Observational Needs for Climate Intervention via Stratospheric Aerosol Injection

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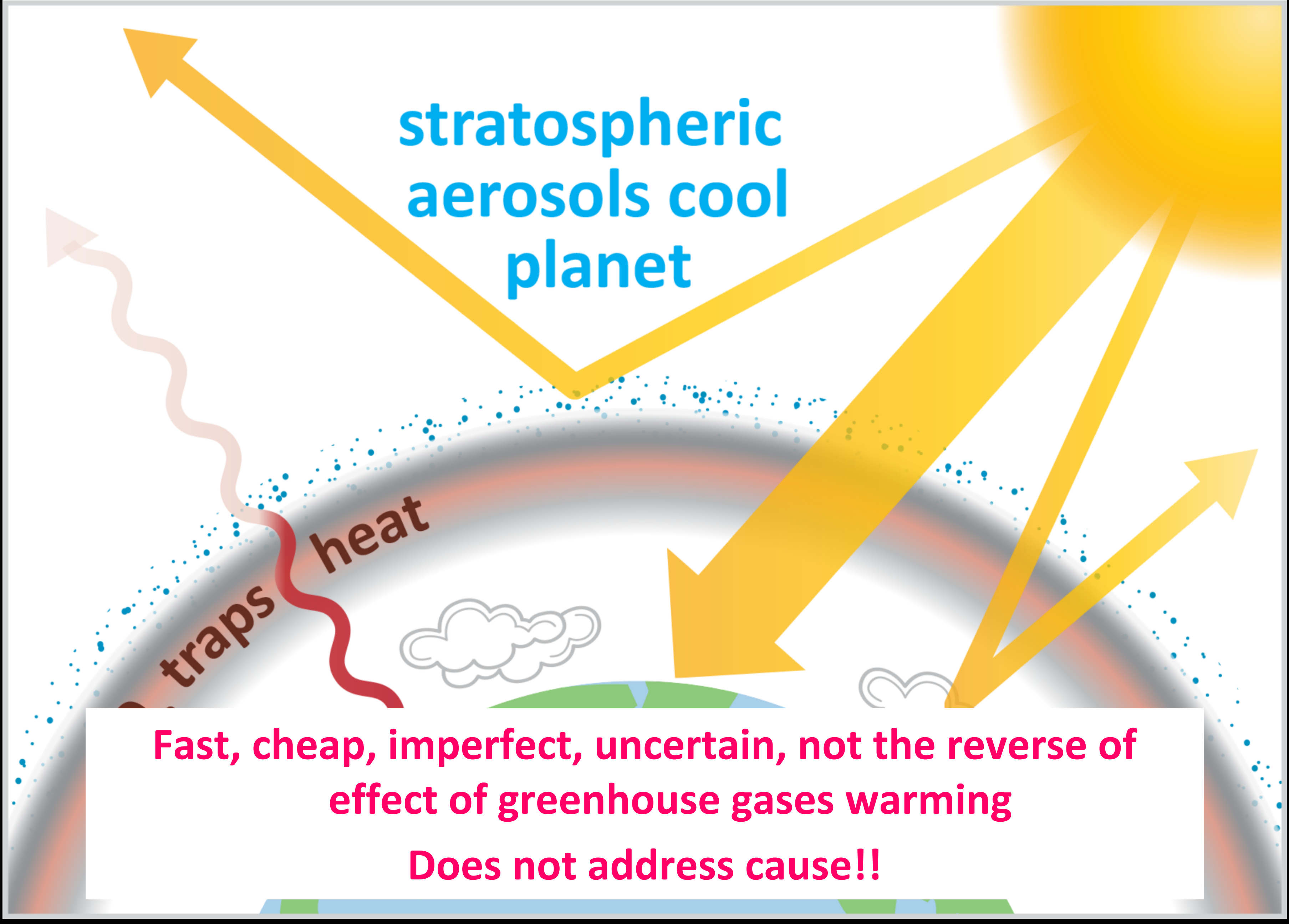
Harvard (Solar Geoengineering Program, Dean's Competitive Fund For Promising Scholarship), ETH Zurich, NASA Earth Venture Suborbital


stratospheric aerosols cool planet
traps heat
Fast, cheap, imperfect, uncertain, not the reverse of effect of greenhouse gases warming
Does not address cause!!

1. Observations

- Improve predictive capabilities for future stratospheric aerosol scenarios
  - Risk per outcome (e.g., radiative forcing, many other metrics in literature)
  - Physical impacts scale with particle type, amount, and size distribution
- HYPOTHETICALLY, Measure relevant quantities associated with SAI deployment

2. Specific Science Objectives

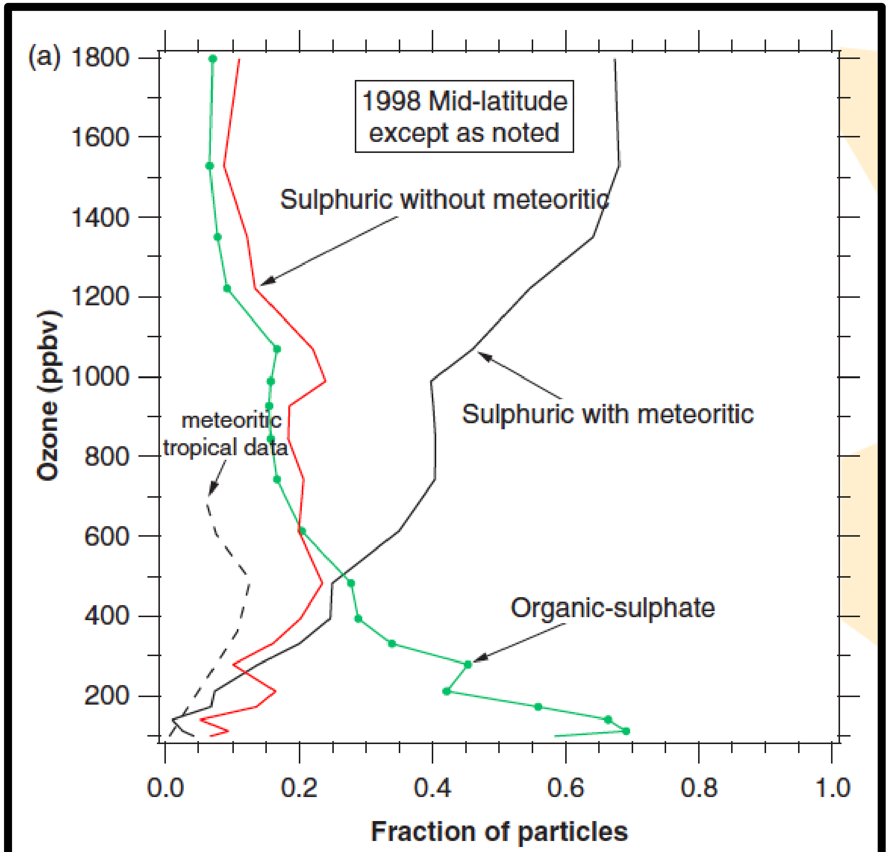
- Improve representations of stratospheric processes
  - Large-scale: transport
  - Small-scale: mixing
  - Aerosol-specific: microphysics, chemistry
  - Combination of above: diabatic (radiation, turbulent dissipation)

3. Desired Outcome: Implementation in Global Model

- Tested against observations at multiple scales (global, plume scale, sub-plume scale)
- Testbed for evaluating hypotheticals, including engineered aerosols

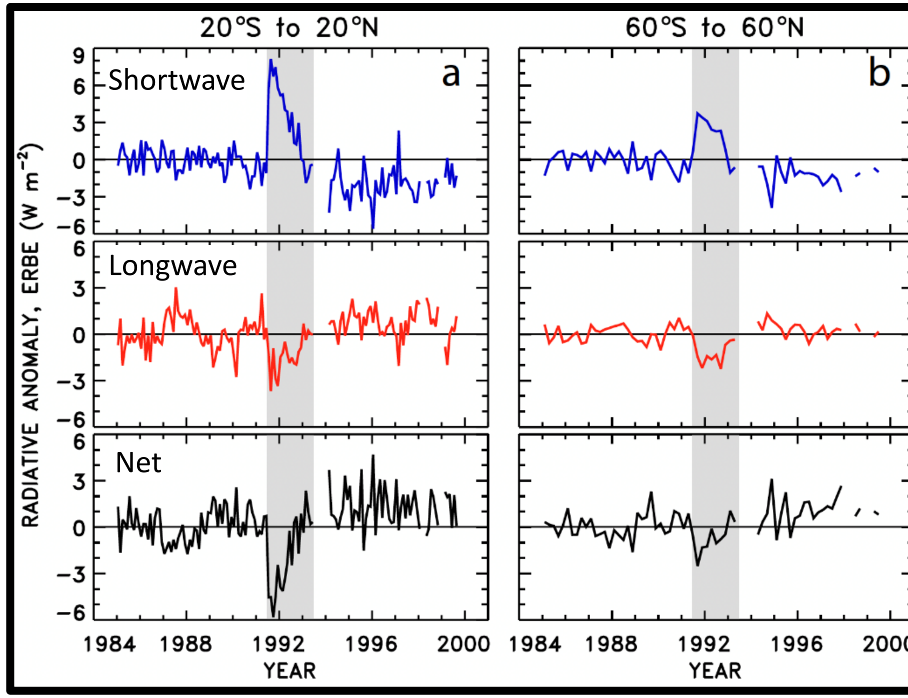
Observations and Baselining

Stratospheric Aerosol ?



Example of uncertainties in stratospheric aerosol

Observations of Radiative Forcing from Pinatubo



Sulfate longwave RF significantly reduces TOA cooling effect

⬇

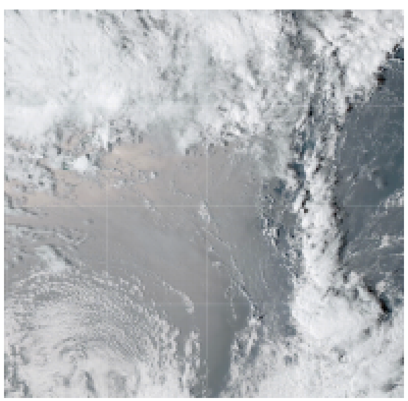
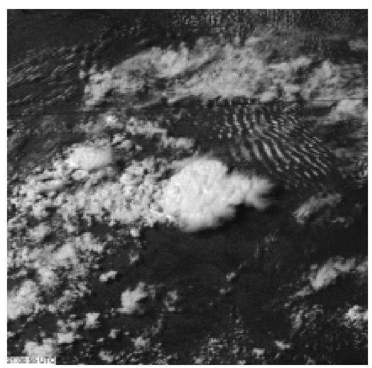
Alternate Materials

Murphy et al. QJRMS 2014; Canty et al. ACP 2013

Spatial and Mass Injection Scales of Observations Useful for SAI

LARGE — Small

Mixing/Plume Evolution ← Injection

Hunga Tonga	overshoots at 19 km Kansas	Space Shuttle	$CaCO_3$ Nozzle
			
Volcanoes	Pyrocumulus Convection	Rocket/Aircraft plumes	Aerosol Injection Nozzle

https://earthobservatory.nasa.gov/images/149347/hunga-tonga-hunga-haapai-erupts

https://apod.nasa.gov/apod/ap180624.html; courtesy Armand Neukerman

Flight Campaign for Stratospheric Aerosol

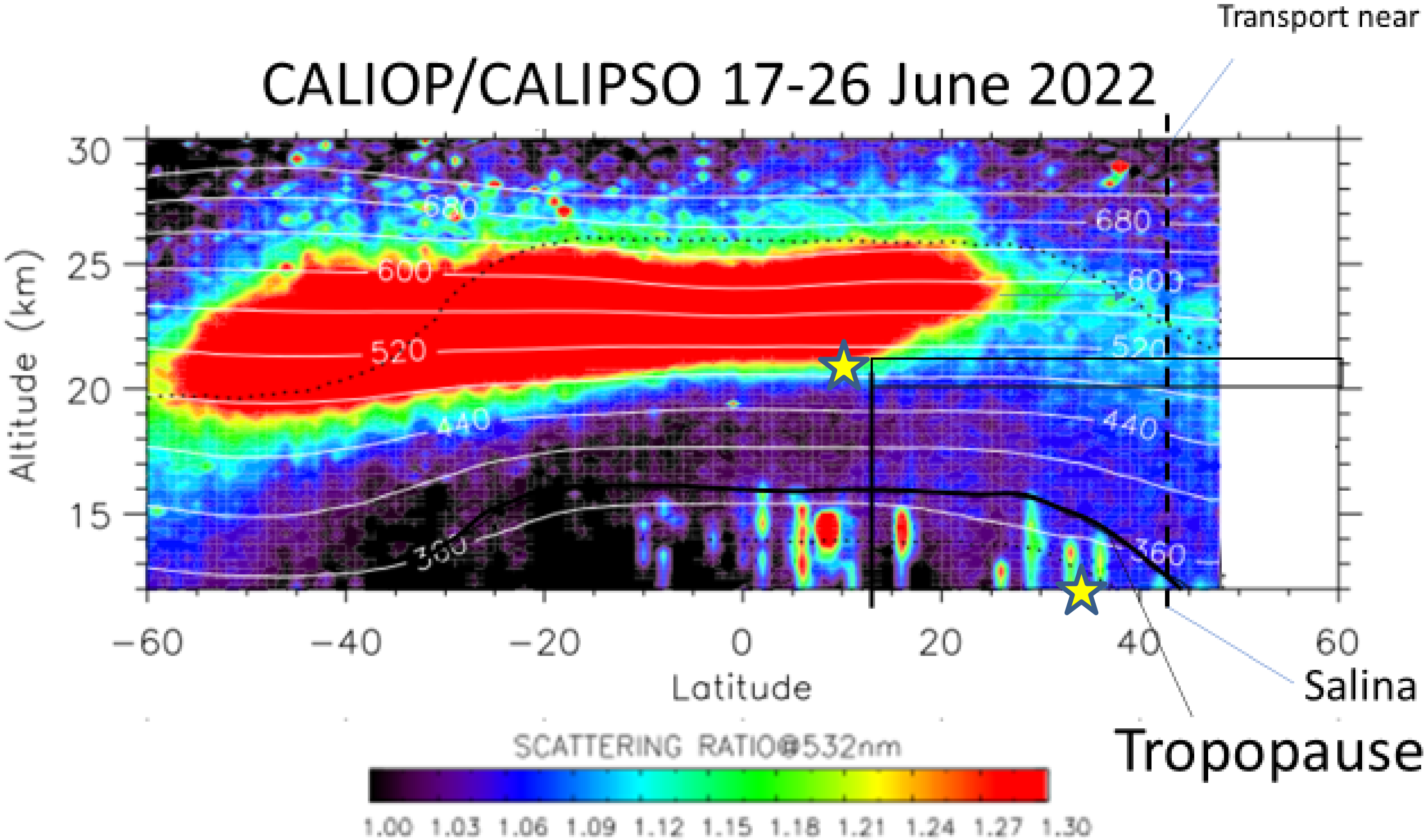
Stratospheric Aerosol processes, Budget and Radiative Effects

A NOAA Earth's Radiation Budget Initiative Project

- Characterize aerosol size distribution, composition, and optical properties
  - Determine sources and chemical, dynamical, and microphysical processes that control these observed size distributions
- Constrain sulfur budget of background stratosphere
- Determine occurrence of new particle formation
- Quantify role of organic species
- Characterize evolution of aerosol properties following injection by volcanic eruptions, pyroCb, rocket launches, etc.
- Quantify aerosol impacts of ozone and dynamics
- Quantify radiative forcing from anthropogenic perturbations to the stratosphere

Paraphrased from SABRE website
https://csl.noaa.gov/projects/sabre/science/goals.html

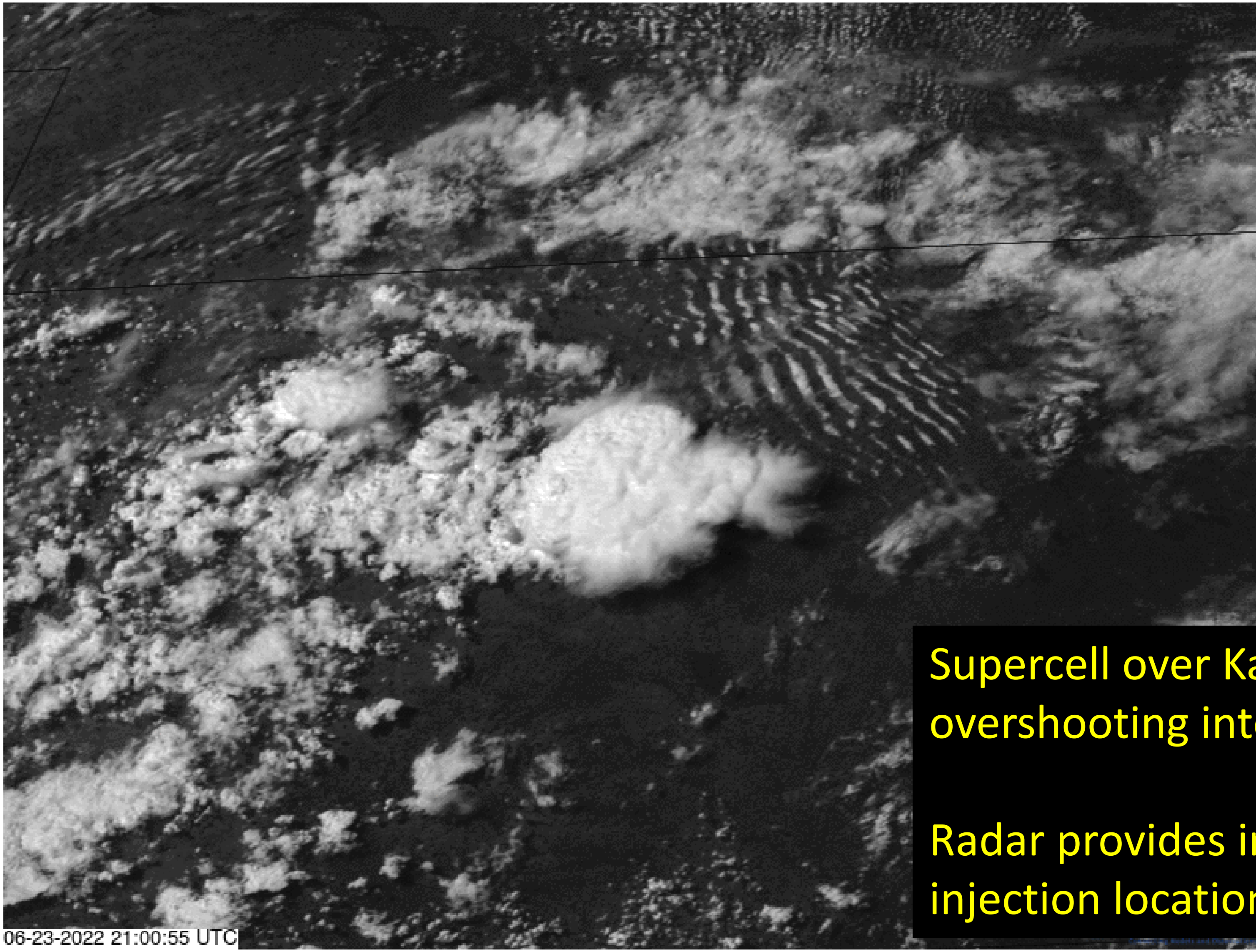
Volcanic Eruptions: Hunga Tonga-Hunga Ha'apai



Very large scale. Range of Observations will allow test of unique stratospheric perturbation 140MT H_2O, lower limit 0.4MT SO_2

Courtesy Jean-Paul vernier, Xu et al. Atmosphere 2022

Plumes from Convective Overshooting in Stratosphere



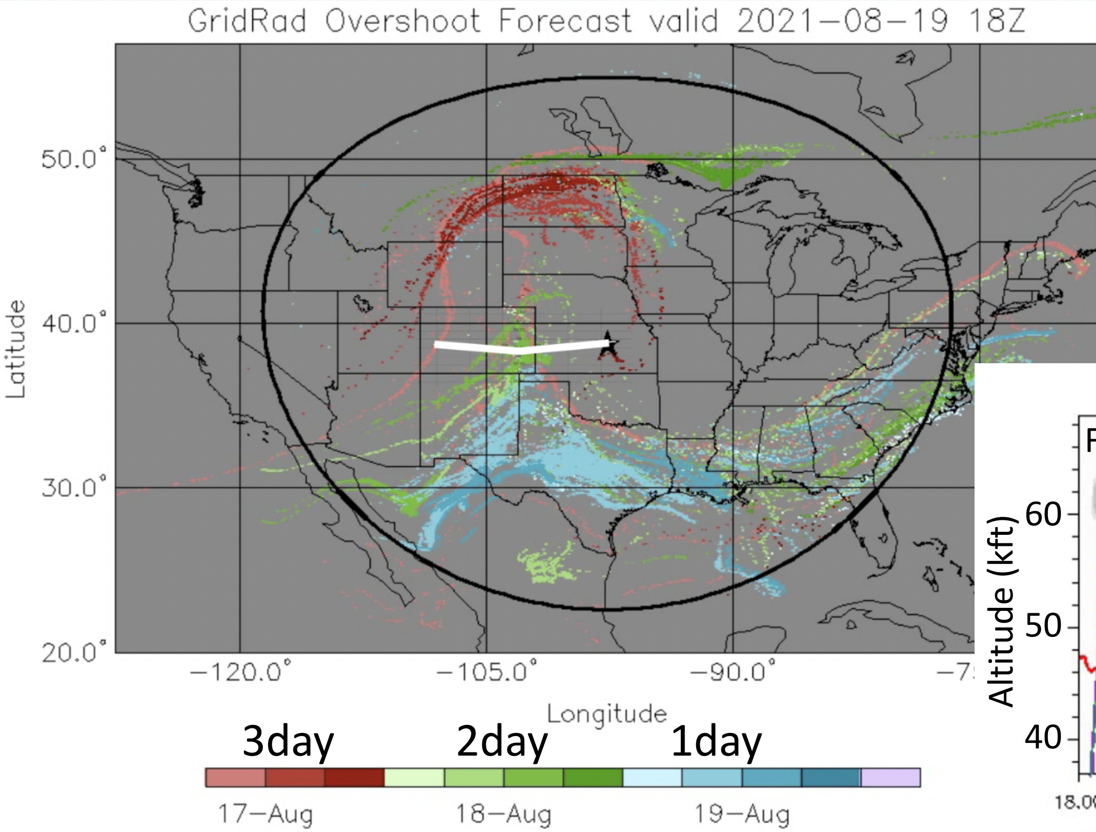
Supercell over Kansas overshooting into stratosphere

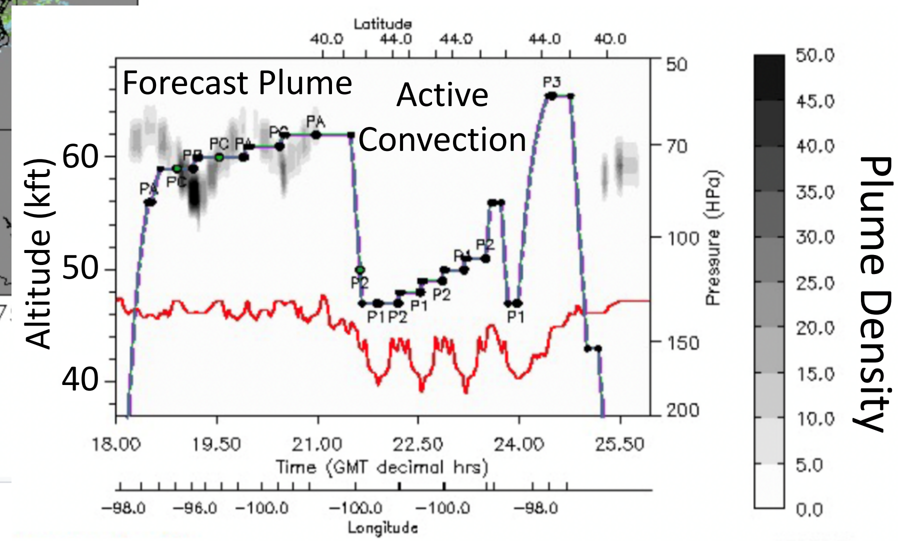
Radar provides information on injection location

https://rammb.cira.colostate.edu/ramsdis/online/images/loop_of_the_day/goes-16/20220624000000/video/20220623000000_kssupercell.GIF

Trajectory Forecasts of Overshoots Observed via Radar Reflectivity

Trajectory Forecast

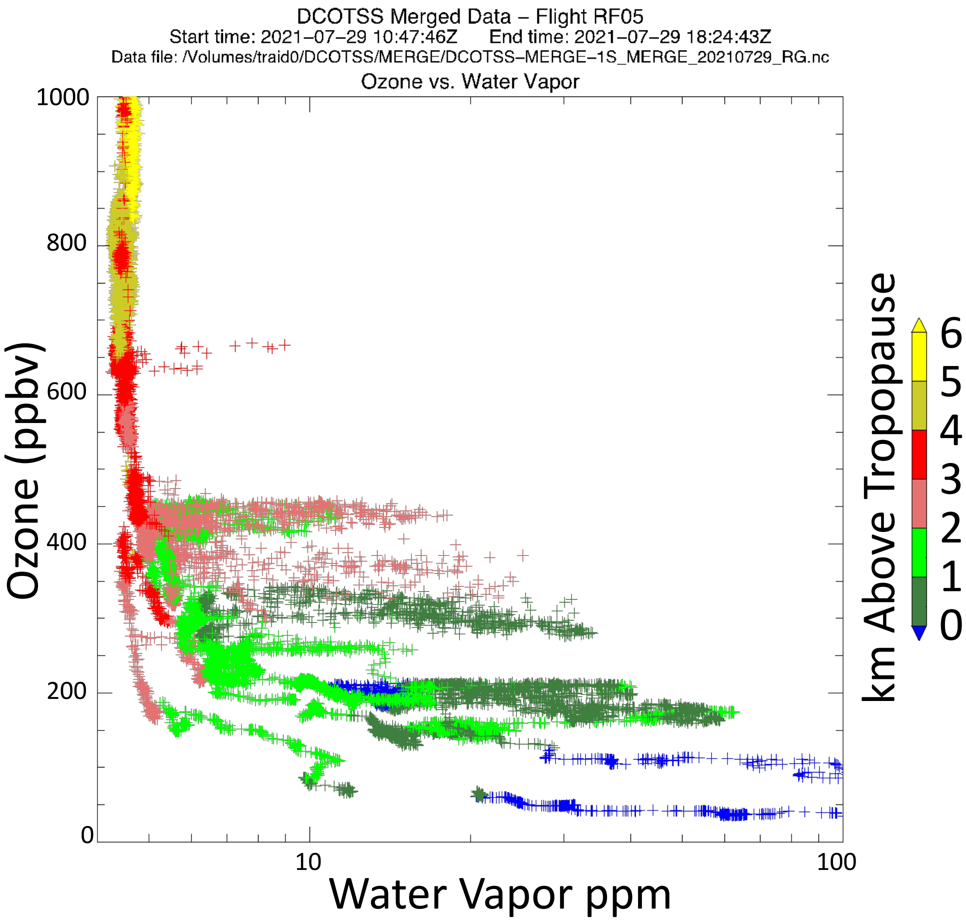




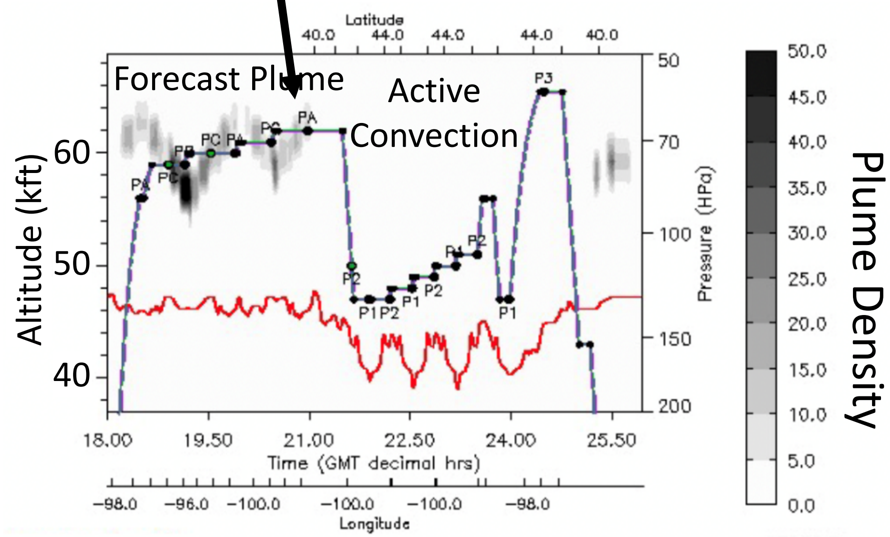
https://rammb.cira.colostate.edu/ramsdis/online/images/loop_of_the_day/goes-16/20220624000000/video/20220623000000_kssupercell.GIF; Cameron Homeyer

Trajectory Forecasts of Overshoots Observed via Radar Reflectivity

Water observations from overshooting convection



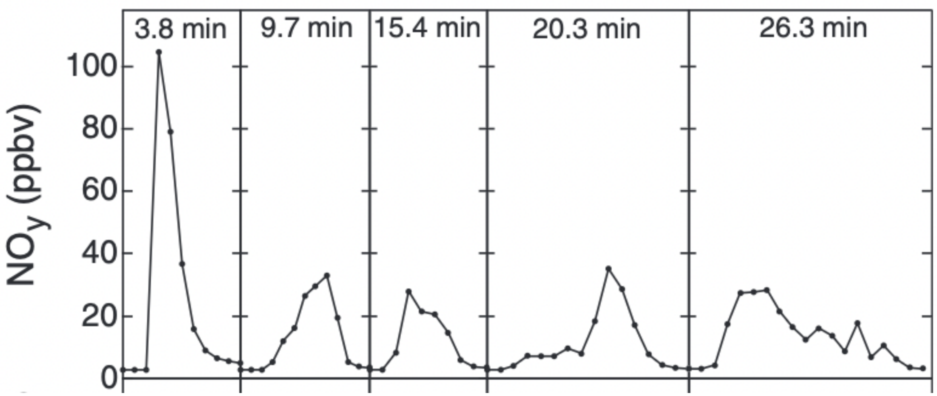
Water at 19km 1350ppb ozone



Rocket Plumes to Study Plume Evolution

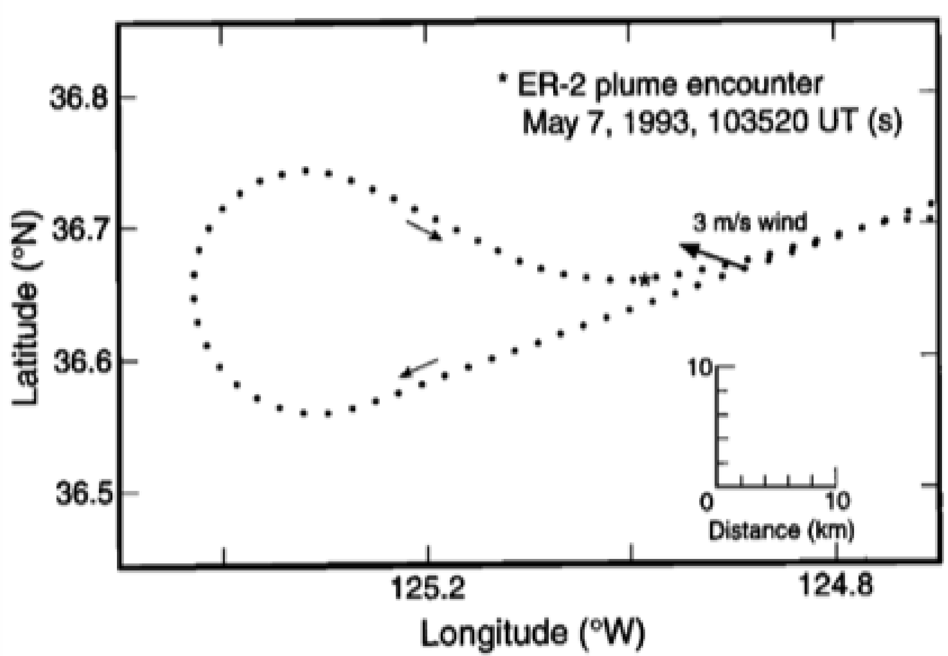
The emission and chemistry of reactive nitrogen species in the plume of an Athena II solid-fuel rocket motor

P. J. Popp,[1,2] B. A. Ridley,[3] J. A. Neuman,[1,2] L. M. Avallone,[4] D. W. Toohey,[5] P. F. Zittel,[6] O. Schmid,[7] R. L. Herman,[8] R. S. Gao,[1] M. J. Northway,[1,2] J. C. Holecek,[1,2] D. W. Fahey,[1,2] T. L. Thompson,[1] K. K. Kelly,[1] J. G. Walega,[3] F. E. Grahek,[3] J. C. Wilson,[7] M. N. Ross,[6] and M. Y. Danilin[9]



Highly energetic, complex (initial) dynamics and chemistry with many chemicals emitted

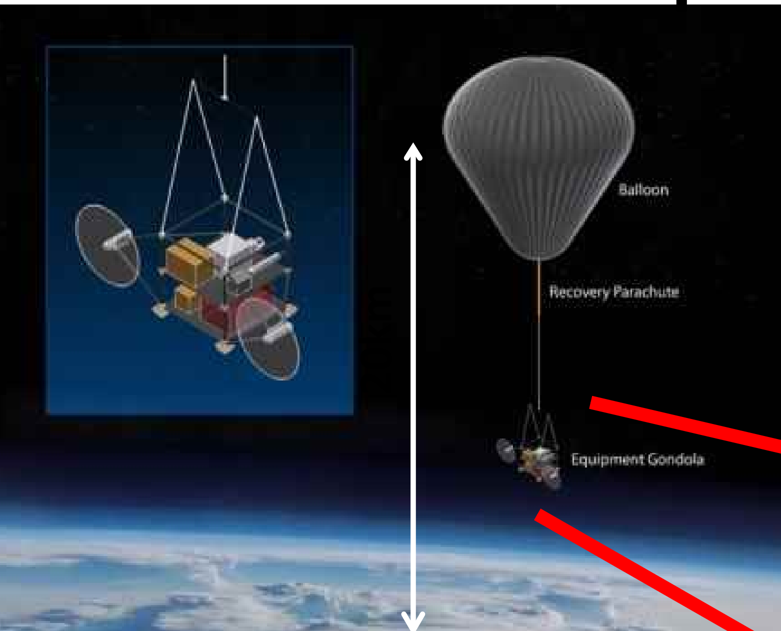
Stratospheric Airplane Wake Crossing



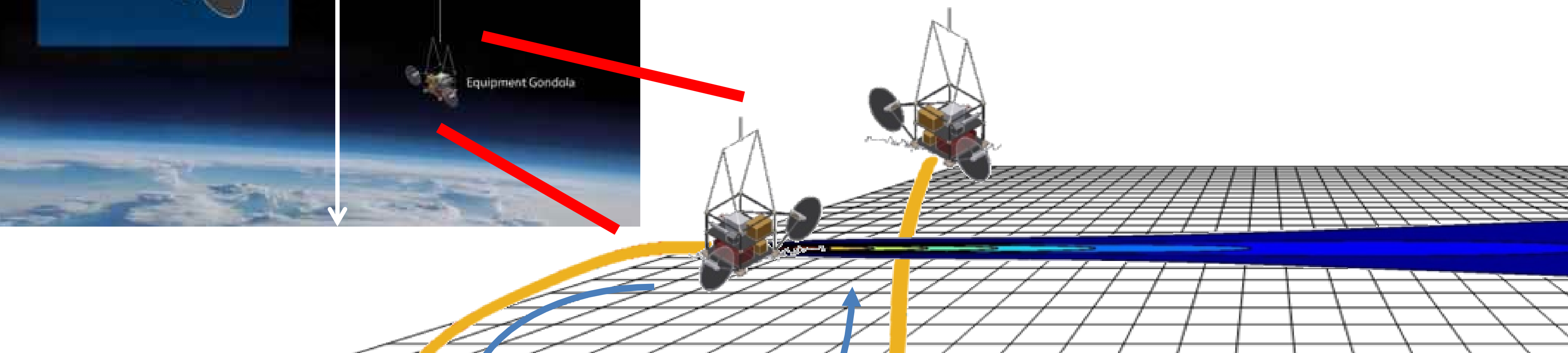
- Fahey: measurements of condensation nuclei (CN) in exhaust plume.
- Fahey: developed aerosol coagulation model to predict particle formation; challenging.
- Yu: Important to first understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.
- Anderson: plume morphology highly variable 5 km post emission; rare study of nearfield chemistry.
- Ion-induced nucleation important from engines.
- Short residence time in plumes.

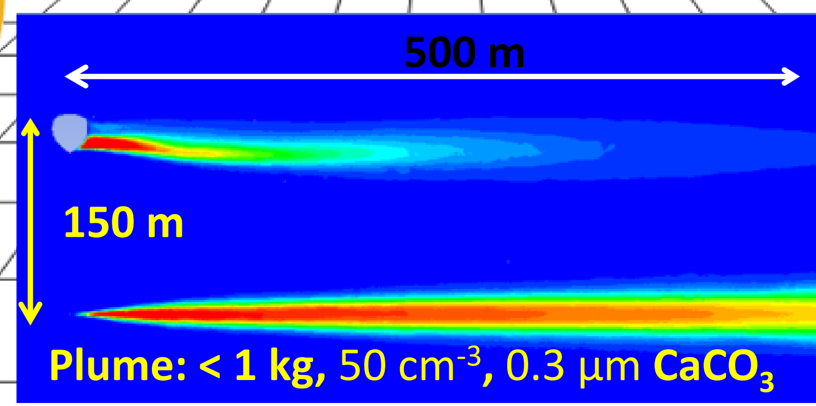
Fahey et al. (1995a, b); Yu et al. (1997); Anderson et al.

Small Scale Stratospheric Controlled Perturbation Experiment (SCoPEx)



- Propeller wake forms well mixed volume in near field (<10km). Particles as tracer of plume.
- Propellers allow gondola to fly back and forth through 'reactor' to map out perturbed air mass compared with background stratosphere.





Outcome:
improved knowledge of initial plume evolution
Small scale turbulence

Same particle mass as 1 minute 747 flight

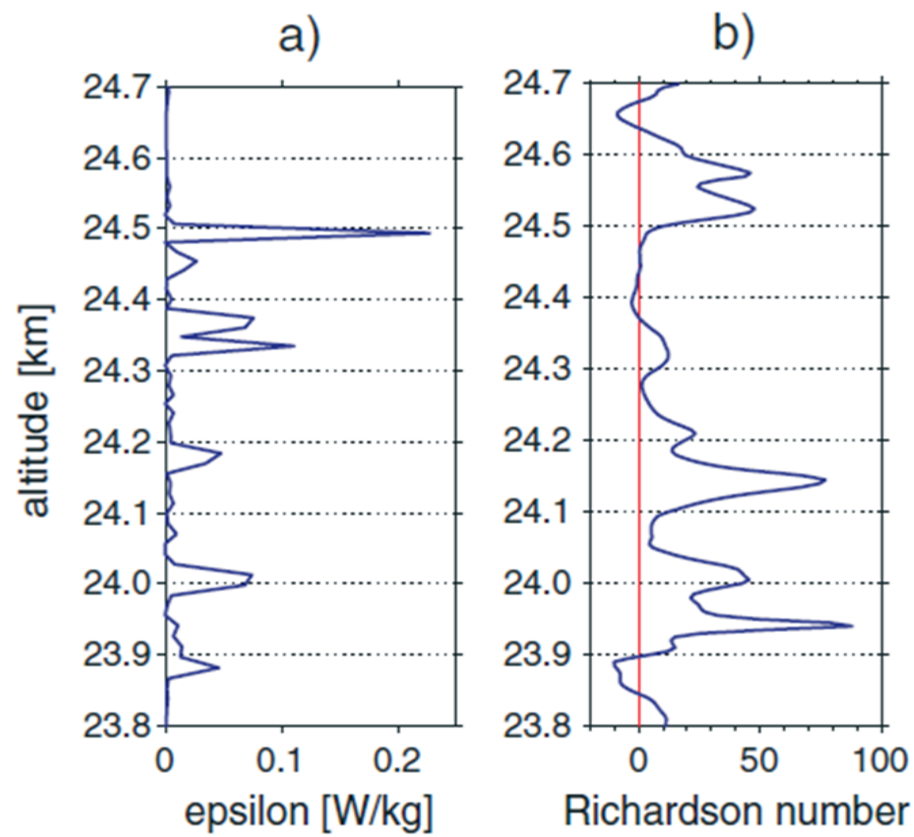
SRM Needs: Background Stratospheric Dynamics Improving the representation of stratospheric aerosols in models

Atmos. Chem. Phys., 17, 7941–7954, 2017
https://doi.org/10.5194/acp-17-7941-2017

Case study of wave breaking with high-resolution turbulence measurements with LITOS and WRF simulations

Andreas Schneider[1,a], Johannes Wagner[2], Jens Söder[1], Michael Gerding[1], and Franz-Josef Lübken[1]

LITOS balloon-borne high speed anemometer measurements show current models of turbulence cannot explain observed stratospheric turbulence



Risk vs Risk Model Comparison of SAI Materials other than Sulfate: Alumina (Al_2O_3), Calcite ($CaCO_3$)

SOCOL-AER (Sandro Vattioni, Rahel Weber, Gabriel Chiodo, Tom Peter) with updated aerosol chemistry.

Differences in: - stratospheric heating (and resulting impacts),
- diffuse radiation
- stratospheric ozone

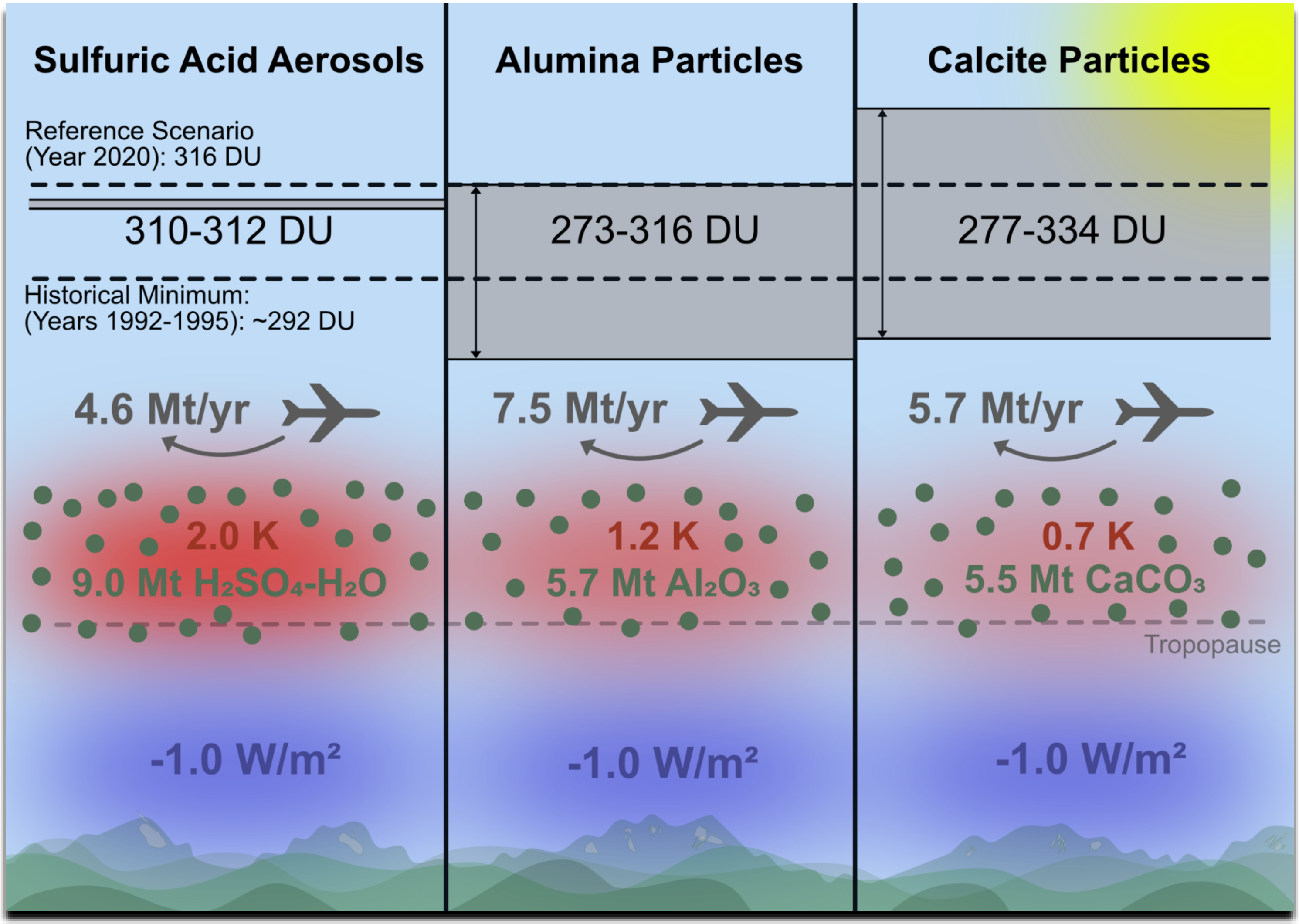
per unit of top of atmosphere (TOA) all sky radiative forcing.

Impacts can scale with injection rate, burden, material type, surface area, …

How big is uncertainty associated with the reduction of different unintended (side) effects of sulfur-based SAI from alternate materials?

Not naturally in stratosphere = no existing measurements!

Summary of Model Risk vs Risk Comparison



Thanks for your attention!