Aerosol Cloud Interaction for Cooling (ACtIon4Cooling)

Requirements Baseline Document (D1)

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German Aerospace Centre - Remote Sensing Technology Institute (DLR-IMF)
German Aerospace Centre – Physics of the Atmosphere Institute (DLR-IPA)
National Observatory Athens (NOA ReACT)
University Leipzig

	NAME	DATE	Signature
LEAD AUTHOR(S)	Pascal HEDELT Athina ARGYROULI	10/06/2025	
Contributing authors	D. Efremenko, S. Gross, Q. Li, , V. Amiridis, A. Tsekeri, A. Gialitaki, J. Quaas		
REVIEWED BY	Michael EISINGER	XX/XX/2025	
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

Solar geo-engineering has attracted significant attention in the recent decades. The European Innovation Council's report "Eyes on the future" demonstrates the thematic on "Exploring solar geoengineering as a piece in multifaceted climate change mitigation strategy" [RD01] as a trend of emerging technology and breakthrough innovation.

The ACtIon4Cooling project is designed to contribute to the global understanding of Solar Radiation Modification (SRM) and its potential role in mitigating climate change. The independent expert review on SRM research by the United Nations Environment Programme (UNEP) [RD02] suggests that our understanding of Aerosol-Cloud Interactions (ACI) could allow for the deployment of SRM approaches with the goal of cooling the Earth within a few years. Such a deployment could potentially help to slow the surface temperature increase and potentially meet the Paris Agreement target of limiting global warming to well below 2°C. According to the State of Global Climate 2023 [RD03], the average global temperature had reached a warming of 1.45°C above the pre-industrial levels in 2023 and future projections show that the warming could reach up to 2.7°C by 2100 [RD04].

While global efforts to reduce Greenhouse Gas (GHG) emissions have been ongoing, including policies to transition to a net-zero energy system (Patt et al., 2022), the severe impacts of climate change persist. Mitigation approaches aimed at reducing carbon dioxide (CO2) emissions and removing excessive GHG concentrations from the atmosphere will likely take decades to produce measurable results, without the deployment of SRM techniques (Parker and Geden, 2016; Matthews and Caldeira, 2007).

This situation highlights the need for further research into SRM techniques that could serve as a temporary or complementary approach to address global temperature rise in the face of urgent climate impacts. Solar Radiation Modification (SRM) refers to deliberate interventions in the Earth's climate system, aiming to modify the Earth Radiation Budget to offset some of the adverse effects of global warming. SRM is not a substitute for emissions reductions, but rather a potential complementary measure that could reduce peak warming and associated risks, particularly if mitigation and adaptation actions are insufficient. Combining climate change mitigation with SRM in a peak-shaving scenario has been proposed to restrict harm into organisms and ecosystem processes (Zarnetske et al., 2021). This peak-shaving strategy considers SRM techniques only as a temporary solution to reduce the peak of mean global temperature rise while reductions on GHG emissions and decarbonization approaches are applied. Assessment of the timeframes for potential SRM deployment is critical [RD05]. Research should not focus solely on the technical feasibility of SRM, but also on the strategic question of when deployment might be appropriate—particularly in relation to the risk of crossing climatic tipping points. One possible scenario involves a climate emergency in which global warming triggers catastrophic consequences, such as extremely high mortality rates or large-scale destruction of infrastructure. In such a case, a planned operational SRM deployment might be activated for a defined duration (Caldeira and Keith, 2010; Buck et al., 2020). In less urgent situations, other SRM deployment frameworks have been proposed. These include phased deployments that become a standard component of climate policy—either as a partial or complete substitute for GHG mitigation (MacMartin et al., 2018)—or approaches aimed at slowing the rate of warming to maintain a stable rate of temperature change alongside mitigation efforts. SRM could also be used to prevent overshoot of temperature targets in scenarios where mitigation is delayed, thereby flattening the peak of global warming (de Coninck et al., 2018). The SAPEA (Science Advice for Policy by European Academies) Evidence Review Report [RD06] presented the scientific, technical, and societal aspects of Solar Radiation Modification (SRM) as a potential response to climate change.

Importantly, SRM must be viewed as a complementary measure to GHG reduction strategies, not a replacement. This distinction becomes clear when considering impacts that SRM cannot address—such as ocean acidification—which results from elevated atmospheric CO_2 concentrations and would persist regardless of SRM deployment (Jin et al., 2022).

1.1 Purpose

The ACtIon4Cooling project aims to contribute to this research by investigating existing Earth Observation (EO) data to enhance our understanding of SRM-related processes and improve monitoring capabilities. The project's work focuses on SRM detection and attribution, with an emphasis on leveraging natural analogues to study potential radiative effects.

Starting from the scientific understanding of aerosol and cloud effects related to SRM, the development of a solid scientific basis for monitoring, detection capabilities of SRM activities is foreseen. By making use of observations from space-borne, ground-based, air-borne and in-situ platforms, we can actively contribute to define the requirements for a future satellite mission dedicated to monitoring SRM activities. This document is the Requirements Baseline Document (RB, Deliverable D1) as part of the ACtIon4Cooling project. This document consolidates the preliminary scientific requirements for the ACtIon4Cooling project, including a detailed review, assessment and cross-comparison of existing relevant products, datasets, methods, models and algorithms, as well as related range of validity limitations, drawbacks and challenges. Futhermore, it includes a survey of all accessible associated datasets and models to be used for development and validation and a provision of requirements on improving model estimations, space-borne, air-borne and ground-based data in the context of SRM. This document represents the basis for all the activities to be carried out during the project and will become Chapter 1 of the Final Report.

1.2 Scope and Limitations

The SRM key mechanisms studied in ACtIon4Cooling are:

- Stratospheric Aerosol Injection (SAI) – releasing reflective particles (e.g., sulfates) into the stratosphere to scatter incoming solar radiation.
- Marine Cloud Brightening (MCB) – enhancing the albedo of marine clouds to reflect more sunlight.
- Cirrus Cloud Thinning (CCT) – modifying high-altitude cirrus clouds to increase outgoing longwave radiation.

The ACtIon4Cooling project focuses on observational analysis and detection challenges relevant to SAI, MCB, and CCT techniques. It does not advocate for SRM deployment but investigates how Earth Observation data can support the monitoring and attribution of SRM-like effects in the atmosphere.

None of these technologies can fully counter the effects of elevated GHG concentrations, and each carries substantial uncertainties and risks, requiring rigorous scientific evaluation.

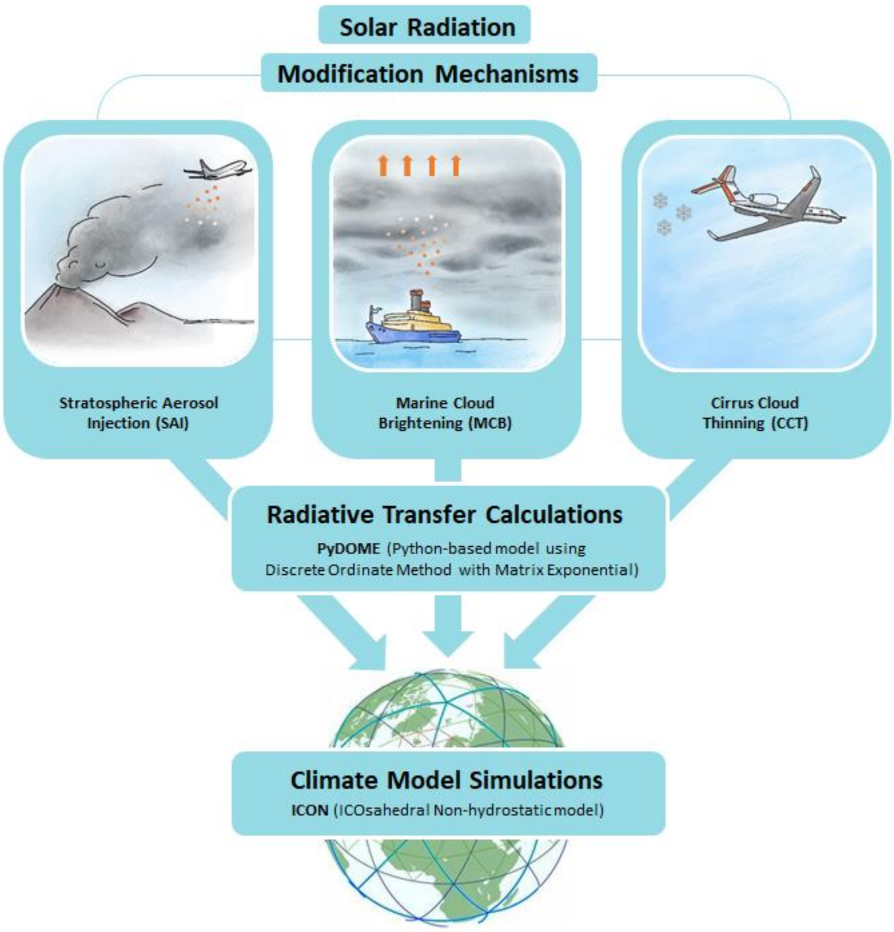

Figure 1 ACtIon4Cooling scheme

The proposed scheme of our research objectives is illustrated in the diagram. The key SRM mechanisms SAI, MCB and CCT are studied via their natural analogues as proposed in literature. The radiation effects are simulated with the use of pyDOME(python-based Discrete Ordinate Method with Matrix Exponential) (Efremenko et al., 2017) Radiative Transfer Model (RTM) and their climatic consequences are studied via ICON (ICOsahedral Non-hydrostatic) (Hohenegger et al., 2023) climate model simulations.

The project has the following limitations: We need to use existing datasets, algorithms, models. When there are knowledge gaps, we need to report them. But we will not be able to develop new theories or algorithms in the limited time of this project. Furthermore, we need to limit our research activities to the fields of our expertise. This implies that impact analysis and risk assessment of SRM on potentially affected areas is mostly restricted to the Weather and Climate impacts, even though the areas relevant for SRM side-effects assessment are numerous. The major SRM-affected areas are summarized in Table 1.

Table 1 Areas Affected by a potential SRM deployment

SRM-Affected Area	Key Impacts	Observational/Modeling Requirements
Weather & Climate	Changes in global and regional temperature, precipitation, extreme weather (Irvine et al., 2019)	High-resolution climate models, reanalysis data, regional downscaling (Kravitz et al., 2013)
Terrestrial Ecosystems	Altered vegetation growth, phenology shifts, terrestrial carbon sink variation (Arora et al., 2014)	Vegetation dynamics models, land surface models (Lombardozzi et al., 2020)
Marine Ecosystems	Ocean warming, acidification, shifts in productivity and fish migration (Patti et al., 2022)	Coupled ocean-atmosphere models, biogeochemical models (Dutkiewicz et al., 2015)
Biodiversity	Habitat loss, migration barriers, extinction risks (Trisos et al., 2018)	Species distribution modeling, biodiversity-climate interaction models (Urban et al., 2016)
Agriculture & Soil	Crop yield changes, soil respiration, degradation (Cheng et al., 2019)	Crop and soil models, land management simulations (Proctor et al., 2018)
Food Security	Regional crop failure, global market effects (Pongratz et al., 2012)	Crop forecasting systems, agro-economic models (Fujimori et al., 2019)
Water Resources	Altered rainfall, glacial melt, hydrological cycle shifts (Keller et al., 2014)	Watershed models, hydrological cycle simulations (Tilmes et al., 2013)
Public Health	UV reduction affecting vitamin D, respiratory impacts from aerosols (Effiong and Neitzel, 2016)	Health risk models, UV-B exposure models (McKenzie et al., 2011)
Vitamin D & UV-B	Reduced UV-B limits vitamin D synthesis (Norval et al., 2011)	Radiative transfer modeling with stratospheric aerosols
Disease Spread	Vector ecology change (malaria, dengue) (Carlson et al., 2020)	Disease transmission models, mosquito lifecycle models (Ryan et al., 2019)
Solar Energy	Reduced photovoltaic output from aerosol scattering (Crook et al., 2017)	Solar irradiance simulation, aerosol-cloud interaction modeling
Air Quality	Stratospheric aerosols affect ground-level pollutants (Visioni et al., 2020)	Chemistry-climate interaction models, air quality modeling (Emmons et al., 2020)
Local Communities	Cultural, economic, and social disruption (Sugiyama et al., 2020)	Socio-environmental impact assessment, participatory approaches
Tourism	Snow and coral-dependent tourism declines (Scott et al., 2020)	Sector-specific modeling, climate impact projections
Geopolitics & Governance	International conflict, inequity (Contzen et al., 2024)	Scenario analysis, global risk modeling
Ethical & Intergenerational	Intergenerational risk, equity, justice (Macnaghten & Szerszynski, 2013)	Normative foresight analysis, stakeholder deliberation

More SRM approaches have been also conceptually proposed in the literature, but they would not be addressed in the ACtIon4Cooling. These techniques are the surface brightening option by artificially changing the surface albedo properties and the space-based reflectors placed between the Earth and the Sun to block a fraction of solar radiation to enter at the Earth's atmosphere (Baum et al., 2022).

1.3 Ethical, Governance, and Scientific Advisory Context for SRM Research

The governance of SRM technologies and their ethical implications are central to their development and deployment. There are ongoing debates about the potential risks and benefits of SRM, with some groups strongly opposing it, while others conduct experimental studies in outdoor environments. In the middle ground, there are calls for a balanced approach. Governance frameworks, such as those being examined by the Co-CREATE EU project [URL-1], seek to establish principles for responsible SRM research. This includes critical questions on who would finance, control, and regulate SRM technologies, and the potential geopolitical risks that could arise. The European Group on Ethics in Science and New Technologies (EGE) [URL-2] plays a key role in providing independent, multi-disciplinary advice on the ethical and societal impacts of SRM and related technologies.

The EGE reports [RD07] on the large knowledge gaps of the effects and risks related to SRM research and potential deployment. The report calls that the large uncertainties on the climate change mitigation and adaptation techniques cannot result to so dramatic scenarios as the SRM uncertainties of impacts and risks related to those technologies can. And the main reason for those potential unintended negative side-effects and risks is the scientific and technical complexity of SRM nature. EGE recommends to establish a moratorium on SRM research. SAPEA Evidence Review Report [RD06] illustrates the complex sociotechnical nature of the SRM system. The system is composed of biophysical impacts (i.e., changes in temperature and precipitation patterns), energy consumption aspects, infrastructure and technology but also non-technical aspects such as cultural norms and policy frameworks. SAPEA characterized the system as coevolutionary and dynamic. The SAPEA evidence review report has been composed by an interdisciplinary working group of Europe's top independent experts and provides a detailed overview of the current scientific knowledge on SRM. Later the Group of Chief Scientific Advisors (GCSA) used the evidence review to form their Scientific Opinion (SO) Recommendations [RD08]:

SO Recommendation 1 *- Prioritise reducing GHG emissions as the main solution to avoid dangerous levels of climate change*

The European Green Deal (EGD), the Fit for 55 package, the goal of 90% emissions reductions by 2040, and achieving net-zero by 2050 are the most important EU climate targets. The suggestion is to continue to treat emissions reductions and adaptation to climate change as the highest priority in reaching net zero by mid-century and minimize "overshoot" and its adverse effects

- Efficiency improvements and substitution of fossil through carbon-free energy sources
- Mitigation of land-use emissions and enhancing sinks (nature-based solutions)
- Carbon Capture and Storage (CCS): A technology aimed at capturing carbon dioxide (CO_2) emissions from fossil fuel use in electricity generation and industrial processes, preventing CO_2 from entering the atmosphere by storing it underground
- Carbon dioxide removal (CDR) from the atmosphere

Continue to actively and vigorously invest in research on and deployment of climate mitigation and adaptation

SO Recommendation 2 *- Agree on a EU-wide moratorium of SRM deployment as a measure for offsetting climate warming (and reevaluate periodically, every 5-10 years)*

The many climatic, ecological and social risks and uncertainties of SRM deployment remain high, insufficiently understood and inherently not fully predictable.

- Acknowledge that there is currently insufficient scientific evidence that SRM would avoid dangerous climate change by reducing some of the resulting global warming.
- Model simulations, observations and theoretical considerations indicate that SRM would not completely offset or reverse dangerous climate change but only temperature raise with differing regional changes.
- Recognise that the deep uncertainties associated with possible SRM deployment are inconsistent with the precautionary and “do not harm” principles. The "do no harm" principles refer to a set of ethical and legal guidelines that aim to avoid causing harm to people, the environment, or society, particularly when designing and implementing policies or technologies.

SO Recommendation 3 - *Proactively negotiate a global governance system for research and deployment of SRM by means of a multilateral process with international legitimacy. Given the current state of knowledge, the EU position in these negotiations should be for the non-deployment of SRM in the foreseeable future*

The proposed governance system under the aegis of UN organizations such as UNFCCC, UNEP, WMO, UNCBD

- Base the EU negotiating position on relevant international and EU law.
- Carry out a broad and inclusive public consultation to inform the negotiation of the international agreement
- Include an exemption in the international treaty, with a clear permitting process that specifies conditions under which to authorize some limited outdoor SRM research, with appropriate consideration of the risks this research poses to the environment and associated social, economic and cultural impacts
- Ensure that the global governance system addresses the risk of militarization of SRM technologies in an international treaty
- Invest in operational Earth observation satellite and other technologies to improve the EU’s capability to detect and quantify any undeclared deployment of SRM by public or private actors, anywhere in the world.
- Oppose the use of “cooling credits” derived from SRM technologies in future negotiations on the implementation of multilateral climate agreements.

SO Recommendation 4 - *Ensure that research on SRM is conducted with scientific rigor, responsibly and in accordance with EU ethical principles in research. This should include research into the full range of the direct and indirect effects and unintended impacts of SRM on the climate system, biosphere and humankind, including governance and justice issues.*

The high uncertainties in the potential benefits and risks at the ecosystem, solar energy production, food production, communities of SRM can only be addressed by further research, which should be supported by public funding.

- Create clear ethical requirements for research projects on SRM, whether they are funded publicly or privately.
- Develop guidelines for outdoor research project on SRM
- Ensure that any public funding for SRM research is additional to and not instead of public funding for research on climate change mitigation and adaptation
- Impose a moratorium on large-scale outdoor SRM experiments

SO Recommendation 5 - *Reassess the scientific evidence on risks and opportunities of SRM research and deployment periodically, every 5-10 years*

Including research on both atmospheric physics and chemistry, and on the governance related to SRM could evolve quickly.

- Consider supporting the participation of the scientific community in intergovernmental assessments.

- Set-up citizens' assemblies to initiate a debate on SRM, promote transparency and develop fair governance.
- Support for the development or adaptation and operationalization of detection-attribution modelling tools, which could cover the range of time horizons and deployment scenarios under consideration.

The aforementioned SO Recommendations from the Group of Chief Scientific Advisors have been taken into consideration from ACtIon4Cooling consortium while conducting the research plan and writing this document.

The goal of ACtIon4Cooling is to contribute to SRM research via examination of the so-called "Observational evidence" from existing EO datasets. The modelling capabilities make suggestions on the potential positive and negative climatic effects. ACtIon4Cooling cannot examine SRM impacts and risks on soil production, public health, biodiversity, local communities and many other fields where SRM deployment could have an impact (see Table 1). ACtIon4Cooling will not deepen into the SRM Governance issues, but it will follow and comply to findings in other relevant EU projects like Co-CREATE and the other relevant funded projects. None of the ACtIon4Cooling partners advocate SRM as an alternative to climate change mitigation techniques aiming to the reduction of GHG concentrations emitted to the Earth's atmosphere.

1.4 Applicable Documents

The following project documents contain provisions which, through reference in this text, become applicable to the extent specified in this document.

Document Title		Document ID	Issue
[AD01]	AEROSOL AND CLOUD INTERACTIONS IMPACT IN THE CONTEXT OF SOLAR RADIATION MANAGEMENT - EXPRO+ Statement of Work	ESA-EOP-S-SOW-0195	1.0

1.5 Reference Documents

The following standards or documents are referenced in this document. They have been used (in the sense of tailoring) to prepare the document on hand.

Title	
[RD01]	European Commission, Joint Research Centre, Bailey, G., Farinha, J., Mochan, A. and Polvora, A., Eyes on the Future - Signals from recent reports on emerging technologies and breakthrough innovations to support European Innovation Council strategic intelligence - Volume 1, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/144136, JRC137811.
[RD02]	United Nations Environment Programme (2023). One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi.
[RD03]	World Meteorological Organization (WMO). (2024). *State of the Global Climate 2023*. WMO-No. 1347.Available online: https://library.wmo.int/idurl/4/68835 (accessed: 02/05/2024)
[RD04]	UNEP (2024). Executive summary. In Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments. United Nations Environment Programme (UNEP). Nairobi. https://doi. org/10.59117/20.500.11822/46404
[RD05]	NASEM. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. National Academies Press; 2021. https://doi.org/10.17226/25762
[RD06]	European Commission: Directorate-General for Research and Innovation & Group of Chief Scientific Advisors. (2024). Solar radiation modification. Publications Office of the European Union. DOI 10.5281/zenodo.14283096

[RD07]	European Commission: Directorate-General for Research and Innovation, Opinion on solar radiation modification – Ethical perspectives, Publications Office of the European Union, 2024, https://data.europa.eu/doi/10.2777/951016
[RD08]	European Commission: Group of Chief Scientific Advisors and Directorate-General for Research and Innovation, Solar radiation modification, Publications Office of the European Union, 2024, https://data.europa.eu/doi/10.2777/391614
[RD09]	Copernicus Climate Change Service (C3S) and World Meteorological Organization (WMO), 2025: European State of the Climate 2024, climate.copernicus.eu/ESOTC/2024, doi.org/10.24381/14j9-s541
[RD10]	Redmond Roche, B.H. and Irvine, P.J. (2024) Deliverable 2.1: Scoping notes on the state of solar radiation modification (SRM) research, field tests, and related activities. Co-CREATE Project. Available on the Co-CREATE Website (pending EC approval)
[RD11]	Redmond Roche, B. H. and Irvine, P. J. (2025). Deliverable 2.3: Case studies of solar radiation modification (SRM) field tests and related activities. Co-CREATE Project. Available on the Co-CREATE Website (pending EC approval)
[RD12]	National Academies of Sciences, Engineering, and Medicine. (1992). *Responsible science: Ensuring the integrity of the research process: Volume I*. Washington, DC: The National Academies Press. https://doi.org/10.17226/1864
[RD13]	Burns, W. and Talati, S. (2025). *The Solar Geoengineering Ecosystem: Key Actors Across the Landscape of the Field*. Jan. 2025, https://sgdeliberation.org/wp-content/uploads/2025/01/DSG-FCEA-Landscape-Report_Update_Jan-2025-4.pdf
[RD14]	World Meteorological Organization (WMO). (2023). State of the Global Climate 2022. WMO-No. 1316. Available online: https://public.wmo.int/publication-series/state-of-global-climate-2022 (accessed 02 May 2024).

1.6 Relevant Websites

Reference ID	Name	URL
URL-1	Co-CREATE	https://co-create-project.eu
URL-2	European Group on Ethics	https://research-and-innovation.ec.europa.eu/strategy/support-policy-making/scientific-support-eu-policies/european-group-ethics_en
URL-3	CleanCloud	https://projects.au.dk/cleancloud/cleancloud-project
URL-4	CleanCloud Arctic campaigns	https://projects.au.dk/cleancloud/cleancloud-project/objectives/activities/campaigns/arctic-spring-campaign
URL-5	SilverLining (co-funder to University of Washington MCB program)	https://www.silverlining.ngo/university-of-washington-marine-cloud-brightening-program
URL-6	SilverLining Roadmap for Climate Intervention Research	https://www.silverlining.ngo/reports/roadmap-for-climate-intervention-research
URL-7	University of Washington MCB program	https://atmos.uw.edu/faculty-and-research/marine-cloud-brightening-program/
URL-8	ACTRIS	https://www.actris.eu/
URL-9	Make Sunsets	https://makesunsets.com/
URL-10	MIT Tech Review – UK Geoengineering Test Flight	https://www.technologyreview.com/2023/03/01/1069283/researchers-launched-a-solar-geoengineering-test-flight-in-the-uk-last-fall/
URL-11	Climate Intervention	https://climateinterventions.org/explore-interventions/

URL-12	SCoPEx Framework, Deliverables and Timeline	https://scopexac.com/framework-deliverables-and-timeline/
URL-13	SPICE Project Cancelled – The Guardian	https://www.theguardian.com/environment/2012/may/16/geoengineering-experiment-cancelled
URL-14	EMODnet Human Activities	https://emodnet.ec.europa.eu/en/human-activities
URL-15	ARIA – Exploring Climate Cooling	https://www.aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling

1.7 Terms and Abbreviations

Abbreviations and terms specific to this document are summarized below.

Abbreviation	Meaning
CCT	Cirrus Cloud Thinning
OCRA	Optical Cloud Recognition Algorithm
ROCINN	Retrieval of Cloud Information using Neural Networks
SAI	Stratospheric Aerosol Injection
TROPOMI	Tropospheric Monitoring Instrument (aboard Sentinel-5 Precursor)
UV-Vis	Ultraviolet and visible spectral range
SRM	Solar Radiation Modification
UNEP	United Nations Environment Programme
ACI	Aerosol-Cloud Interactions
GHG	Greenhouse Gas
SAPEA	Science Advice for Policy by European Academies
EO	Earth Observation
pyDOME	python-based Discrete Ordinate Method with Matrix Exponential
ICON	ICOsahedral Non-hydrostatic
EGE	European Group on Ethics
GCSA	Group of Chief Scientific Advisors
SO	Scientific Opinion
CCS	Carbon Capture and Storage
MCB	Marine Cloud Brightening
CDR	Carbon Dioxide Removal
EGD	European Green Deal
EU	European Union
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme

WMO	World Meteorological Organization
UNCBD	United Nations Convention on Biological Diversity
EMODnet	European Marine Observation and Data Network
C3S	Copernicus Climate Change Service
PACE	Plankton Aerosol Cloud ocean Ecosystem
ESOTC	European State of the Climate
IMO	International Maritime Organization
SATAN	Stratospheric Aerosol Transport And Nucleation
SPICE	Stratospheric Particle Injection for Climate Engineering
E-PEACE	Eastern Pacific Emitted Aerosol Cloud Experiment
SCoPEx	Stratospheric Controlled Perturbation Experiment
UAV	Uncrewed Aerial Vehicle
EPSRC	Engineering and Physical Sciences Research Council
COT	Cloud Optical Thickness
CA	Cloud Albedo
CGT	Cloud Geometrical Thickness
CTH	Cloud Top Height
CF	Cloud Fraction
RF	Radiative Forcing
LWP	Liquid Water Path
CCN	Cloud Condensation Nuclei
AE	Ångstrom exponent
AI	Absorbing Aerosol Index
CER	Cloud Effective Radius
CBH	Cloud Bottom Heigt
INP	Ice Nucleating Particle
PBL	Planetary Boundary Level
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
VFM	Vertical Feature Mask
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
ATLID	ATmospheric LIDar
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
HALO	High Altitude and LOng range research aircraft

ML-CIRRUS	Formation, Lifetime, Properties and Radiative Impact of Mid-Latitude Cirrus Clouds
CIRRUS-HL	Cirrus in High Latitudes
WALES	WAter vapor Lidar Experiment in Space
DIAL	DIfferential Absorption Lidar
HSRL	High Spectral Resolution Lidar
CAS	Cloud Aerosol Spectrometer
CIP	Cloud Imaging Probe
CCP	Cloud Combination Probe
PIP	Precipitation Imaging Probe
PLDR	Particle Liner Depolarization Ratio
RHi	Relative Humidity with respect to Ice
OLR	Outgoing Longwave Radiation
GCM	Global Climate Model
MODTRAN	MODerate resolution atmospheric TRANsmission
OPAC	Optical Properties of Aerosols and Clouds
VIIRS	Visible Infrared Imaging Radiometer Suite
Suomi NPP	Suomi National Polar-orbiting Partnership
OLCI	Ocean and Land Colour Instrument
IRS	InfraRed Sounder
FCI	Flexible Combined Imager
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
SSA	Single-Scattering Albedo
PANGEA	Paleoclimate, Archaeology, and Geophysics of Antikythera Island and the Aegean
ASKOS	Atmospheric Sounding of the Kerguelen Archipelago
RTM	Radiative Transfer Model
SAGE	Stratospheric Aerosol and Gas Experiment
MODIS	MODerate resolution Imaging Spectroradiometer
EARLINET	European Aerosol Research LIdar NETwork
AERONET	AErosol RObotic NETwork
ACTRIS	Aerosol, Clouds, and Trace gases Research Infrastructure
MMSI	Maritime Mobile Service Identity
SST	Sea Surface Temperature
AIS	Automated Identification Signal
MSI	MultiSpectral Instrument

TEMPO	Tropospheric Emissions: Monitoring of Pollution
GEMS	Geostationary Environmental Monitoring Spectrometer
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY
ENVISAT	ENVIromental SATellite
GOME	Global Ozone Monitoring Experiment
EPIC	Earth Polychromatic Imaging Camera
DSCOVR	Deep Space Climate Observatory
ERS-2	European Remote Sensing Satellite
SLSTR	Sea and Land Surface Temperature Radiometer
CMIP6	Coupled Model Intercomparison Project Phase 6
PCA	Principal Component Analysis
KNN	K-Nearest Neighbors
HITRAN	High-Resolution Transmission Molecular Absorption Database
TOA	Top Of Atmosphere
CDR	Carbon Dioxide Removal
CCS	Carbon Capture and Storage
EDF	Environmental Defense Fund
DEGREES	DEveloping country Governance REsearch and Evaluation for SRM
AIMS	Australian Institute of Marine Science
CAARE	Coastal Atmospheric Aerosol Research and Engagement
NGO	Non-Governmental Organization
GEOS-5	Goddard Earth Observing System, Version 5
LR	Longwave Radiation
SR	Shortwave Radiation

2. User and Scientific Requirements

2.1 Aerosol-Cloud Interactions and Climate Relevance

Earth's climate is a complex perturbed system, in which a wealth of chemical, physical and biological processes take place on a wide range of spatial and temporal scales. Global, regional and local regimes are increasingly changing and are driven by changes in the components of the surface-atmosphere system. It is understood that human well-being is subject to climate settings, this specifically holding for populations dependent on favourable climate conditions (Samson et al., 2011) as well as on access to natural resources in specific hot-spot regions. At the same time, specific regions can be considered as natural laboratories for complex processes occurring at the interface between the surface and the atmosphere. Knowledge of the underlying mechanisms driving actual and future climate evolution is identified as one of the grand challenges of Earth Sciences, calling for interdisciplinary approaches.

Among the forcings exerted on these local ecosystems, energy consumption, changes in land and water use, carbon uptake, and injection of aerosols in the atmosphere play a prominent role in cooling the surface and reducing the total precipitation (Levy et al. 2013). Specifically, the latter may change cloud optical properties such as cloud optical thickness (COT) and in consequence cloud albedo (CA) via modulation of the droplet and ice crystal size spectrum and also perturb clouds' lifetime and physical features such as cloud geometrical thickness (CGT), and with it, cloud top height (CTH), as well as horizontal extent (i.e. cloud fraction(CF)). Aerosol-induced alterations of these cloud optical properties are essential to assess and quantify aerosol-cloud interactions (Bellouin et al., 2020; Quaas and Gryspeerdt, 2022). The radiative forcing due to aerosol-cloud interactions (RFaci, also known as Twomey effect or first aerosol indirect effect) is the response of cloud droplet number concentration, Nd, to aerosol and the subsequent cloud albedo change. The adjustments to ACI (a part of which previously was called cloud lifetime effect or second aerosol indirect effect) are the responses of cloud liquid water path (LWP), CGT and CF to these perturbations in Nd. Taken together, the RFaci and the adjustments form the effective radiative forcing due to aerosol-cloud interactions (ERFaci) (Watson-Parris et al., 2022; Forster et al. 2021 IPCC AR6 Chapter 7).

Despite extensive research in ACI, there is still at least a 50% spread in total aerosol forcing estimates (Li et al. 2022). This uncertainty is partly linked to the high uncertainty of aerosol absorption monitoring. Eventually, but not exclusively, aerosols can alter the hydrological cycle, mediated by the clouds which act as water reservoirs in the atmosphere and which produce precipitation. It is well-known that aerosol particles can alter the precipitation formation efficiency of clouds, from drying the atmospheric column via direct absorption of sunlight or by serving as cloud condensation nuclei (CCN), thus modulating diffusion and coalescence processes (Wei-Kuo et al., 2012). This brief, yet incomplete, overview of mutual impacts that aerosols and clouds experience in the atmosphere is termed aerosol-cloud-interactions (ACI, Rosenfeld et al., 2013, Fan et al., 2016) and highlights their role as structural proxies for a multitude of chemical and physical atmospheric processes. Therefore, combined monitoring of cloud and aerosol properties together over time and space unveils one of the underlying drivers of a changing climate.

While aerosols are physically categorised according to their size, shape, and chemical composition, satellite-based estimates of aerosol properties rely on their interaction with electromagnetic radiation - mostly at visible or near-visible wavelengths. Passive sensors focus on the aerosols' ability to attenuate impinging sunlight throughout the atmospheric column. The corresponding aerosol optical thickness (AOT) is a measure of aerosol load while its spectral gradient - the Ångstrom exponent (AE) - is an indicator of the effective size of the bulk particles. Long-term AOT patterns are pivotal in setting the spatio-temporal constraints of possible interactions of aerosols with water vapour and clouds. Size is the property that determines a particle's ability to nucleate a cloud droplet or an ice crystal. The partition of aerosols into absorbing and non-absorbing at ultraviolet (UV) wavelengths through the aerosol index (UVAI) provides further information on particle properties. Active remote sensing instruments, such as lidar and radar, are capable of providing height-resolved observations of aerosols and clouds, respectively, though with much smaller spatio-temporal coverage compared to passive observations. These measurements offer the needed information to verify that observed aerosol layers are indeed occurring at cloud level and, thus, in a position to interfere with them (Costantino and Bréon, 2013). It can therefore be expected that sensors with different spectral, spatial and temporal samplings observe different parts of the aerosol-cloud system.

An increased spatio-temporal resolution of space-borne observations is beneficial to the accuracy of retrieved atmospheric properties, which relies inherently on properly separating between cloudy and cloud-free measurements and on the quantitative inference of the aforementioned aerosol and the concurrent surface and cloud properties. The first procedure is called cloud masking (or clearance) and is not only a prerequisite for an accurate radiation transfer throughout the atmospheric column but also complements the retrieval of aerosol properties for ACI studies, thereby curbing uncertainties in RFaci by constraining the aerosol behaviour in clean, pristine, conditions (Gryspeerdt et al., 2023).

The aerosol response to local thermodynamics is a function of temperature, emission rates and particle injection height, which in turn dictate supersaturation levels and updraft velocities inceptive of ACI (Zheng and Rosenfeld, 2015, Chen et al., 2018, Jia et al., 2022). At the same time, the sign and magnitude of height-resolved ACI are still uncertain (Ma et al., 2018). It becomes then clear that the concurrent retrieval and analysis of the vertical layering of aerosols and clouds is one of the cornerstones ACI studies are based upon. This is because any adjustment of in-cloud microphysical properties, such as CER, Nd and LWP to aerosol perturbation will propagate to changes of cloud macro-physical properties such as CTH and CBH (Lelli, 2019).

Quaas et al. (2020) summarised the challenges in quantifying RFaci from satellite retrievals. The problems on the side of aerosol retrievals from passive observations include the lack of (i) vertical information, (ii) proper proxies for the concentration of those particles that are relevant for cloud processes (CCN and INP rather than bulk aerosol; Stier, 2016), and (iii) aerosol data very close to clouds and particularly for cloudy pixels. On the side of the cloud retrievals, the issues include that (i) parameters are not retrieved independently, i.e. Nd is typically computed from COT and CER retrievals (Grosvenor et al., 2018; Dipu et al., 2022), (ii) passive observations generally relate to conditions near cloud top, and (iii) in-cloud conditions and processes such as droplet activation, coagulation and adiabaticity have to be assumed for determining Nd.

2.2 General User and Scientific Needs

2.2.1 Overview of the knowledge gaps on SRM

Knowledge gaps in SAI mechanism

SAI has been reported as the most efficient SRM mechanism to reduce the global mean temperature of the Earth's atmosphere and surface, in an environment with increasing concentrations of GHGs (SAPEA Evidence Review Report [RD06]). The main knowledge gaps related to SAI are:

1. Effective deployment of SAI, including amount and type of injected aerosols, duration and location(s)/altitude(s) of the injection(s) (Bednarz et al, 2023; Krishnamohan et al., 2019; Sun et al., 2023; Tilmes et al., 2017; Visioni et al., 2020; Visioni et al., 2023; Zhao et al., 2021; Zhang et al., 2023), along with technological readiness and related cost.
2. Quantification of global cooling, along with other indented effects (e.g. reduction of heat waves, extreme temperatures, extreme weather, sustainment of cryosphere, decrease climate change impacts on vegetation, agriculture, drinking water and food security).
3. Identification and quantification of SAI side-effects related to changing the atmospheric dynamics and chemistry, precipitation patterns leading to weather extremes, reduction of solar power, uneven distribution of the stratospheric AOD and corresponding climate impacts between the two hemispheres, effects on natural ecosystems (e.g. failing to compensate climate change effects like the ocean acidification driven by increased CO2 levels), along with effects on social ecosystems.

Investigation of SAI methodologies has been partly motivated by the climate response to large volcanic eruptions of the past (e.g. the Mount Pinatubo eruption; Hansen et al., 1992; Trenberth et al., 2007; Pitari et al., 2014), which provided strong empirical evidence on the global mean surface temperature reduction after the release of large amounts of reflective particles in the stratosphere (i.e. sulfur dioxide (SO2), being oxidized to sulfuric acid (H2SO4), depositing in existing particles or forming new ones). Although volcanic eruptions are imperfect analogues for SAI research - due to the limited time scale and location of particle injections, and limited chemical, microphysical and optical properties of the particles injected in the stratosphere - they provide useful insights for SAI research.

Climate models provide the capability to investigate various aspects of SAI methodologies, including different deployment scenarios, their effectiveness in cooling down the Earth's surface, and the potential side-effects on global weather patterns and the climate. A crucial point is the capacity and limitations of current modeling approaches. To accurately capture the multifaceted nature of SAI, a wide array of climate model capabilities is required, as several factors and feedbacks may affect the simulations:

- Fully interactive aerosol microphysics, chemistry, radiation and transport and dynamics in the stratoshere and troposphere: The distribution of the particles in the stratosphere after the injections strongly depend on the aerosol representation (or the microphysical scheme used) in the model (e.g. see Laakso et al., 2021; 2024) as well as any chemical, dynamical and radiative processes the particles may undergo in the stratosphere (Pitari et al. 2014; Mills et al. 2017).

- Coupling to the land, ocean and the cryosphere.
- High spatial resolution, for properly describing the sub-grid atmospheric processes.

Unfortunately, only few climate models have the necessary capabilities (Pitari et al., 2014; Tilmes et al., 2022; Visioni et al., 2021).
Further, studies can be limited when only one model is used, since multi-model comparisons indicate significant differences in their assessments (Pitari et al., 2014; Tilmes et al., 2021), [RD14]. An ensemble of model would be best suited for SRM research (e.g. see the Geoengineering Model Intercomparison Project (GeoMIP); Kravitz et al., 2015) as it could aid in constraining the simulations, quantifying model uncertainties, and evaluating how various elements influence the effectiveness of SAI, and why.
The simulations duration should be sufficiently large to capture changes in particular processes and weather extremes. For example, Moore et al. (2010) highlight the fact that sea level responds to temperature change can span periods of the order of 102 years. Thus, in order to study the sea-level change due to potential SRM applications would require simulations of centennial time scales.

Different aspects that need to be investigated regarding the efficiency and impacts of SAI methodologies, are the following:

- **Injection duration and frequency**: SAI may mask warming, but an abrupt termination would result in high temperature re-emergence. This may be worse for natural and social ecosystems, than the increase of temperature due to climate change, since they will have a much shorter time to adapt. Different methodologies have been proposed for SAI temporary intervention, with (a) gradual increase of SAI (Kravitz et al., 2015), (b) temporary intervention, that will last decades or centuries, for preventing dangerous tipping-points (Lawrence et al., 2018; MacMartin et al., 2018; Tilmes et al., 2016; 2020), and (c) gradual phasing in of SAI and gradual phase out.
- **Injection height**: Lee et al. (2023) showed that injections at lower altitudes in the stratosphere would be less efficient in cooling down the surface primarily due to the shorter particles' lifetime but also due the water vapor feedback (i.e. lower-altitude SAI would induce more heating in the tropical cold point tropopause (CPT) region, enhancing water vapor transport into the stratosphere which would increase the outgoing terrestrial radiation trapping and offset some of the induced cooling). Furthermore, it was shown that at lower altitudes the amount of particles required to induce the same amount of cooling would be larger with implications for the cost, the frequency and the energy needed for such applications while at the same time, could also mean larger total ozone loss (due to the larger aerosol mass injected).
  Injecting particles at higher altitudes would place them into the upper branch of the Brewer-Dobson circulation (BDC), which would prolong their lifetimes due to slower sedimentation velocities (Niemeier et al., 2011) and thus result in more forcing per unit injection. However, larger aerosol lifetimes (e.g. by continuous SO_2 injections), favors aerosol growth due to coagulation. Since the radiative properties of the particles are directly related to their size distribution; aerosols that are larger than the optimal size for sunlight scattering (Dykema et al., 2016) are less effective at cooling and tend to settle out of the atmosphere faster, which would counteract the benefits of their longer atmospheric lifetimes.
- **Location of injections**: Numerous studies have focused on the optimum distribution of SAI effects across different latitudinal bands. Robock et al. (2008) investigated how the climatic effects of SAI vary depending on the latitude of injection, comparing tropical versus Arctic regions. The concept of injections preferentially over the Arctic originates from the idea that it would prevent the melting of the Greenland Ice Sheet and Arctic Ocean sea ice (Lane et al., 2007). However, injections over the Arctic would be much more short-lived compared to the tropical ones. The results of Robock et al. (2008), indicate that a continuous injection of SO_2 into the lower stratosphere above the tropics would result in long-term cooling across a wide range of latitudes while injection above the Arctic would also have widespread impacts beyond the region itself. Both cases could substantially alternate regional precipitation patterns with potential disruptions to the Asian and African summer monsoons.
  Also, according to Volodin et al. (2011) who studied the impact of continuous hemispheric injections in different latitudes, injections at altitudes above 20km near the equator (0-10°) would be more effective compared to injections at higher latitudes and lower altitudes. Nevertheless, the strongest

cooling effect occurs at high latitudes over land surfaces. Their results are also in agreement with previous studies showing reduction in mean global precipitation and global ozone as well as warming of the stratosphere. SO_2 injections at higher altitudes in the equatorial region have been show to significantly slow down the quasi-biennial oscillation (QBO). This effect may result from SAI inducing a persistent easterly shear, which enhances the confinement of aerosols within the tropics (Aquila et al., 2014; Niemeier et al., 2020).

MacMartin et al. (2017) used the fully coupled whole-atmosphere chemistry climate model CESM1(WACCM) to demonstrate that deploying injections at **multiple locations** (see also Kravitz et al. (2016; 2017; Tilmes et al., 2018) is more effective in offsetting greenhouse gas–induced warming compared to relying solely on equatorial injections. Using a combination of injections at 15° and 30° N/S, resulted in a nearly uniform global AOD distribution and showcased the potential to adjust the relative AOD between high and low latitudes. These results are crucial since a non-uniform global AOD distribution and uneven cooling of the two hemispheres, could lead in reduction in tropical cyclones frequency and droughts in semi-arid regions close to the tropics (e.g. Haywood et al., 2013; Jones et al., 2017).

All strategies

- **Nature of the injected materials**: Although a sulfur-based approach is considered to be the most effective for global cooling, it is also associated with ozone depletion and adverse regional effects on temperature and water cycles (e.g. Abiodun et al., 2021; Egbebiyi - Abstract EGU24-918), which counter the potential SAI benefits. Based on the study of Pierce et al. (2010), direct injections of condensable H_2SO_4 vapor would be more effective compared to non-condensable SO_2 vapor, as it would prevent the particles from becoming too large (and thus less efficient in sun-light scattering; e.g. see also Weisenstein et al., 2022), but also it may mitigate certain adverse such as heating of the lower stratosphere with effects on atmospheric composition and climate. H_2SO_4 will not mitigate though ocean acidification due to increase CO2 concentrations in the atmosphere. Direct injections of H_2S also aid in faster formation of H_2SO_4 while due to its lower molecular weight, the mass of H_2S needed would be half that of SO2 (Moore et al., 2010; Robock et al., 2009). It is however an extremely dangerous gas precursor (e.g. Kilburn and Warshaw, 1995; Kleber et al., 2008).

  Ultra-fine particles from **alternative materials** have also been proposed to partly alleviate some of the side-effects of sulfates, including calcium carbonate, diamond, alumina or titania (Pope et al., 2012; Keith et al., 2016). It has also been demonstrated that depending on their sizes, some of these alternative materials may exert a reduced perturbation on ozone (Weisenstein et al., 2015), or in some cases, may contribute to an ozone column enhancement, thereby even facilitating stratospheric ozone recovery (Keith et al., 2016). Nevertheless, to date research on alternative materials for SAI remains limited both in terms of laboratory studies and modelling efforts. As a result, key aspects such as their efficiency and potential side effects in atmospheric chemistry, radiation and atmospheric dynamics are not well understood yet.

The level of technological readiness for the deployment of SAI is very low, since there are currently limited platforms utilized for industrial, commercial or military use which could potentially carry and inject the amount of aerosols needed at the altitudes considered. This also makes an initial analysis of the energy budget needed for SAI extremely challenging.

The Pinatubo eruption released 20 Tg of SO2 into the lower tropospheric stratosphere which cooled down the surface for about 2 years. It is estimated that injections of 2 to 10 Tg/yr of particles are needed to mimic the Pinatubo effect and halt greenhouse warming of +2K (Wigley, 2006; Izrael et al., 2007; Robock et al., 2008). This mass is found to be comparable to the amount currently transported to near-tropopause altitudes annually by commercial aviation (IPCC, 1999: Aviation and the Global Atmosphere. IPCC Special Report).

Existing aircraft—including military jets and research planes—could potentially be adapted for SAI purposes, with the choice of aircraft depending largely on the required injection altitudes (e.g. see Duffey et al., 2025). However, current aircraft are not capable of sustained operation at the necessary altitudes over extended periods, and their payload capacities are limited, thus a large number of flights would be required to achieve meaningful injection levels. According to recent studies the construction of aircraft carrying ~15 tons up to 20km (in the Tropics) is feasible (Bingaman et al., 2020; Smith, 2020; Smith & Wagner, 2018), but it has not happened as of yet.

An alternative method involves the use of tethered balloon systems. This approach has been highlighted by the Committee on Science, Engineering, and Public Policy (COSEPUP) in its 1992 report Responsible Science: Ensuring the Integrity of the Research Process [RD12] and examined by following studies (e.g.

Robock et al., 2009). It was estimated that injecting 1 Tg of H_2S into the stratosphere via balloons would cost approximately $20 million (at the time of the study). However, this method would also generate significant environmental waste, with millions of kg of plastic from burst balloons falling back to Earth each year. Rockets, jet-hybrid rockets or guns (e.g. light-gas guns) may also be used. It has yet to be demonstrated that for either if the solutions (existing or future ones) the aerosol cloud formed would be optimum in terms of the particles sizes and lifetimes.
Another option is the subpolar deployment, for which the altitudes of injection are lower. Other methods, as using solar-lofting of absorbing particles injected into the upper troposphere instead to the stratosphere are also reported in the literature (Gao et al., 2021), but they need further investigation.

The knowledge gaps in SAI mechanism that will be investigated in the ACtIon4Cooling project:

- Deriving the microphysical and radiative properties of volcanic aerosols, and their evolution with time, used as a natural analogue of SAI.
- Defining the optical properties of alternative materials, for effective cooling of global climate, avoiding the adverse effects of sulfur particles.
- Effects on precipitation patterns and the weather system (if possible)
- Depletion of stratospheric ozone (if possible)
- Overcooling at the tropics or undercooling in the high latitudes (if possible)
- Potential loss of critical habitats resulting from alterations in temperature and ocean chemistry with unpredictable effects for the humans and the ecosystem (if possible)

Knowledge gaps in MCB mechanism

Unlike SAI, MCB could be more limited in its effectiveness to influence the global mean temperatures but it can have other positive impacts for the Earth's climate, as leading to regional temperature effects (Kravitz et al., 2013) and may partially offset certain impacts of climate change, such as extreme weather events, prolonged droughts, and heatwaves. resulting into Regional temperature effects (Kravitz et al., 2013) and compensate some effect of climate warming, like extreme weather or extended drought and heatwaves. Among the potential risks for MCB are the predicted strong temperature reductions at the northern high latitudes due to polar amplification, Antarctica and some low-latitude land areas (Stjern et al., 2018), overcooling of the tropics and residual warming of middle and high latitudes and the modification of precipitation patterns at regional scale. The latter is one of the topics to be studied in the ACtIon4Cooling project.

For MCB studies, the most effective material proposed to feed the marine clouds is the Sea Salt particles (Hernandez-Jaramillo et al., 2023), even though other materials like smoke particles and sodium chloride (salt) particles have been proposed to the literature too. The most widely known technology to persistently feed clouds with appropriate aerosols at the Planetary Boundary Level (PBL) is via using engineering Spray Nozzles (Hernandez-Jaramillo et al., 2023). Increased humidity and thermodynamic instability (systematic updrafts/downdrafts) could facilitate the efficiency of sea salt to act as CCN and enhance cloud reflectivity. Targeting suitable meteorological conditions (seeding location and timing), identifying the optimal particle composition and size, and minimizing adverse environmental effects, are some of the knowledge gaps for the MCB mechanism.

- **Uncertainties in Spray Parameters and Delivery Strategy:** There is limited understanding of the optimal droplet size, spray flux, nozzle design, and marine location for MCB. The effectiveness of cloud brightening depends on background cloud properties (LWP, CCN), updraft conditions, and aerosol-cloud interactions that are poorly constrained. Variability in outcome across modeling studies is large. The effects of timing and rate of marine cloud brightening aerosol injection on albedo changes are examined during the diurnal cycle of marine stratocumulus clouds (Jenkins et al., 2013).

- **Cloud-Aerosol Interaction Complexity:** MCB relies on enhancing cloud albedo by increasing cloud droplet number concentration (CDNC), but non-linear feedbacks such as cloud thinning, precipitation suppression, and evaporative invigoration complicate the response. These interactions vary regionally and temporally, and are highly sensitive to cloud regime (e.g., stratocumulus vs. trade cumulus) (Quaas et al., 2009; Diamond et al., 2020).

- **Environmental and Climatic Side Effects:** MCB may disrupt precipitation patterns, reduce ocean heat flux, alter large-scale circulation or create regional overcooling. The risk of unintended regional impacts (e.g., droughts) is poorly understood (Kravitz et al., 2013; Stjern et al., 2018).

- **Model Uncertainty and Incomplete Representation:** Most climate models simplify marine low cloud processes, often lacking explicit cloud microphysics or resolving mesoscale organization. Cloud feedbacks and aerosol indirect effects in MCB scenarios remain uncertain, as revealed by GeoMIP and MCB-specific modeling studies. The models does not fully capture cloud dynamics, aerosol dispersion, or feedbacks in the real Earth system, limiting confidence in the spatial precision of predicted impacts (Jones et al., 2009). Regional climate responses—such as shifts in tropical rainfall and monsoonal behavior—underscore the model's limited ability to represent complex coupled interactions between atmosphere, ocean, and land. Latham et al. (2012) provide a comprehensive review of MCB modeling and underscore key uncertainties in representing mesoscale cloud dynamics, and the organization of marine stratocumulus systems. They stress that current global models often lack the spatial resolution and process-level detail necessary to simulate cloud microphysics and feedbacks that influence regional climate responses, such as monsoonal shifts and hydrological changes. The findings from Alterskjær et al. (2012), who used the NorESM model to investigate the effects of MCB on marine stratocumulus clouds, reveal that the effectiveness of MCB is highly sensitive to model representations of cloud microphysics, boundary layer processes, and aerosol–cloud interactions. Moreover, they show that regional radiative responses vary strongly depending on model configuration, pointing to persistent uncertainties in simulating feedback mechanisms and cloud-aerosol dynamics.

- **Technological Feasibility and Operational Control:** No scalable and controllable spray technology exists. Prototypes for sea-salt particle generation or/and marine vessel delivery remain in the experimental phase, with concerns about energy requirements, particle dispersion, and operational safety. An initial analysis of the energy budget needed for MCB would imply that we would have to translate the intervention into energy needs.

- **Detectability and Attribution Challenges**: Because MCB effects are expected to be subtle and localized, distinguishing them from natural variability and anthropogenic aerosol signals is difficult. Detecting changes in cloud albedo, microphysical properties, or radiative forcing requires high-resolution, long-term EO datasets with accurate aerosol-cloud characterization (Bender et al., 2016).

- **Ethical and Governance Issues:** Targeting specific marine regions for MCB (e.g., off the coasts of developing nations or vulnerable ecosystems) raises ethical concerns. Unlike SAI, MCB might require more decentralized deployment, complicating international governance and public consent frameworks (Reynolds, 2019).

The knowledge gaps in MCB mechanism that will be investigated in the ACtIon4Cooling project:

- Identify potential MCB intervention zones based on cloud susceptibility and study the modification of precipitation patterns at regional and global scale.
- Monitor changes in cloud microphysics and radiative properties post-intervention.
- Improve model constraints by providing empirical benchmarks.
- Distinguish MCB effects from natural and anthropogenic aerosol-cloud interactions.

Knowledge gaps in CCT mechanism

CCT aims at cooling the planet by reducing high-level cirrus clouds that trap outgoing longwave radiation from the Earth's surface (Mitchell and Finnegan, 2009; Lohmann and Gasparini, 2017). The core mechanism behind CCT is to artificially inject efficient INPs into regions where cirrus clouds form to trigger ice crystal formation via heterogeneous nucleation at relatively warmer temperatures and lower supersaturation. This could lead to the formation of fewer and larger ice crystals due to the competition for available water vapor. As these ice crystals grow larger and heavier, their sedimentation rates increase, thinning cirrus clouds and reducing their optical thickness. Therefore, the resulting thinner cirrus clouds become more transparent to outgoing longwave radiation from the Earth's surface and underlying atmosphere, leading to a cooling effect.

- **Fundamental Uncertainty in Climate Efficacy:** Unlike SAI or MCB, CCT aims to *reduce longwave forcing* by seeding cirrus clouds to reduce their optical thickness or frequency. However, the net radiative impact of cirrus clouds is highly variable and dependent on local cloud properties, vertical motion, and moisture content. Whether thinning them leads to cooling or warming remains uncertain in many regimes (Storelvmo et al., 2013; Gasparini & Lohmann, 2016).

- **Limited Knowledge of Optimal Seeding Conditions**: Yet, the effectiveness of seeding depends on the pre-existing aerosol background, temperature, updraft strength, and cirrus origin, which are poorly constrained (Storelvmo et al., 2014). Some of potential climate side effects for CCT are related to seeding procedure of artificial INPs which could eventually prevent natural cloud formation processes due to the competition for available water vapor. The large ice crystals falling out of high altitudes could cause droughts or shifts in precipitation, altering atmospheric circulation patterns. Unexpected overcooling in specific regions may disturb local ecosystems and weather patterns. There are no long-term effects reported for CCT but this needs to be further verified. Despite the experimental and theoretical progresses in understanding CCT mechanism, the microphysical properties of cirrus cloud including ice crystal size and habit affect their radiative forcing and sedimentation rate, which is, however, not fully quantified. The balance between homogeneous and heterogeneous nucleation and the relative importance under varying conditions are still poorly constrained. The role that aerosol particles play in initiating ice crystal formation are still poorly understood and the effect of aerosols in terms of type and size on CCT is highly uncertain. Observing the cirrus cloud properties comprehensively is still challenging due to the limitations of probing instruments: satellite instruments suffer from resolving thin cirrus and aircrafts provide limited temporal and spatial coverage. The coordinate of observations on different platforms is hence important and imperative.

- **Risk of Overcompensation or Warming:** The risk of "overseeding" and a positive radiative forcing instead (Gasparini & Lohmann, 2016), if the background cirrus clouds are already formed by heterogeneous nucleation, remains uncertain. If CCT is deployed inappropriately—e.g., in regions with cirrus that already have a net cooling effect—it could reduce cloud cover that was beneficial, thereby causing *net warming*. Identifying “safe” regions and seasons for CCT is an unsolved problem (Storelvmo et al., 2014; Gruber et al., 2019).

- **Lack of Real-World Technology and Testing:** CCT assumes a capability to inject INPs (e.g., bismuth tri-iodide or mineral dust) into the upper troposphere (~8–12 km altitude). No current technology is proven to deliver sufficient particle concentrations with the required precision or environmental safety. The ice nucleation properties of candidate materials remain poorly characterized under real atmospheric conditions (Kuebbeler et al., 2012; Cziczo et al., 2015). So far, small-scale field tests have not been conducted yet. The relevant studies of CCT remain primarily in global climate model simulations (e.g. with CESM and ECHAM) (Storelvmo et al., 2013; Gasparini and Lohmann, 2016). Laboratory and chamber studies provide supports to the basic physics behind CCT (Vogel et al., 2022). Mineral dust particles as effective INPs have been proposed as the most efficient material for CCT, while sulfates via homogenous freezing and Bismuthtriiodide (BiI~3~) are also reported in the literature to play a role (Mitchell and Finnegan, 2009).

- **Modeling Limitations:** Few models simulate cirrus microphysics in enough detail to evaluate CCT strategies robustly. Large inter-model differences exist in cirrus representation, ice nucleation schemes, and aerosol interactions. Most GeoMIP models are not yet equipped to evaluate realistic CCT scenarios (Gasparini et al., 2020; Gettelman et al., 2021).

- **Observational Detection is a challenge:** Cirrus clouds are thin, transient, and vary on short timescales, making it difficult to detect CCT-induced changes against natural variability. Detecting reduced ice crystal number concentrations, changes in effective radius, or alterations in longwave cloud radiative effect requires hyperspectral and lidar data with high vertical resolution (Campbell et al., 2016).

- **Potential environment risks:** Injecting artificial INPs into the upper troposphere introduces unknown chemical and environmental risks. Long-range transport, toxicity, and interactions with natural aerosols are poorly studied. Bismuth-based compounds or modified mineral dusts might pose ecological risks or affect stratospheric chemistry (Cziczo & Froyd, 2014).

The knowledge gaps in CCT mechanism that will be investigated in the ACtIon4Cooling project:

- Provided that the impacts of CCT on climate are still unclear, selecting appropriate regions and seasons for CCT as well as examining the type of seeding would be beneficial (Gruber et al, 2019).
- The efficiency of aerosols to act as INPs at relatively low (cirrus-like) temperatures is associated with high uncertainties.
- The effectiveness of CCT in reducing global warming by compensating for the heating effect of cirrus clouds in the infrared spectrum is one of the main questions for ACtIon4Cooling.

2.2.2 Types of users (e.g., climate scientists, policy stakeholders, EO communities)

The pool of users for the ACtIon4Cooling output datasets, originates from the scientists already involved into relevant projects and networks working under the European Commission - ESA cluster on "Improving knowledge of cloud and aerosol interactions", i.e. the CERTAINTY/CleanCloud/AIRSENSE projects. The latter falls within the scope of the Earth System Science Initiative (ESSI), the flagship initiative launched jointly by the European Space Agency and the European Commission to advance Earth System Science and its contribution to addressing the global challenges facing society in the early 21st century.

A joint workshop on Requirement Consolidation is planned, in order to align the scientific needs with other international SRM-related research priorities.

2.2.3 SRM-relevant activities: From the Past to Present

A survey on the past and current activities relevant to SRM research is helpful to identify what has been studied and which are the facts and limitations of each SRM mechanism. The Co-CREATE [URL-1] project in their Scoping note on the state of Solar Radiation Modification (SRM) research, field tests, and related activities [RD10] presented a list of field campaigns and relevant to SAI and MCB activities. A comprehensive overview of the solar geoengineering activities is also presented in the report from The Alliance for Just Deliberation on Solar Geoengineering & Forum for Climate Engineering Assessment (2025, January) [RD13].

- Field Experiments during 2008-2009 in Saratov Oblast, Russia (Izrael et al., 2011) have been reported as potential geo-engineering activities. They appear controversial in references [RD10], [RD13] as candidate experiments for SAI, but the particles were released in the troposphere by a moving vehicle and helicopter.
- SPICE (Stratospheric Particle Injection for Climate Engineering) [URL-13] was a research project (2010–2014), funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and involved leading English universities that aimed to investigate the feasibility, risks, and effectiveness of SAI. Among its objectives were to: (a) Evaluate the technical feasibility of delivering aerosol particles to the stratosphere (e.g., via tethered balloons, aircraft, or other means). (b) Study atmospheric processes and particle behavior. (c) Assess the governance, ethical, and environmental issues of SAI. (d) Engage in public dialogue and stakeholder consultation about geoengineering. A small-scale outdoor engineering test to trial a balloon and hose delivery system was proposed but it was cancelled before starting due to governance concerns and public opposition.
- SCoPEx (Stratospheric Controlled Perturbation Experiment) [URL-12, URL-11] is a small-scale scientific field experiment, led by American researches at Harvard University, to explore the feasibility, risks, and effectiveness of SAI. SCoPEx targeted to improve understanding of: (a) How aerosol particles

behave in the stratosphere, (b) Their impact on stratospheric chemistry, particularly ozone (c) How they scatter sunlight and potentially cool the planet, (d) How they interact with atmospheric dynamics. They proposed an experimental set-up with a balloon-borne platform to release a small amount of aerosol, such as calcium carbonate ($CaCO_3$) or sulfate particles, at about 20 km altitude. The platform would carry instruments to measure: aerosol properties, atmospheric chemistry, light scattering and particle dispersion. The scientific objectives of SCoPEx were to test models of aerosol behavior in the stratosphere, validate how well these particles reflect sunlight and investigate potential side effects, like ozone depletion or stratospheric heating. SCoPEx planned its initial test flight in Sweden but it was cancelled before starting, similar to SPICE due to public opposition and ethical concerns. SATAN (Stratospheric Aerosol Transport And Nucleation) [URL-10] is a modeling framework developed to simulate the microphysical processes and transport of aerosols in the stratosphere, particularly in the context of SAI. It focuses on simulating aerosol nucleation, growth, coagulation, and sedimentation in the stratosphere. It is often used to assess the climate impacts and side effects of injecting sulfate or other aerosols for geoengineering purposes. It is typically embedded in or coupled with climate models or chemical transport models.

- Make Sunsets [URL-9] is a controversial U.S.-based startup founded in 2022. The company aims to combat climate change through solar geoengineering, specifically by releasing sulfur dioxide (SO_2) into the stratosphere to reflect sunlight and cool the planet. Make Sunsets has conducted small-scale experiments by launching weather balloons containing a few grams of SO_2. Initial tests occurred in Baja California, Mexico, without prior consultation with local authorities or scientific oversight. Subsequent launches were carried out in Nevada, USA, where the company claimed to have received necessary approvals, though these claims were later disputed. The company finances its operations by selling "cooling credits," asserting that each gram of SO_2 released offsets the warming effect of one ton of CO_2 for a year. These credits are sold at $10 per gram, targeting both individuals and corporations seeking to mitigate their carbon footprint. Make Sunsets' unregulated experiments have drawn criticism from scientists and policymakers raising ethical questions about unilateral actions that could have global implications. Critics argue that decisions on geoengineering should involve international consensus and public engagement. Following the backlash and regulatory actions, including Mexico's ban on solar geoengineering experiments, Make Sunsets has paused its activities in certain regions. The company has expressed interest in collaborating with governments, particularly those of island nations vulnerable to climate change, to continue its initiatives under more formal agreements.
- E-PEACE (Eastern Pacific Emitted Aerosol Cloud Experiment) (Russell et al., 2013) was a major field campaign conducted in 2011 off the coast of California, designed to study ACI, especially those relevant to MCB and the broader science of climate intervention via aerosol emissions. The experiment aimed to improve understanding of: (a) How aerosols from ships and controlled sources influence cloud microphysical and radiative properties (b) The formation of ship tracks (long brightened cloud features caused by ship emissions) (c) The sensitivity of marine stratocumulus clouds to artificial aerosol perturbations. Key components of the experiment were:

  (1) Controlled aerosol releases: An aircraft released monodisperse aerosols into the marine boundary layer, mimicking MCB-relevant interventions.

  (2) Ship-based emissions: A ship released targeted aerosol plumes under measured conditions.

  (3) Multiple aircraft platforms: Aircraft carried instruments to measure cloud microphysics, aerosol concentration, droplet size distribution and radiation.

  (4) Multiple aircraft platforms: Aircraft carried instruments to measure cloud microphysics, aerosol concentration, droplet size distribution and radiation.

  (5) Satellite validation: Observations were compared to satellite data (e.g., MODIS, CALIPSO) to validate remote sensing of ACI.

  E-PEACE was one of the first controlled experiments relevant to the feasibility of MCB while it provided experimental evidence on: cloud albedo response to aerosol injection and cloud adjustments (i.e., liquid water path and precipitation suppression). Its findings informed model development and observational strategies for future geoengineering and climate monitoring studies.
- The Great Barrier Reef Marine Cloud Brightening (MCB) project, led by Australian scientists from Southern Cross University and the Australian Institute of Marine Science (AIMS) is a pioneering field trial exploring the potential of MCB to help mitigate the impacts of ocean warming on coral reefs, particularly

the coral bleaching (Tollefson et al, 2021). The project aims to cool ocean surface temperatures over the Great Barrier Reef by increasing the reflectivity of low-level marine clouds. This is done by spraying tiny sea salt particles into the atmosphere, acting as CCNs and leading to brighter and longer-lasting clouds that reflect more sunlight. The experiment contributes to assess feasibility, safety, and effectiveness of MCB as a local climate intervention to reduce sea surface temperature during marine heatwaves and protect coral ecosystems from bleaching. The outdoors experiments were conducted on and around the Great Barrier Reef, Australia for the period 2020-2021 and the method involved specialized nozzles on boats or platforms atomize seawater into micron-scale salt particles and spray them into the air under suitable meteorological conditions. Hernandez-Jaramillo et al., (2024) established a new airborne research platform, designed primarily for MCB field studies. This platform, comprising a Cessna 337 aircraft was outfitted with a comprehensive suite of meteorological, aerosol, and cloud microphysical instrumentation normally only found on much larger aircrafts. The aircraft has completed its first field deployment over the Great Barrier Reef supporting the Reef Restoration and Adaptation Program.

- The University of Washington's MCB Program [URL-7] is a leading research initiative by atmospheric scientists at the University of Washington. Key partners include SRI International and the nonprofit organization SilverLining [URL-5], which funds the program through its Safe Climate Research Initiative. Additional support comes from various foundations and individual donors committed to advancing climate research.The MCB Program goals are:

  - Enhance understanding of ACI and their impact on climate.
  - Investigate the feasibility of using sea salt aerosols to increase cloud reflectivity.
  - Assess the potential benefits, risks, and efficacy of marine cloud brightening as a climate intervention strategy.

  Researchers employed a combination of computer modeling, observational studies, and controlled field experiments to study these interactions. For instance, they analyze ship-tracks to understand how aerosols affect cloud properties. Additionally, they conduct small-scale field studies using instruments designed to generate controlled amounts of sea salt aerosols to observe their effects on cloud brightness [URL-7].

  To facilitate field research and public engagement, the MCB Program established the Coastal Atmospheric Aerosol Research and Engagement (CAARE) facility aboard the USS Hornet, a decommissioned aircraft carrier in Alameda, California. This platform allows scientists to conduct experiments in a marine environment and engage with the public through educational displays and demonstrations [URL-7]. However, in 2024, the city of Alameda requested a pause in the experiments conducted on the USS Hornet.

- The CLOUDLAB project, led by Swiss scientists, used supercooled stratus clouds as a natural laboratory for targeted glaciogenic cloud seeding to advance the understanding of ice processes: Ice nucleating particles are injected from an uncrewed aerial vehicle (UAV) into supercooled stratus clouds to induce ice crystal formation and subsequent growth processes. These experiments focused on wintertime stratus clouds as a natural laboratory to study ice crystal formation from injected particles, for model validation purposes (Hanneberger et al., 2023).

Some Non-Governmental Organizations (NGOs) [RD13] have interest in SRM research like SilverLining [URL-6], which is a U.S.-based nonprofit organization dedicated to advancing scientific research and policy development aimed at addressing near-term climate risks, particularly via SRM techniques. SilverLining had funded the University of Washington's MCB Program [URL-5]. Among others NGOs engaged to SRM research, a condense list includes:

- The Degrees (DEveloping country Governance REsearch and Evaluation for SRM) Initiative is a UK-based NGO that seeks to engage the Global South on SRM issues.

- SRM360 launched in November 2024 as a “non-profit knowledge hub that explores the science and evidence behind” SRM.

- Operaatio Arktis is a youth-led Finnish science outreach project promoting equitable climate intervention research with central goal to preserve the Arctic sea ice.

- Environmental Defense Fund (EDF) announced it would be creating an SRM research program to fund impacts-focused research.

Exploring potential field campaigns are also one of the objectives of Co-CREATE project, where in their latest report [RD11], five hypothetical SRM experiments were presented. One of those hypothetical field studies refers to smaller-scale CCT experiment in Arctic Norway, exploring the use of ice-nucleating particles to enhance the escape of longwave radiation and reduce the effects of Arctic Amplification, while addressing the challenges of conducting research in the Arctic. The EU CleanCloud [URL-3] project aims to get a better understanding of ACI mechanisms in the Arctic via their Arctic spring & summer campaigns [URL-4] that took place in 2024.

A major concern on field experiments (even small-scale) is that they could inevitably lead to SRM deployment, and thus the risk of a “Slippery slope” is foreseen, which could happen if incremental steps towards broader SRM implementation occur without sufficient public debate, transparent decision-making, or robust governance frameworks [RD10]. And an SRM deployment has the risk of termination shock. which refers to the rapid and severe climate consequences that could occur if SRM deployment (i.e., SAI) were suddenly stopped after being deployed for some time.

Latest funded activities by the ARIA (Advanced Research Intervention Agency)

ARIA will be funding the Exploring Options for Actively Cooling the Earth Programme [URL-15] which aims to answer fundamental questions of climate cooling approaches that have been proposed as potential options to delay or avert damaging climate tipping points through indoor and (where necessary) small, controlled, outdoor experiments. The programme includes not only experiments but also modelling, simulation, observation and monitoring funded activities required to support the experiments, as well as research into the ethical, governance, law, and geopolitical dimensions of the climate cooling approaches. The information gathered by this programme will allow for more definitive assessments on whether one or more of the approaches examined may one day be used responsibly and ethically to delay or avert the onset of temperature-induced climate tipping points.

Within the ARIA programme, the following modelling activities are planned:

- **GRID-CC: Global to Regional Impacts Downscaling for Climate Cooling**
  [by The Degrees Initiative – University of Cape Town | Cornell University]
  Understanding the regional impacts of Earth cooling strategies is essential—especially for communities in the Global South that may be disproportionately affected. However, research capacity is often centered elsewhere. This project addresses that gap by empowering researchers in the Global South through computational efforts. It will develop an open-access repository of detailed climate data specific to the Global South, enabling more accurate global and regional impact models. Alongside new research tools, expert workshops will support scientists in these regions to build a robust evidence base for scientifically informed decision-making about Earth cooling approaches.
- **Ecological Impact Assessment of Earth Cooling Experiments in the Arctic (Eco-ICE)**
  [by British Antarctic Survey | University of Oxford]
  Polar ecosystems are fragile yet crucial to the global climate system, but the ecological effects of climate interventions in these regions remain poorly understood. Combining laboratory experiments with climate and ecosystem modelling, this project offers an independent, comprehensive assessment of potential interventions in the Arctic marine environment. By integrating biogeochemical and biological data, the team aims to deliver best-practice guidelines for ecological risk assessment, ensuring future Arctic interventions are evaluated with scientific rigor and environmental caution.
- **Investigating the Impacts of Earth Cooling on West African Monsoon Variability and Wet-Dry Spells**
  [by Institut Polytechnique Rural de Formation et de Recherche Appliquée (IPR/IFRA) | University of Cape Town]
  The West African Monsoon sustains millions through agriculture and water resources. This project

examines how Earth cooling strategies might alter critical rainfall patterns, including wet and dry spells, with implications for regional stability and food security. Utilizing advanced climate models, observational data, and scenarios from platforms like GeoMIP, the research addresses gaps in understanding interactions between cooling approaches and existing climate vulnerabilities, offering actionable insights to guide adaptation and risk mitigation in West Africa.

- **Space Reflector Baseline Survey**
  [by Planetary Sunshade Foundation | Cornell University | National Center for Atmospheric Research | University of Nottingham | Redwire Space | NASA Jet Propulsion Laboratory | Ethos Space]
  To evaluate lesser-known climate cooling options such as space-based reflectors, this theoretical study unites top space engineering and climate modelling teams. Six conceptual space reflector designs will be modelled, followed by simulations of their potential climate impacts—including atmospheric dynamics, chemistry, and ocean/ice feedbacks. The goal is not deployment but to identify which concepts merit further research based on modeled efficiency, scalability, and side effects, fostering collaboration between engineering and climate science communities.
- **Towards Robust and Unbiased Validation of SAI Simulations (TRUSS)**
  [by Institut Teknologi Sepuluh Nopember]
  Reliable data is essential for responsible decision-making about interventions like Stratospheric Aerosol Injection (SAI), yet current simulations carry significant uncertainties. This project uses advanced statistical and machine learning techniques to enhance the accuracy and impartiality of climate model outputs, especially regarding regional impacts. By improving simulation trustworthiness, this foundational work builds scientific confidence necessary for informed policymaking and public understanding
- **Simulating Effects of Earth Cooling on Monsoon Dynamics and Precipitation Extremes**
  [by Cochin University of Science and Technology | The Energy and Resources Institute (TERI)]
  Stable rainfall patterns are vital for agriculture and water security in both India and the UK. This study explores how Earth cooling proposals could disrupt seasonal rains and precipitation extremes by analyzing climate simulations from GeoMIP and similar platforms. It aims to unravel the complex drivers behind potential changes, delivering region-specific evidence to assess risks to critical water cycles and resources.
- **Defining the Minimum Scale of a SAI Test: A First Step Toward Outdoor Experiments**
  [by Cornell University]
  One key uncertainty in climate intervention science is how cooling aerosols behave when released into the stratosphere. This project tackles that gap through theoretical modelling, aiming to determine the smallest viable scale for an outdoor experiment that could provide real-world data to reduce uncertainty. Identifying this minimum scale is critical groundwork for responsible future research and for developing necessary governance and oversight frameworks.

Within the ARIA programme, the following outdoor monitoring activities are planned:

- **De-risking Cirrus Modification**
  [by Imperial College London | University of Leeds | University of Vienna | RIKEN]
  Cirrus clouds at high altitudes generally warm the climate, but the role of atmospheric particles (like soot) in their formation is uncertain. This project combines modelling, satellite data analysis, and research aircraft flights to measure how natural and anthropogenic particles influence cirrus clouds. By improving understanding of these processes, it provides essential baseline knowledge for evaluating the safety and effectiveness of potential cirrus cloud thinning as a climate cooling strategy.
- **Ice-Nucleating Particles in the Upper Troposphere: Advancing Cirrus Control and Experimental Science Strength (“INPUT:ACCESS”)**
  [by University of Leeds | CIRES University of Colorado | Imperial College London]
  Ice nucleating particles (INPs) are crucial for cirrus cloud formation but remain poorly characterized. This project develops balloon-borne collectors to sample INPs in the upper troposphere, followed by detailed lab analysis. These data will enhance climate models and improve monitoring of natural atmospheric processes, providing a critical baseline for climate science.

- **StratoGuard – Global Monitoring of Climate Engineering Using Micro High-Altitude Balloons**
[by Voltitude | University of Hertfordshire | Imperial College London | NOAA Chemical Sciences Laboratory]
This project develops small, low-cost balloons equipped with sensors to navigate the stratosphere for up to 30 days, enabling sustained, affordable global climate data collection. StratoGuard aims to support detailed monitoring of natural climate phenomena and any future climate intervention activities, with test launches beginning in 2026 and full regulatory compliance assured.
- **Monitoring Aerosol Climate Engineering (MACE)**
[by University of Bristol]
Natural volcanic eruptions offer opportunities to study aerosols relevant to climate science and interventions. This project develops advanced drones capable of high-altitude flights to sample emissions from active volcanoes in Guatemala, Montserrat, and Chile. By analysing natural aerosol-cloud interactions, the research seeks to establish a rapid-response capability for safely gathering crucial data from future eruptions.

Within the ARIA programme, the following controlled, small-scale outdoor experiments are planned:

- **Re-Thickening Arctic Sea Ice (RASi)**
[by University of Cambridge | University of Manchester | University College London | Nansen Center | Real Ice | Arctic Reflections | University of Washington | Arizona State University]
Accelerated Arctic warming threatens sea ice loss with serious global impacts. This project tests whether deliberately thickening winter sea ice by spraying seawater can reduce summer melt and Arctic warming. Small-scale experiments will take place in Canada over three winters, expanding coverage if ecological safety is confirmed. Conducted under strict governance and community collaboration, the research will deliver critical data on the intervention's feasibility and ecological effects.
- **Marine Cloud Brightening in a Complex World**
[by Southern Cross University]
Marine Cloud Brightening (MCB) aims to cool vulnerable ecosystems by enhancing cloud reflectivity using seawater spray. Building on prior fieldwork near the Great Barrier Reef, this project combines advanced modelling and sea salt sprayer development. Subject to ARIA governance and community partnership, small-scale outdoor experiments are planned for years 3 and 4 over the reef. These will be carefully controlled and transparent, generating real-world data on MCB's effectiveness and risks.
- **A Responsible Innovation Framework for Novel Spray Technology (REFLECT)**
[by University of Manchester | University of Cambridge | Archipelago Technology | University of Exeter | Finnish Meteorological Institute | University of Leeds]
This project develops and tests spray technologies critical for Marine Cloud and Sky Brightening (MCB/MSB). Through modelling, indoor tests, and community co-design, it aims to responsibly assess technical feasibility. Outdoor spray tests, if approved, will be very small and brief, replicating natural sea spray processes. The goal is to create a robust framework for evaluating and safely advancing spray technologies.
- **BrightSpark – Cloud Brightening with Electric Charge**
[by University of Reading | Menapia Ltd | Celestial]
Exploring an alternative to seawater spraying, this project investigates using controlled electric charges to enhance cloud reflectivity. It focuses on the fundamental science of how electrical charges affect cloud and fog droplets, aiming to determine whether this method could safely and effectively influence cloud properties.

2.3 Scientific Objectives and Observational Needs for SAI

The injection of aerosol particles in the stratosphere may significantly change the radiative budget of the Earth and have a direct effect on global temperature. Such an example was the decrease in global temperature due to the injection of volcanic aerosols in the stratosphere after the Mt. Pinatubo eruption, which persisted for a significant period of time (e.g. McCormick et al., 1995).

Volcanic eruptions have been extensively investigated as a natural analog of SAI (Robock et al., 2013; Proctor et al., 2018). Within ACtIon4Cooling we seek to deepen our understanding on the climatic effects of volcanic eruptions focusing on events occurring at different times of the year (i.e. seasonality) and originating from diverse latitudes, such as tropical and high-latitude regions. These observations will provide a natural analogue for SAI at different locations and altitudes, which may be used for increasing the effectiveness of SAI and avoiding possible side-effects.

For monitoring purposes, we plan to utilize space and ground-based remote sensing observations with advanced capabilities, as well as state of the art scattering datasets to properly characterize the volcanic particles injected in the stratosphere in terms of their microphysical and optical properties, and how these evolve after their injection. For example, it is a common belief that volcanic ash is very quickly removed from the stratosphere due to the large particle sizes. Thus, ash particles are commonly neglected in model simulations. However, recent studies using polarimetric lidar data, have highlighted that stratospheric ash-rich aerosols can be observed for months after an eruption (Vernier et al., 2016). Moreover, Zhu et al. (2020) demonstrated that the lifetime of SO_2 in the stratosphere is primarily controlled by its uptake on fine ash particles which can lead to about 43% more sulfur removal from the stratosphere within two months. Thus, there is a need to take such processes into account when using volcanic eruptions as natural analogues to investigate the impact of SAI on stratospheric chemistry and radiative processes.

Special focus will be given to the use of lidar observations (from space and ground like CALIPSO and ACTRIS/EARLINET, or from the new EarthCARE mission), along with their synergy with passive remote sensing observations (e.g. ground-based photometers of the AERONET network or satellite based polarimetric measurements provided from instruments like POLDER and HARP/SPEXone). The synergistic use of the observations is crucial in order to acquire valuable information on the particle vertical distribution and injection height, along with their microphysical and optical properties, to accurately classify the aerosol types injected into the stratosphere from the volcanic eruptions and properly characterize their chemical and radiative impacts within the Earth system. Whenever available, airborne **in-situ** data (e.g. from balloon borne measurements) will be also utilized to help constrain the aerosol microphysical properties like their size distribution (e.g. see Ansmann et al., 1996).

Spatial and seasonal distribution of the case studies

The observations will be acquired at variable locations (i.e., mid latitude (Europe), tropical, and sub-Antarctic regions) and seasons (i.e., winter, spring and summer), as this is available from the observational datasets for each eruption case. This approach will facilitate the need to study the long-term SAI effects like rainfall distribution and ozone layer dynamics as a function of space and time of the year of the eruption. Based on results of previous studies, eruptions at tropical, high northern and southern latitudes can interact in distinct ways with climate phenomena such as the El Niño which would in turn affect the Pacific sea surface temperature (SST) in a different way (Zuo et al., 2018). Also, during different seasons it is expected that the weather patterns including wind motions, atmospheric stability (changes in convective motions) and stratospheric circulation will affect the dispersion of the volcanic air masses.

Provided aerosol properties

The optical properties of the volcanic aerosols injected in the stratosphere will be calculated using the MOPSMAP scattering database (Modeled optical properties of ensembles of aerosol particles; Gasteiger and Wiegner, 2018), assuming spherical shapes for the sulfate and spheroidal shapes for the volcanic ash particles. The microphysical properties (i.e., size distribution, shape and refractive index) of the particles required as input will be derived either from the literature (e.g. the OPAC scattering database; Hess et al., Koepke et al., 2015) or from observational data. The aerosol optical depth, the asymmetry parameter, the single scattering albedo, as well as the extinction coefficient profiles and the phase matrix of the volcanic particles will be provided in the SW and LW for radiative transfer (RT) calculations with the PyDOME RT code, as a function of altitude, latitude and longitude.

2.4 Scientific Objectives and Observational Needs for MCB

The key cloud microphysical and optical properties essential for MCB studies are identified based on the state-of-the-art needs of Aerosol-Cloud Interactions (ACI). Important parameters include cloud droplet number concentrations, which vary with latitude and longitude, as they are critical inputs for Earth system models. Additionally, a dependence on cloud type may be required for more accurate characterization. However, deriving cloud microphysics from space remains challenging due to several assumptions inherent in remote sensing retrievals. For example, the cloud liquid water path, which is influenced by perturbations in cloud droplet number concentrations, may be assumed invariant in some Earth Observation (EO) datasets.

Regions of interest

The regions of interest encompass several marine environments that are potentially relevant for MCB studies. As an initial focus, the European Seas—particularly the Mediterranean region—are highlighted due to the exceptionally high sea surface temperatures (SSTs) recorded in 2023. According to the European State of the Climate 2024 (ESOTC 2024) report, released in April 2025 by the Copernicus Climate Change Service (C3S) and the WMO [RD09], the Mediterranean experienced the most intense marine heat anomalies ever observed, underscoring the escalating impacts of climate change on this region.

An open scientific question is whether these SST anomalies have been amplified by the recent reduction in aerosol emissions from shipping, linked to the implementation of the International Maritime Organization (IMO) 2020 regulation. This regulation, effective from 1 January 2020, mandated a global reduction in the sulfur content of marine fuels from 3.5% to 0.5%. As a result, sulfur dioxide (SO_2) emissions from ships have decreased substantially, leading to a reduction in the formation of sulfate aerosols in the marine boundary layer.

Sulfate aerosols have a well-documented cooling effect through cloud brightening mechanisms—particularly over stratocumulus cloud decks—by increasing cloud droplet number concentration and cloud albedo. Their reduction may lead to less reflective clouds (Gryspeerdt et al., 2021) and a corresponding increase in surface solar absorption, potentially contributing to amplified warming (Yuan et al., 2024) in high-traffic regions such as the Mediterranean. Given the Mediterranean's status as one of the world's busiest shipping corridors, this hypothesis warrants further investigation within the MCB research framework.

Sensitivity to aerosol-cloud interaction retrievals

For complementary ACI information over oceans, PACE payload sensors can provide valuable data. The Ocean Color Instrument (OCI) is capable of retrieving aerosol optical properties over oceans and detecting aerosol plumes, as well as surface albedo, using high-spectral-resolution measurements from UV to NIR wavelengths. SPEXone, a multi-angle polarimeter, is highly relevant for precise aerosol characterization, including aerosol size, composition, and refractive index. This instrument could be instrumental in assessing cloud condensation nuclei (CCN) efficiency, which is crucial for understanding MCB mechanisms. HARP2, also a multi-angle and multi-spectral polarimeter, extends the capabilities of SPEXone by offering higher spatial coverage and providing additional cloud-related data. It is designed to measure cloud properties such as droplet size, phase, and thickness, making it well-suited for MCB studies.

2.5 Scientific Objectives and Observational Needs for CCT

Global aviation exhausts emissions, primarily composed of greenhouse gases, aerosol particles, and water vapor, into the atmosphere at high altitudes, which may lead to the formation of linear contrails and contrail cirrus. They increase global cloudiness and modify the existing cirrus properties indirectly. During the ML-CIRRUS campaign, the particle linear depolarization ratios (PLDR) of cirrus clouds have been measured with the WALES lidar of DLR. A backward trajectory analysis reveals that cirrus clouds with enhanced PLDR formed and evolved in the regions with high aviation emissions and those with smaller PLDR from rather pristine regions (smaller impact of aviation) (Urbanek et al., 2018). Furthermore, cirrus clouds with larger PLDR are characterized by larger ice crystals with smaller number concentration (Groß et al., 2023). The changes in cirrus cloud PLDR depending on aviation emissions have also been seen in the satellite observations (Li and Groß, 2021, 2022).

There may be no perfect natural analogues for CCT, but aviation-relevant cirrus cloud and the involved processes provide helps for us to understand how CCT might work in the real atmosphere. Within ACtIon4Cooling, we will use the existing airborne observations to focus on specific clouds that may form in the regions with either dense aviation emissions or not and further derive the optical thicknesses, ice water content, and ice crystal number concentrations. From a statistical prospective, we will also use the satellite data to determine the optical and microphysical properties of cirrus clouds as a function of latitude and longitude as input for Earth system model studies. During the ML-CIRRUS and CIRRUS-HL campaigns, there were in-situ instruments mounted under the wings of the HALO aircraft. Small particles in the size range from 3 to 50 µm were detected by the CAS (Voigt et al., 2017; Kleine et al., 2018). Larger particles were detected by the CIP (Cloud Imaging Probe, in the size range from 15 to 960 µm) as part of the CCP (Cloud Combination Probe) and the PIP (Precipitation Imaging Probe, in the size range from 100 to 6400 µm) instrument (Weigel et al., 2016). With these instruments, the microphysical properties of cirrus clouds, like ice crystal effective diameter (De) and number concentrations (Ni), can be derived. However, the in-situ instruments can only provide 1-D measurements along the flight track, e.g., no vertical structure. WALES is a multi-wavelength lidar system including DIAL and HRSL capability. So it can measure water vapor mixing ratio and aerosol extinction, backscatter coefficients, and depolarization. With the lidar observations, we will identify the cloud top height and derive the optical thicknesses. From the satellite observations of CALIPSO, we will estimate the extinction coefficients of cirrus clouds and calculate their optical depth. The ice crystal De and Ni can be derived from the DARDAR data (with the synergy of CLOUDSAT and CALIPSO), which, however, are limited only for certain periods. EarthCARE will further provide the microphysical properties of cirrus clouds with the radar-lidar synergy in near future. The determined optical properties of cirrus clouds as a function of latitude and longitude will be provided for RF calculations to ICON model and PyDOME RT code. Especially, the perturbations in ice crystal number concentrations of cirrus clouds responding to aviation-induced impacts will be highly investigated.

2.6 Radiative Transfer Modelling (RTM) for SRM Monitoring

Role of RTM in simulating top-of-atmosphere (TOA) and surface radiative changes

A radiative-transfer model (RTM) such as pyDOME (Efremenko et al., 2017) links the micro-physical properties of atmospheric constituents such as gases, aerosol particles, cloud water/ice particles as well as surface properties to the radiative quantities that govern climate response. By converting profiles of gases, aerosols, clouds and surface reflectance into wavelength-dependent optical properties, the RTM solves the radiative transfer equation for a specified solar and viewing geometry. From the resulting radiance field, the up-welling irradiance at the top of the atmosphere can be derived, yielding the change in reflected energy - or instantaneous radiative forcing - that determines whether the planet experiences cooling or warming. The same solution decomposes the down-welling irradiance at the surface, revealing how much sunlight actually reaches the ground or ocean. Irradiance convergence between layers provides heating-rate profiles, showing where the atmosphere itself is warmed or cooled and how circulation might respond.

Specific RTM configurations needed in pyDOME for each SRM mechanism

TBD

Requirements for input data (aerosol/cloud profiles, surface reflectance)

To perform radiative transfer simulations, the atmospheric model containing the temperature and gaseous profiles should be provided. In pyDOME, aerosol optical properties are normally derived from microphysical inputs - namely the parameters of the particle-size distribution and the complex refractive index - through Mie computations that assume spherical particles. The code offers direct interfaces to the OPAC and MODTRAN aerosol libraries, so users can select mixtures representative of specific environments such as urban, continental, marine or polluted regions without having to build each distribution from scratch. The same Mie routine is applied to cloud droplets when spherical geometry is adequate. If desired, however, optical properties for any aerosol or cloud layer can be supplied explicitly by specifying its spectral optical thickness, single-scattering albedo and phase function. The phase function may be given either as Legendre coefficients or, more simply, via an asymmetry parameter; in the latter case pyDOME adopts a Henyey–Greenstein representation by default.

2.7 Global Climate Modelling

Need for coupling observational constraints with climate model scenarios

Set up of simulations with the atmospheric general circulation model (GCM), the ICOsahedral Non-hydrostatic (ICON) model (Hohenegger et al., 2023) for present-day boundary conditions (sea surface temperature and sea ice concentration distributions, land surface conditions, greenhouse gas and aerosol concentrations). The model will be prepared such that it can digest the relevant perturbations

- to the stratospheric aerosol layer, in terms of a distribution in aerosol optical depth as a function of altitude, with specified optical properties (single scattering albedo, asymmetry parameter)
- to boundary-layer clouds, in terms of a perturbation of the cloud droplet number concentration and potentially of the cloud liquid water path, for specified longitude-latitude boxes and potentially time periods,
- to cirrus, in terms of a perturbation to the ice crystal number concentration and potentially the ice water path, for specified longitude-latitude boxes and potentially time periods,

Key outputs needed from climate models (e.g., temperature anomalies, precipitation shifts, radiative forcing changes)

The model output will involve surface temperature and precipitation patterns for statistical analysis of extreme and mean values resolved by region, and of top-of-atmosphere and surface energy budgets to monitor the effects of the perturbations.

Compatibility with major global models

Similar quantities will be gathered from simulations from available model intercomparison projects (parts of the CMIP6).

2.8 Gaps in Existing Observational and Modelling Infrastructure

Summary of current capabilities and their limitations

The role of RTMs on simulating the SRM scenarios should be considered with some limitations as there are several assumption to be made in each mechanism. For MCB, the limitations are bounded to the Radiative properties of clouds which do not always align well with the microphysical and macro-physical properties used in those RTM simulations. The major uncertainties for MCB will be introduced due to the rapid adjustments of clouds during the spraying process. The biggest challenges for the global and regional climate models to study the impacts of MCB are the large uncertainties in cloud microphysics and prevailing turbulence.

Limitations for SAI research are also due to the derived microphysical and optical properties of volcanic aerosols, since there is no extensive observational dataset for volcanic eruptions from both remote sensing and in-situ instruments. The associated uncertainties propagate in RTM calculations. The uncertainty grows larger for monitoring the evolution of particle properties with time. The change in particle properties, as well as their removal from the stratosphere, is also challenging for global models, which have limitations in the processes that can include in their calculations. Excellent representation of the chemical interactions in the stratosphere is required for the modelling of SAI scenarios, as the uncertainties related to the particle interactions with other particles present in the stratosphere (e.g. smoke) can be huge.

The biggest GCM challenges to study CCT effects are in cirrus formation and dissipation mechanisms.

The RTMs have limited capabilities due to the large uncertainties in cirrus microphysical and turbulent processes.

2.8.1 Relevance of satellite-based, airborne, and ground-based observations

For investigating the SAI approaches, we will use the natural analogue of volcanic aerosol injection in the stratosphere after volcanic eruptions, utilizing satellite observations from SAGE, CALIPSO, EarthCARE and PACE missions, and possibly from geostationary satellites (e.g. MSG, MTG). Moreover, we will use ACTRIS ground-based lidar and photometer observations, and available in-situ measurements from high altitude tethered balloons.

The detection and monitor capabilities of potential MCB activities can be examined by natural (non-perfect) analogues like cloud tracks observed from degassing volcanoes or ship tracks. Spaceborne measurements are crucial for studying the changes in sunlight reflectivity caused by MCB, while ground-based observations (e.g., ACTRIS network) are valuable for characterizing the aerosols beneath the cloud base.

Aircraft-induced contrails can have similar properties as natural cirrus clouds. Further, cirrus clouds that form and develop under aerosol indirect effects from aviation emissions may exhibit different properties compared with those from pristine regions. We can monitor the changes in cirrus cloud properties (optical, microphysical, and radiative) responding to aviation emissions to understand the effects of CCT. For this purpose, we make use of all possible airborne measurements (both in-situ and remote sensing techniques) during the ML-CIRRUS and CIRRUS-HL campaigns and satellite measurements of CALIPSO, EarthCARE, and MSG/MTG.

Table 2 The associated EO datasets from spaceborne platforms suitable for MCB, CCT and SAI development and validation studies

Sensor	**Platform**	**Type**	**Spectral Range**	**Spatial Resolution**	**Temporal Resolution**	**Key Capabilities for MCB**	**Key Capabilities for CCT**	**Key Capabilities for SAI**
TROPOMI	Sentinel-5P	Spectrometer	UV–VIS–NIR–SWIR	~5.5 × 3.5 km²	Daily (global)	Aerosol layer height, UVAI, absorbing aerosols, limited cloud properties	N/A	Stratospheric and tropospheric ozone profile, total column density
CALIOP	CALIPSO	Lidar	532 & 1064 nm	~30 m vertical, ~333 m horizontal	16-day repeat (narrow swath)	Vertical aerosol/cloud profiles, layer typing, depolarization	Cloud profiling, aerosol extinction and depolarization	Profiles of aerosol and cloud backscatter coefficient and depolarization Target classification Mass concentrat

								ion profiles
CPR	Cloud Sat	Cloud Profiling Radar	94 GHz, W-band	500 m vertical , /1.4 km horizontal	16-day repeat	N/A	Partical size and number concentration with synergic CALIOP and CPR	N/A
IIRS	Suomi-NPP	Radiometer	VIS–NIR–SWIR–TIR	370 m (I-band), 740 m (M-band)	Daily (global)	Cloud optical thickness, cloud top properties , AOD	N/A	N/A
MODIS	Terra/ Aqua	Radiometer	36 bands (VIS–TIR)	250 m (bands 1–2), 500/1000 m (others)	1–2 days (global)	Aerosol/cloud properties , cloud phase, droplet radius, optical depth	Cloud top properties, COT, cloud fraction	Aerosol spatial distribution in 2D, AOD
ATLID	EARTHCARE	High-spectral Resolution Lidar	355 nm	~100/500 m vertical (below/ above 20km), /~100 m horizontal	25-day repeat	Profiles of aerosol/cloud extinction, backscatter and depolarization,	Aerosol and cloud profiling, lidar ratio, aerosol extinction and depolarization	Profiles of aerosol and cloud backscatt erand extinction coefficients, and depolarization Target classification Cloud top height
CPR	EarthCARE	Cloud profiling radar	94 GHz W-band	100/500 m vertical and 750 horizontal	Twice per day	N/A	Thick cloud profiling, Particle size and number concentration with synergic ATLID and CPR	N/A

MSI	EARTHCARE	Imager	4 channels (VIS - SWIR) 3 channels (TIR)	500 * 500 m (VIS–SWIR), 1 km (TIR)	25-day repeat	Scene context for ATLID, cloud top height, aerosol optical depth, cloud masking	Cloud top properties, COT, cloud fraction, ice crystal size	Aerosol optical thickness at 0.67 and 0.865 um Cloud masking (up to 4) Aerosol types vertical distribution, AOD, SSA, CRI (in synergy with ATLID)
OCI	PACE	Spectroradiometer	340–885 nm (hyperspectral), NIR–SWIR bands	~1 km	1–2 days (global)	Ocean color, AOD over water, large-scale aerosol monitoring	N/A	N/A
SPEXone	PACE	Multi-angle Polarimeter	400–770 nm (spectral resolution of 2-5nm for intensity, 10-40nm for DoLP, 5 viewing angles)	~2.5*2.5 km	1–2 days (narrow swath)	Fine-mode aerosol size/composition, CCN proxy, aerosol–cloud interaction metrics	N/A	For fine and coarse mode aer-osols: AOD, AE, CRI, SSA, Sphericity fraction, ALH, Vol-ume den-sity, reff, veff
HARP2	PACE	Wide-angle Polarimeter	440, 550, 670, 870 nm (60 viewing angles for intensity and DoLP at 670nm, 20 in other wavelengths)	~7 * 5 km	1–2 days (broad swath)	Cloud droplet size, aerosol type, cloud thermodynamic phase	N/A	Similar to SpexONE Cloud masking

SLSTR	Sentinel-3A/B	Radiometer	VIS–SWIR–TIR (9 bands)	500 m (VIS/SWIR), 1 km (TIR)	2–3 days (global)	SST, cloud temperature, cloud mask, fire/aerosol detection	N/A	N/A
OLCI	Sentinel-3A/B	Spectrometer	400–1040 nm (21 bands)	300 m	2–3 days (global)	Ocean color, AOD, cloud optical thickness, water vapor	N/A	N/A
FCI	Meteosat Third Generation	Imager	VIS–IR (16 channels)	0.5-1 km (VIS/NIR), 2 km (IR)	Every 2.5 minutes (Europe) / Every 10 minutes (full disk)	Rapid cloud/aerosol evolution, optical properties, nowcasting	Cloud top properties, COT, cloud fraction	Aerosol spatial distribution in 2D
SEVIRI	MSG, Meteosat Second Generation	Imager	0.4 – 1.6 µm (4 visible/NIR channels), 3.9-13.4 µm (8 IR channels)	3 km (narrowband), 1 km (HRV)	5 min for rapid scanning,15 min for full disk scan		Cloud top properties, COT, cloud fraction	Aerosol spatial distribution in 2D
POLDER	PARASOL	Polarimeter	UV-NIR (7 channels between 443-1020nm)	6 * 7 km	16-day repeat			Similar to SpexONE and HARP
AERONET	Ground-based	Sun/Sky-radiometers	UV-NIR (340-1020nm)	N/A	Direct sun measurements every 15min, solar almucantar every 1h			Column-effective AOD, AE, SSA, SD, phase function, calibrated radiances

EARLINET	Ground-based	Multi-wavelength polarization lidars	UV-NIR (355-1064nm)	N/A	Continuous			Extinction, Backscatter coefficient, Depolarization profiles (at least in 2 wavelengths)
OMPS/LP	S-NPP	Limb profiler	VIS-NIR (510-997 nm)	(horizontal) 125km (vertical) 1km				Ozone profile
ACE-FTS	ACE	high-resolution infrared spectrometer ("solar occultation" technique)	750-4400 cm^{-1}	3km				Ozone depletion
MLS	Aura	Limb sounder	Microwave (118-2500 GHz)	(horizontal) 200-500km (vertical) 0.5km in stratosphere				Ozone and water vapor profiles (and other atmospheric gases)
SAGE III	ISS	Spectrometer (solar and lunar "occultation" technique)	(UV-IR)	(vertical) 0.75-1.5km				Upper-troposphere and strotosphere: ozone, and water vapor aerosol extinction coefficient 0.385-1.550 μm, AOD
CERES	TRMM, Terra, Aqua, S-	Radiometer	SW (0.2–5 μm, Thermal (8–12 μm)	1 degree				Radiation fluxes at TOA

	NPP, NOAA-20		Total (>0.2 µm)						
BBR	EarthCARE	Radiometer	SW (0.25-4.0 µm) Total (< 0.25 to > 50 µm)	10km					Radiances and fluxes at TOA

3. Technical Approach and Methods

3.1 Overview of Methodological Frameworks

3.1.1 Marine Cloud Brightening studies

For MCB, the primary information on cloud properties will be acquired from the space-borne spectrometer TROPOMI on Sentinel-5 Precursors (Veefkind et al., 2012). The operational algorithms for the retrieval of cloud parameters from the atmospheric Sentinel missions make use of Earth-shine reflectance measurements in the spectral windows of UV, VIS and NIR. The TROPOMI operational cloud algorithms OCRA/ROCINN (Loyola et al., 2018) have a long-standing heritage and they were applied operationally to several instruments starting with GOME (Global Ozone Monitoring Experiment) on ERS-2 (European Remote Sensing Satellite) (Loyola et al., 2010), SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY) on ENVISAT (ENVIromental SATellite) (Loyola et al., 2004), the GOME-2 instruments on board MetOp-A/B/C (Meteorological Operational satellite) (Lutz et al. 2016), and the EPIC (Earth Polychromatic Imaging Camera) instrument on the DSCOVR (Deep Space Climate Observatory) satellite, located at the Lagrangian point L1 (Molina García, 2022).

The MCB data can be enriched from observations acquired from future missions like Sentinel-4 on the geostationary Meteosat Third Generation satellites and Sentinel-5 carried on the polar-orbiting MetOp Second Generation satellite. Sentinel-4 will provide data from an UVN spectrometer and EUMETSAT's thermal InfraRed Sounder (IRS), both embarked on the MTG-Sounder (MTG-S) satellite. In addition, the Sentinel-4 mission is planned to include data from Eumetsat's Flexible Combined Imager (FCI) embarked on the MTG-Imager (MTG-I) satellite. The Sentinel-4 mission is part of the so-called Geo-Ring for Air Quality, which consists of three geostationary instruments to monitor the air quality and atmospheric composition over large parts of the northern hemisphere with a high temporal resolution: (a) the European S4 instrument, (b) the Korean Geostationary Environmental Monitoring Spectrometer (GEMS, launched 2020), the US-American Tropospheric Emissions: Monitoring of Pollution (TEMPO, launched 2023). These geostationary instruments can benefit substantially from the knowledge gained by heritage LEO missions like OMI/Aura, GOME-2/MetOP-A/-B/-C and TROPOMI/Sentinel-5P and provide a great synergistic potential to combine the global spatial coverage of the LEO missions with the regional high temporal coverage of the GEO missions (Lutz et al., 2024). The Geo-Ring for Air Quality, can provide scientific evidence about cloud properties modifications which can be used for monitoring the effectiveness of potential SRM activities. The Sentinel-5 mission comprises an Ultraviolet Visible Near-infrared Shortwave (UVNS) spectrometer and data from EUMETSAT's IRS, the Visible Infrared Imager (VII) and the Multi-viewing Multi-channel Multi-polarization Imager (3MI).

The existing satellite records of cloud-aerosol properties have been so far derived either from measurements in the optical range of MERIS (Mei et al., 2017a,b, 2018) and near infrared (NIR) from passive sensor (as in Lelli et al. 2012, 2014 for clouds and Lelli et al., 2015, Sanders et al. 2015, Kylling et al. 2018 for aerosols) of the GOME/GOME-2 and SCIAMACHY sensor family or from signal returns of the active sensors CALIOP on CALIPSO (Winker et al., 2009) or CPR on CloudSAT (Stephens et al., 2002). Despite their operation dates back in time, being commendable for long-term global climatological and trend studies, the coarse footprint of the NIR passive sensors inherently favours the detection of high clouds over low clouds, which have higher probability of being shielded in multi-layered cloud systems. When an instrument with higher spatial resolution is used such as TROPOMI, it must be expected that the derived cloud retrievals will improve the representativeness of tropospheric low-level cloud structures. Due to the vertical structure of the troposphere, low-altitude cloud textures, that are the manifestation of the manifold pathways aerosols influence their microphysics, will be better captured. Complementary information for the clouds captured by TROPOMI instrument will be exploited from VIIRS on Suomi-NPP. When MTG-S is on track, the complementary information for the clouds captured by Sentinel-4 will be exploited from the FCI sensor. The diurnal cycle of marine clouds over the European Seas can be studied with a high temporal and spatial resolution from the S4 observations.

The marine clouds with ship-track emissions will be studied. Changes in the cloud cover and reflectivity of those marine clouds with ship emission signature will be monitored. The marine clouds with ship-track signature over the Mediterranean Sea (and elsewhere) could function as the cloud brightening geoengineering experiment within the ACtIon4Cooling project. Already in 1966, ship-tracks were observed as anomalous cloud lines from weather satellites. Those lines have been attributed to the aerosol emissions of ships, mainly referring to sulphates and black carbon (Conover et al, 1966). The aerosol information is captured by the TROPOMI sensor in the Oxygen absorption bands (i.e., Aerosol Layer Height), and in the UV spectral window as well. In particular, the ultraviolet (UV) Absorbing Aerosol Index (AAI) is widely used as an indicator for the presence of absorbing aerosols in the atmosphere (Kooreman et al., 2020; Torres et al., 1998a). The ship-track signature of aerosols in the TROPOMI cloud retrievals will be investigated via the scientific NASA TropOMAER (TROPOMI aerosol algorithm), which simultaneously retrieves aerosol optical depth (AOD), Single-Scattering Albedo (SSA), and the qualitative UV aerosol index (UVAI) (Torres et al., 2020).

Validation of the MCB dataset is foreseen for the marine clouds captured by PANGEA (PANhellenic GEophysical observatory of Antikythera) observatory at the island of Antikythera (35.861N, 23.310E, 110m a.s.l). PANGEA is an active member of ACTRIS and AERONET network and a satellite Cal/Val center in the Mediterranean region. Validation of the MCB dataset will be strengthened from the ESA funded experimental campaigns (e.g. the ASKOS experiment). Finally, the ESA EarthCARE mission (Illingworth et al. 2015, Wehr et al., 2023), supported by the complementary datasets of the NASA PACE mission (Werdell et al., 2019), thanks to their unique designs, offers the unparalleled opportunity to generate and exploit novel parameters of the aerosol-cloud system and pave new ways for studying ACI and RFaci and advance atmospheric science as a whole.

In addition, it can also be applied to mitigate the negative effects of strong extended heatwaves and droughts on human health, agriculture and the ecosystem (Jones et al., 2022).

3.1.2 Stratospheric Aerosol Injection studies

Aerosols in the Earth's stratosphere have a cooling effect upon the Earth's climate, as the aerosol droplets scatter part of solar radiation directly back into the space. Furthermore, the thermal radiation emitted by the Earth is absorbed in the stratosphere, resulting in warming of the upper atmosphere. The quantity and nature of the aerosols determine the degree of cooling or warming and affect the course of important chemical processes in the stratosphere. In Action4Cooling we will study the impacts of aerosols in the stratosphere, related to SAI, using natural analogues of volcanic aerosols injected in the stratosphere after volcanic eruptions. Detailed measurements for the derivation of their microphysical and optical properties is essential for the quantification of their radiative effect, as well as model evaluation and understanding of the processes that take place.

For SAI, the primary information on sulfate and volcanic ash aerosol vertical distribution, injection heights and radiative properties will be acquired from space-borne and ground-based lidar systems like the dual wavelength (532 and 1064 nm), elastic, polarization lidar CALIOP on-board CALIPSO and the single wavelength (355 nm) HSRL lidar ATLID on board EarthCARE. For CALIOP the latest version of the stratospheric aerosol subtyping algorithm (v4.5; Tackett et al, 2023) incorporates new thresholds to enable efficient discrimination between volcanic ash, smoke, sulfate in the stratosphere, and polar stratospheric aerosols. Important revisions in the new algorithm version relevant to Action4Cooling, include updated values of the volcanic ash lidar ratio (LR; extinction to backscatter ratio) and higher confidence level for the sulfate subtype along with the relevant uncertainties. By applying this algorithm for recent volcanic eruptions in Southern America, Tackett et al. (2023) also demonstrated that it is possible to derive a decay rate in PLDR values at 532nm which is a very useful parameter to describe particle aging and removal of ash aerosol from the stratosphere. CALIOP data are openly available through the Aeris database (https://www.aeris-data.fr/en/projects/calipso-4/)

EarthCARE target classification product (A-TC; Donovan et al., 2023) relies on PLDR, extinction and backscatter profiles together with auxiliary model data from ECMWF to classify different type of targets. A set of four aerosol components with pre-defined PLDR and LR values are the main driver to form the different aerosol mixtures (Wandinger et al., 2023) characterized from the target classification process. Since ATLID is an HSRL system, extinction values (and thus LR) are derived directly without the need to rely on climatological data (as in the case of CALIOP). Currently openly available, EarthCARE products can be found through: https://earth.esa.int/eogateway/missions/earthcare

The dataset for sulfates and ash aerosol properties will be enriched with multi-wavelength, polarization Raman lidar data from the ground-based EARLINET network (Pappalardo et al., 2014). Ground-based lidar systems like those employed in EARLINET are commonly of higher capabilities compared to space-borne instruments, and thus can be utilized for enhanced aerosol characterization. EARLINET data are distributed to registered users through the EARLINET database: https://www.earlinet.org

In Action4Cooling we will leverage also on synergies between the different lidar systems and observations provided from passive remote sensing sensors, namely the AERONET photometers for the ground based systems, radiometric data from the multi-spectral imager MSI on board EarthCARE and polarimetric data from HARP and SpexONE instruments on board PACE (Petro et al., 2020) or POLDER instrument on board PARASOL (Deschamps et al., 1994) for the space-borne systems. MSI data are distributed as mentioned above for EarthCARE, while for HARP and SpexONE currently only L1C data can be found through Earthdata (https://www.earthdata.nasa.gov/). Database of POLDER retrievals using GRASP codes can be found in: https://www.grasp-open.com/products/polder-data-release/

Depending on the availability of the data, for the ground-based observations we plan to apply different methodologies like the GARRLiC algorithm (Lopatin et al., 2013; 2021) that combines lidar and photometer L1 radiances to provide AOD, AAOD, SSA, CRI, SD and the vertical distribution of up to five aerosol types. Other methods include lidar stand-alone inversions and evaluation against collocated sun-photometer radiances (e.g. Gasteiger et al., 2011). For the satellite based measurements synergies between ATLID/MSI/HARP are already realized in the context of ESA-ECAMS project (https://www.grasp-earth.com/portfolio/ecams/) for aerosol and surface properties retrievals. Due to the limited information in satellite data (compared to the ground-based measurements), for this approach aerosols are described as an external mixture of several species with predefined microphysical properties, and their vertical distribution is the primary information in the state vector.

Apart from the remote sensing data, airborne in-situ data will be utilized when available.

In the context of Action4Cooling, a database of **i)** bi-modal and mono-modal size distributions, with different effective radii (reff) and variances (veff), **ii)** refractive indices that reflect different ash minerals in the atmosphere (e.g. see Vogel et al., 2017) and their mixtures with sulfates, **iii)** different particle shapes (including spheres, spheroids and irregularly shaped particles), as well as **iv)** different values of relative humidity (RH) and particle hydroscopicity, will be developed to cover the range of realistic microphysical properties of volcanic particles (see for example Table XX). In order to define the values of different microphysical parameters, we rely either on the literature (e.g. the OPAC database) or the available measurements described herein. For example, using a combination of balloon-borne in-situ measurements of the Pinatubo particle size distribution above Laramie, Wyoming (Deshler et al., 1993) and ground-based single-wavelength lidar data from Geesthacht, Germany (Ansmann et al., 1995), we managed to constrain the simulated sizes of volcanic particles to provide aerosol optical properties for mixtures of sulfate and ash particles.

Table 3 Example of the range of the microphysical properties (and RH) used to calculate optical properties of volcanic ash particles with MOPSMAP database. A similar approach is utilized for sulfate/ash mixtures and sulfate-only particles.

Parameter [step]	Range	
reff (um)	0.8, 1.0, 1.2, 1.5, 2.0, 3.0	Mono/Bi-modal log-normals
veff	1.8, 2.4	
Real Refr. Index (0.3 – 1.5 um)	~1.4 – 1.6	
Imag. Refr. Index (0.3 – 1.5 um)	~ 0.0005 – 0.002	
aspect ratio (spheroids)	1.3 – 1.6 [0.05]	Mono-modal log-normals
veff_s (shape distr. aspect ratio)	1.65	
RH [step]	0 – 60 [20]	
K [log step]	0.01 – 0.2 [15 log equidistant steps]	

The optical properties of the volcanic aerosols injected in the stratosphere will be provided for radiative transfer (RT) calculations to ICON model and PyDOME RT code, as a function of altitude, latitude and longitude. Specifically, the AOD, the asymmetry parameter, the SSA, as well as the extinction coefficient profiles and the phase matrix of the volcanic particles will be provided for SW and LW.

Although the injection of volcanic aerosols is widely used as the natural analogue of SAI, it may not be the optimum solution due to its adverse effects (e.g. depletion of stratospheric ozone). For this reason, we will also investigate simulated cases of SAI, with varying microphysical and optical particle properties. The size distributions will be similar to volcanic aerosols, but we will also take into account larger and smaller particles, in order to investigate the effects of quicker or slower deposition of the particles, respectively. The refractive index that will be examined (with priority) will be that of calcite particles, which have been reported to not have an effect on ozone depletion (e.g. Tilmes et al., 2022), and the shape will be non-spherical (spheroidal). For the calculation of the corresponding optical properties we will use appropriate scattering codes (e.g. T-matrix). A sensitivity study using RT code (e.g. libRatran; Mayer and Kylling, 2005) will be performed in order to constrain the volcanic particles' radiative forcing in the stratosphere and work backwards to derive the artificial particle properties that achieve this forcing.

3.1.3 Cirrus Cloud Thinning studies

Cirrus clouds, composed entirely of asymmetric ice crystals, have a wide global coverage and, thus, play a crucial role in modifying the Earth's radiation budget (Liou, 1986). Not like the liquid water clouds, cirrus clouds have a net warming effect (Chen et al., 2000). They tend to trap more outgoing longwave radiation than they reflect incoming solar radiation. However, the radiative effect strongly depends on the cloud geometrical, optical, and microphysical properties, which are further governed by the ice formation pathways dependent of the ambient meteorological conditions, including temperature, humidity, and presence of INPs (Fu and Liou, 1993; Krämer et al., 2016; Heymsfield et al., 2017; Marsing et al., 2023). Furthermore, high cirrus clouds have a significant impact on the top-of-atmosphere (TOA) longwave fluxes, especially at high-latitudes, since they are nearly transparent to solar radiation but still capable to absorb outgoing longwave radiation. The proposed CCT is to reduce cirrus cloud coverage or optical thickness of high cirrus clouds and consequently to increase outgoing longwave radiation escaping to space.

Previous studies indicated that the enhanced heterogeneous nucleation caused by aviation exhaust particles can be responsible for the high values of PLDR of cirrus clouds (Urbanek et al., 2018; Li and Groß, 2021, 2022). Furthermore, cirrus clouds with enhanced PLDR exhibit larger effective ice particles and lower number concentrations (Groß et al., 2023). This indicates that there were more heterogeneous nucleation occurring due to aviation-induced emissions, as homogeneous nucleation is expected to be suppressed by heterogeneous nucleation (Gierens, 2003). During the COVID-19 pandemic, however, there was a significant increase in ice particle number concentration detected by CALIPSO, which indicates more homogeneous nucleation due to less aviation emissions (Zhu et al., 2023). The changes in the cirrus cloud properties can act as CCT analogue for further studies.

During the HALO missions (including ML-CIRRUS and CIRRUS-HL campaigns), a comprehensive suite of sophisticated in situ and remote sensing instruments were mounted onboard the aircraft for scientific aims. Within ACtIon4Cooling, we will use the available airborne observations during the HALO missions (including ML-CIRRUS and CIRRUS-HL) to trace specific clouds forming in the regions with either dense aviation emissions or not according to the distribution of PLDR of cirrus clouds. We will further identify the cloud top height and calculate the cloud optical thickness, ice water content, and ice crystal number concentrations with in situ instruments and lidar. From a statistical prospective, we will also use the satellite data to determine the optical microphysical properties of cirrus clouds temporally (e.g. the COVID-19 period and year-to-year variation) and spatially (comparison of Midlatitudes and high-latitudes as well as between northern and southern hemispheres). The derived optical properties of cirrus clouds as a function of latitude and longitude will be provided for RF calculations to ICON model and PyDOME RT code.

3.2 Identification of SRM Proxies and Natural Analogues from EO data

3.3.1 Stratospheric Aerosol Injection (SAI) Analogues

We will investigate the following volcanic eruptions, using space and ground-based remote sensing observations to derive the microphysical and optical properties of volcanic particles injected in the stratosphere:

- Mnt. Pinatubo eruption, using balloon-borne in-situ and satellite (SAGE) observations (e.g. Ansmann et al. 1997).

- Calbuco volcano eruption using satellite lidar observations (CALIPSO) and collocated ground-based sun-photometric observations provided by AERONET global network (e.g. Lopes et al., 2015).

- Eyjafjallajökull eruption using ground-based lidar and sun-photometer observations from ACTRIS European network (e.g. Gasteiger et al., 2011)

- Recent eruptions of Mnt. Etna, with the transported stratospheric volcanic particles to be observed above PANGEA station with ground-based lidar and sunphotometer measurements (Amiridis et al., 2023), and possibly EarthCARE and PACE observations.

Algorithmic approach for identifying and characterizing stratospheric aerosol layers

TBD

Algorithm approach to derive particle microphysical and optical properties

TBD

3.3.2 Marine Cloud Brightening (MCB) Analogues

Marine vessels inadvertently contribute to MCB by releasing sulphate aerosols into the atmosphere, which act as CCN and form ship tracks – a terminology used to describe the type of cloud associated with shipping activity (Hobbs et al., 2000).

From the current existing EO datasets, we will examine the detection capabilities of complimentary sensors (starting from the S5P datasets) to identify which marine clouds appear with enhanced brightness due to the presence of exhausted particles from the ship engines. We aim to collocate the considered EO datasets with the ship tracks originating from the AIS (Automatic Identification System) data at the ship level (high temporal resolution of 5-6 minutes), which contain the exact geographical location of the vessel with the registered MMSI tracker number, as long as other type of complimentary information, like the type of the vessel (e.g., Cargo, Tanker, Pleasure Craft, Passenger Ship and more types), destination, vessel dimensions and speed. The AIS datasets are ideal for building ship-track cloud datasets but are not publicly available and therefore, there is a risk that we will not get access to them as they need to be purchased for the needs of this project. An alternative is to use the Vessel density and route density maps which are created since the 2019 by Cogea for the European Marine Observation and Data Network (EMODnet). Route Density Map at 1 km resolution was created by EMSA in 2019 and made available on EMODnet Human Activities, an initiative funded by the EU Commission. The dataset is updated every year and is available for viewing and download on EMODnet Human Activities web portal [URL-14]). The maps are based on AIS data monthly aggregated and show shipping density in 1x1km grid covering all EU waters and some neighbouring areas. Density is expressed as hours per square kilometer per month.

Analysis of tropospheric NO_2 column measurements from the TROPOMI instrument in the central Mediterranean showed that plume-like emission structures in tropospheric NO_2 columns when they were collocated to Automated Identification Signal (AIS) data of ship locations (Georgoulias et al., 2020). The Mediterranean Sea is an ideal testbed for our MCB natural analogues as they are characterized among the busiest worldwide international shipping corridors.

Complementary information about the wind fields (i.e., speed and direction) prior to the TROPOMI overpass showed that the plume-like tropospheric NO_2 structures were very well aligned to the the ship tracks. Additional information about ship length and ship speed, combined with an analysis of ship tracks and ship position, reveal that nearly all emission plume-like tropospheric NO_2 structures can be attributed to the largest ships, mostly container ships and crude oil tankers. Georgoulias et al., (2020) via their pioneering approach proved that NO2 emission plumes from ships can be detected and attributed to individual ships using satellite measurements with fine spatial resolution like the one of TROPOMI. During the COVID-19 period, Riess et al. (2022) conducted an analysis of the decreased NO_x emissions over the European Seas by making use of the TROPOMI tropospheric NO_2 columns and demonstrated that the spatial resolution of TROPOMI allows for the detection of several lanes of NO_2 pollution ranging from the Aegean Sea near

Greece to the Skagerrak in Scandinavia, which have not been detected with any other satellite instrument before. The observations showed a decreasing trend in NO_2 ship emissions, occurring at the beginning of the Pandemic (i.e., March–April 2020), and those reductions were correlated to the restrictions in shipping activity as inferred from the AIS data on ship location, speed, and engine. Later, Kurshaba et al. (2023) proposed an approach for a large-scale ship NO_2 estimation using TROPOMI measurements via a supervised machine learning-based segmentation of ship plumes.

The TROPOMI cloud structures were not so far correlated to the ship-emission over the European Seas and this attempt will be a key scientific objective of this project. Matching cloud/aerosol measurements from CALIPSO, PACE and the EARTHCARE missions to the TROPOMI overpasses would be our strategy to minimize the knowledge gaps which are expected to appear at the cloud retrievals from Spectrometers, as some assumptions are required in the forward models used in retrieval algorithms accepting reflectance from passive remote sensing sensors.

Methodology on how to detect marine clouds with ship emission signatures

Regarding the methodology on how to detect the marine clouds with ship emissions, we plan to apply several classification models and evaluate their performance. The use of Machine Learning techniques at this task is critical, so we will investigate a broad range of algorithms starting from simplistic approaches like Logistic Regression or K-nearest neighbors (KNN) algorithm to more advanced classifiers like the Decision Trees, Random Forest or Voting Classifiers and Stacking.

At a later phase, we will aim to apply dimensionality reduction, an important technique to reduce the number of variables in a data set while preserving essential information. Principal component analysis (PCA) is the most commonly used method that transforms correlated variables into a new set of uncorrelated variables called principal components. This allows the data to be represented at a lower dimension while keeping as much information as possible.

Other potential natural analogues

In literature, volcanic eruptions have also been considered as potential analogues to MCB studies (Breen et al., 2021) by analyzing the effects of aerosols on marine clouds after volcanic eruptions or degassing events. the researchers identify a significant increase in reflected sunlight, primarily due to aerosol-induced enhancements in cloud cover. These findings suggest that MCB could be more effective than previously estimated, especially when implemented under humid and stable meteorological conditions.

Smoke (e.g., Biomass Burning emissions from the 2019–20 Australian wildfires (Fasullo et al, 2023) or other types of aerosols which could have a brightening impact on clouds will be investigated in the available EO datasets.

3.3.3 Cirrus Cloud Thinning (CCT) Analogues

There are several best-known natural analogues of CCT. Volcanic eruptions inject sulfur dioxide and water vapor into the atmosphere, forming sulfate aerosols and affecting cirrus formation indirectly. During a mineral dust episode (like Saharan dust), a significant amount of mineral dust is lifted into troposphere, which may act as INPs. The consequent transport of dust particles, depending on meteorological factors, from their source regions across large distance will spread the influence into larger scales. Aircraft-emitted particles may also act as INPs, causing heterogeneous nucleation in regions with a favorable atmospheric state. It leads to the formation of contrails and exerts indirect effects on the existing cirrus clouds. In the frame of the current project, we will focus on the changes of cirrus cloud properties responding to aviation impact as a natural analogue of CCT.

Previous studies indicated that the enhanced heterogeneous nucleation caused by aviation exhaust particles can be responsible for the high values of PLDR of cirrus clouds (Urbanek et al., 2018; Li and Groß, 2021, 2022). Furthermore, cirrus clouds with enhanced PLDR exhibit larger effective ice particles and lower number concentrations (Groß et al., 2023). The findings provide strong support that changes in microphysical properties of cirrus clouds depending on aviation emissions can serve as a natural analogue of CCT.

With the existing lidar observations during the ML-CIRRUS and CIRRUS-HL campaigns, we will classify the specific cirrus clouds influenced by mineral dust or biomass burning and aviation-induced cirrus with modified microphysics as analogues of CCT. With in-situ measurements, we will further compare the ice crystal number concentration (Ni) and effective diameter (De) of cirrus clouds forming under enhanced INP conditions with those of typical cirrus clouds. The determined optical properties of specific cirrus will be input for RF calculations to derive the outgoing longwave radiation (OLR) from the Earth's surface. Lower optical thickness and reduced infrared trapping are presumed for cirrus clouds tied with enhanced INPs. In order to exclude misclassified mixed-phased clouds and noise-contaminated signals, we will only select the flight segments at temperatures below -38 ºC, above 6 km altitudes, and with RHi > 100%. In addition, we will focus on the flights with HALO flying through aerosol-rich layers, e.g., during a major Saharan dust outbreak from 2 to 5 April, 2014 (Weger et al., 2018). Backward trajectory analysis will also be carried out to trace back sampled air masses where cirrus clouds formed and evolved to aerosol-rich conditions.

EO instruments like CALIOP aboard CALIPSO and ATLID aboard EarthCARE are optimized for global profiling of the atmosphere, providing vertical structure and optical properties of aerosols and clouds. With the vertical feature mask (VFM) products, we can distinguish cirrus clouds from aerosols and non-cirrus clouds. Besides the measured cloud properties with lidar instruments, including cloud height, attenuated backscatter, and depolarization, temperatures are interpolated from the GEOS-5 analysis fields along the satellite tracks. Aiming to avoid misclassified mixed-phased clouds and noise-contaminated signals, we will only consider measurements at temperatures below -38 ºC, above 6 km altitudes, and with geometric thickness larger than 0.1 km. Furthermore, VFM can help to distinguish cirrus clouds due to deep convection. We will screen moderately thick cirrus with optical thickness between 0.1 and 1.5 to exclude deep convective outflows and opaque clouds. With the measured depolarization of cirrus clouds, we can identify the horizontal distributions of cirrus optical properties, which will be compared with the density maps of aviation emissions (e.g., from EUROCONTROL), especially with the resulting formation of persistent contrails (Teoh et al., 2024).

3.3 Radiative Transfer Simulations

RTMs will be used to simulate the radiative impact of SAI, MCB, CCT scenarios

For SAI studies, one of the major objectives is to perform sensitivity analysis on layer injection height and latitude. The changes in surface solar radiation and the diffuse-to-direct radiation ratio can be investigated with pyDOME. More specificly, the total radiance can be decomposed into direct and diffuse components and their ratios can be analyzed across different atmospheric conditions.

For MCB studies, one of the major objectives is to perform sensitivity analysis on the size distributions and the cloud water content of the studied marine clouds. For every SRM pathway we build a dedicated Python wrapper that sits "above" pyDOME, assembles the atmospheric state, perturbs the variables of interest, and then invokes the radiative transfer solver. Gas absorption coefficients from HITRAN are merged with Mie-derived aerosol and cloud optics, so that each atmospheric layer is characterised by its spectral optical thickness, single-scattering albedo and an effective phase function. These quantities are passed directly to pyDOME, which returns the full radiance field together with TOA forcing, surface irradiance and heating-rate profiles for every perturbation.

For CCT studies, one aspect to study with RTM simulationg is to examine how ice crystals with irregular shapes, can be parameterized in a vectorized version of pyDOME as a pre-requisite to account for the depolarization effect.

Calculation of radiative properties

The radiance field is computed with a discrete-ordinate solver for the radiative-transfer equation. Accuracy increases with the number of angular streams, but so does cost, so we determine an optimal stream count that preserves sub-percent accuracy while keeping run times practical. The solver expands the radiance field in Fourier azimuth modes, solves the transfer equation for each mode independently, and then reconstructs the full field by summation. Across the solar spectrum, computational speed is boosted by applying a principal-component representation of optical properties; this reduces the number of monochromatic calculations required in each band by roughly an order of magnitude without compromising spectral fidelity.

3.4 Global Climate Modelling and Integration (TBD)

- Selection and justification of climate models
- Simulations of SRM scenarios using inputs derived from natural analogues
- Sensitivity analysis and uncertainty quantification
- Potential links with IPCC scenarios (SSP pathways, etc.)?

3.5 Cross-validation and Uncertainty Assessment (TBD)

- Comparison of model outputs with observations
- Metrics for evaluating simulation accuracy (e.g., TOA flux, AOD, SWCRE/LWCRE)
- Uncertainty propagation across datasets and models

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