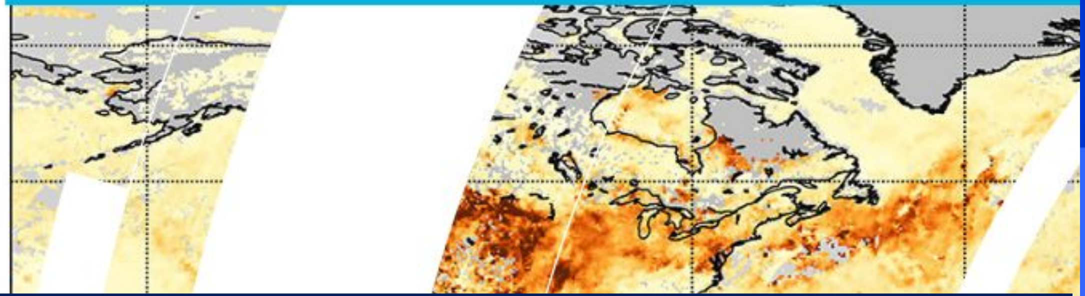
# JOINT TRAINING IN ATMOSPHERIC COMPOSITION

13 -17 OCTOBER 2025, BRUSSELS



# Stratospheric aerosols

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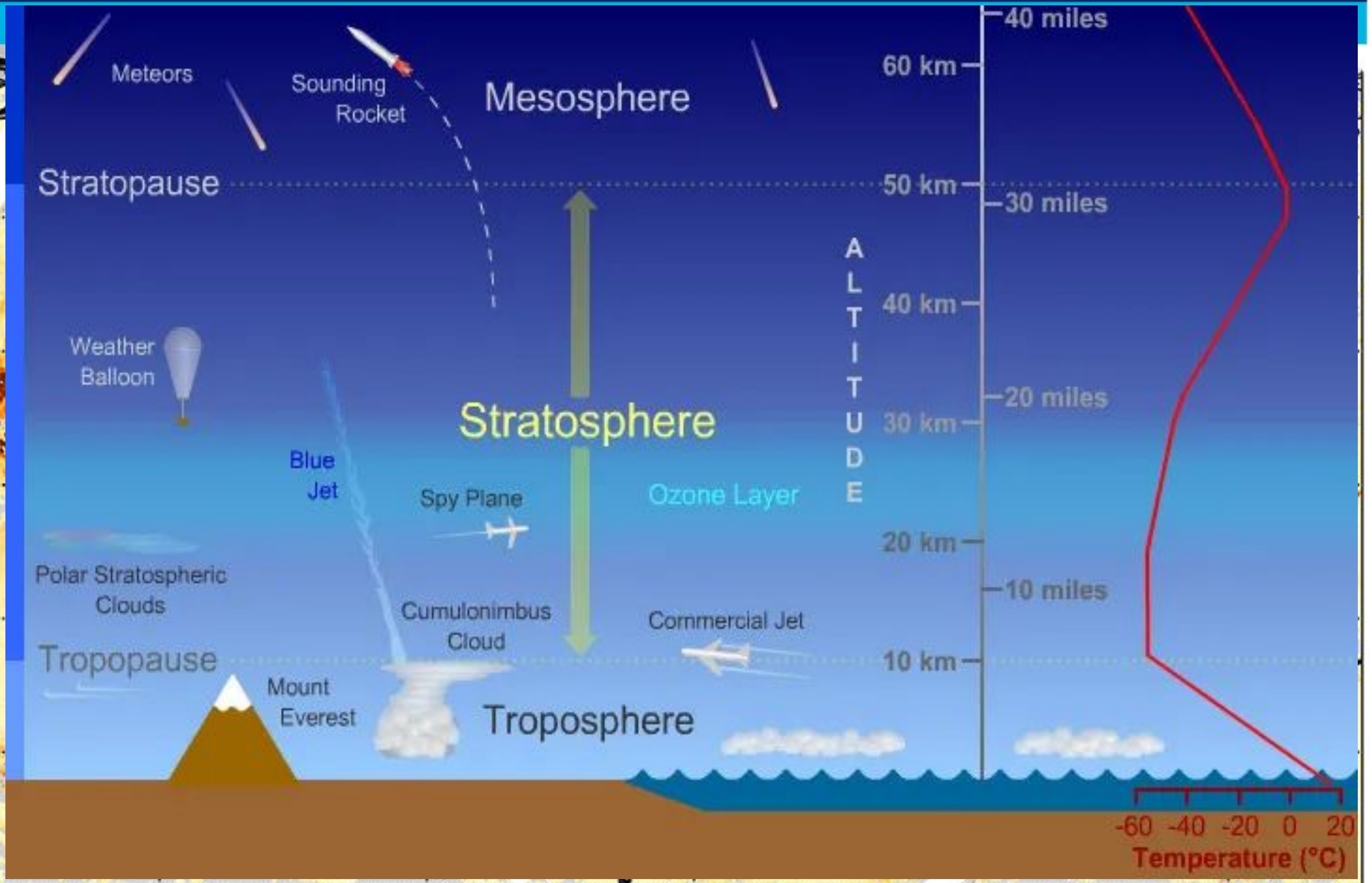
*Lecture/9 October 2025*



# Contents



## Stratospheric aerosols: introduction

Discovery, composition, properties

## Observations

Observation  techniques, observable parameters

## The role in the energy balance of the Earth

# Discovery of the Junge aerosol layer



- A global, worldwide-dispersed layer of microscopic aerosol particles, was discovered by Christian Junge in 1961.
- After performing balloon and aircraft aerosol collection programs, Junge published his findings in the journal Meteorology
- Junge's discovery:
  - aerosol layer at 15-25 km, with a peak at ~ 20 km
  - this layer is stable, constant in time and space, and composed mainly of sulfate particles.
  - Formed from volcanic eruptions and human-made emissions

**A view of Earth from space, visualizing the stratospheric aerosol layer. Credit: Timothy Marvel, SSAI, Hampton, Va.**

# Junge's observations and explanations



- Junge tentatively concluded that there are three major populations of particles present in the stratosphere.
  - Those smaller than 0.1 µm are of tropospheric origin.
  - Those between 0.1 and 1.0 µm are most likely formed within the stratosphere, possibly by oxidation of $SO_2$ gas traces.
  - Fall speed considerations make it very likely that the majority of particles larger than one micron are of extra-terrestrial origin.

# Composition of stratospheric aerosols: Primary components

- Sulfate aerosols
  - The most abundant component is sulfuric acid ($H_2SO_4$) mixed with water, often forming a 75% solution by weight.
- Meteoric material:
  - Particles from ablated meteoroids, containing elements like iron, magnesium, aluminum, and silicon, are found within the sulfate particles.
- Organic material:
  - Significant amounts of organic compounds, primarily from wildfires but also other sources, are found in the stratospheric aerosol, often mixed with the sulfate particles

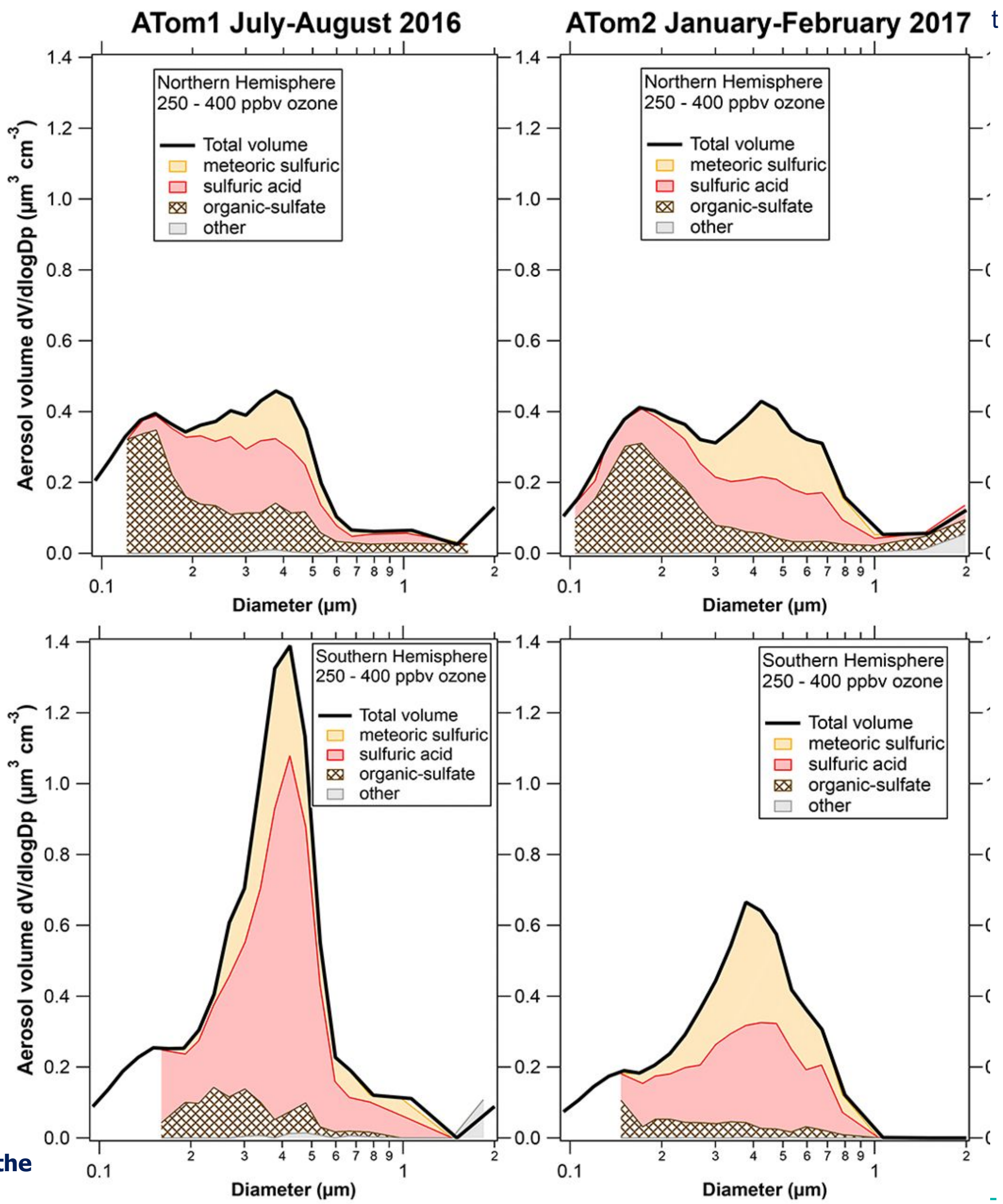
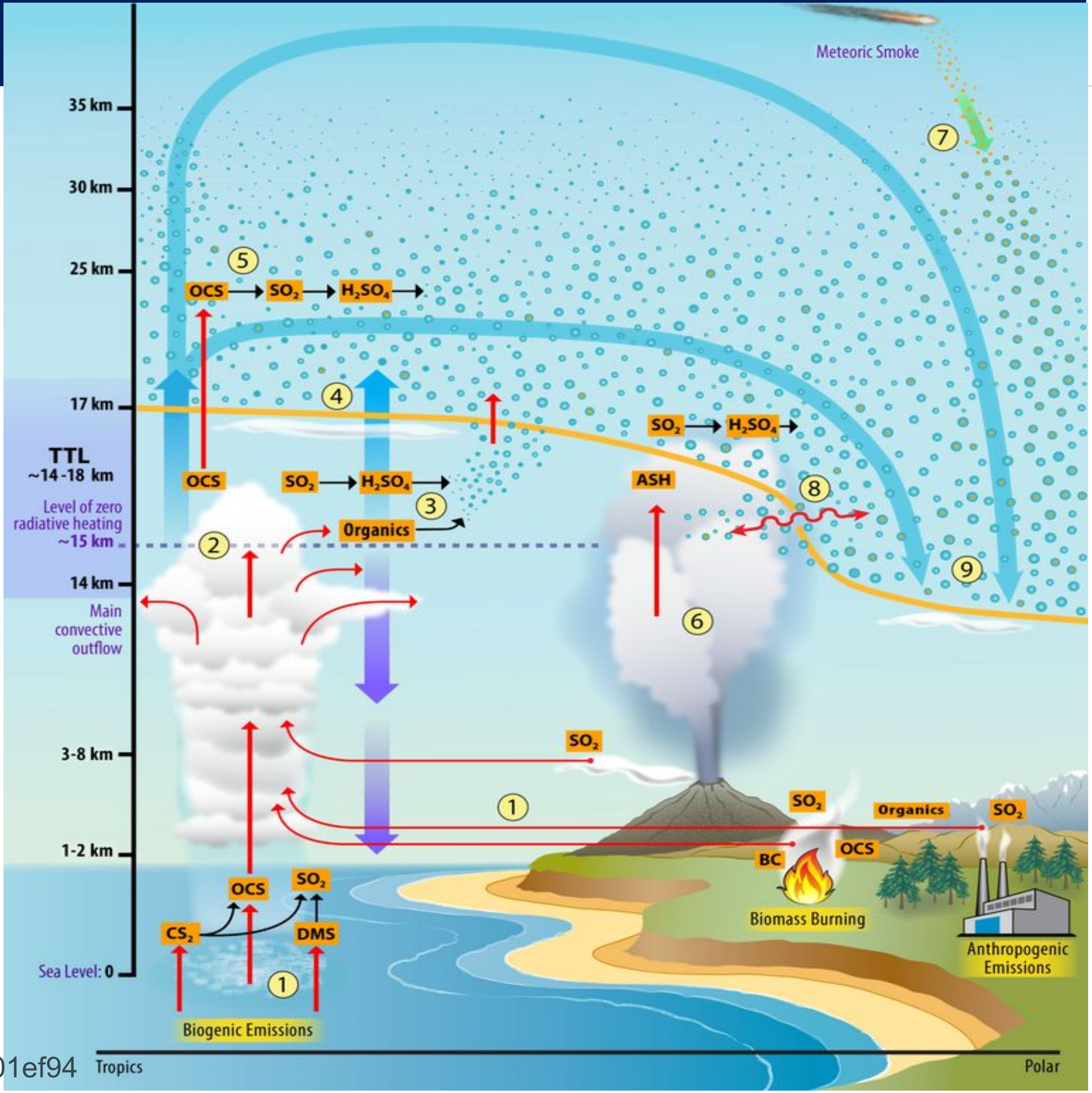



**Figure adapted from Murphy et al., 2021: Composition resolved size distributions from the lower stratosphere during the Atmospheric Tomography (ATom) mission using particle counter .**

# Formation and sources

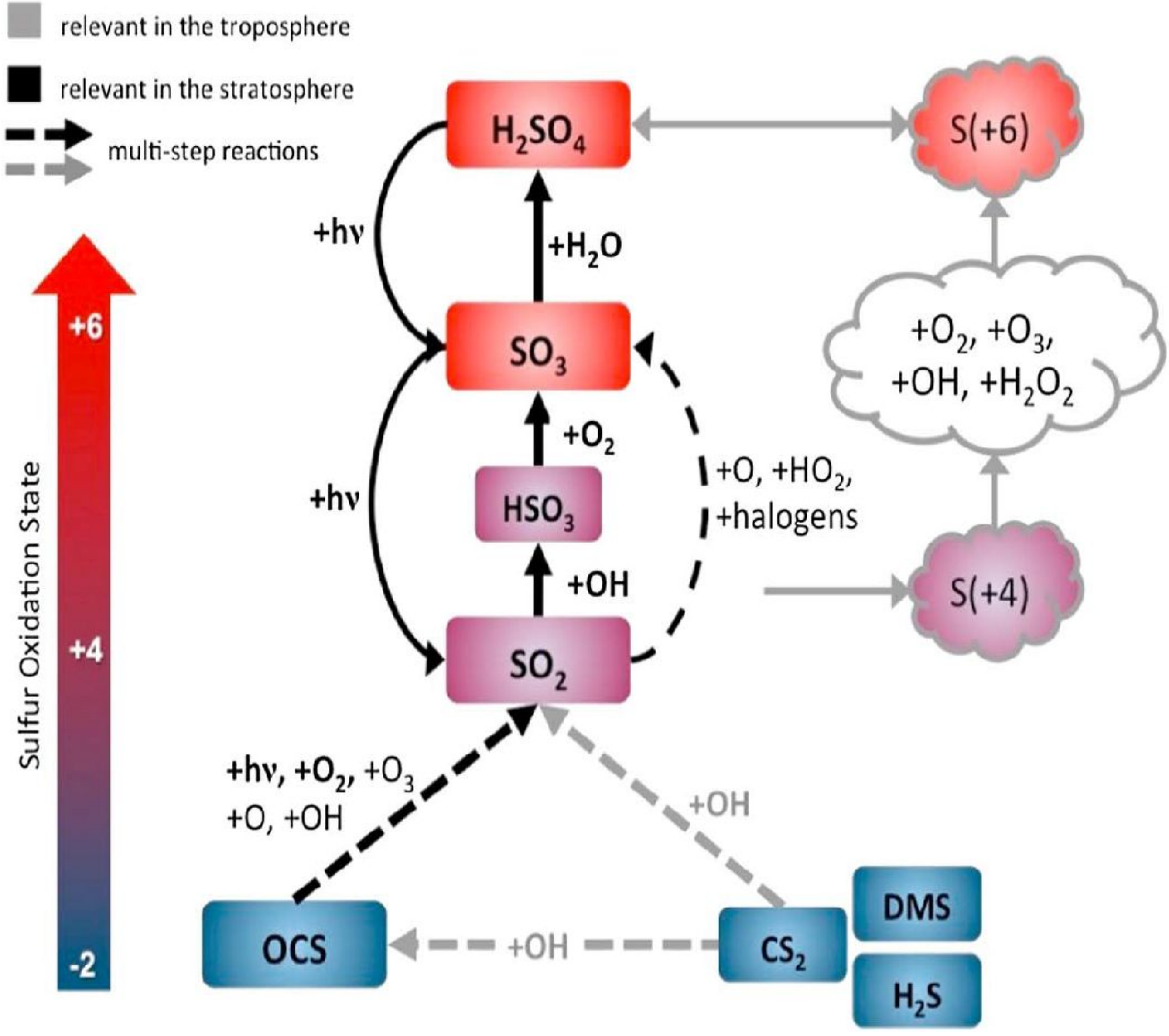
- Sulfur Precursors:
  - The sulfuric acid is produced from gases like carbonyl sulfide (OCS) and sulfur dioxide ($SO_2$) that are transported into the stratosphere.
- Photochemistry:
  - These gaseous sulfur compounds undergo photochemical oxidation to form sulfuric acid, which then condenses to form new particles.
- Tropospheric Inputs:
  - Organic aerosols can be lofted from the troposphere, especially by large wildfires, and enter the stratosphere.




Adapted from Kremser et al., 2016;
https://storymaps.arcgis.com/stories/d00ae4acebff48d08f8df953f101ef94

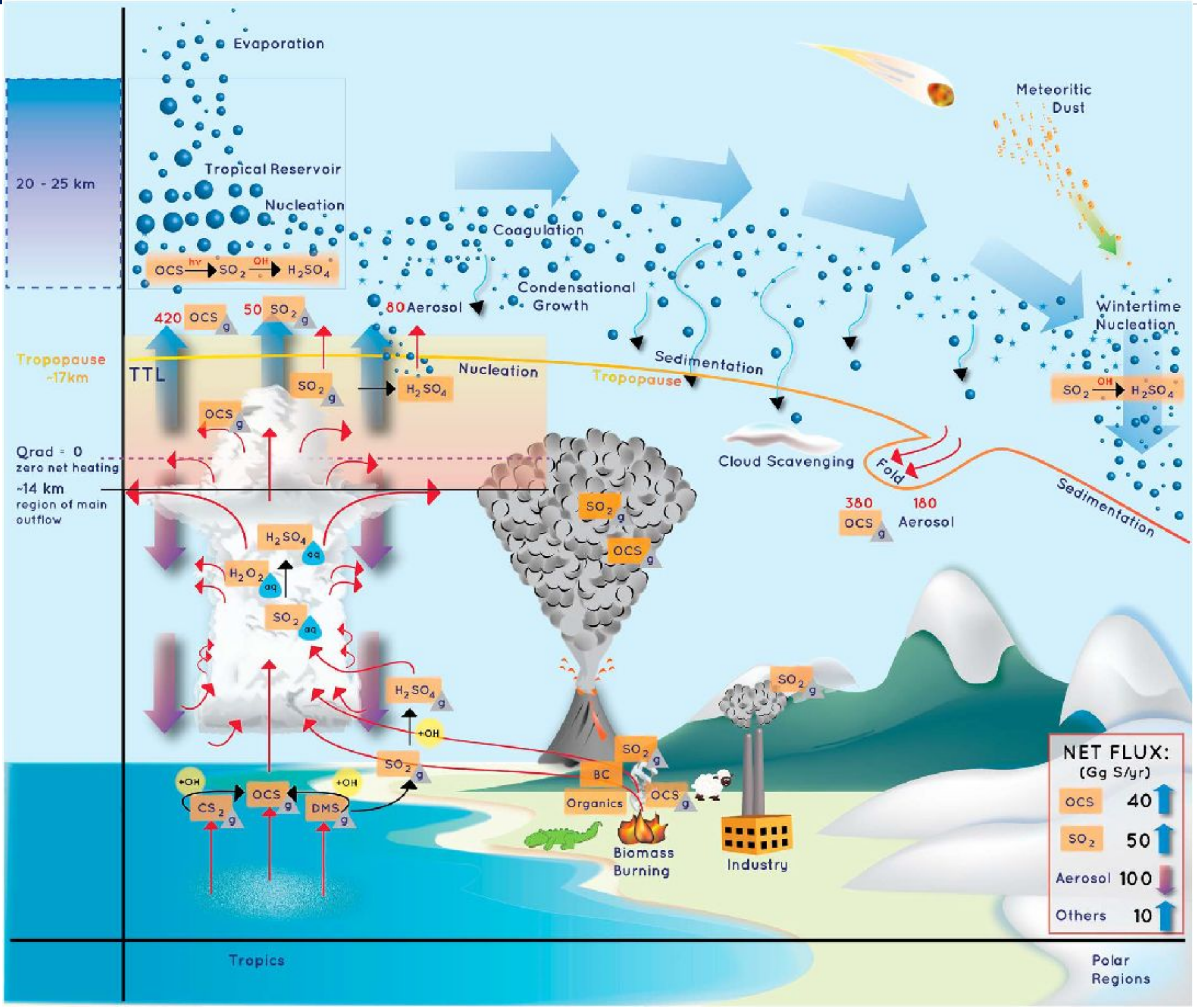
# Step-by-step formation process

- Oxidation to $SO_3$:
  - Within a few weeks, the $SO_2$ is oxidized to sulfur trioxide $SO_3$.
- Sulfuric Acid Formation:
  - The $SO_3$ vapor quickly reacts with water vapor $H_2O$ to form sulfuric acid $H_2SO_4$.
- Aerosol Formation:
  - The sulfuric acid vapor then condenses, either onto existing particles or by forming new, tiny sulfuric acid droplets (aerosols).



# Stratospheric aerosols life cycle

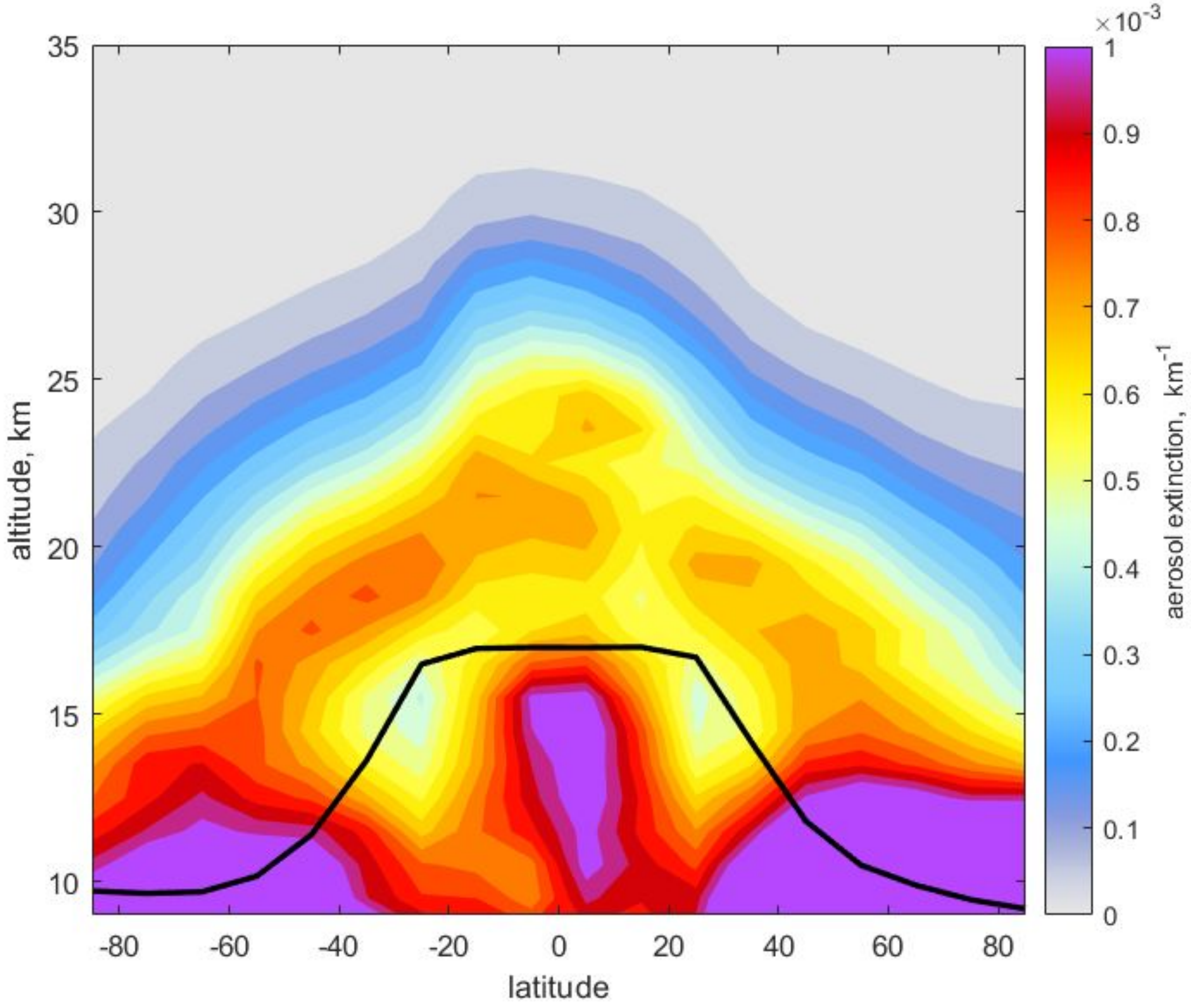
- **Particle growth:**
  - Aerosols grow in size through coagulation and condensation of sulfuric acid with existing particles
- **Global circulation:**
  - Once formed, these aerosols are transported globally by large-scale atmospheric circulation patterns (Brewer-Dobson circulation).
- **Removal processes:**
  - Aerosols are removed from the stratosphere mainly at mid- and high latitudes through isentropic transport (transport along constant potential temperature surfaces) across the tropopause, moving them into the troposphere.
- **Lifetime:**
  - The lifetime varies depending on the injection height and latitude. Volcanic aerosol from large tropical eruptions can remain in the stratosphere for 1-2 years, while high-latitude have shorter lifetimes, around 6-9 months.



# Background stratospheric aerosol  morphology



- “Umbrella”- shaped as a function of latitude
    - due to global circulation
- Located at 15-25 km
    - Major volcanic eruptions inject sulfur dioxide ($SO_2$) into the stratosphere, often reaching altitudes between 18–25 km
    - slow sedimentation and long residence time of particles in this altitude range
- Particle size from <0.1 µm  to more than a few  µm



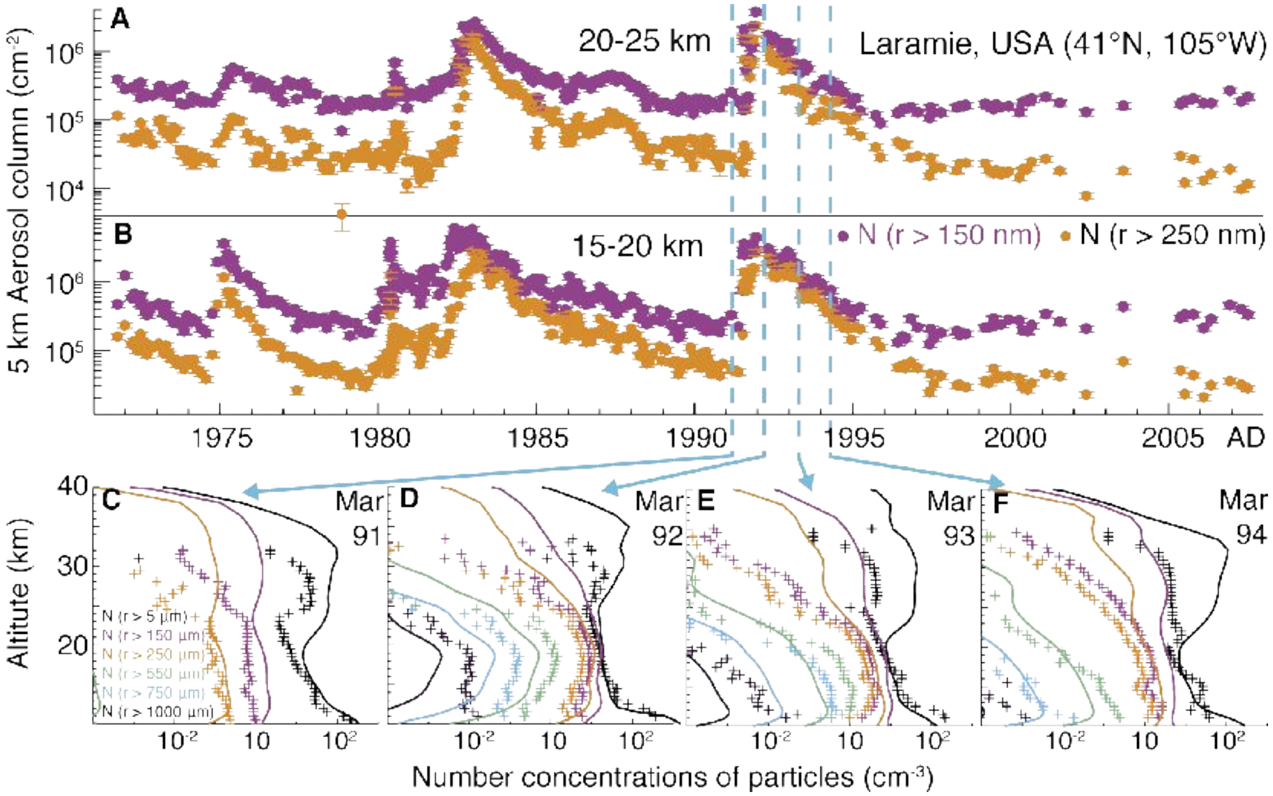
# Stratospheric aerosol observations



- In-situ
  - direct measurements of aerosol properties collected by instruments that are physically present within the stratosphere
- Remote sensing
  - Instruments are not physically present in the stratosphere
  - Instruments measure parameters (e.g., solar light spectra) that contain the information about the stratospheric aerosols
  - The information about the stratospheric aerosols is obtained from measurements via solving the inverse problem

- **Methods of In-Situ Observation**
  - Aircraft-borne instruments:
    - High-altitude aircraft, such as NASA's ER-2, are equipped with instruments to collect stratospheric aerosol samples and directly measure particle properties.
  - Balloon-borne instruments:
    - Balloons carry instruments to high altitudes to measure aerosol size distributions and other properties.
  - Rocket-borne instruments:
    - Rockets are used to obtain highly vertical profiles of stratospheric aerosols.

- **Key Data Collected**
  - Aerosol number concentration
  - Aerosol size distribution
  - Aerosol surface area density
  - Aerosol composition: Identifying the chemical components of the aerosols, such as sulfate, which is the primary component of volcanic aerosols




Adapted from G. Mann et al., 2015: 30+ year record of column-integrated size-resolved stratospheric aerosol particle concentrations at altitudes of (A) 20-25 km and (B) 15-20 km from balloon soundings at Laramie, USA (from Deshler 2008). (C-F) Example evaluation of the UM-UKCA model (Dhomse et al. 2014) simulated particle size distribution (dashed lines) before (C) and after (D, E, F) the June 1991 Pinatubo eruption compared to measured particle concentrations (crosses) larger than different size thresholds (colors) and total particle concentrations larger than 5 nm radius (black)

# Remote-sensing  of stratospheric aerosols



- Ground-based
- Satellite
- Before listing of remote-sensing techniques of stratospheric aerosol,  let us discuss optical properties of stratospheric aerosols

# Absorption, scattering

- Incoming solar light is absorbe by gases and scattered by air molecules and by aerosols
- Direct effects of stratospheric aerosols:
  - Reflect  shortwave solar radiation back to space □ tropospheric cooling
  - They also absorb and scatter Earth's outgoing heat radiatior (longwave forcing), leading to some warming in the stratosphere
- Dominant Cooling:
  - The effect of scattering shortwave solar radiation is more significant than the absorption and scattering of longwave terrestrial radiation.

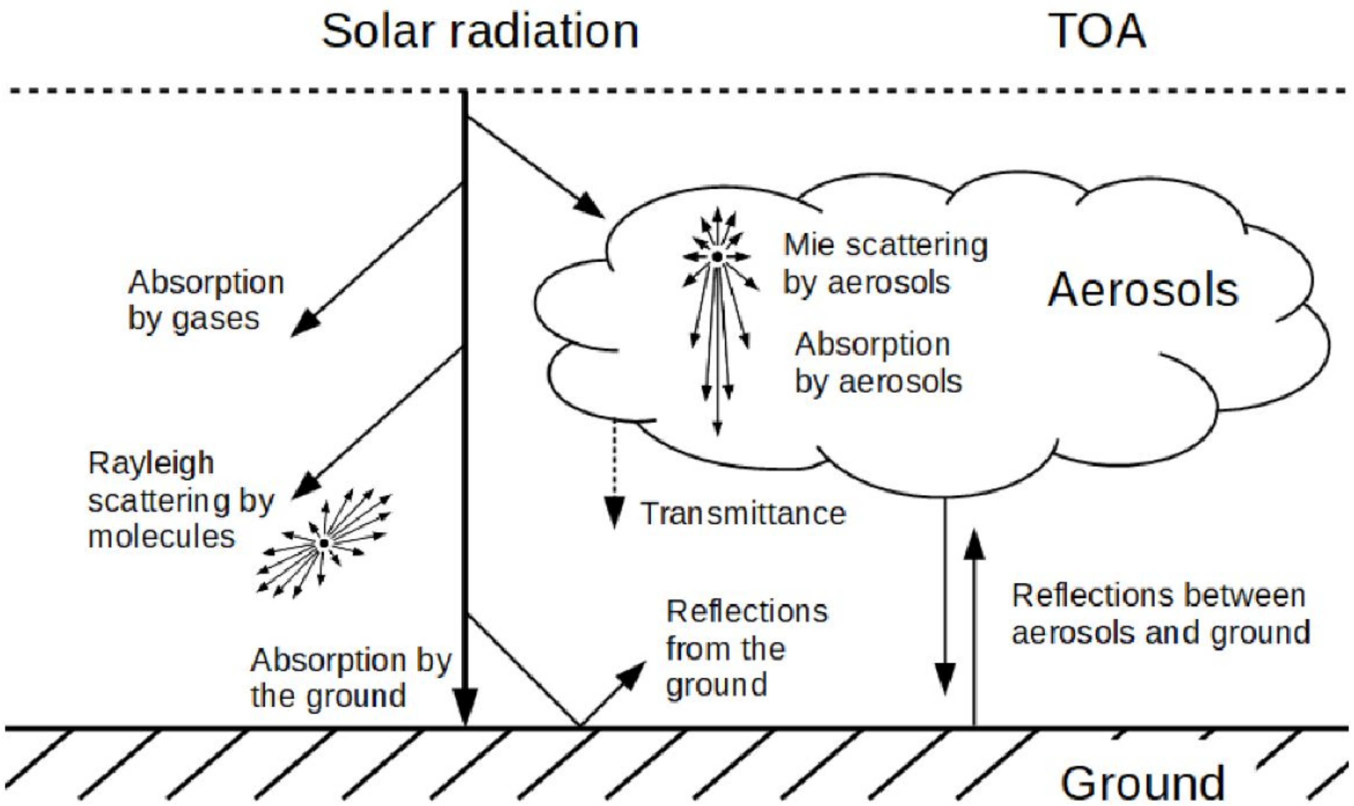
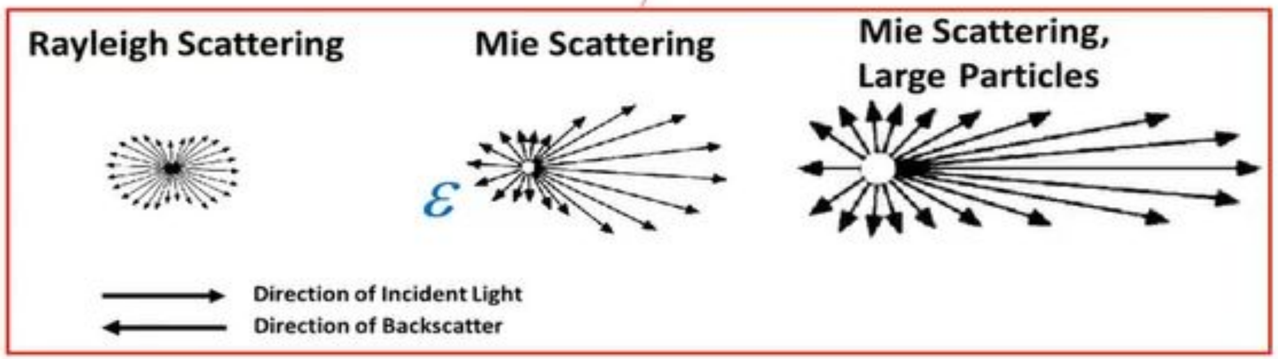



Figure: (Zoega, 2020)

**Aerosol extinction** describes the reduction in light intensity caused by atmospheric aerosols through scattering and absorption.

# Scattering by aerosols: Mie theory

- Rayleigh scattering on air molecules, r<<λ ( VIS λ ~400-700 nm, r~0.1 nm)
  - $I \propto (1/\lambda)^4$
  - The intensity of scattered light is symmetrical in the forward and backward directions.
- Mie scattering on particles (r~100- 1000 nm, large particles tens of μm)
  - Less dependent on wavelength than Rayleigh scattering, making the scattered light appear white.
  - Produces non-uniform scattered light, with a strong preference for forward scattering, especially in case of larger particles.



# Qualitative observations: photos

t.int

## Mount Pinatubo (1)

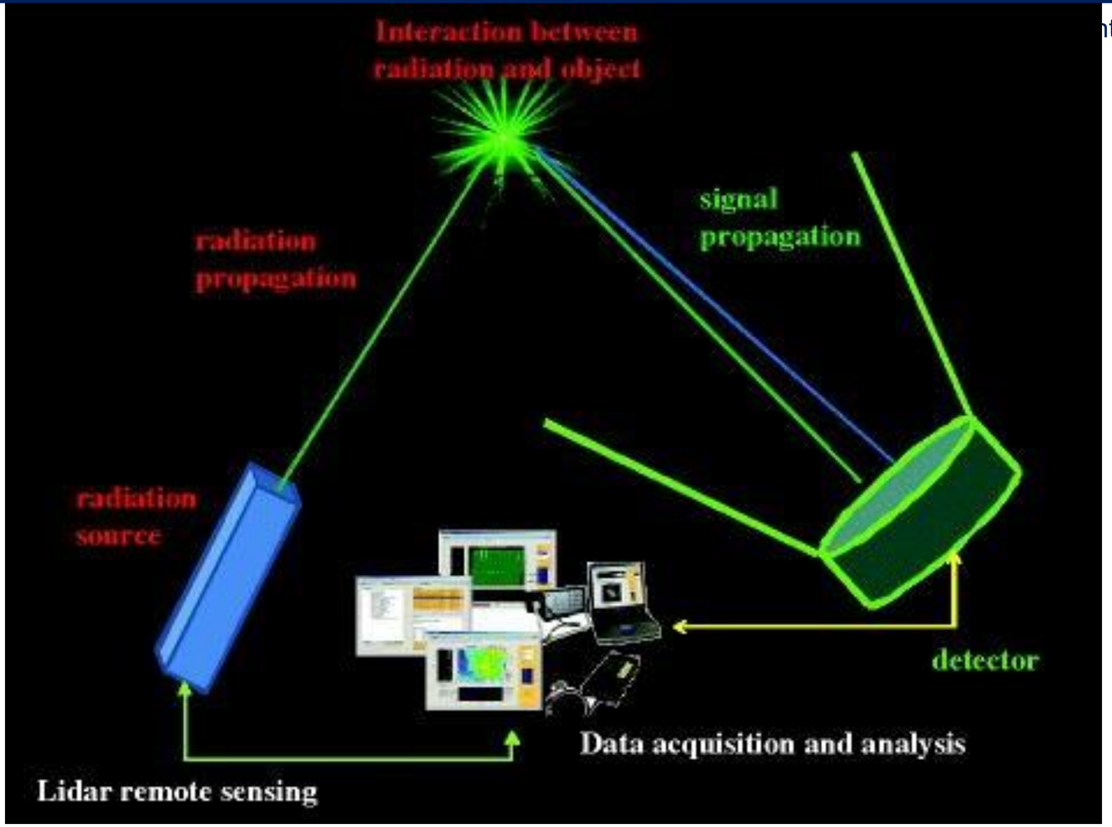
### Eruption June 1991

Photo: NASA

before

after

# Ground-based remote sensing: lidar (Light Detection and Ranging)



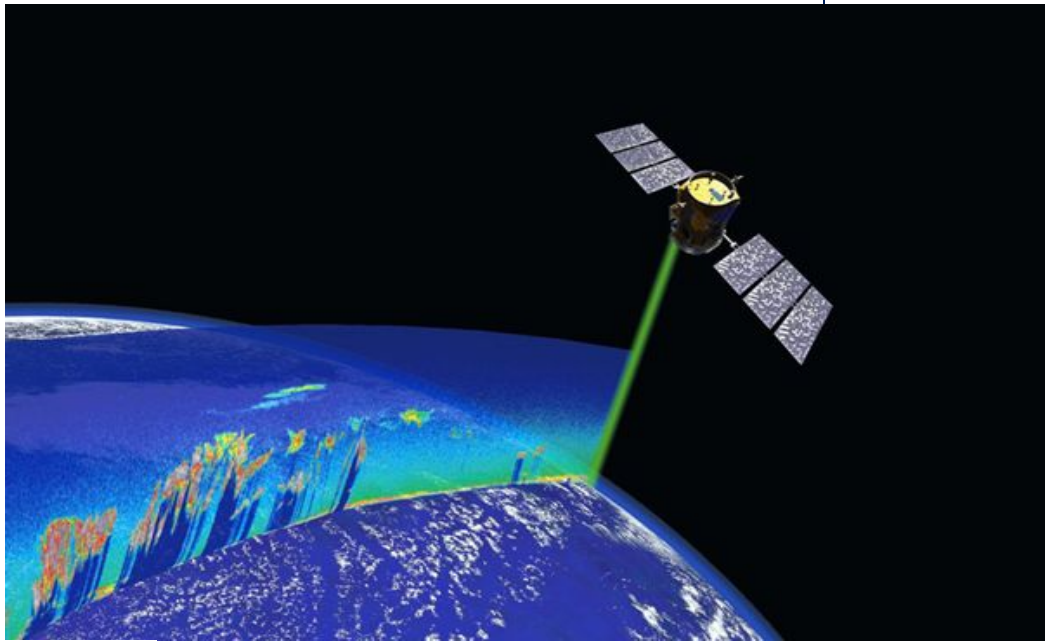

- How it works:
  - A powerful laser beam is transmitted vertically into the atmosphere. As the light interacts with aerosols and molecules, a small portion of the energy is scattered back towards the instrument.
- Data collected:
  - The received signal, recorded as a function of time, provides an altitude-resolved profile of aerosol backscatter and depolarization ratio.
- Measurements:
  - Backscatter coefficient: A measure of how much light is scattered back by aerosols.
  - Depolarization ratio: Indicates the non-sphericity of the aerosol particles.

- Benefits:
  - Provides frequent, daily measurements when weather permits.
  - Allows tracking  the spread and evolution of volcanic plumes and wildfire smoke.
  - Allows for the separation of aerosols from different sources, like volcanic ash and wildfire smoke.
- Limitations:
  - Cloud-free conditions
  - Local

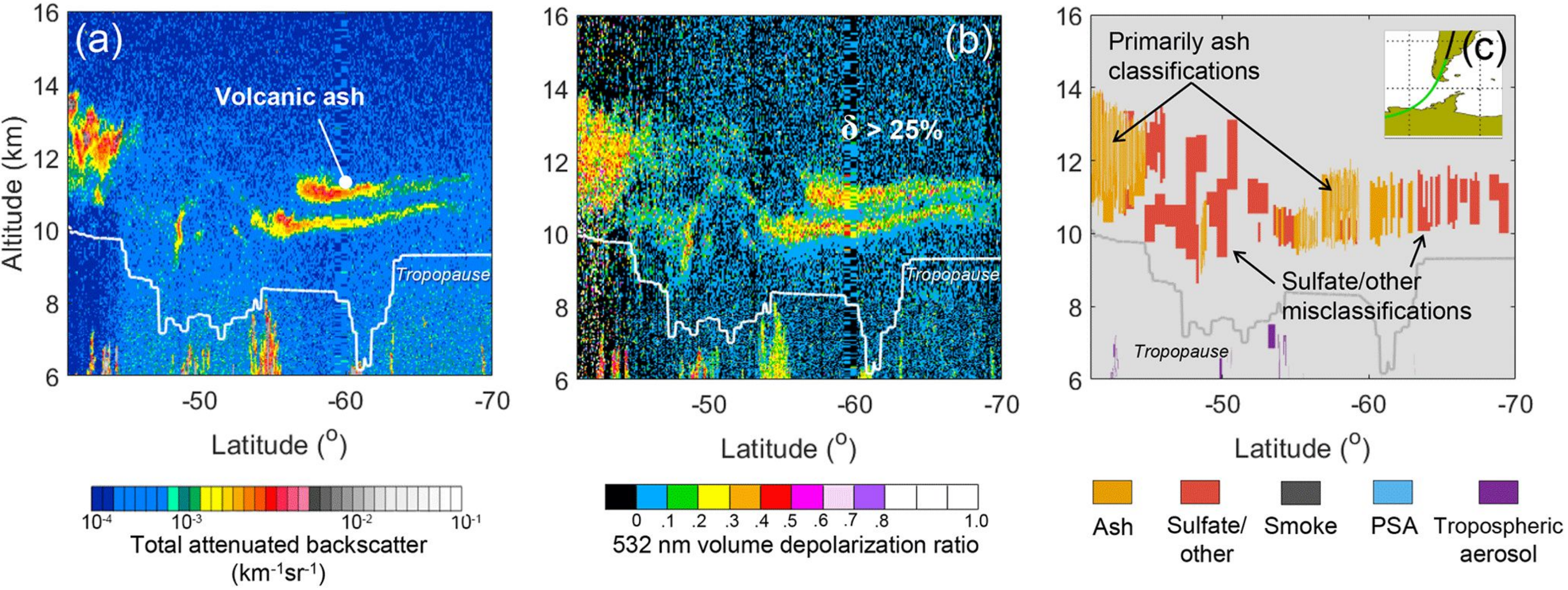
# CALIPSO (**Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations)**

copernicus.eumetsat.int

- Operated in 2006-2023
- The objective: to study the roles of clouds and aerosols on climate and weather
- The main instrument **CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization)**
  - CALIOP is a lidar with backscattering at two wavelengths (532 and 1064 nm) and polarization sensitivity at 1064 nm. It provides high-resolution vertical profiles of clouds and aerosols.
  - a footprint of about 90 m in diameter



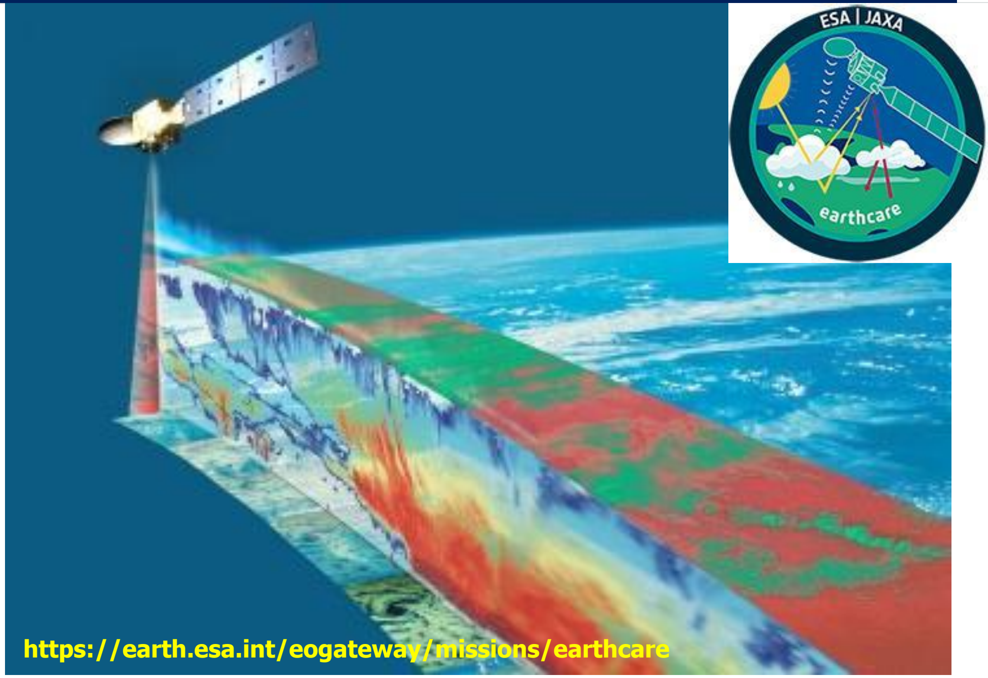
[Tackett et al. ,2023]



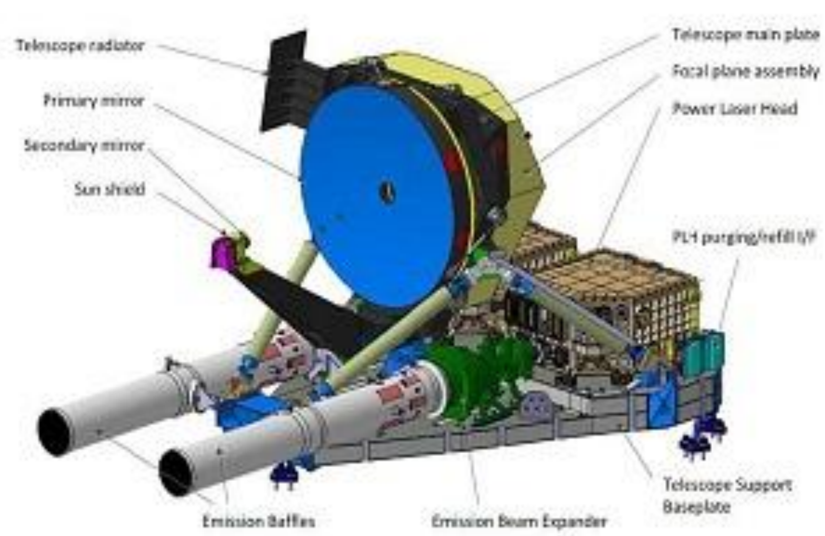

- CALIOP lidar allowed for the classification of stratospheric aerosol particles into categories like volcanic ash, smoke, and sulfate/other, based on depolarization ratios and backscatter ratios
- CALIPSO has been crucial for observing the impacts of volcanic eruptions and pyroCb events on the stratosphere, tracking the distribution and composition of these injections

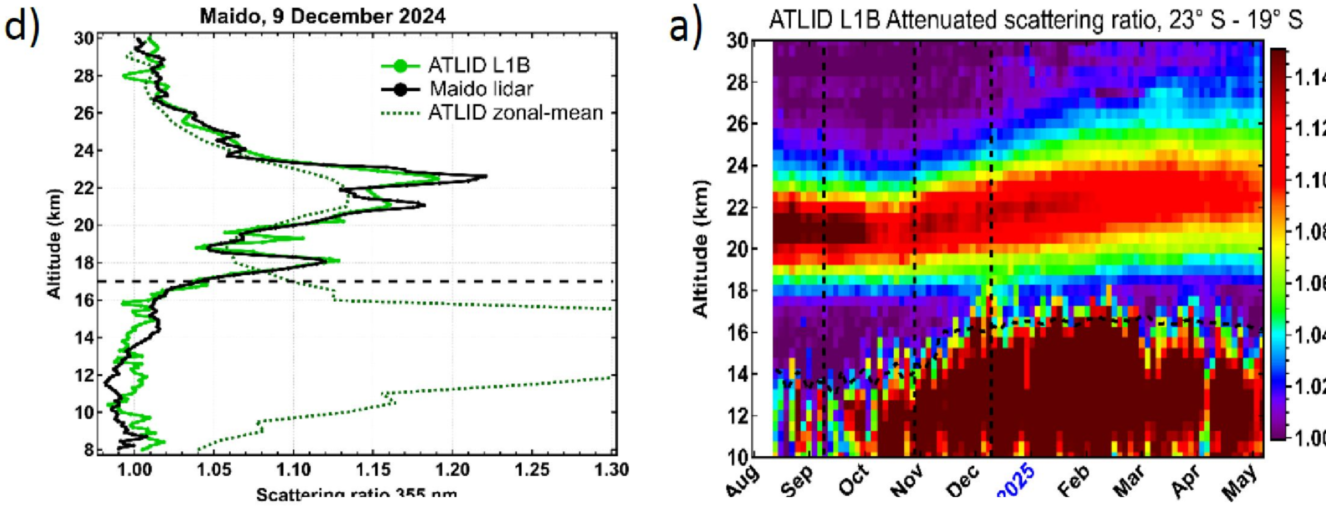
# EarthCARE ( Earth Cloud, Aerosol and Radiation Explorer, 2024 )

- EarthCARE employs high-performance lidar and radar technology that has never been flown in space before, with the objective to deliver unprecedented datasets to allow scientists to study the relationship of clouds, aerosols and radiation at accuracy levels that will significantly improve our understanding of these highly variable parameters.
- Specifically, EarthCARE measures properties of aerosol layers: occurrence, extinction profiles, boundary layer height, distinction of aerosol types
- 3D cloud and aerosol scenes will be constructed over a swath width of about 30 km



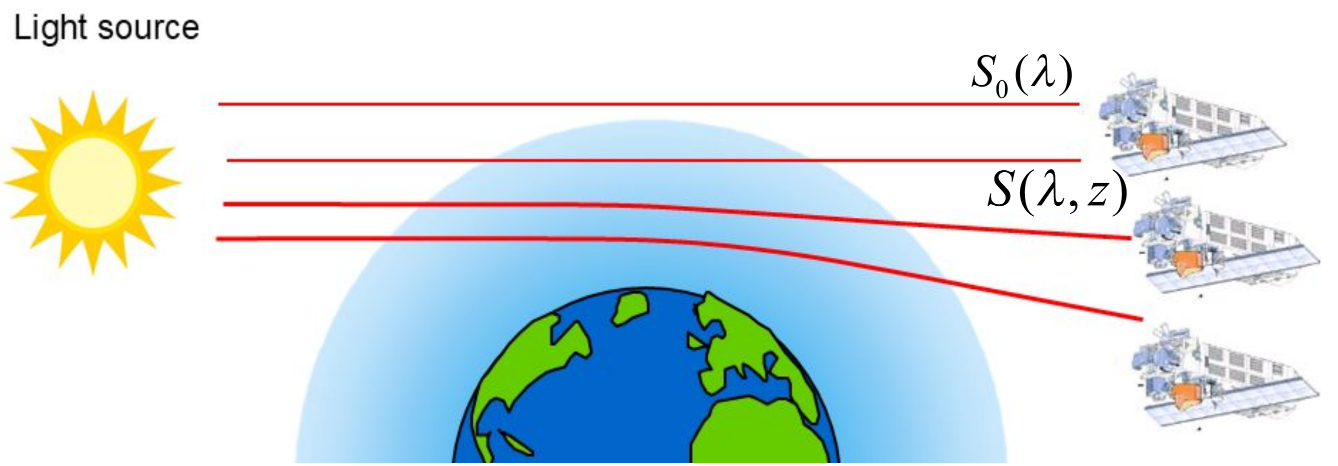

**The Atmospheric Lidar (ATLID) provides vertical profiles of aerosols and thin clouds. It operates at a wavelength of 355 nm and has a high-spectral resolution receiver and depolarisation channel.**




ATLID measurements, Khaykin et al, 2025

# Solar occultation instruments (SAGE)


- Self-calibrating measurement principle
- A basis for retrievals: horizontal transmittance spectra

$$T(\lambda, z) = \frac{S(\lambda, z)}{S_0(\lambda)}$$

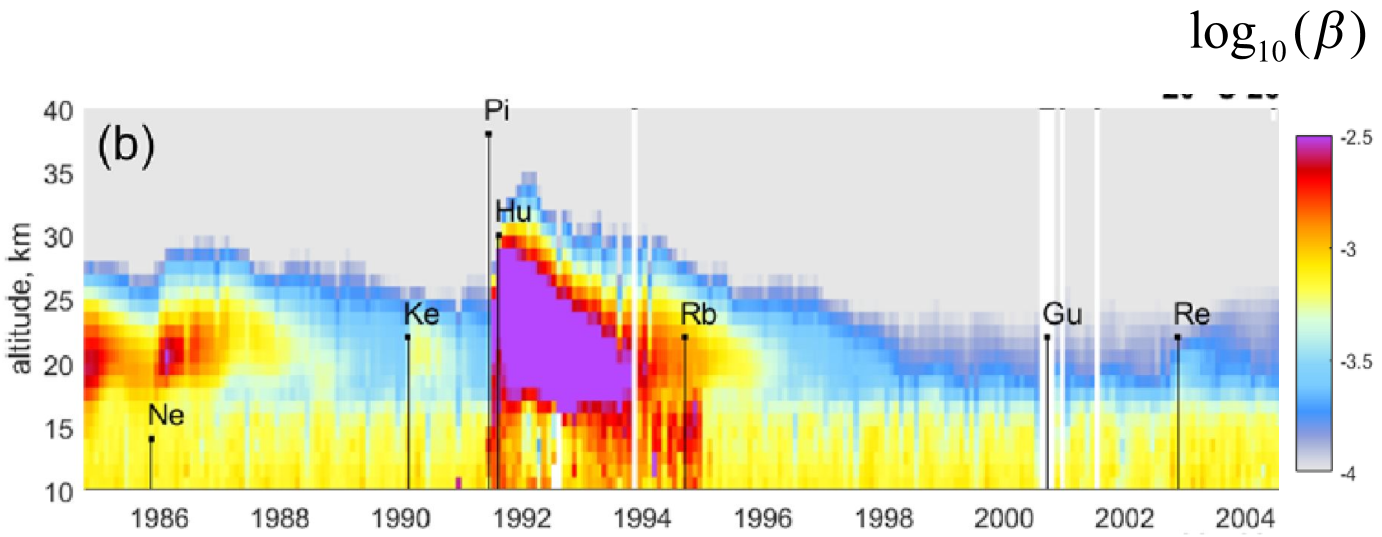
**Stratospheric Aerosol and Gas Experiment**

# SAGE II and SAGE III/ISS aerosol extinction profiles

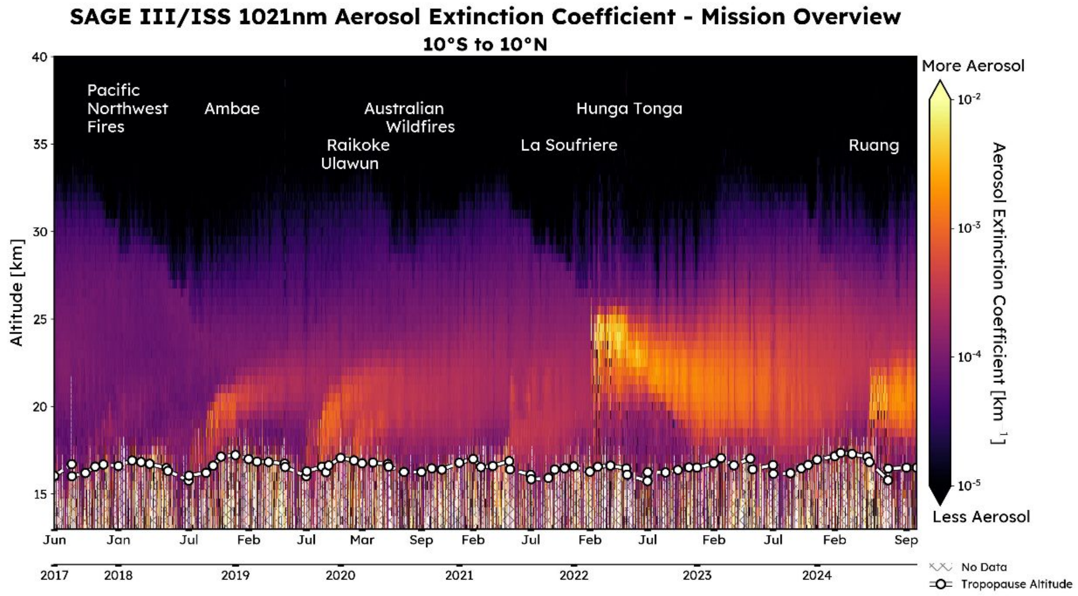


- The main aerosol data are extinction profiles with ~1  km vertical resolution
    - SAGE II: at  386, 452, 525 and 1020 nm
    - SAGE III/ISS:  at 384, 449, 520, 602, 676, 756, 869, 1021 and 1544 nm
- Additional parameters:
    - Aerosol size distribution

[1]The extinction coefficient is the sum of absorption and scattering in the atmosphere along the radiation path per unit distance. It is equal to $\sum N_i(\sigma_{a,i}(\lambda)+\sigma_{s,i}(\lambda))$, where $N_i$ is the number density of atmospheric constituent $i$, $\sigma_{a,i}(\lambda)$ is the absorption coefficient of species $i$ at wavelength $\lambda$ and $\sigma_{s,i}(\lambda)$ is the scattering coefficient of species $i$ at wavelength $\lambda$.




Aerosol  extinction coefficient at 20S-20N, adapted from (Sofieva et al., 2024)

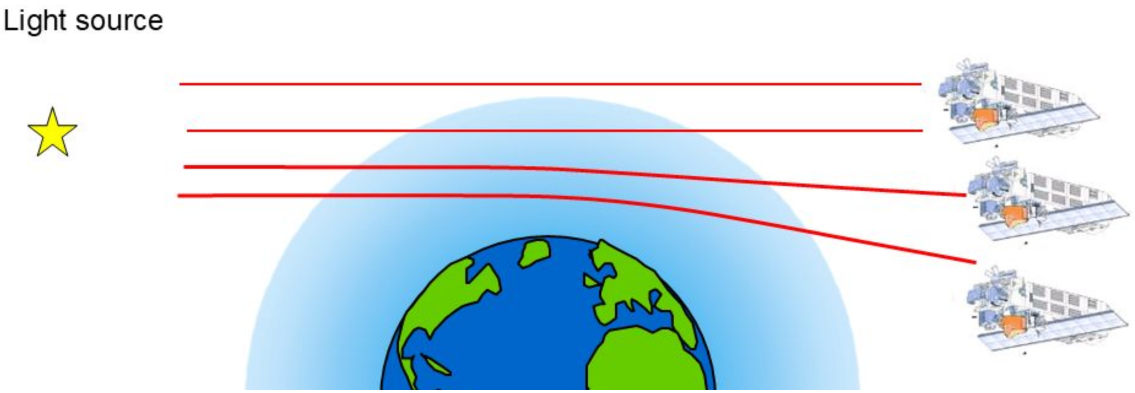


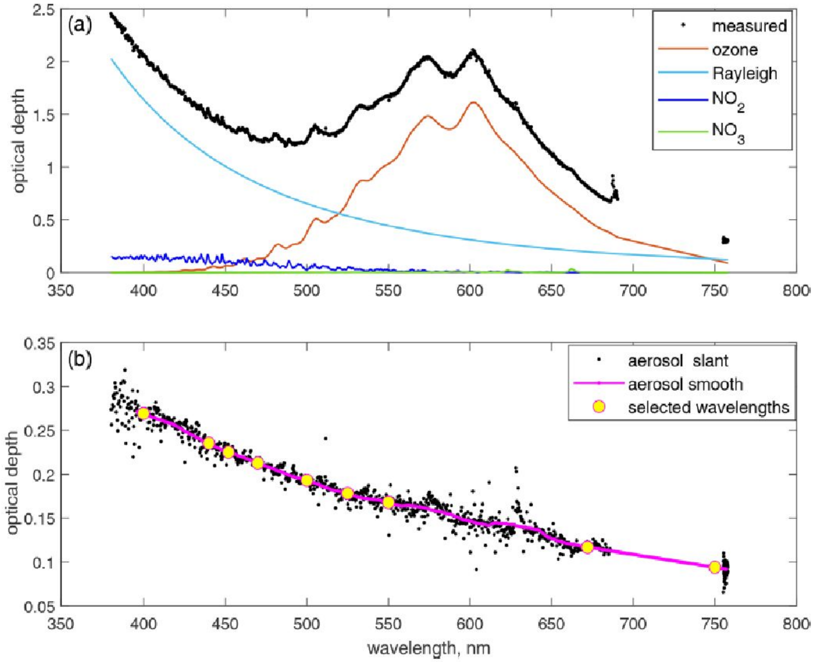

**Aerosol extinction time series for tropics during the SAGE III/ISS mission. Most notable recent events are January 2022 eruption of Hunga Tonga and April 2024 eruption of Ruang. https://sage.nasa.gov/outreach/**

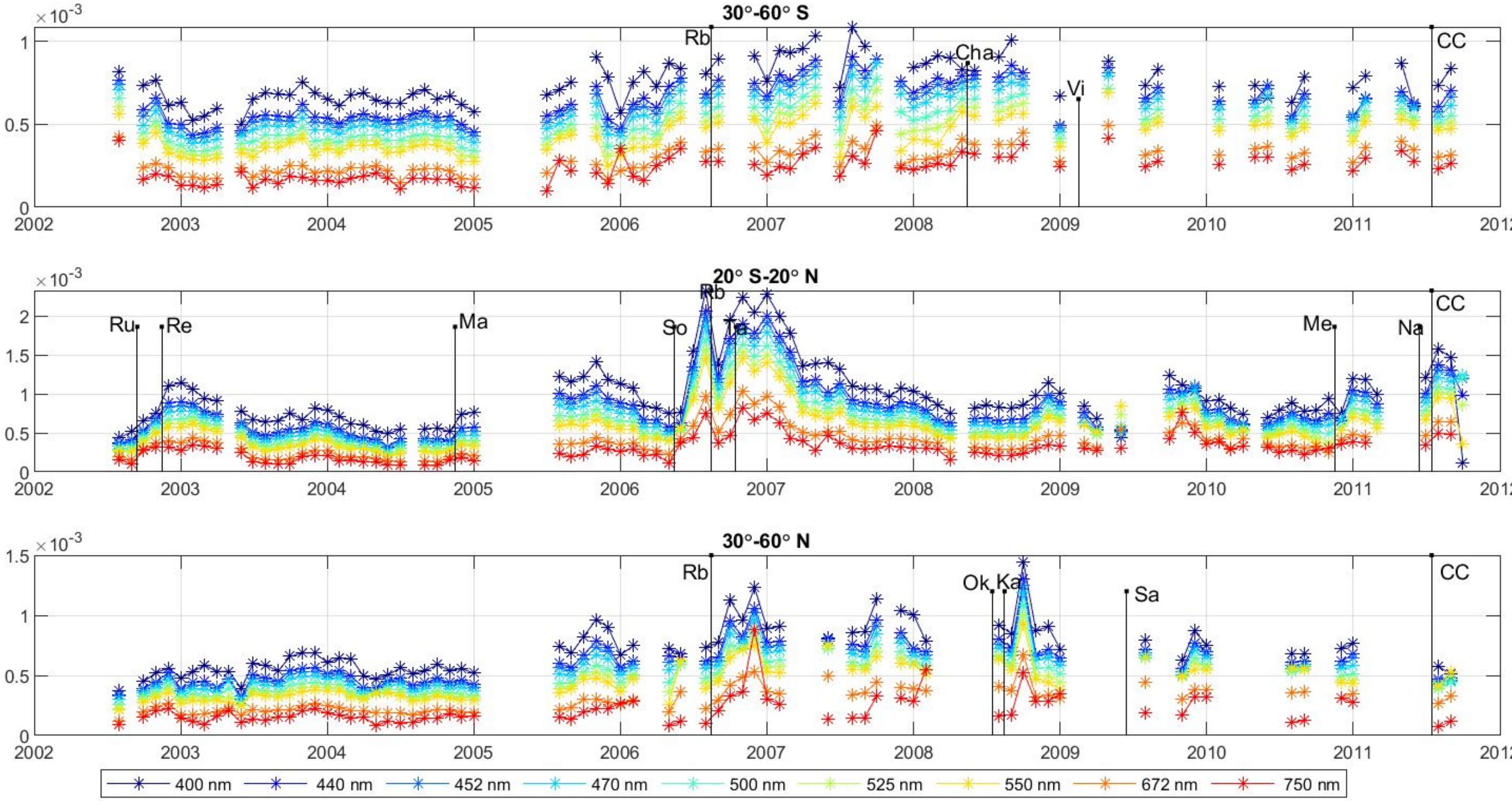
# Stellar occultation instrument: GOMOS



- GOMOS(Global Ozone Monitoring by Occultation of Stars) operated in board Envisat in 2002-2012
- Stars are used as a light source
- As solar occultation, self-calibrating measurements
- UV-VIS and IR spectrometers
- A recent development: a multi-wavelength dataset of aeroso profiles



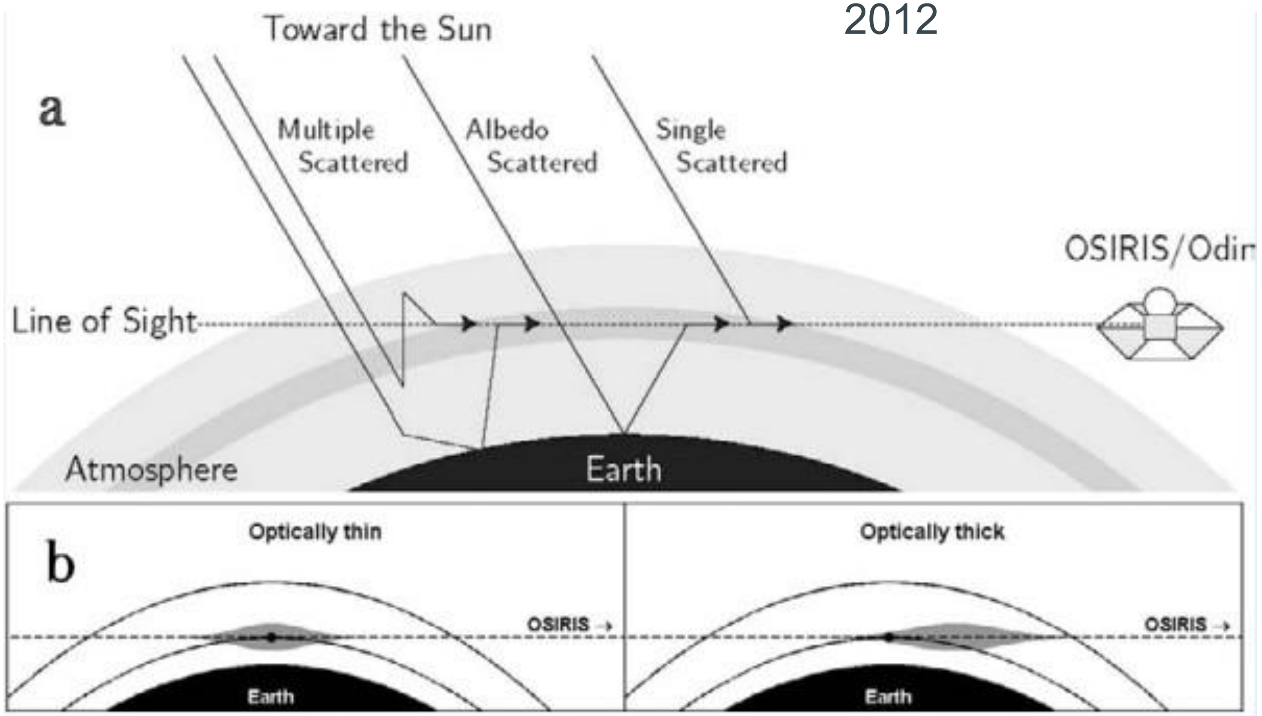

Sofieva et al., 2024

# Limb scattering measurements



- Limb instruments get information about aerosols from scattered solar light
- Information on the composition vertical profile is obtained by combining observations at multiple tangent heights.
- The sunlight collected by the sensor may have taken any number of different paths through the atmosphere. The simplest path is single scattering of the incoming sunlight into the line of sight. Alternatively, the path may include one or more scattering events prior to entering the instrument line of sight and/or one or more reflections off the surface or cloud
- Transforming the limb-scatter measurements as a function of tangent height into a vertical profile requires an inversion algorithm with radiative transfer model

McLinden et al., 2012



# Aerosol data from limb scattering measurements

copernicus.eumetsat.int

- **OSIRIS** (Optical Spectrograph and InfraRed Imaging System) on Odin
- 2001- present
- Aerosol extinction profiles at 750 nm
- ~2 km vertical resolution

- **SCIAMACHY** (Scanning Imaging Spectrometer for Atmospheric Chartography) on Envisat
- 2002-2012
- Aerosol extinction profiles at 750 nm
- ~ 3 km vertical resolution

- **OMPS-LP** (Ozone Monitor Profiling Suite Limb Profiler ) on Suomi-NPP
- 2012 -> present
- Aerosol extinction profiles at 869 nm (UBr), 749 nm (USask) and multi-wavelength (NASA)
- ~3 km vertical resolution

# Climate data records of stratospheric aerosols

- Duration of each satellite mission is limited in time, while a long-term evolution and variability of stratospheric aerosols is of great interest
- A challenge: data from different instruments are biased with respect to each other, and often aerosol extinction profiles are retrieved at different wavelength
- A merging methods are applied to create so called climate data records.

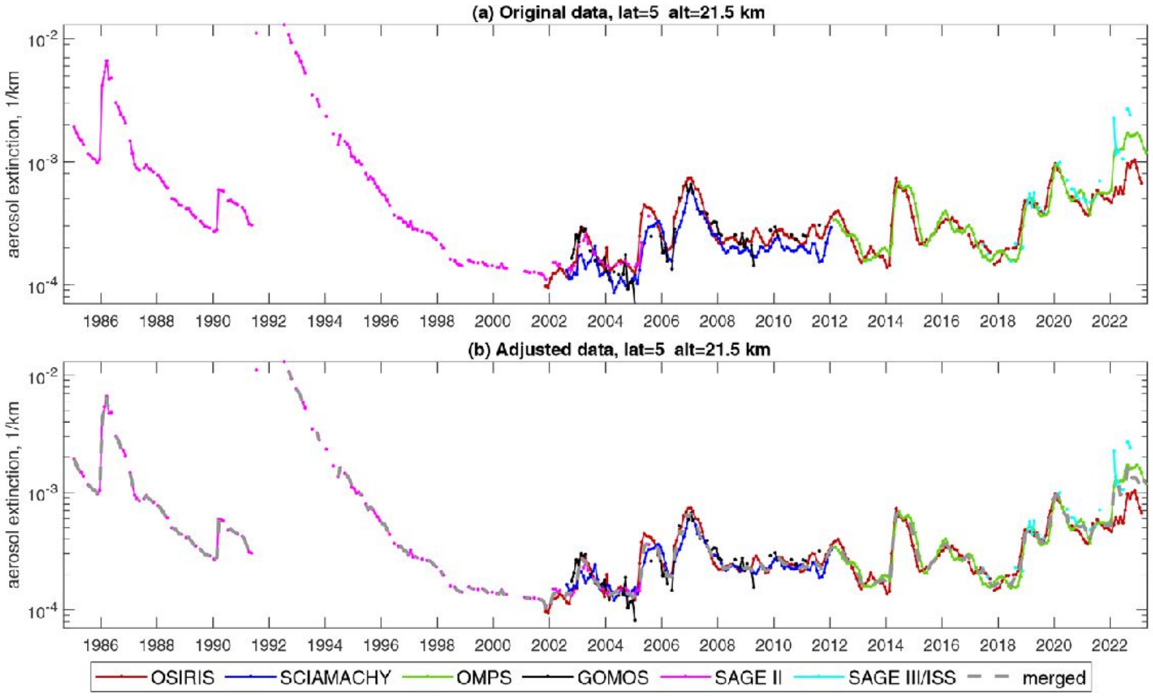


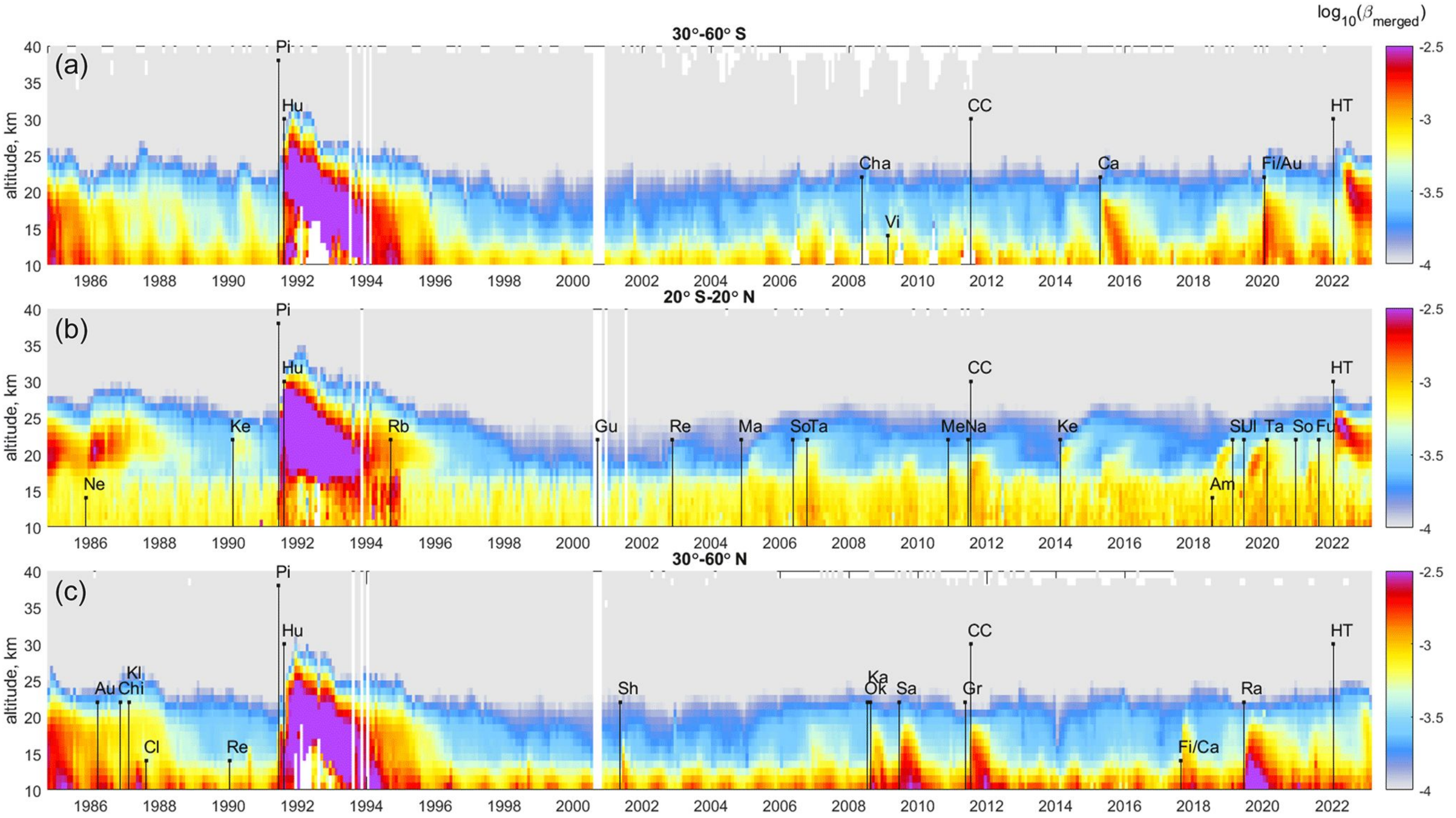

**Figure 1.** Aerosol extinction coefficient ($km^{-1}$) at 21.5 km in the 0–10° N latitude zone. Colored lines correspond to aerosol records from individual instruments for the **(a)** original data and **(b)** adjusted data. The merged aerosol extinction coefficient is shown by the gray line in panel **(b)**.

(Sofieva et al., 2024)

- Existing merged aerosol datasets(extinction profiles):
  - GLOSSAC (Global Space-based Stratospheric Aerosol Climatology, NASA), 525 and 1020 nm
    - Merged SAGE II, OSIRIS, CALIPSO, SAGE III/ISS data
    - Reference SAGE II
  - CREST (Climate Data Record of Stratospheric Aerosols, ESA), 750 nm
    - Merged SAGE II, OSIRIS, GOMOS, SCIAMACHY, OMPS-LP UBr, SAGE III/ISS
    - Reference OSIRIS

# Stratospheric aerosol extinction profiles (CREST)

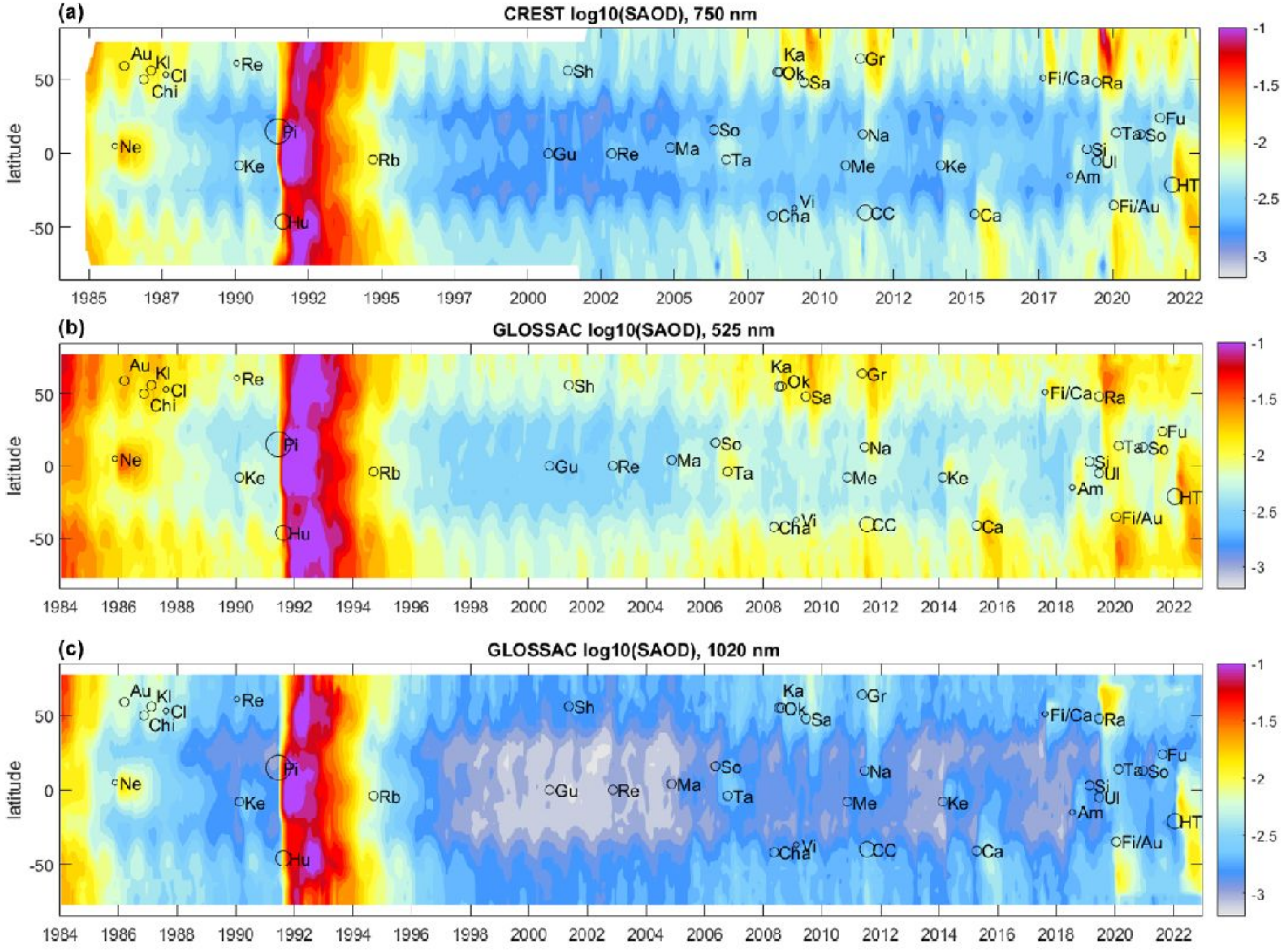
The stratospheric aerosol layer is not constant: it has large enhancements due to volcanic eruptions and wild fires




(Sofieva et al., 2024)

# Stratospheric aerosol optical depth

- Aerosol enhancements match very well with volcanic eruptions and strong wildfires
- The overall morphology of SAOD enhancements is very similar (considering the wavelength dependence) in CREST and GloSSAC




*CREST stratospheric aerosol optical depth (SAOD) at 750 nm. Color indicates $\log_{10}$(SAOD). Main aerosol events (volcanic eruptions and wildfires) are indicated by black circles of the size proportional to their volcanic explosivity index VEI.*

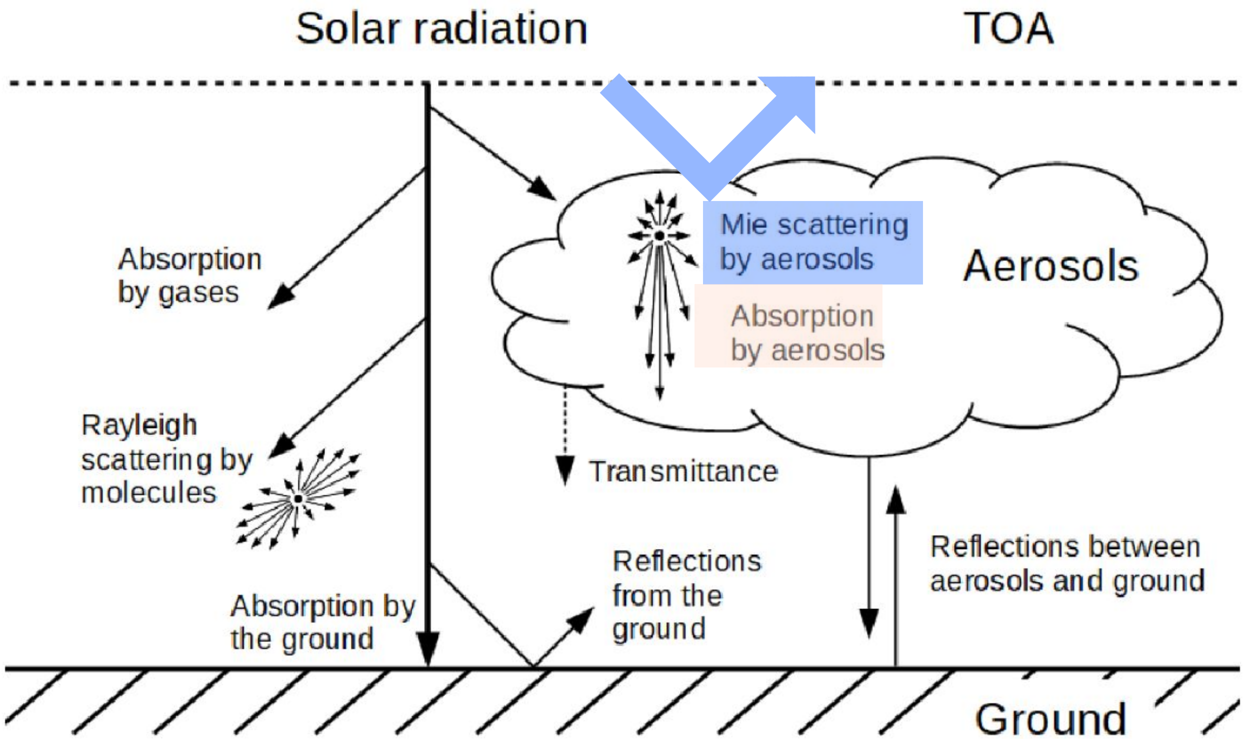
# Why do stratospheric aerosols matter?

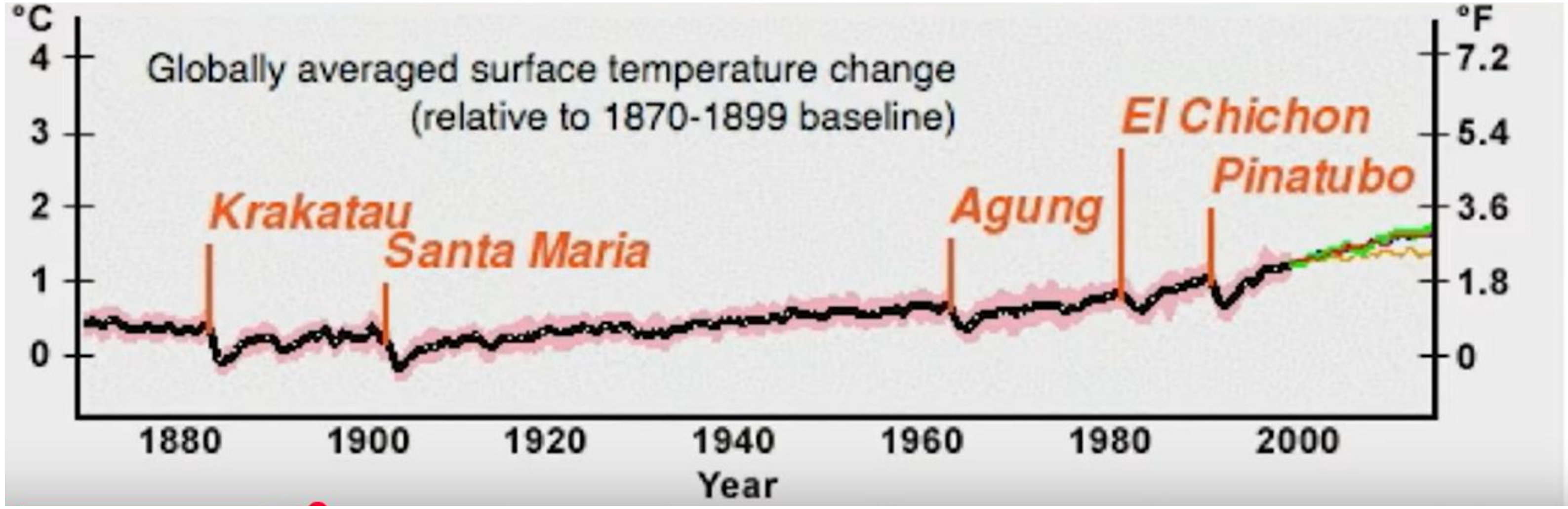


- They influence climate (and surface temperatures) by reflecting sunlight
- Affect ozone chemistry and cloud formation
- Key to climate modeling and geoengineering research

# The role in energy balance

- Reflect shortwave solar radiation back to space  tropospheric cooling
- absorb Earth's outgoing heat radiation (longwave forcing), leading to some warming in the stratosphere
- Dominant cooling




A decrease of global surface temperature after major volcanic eruptions is observed

# Influence on ozone chemistry

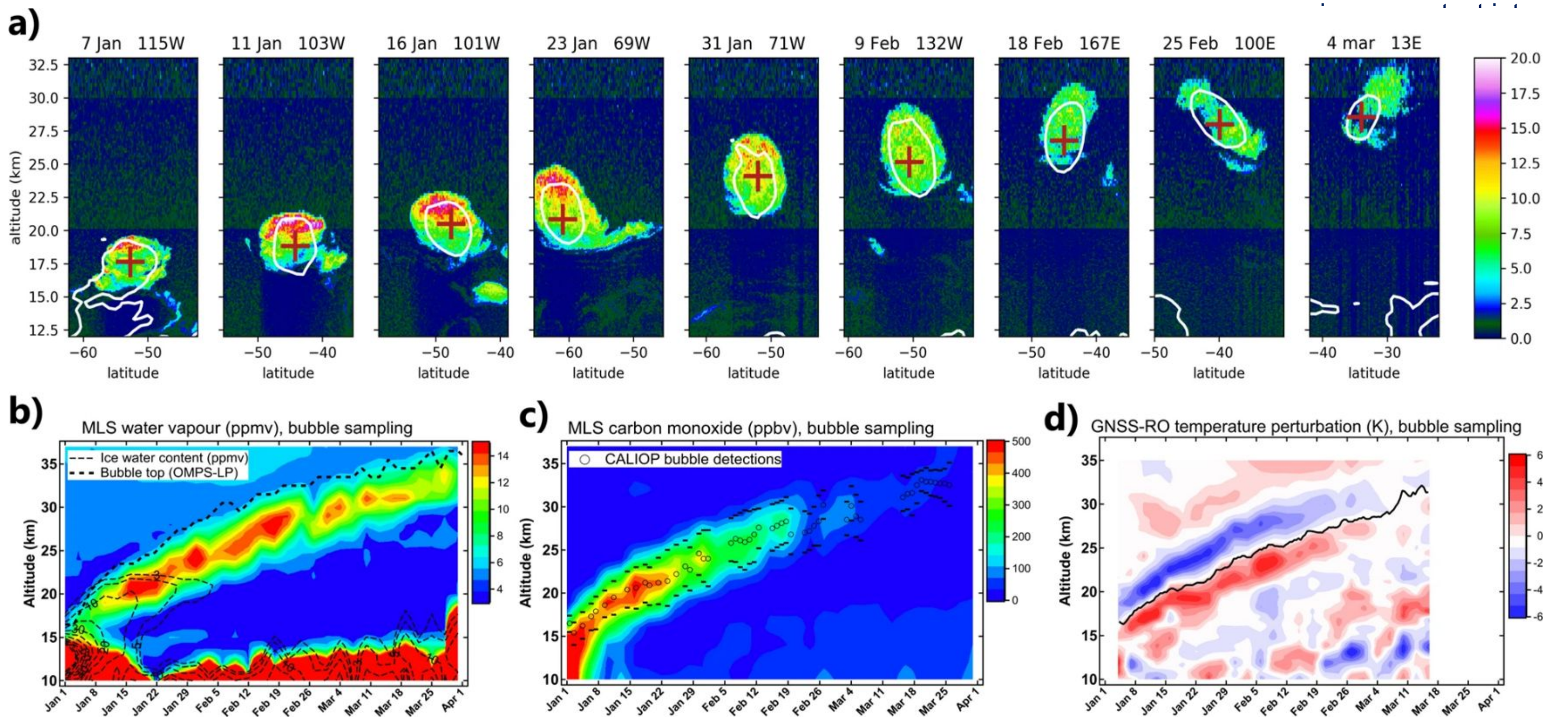


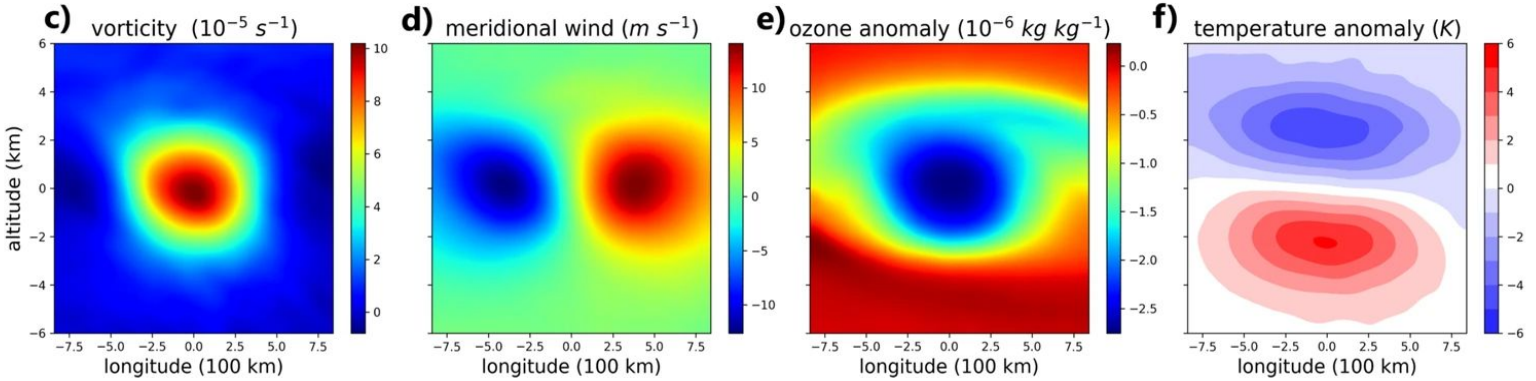
Stratospheric aerosols increase ozone depletion by providing surfaces for chemical reactions

- Activation of Halogens:
  - Sulfuric acid aerosols offer a surface area that facilitates chemical reactions that convert stable chlorine and bromine compounds into more reactive, ozone-destroying forms.
- Removal of Nitric Acid:
  - Aerosols also act as sites for the removal of nitric acid $HNO_3$ from the gas phase. This removal is critical because nitric acid normally interacts with reactive chlorine species, converting them into more stable forms that are less damaging to ozone.
- Polar stratospheric clouds:
  - Under very cold conditions, stratospheric aerosols can also serve as condensation seeds for the formation of PSCs. These clouds are particularly important because their surfaces provide an even more effective platform for the activation of chlorine and bromine, significantly accelerating ozone depletion in the polar regions.

# Natural “experiment”

- The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude
- A striking effect of the solar heating of an intense smoke patch was the generation of a self-maintained anticyclonic vortex measuring 1000 km in diameter and featuring its own ozone hole.
- The highly stable vortex persisted in the stratosphere for over 13 weeks, travelled a long distanceand lifted a confined bubble of smoke and moisture to 35 km altitude.
- Its evolution was tracked by several satellite-based sensors  and modelled by ECMWF
-  Because wildfires are expected to increase in frequency and strength in a changing climate, extraordinary events of this type may contribute significantly to the global stratospheric composition in the coming decades.



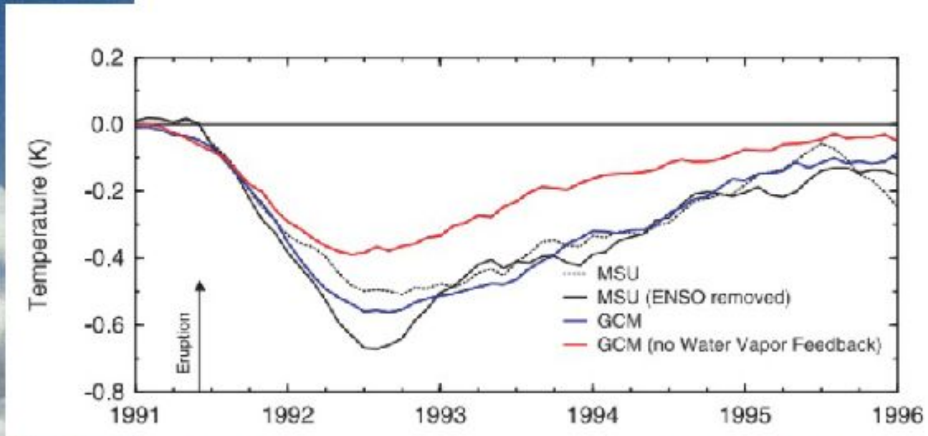

(Khaykin et al., 2020)

# Geoengineering: stratospheric aerosol injection



## Is there evidence that the SAI method is a viable method to cool Earth?


- Explosive volcanic eruptions demonstrate the cooling possible from stratospheric aerosol injection (SAI) of sulfur-containing aerosol, i.e., volcanic eruptions are a natural analog of SAI.




- Global temperatures in satellite (MSU) observations dropped by up to 0.5°C in the years after the Mt. Pinatubo eruption.

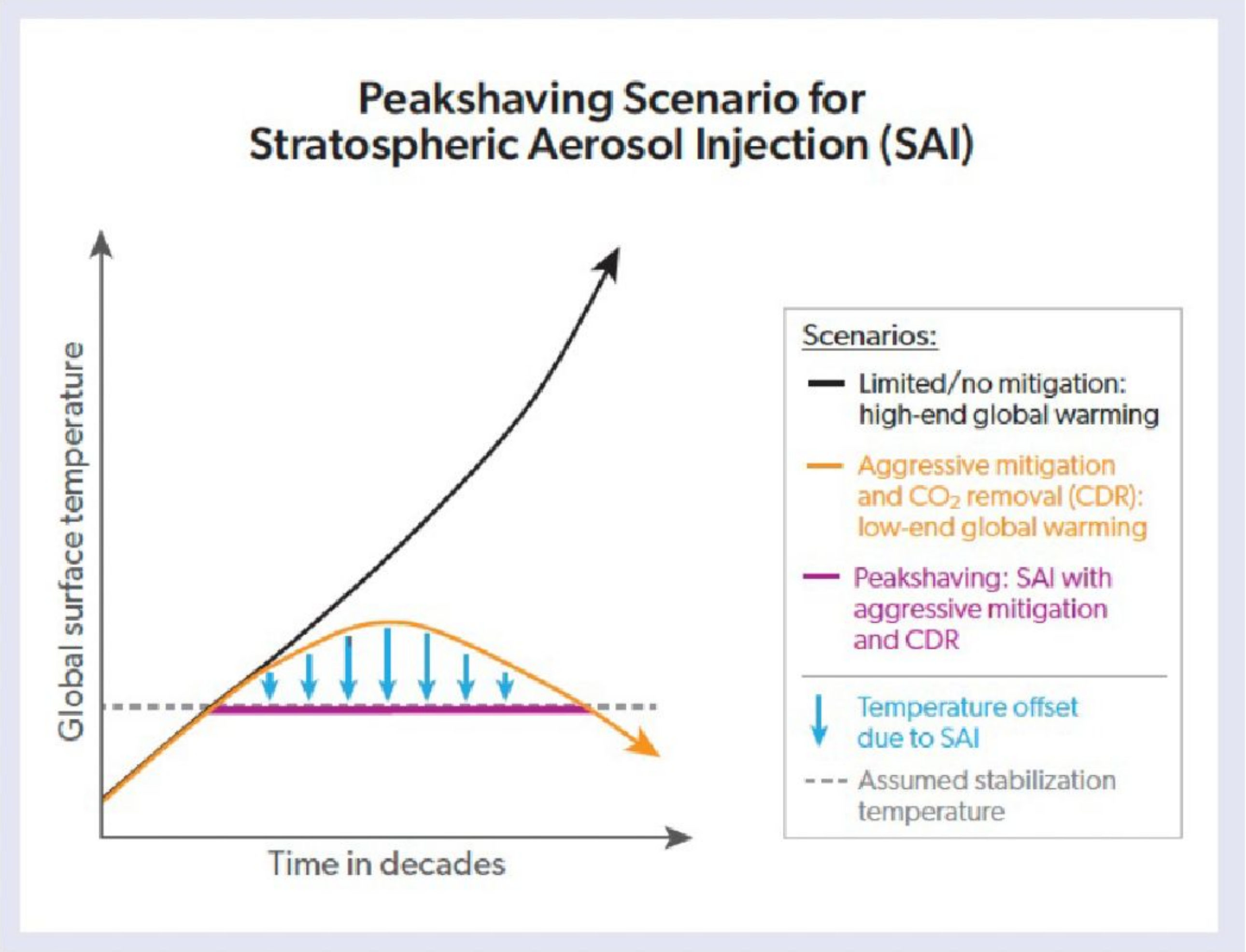
https://www.science.org/content/article/massive-volcanoes-could-cool-earth-more-warming-world

Brian J. Soden, et al. *Science* 296, 727 (2002); DOI: 10.1126/science.296.5568.727 9

From presentation of D. Fahey at ORM

# Geoengineering: stratospheric aerosol injection

- Hopefully, this will be never needed
  - But it is better to make simulations in order to evaluate (some) consequences
- Based on the observed cooling after large volcanic eruptions and various model studies, stratospheric aerosol injection (SAI) has the potential to reduce global mean temperatures.
- SAI cannot fully offset the widespread effects of global warming (e.g., temps, precipitation, ocean acidification) and produces unintended consequences, including effects on ozone.
- Details of these effects depend on the specifics of the SAI scenario and injection strategies (e.g., latitudes, altitudes, amounts and duration).
- The peak-shaving scenario is an essential framework to discuss SAI options



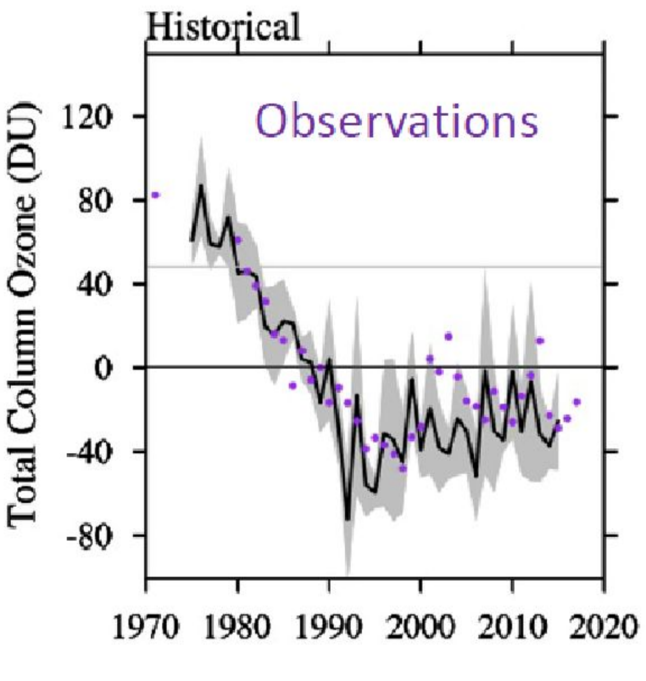

UNEP/WMO Ozone Assessment Executive Summary, Figure ES-7

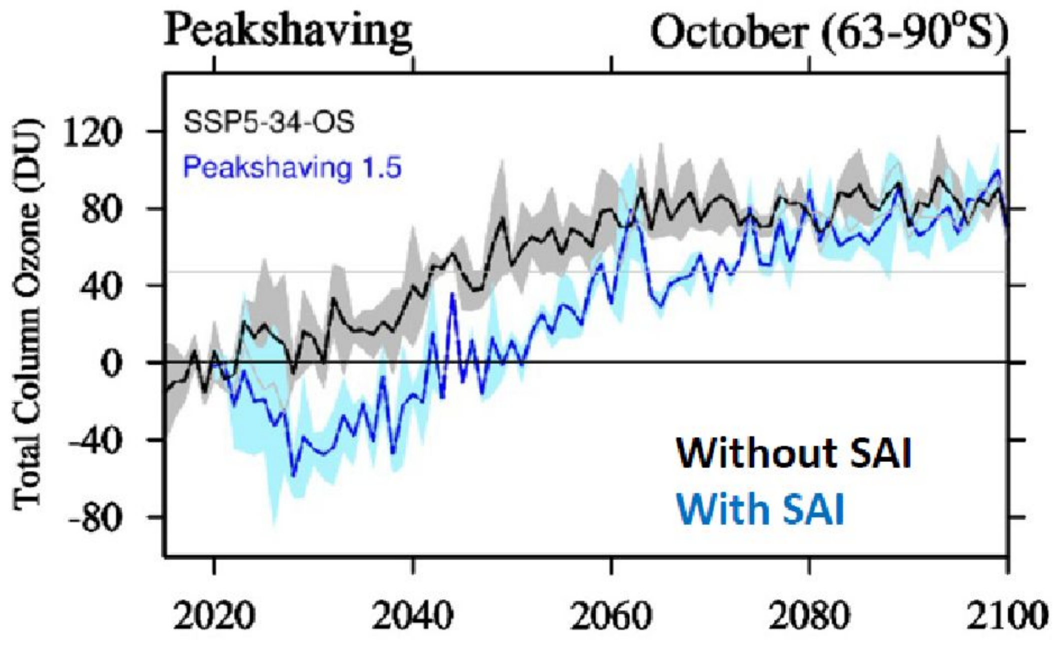
Amount needed: 8-16 Tg-$SO_2$/year for 1 ° surface cooling

# Stratospheric aerosol injection: influence on ozone



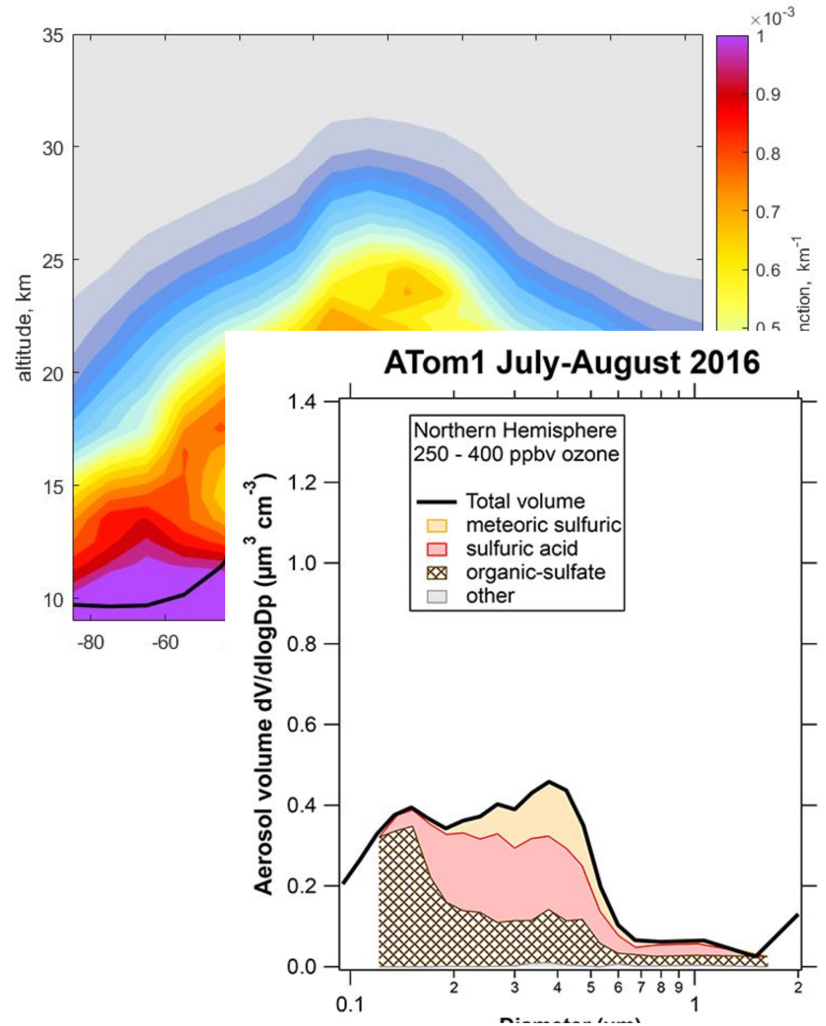
- SAI will destroy ozone
  - In the first years, total ozone column over Antarctica in October will achieve the minimum similar to values in 1990s
  - Ozone hole recovery from ozone-depleting substances will be delayed by 25-50 years

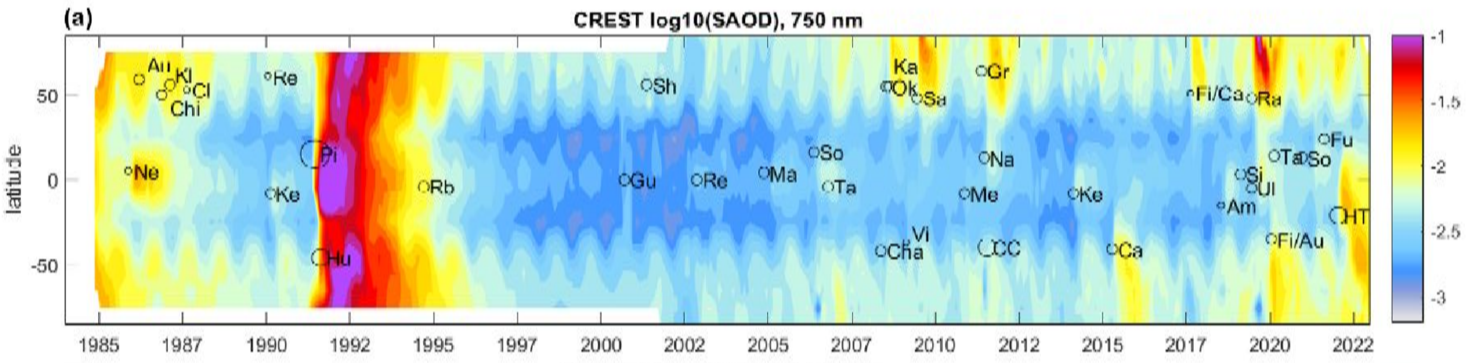


# Summary on stratospheric aerosols

- Stratospheric aerosols layer is at 15-25 km, umbrella-shaped
- Composition: sulfate aerosols, meteoric material, organic material
- Size distribution from <0.1 μm to >a few μm
- The aerosol layer has large variations due to volcanic eruptions and strong fires
- Stratospheric aerosols can be observed by in-situ, ground-based and satellite instruments
- Stratospheric aerosols:
  - Influence climate by reflecting sunlight
  - Affect ozone chemistry and cloud formation
  - Key to climate modeling and geoengineering research



# Thank you!

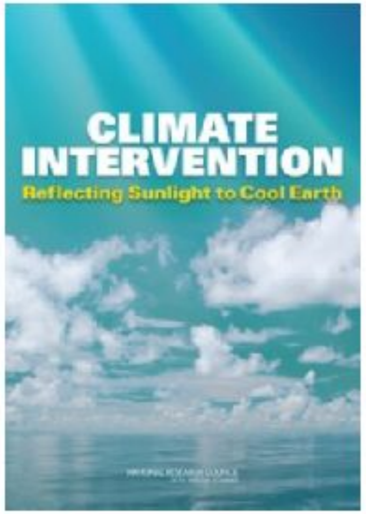
Questions are welcome.

- Back-up slides

# What is climate Intervention?

- Climate intervention (*aka, geoengineering, solar radiation modification (SRM)*) is cooling the Earth by human means to offset the warming and other impacts due to greenhouse gas accumulation.

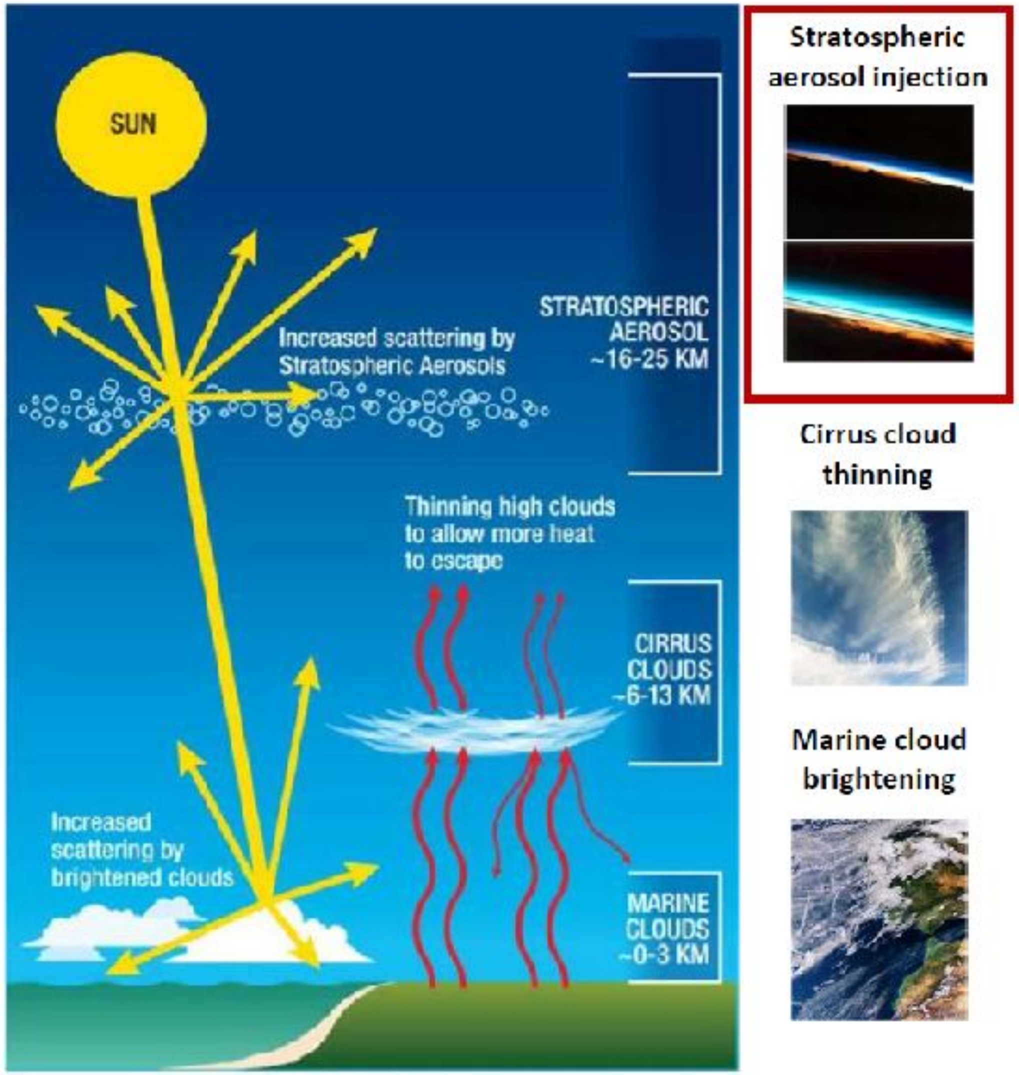
- "Should it ever become important for society to cool Earth rapidly, albedo modification approaches (in particular stratospheric aerosol injection (SAI) and possibly marine cloud brightening) are the only ways that have been suggested by which humans could potentially cool Earth within years after deployment."




US National Academies Press, 2015

- The principal climate intervention methods are stratospheric aerosol injection (SAI), marine cloud brightening (MCB) and cirrus cloud thinning (CCT)

- Stratospheric aerosol injection (SAI) injects aerosol or aerosol precursors into the stratosphere to reflect solar radiation that otherwise would add heat to the Earth system.




*US National Academies, 2021*