lived gases, whereas others are SLCFs. The colours represent the causal pathways by which emissions lead to either cooling or warming. Source: Szopa et al. 2021.

2.1.1 Scenarios consistent with 2°C and 1.5°C warming

Scenarios that limit warming to between 1.5°C and 2°C incorporate substantial reductions in SLCFs relative to an assumed baseline, and in the case of methane substantial absolute emissions reductions. The most commonly cited scenario is RCP2.6[17] (van Vuuren et al. 2011). Figure 2.2 illustrates the changes in various GHGs in the RCP2.6 scenario: as can be seen, emissions of N_2O (not a SLCF) and while the various F-gases (CFC + HCFC) stabilize by 2020, whereas methane emissions decline by roughly half. Contributing to the decline in methane emissions is their near-total elimination from all sectors except agriculture, and a slight reduction of methane emissions within agriculture. Within a separate shared socio-economic pathway (SSP) associated with RCP2.6, methane emissions from agriculture decline by 56% (van Vuuren et al. 2017).

[17] RCP stands for Representative Concentration Pathway. There are several RCPs, differentiated according to the greenhouse forcing from anthropogenic forces in 2100. RCP2.6 is one that achieves 2.6 W/m^2 forcing.

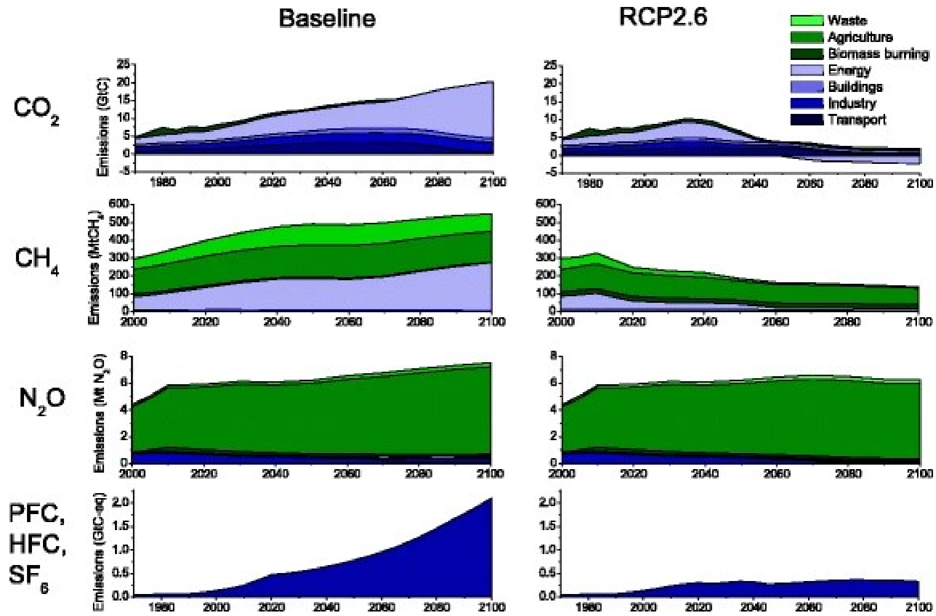


Figure 2.2: Emissions pathways for different gases in the RCP2.6 scenario. Source: van Vuuren et al. 2011.

2.2 Reducing fugitive methane emissions

Methane is the most important SLCF in terms of its effects on global temperatures, and among anthropogenic sources, emissions from industry – including the production of fossil fuels – is the largest. These are known as fugitive methane emissions.

2.2.1 Global aspects of fugitive methane emissions

Minx et al. (2021) estimate total methane emissions in 2019 to have stood at slightly in excess of 350 Mt annually, although there are large uncertainties. Of these, roughly 200 Mt were fugitive emissions, while most of the remaining 150 Mt derived from agriculture. Note that this represents a major change in estimates since van Vuuren et al. (van Vuuren et al. 2011), as data in the intervening years suggested fugitive emissions to be far higher than previously estimated (Worden et al. 2017).

Oil and gas extraction, transport and storage are the primary causes of fugitive emissions, accounting for roughly 85% of their quantity, while coal mining accounts for most of the remaining 15% (Laconde 2018). One recent estimate suggested that fugitive emissions from North American natural gas production represents 3.7% of total amounts (Zhang et al. 2020). It is unclear whether other methane producing regions have correspondingly high leakage rates, although a database of large methane leaks suggests correspondingly high numbers of events in central Asia and the Middle East (Carrington 2023).

Taking the 200 Mt estimate from Minx et al. (Minx et al. 2021), what effect would the elimination of these emissions have, both in terms of cooling and in terms of offsetting current emissions? Figure 2.1 allows one to quickly estimate the cooling effect. Given that the central estimate of the overall warming effect of all methane emissions is roughly 0.6°C, and fugitive methane emissions account for about 60% of total methane emissions, the immediate elimination of fugitive methane emissions would have a cooling effect – over one to two decades – of about 0.36°C. It is important to note that the RCP2.6 scenario takes this partly into account, as the scenario includes the elimination of fugitive methane emissions, although the estimates for the total quantity of fugitive emissions at the time of developing the RCP2.6 scenario were lower than they are today. In terms of CO_2 equivalent effects, one option is to use the GWP20 conversion factor of 86; this equates the cessation of fugitive methane emissions – each year for the next twenty years – with avoiding 17.2 $GtCO_2$ each year for the next 20 years, or 344 $GtCO_2$ in total.

How could one eliminate fugitive emissions? The sources from the oil and gas sector are both intentional – in terms of the practice of flaring – and unintentional, the result of leaks in wells, pipelines, and storage containers. Since 2016 there has been a reduction in flaring because of industry initiatives. However, there is no indication of reductions in unintentional fugitive methane emissions, and indeed researchers are primarily preoccupied with estimating their full extent (Laconde 2018). What is clear is that unintentional fugitive methane emissions result from many small leaks, and that fixing them would require actions by actors within the natural gas industry. The problem, as Laconde (2018, p. 113) describes, is that "it is not always economically profitable to reduce fugitive emissions: indeed, to detect leaks, to determine their source and correct them requires investments which may be much higher than the cost of the lost gas." While regulatory approaches can potentially lead to a reduction in fugitive emissions, there is yet no widespread evidence of success (Laconde 2018). The clearest way to eliminate emissions, then, would be to cease consumption of oil and natural gas, in particular the latter.

2.2.2 Concerns about hydrogen

The issue of fugitive methane emissions intersects with possible production pathways for hydrogen, in two ways: the impacts of fugitive methane emissions associated with blue hydrogen production, and the impacts of fugitive hydrogen emissions.

In terms of the first, it is important to make note of the production pathways for hydrogen. These are commonly referred to as grey, blue, and green. Grey hydrogen production, which currently dominates the market, makes use of steam to convert natural gas into hydrogen and CO_2, through an energy intensive process known as steam methane reformation (SMR). It is clear grey hydrogen production is not compatible with climate mitigation, as the resulting lifecycle emissions from using grey hydrogen as an energy source are higher than they would be from simply using the original natural gas. Blue hydrogen combines SMR with CCS: capturing CO_2 emissions from the steam reformation process and then sequestering these. Green hydrogen production, by contrast, does not make use of natural gas as feedstock, but rather uses electricity from renewable sources to split water into hydrogen and oxygen.

Howarth and Jacobson (2021) estimated the effects associated with fugitive methane in the blue hydrogen production process. They assumed a methane leakage rate of 3.5%, slightly lower than the 3.7% reported by Zhang et al. (Zhang et al. 2020), took into account the additional energy required for the CCS processes, and assumed natural gas combustion (also including CCS) to be the heat and energy source for the SMR. Because CCS is itself an energy intensive process, generating both fugitive methane emissions and uncaptured CO_2 emissions, they calculated the overall gains from switching from grey hydrogen to blue hydrogen to be minor. Indeed, blue hydrogen still resulted in greater overall emissions than obtaining the same amount of energy directly from natural gas, oil, or coal.

Hauglustaine et al. (2022) examined the effects of both fugitive methane and fugitive hydrogen emissions. The latter are a concern, because molecular hydrogen (H_2) in the atmosphere reacts with OH molecules, reducing the latter's concentration. However, OH is the primary reactive agent for atmospheric methane. Thus, increases in atmospheric hydrogen concentration have the effect of lengthening the residence time of methane, increasing its warming potential. Hydrogen leakage rates are highly uncertain, although given the small molecule's ability to permeate many materials, values of 10% or more cannot be ruled out (Hauglustaine et al. 2022). At leakage rates over 10%, hydrogen leakage becomes a concern even in the case of green hydrogen production, potentially eliminating the climate benefits of the switch from fossil fuels to green hydrogen as an energy carrier. This is a potentially serious issue, albeit one that is out of scope for this report.

2.2.3 Potential for Swiss action

The Swiss greenhouse gas inventory reports fugitive emissions from fuels to have totalled 219 ktCO_2e in 2018, representing a 40% reduction since 1990 primarily on account of the replacement of steel gas distribution pipelines with plastic, reducing leakages (FOEN 2020).[18] This represents less than one-half of one per cent of Swiss emissions, and suggests that there is little that Switzerland can do to effect cooling through reductions in domestic fugitive emissions.

However, in this area it may be important to consider the life cycle emissions associated with the oil and gas that Swiss people consume, such as due to gas flaring or well leaks taking place elsewhere associated with the oil and gas that are used within Switzerland. Switzerland consumes roughly 36 TWh of natural gas annually (Gaznet 2022), representing 2.4 million tons. Were Swiss natural gas to come from sources with leakage rates of 3.7% as reported in Zhang et al. (Zhang et al. 2020), it would imply roughly 90 kt of leaked gas annually. Using the GWP20 conversion factor, this would correspond to 6.48 MtCO_2e over the next 20 years, for a total of 130 MtCO_2. This is equivalent to roughly 3.5 years of Swiss CO_2 emissions at their current value, or to net projected Swiss CO_2 emissions over the years 2040-50 in the Swiss Climate Strategy (Federal Council 2021). In other words, accelerating the elimination of fugitive methane emissions – by ending the use of natural gas within Switzerland – would have a cooling effect over 20 years equivalent to those final ten years of planned net emissions.

2.3 Reducing agricultural methane emissions

Until recent revisions to the estimates of fugitive methane emissions, agriculture was taken to be the primary source of methane emissions; by contrast, it is now currently estimated to contribute roughly 40% of total methane emissions, or about 140-60 Mt annually (Minx et al. 2021). Using the same method to calculate the cooling effect from eliminating fugitive methane emissions, eliminating methane emissions from agriculture would have a cooling effect over the following 20 years of approximately 0.24°C. As previously stated, the IPCC emissions scenarios consistent with limiting climate change to 1.5°-2°C assume a decline in agricultural methane emissions of about 50% by 2100 (van Vuuren et al. 2017).

Various datasets suggest four main sources of agricultural methane emissions (Minx et al. 2021): Enteric fermentation accounts for roughly 67%; rice cultivation 23%; manure management 7.5%; and, agricultural biomass burning 2.5%. In many world regions, additional methane emissions derive from other forestry and land-use (FOLU) practices. Figure 2.3 shows the regional breakdown of the different sources, for each of the last three

[18] As will be described later, methane emissions from agriculture in Switzerland were estimated at 4,040 ktCO2e, roughly 20 times more than those from fugitive emissions.

decades. As can be seen, European methane emissions are more heavily weighted towards enteric fermentation and manure management.

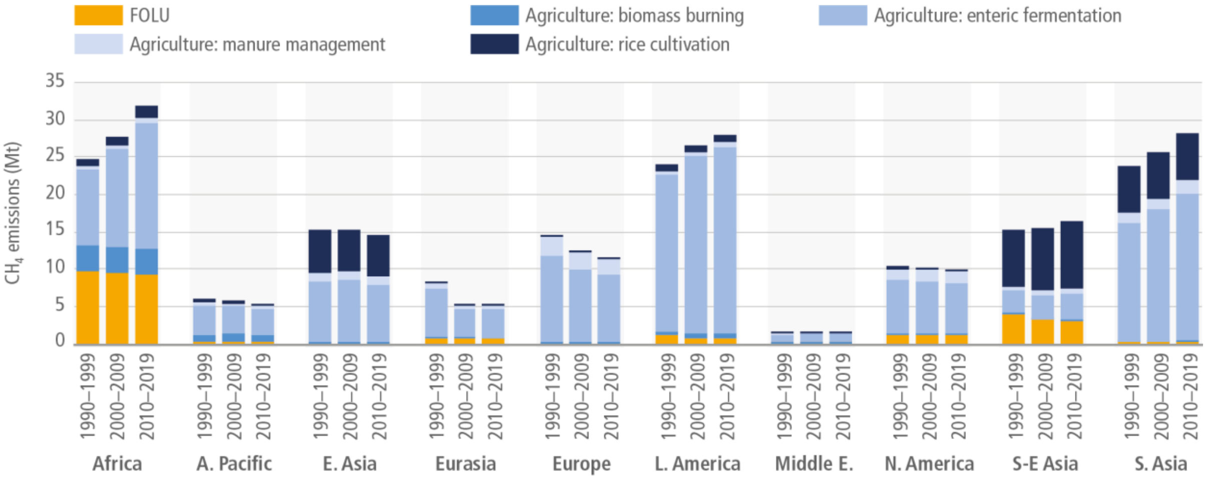


Figure 2.3: Agriculture, forestry and land-use sources of methane emissions.
Source: Nabuurs et al. 2022.

The two main pathways for reducing methane emissions associated with enteric fermentation are (a) technical approaches that alter methane formation and release in individual animals, as well as improvement in manure management, and (b) reduction in demand for meat and dairy products, which would lead to a contraction in the number of animals and their associated emissions (Herrero et al. 2016). Across the two pathways, Reisinger et al. (2021) suggest that up to 55 $MtCH_4$ could be mitigated annually by 2050, with 20 $MtCH_4$ of these at costs below USD100 per tonne CO_2eq. This would bring a short-term cooling effect of roughly 0.08°C.

2.3.1 Options for reducing the methane intensity of agriculture

The IPCC assesses that a variety of technical measures could result in a global decline in methane emissions of 0.8 GtCO2eq annually (with an uncertainty range of 0.2-1.2 $GtCO_2$eq) using the GWP100 conversion metric (Nabuurs et al. 2022). That corresponds to roughly 29 $MtCH_4$ emissions annually; ending these emissions would have a cooling effect of 0.05°C. The IPCC reports that a quarter of these reductions could be achieved at a cost of less than USD 100 per tonne CO_2eq (Nabuurs et al. 2022).

The technical options fall into three main categories. The first, which would be a continuation of current trends, is increasing production efficiency of the associated livestock through animal breeding, a change in feed regimens, as well as prophylactic use of antibiotics. Especially the latter option increases risks associated with bacterial acquired immunity, and hence major public health concerns. Beauchemin et al. (2020) suggest that this could be effective to moderate the growth in methane emissions, and also highlight that its potential is fairly limited, for reasons such as those associated with antibiotic use. The second option is with specialized feeds (such as seaweed), feed additives, and vaccines that suppress the production of methane inside the animal. Estimates for the potential of these methods to reduce emissions vary widely, ranging from 16-70% depending on the study (Nabuurs et al. 2022; Beauchemin et al. 2020). The innovations needed are still not fully mature, although Reisinger et al. (Reisinger et al. 2021) suggest that the first of them – feed additives – could become feasible by 2025 for total mixed rations (TMR) feeding systems, and by 2030 for grazing management systems; as discussed below, progress may be even faster than this. The third option is breeding low emissions animals. The scientific basis for viewing this as possible is the observation that methane production among sheep varies and is hereditable. Reisinger et al. (Reisinger et al. 2021) suggest that genetic research is well advanced for sheep, but less advanced for cattle due to the higher costs of measuring emissions, but do suggest that breeding, like the development of feed additives, could result in significant methane emissions reduction by 2050. Table 2.1 provides an overview of these options.

Table 2.1: Technical options for reducing methane emissions from enteric fermentation. Source: Reisinger et al. 2021.

Technology	Key constraint	Relative emissions reduction	Widespread commercial availability
Methane inhibiting feed additives	Cost	20-30%	2022-2030
Methane vaccine	R&D, veterinary services, cost	Potentially 30%	2050
Seaweed (as methane inhibiting feed)	Production scale, cost, toxicology, regulatory and market acceptance	20-50%	Potentially 2030
Low emissions breeding	Current scale of breeding programme	1% per year, 15% maximum	Sheep 2030, cattle potentially 2035

The most well-developed of these methods is the feed additive 3-nitrooxypropanol (3-NOP). Multiple tests have confirmed that it reduces methane production in cattle by roughly 20-30% when used as an additional supplement to grazing regimens, and by up to 60% when incorporated into total mixed rations (TMR) feeding systems (Melgar et al. 2020). Furthermore, studies have shown that its use does not affect overall animal eating patterns, body weight or body weight change, while also slightly increasing milk fat composition and overall production (Van Wesemael et al. 2019; Hristov et al. 2022). It appears to have a rapid effect, and these effects wear off within a week of discontinuation (Melgar et al. 2020). However, studies are still needed to see if it has a long-term effect on animal health (Hristov et al. 2022).

The first commercial product utilizing 3-NOP is Bovaer, a feed additive manufactured by the Dutch company DSM. It was first approved for use in Brazil in 2021, and then approved for use in dairy cows in the EU and Switzerland in early 2022. Several pilot studies have been going on, results from which are recently available. A study of 20,000 cows in the Netherlands suggested that the cost of using Bovaer added CHF 0.01 per kg to the cost of milk production; it was also determined that there were no effects on cow health (Bodde 2022).

2.3.2 Options for reducing consumption of methane-intensive products

The second pathway for reducing methane emissions from agriculture is through demand reduction. Globally, meat and milk consumption rose roughly 30% over the 30-year period

1990-2020, with the main drivers being a combination of population growth and rising per capita meat consumption in middle-income countries. In developed countries, animal stocks of all types declined over this period, with the one exception of poultry (Nabuurs et al. 2022).

While the IPCC described the potential for demand reduction to limit methane emissions, and the scenarios consistent with achieving 1.5°C implicitly assume this (since the reductions in methane emissions from agriculture are far more than what have been assessed as feasible through technological changes), neither describes the pathways by which demand reduction could take place. Generally, per capita meat consumption rises as a function of available income; for various reasons, people like to eat meat, and do so when it becomes more affordable. As Godfray et al. (2018) describe, there are various theories from the social and behavioural sciences suggesting possible government interventions to reduce meat consumption. Figure 2.4 summarizes these, with different interventions designed to intervene in both conscious and unconscious decisions to consume meat. At the same time, the authors are clear that such interventions have not yet been tested, and so there is little data to directly support their effectiveness, or link that effectiveness to particular features of policy design. The one exception to this is the presence of data suggesting that choice architecture changes – giving people smaller meat portions in restaurants, and reposition meat to later parts of a menu – have led to reductions in consumption.

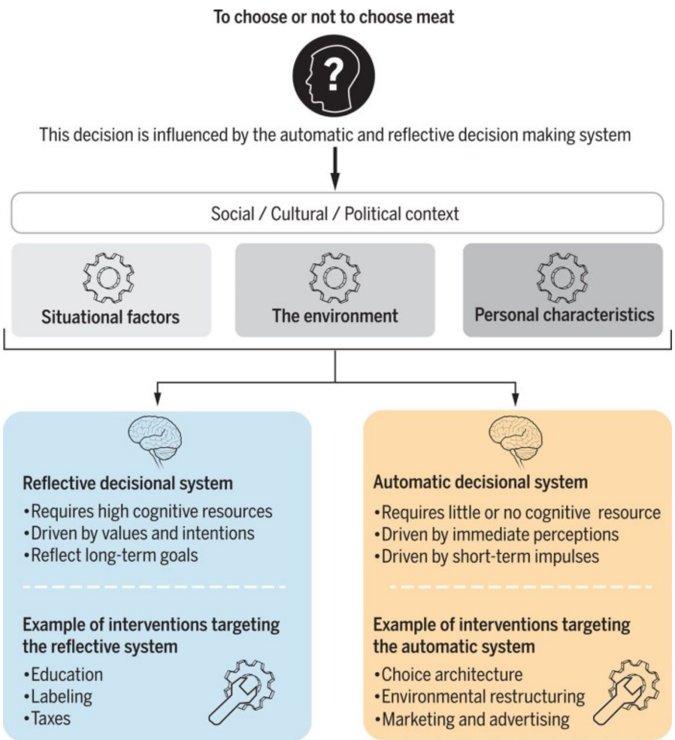


Figure 2.4: Factors influencing meat consumption, and interventions to change this. Source: Godfray et al. 2018. Reprinted with permission from AAAS. © 2018 AAAS

Another alternative that has gained recent attention is the development of foods that look, smell, and taste like meat, but do not come from an animal; these can include both plant-based meat alternatives, as well as meat tissue growth in the lab or factory. In terms of the former, a number of new options have become commercialized in recent years, with industry growth of 20% in the year 2018 alone (Van Loo et al. 2020). At the same time, there is evidence that consumers do not consider plant-based alternatives to be "real" meat, for example in wanting plant-based meat alternatives to be labelled as such, rather than as meat (Van Loo et al. 2020). This suggests that the choice to switch from meat to these products would require the same types of interventions as those shown in Figure 2.4.

In the case of laboratory-grown meat, also known as cultured meat there is absolutely no clarity, simply because such meat is still being invented, and not yet commercially available (Behera and Adhikary 2023). In fact, the world's first piece of cultured meat food was a hamburger that was cooked and eaten at a London press conference in 2013, at a cost for that single hamburger of over USD 200,000. Since then, a number of start-up companies have entered the market, promising to commercialize the technology; currently there are over 100 such companies, many of them having raised millions of dollars in venture capital. On the one hand, there are a number of obstacles, primarily technical and economic but also regulatory and marketing related, that have to be overcome before cultured meat will be commercially viable. On the other hand, there are studies suggesting this will happen, and projecting that together with plant-based meat alternatives up to 60% of meat consumption could be displaced by 2040 (Behera and Adhikary 2023).

2.3.3 Potential for Swiss action

Figure 2.5 illustrates Swiss emissions for the years 1990 and 2018, using the GWP100 conversion factors for methane, nitrous oxide and F gases. The purpose of showing this here is to illustrate the relatively significant contribution of methane to overall warming over long time periods, and the fact that methane emissions have been declining. The 2018 value for absolute methane emissions was 195 kt CH_4. Recalibrating to the GWP20 value, this would correspond to 14 $MtCO_2e$ annually over the next 20 years, for a total of 280 $MtCO_2$. This is equivalent to roughly 7.6 years of Swiss CO_2 emissions at their current value, or to net projected Swiss CO_2 emissions over the years 2036-50 in the Swiss Climate Strategy (Federal Council 2021). In other words, if it were possible to immediately end methane emissions by 2030, that would have a cooling effect corresponding to the warming resulting from all net emissions envisioned for after 2035.

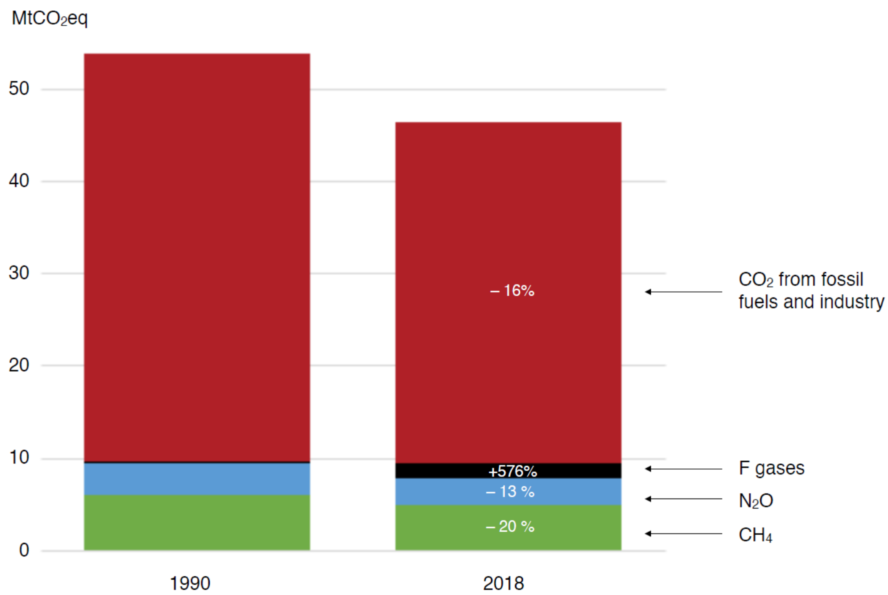


Figure 2.5: Swiss emissions using the GWP100 metric.
Data source: FOEN 2020.

Agricultural methane emissions in Switzerland come primarily from enteric fermentation (82%), whereas the remainder come from manure management, which is also attributable to those same animals. Looking at enteric fermentation alone, it is nearly all an issue of cattle. Using the data and methods described in FOEN (FOEN 2020), we arrive at 96.0% of these emissions deriving from cattle, 2.7% from sheep, 1.2% from swine, and 0.1% from poultry. Eliminating agricultural emissions is therefore primarily an issue of beef and milk production. 61% of the emissions attributable to cattle, or 59% of total emissions associated with enteric fermentation, derive from mature dairy cattle.

The most obvious means of having a rapid impact would be through the use of 3-NOP, in the form of Bovaer or a similar supplement, for Swiss dairy cows. Putting the numbers together from the previous paragraphs, enteric fermentation in dairy cows accounts for 94 kt CH_4 emissions globally. These could be reduced by 30%, or 28 kt CH_4, through the complete use of 3-NOP. Using the GWP20 metric, this would have an immediate cooling effect equivalent to 2 $MtCO_2$; if continued for 20 years it would have offset the warming from 40 $MtCO_2$, slightly more than 1 year of current Swiss emissions and slightly more than the net CO_2 emissions planned for 2045-50. Switzerland produces roughly 3.4 billion kg of milk per year; at a cost of CHF 0.01 per kg, the direct cost would be CHF 34 million annually, or CHF 680 million over 20 years. Using the GWP20 conversion metric, this would be equivalent to a cost of CHF 17 per tonne CO_2. That is a highly cost-effective means of gaining cooling. Using the GWP100 conversion metric, this would be equivalent to a cost of CHF 49 per tonne CO_2. That too is relatively affordable.

Other options to reduce agricultural methane emissions are more speculative. Potentially government policies could promote a shift to less meat consumption, or from beef towards other forms of meat with a far lower methane footprint, such as pork and chicken. It is unclear the extent to which policies could promote a shift from dairy consumption, however. Government policies could also promote the development of cultured beef, as well as plant-based dairy and cheese replacements. Again, it is challenging to estimate the impacts of these policies, either in terms of costs or methane emissions reductions, even before one considers the political challenges associated with government policies aimed to reduce the market for beef, milk, and cheese. One possibility is that if Switzerland were to be a global technology leader in this area, it could have an impact in terms of global methane reductions far larger than Swiss methane emissions.

2.4 Options to reduce short-lived emissions from aviation

A second major source of SLCFs is aviation. Aviation contributes both long-lived forcers (primarily CO_2) and a variety of gases that – on their own or through interactions within the atmosphere – act as short-term forcers. The aviation induced SLCFs are extremely short-lived, namely from hours to days (compared to multiple years for methane). Because of their short lifetime it can be misleading to describe them in CO_2 equivalent terms using metrics such as GWP100.

Instead, one can say that roughly 4% of the anthropogenic forcing and associated warming due to all GHG emissions since pre-industrial times can be attributed to aviation, and of that, roughly two-thirds are attributable to the SLCFs (Lee et al. 2021; Brazzola et al. 2022). Given that average global surface temperatures have risen 1.2°C since pre-industrial times because of anthropogenic emissions, that means that the SLCFs from aviation currently account for a warming of 0.032°C. If emissions of SLCFs from aviation were to immediately cease, then global average temperatures would quickly fall by about that amount. By contrast, a doubling of aviation volume, holding all other factors equal, would lead to an additional warming attributable to SLCFs of about 0.032°C. That is not entirely unreasonable to assume, as aviation emissions did double between 1990 and 2020 (Lee et al. 2021). In 2019 (i.e. pre-COVID), aviation accounted for 905 $MtCO_2$ emissions (IATA 2022). If aviation emissions were to remain constant, it would take roughly 70 years to generate additional warming of 0.032°C due to the effects of CO_2. If aviation continues to grow, then the effects attributable to CO_2 would accumulate more quickly.

The pathways of SLCF formation and effects from aviation are complicated, and not entirely understood. Figure 2.6 provides an overview of the main gases and their interactions. Of these, nearly all of the net warming effects appear to be the result of contrail plumes arising from flying in low-temperature ice-supersaturated air. High altitude contrails consist in large ice particles that not only reflect the incoming solar radiation but also the thermal radiation from the Earth, like Cirrus clouds, and thus contribute to warming of this atmosphere (Lee et al. 2021).

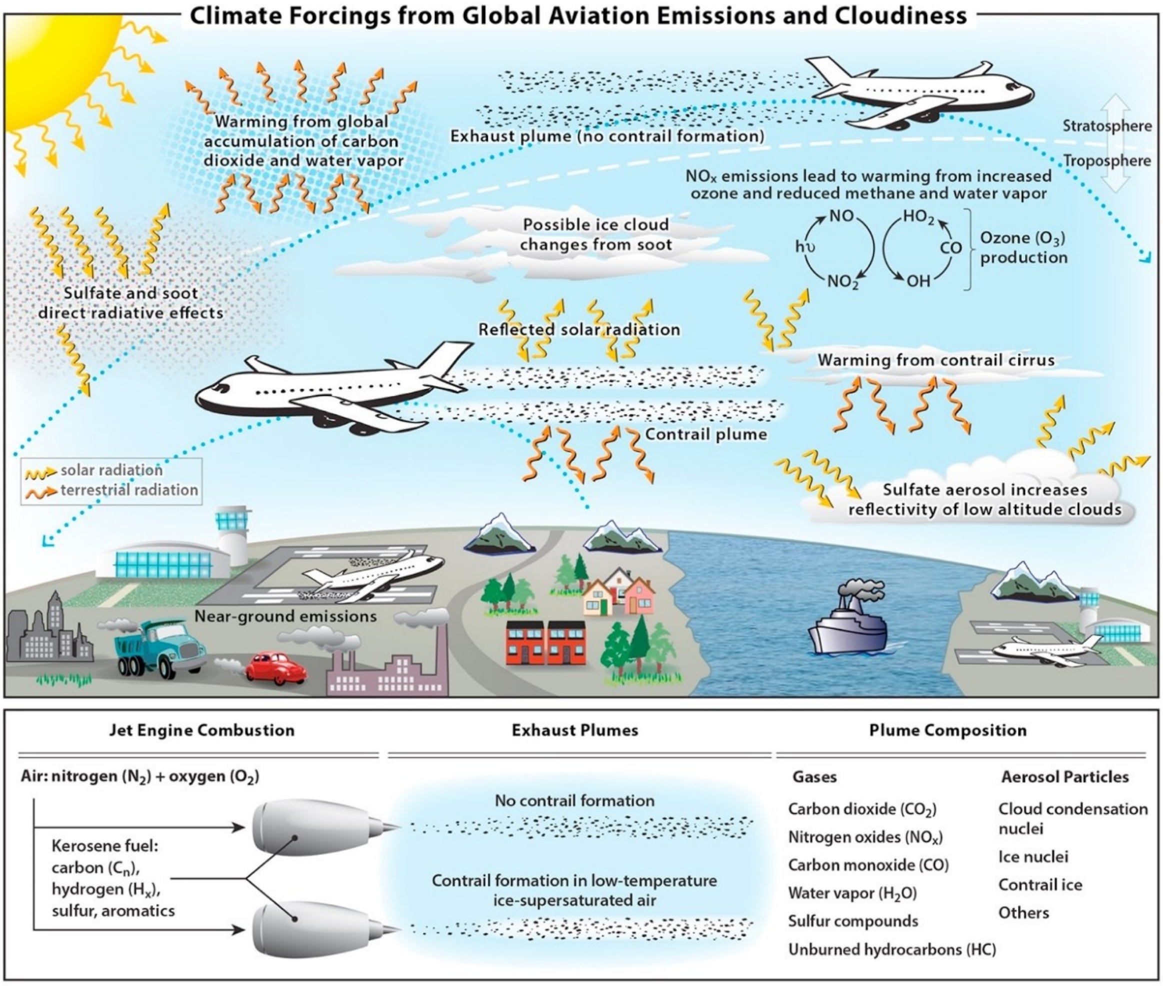


Figure 2.6: Aviation effects on the climate. Source: Lee et al. 2021. Reprinted with permission from Elsevier. © 2021 Elsevier

2.4.1 Reducing aviation demand

One way to reduce SCLF emissions from aviation would be to reduce overall demand. As Liu et al. (2020) describe, the primary driver of global aviation demand growth is global economic integration, making more people both want to and be able to travel to other parts of the world. As IATA (2008) note, there is an income elasticity effect of roughly +2: every time that incomes rise by 10%, aviation demand would then rise by 20%. The effects are therefore the strongest in developing country regions, where income growth is faster. Gössling and Humpe (2020) project annual growth rates above 5% in Africa, Asia-Pacific, Latin America, and the Middle East, and slowest – roughly 3% – in Europe and North America. Currently, Europe accounts for 49% of aviation demand; by 2050, the authors project these two regions to account for 34%, with the Asia-Pacific region accounting for 44% (Gössling and Humpe 2020). At the same time, per capita passenger volume in developing countries is much lower than in wealthy countries. It is hard to imagine developing countries taking active steps to cap, or reduce, aviation demand levels, even as their own demand is far lower than in wealthy countries.

One possibility for demand reduction is to implement policies that would make flying more expensive. These could include taxes or fees, a limitation in the landing rights available at airports, or a mandated shift to more expensive sustainable aviation fuel, an option that we describe in greater detail below. So far in Europe, the Emissions Trading System requires emissions certificates to be purchased for intra-European flights, amounting to a tax of up to CHF 100 per tCO_2, while the European Green Deal foresees implementing a sustainable fuels requirement, rising to cover at least 60% of fuels used on all flights departing Europe. Estimates of the effects of increases in aviation prices on demand levels vary widely, according to (among other things) whether it is business or pleasure travel, as well as the distance and length of stay. IATA (IATA 2008) report on specific values ranging from -0.24 up to -2.34, with a weighted average somewhat higher than 1. That means that an increase in aviation prices of 10% would lead to a reduction in demand of somewhat more than 10%, all else (including incomes) being equal. Imagine that the shift to sustainable aviation fuels (SAFs) leads to a doubling in fuel costs. Given that fuel accounts for roughly 30% of airline ticket prices, a 100% increase in fuel costs would lead to a 30% increase in ticket prices. This in turn could lead to a somewhat great – perhaps 40% – decline in passenger volume. This would offset more than a decade of growth but be unlikely to offset all of the growth anticipated between now and 2050. It would require other policies specifically targeting aviation volume to lead to a shrinking of the sector.

Put together, it is challenging to imagine policies that could lead to a meaningful reduction in aviation demand. There may, of course, be disruptive surprises. COVID led to an immediate demand reduction of 50%.

2.4.2 Flight routing

A second way to reduce the effects of SLCFs is through flight-rerouting, designed in such a way as to cause airplanes to avoid flying through low-temperature ice-supersaturated air, where contrail formation is most pronounced. Research more than 15 years ago identified significant variability in contrail formation, as a result of atmospheric conditions, and suggested that flight routing taking advantage of this variability could be an effective policy approach to reducing the short-term climate forcing from aviation (Williams and Noland 2005). Since then, numerous papers have estimated the warming effects, and their variability, due to the interaction of aviation and atmospheric conditions (e.g., Teoh et al. 2022; Kärcher

2016). Estimates of cooling effects can be obtained from climate models that include the effects of persistent contrails. One study validated these model results by comparing them with observed cooling over a 6 month period during the initial COVID crisis, when aviation volume over Europe declined by 72%, and found the agreement between model predictions and observations to be roughly 90%, suggesting that the model estimates are valid (Schumann et al. 2021).

Several studies have explored the option of flight rerouting to avoid contrail formation. Initial research raised concerns about increased fuel use due to longer flights, when efforts are made to avoid locations where contrail formation will be greatest (Sridhar et al. 2011). More recent modelling work has suggested that it may be possible to eliminate nearly all contrail-induced forcing through minor changes in altitude of roughly 20% of flights over Europe, with only a 0.7% increase in fuel consumption for those flights (Teoh et al. 2020); similar results have been obtained for the United States (Avila et al. 2019). These results are model-derived, and have yet to be tested through observational studies; Molloy et al. (2022) suggest how a trial over the North Atlantic could be conducted in order to validate the model predictions. Such a study has yet to be carried out. There are also no data available as to whether these changes have any effects on passenger (dis-)comfort due to turbulence.

One can conclude, then, that there is likely to be a major opportunity for flight routing to lead to a large reduction – potentially close to a complete elimination – of warming caused by contrail formation, with only a modest impact on fuel consumption. This could achieve close to the 0.032°C of cooling that would result from the immediate end to SLCF from aviation. Before such changes can be made on a permanent operational basis, there needs to be additional testing.

2.4.3 Fuel switching

Finally in the area of aviation, there appear to be potential synergies between CO_2 reduction and reduction in SLCF effects through the switch to sustainable aviation fuels (SAFs), hydrogen, and electric propulsion systems.

Fully electric propulsion systems emit no gases, and hence do not contribute to the concentration of SLCFs in the atmosphere. There has been recent progress in developing both hybrid electric and full electric planes for commercial use (Wheeler et al. 2021). All of the full electric designs currently under development are both short-range – up to 350 km – and small, the largest of them designed to seat 11 passengers. In order to achieve a range of more than 350 km, battery technology would have to develop significantly, and energy densities would have to increase by an order of magnitude or more in order to enable electric flights of more than 1,000 km. Simply put, electric drive trains may become adopted, but between now and 2050 they are likely to fit into small regional niches, and are very unlikely to be able to spread to larger planes flying most current routes. Hybrid planes, by contrast, would be more feasible. These however rely primarily on fuel for most of the flight, with the electric component kicking in primarily to increase power – and decrease noise – at take-off (Friedrich and Robertson 2015). That would leave little impact on emissions of SLCFs, as these primarily occur once the plane has reached cruising altitude. In short, electrification does not currently appear to offer an opportunity to reduce SLCFs by any substantial amount.

A second option for fuel switching involves the use of hydrogen, notwithstanding the concerns raised earlier in this report about hydrogen leakage. Hydrogen can be used in two ways: as a combustion fuel in conventional jet engines, and as an electricity storage medium (instead of batteries) when coupled to a fuel cell and electric drive train. The primary advantage of the former is that it would allow hydrogen to be used in aircraft designed with conventional engines, requiring less of a change in aircraft design; the primary advantage of the latter is the much greater energy efficiencies that can be achieved (Massaro et al. 2023). In either case a primary challenge is in configuring an airplane to be able to carry the required amount of hydrogen. Hydrogen's energy density by weight is 2.8 times as great as that of kerosene, meaning that a switch to hydrogen as a fuel source could result in lighter aircraft, with greater energy efficiency; the question mark here is whether the tanks required liquid hydrogen would themselves have to be substantially heavier, eliminating much or all of the gain (Khandelwal et al. 2013). On the other hand, hydrogen needs four times the volume of kerosene to store a given amount of energy; hydrogen-powered aircraft would thus need far larger fuel tanks than current models, if the energy efficiency of the drive train were similar. Given the need for insulation of the hydrogen tanks, fuel tanks would have to be relocated from the wings (where they currently are on all commercial planes) to the main fuselage, in addition to becoming larger (Baroutaji et al. 2019). With a great deal of funding flowing into research on hydrogen powered aircraft, many researchers see these as becoming technically viable within the next decade (Yusaf et al. 2023). Unfortunately, it is not yet entirely clear the extent to which hydrogen aircraft would reduce SLCF production. Compared to kerosene, hydrogen aircraft generate a greater amount of water vapor, in the case of fuel cells no (and in the case of hydrogen combustion less) NO_x, and no fine particulate emissions. One modelling study suggests that hydrogen aircraft would result in a substantial decrease non-CO_2 induced forcing, but not a complete elimination (Sáez Ortuño et al. 2023). More research is needed. This could suggest that the switch to hydrogen would be a way of substantially reducing contrail formation; currently this is unclear. What is also unclear is whether hydrogen-powered planes could be rolled out quickly enough to lead to a cooling effect prior to 2050.

The third fuel switching alternative is the move towards drop-in sustainable aviation fuels (SAFs), especially synthetic fuels produced from water and air-captured CO_2 using renewable energy sources. Legislation within the EU, and potentially to be adopted by Switzerland, would mandate a growing share of such fuels as a means of eliminating the CO_2 emissions from aviation. But these fuels are also chemically purer than fossil kerosene, and as a result burn cleaner, emitting fewer fine particulates (Zhang et al. 2022; Undavalli et al. 2023). The best study conducted to date, using the engine type found on an Airbus A320, indicated particular emissions 70% below those of fossil kerosene (Schripp et al. 2022). This in turn could lead to a 50% reduction in contrail formation (Burkhardt et al. 2018). Studies suggest that this factor could make it substantially easier to achieve climate neutral aviation via the use of synthetic aviation fuels, compared to the continued use of fossil kerosene combined with negative emissions elsewhere (Brazzola et al. 2022). On its own, switching to entirely synthetic fuels would not lead to a net cooling effect, if aviation demand continues to grow at close to its current rate. There have been concerns raised about the viability of producing the volume of synthetic fuels required, given the relatively low efficiency in converting electricity or sunlight into a liquid energy carrier (Sacchi et al. 2023). Given the projected efficiency of the solar-to-liquid production pathway developed at ETH, roughly 40,000 km^2 of semi-arid to arid land would be required for the needed solar energy collection to fuel the existing global aviation fleet (Schäppi et al. 2022). That is, needless to say, a lot of land. At the same time, however, as one example the country of Oman recently announced that it was earmarking an unoccupied region comprising 50,000 km^2 for renewable energy and sustainable fuels production.

2.4.4 Potential for Swiss action

Most likely, the greatest potential for rapid decreases in SLCFs from aviation lie in changes in flight routing, if envisioned field-studies confirm the results of model-based analyses. Deploying the option of flight rerouting would require international cooperation in the area of flight control, especially in Europe, where most flights are international. Switzerland lies at the centre of Europe, with a huge volume of flights passing over the country every day. Swiss cooperation with other countries would be essential for changes made in European airspace.

The other possible area for Swiss contribution is in R&D related to fuel switching. Primarily, Switzerland is a technology leader in the area of sustainable aviation fuel production, both in terms of the needed direct air capture of CO_2 and in the transformation of CO_2 and water into aviation fuel. Researchers at ETH Zurich, for example, demonstrated one of the most promising technology pathways for the latter (Schäppi et al. 2022). The patents for this technology are owned by the Swiss firm Synhelion, which is currently seeking to scale up production, and has entered into fuel supply agreements with Swiss and Lufthansa airlines.

3 Negative CO_2 emission technologies

All scenarios that achieve 1.5°C of global average temperature rise make use of negative emission technologies (NETs), both to offset residual CO_2 emissions and enable the achieving of net zero, and to reduce the atmospheric concentration of CO_2 during the second half of the century (Kikstra et al. 2022). NETs can also be described as carbon dioxide removal (CDR). The recently adopted Swiss Climate Law also specifies the use of NETs to achieve both net zero by 2050, and net negative emissions after 2050, and lists these as "biological or technical processes, in order to remove CO_2 from the atmosphere and sequester it permanently in forests, soils, wood products, or carbon storage media" (United Federal Assembly 2022).

3.1 Global assessments of NETs

Figure 3.1 shows the overview of NETs described by the IPCC in its Sixth Assessment Report.

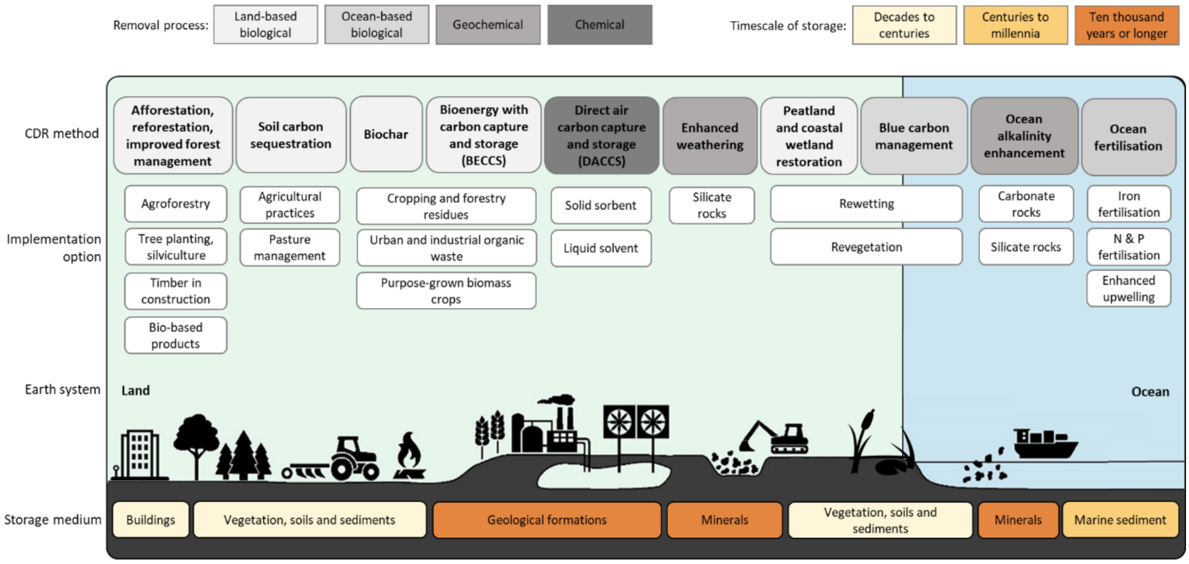


Figure 3.1: Overview of NETs / CDR methods. Source: Babiker et al. 2022.

Figure 3.2 illustrates a schematic diagram of the different classes of NETs, showing that they fall into three temporal categories: those that will likely be deployed prior to the achieving of net zero emissions; those deployed as part of reaching net zero emissions, first of CO_2 and later of all GHGs; and, those deployed as part of achieving net negative emissions. During the latter period, the total quantity of NETs exceeds the level of net negative emissions, due to the need to continually offset residual CO_2 and non-CO_2 emissions.

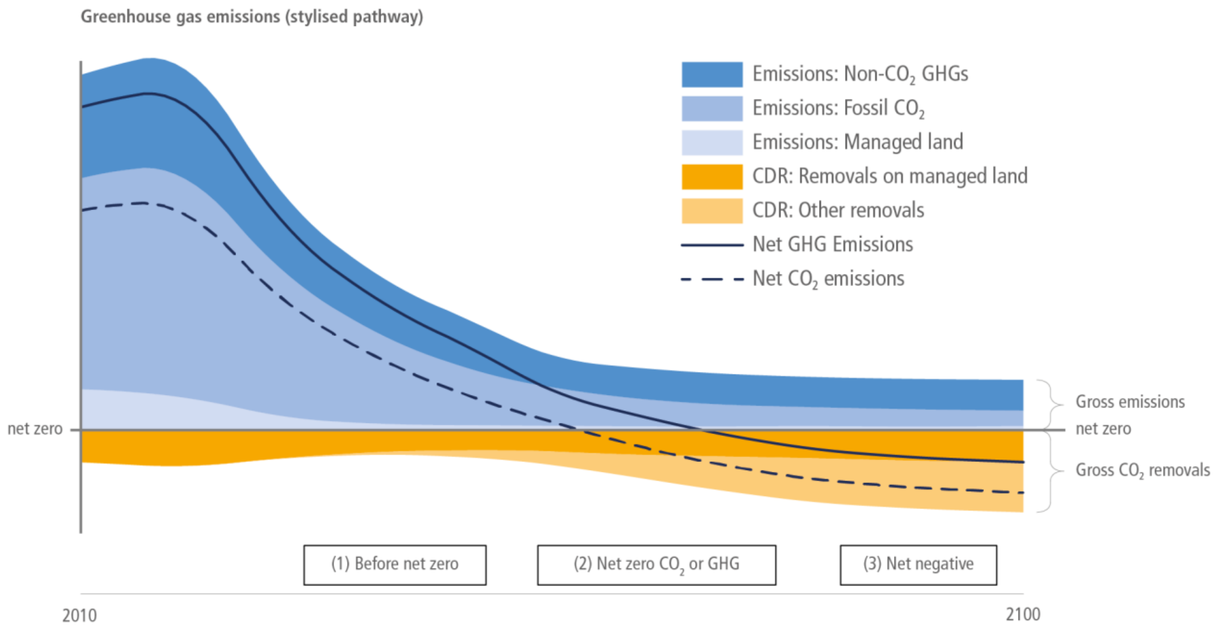


Figure 3.2: Schematic of CO_2 removals. Source: Babiker et al. 2022.

The total amount of NETs needing to be deployed in order to achieve 1.5°C warming scenarios is, simply put, massive. Figure 3.3 shows a large number of IPCC scenarios, several of which are known as Illustrative Mitigation Pathways (IMPs). The line depicting IMP-GS would limit warming to 2°C, while the line depicting IMP-Neg would achieve 1.5°C by 2100 after a period of temperature overshoot. As can be seen in the right-hand graph, the IMP-Neg line is on the order of 12 $GtCO_2$ per year during the final decades of the century. Given an additional need to offset residual CO_2 emissions, total CO_2 removals would need to be somewhat larger, more on the order of 15 $GtCO_2$ annually.

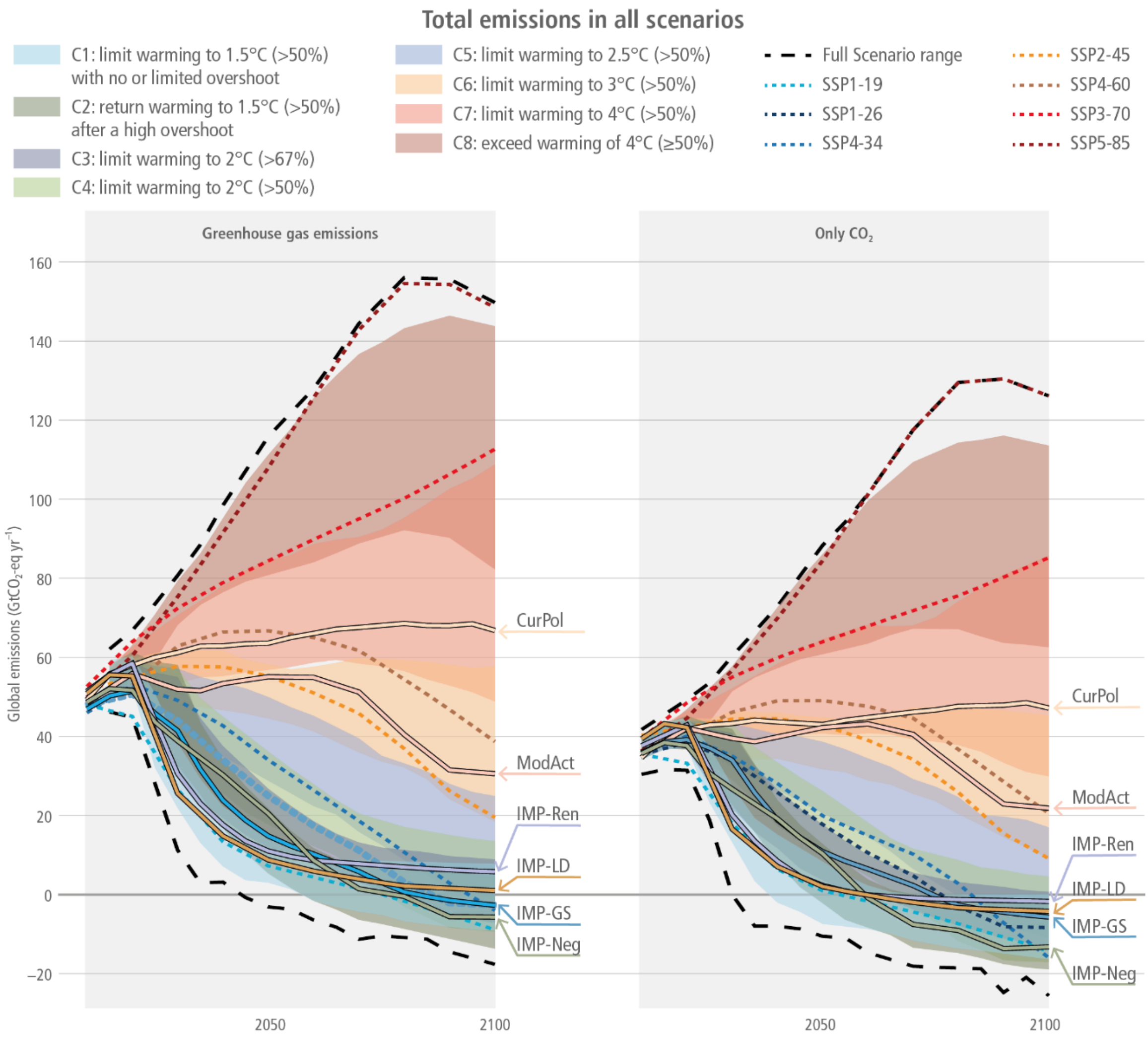


Figure 3.3: IPCC emissions pathways. Source: Riahi et al. 2022.

Beyond this global overview, in the following section we describe key features of these NETs that are relevant for Swiss deployment. We need to note that greater detail can be found in a recently released report from TA Swiss (Cames et al. 2023).

Table 3.1: Terrestrial NETs technological, potential, and costs. Status refers to the Technological Readiness Level (TRL), where a TRL of 8-9 indicates readiness for deployment, TRL 6 indicates it has been demonstrated in the relevant environment, and TRL 3-4 indicting that it has been demonstrated in laboratory conditions. The economic potential shows the central estimate of deployment at costs below USD 100 per tCO_2. BECCS stands for bioenergy with carbon-capture and storage. DACCS stands for direct air carbon capture and storage. Sources: Babiker et al. 2022, Nabuurs et al. 2022.

Technology	Status (TRL)	Cost range (USD per tCO_2)	Technical potential ($GtCO_2$ annually)	Economic potential ($GtCO_2$ annually)
Afforestation and forest restoration	8-9	0-240	0.5-10	1.5
Bioenergy with carbon capture and storage (BECCS)	5-6	15-400	0.5-11	1.5
Biochar	6-7	10-345	0.3-6.6	1
Soil carbon enhancement of crop and grasslands	8-9	-45-100	0.6-9.3	1
Agroforestry	8-9	n.a.	0.3-9.4	0.75
Peatland management	8-9	n.a.	0.5-2.1	0.5
Use of wood products	8-9	n.a.	0.1-3.5	0.4
Enhanced weathering	3-4	50-200	2-4	n.a.
Direct air carbon capture and storage (DACCS)	6	100-300	5-40	n.a.

3.2 Key findings from the TA Swiss study of NETs and other studies

Researchers in Switzerland recently conducted an extensive review of NETs, with the purpose of informing Swiss policymakers concerning the strengths and weaknesses of key options (Cames et al. 2023). Here we provide a synopsis of their key findings, which represent state of the art insights relevant for Switzerland. The report focused on five main NETs, which encompass the main options seen in Table 3.1. Across the five options, the report concluded that none of the options on their own could completely offset residual Swiss emissions, and hence put Switzerland into the territory of negative emissions. Rather, one would need to combine multiple options in order to do so.

3.2.1 Forest management and wood utilization

The TA report relies to a large extent on data from the most recent Swiss Forest Report, which is published every ten years by the WSL research institute under contract to the federal government (Rigling and Schaffer 2015). That report suggested that Switzerland was undergoing net afforestation annuals, with there having been a net increase in the overall wood volume to be found in Swiss forests of 3% over the time-period 1995 – 2013. In turn, this suggested that wood harvests could be substantially increased in Switzerland without leading to net emissions due to deforestation; alternatively, sticking with the status quo would result in annual afforestation, in line with climate protection goals. The 2015 report suggested that over the period 2008-12, the growth in Swiss forests sequestered 1.6 $MtCO_2$ annually, corresponding to about 3% of Swiss emissions over that period (Rigling and Schaffer 2015).

It must be noted, however, that the data underlying the 2015 WSL report, and thus the TA report, are becoming dated. More recent data suggest that the picture has changed somewhat. For example, the 2015 WSL report estimated the use of wood products at 2.77 million m^3 annually. In a more recent report, this use was estimated at averaging roughly 3.2 million m^3 over the years 2019 and 2020, a substantial increase (Winterberg et al. 2021/2022). What the more recent data do not include, however, is the use of wood for energy purposes, as well as for paper and cardboard production; in the 2015 data, these comprised roughly 7 million m^3 annually, and hence somewhat overshadow the use of wood products themselves. While an update to the full 2015 report is currently under preparation, it is not yet finalised, and it would be premature to cite it.

The TA Swiss report notes that the use of wood for construction has a long tradition in Switzerland, and that since the revision to the fire codes in 2015, wood can be used in all building types. It cites a price range of USD 1 – 100 per ton of CO_2 that is sequestered in wood products, based on the costs of substituting other materials that may be of lower production cost. Clearly this is a wide range, and the report does not attempt to specify which potential applications could be the most cost effective. The report notes that the mitigation potential – which includes both the negative emissions from carbon being locked up in wood products, and the reduction of emissions due to decreased use of other carbon intensive materials – totals roughly 3 $MtCO_2$ per year. Of this, the pure negative emissions that can be realized are in the range of 1 – 2 $MtCO_2$ per year. The report notes multiple risks associated with increasing wood utilisation, and hence suggests that more study is required, in order to develop a sustainable management plan for Swiss forests including the additional use of wood products.

We have identified two other studies that complement the TA results, giving additional insights. First, Suter et al. (2017) conducted a study, focusing on Switzerland, comparing the carbon impacts of different uses of harvested wood. While there were substantial uncertainties, the best performance was obtained when using wood for sawn timber products (i.e. beams and boards), while also using the waste products over the entire life cycle (ultimately including the timber products themselves) for energy production. The researchers did not, however, compare scenarios with different wood harvesting rates. Researchers taking Finland as a case study did this, with results that are potentially important for Swiss forest policy (Soimakallio et al. 2021). First, their results agreed with those from Switzerland, showing that the CO_2 mitigation benefits were highest when wood products were used to substitute energy intensive building materials, rather than being used directly for energy production. Second, however, they found that overall CO_2 fluxes into the atmosphere were reduced the most when wood harvesting itself was reduced, and the stock of wood within the forest itself was allowed to increase. The reason was that with forest growth, most CO_2 removed from the atmosphere is locked up in living trees; by contrast, when wood is harvested, roughly half of the biomass is not used to substitute for other materials or energy, but rather decomposes, increasing CO_2 fluxes into the atmosphere. The researchers conclude that even in the case of using wood for energy, combined with BECCS, the overall CO_2 emissions are higher than with obtaining energy from other sources, and allowing forests to grow.

So on the one hand, there may be potential for Switzerland to generate negative emissions through increased use of wood for energy or wood products, although the updated WSL report, due for publication in 2025, will likely shed more light on this issue. On the other hand, the negative emissions would likely be higher by not using wood for these purposes – especially for energy production – but rather allowing the stock of CO_2 locked up in Swiss forests to grow. A continuation of current trends, where harvesting of wood is below the growth rate of the forests, may achieve this outcome, again pending the data to become available in 2025.

3.2.2 Soil management, agroforestry and biochar

The TA Swiss report next examines the possibility of increasing carbon storage in agricultural soils, including through the use of biochar. It notes, consistent with the global assessment, that methods to enhance soil carbon already exist, and indeed are already practised by many Swiss farmers. Similarly, practising agroforestry in some locations is also feasible, already being practised by some farmers. The utilization of biochar is somewhat less advanced, at TRL 9 rather than 10, and the report notes that there is currently no practice of biochar production and storage in Switzerland. The report cites Swiss specific costs for soil management of USD 0-100 per tCO_2, but these ultimately derive from studies conducted outside of the country, such as those informing the IPCC report, and there are no studies suggesting Swiss-specific values. The situation is different with respect to biochar: cost estimates range from USD 8-300 per tCO_2 from non-Swiss studies, whereas Swiss estimates range CHF 10-135 per tCO_2, with a central estimate of CHF 30 per tCO2 in 2030, falling to CHF 10 per tCO_2 in 2050.

The report suggests that soil management could lead to negative CO_2 emissions of up to 2.7 $MtCO_2$ per year. The report does not report on negative emissions possible through agroforestry, but does suggest that it has the potential to reduce, or even eliminate, the net emissions from agriculture. For example, Agroscope reports that if 13.3% of the agricultural land in Switzerland switched to agroforestry practices, it would offset roughly 13% of the country's agricultural emissions. In short, agroforestry could be a means of reducing residual emissions, ensuring that a higher proportion of the NETs deployed are going to actually reducing atmospheric CO_2 concentrations, rather than offsetting emissions. Finally, the report suggests that biochar has the potential in Switzerland to generate up to 2.2 $MtCO_2$ in negative emissions.

The report notes some risks associated with each of the three options. In the case of increased soil carbon, the report notes the challenge of accurately monitoring soil carbon levels, as well as potential problems with increased fertiliser use associated with more intensive production. In the case of agroforestry, the report mentions the likelihood that crop yields would decline, although it does not report how much. In the case of biochar, the report notes the possibility of introducing more pollutants, including heavy metals, into the soil, and potentially disrupting the nitrogen cycle.

3.2.3 Bioenergy with carbon capture and storage (BECCS)

The TA Swiss report then examined BECCS; consistent with our literature review, it identified no Swiss-specific studies on BECCS methods or costs, although it did identify a study that estimated the Swiss potential. In terms of technological maturity, it reported – similar to the IPCC – a TRL 9 level, indicating that it could easily be deployed in the near future, demonstration plants having already been in operation in other countries. It notes cost estimates covering the range of USD 30-400 per tCO_2, derived from the global literature. It notes that costs are lowest in locations with low-cost biomass availability, as well as close access to CO_2 underground storage sites.

The report noted that there already exists an agreement between the federal administration (UVEK) and the Association of Swiss Waste Disposal Facilities to develop at least one location for carbon capture and storage (CCS) at a waste incineration facility. As the carbon content of waste in Switzerland derives from roughly 50% biomass (the other 50% being fossil), roughly half of the emissions captured and stored from these facilities can be considered to represent BECCS negative emissions. The TA Swiss report suggests that the theoretical potential for BECCS in Switzerland is up to 5.1 $MtCO_2$ per year by 2050, with a nearer term potential of 3 $MtCO_2$ per year. With respect to the latter, this would make use of existing point sources of CO_2 of biological origin, especially biomass and waste power plants, and also including cement factories using biomass as a heat source, and pulp and paper producers.

The TA Swiss report notes the potential for negative impacts associated with BECCS, particularly if it comes into conflict with food production or the utilization of wood for wood products. As we mentioned in a previous section, directly utilizing harvested wood for BECCS would likely be counterproductive, and a greater amount of CO_2 sequestration could take place through the avoidance of the associated wood harvesting, and the accumulation of forest biomass. Indeed it is for this reason that the use of BECCS in Switzerland may be best limited to the lower, 3 $MtCO_2$ per year, estimate, which is associated with adding CCS to existing biomass combustion facilities, rather than seeking to expand biomass combustion in the future.

A major cost and feasibility issue with BECCS, which is also relates to DACCS, is the availability of suitable CO_2 storage sites. The TA Swiss report notes that there is, in Switzerland, a theoretical potential to store 2.5 $MtCO_2$ per year, by 2050. This value lies substantially beneath the combined potential for BECCS and DACCS to generate the CO_2 needing to be stored. Moreover, there have been no CO_2 storage sites in Switzerland that have actually been tested; it would take years, more likely a decade or more, to determine whether in fact the geological storage sites are in fact appropriate. For both reasons, the TA Swiss report notes that some or all the CO_2 from BECCS and DACCS would need to be transported to other locations for storage, such as the North Sea or Iceland. In both locations, pilot projects have already demonstrated the suitability for permanent storage. There is a great deal of variation in the costs of CO_2 transport, depending on geography, distance, and means of transport (e.g. pipeline, rail, ship) (Smith et al. 2021), and it has not been possible to determine precise estimates for the Swiss case.

3.2.4 Direct air carbon capture and storage (DACCS)

The TA Swiss report then considers DACCS. First, it provides an overview of the technology, differentiating between processes relying on adsorption (as with the Swiss Climeworks process) and absorption (as with the Canadian Carbon Engineering). It notes that the two processes vary in terms of the thermal and electrical energy requirements, and the temperature needed for the thermal energy. With the absorption process, 2.4 MWh of thermal energy, at temperatures of 850-900°C are required, whereas with the adsorption process 0.6-1.7 MWh of thermal energy at temperatures of 80-120°C are required, in both cases per tCO_2 that is removed from the air. Both processes require additional electrical energy of 0.2-1 MWh per tCO_2. The processes are at TRL 7-8, meaning that both have been successfully demonstrated in field sites, but not yet at the scale that would be required.

In terms of potential, the TA Swiss report notes that the Federal Council suggests up to a cumulative amount (not annual) of 2.5 $GtCO_2$ would be possible within Switzerland, although it also notes that higher priority would be given to local CCS and BECCS. The global potential has been suggested to be up to 10 $GtCO_2$ annually, although this too is speculative; ultimately the limiting factor is the availability of renewable energy, and geologic storage locations. One needs to note that at 3 MWh of energy per tCO2, 10 GtCO2 would require 30,000 TWh of energy per year. Total global primary energy demand in 2021 was roughly 160,000 TWh (BP 2022), suggesting that deployment of DACCS at the 10 $GtCO_2$ level would require energy equivalent to about 19% of current energy use.

The costs estimates are quite preliminary and range from CHF 90-221 per tCO_2 for the absorption process to CHF 600-800 per tCO_2 for the adsorption process. In the case of both technologies, the developers project costs eventually falling towards USD 100 per tCO_2. Not explained in the TA Swiss report, is that, to a large extent this depends on the energy costs; assuming roughly 3 MWh of energy being needed, at energy costs of USD 25 per MWh this alone would yield a cost of USD 75 per tCO_2. Note that both wind and solar PV, in ideal locations, have achieved costs below USD 25 per MWh, whereas in less than ideal locations their costs are up to several times higher (IRENA 2022). At a cost of USD 100 per tCO2, deploying DACCS to achieve 10 $GtCO_2$ annual removal would incur costs of USD 1 trillion annually. To put this into perspective, global military spending in 2022 was USD 2.24 trillion, while global GDP was USD 100 trillion. From an economic perspective, it appears that investing 1% of global GDP into sufficient NETs to reduce the temperature from 2°C to 1.5°C would be cost effective. Burke et al. (2018) find that under a scenario of 1.5°C temperature rise, compared to 2°C, the reduction in climate-associated damages would result in additional 1.5-2% of global GDP by 2050, and an additional 3.5% by 2100.

It is also clear that cost-effective deployment of DACCS would likely see it being built in regions with abundant and low-cost renewable energy sources combined with proximity to geologic storage sites. Almost certainly this would mean places other than Switzerland.

3.2.5 Carbon mineralisation

Finally, the TA Swiss report covers various mechanisms for carbon mineralisation, including enhanced geological weathering. The report details several different processes, including the carbonisation of cement, and of basalt stone. It notes that both processes are at a relatively unadvanced stage of technological maturity, consistent with the table from the IPCC reports. It suggests cost estimates for the mineralisation of cement and concrete in the range of CHF 150-1,000 per tCO_2, and for weathering of stone dust in the range of CHF 70-140 per tCO_2. It suggests that by 2050, mineralisation in Switzerland could generate negative emissions of up to 2.5 $MtCO_2$ annually.

3.3 Comparison of NETs in a Swiss context

Comparing the various options for NETs in a Swiss context, it is clear that it would be challenging to scale them quickly enough, within the country, to offset much more than the country's residual emissions. Indeed the Swiss Climate Strategy for 2050 basically suggests this possibility. Afforestation in Switzerland is currently sequestering 1.6 $MtCO_2$ annually. Scaling this up would require a sacrifice in land availability for agriculture, or would require a major reduction in harvests, cutting into the current use of wood for district heating and construction. Scaling up carbon storage in construction wood would face the constraint imposed by the forest, and come at the expense of afforestation. Similarly, scaling up BECCS beyond the current point sources of biogenic CO_2 emissions – biomass fueled power plants and waste incineration facilities – would be counterproductive, also coming at the expense of deforestation. The limit here would appear to be roughly 3 $MtCO_2$ annually. Carbon mineralisation could occur at scales up to 2.5 $MtCO_2$ annually. Combined, this would result in 7.1 $MtCO_2$.

A major cost and feasibility issue for both BECCS and DACCS is the availability of suitable CO_2 storage sites, and the cost of transportation to those sites. The TA Swiss report notes that there is, in Switzerland, a theoretical potential to store 2.5 $MtCO_2$ per year, by 2050. This value lies substantially beneath the combined potential for BECCS and DACCS to generate the CO_2 needing to be stored. Moreover, there have been no CO_2 storage sites in Switzerland that have actually been tested; it would take years, more likely a decade or more, to determine whether in fact the geological storage sites are in fact appropriate. For both reasons, the TA Swiss report notes that some or all the CO_2 from BECCS and DACCS would need to be transported to other locations for storage, such as the North Sea or Iceland. In both locations, pilot projects have already demonstrated the suitability for permanent storage. There is a great deal of variation in the costs of CO_2 transport, depending on geography, distance, and means of transport (e.g. pipeline, rail, ship) (Smith et al. 2021), and it has not been possible to determine precise estimates for the Swiss case.

The most recent analysis on these issues of storage sites and transportation costs is contained in a manuscript prepared by ETH researchers, and which is currently under review at a leading international journal. Because it is not published, we do not cite it here, but do allude to some of the previous results on which it relies. The starting point for their analysis is the observation that currently operated European sites for geological storage of CO_2 are located primarily in the north.

The largest and oldest site is Sleipnir, which has been injecting CO_2 into a gas field operated under the North Sea, roughly halfway between Norway and Scotland by the Norwegian fossil fuel company. It started operations in 1996, and has thus been generating data over the more than 25 years since then, both contributing to the development of monitoring technology, and demonstrating the feasibility of such geological storage (Furre et al. 2017). As of 2018, several million tons of CO_2 had been deposited in Sleipnir (Kvamme and Aromada 2018), with no evidence of leakage, and leading to estimates that the geological field could ultimately accept 600 billion tons CO_2. Other, smaller European storage sites currently in operation are close to the Norwegian coast, in the UK, Ireland, the Netherlands, and Italy. The latter lies off the coast near Ravenna, began operation in 2022, with plans for it to store 25,000 tons per year during the pilot phase until 2027, with the possibility of storing up to 4 million tons per year thereafter. Finally, there is a unique storage site in Iceland, where it has been demonstrated that the volcanic conditions allow for rapid CO_2 mineralization, removing any doubts of leakage, as the CO_2 reacts chemically with the rock formations within a timeframe of several months, rather than up to 1,000 years in other geologic conditions (Matter et al. 2016). The Iceland storage site is also the testing facility for the one DACCS facility currently being operated, currently capturing and storing 4,000 tons CO_2 per year. It has been estimated that the geological formation in Iceland, together with similar formations to be found along oceanic ridges, could accept 100,000-250,000 $GtCO_2$, thereby orders of magnitude larger than would be required (Snæbjörnsdóttir et al. 2014).

Switzerland currently has no CO_2 storage sites in the planning or testing phases. Personal communications with the authors of the ETH study suggest that storage sites in Switzerland may be possible, and yet these would differ qualitatively from storage sites that have been developed so far, all of which utilize existing oil and gas fields with known permeability properties, with the exception of the Iceland site utilizing volcanic rocks for rapid mineralization. Hence, before utilizing a Swiss site, it would take extensive testing and monitoring to guarantee long-term suitability. This would likely require decades. Before mid-century at the earliest, then, Switzerland would need to make use of other storage sites.

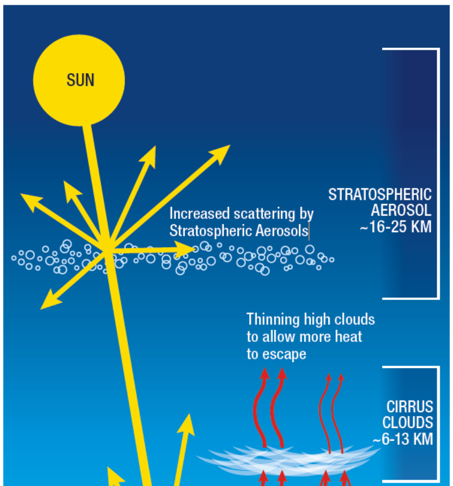
Shipping CO_2 from Switzerland to these other sites would require one or more technological solutions. For large volumes of continuous shipping, pipelines (which can include repurposed natural gas pipelines) appear to be the most cost-effective option. Their costs depend on distance, size, and whether they need to be built new, or can make use of pre-existing natural gas infrastructure, and under ideal circumstances would be as low as CHF 0.01 per tCO2 per km. Other options make use of ISO containers, which can be transported by train, barge, and ship. For container-based shipping, costs decrease as a function of distance, generally reach CHF 0.10 per tCO_2 per km. Given that Sleipnir, for example, is roughly 1,000 km from Switzerland, the costs for CO_2 shipping would be at least CHF 10 per tCO_2 under a least-cost pipeline scenario, and potentially CHF 100 per tCO_2 for other options, including more expensive pipelines of container-based shipment. Especially the latter number suggests that it could make good economic sense for Switzerland to finance DACCS or BECCS activities closer to the site of geological storage, rather than at home.

4 Solar radiation modification

A natural option to modify the radiative balance towards cooling is to reduce the incoming solar radiation, i.e. enhance the albedo of the Earth. Another possibility consists in increasing the atmospheric transmission of the infrared thermal radiation from the planet by, for instance, changing the transmission properties of cirrus clouds (Leisner et al. 2013). The most studied options to date can be split into the following topics (National Research Council 2015, National Academies of Sciences and Medicine 2021):

1. **Stratospheric aerosols injection (SAI)**
   SAI aims at reflecting the incoming visible solar radiation by increasing the stratospheric albedo. To this end, additional stratospheric aerosols or precursors are injected into the stratosphere.

2. **Marine cloud brightening (MCB)**
   MCB aims at increasing the albedo of low lying



clouds above the oceans by increasing the number of condensation nuclei.

3. **Cirrus clouds thinning (CCT)**
CCT aims at modifying the transmission properties of cirrus clouds in the infrared to enhance the evacuation of thermal radiation from the Earth.

4. **Surface Albedo Modification (SAM)**
SAM aims at enhancing the reflection of the incoming visible solar radiation by modifying the surface albedo and/or land use.

Figure 4.1: Illustration of current solar radiation management activities. Source: National Academies of Sciences and Medicine 2021. Used with permission of the National Academies Press. © 2021 NASM

4.1 Stratospheric Aerosols Injection (SAI)

4.1.1 A “real scale experiment”: the Mount Pinatubo eruption

Proposals of cooling the Earth’s climate by intentionally injecting aerosols in the stratosphere backs to the 70s (Budyko 1977). The concept attracted significant attention after the publication of seminal articles from prominent scientists in the early 2000s, like the Nobel laureate Paul Crutzen (Crutzen 2006; Cicerone 2006). A major natural event concretized the early concepts by a “real scale experiment”: The eruption of Mount Pinatubo in June 1991. Such major eruptions, which inject massive amounts of sulphur aerosols in the stratosphere are relatively rare. Mount Pinatubo remains today the most documented model case for stratospheric aerosol injection and atmospheric cooling, but other eruptions like El Chichon in 1982, Krakatoa (1883), and Mount Tambora (1815) were also considered in the literature.

SO_2 injected	Aerosol size (H_2SO_4-H_2O)	Height of injection	Global spread time	Radiative cooling	Surface temperature
10-26 Tg	0.1-0.5 um	Around 15-25 km	5 months	From -3W/m^2, decay time: 2yrs	-0.3°C to -0,5°C on average over 3yrs

Summary of the cooling effects of the Mount Pinatubo eruption in June 1991 (Dutton and Christy 1992; Goodman et al. 1994; IPCC 2007, 2013; Read et al. 1993; Russell et al. 1996; Stein et al. 1994; Thompson and Solomon 2009) NB: 1 Tg = 1 million tons = 1 Mt

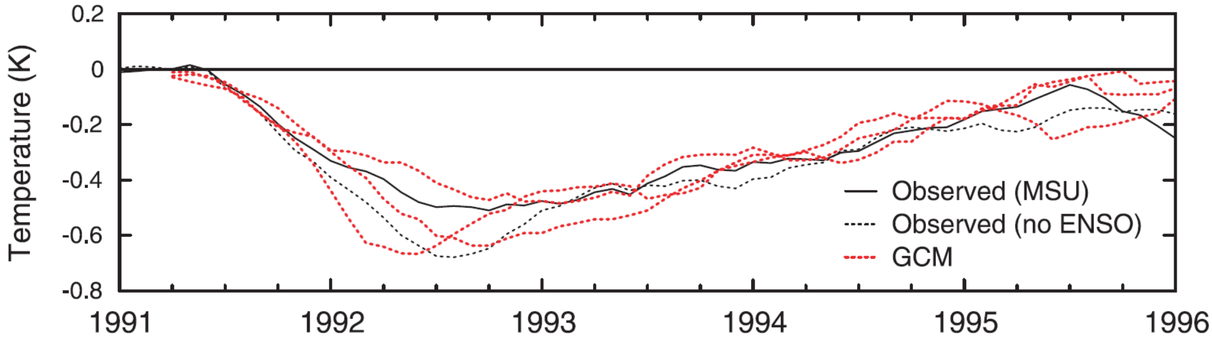


Figure 4.2: Global-mean temperature change in the lower troposphere after Pinatubo eruption. Comparison between observations and Global Circulation Models. Source: Soden et al. 2002.

As well established and celebrated by the Nobel Prize of P. Crutzen, F.S. Rowland and M. Molina in 1995, stratospheric aerosols are, however, strongly involved in stratospheric ozone destruction in the presence of chloro-fluoro-carbons (CFC) (Mccormick et al. 1995; WMO 2011, 2003; Solomon 1999). In particular, stratospheric aerosols and Polar Stratospheric Clouds (PSC) catalytically reconvert chlorine reservoir molecules (e.g., $ClONO_2$ and HCl) that were formed after photodissociation of CFCs into active ClO and Cl_2 species (Salawitch et al. 2005; Solomon et al. 1996). Additional pathways also involve other halogens, like bromine. As these mechanisms rely on catalytic photochemistry, the size, shape, and composition of PSCs are of key importance (Solomon 1999; Stefanutti et al. 1992; Stein et al. 1994; Deshler 2008; Deshler et al. 2019; Tritscher et al. 2021). PSCs have been categorized in PSC type I, of smaller sizes (typically 1 um) made of NAT (Nitric Acid Trihydrate) or SSC (Stratospheric Sulphuric Acid) and larger PSC of type II, which are large ice crystals. The combination of CFC and PSCs led to massive ozone depletion at the poles after the winter season, since its first observation as a “hole” in 1985 by the British Antarctic Survey Station at Halley (Farman et al. 1985). An additional, mechanical, effect associated with PSCs is denitrification and dehydration of the stratosphere by sedimentation, reducing the probability of forming reservoir molecules that capture the halogens.

As compared to the 1979-1990 period, the global average ozone column was decreased by an additional ~ 6% due to the aerosols injected by Mount Pinatubo during 1992 and 1993 (Mccormick et al. 1995).

The understanding of the catalytic ozone destruction by chlorofluorocarbons and PSCs led to the ban of the CFC production by the Montreal Protocol in 1987. However, due to the long lifetime of CFCs, 50 and 100 years for CFC11 and CFC12 respectively (Hoffmann et al. 2014), ozone depletion will still be observable for several decades (Weber et al. 2022).

Another effect induced by the Pinatubo eruption is a local temperature increase of 2.5–3.5K in the tropical lower stratosphere in summer 1991 (Labitzke and McCormick 1992; Randel et al. 2009), due to radiation absorption characteristics of sulphuric acid aerosols. Further impacts have also been investigated, like changes in regional hydrological cycle (Soden et al. 2002), increase of cirrus coverage (Robock et al. 2013), increase of light scattering, leading to higher photosynthetic activity of plants (Roderick et al. 2001), and modulation of the ocean circulation (e.g., Predybaylo et al. 2017). These latter impacts are still debated and often have not yielded definitive and quantitative conclusions yet (National Research Council 2015, National Academies of Sciences and Medicine 2021).

4.1.2 Volcanic eruptions: testbeds for SAI modelling

The only observations of stratospheric aerosol injections are linked to strong volcanic eruptions, which are rare events. The parameters in these natural "experiments" like size, composition, and optical properties of the injected particles, as well as altitude, location and timing of the injection can't be modified and have to be taken as such. For instance, sulfate aerosols, which absorb solar radiation and inherently heat the atmosphere, might not be an optimal solution for negative radiative forcing purposes.

Modelling the observed evolution of stratospheric aerosols has been intensively carried out and turned out to be challenging (Auchmann et al. 2013; Foley et al. 2014; Muthers et al. 2014; Thomason et al. 2008; Timmreck 2012; Toohey et al. 2013). Most recent models that include aerosol microphysics proved capable of qualitatively simulating the stratospheric dynamics associated with the Mt. Pinatubo and other volcanic eruptions (see, e.g., Gettelman et al. 2019; Marshall et al. 2019; Mills et al. 2016; Sukhodolov et al. 2018). In particular, the models could fairly reproduce the observed changes in stratospheric aerosol optical depth, radiative forcing changes, ozone loss, excess stratospheric heating, and enhanced transport of water vapor to the stratosphere. The uncertainties and discrepancies among the models amount, however, to several tens of per cents for most of the observables. Some parametric adjustments were also necessary to obtain a fair agreement with the observations (e.g. total SO_2 quantity injected and injection altitudes).

Modelling and simulations have progressed throughout the years thanks to intense international collaborations of scientists, such as for example the "Coupled Model Intercomparison Project (CMIP)" from the World Climate Research Program (WCRC; www.wcrp-climate.org/wgcm-cmip; Zanchettin et al. 2016). Despite the fruitful international collaboration, the accuracy and causal conclusions of the simulations are, however, still debated among the scientific community (Pauling et al. 2023).

Volcanic eruptions may also induce unexpected consequences on radiative forcing. The recent eruption of the (underwater) Hunga Tonga in 2022 led to heating instead of global cooling because it launched massive amounts of water vapor in the stratosphere in addition to SO_2 and ashes, and water vapor is, by far, the most efficient greenhouse gas in the atmosphere (Jenkins et al. 2023).

4.1.3 Technical Options and Potentials

Reflecting roughly 1-2% of the sunlight that the Earth absorbs would counteract the warming caused by the CO_2 increase (e.g., Kravitz et al. 2013). Most of the models show that the forcing (~ 4 W/m^2) associated with a doubling of CO_2 concentrations could be compensated by injecting of the order of 10 Tg of SO_2 per year in the stratosphere, which is of the order of magnitude of a Pinatubo eruption. As a rule of thumb, radiative cooling would amount to -0.11 to -0.31 W m^{-2} per $TgSO_2$, when injected at the optimal altitude and latitude (Kravitz and MacMartin 2020). Cumulative effects will occur if repeated yearly, depending on the SO_2 lifetime in the stratosphere.

In many studies, the interventions will have to be carried out over several decades to counteract the long CO_2 lifetime.

The efficiency of the negative radiative forcing process and the side effects of stratospheric injections strongly depend on the following parameters:

- Composition of the injected precursors or aerosol particles (SO_2, sulphates, mineral, etc.)
- Initial size distribution and its evolution, including aggregation and sedimentation
- Photochemistry and catalytic reactions (e.g., ozone depletion)
- Injection latitude
- Injection altitude
- Time of injection (season, QBO, El Nino, etc.)

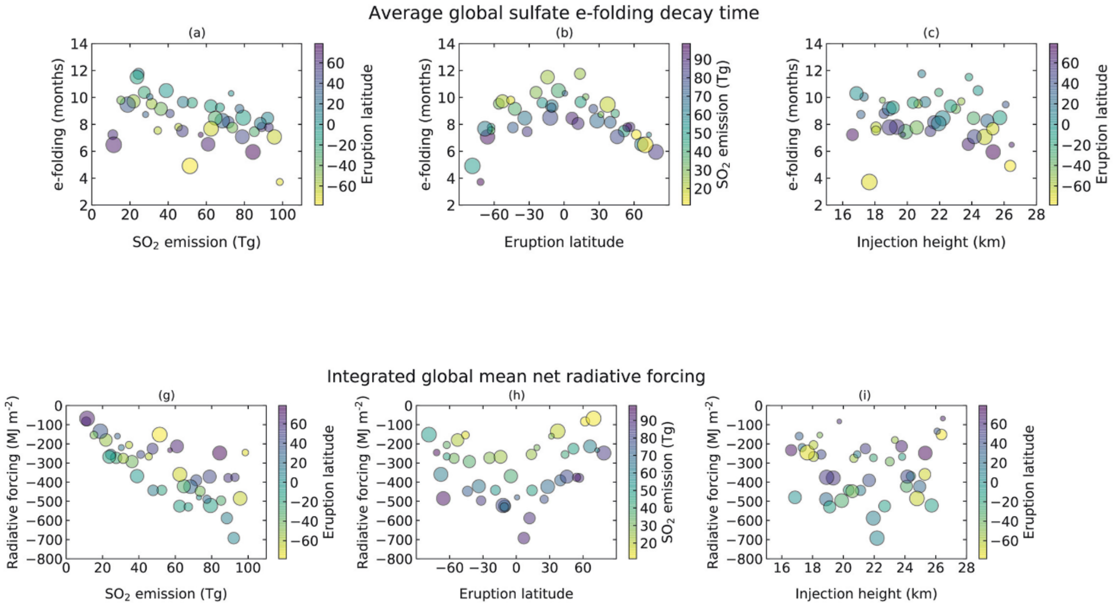


Figure 4.3: Results from 41 model simulations calculating the climate response to real and hypothetical volcanic eruptions. By emulating volcanic eruptions, the authors investigate the effects of key parameters, such as SO_2 emission load, latitude and altitude. In the upper row, the influence of these parameters on the sulfate decay time (at 1/e) and in the lower row on the mean net radiative forcing (From Marshall et al. 2019)

An example of exploration of this parameter space was performed by Marshall et al. 2019. In this study 41 model simulations were carried out, corresponding to real and virtual volcanic eruptions, with various intensities (from 10 to 100 Tg SO_2), latitudes (80S to 80N), and altitudes (15-25 km). Seasonal effects were not considered. From the results, it is concluded that negative forcing increases with the amount of injected SO_2, that the lifetime (at 1/e) of the aerosols is maximized when injected in the tropical belt, and that no clear trend is observed for the injection altitude. Within the considered parameter space, maximal values for the searched optimized outputs are:

	Maximum Obtained Value	SO_2 Emission	Latitude	Altitude
Decay time (1/e)	12 months	25 Tg	14° N	20.5 km

Integrated Forcing	-692 MJ/m^2	92 Tg	7° N	22.5 km
Forcing Efficiency	-11 $MJ/m^2/Tg$	24 Tg	14° S	23.5 km

As a comparison, for the Pinatubo eruption, the integrated global radiative forcing (global radiative forcing in W/m^2 integrated over the time on which it is active) was of the order of 130-230 MJ/m^2. Some tens of Tg of SO_2 would thus be necessary to achieve the observed cooling of the atmosphere, which is of the order of the Pinatubo eruption, and significantly less if injections are carried out at optimal latitudes, altitudes and season. A rough estimate of the negative forcing produced by SAI leads to -0.11 to -0.31 W m^{-2} per Tg of injected SO_2 (Kravitz and MacMartin 2020).

Interestingly, the net change in forcing per Tg SO_2 added to the stratosphere decreases as the total aerosol burden increases. As a consequence, the maximal negative forcing is reached for 92 Tg SO_2, while the maximal efficiency is reached for 24 Tg only. The main reason relies on the change in size distribution due to aggregation, and thus changes in the optical scattering properties, as well as sedimentation. Recently, Kleinschmitt et al. 2018 suggested that cooling by SO_2 injection may saturate around -2 W/m^2, while other studies suggest that much larger values can be obtained (Kravitz et al. 2019b; Niemeier and Timmreck 2015).

A key element is also the timeline over which these injections will have to take place, which depends on the GHG mitigation scenario. Most of the studies consider a period spanning over the whole century. A sudden stop after several years of stratospheric aerosol injection may lead to severe instabilities associated to temperature jumps (Parker and Irvine 2018; National Research Council 2015).

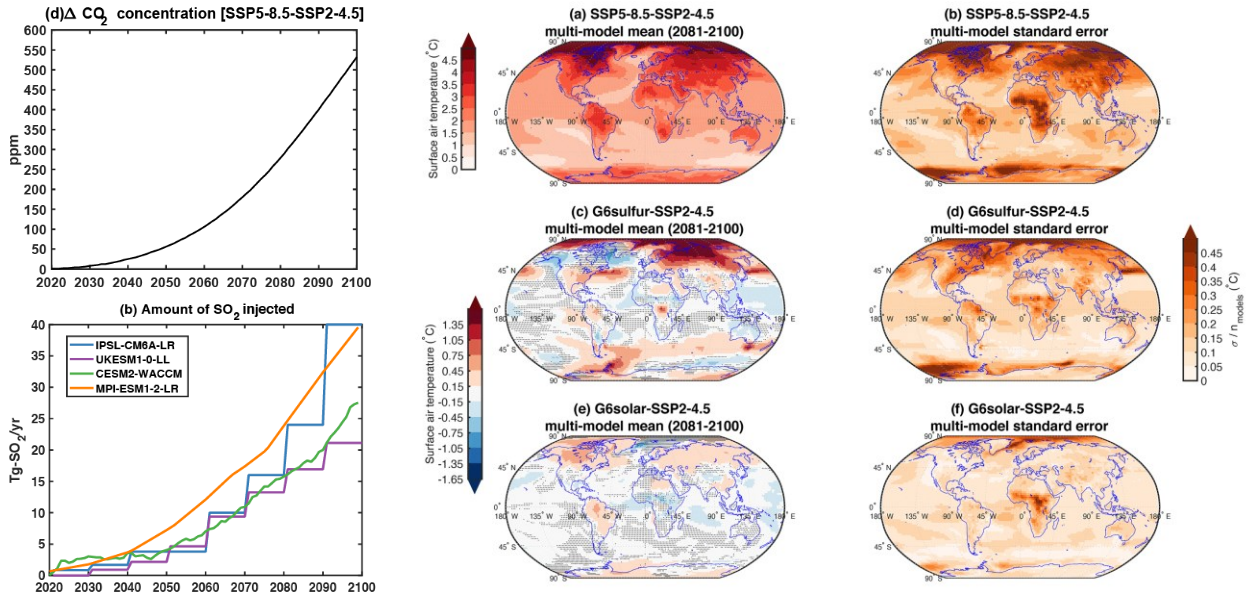


Figure 4.4: **Maps in the middle columns** (a, c, e): Multi-model intercomparison of surface temperature changes averaged over 2081-2100 in different cases: (a) high CO_2 scenario SSP5-8.5, (c) Compensation by SAI from G6sulphur (model that includes aerosol physics), and (e) Compensation by SAI from G6solar

(simple model of solar radiation decrease). Compensation is intended to reach the lower CO_2 scenario SSP2-4.5. **Maps in the right column**: Standard error in the multi-model mean for the same reference cases. The figure on the upper left corner displays the difference in CO_2 concentration between the 2 scenarios. The figure on the lower left corner displays the needed SO_2 injections to compensate for this additional CO_2 and remain on the lower-tier scenario.
Source: Visioni et al. 2021.

A detailed study of stratospheric aerosol injection over the century has been carried out within the framework of CMIP phase 6, which compiles results from many different models (Visioni et al. 2021). The considered cases comprised 2 different CO_2 emission evolutions: SSP5-8.5 (high tier emission scenario with a final radiative forcing due to GHG of 8.5 W/m^2 in 2100) and a moderate tier scenario (SSP2-4.5 with 4.5 W/m^2 in 2100). Concerning solar radiation management, one model (G6sulfur) considers injection of stratospheric precursor gases (SO_2) such that the radiative forcing of the high tier CO_2 emission scenario (SSP5-8.5) is reduced to the one of the moderate tier scenario SSP2-4.5. The other model (G6solar) is a simplified version where the cooling is achieved by reducing artificially the solar irradiance. In order to compensate for the increasing CO_2 concentration in SSP5-8.5 (Fig 4.4, upper left), the quantity of the yearly SO_2 injection has to be increased as well until 2100. With this considered injection profile, the average Earth temperature is well maintained over the century, as seen in Fig 4.4c and Fig 4.4e. However, regional variations are clearly observable, with some temperature increase (< 1.5°C) in the Northern latitudes and some cooling in the tropics. The uncertainty due to variations among the different models (4.4d and 4.4f) is of the same order of magnitude as the values themselves. These results also show that a GHG emission scenario such as SSP5-8.5 over the whole century would require rising levels of stratospheric aerosol injections that exceed 30Tg/yr, pointing towards the necessity of more efficiently mitigating GHG emissions.

Reducing radiative heating of the atmosphere will be beneficial for most of the predicted, and already observed consequences of global warming, like drought and associated agricultural impacts, ice melting in the mountains and at the poles, forest fires, etc. This is particularly significant for long-term and irreversible effects. Simulations (Kravitz et al. 2019a) exemplified the beneficial effect of solar management measures on the ice melting in polar regions, where the sea ice extent could be preserved instead of disappearing over the century.

While model simulations of solar geoengineering indicate that perturbations due to greenhouse gases like global mean temperature, hydrological cycle (Tilmes et al. 2013), cryosphere (Moore 2014), ocean circulation (Hong et al. 2017), and extreme events (Curry et al. 2014) could be offset (Govindasamy and Caldeira 2000; Irvine et al. 2016; National Research Council 2015), they can't be offset simultaneously and trade-offs have to be chosen (Irvine et al. 2010; Schmidt et al. 2012). For instance, uniform solar geoengineering cannot completely offset both temperature and precipitation changes (Tilmes et al. 2013): if global mean temperature is restored to a target state, the climate system reacts with lower global precipitation (Kravitz et al. 2019a). ln addition, there are numerous critical side effects and implications that extend beyond natural science, including economics, politics, ethics, international law, and governance.

4.1.4 Costs

Costs are mainly driven by the cost of lifting the aerosols or their precursors into the stratosphere. Several methods have been evaluated, like aircrafts, airships, balloons, rockets, and artillery (Robock et al. 2009; Katz 2010; McClellan et al. 2012; Moriyama et al. 2017; National Research Council 2015). In general, costs increase with the altitude of injection, due to technological limitations. Estimations widely vary among the authors and the reports, ranging from 0.2 billion USD/year/(W/m^2) (Sheperd 2009) to 50 billion USD/year/(W/m^2) (Crutzen 2006). A more recent overview and analysis of costs (Moriyama et al. 2017) concludes that injection using aircrafts is the most cost-effective option, especially if a dedicated fleet of newly designed aircrafts would be implemented. This would lead to a cost of approximately 5 billion USD/year/(W/m^2), i.e., 10 billion USD/year for the targeted -2 W/m^2 radiative forcing. The new aircrafts are expected to allow launching 1 Tg of sulphur for 1 billion USD. Using the current fleet of military aircrafts like F15s would significantly increase the costs, almost by a factor 10 (McClellan et al. 2012). The direct costs of solar radiation management by stratospheric aerosol injection are therefore relatively low, which implies that such actions could be launched unilaterally by a single country or private industry. This remark reinforces the need for a global and concerted governance about climate change mitigation strategies and associated international regulations.

It is worth comparing these figures to the recently reported 165 billion USD costs in 2022 in the USA only (Smith 2020) due to climate and weather disasters, and estimated 2 trillion USD/year in revenue loss by the end of the century. A recent study estimated the worldwide averaged costs associated with each additional emitted ton of CO_2 to 185 USD (Rennert et al. 2022), which translates into roughly 7 trillion dollars in 2022.

Target forcing	Sulphur quantity	Altitude	Costs/yr	Costs due to CO_2/yr
-2 W/m2	~ 10 Tg/yr	20 km	10-50 billion USD	165 billion - 7 trillion USD

In addition to lifting costs, monitoring will also require additional investments, depending on the strategy, i.e., satellite missions (ozone, CFC, water vapor, aerosols), in-situ balloon measurements of aerosol sizes, network of ground-based lidars, etc.

The effect of each SAI operation is limited to a time scale of 1-2 years, requiring a yearly application over several decades. CO_2 capture, conversely, has long-term and durable effects, but requires time and large investments to be implemented. A study was recently carried out (Belaia et al. 2021; Baur et al. 2023), which combines both methods and makes use of their differences. They show, in particular, that cooling due to stratospheric aerosols injection can be slowly decreased and stopped by the end of the century, as CO_2 capture takes over.

4.1.5 Risks

Stratospheric Ozone Depletion

This section about risks is focused on the use of sulphate aerosols, since most of the simulations validate their parametrizations by comparison with volcanic eruptions. Alternatives have been proposed, such as mineral and salt nanoparticles (Keith et al. 2016; Ferraro et al. 2011; Pope et al. 2012; Weisenstein et al. 2015), which have the potential to reduce the risk of stratospheric heating (they are transparent to optical and NIR radiation). However, the photochemical impacts of these particles in the stratospheric environment are insufficiently evaluated (Santschi and Rossi 2006; Keith et al. 2016; Harrison et al. 2020). A test experiment, SCOPEX

(Dykema et al. 2016; Golja et al. 2021), consisting of injecting small amounts (2 kg) of calcite aerosols in the stratosphere by a stratospheric balloon and measure their evolution, was proposed by Harvard researchers but was not deployed yet and heavily disputed in the community.

The most obvious concern about injecting aerosols in the stratosphere is ozone depletion by heterogenous chemistry. A detailed report on the evolution of the ozone layer since the ban of CFCs by the Montreal protocol has been published by the WMO in 2018 (WMO 2018a), which also includes a review of the impacts from potential stratospheric aerosols injection. It is shown that injecting 2.5-4 Tg sulphur yearly from 2020 to 2070 would induce ~ 4 % reduction of the global stratospheric ozone column for 2020, and 1% reduction by 2070 (Pitari et al. 2014; Xia et al. 2017), illustrating the progressive fate of CFCs in the stratosphere. Higher sulphur loads (WMO 2018a), around 16 Tg/yr, would not only induce larger depletion values in the Antarctic (Fig 4.5) but also significant vertical and latitudinal gradients between the Antarctic (-8% to -25%) and the Northern hemisphere (with an increase of +0% to +15%). In turns, these gradients modify temperature profiles and thus circulation dynamics (Tilmes et al. 2018, 2022).

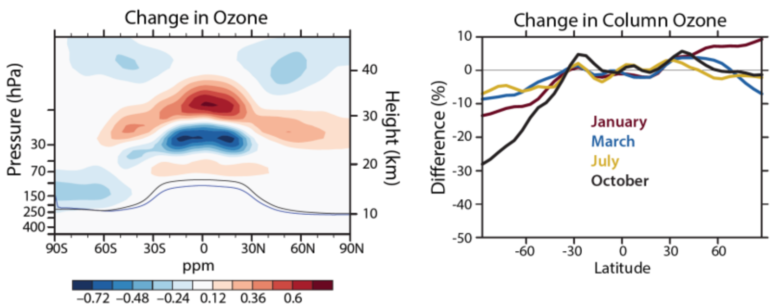


Figure 4.5: Change in stratospheric ozone in 2042-2049 following RCP8.5 for SAI of 16 Tg/yr injections at 15°N/15°S. Impact of enhanced sulfate aerosols on ozone concentration (left). Right: Differences in column ozone (%) between the geoengineering and the control simulation are illustrated for different months. Source: WMO 2018b.

The impact on ozone depletion may be influenced by the injection altitude (due to variations in UV radiation, temperature, water vapor, etc.), latitude (closer to the poles or equatorial), season, and year of intervention. The fate of stratospheric CFCs may favour intervention at later times. Alternately, the stratospheric aerosol injection impact can be seen as a delay in the ozone layer total recovery (estimated for the end of the century), by 25 to 55 years (Tilmes et al. 2022).

Heating of the equatorial stratosphere

Most of the models predict a global cooling of the Earth surface, as a result of SAI, and a temperature increase in the stratosphere in the tropics (typically -20°S to -20°N) (Visioni et al. 2021). These features are also confirmed by observations and modelling of the Pinatubo eruption (Sukhodolov et al. 2018). For the high-tier scenario SSP5-8.5, used for instance in the simulations of Fig 4.4, heating of the equatorial stratosphere due to aerosol injection may amount to as much as +3°C to +10°C, by the years 2080-2100, depending on the model. Equatorial stratospheric heating is mainly due to the absorption characteristics of sulphate aerosols, sedimentation by aggregation at high aerosol concentrations, and injection strategies. Spreading in space and time the sulphate injection actions instead of local equatorial injection is assumed to partially smooth stratospheric temperature gradients (Kravitz et al. 2019a). Heating of the equatorial tropopause also leads to a water vapor increase in stratosphere by 2-7 ppm, and an increase of stratospheric circulation, which might impact the Quasi-Biennial-Oscillation (QBO) (Jones et al. 2022).

Precipitations and water cycle

The water cycle of the Earth is significantly perturbed by global warming, which increases evaporation and thus the concentration of water vapor in the atmosphere (Pendergrass and Hartmann 2014). As a consequence, global precipitations are expected to increase steadily during the century. At the end of the century, if a high-tier SSP5-8.5 scenario is followed, increases by as much as 1 mm/day are predicted to appear around the tropics (Visioni et al. 2021) on a yearly averaged basis. If seasonal variations are taken into account, these variations would lead to heavy flooding and stronger monsoon. If the rise in surface temperature is compensated by SAI, simulations consistently show that precipitations around the equator will be overcompensated, by values of about -0.1 mm/day to -0.5 mm/day. Notice that the uncertainties in these simulations are of the same order of magnitude as the values themself. Perturbations are localized around the equator, but heavy impacts could occur in Asian regions where climate is driven by seasonal monsoons (Simpson et al. 2019; Visioni et al. 2020a).

SAI, implemented at a moderate intensity, for example by compensating half of the global warming, is expected to reduce negative effects such as reduced precipitation (overcompensation) that are associated with fully offsetting global mean warming (Irvine et al. 2019; Irvine and Keith 2020; IPCC 2022).

Tropospheric pollution and soil acidification

SAI may have some impact on tropospheric pollution by modifying the efficiency of photochemical pathways, but no definitive conclusions could be drawn so far. The risk of acidification of the soils and the troposphere due to injection of SO_2 in the stratosphere appears also limited. First, 10 $TgSO_2$/yr corresponds to about 7% of the anthropogenic emissions in the troposphere in the 1980s (Klimont et al. 2013), when acid rains became a significant issue. The exchanges between troposphere and stratosphere are also quite limited, reducing further the deposition of sulphates or sulfuric acid from the stratosphere. Modelling has been carried out to investigate in detail these effects, even for compensations of the high-tier scenario RCP8.5, and conclude that the impacts should remain modest, and compensated by the global fate of anthropogenic SO_2 emissions in the troposphere in the present and next decades (Visioni et al. 2020b; Kravitz et al. 2009; Tracy et al. 2022). The main rationale for replacing SO_2 by mineral particles (e.g., $CaCO_3$) is therefore related to stratospheric ozone depletion and heating of the lower troposphere due to absorption properties of solar radiation by sulfate aerosols.

Governance risks

A significant governance risk, valid for every geoengineering measure but in particular for SAI (relatively low cost), is the reduction of CO_2 mitigation efforts because of an alternative of a lower cost / less socially invasive approach. In this respect, SAI should be strongly emphasized as an emergency measure and not as an alternative to CO_2 mitigation.

Further risks

SAI does not modify the concentrations of CO_2 in the atmosphere and does not compensate for other detrimental effects than warming compensation, like, for instance, oceanic acidification (IPCC 2022).

Other impacts of SAI have been investigated (National Academies of Sciences and Medicine 2021; IPCC 2022), like generation of acid rains, affecting biodiversity and ecosystems, crop production and efficiency of solar energy production. However, no clear conclusive outcomes have emerged due to uncertainties and contradictory statements (see "key uncertainties" section).

Finally, the risk associated to SAI has to be compared to the risk of not having access to the technology. The current lack of knowledge about SAI efficiency and impacts represents a significative risk in case of a sudden emergency deployment (due to uncontrollable rise of temperature, drought leading to water and food shortage, socio-economic collapse, war, etc.).

4.1.6 Global governance concerns

Governance is probably the most critical aspect of geoengineering deployment, as it combines natural sciences knowledge, ethical issues, public acceptance, equity, law, national and international politics, economics and strategic issues (defence). Governance problems have been discussed in several comprehensive assessment reports, the most recent of which are (IPCC 2022; National Academies of Sciences and Medicine 2021). SAI is the most debated subject of all geoengineering actions, as it impacts the Earth globally with a significant level of uncertainty and with uneven effects across the globe. A global deployment of SAI measures to counteract CO_2 emissions within an international acceptance agreement is today very unlikely.

To be successful, a research program on geo-engineering, and especially SAI, requires a highly multidisciplinary approach, involving natural sciences, social sciences, ethics, international law and international governance. An example of recommendations for a proper geoengineering governance was presented on the basis of the "Oxford Principles" (Rayner et al. 2013), a set of guidelines commissioned by the UK House of Commons Committee on Science of Technology: (1) the regulation of geoengineering as a public good, (2) public participation in geoengineering decision-making, (3) disclosure of geoengineering research and publication of results, (4) independent assessment of impacts, and (5) governance before deployment. While these principles are certainly theoretically sound, they don't provide operational solutions. More research in governance strategy is therefore also required in the future.

There is no International Geoengineering Governance Agreement today. The relatively modest impact of the implementation of climate protocols under the United Nations Framework Convention on Climate Change (UNFCC) also interrogates upon the efficiency of such a potential agreement on Geoengineering. As described in chapter 2, CO_2 emissions in the atmosphere are steadily increasing (IPCC 2022) with an absolute maximum of ~ 40,000 Tg/yr in 2022, despite the signed Paris 2015 protocol. The ease for withdrawing from such international agreement, highlighted by the withdrawal of the US government in 2020, is also a major concern, as it jeopardizes the credibility of international commitments.

Although international coordinated actions are highly desirable considering the global impact of SAI and other SRM actions, the United States Administration launched a research program on SRM in 2022 (OSTP 2023; US Congress 2022) based on the conclusions of the US National Academies of Science (National Academies of Sciences and Medicine 2021). The aim of the program is to reduce uncertainties associated to SRM including all their aspects in an interdisciplinary way. It also intends to play the role of worldwide example of action and initiate a global effort towards research in this field.

As already mentioned, in the absence of international regulations, the relatively low cost of SAI experiments or deployment allows unilateral national actions to be carried out. It is likely that nations other than the USA will follow, like China, who has already carried out massive cloud seeding actions for increasing precipitations for many years, with only minor international reaction (see section 5: "Extreme weather events and weather engineering"). Moreover, ethics, public acceptance or politics are less likely to interfere with such initiatives in China than in the USA.

The risk of using unilateral geo-engineering (by nations or private consortia) promotes the implementation of dedicated global monitoring systems. Calls for constellations of satellites tracking plumes of stratospheric injections are now emerging. In addition, new technologies are investigated to counteract geoengineering actions (Parker and Irvine 2018; Parker et al. 2018), in a similar way as countermeasures are developed in the military context.

Some treaties and conventions could be called in specific cases: (1) the United Nations (UN) Convention on Biological Diversity (CBD), in which some extracts could be interpreted as "limiting outdoor experiments to experiments that have been previously assessed as non-damageable to the environment", (2) the Vienna (1988) and Montreal (1985) protocols about the protection of the ozone layer, in which aerosol injection in the stratosphere should be included in the list of forbidden compounds, (3) The UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), which was concluded as a reaction to hostile weather modification attempts during the Viet Nam war, but which only held 2 meetings since promulgation and is thus considered inactive (Reynolds 2019).

4.1.7 Public perception of SAI and SRM

Studies on the public perception of SRM in Western societies, based on surveys, workshops, and focus group interviews (IPCC 2022) found that respondents are unaware of SRM. In general, public acceptation of carbon dioxide removal (CDR) is higher than SRM (Pidgeon et al. 2012), due to weaker side effects and governance concerns. Studies also suggest limited support for future research actions, including field experiments, and conditioned by proper governance (Sugiyama et al. 2020). Some studies dedicated to developing countries show a tendency for respondents to be more open to SRM (Visschers et al. 2017; Sugiyama et al. 2020), perhaps because they experience climate change more directly (Carr and Yung 2018).

4.1.8 Key uncertainties

Most of research activities related to SAI consist in performing numerical simulations. Intercomparisons between different models have been carried out among the CMIP-GEOMIP6 international program (Visioni et al. 2021). While simulations reveal similar trends, like surface air temperature cooling, equatorial stratospheric heating (for equatorial injection), precipitation decrease in the tropics, and ozone layer depletion in the Antarctic but not in the Arctic, *quantitative* predictions vary widely, with standard deviations as large as the values themselves by the end of the century. The uncertainties for shorter periods of times are less prominent, but significant.

A major driver for uncertainties in the outputs of numerical simulations is critically related to the uncertainty in the input parameters, which are obtained experimentally. The assessment of the reliability and precision of simulations also requires confrontation to actual observations. These are limited to some volcanic eruptions, for which experimental uncertainties are large as well e.g. +/-15% in the global aerosol burden, +/-30% in aerosol optical depth and spatiotemporal aerosol distribution, +/-40% in the particle size, and +/-0.5K in the lower stratospheric temperature anomalies (Sukhodolov et al. 2018).

Key uncertainties are summarized below (Kravitz and MacMartin 2020; IPCC 2022; National Academies of Sciences and Medicine 2021):

Aerosols size, radiative, and chemical properties

The size distribution and composition of aerosols is a key uncertainty. Size has a crucial effect in radiative forcing as scattering properties depend on the ratio a/λ, where a is the particle size and λ the wavelength. Smaller particles efficiently scatter (and thus reflect) the UV-visible wavelengths but weakly infrared radiation (and thus transmit), while large particles scatter both almost equally. Importantly, the angular distribution of scattering also depends on the size parameter a/λ. Therefore knowing precisely the size distribution and the shape (e.g. liquid droplets versus ice crystals) is essential to evaluate the albedo of aerosol layers. In addition to scattering, aerosols may also absorb light (like sulphates) and then heat locally the stratosphere, as already mentioned. Moreover, particles may eventually grow, e.g., by water accommodation, or coagulate into larger particles that may sediment to lower altitudes.

The size, shape and composition of aerosol particles are also crucial for the stratospheric photochemistry, with associated uncertainties about ozone depletion and dehydration/denitrification processes.

The optical and chemical properties of particles other than sulphates, like calcite and other minerals/salts (Dai et al. 2020; Keith et al. 2016; Santschi and Rossi 2006) are even less known.

Atmospheric circulation dynamics, water cycle

Temperature gradients, both in altitude and latitude, induce instabilities and variations in the stratospheric transport. As already described, SAI injections, especially using sulphate, heat some specific regions of the stratosphere, and induce such gradients. Injecting outside the tropics and at several different locations (Bednarz et al. 2023), and at lower altitude reduces these effects, but does not annihilate them. These dynamical changes increase the amplitude of planetary waves in the stratosphere, and in particular of Quasi Biennial Oscillations (QBO) (Osprey et al. 2016; Scaife et al. 2000). Several models (Aquila et al. 2014; Bednarz et al. 2023) evaluated the effects of SAI on the stratospheric dynamics but revealed significant spread in the results. Significant variations are also observed among the models for changes in tropical precipitations and stratospheric water content.

Agriculture and food

Studies about the impacts of SAI on crop yields have very large uncertainties and even opposite conclusions. On the positive side, it was suggested that SAI would reduce heat stress (Pongratz et al. 2012; Xia et al. 2014; Zhan et al. 2019) and ozone pollution (Xia et al. 2017; Pitari et al. 2014; Tilmes et al. 2018), while on the negative side, SAI may decrease photosynthesis because of the lower incoming solar radiation (Proctor et al. 2018) and decrease precipitations in the tropics, which may cause for instance a reduction in groundnut yields in Asia (Xia et al. 2014; Yang et al. 2016).

Impacts on human health and well-being

Few studies have assessed uncertainties on the SAI impacts on human health and well-being, due to the complexity of the problem. Ozone depletion in the Southern hemisphere increases the risk of skin cancer and may increase the aerosol concentration due to deposition, but lower incoming solar radiation would reduce photochemical air pollution and tropospheric ozone (Effiong and Neitzel 2016; Eastham et al. 2018; Dai et al. 2020). Considering only mean annual temperature and precipitation, SAI that stabilizes global temperature at its present-day level is projected to reduce income inequality between countries compared to the highest warming pathway (RCP8.5) (Harding et al. 2020). Some integrated assessment model scenarios have included SAI (Arino et al. 2016; Emmerling and Tavoni 2018; Heutel et al. 2018; Helwegen et al. 2019; Rickels et al. 2020) showing benefits to welfare, since because the direct economic cost of SAI itself is expected to be relatively low (Moriyama et al. 2017; Smith and Wagner 2018). There is a general lack of knowledge on the wide scope of potential risk to human health and sustainable development, and even more on their distribution across countries and vulnerable groups (Honegger et al. 2021; Carlson et al. 2022).

Response of ecosystems

Impacts on ecosystems are globally unknown and require further research (IPCC 2022). The risk assessment is also dependent on the large uncertainties in the geophysical simulations mentioned above, e.g. amplitude of surface temperature decrease, rainfall and evaporation variations, stratospheric ozone depletion, decrease of solar irradiance, atmospheric pollution, tropospheric ozone reduction, geographical variations, etc. A specificity of SAI and SRM in general, is that the rise of atmospheric CO_2 is not mitigated and therefore, acidification of the oceans and other CO_2 related impacts are not prevented.

4.1.9 Research to reduce key uncertainties

In order to reduce the key uncertainties listed above, the following research activities could be encouraged:

Modelling and simulations

Although several intercomparison studies have been conducted so far, the origin of the large discrepancies, observed among the models should be identified. Also, sensitivities for lower-tier scenarios should be evaluated, as well as predictions for combined effort strategies, e.g., optimizing the combined implementation of GHG mitigation, CO_2 capture/sequestration and SAI actions (Belaia et al. 2021; Baur et al. 2023).

An additional research need is the evaluation of sub-grid scale mixing of aerosols, which is not accounted for in the current models (Kravitz and MacMartin 2020). Associated effects on the aerosol size distribution and geographical spread should be evaluated for plume dispersion in case of local SAI. The importance of the altitude, latitude and season of SAI should also be further evaluated for optimizing the benefit/risk ratio.

In addition to reducing key *known* uncertainties, modelling should also include some basic research, in order to prevent some missing key process. As recently published, a new feedback loop was identified between forest fires, increased by global warming, and stratospheric ozone destruction (Solomon et al. 2023).

Laboratory experiments

Large uncertainties are due to the optical, physical and chemical properties of aerosols. Laboratory experiments involving single trapped aerosol particles could provide key insights on the scattering (amplitude and phase) and absorption properties of aerosol particles as a function of size and shape. This is valid for sulphate and mixture particles, but also for alternative particles like calcite or other minerals. Physical processes like aggregation yields as a function of size, shape, and electric charge would also be highly valuable. Coagulation and growth of ensemble of particles in relevant stratospheric conditions should be performed as well in the laboratory in order to simulate actual conditions and refine models' parametrization. Radiative forcing efficiency strongly depends on the size distribution.

The initial process leading to nucleation of nanoparticles from the gas phase is also essential and should be further investigated using large cloud chambers, closer to the actual atmospheric conditions, like CLOUD at CERN and AIDA II at KIT. SO_2 oxidation and nucleation efficiency as a function of temperature, other gases and ions have now been accessible (Almeida et al. 2013; Wang et al. 2022b; Baumgartner et al. 2022) in these facilities and further experiments, especially relevant for SAI could be carried out at these unique infrastructures.

Chemical reactivity of aerosol particles must be further characterized as well. Many relevant parameters, like sticking coefficients of gases onto the particles and catalytic processes, are nowadays only available for flat surfaces, but not on aerosols, which have other shapes, electric charges, surface defects, local compositions, etc. This is particularly important for assessing potential ozone depletion processes, as well as dehydration and denitrification. Very little is known on the properties of calcite and other alternative particles, which is a major shortcoming, in particular in the context of benefit/risk optimization (reduction of stratospheric heating vs evolution and fate of these particles).

Observational network

Collecting observations after volcanic eruptions, such as those suggested in the NASA Major Volcanic Eruption Response Plan (NASA 2018), will be helpful to constraint models, in particular for sulphate injections. This includes optical density measurements of aerosols by satellites, stratospheric water measurements, ozone depletion, heating rates, and air mass velocities. However, the 10th report of the World Meteorological Organization's Ozone Managers' Meeting (WMO 2019) mentions that satellite observations of key stratospheric parameters to understand ozone depletion processes will stop in 6-8 years, and will have to be replaced by new missions. In-situ balloon-borne measurements will be necessary for measuring aerosols size distribution, shape and composition. Ground-based measurements should be developed, in order to get continuous monitoring on aerosol profiles (lidar), ozone and trace gas concentrations. Development of new ground-based instruments, which would allow higher accuracy and/or vertical profiling, would be beneficial too.

Field experiments

Field experiments using small amounts of aerosol particles may provide some valuable tests for evaluating the efficiency and risks of SAI. For any experimental research at the atmospheric scale, laboratory experiments and numerical models may not be sufficient to validate a field experiment. Confronting the model outputs to actual observations is the final step of validation for a model. To date, this was achieved by comparing simulations to the observation of some volcanic eruptions, like Pinatubo. Being prepared to accurately characterize the effects of a future massive volcanic eruption, with advanced instrumentation (able to be deployed rapidly, measuring the aerosol size distribution evolution, sedimentation, spread, composition, water vapor uptake, temperature gradients and stratospheric circulation) is certainly a valuable effort. However, as already detailed, volcanic eruptions are only an imperfect proxy, as the latitude, altitude, season and burden are imposed, as well as the aerosol type (sulphates) and size distribution. Although very controversial, even concerning small scale experiments, focused field experiments with small amounts of aerosol injection might be valuable to gather scientific knowledge in case of a potential emergency deployment.

4.1.10 Options for Switzerland

Solar radiation management by SAI induces global effects and requires global governance. In this respect, the idea of a unilateral Swiss action to reduce global warming by SAI is obviously pointless. The impact of Switzerland could, however, be relevant in the following contexts:

(1) Swiss involvement in facilitating negotiations on global governance agreements. Switzerland is a well-established and recognized neutral partner, with international organizations like the UN and the WMO in Geneva and an impressive track record of historical agreements. As mentioned above, national programs are emerging in the USA and China, which unfortunately deviate actual climate issues towards geo-strategic objectives, so that international agreements are urgently needed.

(2) The academic research in Switzerland is of very high level, so that dedicated scientific programs could accelerate solving key uncertainties on the potential and impacts of SRM. Moreover, most of the international research activities are focused on the application of old concepts (sulphate aerosol injection, cloud seeding, etc.). There is a lack of basic research programs dedicated to the finding of new scientific alternatives, where Switzerland could play the role of leader and international example.

4.2 Cloud brightening

Cloud brightening is based on the idea that low-lying stratocumulus clouds cover 20-40% of the world's ocean on a daytime annual average, and therefore represent a key player in the Earth's albedo (National Research Council 2015; Russell et al. 2013). Increasing the surface covered by low lying clouds could thus be used for better balancing the radiative forcing due to GHG. In addition, a simple argument shows that for a fixed quantity of liquid water, a large number of small droplets reflects light more efficiently than a small number of large droplets (scattering scales with the droplet surface and total liquid water with the droplet volume). Increasing the concentration of cloud condensation nuclei (CCN) in a humid environment (e.g., over the ocean) appears therefore as a possible method to create additional, “brighter” clouds to reflect the incoming solar radiation.

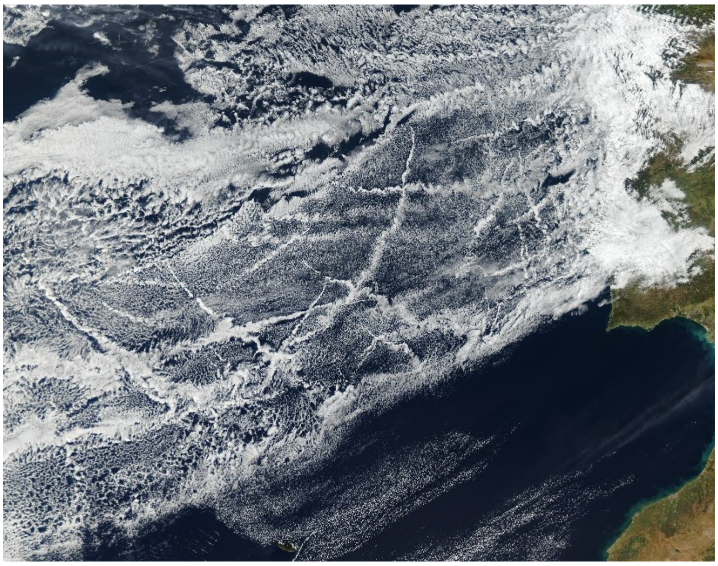


Figure 4.6: Emissions from ships create lines of clouds that span over hundreds of miles off the European coasts in January 2018. Source: NASA Earth Observatory.

Marine cloud brightening (MCB) is easily observed by satellites in the case of “ship tracks” over the oceans. The aerosol plumes emitted by the engines of large commercial cargos act as CCN and create extended cloud structures in their wake (see, e.g., https://earthobservatory.nasa.gov/images/91608/signs-of-ships-in-the-clouds). The idea then emerged to artificially increase the aerosol concentration by injecting particles over the ocean. The resulting albedo modification is, however, very difficult to simulate, as it strongly depends on the aerosol-cloud interaction, the local turbulent dynamics, and the mesoscale cloud structure (Chen et al. 2015; Chun et al. 2023).

4.2.1 Technical options and potentials

There are significant differences between injecting aerosol particles in the troposphere and in the stratosphere. In the marine troposphere, the lifetime of an aerosol particle is limited to only a couple of days, large amounts of aerosols are already present, “injections” are constantly carried out by ships, but in-situ measurements are more easily accessible. Several field experiments were carried out on MCB, like E-PEACE (Russell et al. 2013), SOLEDAD (Schroder et al. 2015; Modini et al. 2015), MASE I/II (Lu et al. 2009, 2007; Russell et al. 2013) and RRAP (Tagliafico et al. 2022). An additional distinctive aspect of MCB is its relatively local action when deployed (typically some tens of km), allowing a better controlled and more targeted application than SAI. Even considering the wind transport, the range of action remains limited, due to the short lifetime of aerosols in the troposphere (deposition, scavenging). MCB can thus be considered for adaptation measures as well. For instance, its efficiency was evaluated for protecting coral reefs in Australia (Tagliafico et al. 2022) and in the Gulf of Mexico (Goddard et al. 2022).

Two main types of particle seeding have been proposed and evaluated: (1) combustion smoke from large ships and (2) sea salt aerosols.

Combustion smoke aerosols

Injecting combustion smoke in the atmosphere inherently suffers from the disadvantage of simultaneously emitting CO_2 and increases regional pollution. On track forming days, cargo vessels may, however, cause twice as much cooling as warming (Russell et al. 2013). A major issue is to identify conditions in which condensation occurs and forms cloud or fog. Although several outdoor campaigns have been carried out, either using existing emissions from cargos, or using dedicated smoke generators, the understanding of the aerosol-cloud interaction and the role of the cloud dynamics and structure remain unclear. A rough estimate of the required efforts for offsetting global radiative forcing by -5W/m^2 was presented (National Research Council 2015) and consists of 2000 vessels deployed over 20 regions of 100 km x 100 km and burning a daily fuel quantity of 3800 m^3/day. Notice that paraffin oil particles have been also proposed as smoke generators (Russell et al. 2013), which are more efficient than the usual fuel used for cargo engines. Paraffin oil is used for military fog generators and for “sky writing” (National Research Council 2015).

Sea salt aerosols

Because of their carbon footprint and their regional pollution issues, combustion aerosols are not the most attractive option for MCB. An alternative was proposed in 2002 by Latham, consisting in injecting small sea water droplets in the boundary layer, which would quickly lead to sea salt aerosols by evaporation. Early simulations (Latham 2002; Salter et al. 2008) estimated that emission rates of the order of 10^6 particles per second and square metre over a surface area of 77,000 km^2 would be required to fully compensate for a doubling of the atmospheric CO_2 concentrations. The cost associated with such intervention would amount to about 100 M USD/week (National Research Council 2015).

Although special nozzle technologies are required to produce well-defined sub-micron-sized marine aerosols with fluxes of 10^{16}-10^{18} s^{-1}, devices have been developed and are nowadays available (Neukermans et al. 2014; Cooper et al. 2014; Tagliafico et al. 2022).

Significant modelling efforts have been dedicated to the global efficiency of MCB for counteracting GHG emissions. A comparative study between 9 different models was, for instance, recently carried out by Stjern et al. 2018 for an idealized situation. The experiment considers an increase of the droplet number density by a factor 1.5 in low marine clouds (modified radius of the droplets accordingly), from 2020 to 2070 (50 years), and then terminated to observe the rebound effect. The CO_2 evolution followed the mid-tier scenario RCP4.5. All models consistently reported a global cooling but within a wide range of amplitudes -0.58 W/m^2 to -2.48 W/m^2. The authors also conclude that large uncertainties are found on the precipitations, but that in average precipitations are slightly decreased by some per cents, due to the colder climate, although there might be some increase at lower latitudes overland.

In the latter intercomparison, cloud droplet size and number density were artificially modified, which represents a drastic simplification as compared to actual sea salt injection. A more realistic intercomparison was reported by Ahlm et al. 2017. For compensating a 2 W/m^2 forcing scenario, a rate of 200 to 590 Tg/yr of injected particles was required, depending on the model. The injections are supposed to be carried out in the tropical region (30 N to 30S) and over the period 2020-2070. At the termination of the experiment, the radiative forcing effect of the 50 years MCB does not show any memory and returns almost instantaneously to its original value.

The net result of sea salt aerosols injection is, however, still debated and remains unclear. A recent simulation reported that the global radiative forcing induced by MCB could even be positive (Mahfouz et al. 2023). The tentative explication of these counter-intuitive results is the predominance of direct scattering from the aerosols compared to the indirect effect of reflectance of the clouds.

4.2.2 Key uncertainties

As highlighted above, there are major uncertainties on the simulations of global radiative forcing effects of MCB. Not only the aerosol-cloud interactions are insufficiently understood, but local, sub-grid turbulent dynamics and cloud structuring and layering play a key role. Before envisaging a potential deployment at a global level, significant research has to be undertaken on numerical simulations, on experiments dedicated to nucleation, growth and interaction between sea salt aerosols and other gases or particles, local field experiments, and on dedicated observational instrumentation (especially on nanoparticle characterization and high-resolution satellite imaging/lidars).

MCB may have some relevant regional applications, like preserving coral reefs, and for other adaptation measures. Finally, as for SAI, MCB does not impact other aspects of rising concentrations of CO_2, e.g., acidification of the oceans.

4.2.3 Options for Switzerland

The involvement options of Switzerland in cloud brightening are similar to those for SAI, but with some differences. Research on fog/cloud formation in non-oceanic regions, but in specific regional conditions like mountains (strong vertical temperature gradients) and lakes has been relatively rare to date. Cloud seeding in these regions was mainly carried out for increasing rain/snowfall, or to prevent hail (see chapter 5). While seeding humid atmospheres with polluting particles may be controversial, alternative new technologies may be of interest to further theoretically and experimentally investigate these options, like ion injection, charged droplet injection or laser-induced condensation (see chapter 5).

4.3 Surface Albedo Modification

4.3.1 Technical options and potentials

White painting roofs and infrastructures

Surface albedo management like white painting of roofs ("cool roofs") or pavements (Santamouris 2014) has the advantage of not inducing significant risk or uncertainty for the future and has mainly only local impacts. Several studies have been conducted to evaluate the cooling effect provided by roofs with increased albedo in urban areas. Main purpose of these studies was reducing the heat island effect and improving the well-being of populations in large cities. On the other hand, white roofs have negligible effects on global warming, as illustrated by the study from Zhang et al. 2016.

	Local scale (city)	Regional scale	Global scale
Temperature decrease	-1.2 to -1.6 °C	USA: -0.14 °C China: -0.11 °C Europe: negligible India: negligible	-0.0021 °C

Earlier studies provided similar conclusions about the negligible global impact of "cool roofs", ranging from -0.07 °C to +0.07 °C (Akbari et al. 2009; Akbari and Matthews 2012; Jacobson and Ten Hoeve 2012). Roof painting is therefore an adaptation method, which is relevant for reducing extreme temperatures in summer in large tropical and mid-latitude cities, and thus reducing heat wave related over-mortality and energy costs associated with air conditioning systems. On the other hand, at more northern latitudes, white painting of roofs may increase the household heating in winter (Epstein et al. 2017).

On the research side, a significant effort has been recently dedicated to the development of new materials and photonic structures that direct radiative thermal energy selectively towards deep space outside the spectral regions occupied by GHG, for daytime passive radiative cooling (Raman et al. 2014). A wealth of efficient and cost-effective materials are currently developed and tested, mainly driven by research in the USA and China. Some commercial products recently became available, e.g. from 3M.

Notice that the analysis above does not consider "green roofs", for which the main purpose is to capture carbon by vegetation rather than albedo optimization. The question of additional heating due to the implementation of solar panels (80% of the absorbed energy by a solar panel is heat) (Taha 2013) is not considered in the present section either.

Agriculture and rural environments

The cooling potential of solar radiation management in the farming sector is larger than the one for "cool roofs". Two different strategies have been followed to increase the crops albedo: alternative plant varieties and no-till farming (Seneviratne et al. 2018; IPCC 2022; Sieber et al. 2022; Singarayer and Davies-Barnard 2012).

Alternative varieties mainly rely on selected (or genetically modified) species that are more reflective than the natural ones. This is achieved, for instance, by reducing the chlorophyll content. To date, increases of albedo from +0.02 to +0.14 have been reported (Breuer et al. 2003; Uddin and Marshall 1988) for variants of barley, soya beans, wheat, maize, sunflower and rye. No-till farming, for which the albedo is increased by the presence of crop residues on the ground, can also provide an increase from +0.05 to +0.2, and is particularly efficient for wheat (Davin et al. 2014). Notice that unlike cool roofs, the albedo varies along the year according to the life cycle of vegetation (Sieber et al. 2022).

Global and regional cooling induced by land surface albedo management has been evaluated on the basis of simplified models. The maximum global mean temperature cooling is of the order of -0.7 °C in a scenario considering an increase of 4 x the CO_2 concentration in the future and an increase of temperature of +3.7 °C (Seneviratne et al. 2018). This upper bound was found by assuming a massive albedo increase of 0.1 over all the agriculture areas on Earth. When reducing the management to a single continent, the global cooling drops to negligible, as the overall surface covered by agriculture activities amounts to about 11% of the Earth surface. However, the relevance of land surface albedo management is found efficient for regional measures (cooling by up to -2°C in the case of the albedo increase by 0.1), and particularly for reducing extreme temperatures (local reduction up to -4 °C) (Seneviratne et al. 2018). Further simulations point towards similar conclusions, i.e., the efficiency of smoothing maximal temperatures, but with a reduced amplitude (Hirsch et al. 2017). This suggests relevant adaptation possibilities, in particular for smoothing and shortening the occurrence of damaging heat waves (Kala et al. 2022). However, more modelling studies and field experiments are required for a quantitative assessment of crop albedo modification.

No-till farming is a growing tendency and is already widespread in North and South America (Derpsch R Kassam A Hongwen Li 2010). Downsides are possibly higher herbicide use or additional soil work (Powlson et al. 2014) and risks of waterlogging in wet weather conditions (Turmel et al. 2015).

The use of alternative crop species may be more critical to adopt by farmers because of their uncertainty on yield and sensitivity to pest or weather conditions. The question of using genetically modified organisms may also be controversial for some alternative species (Karavolias et al. 2021).

4.3.2 Key uncertainties

Although most of the models predict minor global cooling effects and significant local cooling induced by surface albedo modification, the observed spread over quantitative values in the literature is large, as acknowledged by the authors (Seneviratne et al. 2018; Hirsch et al. 2017; Wang et al. 2020; IPCC 2022). In particular, simulations of albedo management in agriculture require higher resolution grids and a refined model that includes water management, as well as biological, vegetal and soil feedbacks.

Impacts of such SRM actions may also have impacts on biodiversity, regional precipitations, and circulation (IPCC 2022).

4.3.3 Options for Switzerland

Surface albedo modification is the most widely accepted geoengineering measure, because of its local impact, reversibility and reduced risk. A possible implementation scheme could be gradual, and as its implementation widens, surface SRM could evolve from a status of adaptation measure (reducing heat waves, improving human well-being and health, preserving crops) to a more regional cooling method. Monitoring of the effects is also easily accessible by existing instrumentation. The main impact of cold roof implementation will be mostly for accommodation measures for the inhabitants during heatwaves. It can be useful in specific cases where air conditioning systems can be avoided. White painting of roofs and building is widely used in southern Europe (Spain, Greece, Southern Italy) where the average annual solar radiation is highest (~ 1900 kWh/m^2 in Crete vs ~ 1100 kWh/m^2 in Switzerland).

5 Extreme weather events and weather engineering

5.1 Difference between weather and climate engineering

The difference between weather and climate engineering is the same as the difference between weather and climate: (1) weather relates to meteorological processes like rain, snow, hail, fog, lightning, hurricanes, etc., i.e., atmospheric processes that occur on a short period and (2) climate is the long term evolution of these meteorological processes, averaged over much longer timescales (evolution of temperatures, humidity, sea levels, cloud coverage, ice and glacier extent, etc., over years, centuries, millennia and more).

Although amplified by global climate changes, the use of weather engineering is not limited to it. The economic and military interests to modify weather conditions go back a long way. Concerning cloud seeding and rain making, for instance, the first demonstration using silver iodide and dry ice were carried out in the late 40s (Schaefer 1946; Vonnegut 1947; Langmuir 1948; Bruintjes 1999). These demonstrations attracted considerable interest worldwide for research and for commercial opportunities. The US Congress reported in 1953 that farmers, municipalities and other water users were annually spending 3-5 MUSD/yr on weather modification activities, which motivated the creation of an Advisory Committee on Weather Control (ACWC 1957). By 1951, weather modification research was already active in about 30 countries. Due to the lack of understanding of how seeding works and under which conditions it can be effective ("seedability"), the market rapidly declined because of the randomness of the results.

Scientific research and military activities (as for example during the Viet Nam war) took over these activities for several decades. In particular extensive weather control activities were deployed during the Cold War to develop meteorological weapons, which led, in 1977 to the "UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modifications Techniques" (ENMOD). The agreement is, however, mostly oriented towards military conflicts between different countries and difficult to apply for most of the currently ongoing national weather modification programs.

Weather geoengineering targets mitigation of damages and costs due to drought, flooding, hail, lightning, wildfires, fog, etc. (Qiu and Cressey 2008). As an example, damages only associated to lightning amount to ~ 5 US billion/yr and to hail to ~ 10 US billion/yr (Allen et al. 2020) in North America. In a broader context, the total cost of weather disasters over the last 5 years (2015-2019) exceeds USD 525 billion (Smith 2020).

5.2 Cloud seeding and rain/snow management

Since the first demonstration in the 40s by Vonnegut, Schaefer and Langmuir, many thousands of cloud seeding experiments have been carried out by at least 50 countries around the World (Czys 1995; Flossmann et al. 2019; WMO 2018a; Qiu and Cressey 2008; National Research Council 2003), which contrasts with the few field experiments dedicated to SAI and MCB. The most active nation in the field is, by far, China, and then the USA. Among other active countries, large efforts are nowadays deployed by the United Arab Emirates, Russia, Australia, India, Japan, Iran, Israel, South Korea and Thailand.

China has launched the largest program on weather geoengineering in the World. All provincial governments except Shanghai have their own Weather Modification Bureau with budgets for cloud seeding in their region (Chien et al. 2017). Already in 2008, the Weather

Modification Programme employed 32,000 people, operated 35 equipped planes, 7,000 canons and 5,000 rocket launchers (Qiu and Cressey 2008). The China Meteorological Administration claimed that between 2002 and 2012, they conducted more than half a million weather modification operations, resulting in 500 billion tons of rain (Chien et al. 2017). Although these numbers are difficult to verify, they provide a measure of the efforts and the intentions of the Chinese Government towards leading global weather modification actions. The objectives of cloud seeding in China is not only to prevent drought and improve agricultural yields (e.g., Northern China and Qinghai-Tibet plateau), but also to prevent rain on some locations (e.g., for the Olympics in Beijing 2008), prevent hail, clear fog, reduce pollution by scavenging, power hydro-power plants and increase snowfalls for ski resorts. In 2020, China's State Council announced a further expansion of their weather modification programs to cover 5.5 Mio km^2, i.e., 1.5 times the surface of India (Geerts and Rauber 2022).

In the USA, 922 projects about weather modification, mainly rain/snow enhancement and hail suppression, have been registered by the NOAA between 2000 and 2022 (NOAA 2023). The most active states are Texas, Arizona, Kansas, Wyoming, Illinois, Utah, Colorado, California, North Dakota, Idaho, and Nevada, which often fund or co-fund these programs at the State level, and/or with industrial partners and users. The objectives span over helping agriculture, which increasingly suffers from drought due to global warming, helping the tourism sector and ski resorts by increasing snow falls, the hydro-electricity industry by replenishing the reservoirs that start to reach critically low levels, extinguish large wild fires, and save ecosystems (including biodiversity). Many of these actions claim a precipitation increase by 5-15%, although quantitative assessments were not available until recently (Tessendorf et al. 2019; Friedrich et al. 2020). For instance the large hydroelectricity consortium Idacorp (Idaho Power Company) spends about 4 Mio USD per year for cloud seeding, and claims an increase of 12% in some snow parks resulting in billion of gallons of additional water at the very affordable cost of 3.5 USD per acre-foot (1 acre-foot = 1233 m^3). Notice that other private companies worldwide (e.g., Weather Modification Inc. (USA), RHS Consulting (USA), Seeding Operations & Atmospheric Research (SOAR) (USA), NAWC Inc (USA), Snowy Hydro (AUS), Cloud Seeding Technologies (DE), Selerys (FR), WeatherTec AG (CH), etc.) offer cloud seeding services to private or institutional customers.

A third country very active in precipitation management and cloud seeding are the United Arab Emirates. In 2005, the UAE launched the "UAE Prize for Excellence" in Advancing the Science and Practice of Weather Modification in collaboration with the World Meteorological Organization (WMO) and then converted it in 2016 into the International Research Program for Rain Enhancement Science (UAEREP). These activities allowed to set up an active international network centred on precipitation enhancement and support several research projects (www.uaerep.ae/en/app/3) in the field. The UAE carry out typically 200 cloud seeding missions per year to test different new technologies like drone spreading, new nanotechnology developed seeds, or use of ionization technology, often in collaboration with international partners who were awarded the UAEREP funding.

Although widely used, the actual efficiency of cloud seeding is still questioned. Assessing the actual efficiency of cloud seeding is a difficult task because of the complexity and the sensitivity of the process and the variability of meteorological conditions. It requires significant instrumentation deployment and observation measures, as well as multiscale modelling involving condensation microphysics, turbulent mixing and transport, and precipitation. Quantitative observations of the whole process could only be realized very recently (French et al. 2018; Tessendorf et al. 2019; Rauber et al. 2019; Friedrich et al. 2020;

Xue et al. 2022; Heimes et al. 2022; Zaremba et al. 2022). However, more experiments of this type are required to obtain sufficient statistics to be conclusive.

5.2.1 Methodologies

Two main processes have been investigated so far (WMO 2018a; Flossmann et al. 2019): (1) Glaciogenic experiments, in which particles such as AgI or dry ice are injected to help nucleating ice particles or converting supercooled water droplets into ice crystals, which then induce either snow or rain and (2) Hygroscopic seeding in which salt particles (NaCl, KCl, $CaCl_2$) or hygroscopic flares are used to enhance condensation, coalescence and then rainfall.

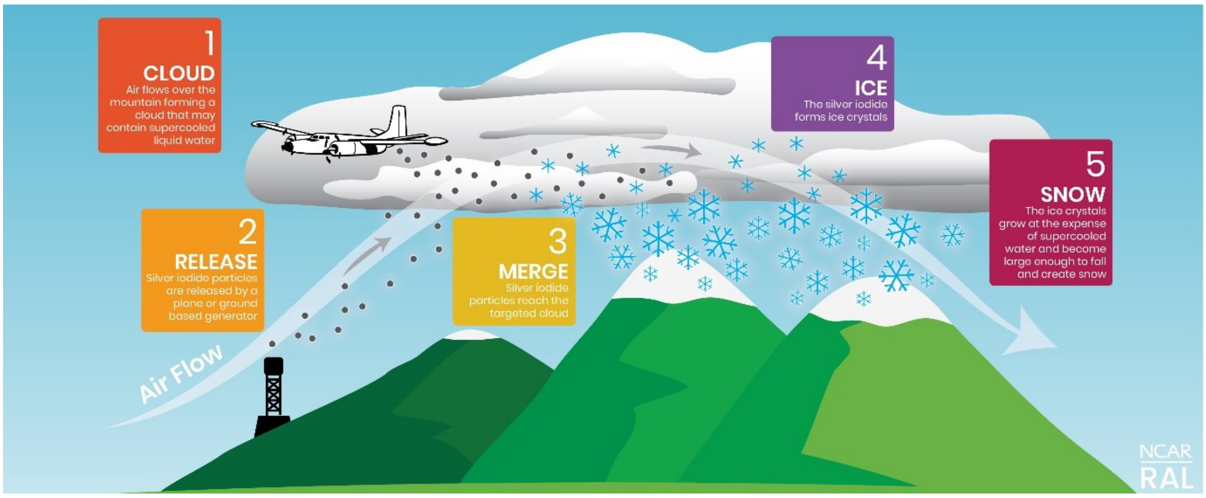


Figure 5.1: Principle of glaciologic seeding of orographic clouds, to induce snow precipitation. Source: https://ral.ucar.edu/projects/seeded-and-natural-orographic-wintertime-storms-the-idaho-experiment-snowie. Used with permission from the US National Center for Atmospheric Research (NCAR) © 2020 UCAR

The meteorologic conditions and the cloud properties play a key role in the success of cloud seeding induced precipitation. Most of the studies to date were focused on 2 typical cloud systems:

(1) *Orographic clouds* (induced by a mountain slope), mainly in winter and in the mid-latitudes. Glaciogenic seeding of wintertime orographic clouds is realized by introducing ice nucleating particles (INP) in a region where a humid air mass rises along a mountain slope, and thus cools down. In this process supercooled liquid water droplets are formed and eventually freeze when they reach sufficiently cold conditions. By seeding the cloud with, e.g., AgI, ice particles can be formed at higher temperatures (-5°C) and thus at an earlier stage in the orographic process (Flossmann et al. 2019; Tessendorf et al. 2019; French et al. 2018). AgI has the property of exhibiting a similar lattice structure as ice, which favours freezing of supercooled droplets. This aims at accelerating growth and increasing snowfall on the mountains.

(2) *Convective clouds* in summer over mid-latitude or at any season in tropical regions.

In convection clouds, the vertical motion (and cooling) is not due to the topography, but due to the elevated ground temperature. Seeding can also increase the buoyancy of the cloud by the release of the latent heat from freezing supercooled liquid droplets. Hygroscopic seeding with salts is, conversely, injected into the cloud warmer base to favour condensation, coalescence, and rain. To this end, the injected particles must have higher efficiency than the CCN already present in the air, for example by being more hydrophilic or by having larger sizes (micrometric or more). Glaciogenic seeding using AgI or dry ice can also be used in the top and cold part of a convective cloud with similar objectives.

Dispersion methods for AgI seeding are (1) aircraft-based acetone burners or burn-in-place flares, (2) flares ejected from aircrafts at altitudes higher than the region that contains supercooled droplets, (3) ground-based acetone burners, artillery shells and rockets, and more recently (4) Drones (Jung et al. 2022).

For NaCl (or other similar salts) hygroscopic seeding, similar methods have been used: (1) aircraft-based micropowder dispersion and flares (burn-in-place or ejectable), (2) ground-based flares, rockets, and artillery shells.

5.2.2 Efficiency and uncertainties

Despite the large efforts and continuous experimental trials, the efficiency of cloud seeding could not be conclusive until recently. For instance, the National Academies report in 2003 (National Research Council 2003) concluded: "*Although there is physical evidence that seeding affects cloud processes, effective methods for significantly modifying the weather generally have not been demonstrated*". Quantitative assessment of the causality between cloud seeding and precipitation observed on the ground is indeed a very challenging task. Some key issues experienced in this context are the following: (1) for assessing the efficiency of cloud seeding, there should be 2 almost identical meteorological situations in which one is a reference and the other the seeded case. This ideal comparison is, unfortunately, elusive because of the natural variability of cloud systems and meteorology, (2) Background aerosols (e.g. pollution) compete with seeded particles in a complex way, (3) Growth and processing are often related to turbulent mixing within the cloud, the dynamics of which is often unpredictable, (4) The location where precipitation occurs after seeding is difficult to predict and thus dispatching probes on the ground is challenging. As an alternative, Radars are used for measuring the quantitative amount of precipitation, which they can only provide under specific assumptions. The recorded results on the efficiency of cloud seeding around the world, ranging from 1.8% to 27% in the scientific literature (Benjamini et al. 2023; Flossmann et al. 2019; Geerts and Rauber 2022; Kulkarni et al. 2019; Rauber et al. 2019) illustrates these major variability issues.

In contrast to *statistical assessment* of the cloud seeding efficiency, *physical assessment* by the direct observation of the chain-of-effects from the cloud seeding to the precipitated snow has significantly progressed in the recent years (Geerts and Rauber 2022). A typical example of such a physical evaluation is the SNOWIE project (Seeded and Natural Orographic Wintertime Clouds: The Idaho Experiment) (Tessendorf et al. 2019), which was set up by the NCAR, the University of Colorado, the University of Wyoming, the University of Illinois and the Idaho Power Company (IPC). The SNOWIE field campaign took place between January 7 and March 17, 2017 in the Payette Basin. It was co-funded by the NSF and IPC. Impressive equipment and diagnostics tools were deployed, including 2 aircrafts, one for the cloud seeding and the other for in-situ diagnostics, comprising cloud particle probes, liquid water content sensor, a Radar and a Lidar. In addition, 2 mobile dual-polarization X-band Radars were mounted on the top of 2 mountain ridges (Snowbank and Packer John), in addition to a fixed Ka-band Vertical Doppler Rain Radar, 6 microwave radiometers, particle sizers, a particle velocity disdrometer, rawinsondes and standard weather measurement stations. Snow was collected on the ground by 12 high resolution gauges. These experimental deployments were completed by simulations and modelling, based on the Weather Research and Forecasting (WRF) Model with an AgI seeding adapted microphysics module (Xue et al. 2013; Thompson and Eidhammer 2014).

The SNOWIE campaign provided unprecedented detail on the mechanism of precipitation enhancement by glaciogenic seeding in orographic clouds, from the initial phase of injection to the final harvesting of snow on the ground (Tessendorf et al. 2019; Rauber et al. 2019; Xue et al. 2022; Friedrich et al. 2021, 2020; Zaremba et al. 2022; Heimes et al. 2022; Deng et al. 2022).

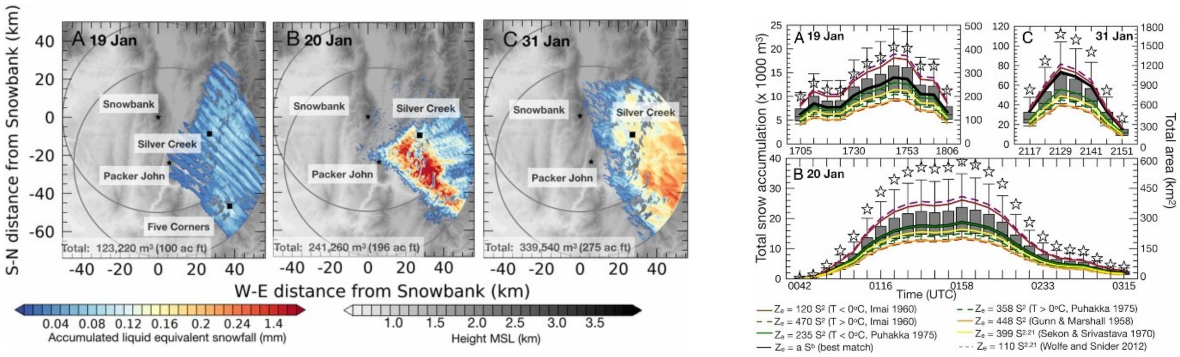


Figure 5.2 Snow precipitation induced by glaciologic seeding of orographic clouds during the SNOWIE campaign. Left: Spatial distribution of the snowfall after seeding for 3 different episodes, measured by Radars. Right: Retrieved total quantity of snowfall attributed to seeding during the same 3 days.
Source: Friedrich et al. 2020.

The combination of Radar mapping, aircraft-based in-situ measurements before and after seeding, and snowfall gauges on the ground allowed to estimate the total increase of snow precipitation, attributable to the AgI cloud seeding, as shown in Fig. 4.8. Over three illustrated events, from Jan. 19 to Jan. 31, the authors report the generation of 1.2 10^5 m^3, 2.4 10^5 m^3 and 3.4 10^5 m^3 of water by cloud seeding (Friedrich et al. 2020).

SNOWIE provided a wealth of experimental information and advances in numerical modelling. In particular, it was possible to simulate the interaction of silver iodide with clouds, droplets freezing and the resulting fall of snow on the ground (Xue et al. 2022). However, it also highlighted difficulties such as sensitivity to initial and boundary conditions, uncertainties on the aerosol-cloud and precipitation processes, as well as the turbulent transport within the cloud systems. Similar well prepared and large-scale campaigns will be highly valuable in the future to better constraint the models and quantitatively assess the seedability of an orographic cloud system. Further work should also be undertaken for obtaining a similar level of accuracy for warm convective clouds.

Finally, cloud seeding requires humid atmospheres, which also limits its applications. Important applications are indeed interventions in case of drought or forest fires, for which atmospheric humidity is typically relatively low.

5.2.3 Precipitation reduction

Cloud seeding is also implemented for precipitation reduction to prevent flooding or to preserve some large public events from bad weather, like the Beijing Olympic games in 2008

(Chien et al. 2017). Another illustrative example is the use of cloud seeding by the Russian Army after the Chernobyl catastrophe in 1986 to induce raining over Belorussia and thus prevent radioactive precipitations to reach Moscow. This "precipitation redistribution", which enhances or reduces precipitation over some regions vs others represents a significant risk of provoking regional or national tensions, even unintentionally (Geresdi et al. 2017).

On the technological side, precipitation reduction can be achieved by multiplying the number of CCN and thus distribute the available water vapor on many particles, which limits their growth. The presence of natural CCN has then to be carefully considered before seeding in order to prevent producing the opposite effect to that intended (i.e., hindering precipitation instead of enhancing it).

5.2.4 Risks

Several concerns are associated with cloud seeding. First the toxicity of silver ions and its compounds in air, water, soil and vegetation is debated in the literature. While sub-ppb levels are found in the rainwater after some seeding experiments, continuous and extensive use of cloud seeding might significantly increase the dose. Increased concentrations of silver were found (up to 10 mg/kg) in the soil in the vicinity of ground-based silver iodide generators (Causape et al. 2021).

Silver and its compounds are listed as toxic pollutants by the US EPA (Clean Water Act 1977, Code Federal Regulations 40 CFR 401.15). For instance, silver compounds and especially Ag^{+} are well-known bactericides (Clement and Jarrett 1994). However, AgI's low solubility in water reduces the release of silver ions. Some reviews conclude that environmental impacts of AgI are negligible (Almeida et al. 2013). Conversely some studies report that exposure to AgI concentrations as low as 0.43 uM (threshold value in potable water prescribed in Australia (NHMRC/NRMMC,2004), shows significant impacts on phytoplankton and soil bacteria (Fajardo et al. 2016). The mechanisms behind AgI's toxicity are not fully understood yet.

Another risk, expressed in the media, is the possibility of inducing accidental flooding. Typical examples of these worries are floodings in Tasmania in 2022, in the UAE in 2019 and in Chongquin (China) in 2022. Also, due to the unpredictability of the seeding induced rainfall, some extra target area effects have been observed. In some cases, rainfall outside the target area was larger than the one in the target area (Wang et al. 2019).

A major issue of cloud seeding is, however, geopolitical and geostrategic. In the global context of water scarcity, the problematic of "stealing rain" from neighbouring countries or neighbouring regions is rapidly rising. Cloud seeding is not the only "unconventional water resources" harvesting method (Karimidastenaei et al. 2022) but may have a central political role (Chien et al. 2017). A symptomatic example is the implementation of the Chinese "Ecological Program" and its impact on the neighbouring countries (Bluemling et al. 2020), especially India. More precisely, to increase the rainfalls on the Tibetan Plateau, a massive program was launched aiming at implementing a network of more than 500 stationary burners on the Alpine slopes of Tibet, Xingjiang (Chen 2018). These stationary emitters point towards cloud seeding activities in a continuous manner and over a long period of time, which worries Indian authorities. The surrounding Indian states (Arunachal Pradesh, Sikkim, Assam, Uttarakhand, Himachal Pradesh and the Union Territory of Ladakh) could be significantly affected by the Chinese weather modification programs either by drought or flooding.

The concerns at the international level are shared at the regional level, or even locally. For instance, in 2004, 5 cities in Henan (China) sought to fight against drought by seeding clouds but 2 upstream cities did it beforehand, leaving the downstream cities with little or no precipitation, resulting in accusations of rain "theft". Similar accusations have been made since, in different cities and provinces (Wuzhou, Guanxi province; Xian, Xiyang, Shannxi province) (Chien et al. 2017).

In addition, commercial activities related to rain/snow harnessing are rapidly growing, offering cloud seeding to farmers, ski resorts, cities (for smog clearing) etc. and no satisfactory legal framework regulating these activities is currently available. Establishing national and international policies to provide such regulations requires large efforts but is urgently needed. A first step would be requiring all cloud seeding activities to be (nationally) registered, including the location, time span, and reason (scientific, agriculture, hydropower, drought, forest fire, tourism, large events).

5.3 Weather geoengineering: hail, fog and lightning control

5.3.1 Hail

Hail protection activities by cloud seeding have been as heavily used as rain/snow enhancement (National Research Council 2003; Qiu and Cressey 2008). On the technological side, both are very similar, namely injecting AgI or other salts in clouds from aircrafts, artillery cannons, ground-based burners and rockets, so that operational campaigns and commercial activities often propose both options. The difference between hail and rain/snow precipitation lies in the dynamics of the cloud system and growth of the particles. Hail is produced in thunderstorm clouds with strong updrafts, high water content, great vertical extent and with a significant part of it below freezing temperature. When a droplet moves upwards at high velocity, it gets supercooled, freezes in contact with an ice nucleating particle (INP), and travels through regions of different humidity and water droplet concentration inside the cloud. It then rapidly grows because of high humidity and captures water droplets as its cross-section increases. Because of the strong vertical wind and the large vertical extent of the cloud, hailstones can reach very large dimensions, on the cm scale. When their weight can't be compensated by the updraft, they fall and continue to grow while falling. They then leave the cloud and increase their kinetic energy until they hit the ground. Damages due to hail are therefore considerable, to infrastructures, agriculture, cars, etc. and amount to ca 10 billion USD per year in the USA (Allen et al. 2020).

As for rain/snow enhancement, hail protection activities have been widely carried out around the world, including China, Russia, USA, Europe, Argentina, Australia and Canada. It is worth mentioning that Switzerland has been very active on this topic in the 1960-1980s, and organized 2 large frame campaigns (with French and Italian partners), one in Tessin from 1957 to 1963 ("Grossversuch III", Schmid 1967) and the other in Central Switzerland from 1977 to 1981 ("Grossversuch IV", Federer et al. 1986; Auf der Maur and Germann 2021). The effects of cloud seeding on hail suppression during both campaigns have not been assessed as statistically significant.

The idea behind hail prevention by cloud seeding is that increasing the number of ice-nucleating particles, the number of hail embryos may increase, deplete the supercooled water earlier and thus reduce the hailstone size. Smaller hail will produce smaller damages, and may even melt before reaching the ground (Rivera et al. 2020; Auf der Maur and Germann 2021; Tsykunov 1974).

The efficiency of the method has been and still is highly controversial, although operational campaigns and commercial activities are still ongoing (and even increasing). The conclusions from the historical "Grossversuch" campaigns were rather negative, as more recently reported in Rivera et al. 2020; WMO 2018a. However, some other authors enthusiastically reported positive results from their measurement campaigns (Vukelic et al. 2018; Dessens 1998; Dessens et al. 2016). The fact that the validity of hail suppression by cloud seeding is today still an open question calls for scientific research that better targets the underlying processes than statistical evaluation of events during operational campaigns.

5.3.2 Fog

Fog management is one of the earliest weather control activities. Already in the 1930s hygroscopic salt seeding was used to clear fog by creating larger water droplets and reduce relative humidity in the air so that fog dissipates (Brunt 1936). Fog seeding using liquid or solid CO_2 (dry ice) was then used to clear airfield runways with success (National Research Council 2003), but the increased capacity of aircrafts for flying low visibility has reduced the widespread of the technology. Some airports are, however, still using fog dispersal methods (e.g. https://www.voanews.com/a/fog-busters-airports/3765780.html).

Fog seeding has regained popularity because of health impacts in large cities. The combination of fog and pollution increases the impact on human health, and seeding is now considered as a mean to "clean" foggy urban pollution (Bluemling et al. 2020; Shi and Cui 2012; Reuge et al. 2017; Qiu and Cressey 2008). The methodology is similar to the one used for other cloud seeding techniques, dispersion of hygroscopic salt or dry ice using drones or small aircrafts.

5.3.3 Lightning

Costs due to lightning damages to homeowners amount to about 1-2 billion USD /yr in the USA only (Insurance Information Institute 2023; https://www.iii.org/fact-statistic/facts-statistics-lightning#Homeowners%20insurance%20losses). In addition, lightning strikes strongly affects the air traffic, electricity networks, large infrastructures and are a major igniter of wildfires (Perez-Invernon et al. 2023; Krause et al. 2014). The occurrence of lightning activity is also expected to be influenced by the global climate change (Perez-Invernon et al. 2023; Krause et al. 2014; Finney et al. 2018).

The connection between electrostatics and particle growth is complex and only partially understood. On one hand, the interaction between water/ice particles and graupel is assumed to be central for cloud electrification and charge separation (Pereyra and Avila 2002; Luque et al. 2020; Barthe et al. 2012; Saunders 2008; Popova et al. 2022). On the other hand the presence of electric field or charged particles enhance the nucleation, growth and coalescence of the existing particles (Tinsley et al. 2000; Weon and Je 2010; Zheng et al. 2021, 2020; Harrison et al. 2022). Finally, charge separation leads to strong electric fields, which eventually induce lightning discharges, which, in turn, re-ionize the air and produce NOx and O_3.

For the reasons mentioned above, the link between lightning and rain gush in thunderstorms, although widely evidenced, is still unclear (Moore et al. 1964; Vonnegut 1947; Vonnegut and Moore 1986; Mudiar et al. 2018; Wu et al. 2017). The initiation and control of lightning discharges could thus also be used to modulate precipitation.

Lightning control has been mainly performed by launching wire-pulling rockets (Newman et al. 1967; Fieux et al. 1975; Hubert 1984; Rakov et al. 2005; Wang et al. 2022a). While successful, the rocket triggered lightning method is primarily used for scientific investigations rather than for protection. The availability of large numbers of rockets and their fall after operation significantly restricted their widespread implementation.

5.4 Alternative methods

5.4.1 Ionization and droplet charging

As mentioned above, electrostatics and ionization play an important role in clouds but are less understood than nucleation/condensation induced by chemistry or thermodynamics. Rain/snow enhancement and fog dispersal by charge seeding has recently attracted much attention because of a lower environmental impact than its chemical counterpart.

Many laboratory-based experiments have been carried out, investigating the efficiency of droplet growth and coalescence due to electric charges and fields, but field experiments are recent. In particular, a large scale deployment of corona-based ion generators has been performed in China, on the Qilian Mountain, Liupan Mountain and Wushaoling experimental area (Zheng et al. 2020). After one year of operation, first results claim a statistically relevant precipitation increase of ~ 20% attributed to negative ion seeding (Shi et al. 2021).

Field campaigns have also been carried out using UAVs (Harrison et al. 2022, 2021) carrying corona generators. Although preliminary, results show an increase of droplet size and/or concentration, but no rain enhancement. This research, supported by the UAE Research Program for Rain Enhancement, is ongoing.

5.4.2 Laser-based methods

Significant progress occurred in laser-based weather modulation technologies with the advent of ultrashort high intensity lasers (Kasparian et al. 2003; Wolf 2018). Thanks to laser pulse durations from the femtosecond (1 fs = 10^{-15} s) to the picosecond (1 ps = 10^{-12} s) regimes, even very modest energies lead to very high intensities. These high intensities produce highly non-linear effects while propagating in the atmosphere, such as non-linear photochemistry, ionization, etc. (Berge et al. 2007). A first success of laser-based techniques is lightning control. As the air is ionized along the laser path, it becomes electrically conductive and acts thus like a metallic conductor, i.e., a virtual lightning rod, that can be switched on and off at will. In addition, high intensity lasers are able to produce these “light filaments” up to kilometric distances (Durand et al. 2013; Rodriguez et al. 2004), widely exceeding the height of conventional lightning rods. As the region on the ground, protected by a lightning rod, scales roughly with its height, this opens the possibility of protecting large areas from lightning damages, such as airfields, electrical power plants, refineries, wind farms, etc. First demonstrations were performed at high voltage facilities already in the early 2000s (Pepin et al. 2001; Rodriguez et al. 2002; Wolf 2018), but field campaigns were also carried out in actual lightning conditions in New Mexico (Kasparian et al. 2008), and more recently in Switzerland (Houard et al. 2023). The campaign in summer 2021 performed at the Säntis mountain (2500 m altitude) demonstrated for the first time that a natural lightning could be guided along a laser path over 60 m distance, realizing the first “laser lightning rod”.

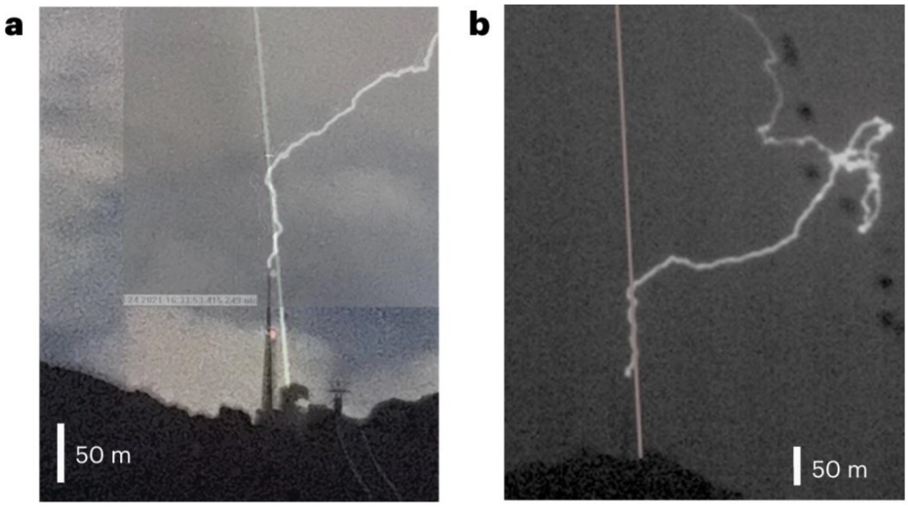


Figure 5.3: First demonstration of lightning guiding over 60 metres by a high intensity ultrashort pulse laser at the Säntis Mountain (CH) in 2021.
Source: Houard et al. 2023.

These results are not only encouraging for protection purposes, but also allow for new experimental schemes to test lightning physics models. For instance, modelling upward flashes of different polarities from a tower in this topographic situation was carried out in this study. Further research is ongoing on this topic, in particular for evaluating possible schemes of inducing rain by laser-controlled lightning, as mentioned at the end of section 5(c).

Significant research was also dedicated to laser-induced water condensation. It was shown that the non-linear interaction of these ultrashort lasers with the atmosphere created aerosol nucleation and condensation even for relative humidities as low as 70%. Demonstrations have taken place in the laboratory (Shumakova et al. 2021; Matthews et al. 2013; Joly et al. 2013; Petrarca et al. 2011; Kasparian et al. 2003), at large cloud chamber facilities, like AIDA (Saathoff et al. 2013), and directly in the actual atmosphere (Mongin et al. 2015; Henin et al. 2011; Rohwetter et al. 2010), where small artificial clouds could be remotely produced by the laser on long horizontal paths or between 40 and 100 m altitude.

The mechanisms of laser-induced condensation rely on both ion/charge generation in the atmosphere, ionization of aerosols, and nonlinear photochemical reactions, which involve NOx, O_3, H_2O or VOCs (Mongin et al. 2015; Henin et al. 2011; Rohwetter et al. 2011; Shumakova et al. 2021). More research is needed to better understand the involved processes under different conditions (initial presence of aerosols, weather conditions, concentration and evolution of the ions, role of the ionized droplets, etc.) and their relative importance in the observed condensation events.

Ultrashort lasers were also used to clear fog to allow free space optical communication in such detrimental conditions. Laboratory experiments demonstrated that high bit rate optical telecommunications could be transmitted through thick fogs by laser clearing (de la Cruz et al. 2016; Schimmel et al. 2018). The communication channel was opened by an opto-mechanical process: the laser produced a radial shock wave that displaces the droplets out of the transmission channel instead of evaporating them, which would be energetically too costly. The average power required to opto-mechanically clear the transmission channel in fog was estimated to about 1 watt per meter. This technique was, however, not demonstrated in the real atmosphere over realistic distances (~ 100-1000 m).

Finally, experiments were also carried out to evaluate the possibility of using lasers to thin cirrus clouds (Leisner et al. 2013; Matthews et al. 2016). At the AIDA facility, it was observed that lasers could produce secondary ice multiplication by shattering existing cirrus-like ice crystals. The simultaneous evaporation of the particles and the presence of ions, both induced by the laser, gave rise to a large number of small ice particles. This resulted in the desired effect consisting in replacing a small number of large crystals by a large number of small crystals, and thus changing the optical properties of cirrus cloud particles. Because of the small size as compared to wavelength, secondary ice transmits infrared (thermal earth emission) but reflects/scatters the visible light (incoming solar radiation).

5.4.3 Acoustic waves

Although the use of acoustic waves was suggested already in the 1960s, actual field tests have mainly been carried out only recently, due to technological limits. Several field campaigns were conducted in China (Shi et al. 2021; Wang et al. 2023; Wei et al. 2021) using large loudspeakers that emit acoustic frequencies around 50 Hz and 150 Hz at levels of ~ 135 dB. Some encouraging results have been claimed, especially on relatively small scales (few km), but definitive assessments on the efficiency of the technology require more investigations. Side effects and impacts of such loud acoustic waves should also be carefully evaluated in the future.

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