STATISTICS
(Satellite and Model Data to Inform Solar Radiation Modification Techniques)

Pasquale Sellitto, CNRS-LISA

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Project Objectives

- **ESA ITT:** Aerosol and Cloud Interactions Impact in the Context of Solar Radiation Management
- **Goals of project:** bridge knowledge gaps by better integrating satellite-based Earth observations with advanced modelling techniques to improve the accuracy and reliability of SRM assessments. Both scientific and policy-related challenges are addressed to ensure a comprehensive and responsible approach.
- **Timeframe:** March 2025 – Feb 2026;
- **Objectives:**
    1. Stratospheric Aerosol Injection (SAI) Model Intercomparison and Evaluation
    2. Marine Cloud Brightening (MCB) and Aerosol-Cloud Interactions
    3. Cirrus Cloud Thinning (CCT) and Mixed-Phase Cloud Thinning (MCT)
    4. Impact of SAI on Solar Energy Resources
    5. Detectability of SRM Field Experiments and Deployment

Secondary objectives: Connect with the wider community, contribute research relevant to assessments from UNEP and IPCC to inform governance and policy discussions, liaise with the Co-CREATE initiative to inform requirements for monitoring capabilities needed to support informed policy on SRM.

Skeleton overview of the approach

- Desktop Research
- Liaison with ongoing CCI and Horizon Europe Projects
- Research and Monitoring Gap Analysis
- Bridging Modelling and Earth Observation
- Further Potential of Natural and Anthropogenic Analogues
- Mid-Project Workshop Organization
- Compilation of Existing Datasets
- Targeted Simulations and Satellite Retrievals
- Targeted Impact and Detectability Assessments
- Synthesis

Climate & climate-chemistry models

RT models

Satellite retrieval algorithms

OSSE & new instruments

Collaborative network

ECVs being used

- Which ECVs are being used :
  - Aerosols
  - Clouds
  - Surface radiation: in situ data and satellite (SARAH-3)
- Why they were chosen
  - Aerosol were retrieved using GRASP algorithm to control the retrieval of aerosols in the vicinity of clouds
  - Surface radiation ECV was needed to validate the RT calculations
- Strengths and weaknesses
  - S: Long-term stability
  - W: Lack of simultaneous aerosol and cloud retrievals
  - W: Lack of downscaling tools for surface radiation to point measurements
- Wish list for how to improve the ECVs
  - Consistent satellite retrievals of aerosol, cloud and surface radiative fluxes

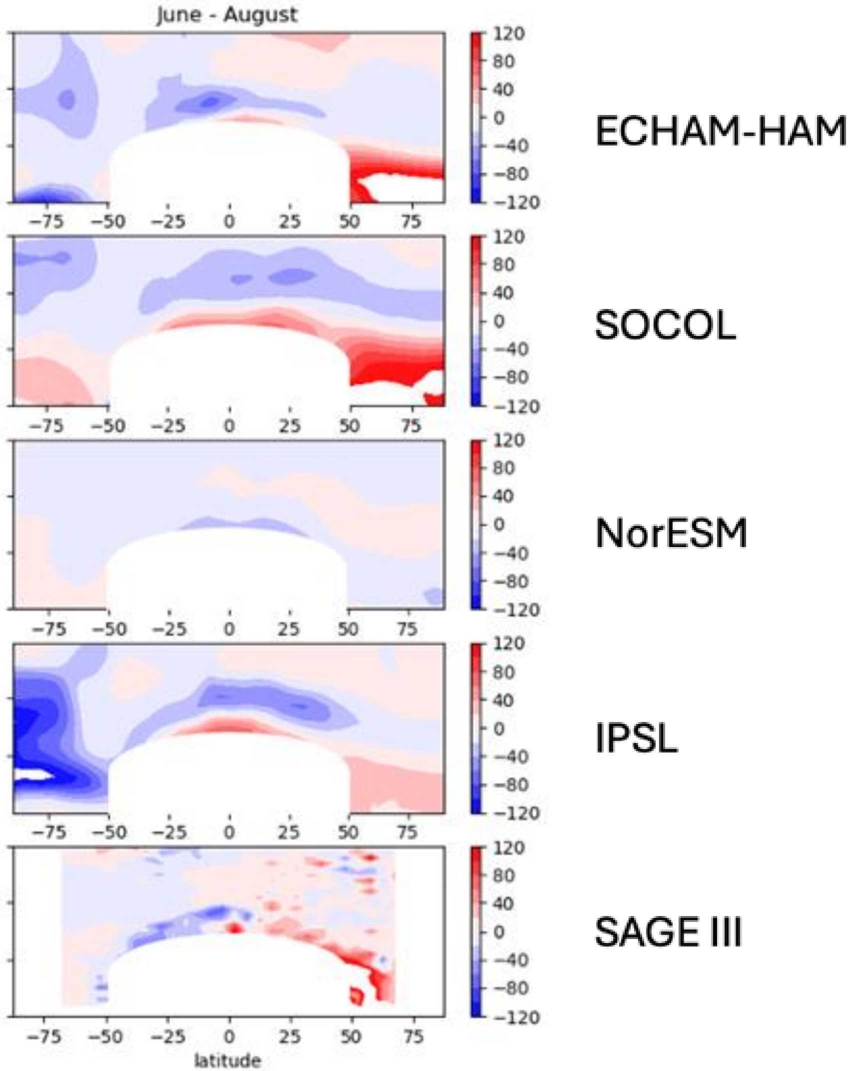
Results (1) – Stratospheric Aerosol Injection

- **Goal:** Investigate SAI by looking at its natural analogues – Raikoke and Ulawun eruptions in 2019

- These two eruptions produced opposite effects on the stratospheric aerosol size distribution.

- Models can reproduce the hemispheric sign of the response, but differ substantially in the evolution and the magnitude of the signals

- **Why?** -> process-oriented study (microphysics and transport)



Zonal means of the monthly averaged effective radius anomalies(nm) for four models vs. SAGE III: June-August.

Results (2) – Marine Cloud Brightening

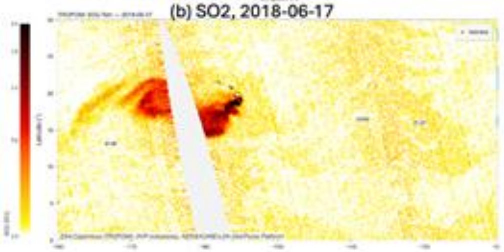
- **Atmospheric species**

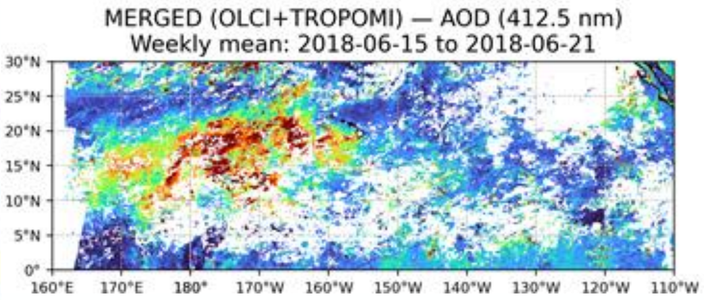
  SO2, SO4, other gases

  Aerosol

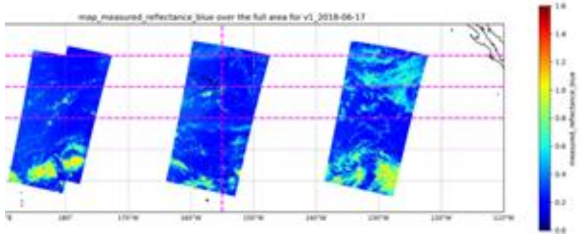
  Clouds
- **Approach**:
  Synthesis of of gas-aerosol-cloud **remote** sensing and chemical **transport** modelling approaches
- **Key Findings:**
1. A dimming effect is observed in optically thin and moderate clouds when influenced by sulfate-like volcanic aerosol plumes;
2. Strong link observed between aerosol/CCN properties and the conversion of SO2 to SO4.

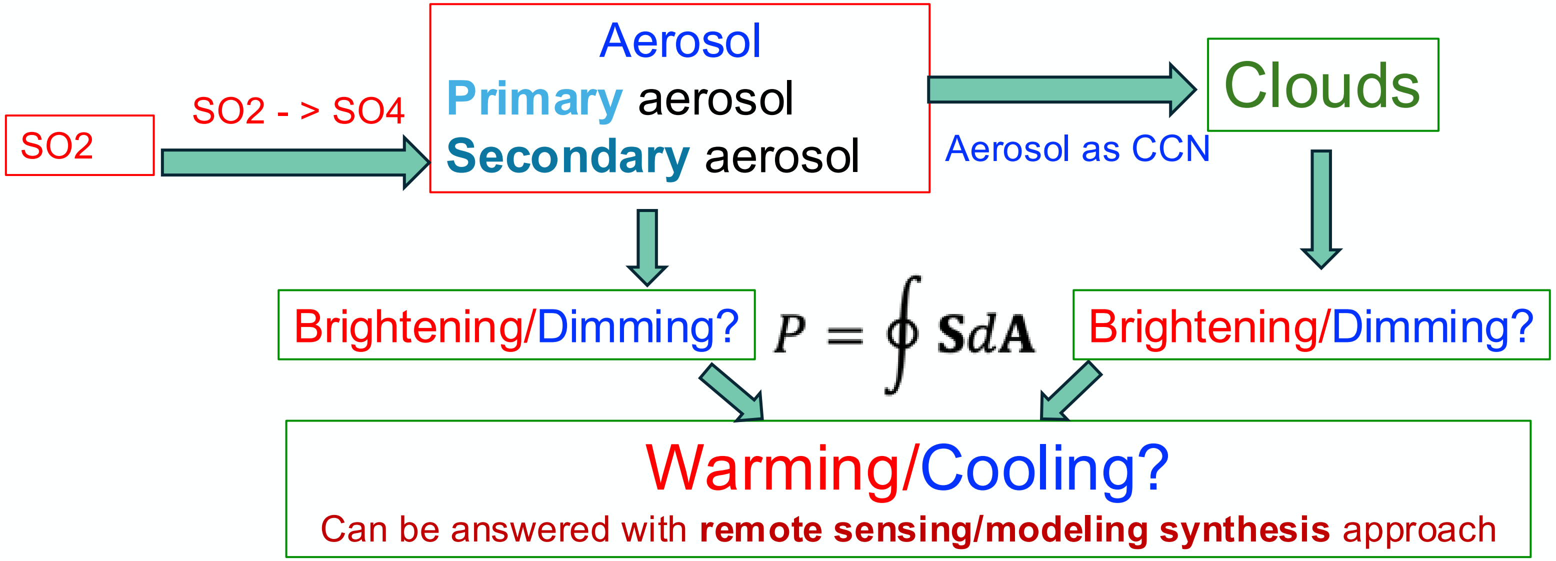
TROPOMI SO2 vertical column density, 2018-06-17





TOA reflectance at 412nm, 2018-06-17



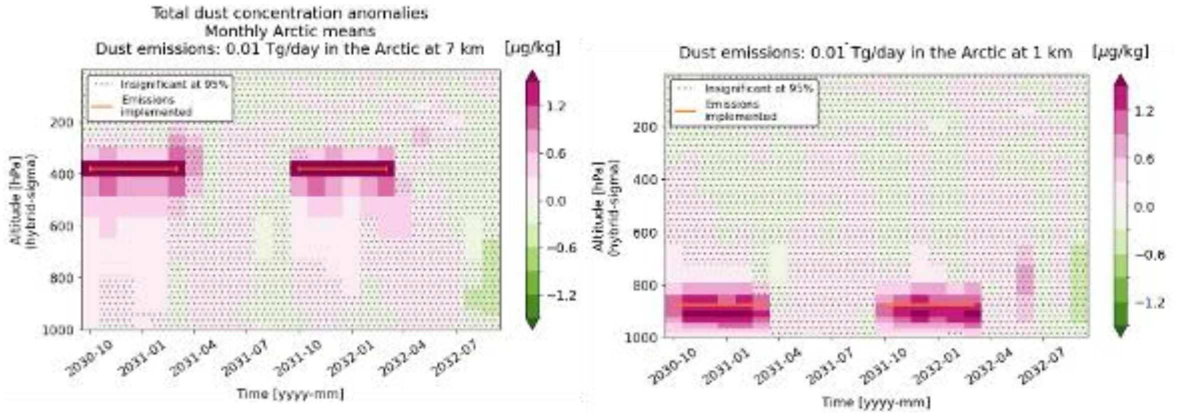


Results (3) – Cirrus & Mixed-phase Cloud Thinning

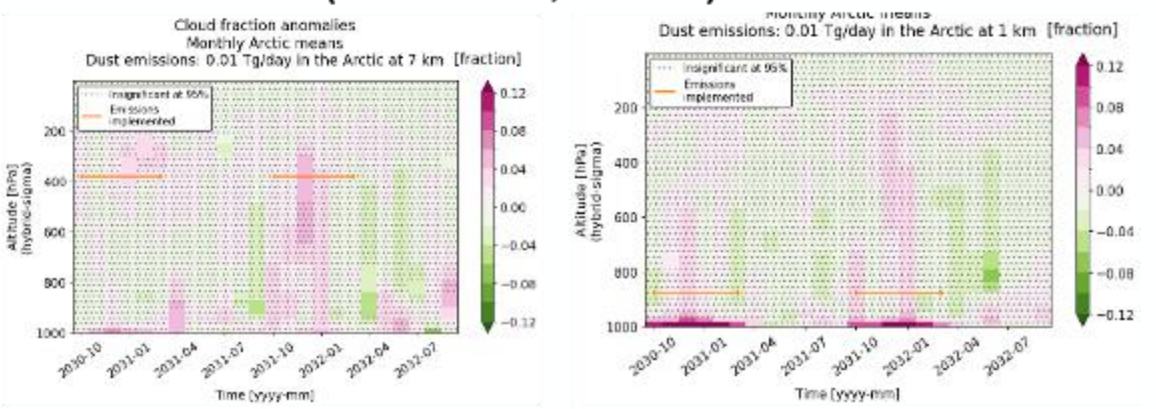
Mixed-phase and cirrus cloud thinning experiments with NorESM2.3

- **Goal:** Simulate the Arctic's climate response to the seeding of mixed-phase and cirrus clouds with dust with Norwegian Earth System (NorESM2.3).
- **Key Findings**: Model evaluation (NorESM2.3) shows that the unperturbed Arctic mixed-phase and cirrus clouds have too much ice nucleation compared to satellite observations, making them insensitive;

Experiments with Arctic Dust Injection



But the effect is opposite of desired (more clouds, not less)



Model evaluation shows that the unperturbed Arctic mixed-phase and cirrus clouds have too much ice nucleation compared to satellite observations, which makes them insensitive – correcting this bias and then repeating the dust seeding experiments will be the focus of follow-up research

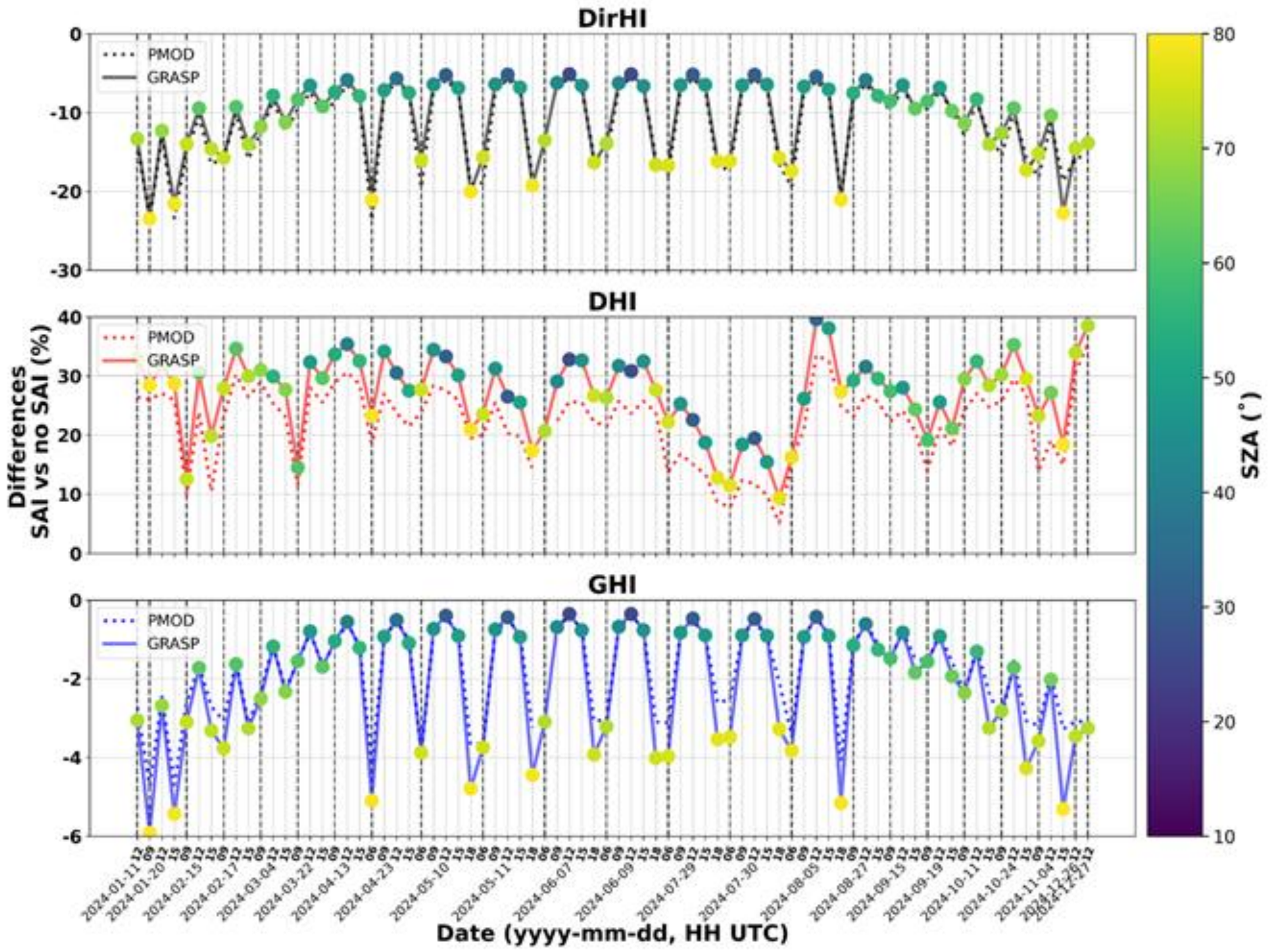
Results (4) – Photovoltaic Potential under SAI

- **Goal:** Improve clear-sky surface solar radiation documentation under SAI using benchmark radiative transfer calculations, evaluate SAI impacts on solar PV output, and test optimization strategies.

- **Key Findings:**

1. The models, despite different architectures, show good agreement for Direct (DirHI), Diffused (DHI), and Global (GHI) irradiance on flat and tilted surfaces;
2. The altitude of sulfate aerosol injection non-linearly governs surface flux and, consequently, solar energy yields;

Comparison of SAI and non-SAI scenarios (2024) at SIRTA station: changes in three broadband flux parameters on a horizontal surface

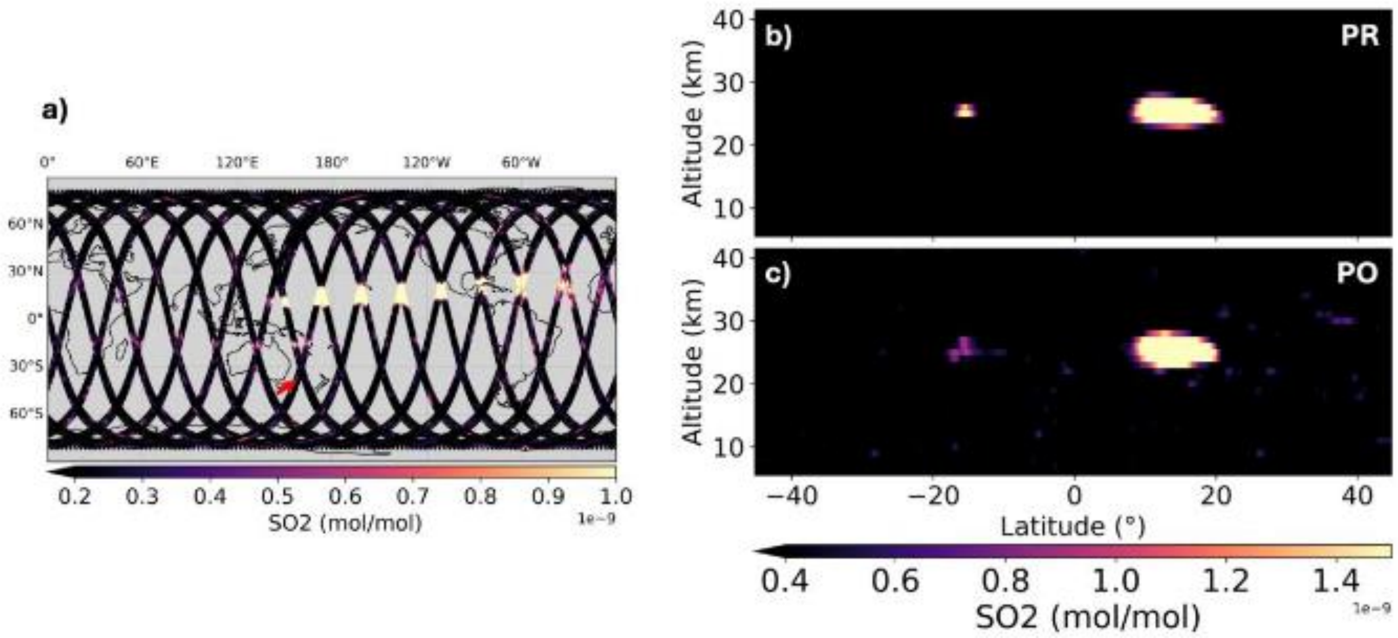


Results (5) – SRM Detectability

- **Goal:** Assess the potential to detect SAI signals in the climate system using new observing systems (CAIRT mission concept, and AOS LUCE lidar), even during the early stages of SAI deployment.

- **Key Findings:**

1. Current observing systems lack the capability to detect and characterize near-term SAI experiments (e.g. weak injections, unilateral or regional tests) and their impacts on the stratospheric aerosol layer and composition;
2. An ideal satellite sensor for this purpose would be mid-infrared limb-emission sounding (such as the CAIRT concept).



(a) CAIRT PO of the SO2 concentration for February 2034, at 25 km altitude.
(b-c) Average PR (panel b) and CAIRT PO (panel c) of the SO2 vertical profiles, for the orbit individuated with a red arrow in panel a.

Knowledge Gaps

- Structural uncertainties in models and observational analyses;
- Poorly constrained cloud responses to aerosol perturbations;
- Enhanced monitoring capabilities and coordinated observation strategies required for early detection of trials and deployment;
- Risk analysis to inform policy:
  a) Physical risks, regional hotspots
  b) Governance risks, public trust in research
  c) Insufficient scientific understanding