Aerosol Cloud Interaction for Cooling (ACtIon4Cooling)

Executive Summary

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TABLE OF CONTENTS

1.   Introduction

1.1   Purpose

This document is the Executive Summary as part of the ESA *ACtIon4Cooling* project. This document summarizes relevant achievements of the project.

1.2   Applicable Documents

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

Table 1 List of Applicable Documents

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

1.3   Reference Documents

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

Table 2 List of reference documents

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]	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

1.4   Relevant Websites

Table 3 List of relevant websites

Reference ID		URL	Last accessed
[URL01]	ESA ACtIon4Cooling project website	https://climate.esa.int/en/solar-radiation-modification/action4cooling/	14 Feb 2026
[URL02]	ESA ACtIon4Cooling LinkedIn Group	https://www.linkedin.com/groups/10061777	14 Feb 2026

1.4.1   Terms and Abbreviations

Abbreviations and terms specific to this document are summarized below.

Table 4 List of abbreviations

Abbreviation	Meaning
ACI	Aerosol-Cloud Interactions
AIS	Automated Identification Signal
ATLID	ATmospheric LIDar
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CCT	Cirrus Cloud Thinning
CIRRUS-HL	Cirrus in High Latitudes
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
EMODnet	European Marine Observation and Data Network
EO	Earth Observation
EU	European Union
GCM	Global Climate Model
ICON	ICOsahedral Non-hydrostatic
MCB	Marine Cloud Brightening
ML-CIRRUS	Formation, Lifetime, Properties and Radiative Impact of Mid-Latitude Cirrus Clouds
pyDOME	python-based Discrete Ordinate Method with Matrix Exponential
RTM	Radiative Transfer Model
SAI	Stratospheric Aerosol Injection
SRM	Solar Radiation Modification
TOA	Top Of Atmosphere
TROPOMI	Tropospheric Monitoring Instrument (aboard Sentinel-5 Precursor)
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity
UNEP	United Nations Environment Programme
VIIRS	Visible Infrared Imaging Radiometer Suite

2. Overview about the ACtIon4Cooling project

2.1 Introduction

Solar geo-engineering, and in particular Solar Radiation Modification (SRM) has emerged as a topic of increasing scientific and policy relevance in response to accelerating global warming. With global mean temperature reaching approximately 1.45 °C above pre-industrial levels in 2023 (see [RD03]) and projections indicating potential warming up to 2.7 °C by 2100 (see [RD04]), and the current lack of sufficient mitigation efforts, severe climate impacts may not be prevented within critical timeframes.

Deep decarbonization and greenhouse gas removal - net zero greenhouse gas emissions - remain essential. Nevertheless, SRM is increasingly discussed as a potential temporary or complementary measure to reduce peak warming and associated risks, particularly in scenarios involving tipping points or climate emergencies. SRM encompasses deliberate interventions in the Earth's radiation budget to counteract warming. Proposed mechanisms include:

- **Stratospheric Aerosol Injection (SAI)** – introducing reflective particles into the stratosphere to increase planetary albedo.
- **Marine Cloud Brightening (MCB)** – enhancing cloud reflectivity, usually discussed for application over oceans.
- **Cirrus Cloud Thinning (CCT)** – modifying high-altitude cirrus clouds to increase outgoing longwave radiation.

Despite growing international assessments of SRM's scientific, technical, and societal implications, substantial uncertainties and risks remain. SRM is in general not considered a substitute for emissions reductions, and it requires rigorous evaluation of feasibility, detectability, timing, and governance considerations.

The ESA *ACtIon4Cooling* project contributes to this research landscape by strengthening the observational and analytical foundations necessary for monitoring and attribution of SRM-related processes. The project leverages existing Earth Observation (EO) data to improve detection capabilities and to lay the groundwork for the definition of mission requirements for a future satellite mission dedicated to SRM monitoring.

ACtIon4Cooling focuses on (see also Figure 1):

- Advancing scientific understanding of aerosol–cloud–radiation interactions relevant to SRM.
- Investigating natural analogues to assess potential radiative, weather and climate impacts.
- Developing detection and attribution methodologies for SRM-like atmospheric perturbations.
- Simulating radiative effects using the pyDOME radiative transfer model and assessing climatic responses through ICON climate model simulations.

The *ACtIon4Cooling* project website can be found at [URL01]. It provides direct access to general information as well as deliverables. Furthermore, the *ACtIon4Cooling* LinkedIn group can be found at [URL02].

Importantly, *ACtIon4Cooling* does not advocate deployment of SRM technologies. Instead, it provides an independent, science-based framework to enhance transparency, monitoring capacity, and informed decision-making regarding potential SRM activities.
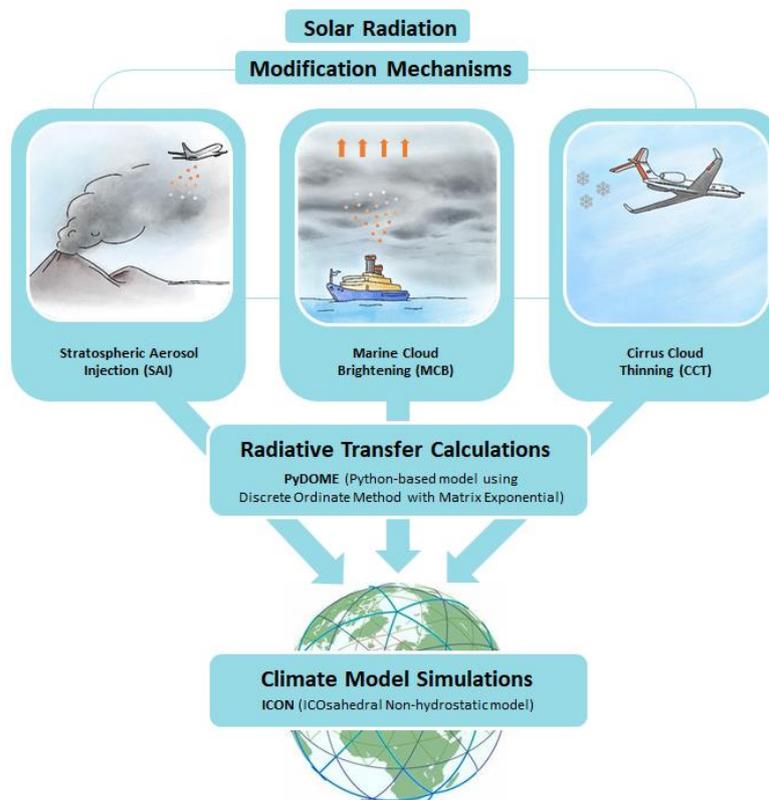
Figure 1 *ACtIon4Cooling* scheme

2.2 Stratospheric Aerosol Injection (SAI)

Stratospheric Aerosol Injection (SAI) is widely considered the most effective SRM approach for rapidly reducing global mean temperature in a high-greenhouse-gas environment (see SAPEA Evidence Review Report [RD04]). Its conceptual foundation is largely derived from observations of major volcanic eruptions, which demonstrated measurable global surface cooling following the injection of large quantities of reflective particles into the stratosphere. Events such as the 1991 Mt. Pinatubo eruption provided empirical evidence that stratospheric aerosols can substantially perturb the Earth's radiation budget.

The primary climatic mechanism of SAI involves increasing planetary albedo: injected aerosol particles scatter incoming shortwave solar radiation back to space, thereby inducing surface cooling. Simultaneously, these particles absorb terrestrial longwave radiation, leading to warming of the lower stratosphere. The magnitude and balance of these effects depend strongly on aerosol composition, size distribution, optical properties, injection altitude, and spatial distribution. In addition, the nature of injected stratospheric aerosols drives their interactions with chemical processes, including those affecting ozone concentrations, and thus is crucial.

Although volcanic eruptions are imperfect analogues due to their episodic nature, limited spatial control, and fixed aerosol chemistry, they however provide valuable real-world constraints on aerosol microphysical and optical properties, transport pathways, residence times, radiative and climate impacts. Variations in eruption latitude and season further inform understanding of dynamical influences on aerosol dispersion and climate response.

Within this framework, the ACtIon4Cooling project addressed key knowledge gaps related to SAI, including:

- Characterization of the microphysical and radiative evolution of volcanic aerosols as natural analogues.
- Evaluation of potential impacts on precipitation patterns and atmospheric circulation.
- Analysis of possible regional imbalances, such as tropical overcooling or insufficient high-latitude cooling.

2.3 Marine Cloud Brightening (MCB)

Marine Cloud Brightening (MCB) is considered an SRM approach with more control over climate effects due to shorter lifetime, but more limited influence on global mean temperature compared to Stratospheric Aerosol Injection. A potential value lies in modulating regional climate conditions, including – particularly if applied over oceans adjacent to land or over land directly – mitigation of extreme heat events, droughts, and certain weather extremes. However, significant uncertainties persist regarding its overall climatic efficacy and potential unintended consequences, such as disproportionate cooling in summer, overcooling in the tropics, residual warming in mid–high latitudes, and shifts in regional precipitation patterns. The latter represents a central focus of *ACtIon4Cooling* through analysis of precipitation responses linked to natural and anthropogenic MCB analogues.

MCB aims to enhance the albedo of marine low clouds by increasing cloud droplet number concentrations through aerosol injection in the planetary boundary layer. Sea salt particles are currently considered the most suitable aerosol candidate due to their natural abundance and hygroscopic properties, although alternative materials have been discussed. Proposed deployment concepts rely on engineered spray systems to introduce aerosols into marine cloud layers. Effectiveness depends strongly on meteorological conditions, aerosol size distribution, ambient humidity, thermodynamic structure, and cloud regime characteristics.

From a process perspective, MCB research requires robust characterization of aerosol–cloud interactions. Critical parameters include cloud droplet number concentration, cloud optical depth, liquid water path, and top-of-atmosphere reflectance. These variables are essential for constraining Earth system models but remain difficult to retrieve accurately from satellite observations due to inherent assumptions in remote sensing algorithms.

ACtIon4Cooling addressed key knowledge gaps related to MCB through observational analysis of natural and anthropogenic analogues such as ship tracks. The project focused on:

- Identifying regions where marine low clouds exhibit high susceptibility to aerosol perturbations.
- Quantifying associated radiative and precipitation responses at regional and global scales.
- Monitoring changes in cloud microphysics and top-of-atmosphere radiative properties using Earth Observation data.
- Providing empirical constraints to improve aerosol–cloud interaction parameterizations in climate models.
- Developing methodologies to distinguish MCB-like signals from natural variability and broader anthropogenic aerosol effects.

2.4 Cirrus Cloud Thinning (CCT)

Cirrus Cloud Thinning (CCT) is an SRM concept designed to enhance the emission of outgoing longwave radiation by reducing the optical thickness of high-level cirrus clouds. Cirrus clouds exert a net warming effect because they efficiently trap terrestrial infrared radiation. CCT seeks to counteract this by injecting efficient ice-nucleating particles (INPs) into cirrus-forming regions, promoting heterogeneous ice nucleation at lower supersaturation and relatively warmer temperatures. This process can lead to the formation of fewer but larger ice crystals. Larger crystals sediment more rapidly, resulting in thinner, optically less dense cirrus clouds that allow greater longwave radiation to escape to space, thereby inducing a cooling effect. The key idea is that CCT may involve fewer side-effects on e.g. precipitation or latitudinal distribution of cooling since it acts in the same radiation spectrum (terrestrial) as greenhouse gases. It is considered here as SRM even if it technically does not aim to modify solar, but rather terrestrial, radiation.

Aviation emissions provide an important analogue for CCT processes. Aircraft exhaust, emitted at cruising altitudes, introduces aerosol particles, greenhouse gases, and water vapor that can modify cirrus properties and form contrails and contrail cirrus. Observations from the ML-CIRRUS campaign, including airborne lidar measurements of particle linear depolarization ratio (PLDR), indicate systematic differences between cirrus clouds influenced by aviation emissions and those forming in relatively pristine air masses. Enhanced PLDR values are associated with larger ice crystals and lower number concentrations, consistent with modified nucleation processes. Satellite observations corroborate these findings, demonstrating aviation-related perturbations of cirrus optical and microphysical properties.

Within this context, ACtIon4Cooling addresses key scientific gaps related to CCT:

- Identification and characterization of aviation-induced cirrus modifications as natural analogues for CCT.

- Analysis of cirrus microphysical and optical properties in high-aviation versus pristine regions using airborne measurements and backward trajectory analysis.

- Regional comparison of cirrus optical depth, depolarization ratio, and microphysical parameters across midlatitudes and high latitudes, accounting for meteorological influences using ERA5 reanalysis data.

- Assessment of long-term trends in cirrus properties in regions with increasing aviation activity using CALIPSO observations.

- Evaluation of potential impacts on precipitation patterns and regional atmospheric circulation.

- Quantification of radiative forcing from CCT-like perturbations using radiative transfer modeling and provision of observational constraints for ICON climate model simulations.

3. Executive summary of the project

The ESA ACtIon4Cooling project led by DLR with the collaboration of NOA Greece and Leipzig University has been kicked-off on 10th March 2025 and successfully finished on 06th of March 2026.

DLR has led the project and performed the analysis of scientific requirements, impacts and risks. DLR has furthermore led the work packages related to Marine Cloud Brightening and Cirrus Cloud Thinning, as well as the Observational synergies and radiation closure work package. NOA has performed the coordination with other EU projects and led Stratospheric Aerosol Injection work package. Leipzig University has used the output result from the three SRM work packages (SAI, MCB, CCT) to perform the scientific synthesis with the ICON climate model.

For SAI, volcanic aerosol detection and information on their vertical distribution, injection heights and the resulting perturbation in stratospheric optical depth was obtained from the high spatial resolution spaceborne lidar ATLID on board EarthCARE. More specifically, to identify the aerosol layers of volcanic origin, the ATLID L2 optical property profiles and target classification product have been utilized. The case study of Ruang volcano eruption (April 2024) was selected to demonstrate the analysis results. ATLID observations show that four months after the eruption, peak stratospheric AOD within ±25° latitude reached ~0.06 at 355 nm, with low linear depolarization (<0.10), indicating predominantly spherical aerosols presence. From August 2024 to September 2025, AOD gradually declined (~0.04) while depolarization remained stable, indicating slow particle removal from the stratosphere; the aerosol layer ascended from ~19–25 km until April 2025, though layer-top estimates remain uncertain due to ATLID resolution changes near 20 km. Synergies between ATLID measurements and observations provided from the Hyper-Angular Rainbow Polarimeter (HARP2) on board PACE mission were also used. The methodology applied exploits aerosol-induced modifications on the polarized light signal measured at TOA, emerging from liquid clouds that are found below the stratospheric aerosol layers. This method was first presented by Wanquet et al. (2009; 2013) to derive tropospheric particle size (r_{eff}) and AOD above pixels containing liquid clouds. In addition to the satellite observations, optical modelling simulations have been performed to support the characterization of stratospheric aerosol particles using the *Modeled optical properties of ensembles of aerosol particles* (MOPSMAP) scattering database (Gasteiger and Wiegner, 2018). The satellite-observed stratospheric AOD perturbations for the case of the Ruang volcanic eruption, were implemented in an ICON climate model simulation to evaluate the global impacts of SAI. The observed monthly area-averaged AOD perturbations over the tropical region between ±25° in latitude, together with the corresponding aerosol layer top and bottom heights, from August 2024 to September 2025, were used as inputs to the ICON model. RTM simulation results generated with the pyDOME model indicate that the radiative impact of SAI is not uniform but strongly modulated by the underlying surface albedo. Over dark surfaces (e.g., ocean) increasing AOD effectively masks a low-albedo surface. The enhanced aerosol scattering increases upward radiation at TOA. Over bright surfaces aerosol layers intercept radiation that would otherwise be reflected upward by the surface. Part of this radiation is absorbed or redirected downward, reducing TOA outgoing irradiance. That implies that there exists a ground albedo, such that aerosol-induced scattering and surface-reflection feedback compensate each other. This transition marks a regime shift in the aerosol radiative effect. The ICON simulation shows a consistent climate forcing in clear skies, blurred by cloud adjustments. A very strong precipitation shift is simulated. A detailed analysis of the exact mechanisms has yet to be done, but it is evident that such very large consequences for precipitation patterns and intensity are a serious risk to be taken into account for SAI application, and even for any large-scale field experiments.

For MCB the vessel density maps from the European Marine Observation and Data Network (EMODnet) were used for defining where the ships are located. The primary information on cloud properties was acquired from the space-borne spectrometer TROPOMI on Sentinel-5 Precursor (Veefkind et al., 2012; Loyola et al., 2018). Complementary information for the clouds captured by TROPOMI instrument was taken from VIIRS on Suomi-NPP. The TROPOMI NO_2 Tropospheric Vertical Column Densities (VCDs) were analyzed to quantify shipping-related nitrogen dioxide enhancements along major maritime corridors in the Mediterranean Sea and North Eastern Atlantic. The shipping emissions can be systematically detected in the NO_2 Tropospheric column. The sign of the perturbation is always positive; the magnitude of the NO_2 perturbation is large (~30% for the Mediterranean region). On the contrary, the perturbations of the cloud parameters may change sign from day to day. The natural variability of the clouds masks the signal of the modification due to the ship-emitted particles at their cloud base. Therefore, the automatic ship-track detection in all conditions could be challenging with the use of Machine Learning (ML) techniques. The primary goal is to develop a ship-track detection model accurate enough to enable the estimation of local pixel-by-

pixel cloud perturbations, computed as the difference between ship-affected pixels and background reference pixels within the same scene and meteorological regime. The latter is only possible with densely populated ship-relevant datasets which could be used for the training of a ML classifier. Until that trustworthy ship-track detection model is built, the most robust way to quantify cloud perturbations due to ships is the regional mean perturbation formula (i.e., the difference of the mean of ship-affected pixels per day and grid box minus the mean of background pixels per day and grid box). The regional daily perturbation dataset (ship-mean versus background-mean approach) is more directly aligned with policy-relevant detectability questions. By aggregating signals at regional and daily scales, it reflects how monitoring systems for SRM would likely be operationalized in practice. This approach enables statistical robustness and provides a bridge between process-level understanding and operational climate intervention monitoring strategies. The satellite-observed ship-affected marine cloud perturbations were reproduced in the ICON simulation to evaluate the global impacts of MCB. Pairs of global simulations were performed for attribution of effects, with and without the observations-based cloud perturbation. In the perturbed simulation, the liquid water path was increased by 1%, as suggested by observations over the region of interest. For the observations-derived perturbation of a mere 1%, no clear perturbation to the top-of-atmosphere radiation budget or surface air temperature is detected within the region of interest suggesting that the imposed perturbation is masked by signals arising from cloud adjustments. In turn, for a strong perturbation of a factor of 10, a regional effective radiative forcing of -15 Wm^{-2} was obtained, with little perturbation to the top-of-atmosphere radiation budget outside the region of interest. In consequence, there is no discernible perturbation of temperatures in the observations-tied perturbation. For the strong perturbation, in turn, surface air temperature increased locally by up to 0.5K, suggesting the relevance of Earth system feedbacks for the analysis of MCB climate effects. Precipitation responses extend beyond the region of imposed perturbation, reflecting the strong coupling between latent heating, large-scale circulation, and atmospheric energy balance. A similar spatial pattern of precipitation response is obtained for the strong and the weak perturbation simulations. This suggests that the precipitation changes are instead dominated by internal variability and rapid adjustment processes.

For CCT, the available airborne measurements during the ML-CIRRUS were used to trace specific clouds forming in the regions with either dense aviation emissions, which exhibit enhanced PLDR (Urbanek et al., 2018). Furthermore the cloud optical thickness, ice crystal effective diameters and number concentrations were calculated with coordinated in situ instruments and lidar, revealing that high-PLDR-mode cirrus clouds are characterized by larger particles with smaller number concentrations (Groß et al., 2023). From a statistical perspective, the available CAPLISO satellite data have also been exploited to determine the optical and microphysical properties of cirrus clouds temporally (e.g. during the pre-COVID years period and year-to-year variation) and spatially (comparison between midlatitudes and high latitudes) for studying aviation impacts on cirrus cloud properties (Li and Groß, 2021, 2022, 2025). The derived microphysical and optical parameters of cirrus clouds as a function of latitude and longitude have been provided for model simulation of ICON and RTM. The RTM results clearly demonstrate that reducing COT decreases the cloud reflectance, leading to lower TOA upward irradiance. This corresponds to a positive shortwave radiative forcing (warming), since less solar radiation is reflected back to space. Thus, in the shortwave domain, cirrus cloud thinning produces a warming tendency. In the longwave domain, the radiative effect of cirrus clouds is different. Cirrus clouds act as semi-transparent emitters and absorbers of terrestrial radiation. A reduction in COT decreases the cloud emissivity, allowing more outgoing longwave radiation to escape to space. This leads to a negative longwave radiative forcing (cooling). In ICON simulations, no clear perturbation to the top-of-atmosphere radiation budget is detected within the region of interest, suggesting that the imposed perturbation is masked by signals arising from cloud adjustments. Changes in the top-of-atmosphere radiation budget induced by cloud adjustments are particularly pronounced in the tropics. A small increase in surface air temperature of approximately 0.2 K is detected within the region of interest, even if the expected signal was a cooling. Globally, a mean decrease of 0.01 K in surface air temperature is simulated. The magnitude of the change in surface air temperature over land exceeds that over the oceans. Precipitation responses extend beyond the region of imposed perturbation, reflecting the strong coupling between latent heating, large-scale circulation, and atmospheric energy balance. These model-based results point to the large challenge detecting and attributing desired climate effects of CCT – and similarly, of SAI and MCB as well – to occur in field trials or short-term deployment.

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