Examining the response of cirrus cloud microphysics to volcanic aerosol emissions in satellite observations and CESM2

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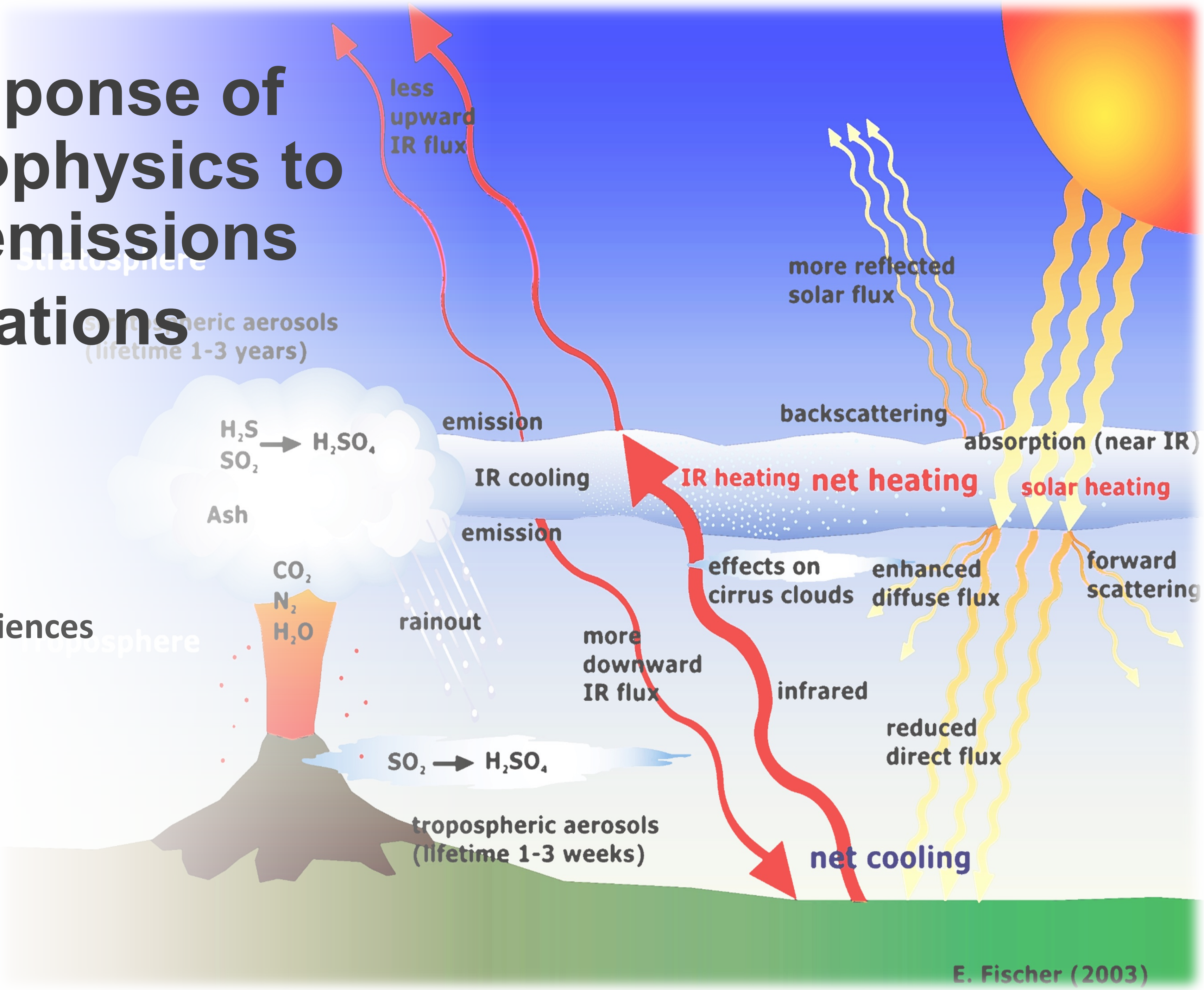


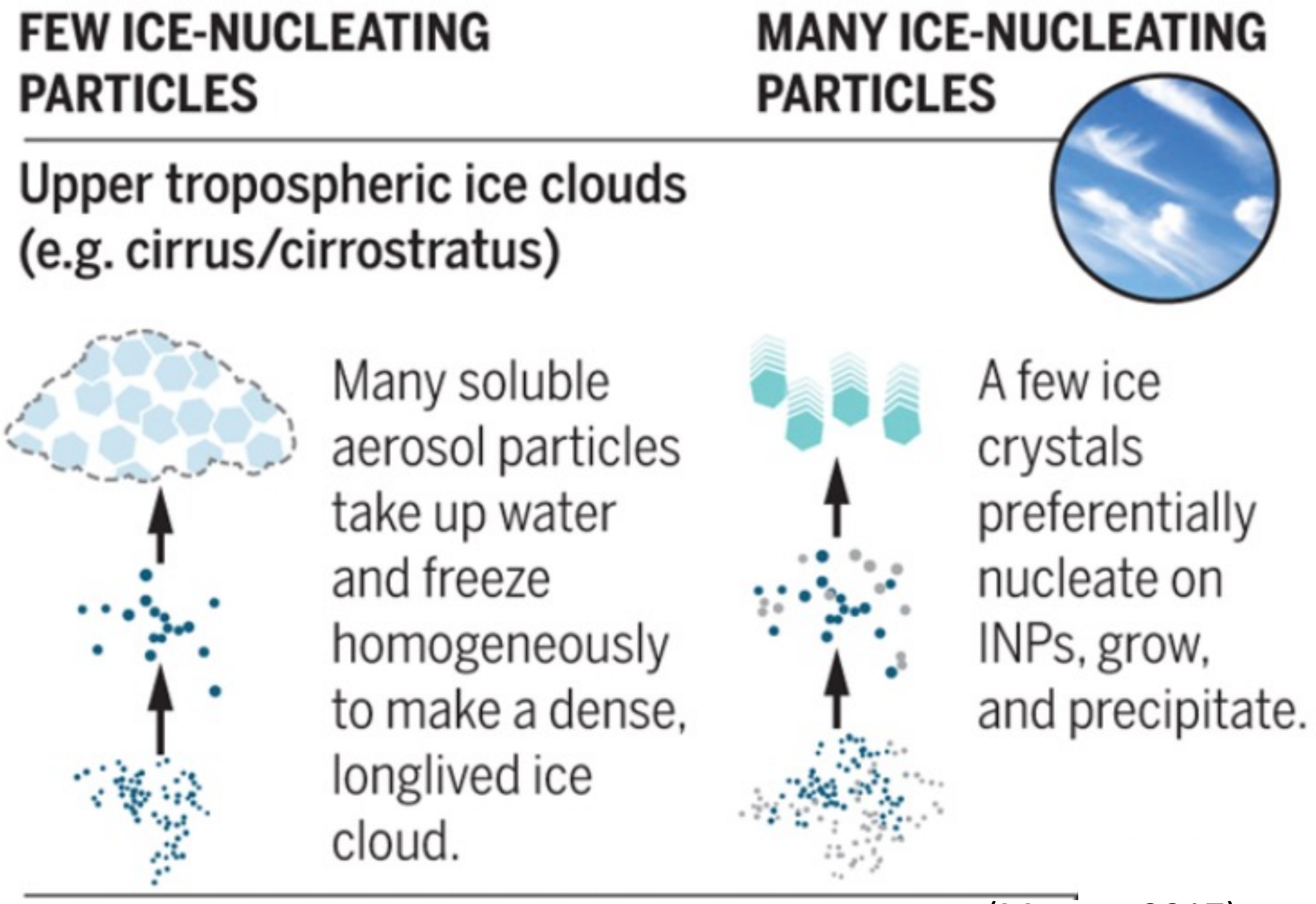
Objective

- **Investigate how volcanic aerosols change the microphysical properties of cirrus clouds using satellite observations.**

- **Evaluate climate model simulation of volcanic aerosol effects on cirrus clouds against observations.**

Overview of Cirrus Cloud Formation

Homogeneous | **Heterogeneous**



(Murray, 2017)

e.g., liquid **sulfate aerosol**

e.g., **volcanic ash particles** (e.g., Steinke et al., 2011; Schill et al. 2015)

Overview of Cirrus Cloud Formation

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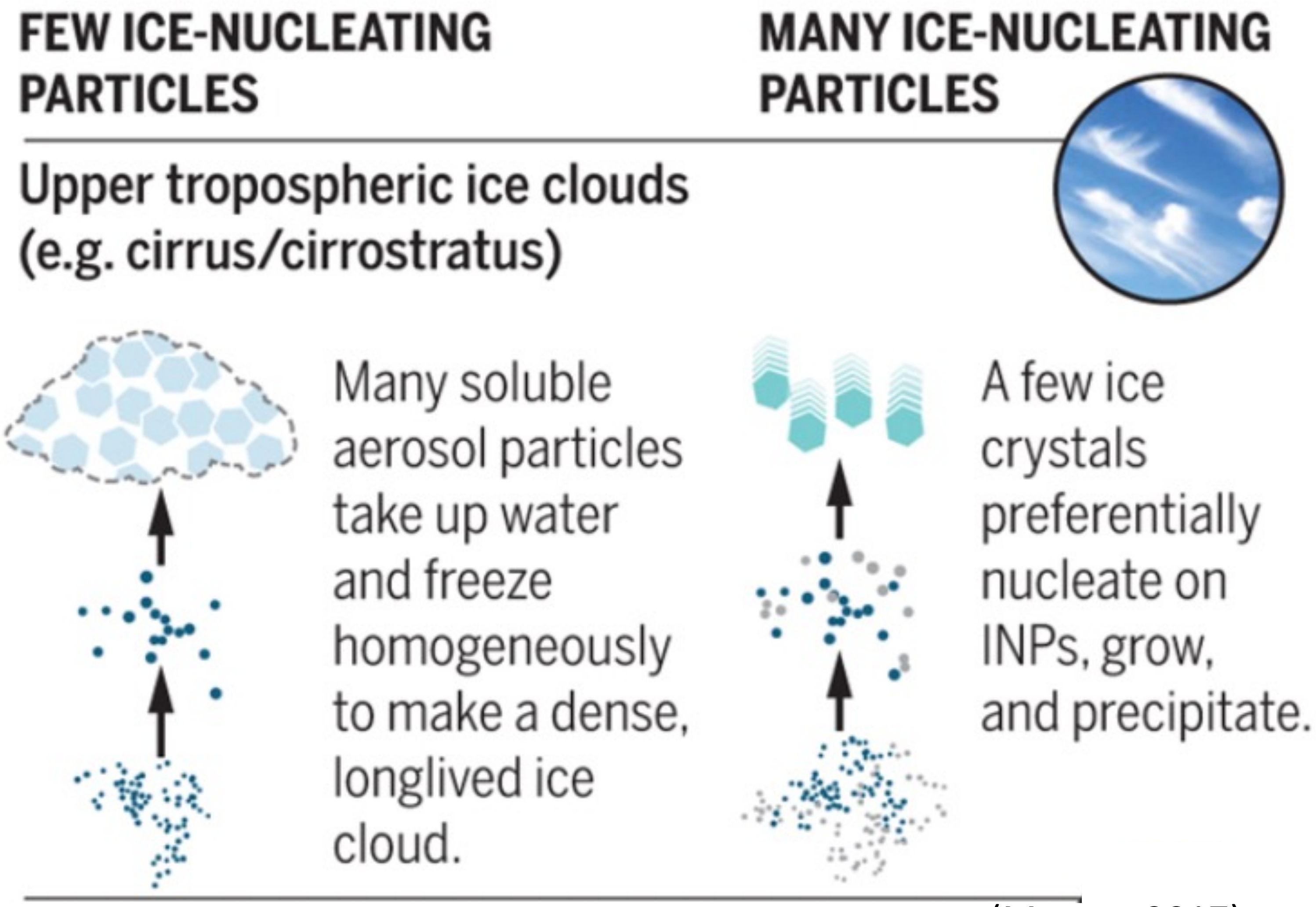

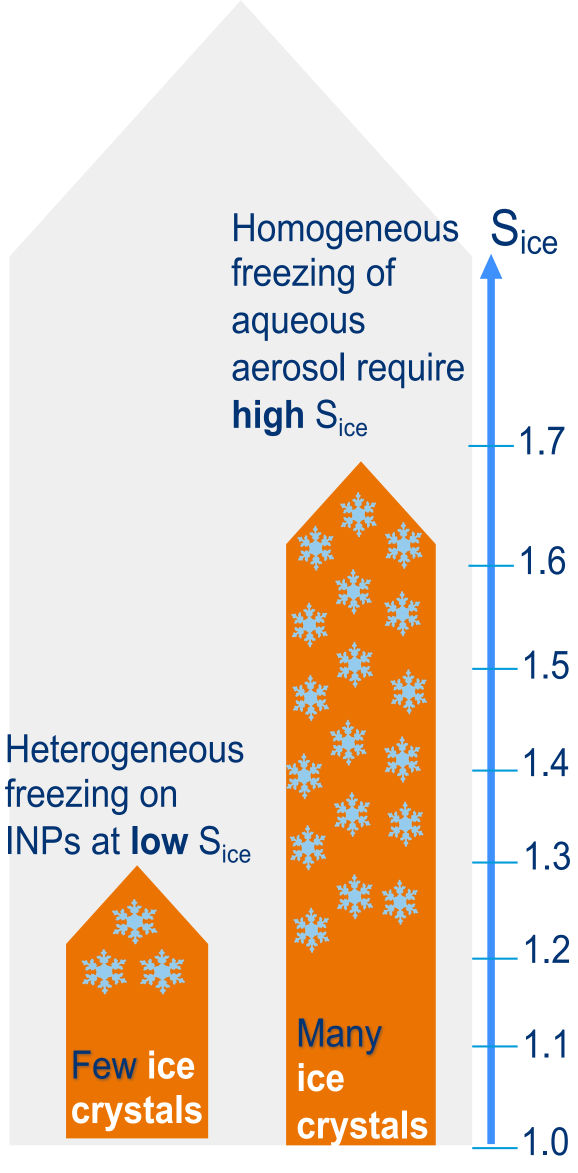

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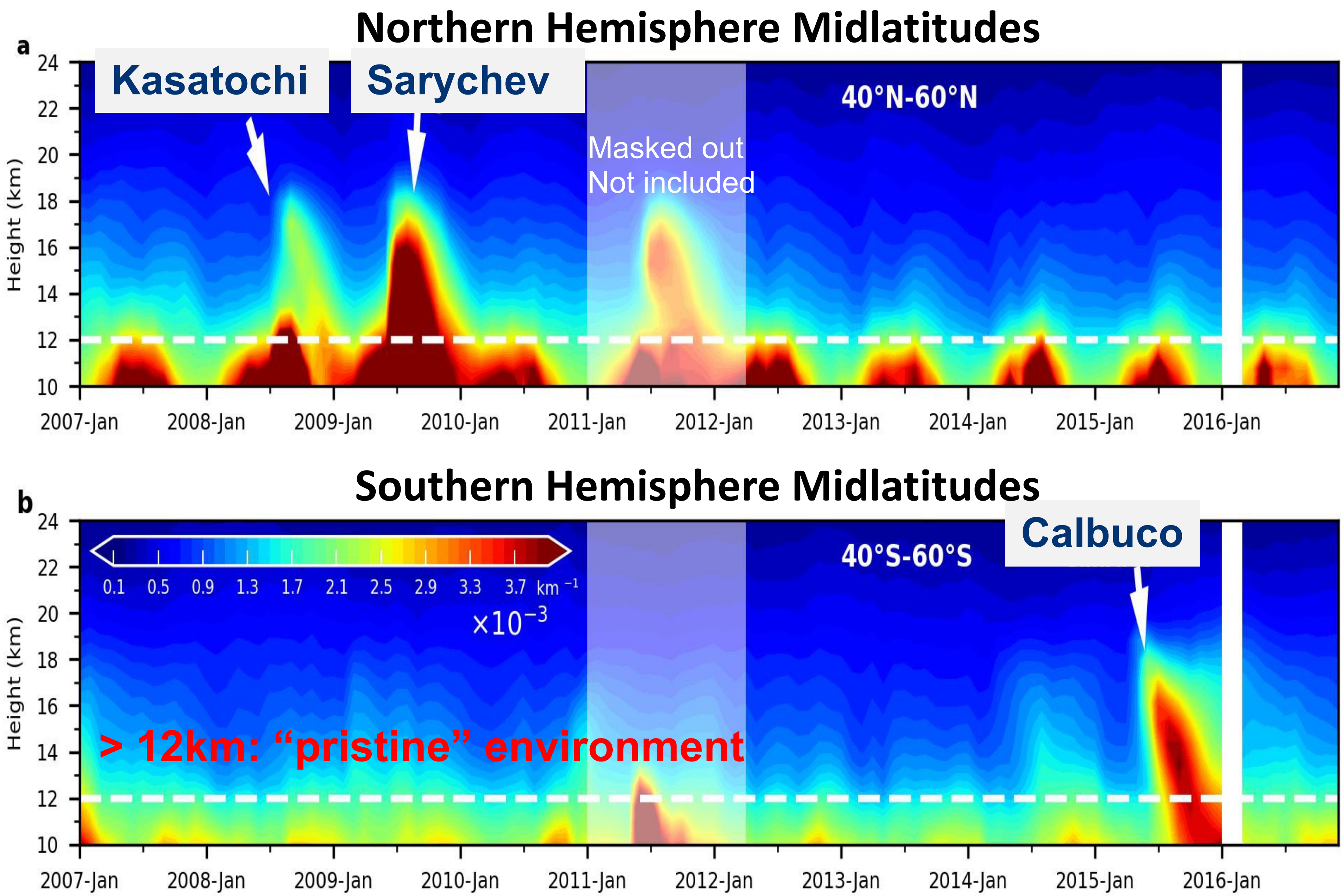
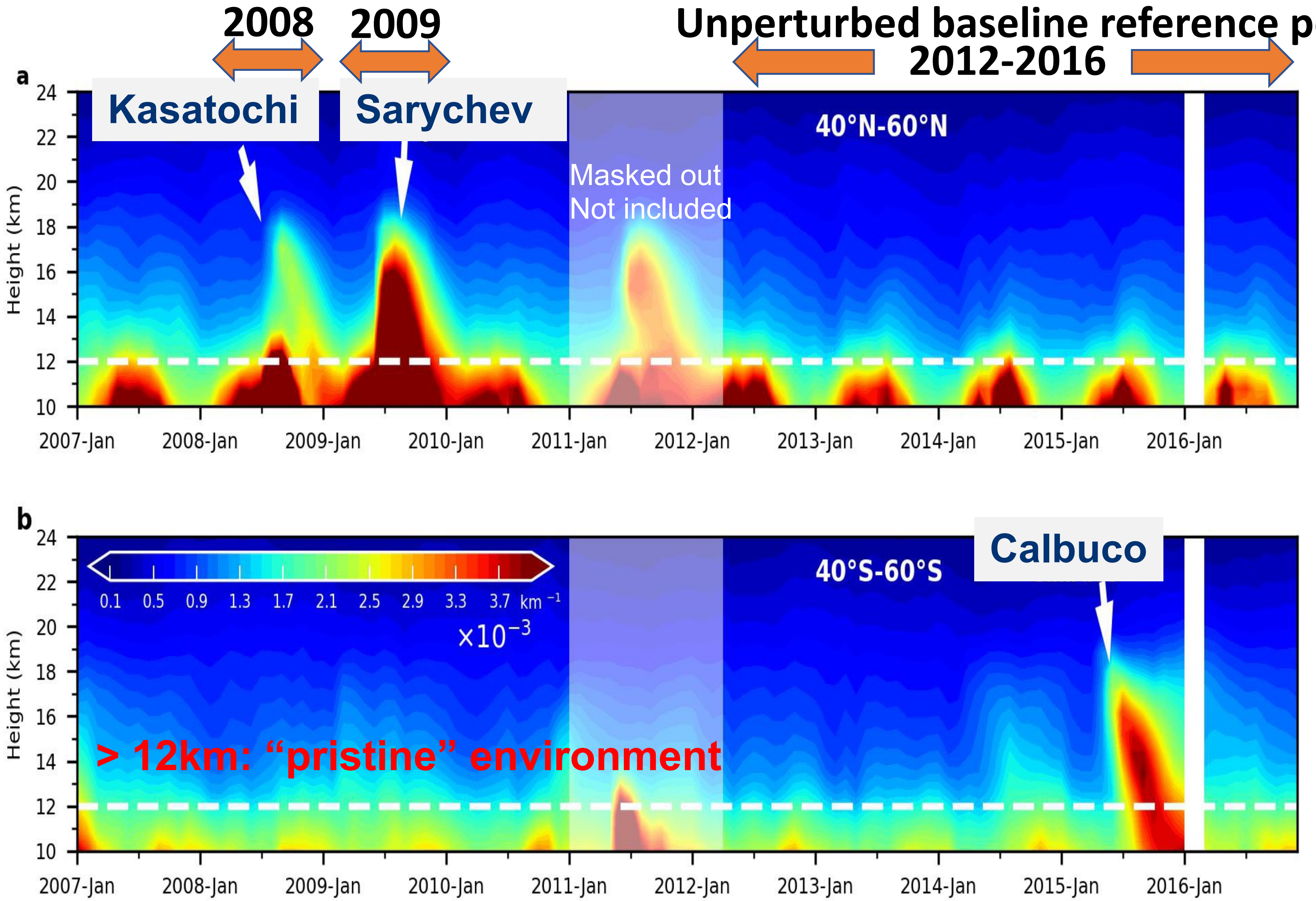
Aerosol Extinction during Volcanic & Unperturbed Periods



Using CALIPSO L3 stratospheric aerosol profile product

Aerosol Extinction during Volcanic & Unperturbed Periods



Study area:

2008/Aug Kasatochi: 50-60N, 180W-180E

2009/Jun Sarychev: 40-60N, 180W-180E

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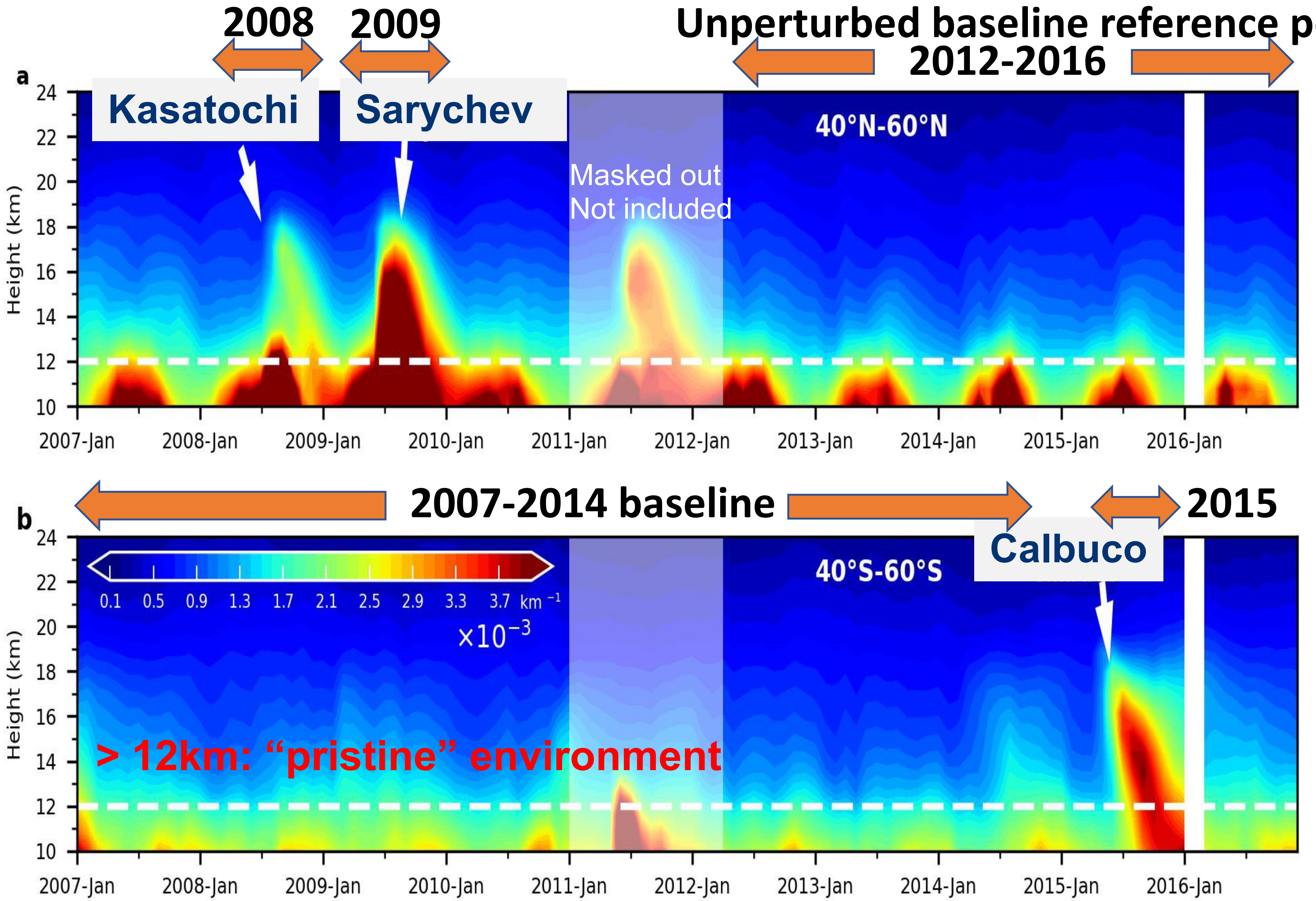


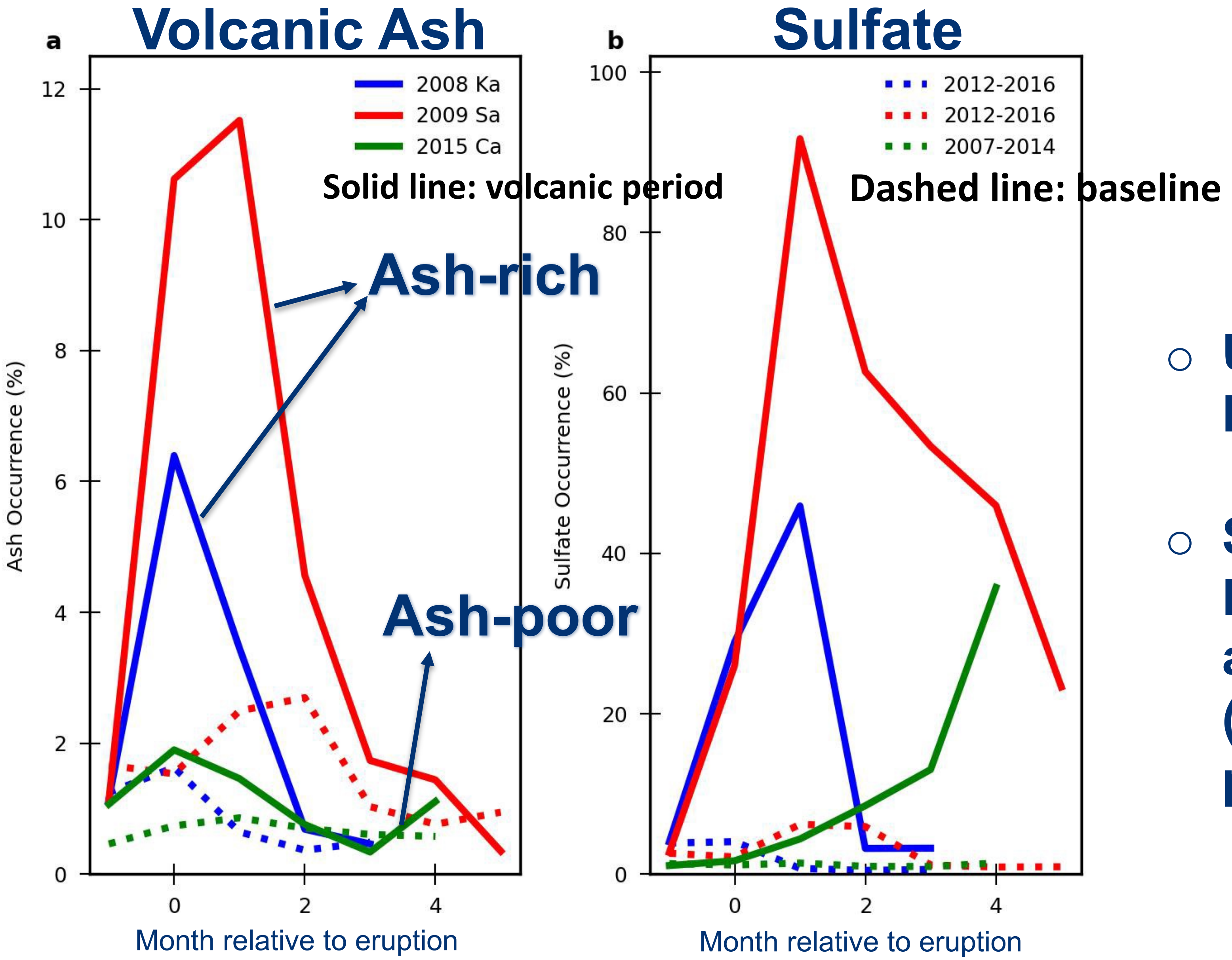
Study area:

2008/Aug Kasatochi:
50-60N, 180W-180E

2009/Jun Sarychev:
40-60N, 180W-180E

2015/Apr Calbuco:
40-60S, 180W-180E

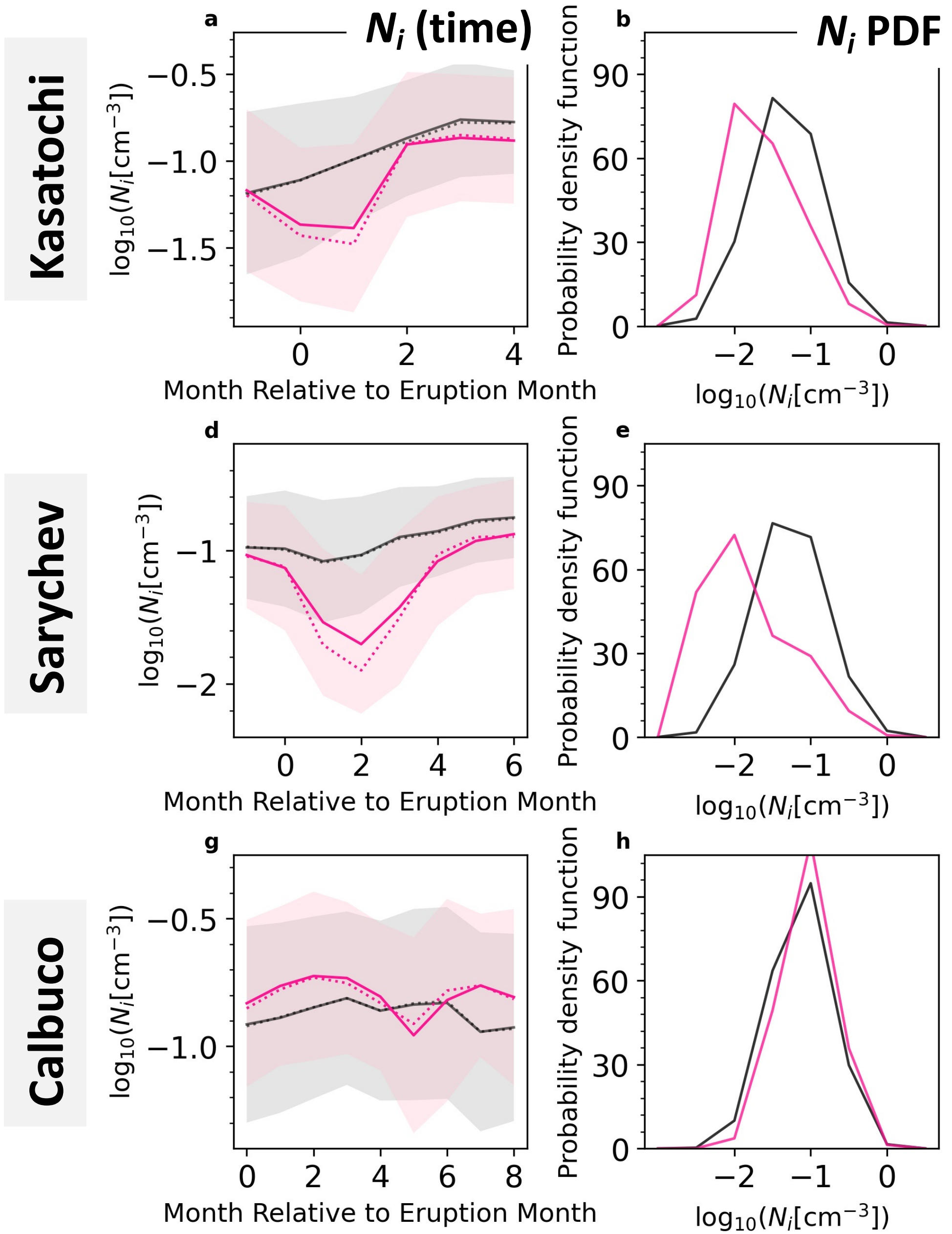
Stratospheric Aerosol Subtyping Occurrence



- 2008 Kasatochi v.s baseline
- 2009 Sarychev v.s baseline
- 2015 Calbuco v.s baseline

- Using CALIPSO L2 Vertical Feature Mask
- Showing Occurrence Frequency of Volcanic Ash and Sulfate during volcanic (solid line) v.s. unperturbed periods (dashed line)

Observed Changes in Ice Microphysics



Unperturbed period
Volcanic period

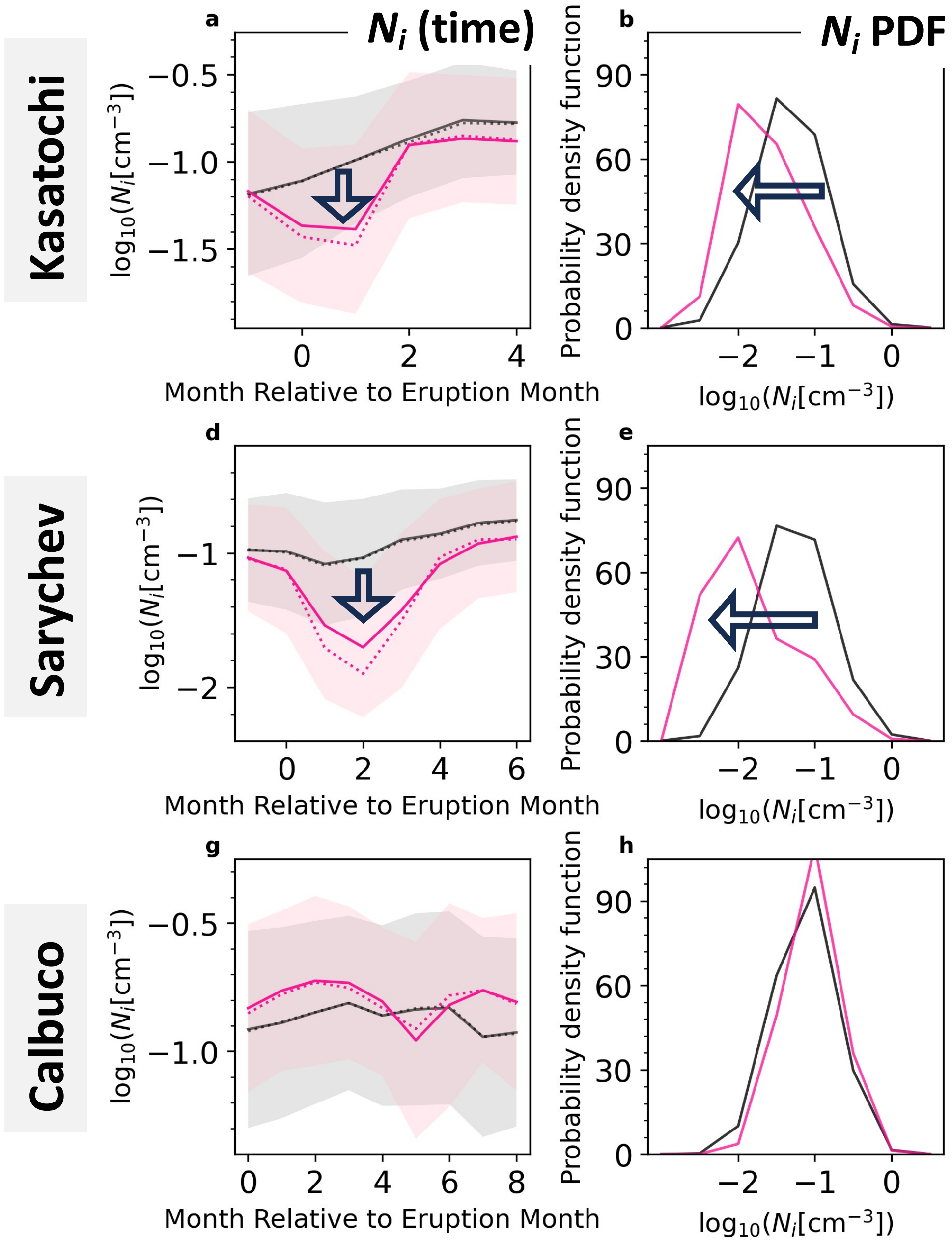
Shading area: 1 std dev

Solid: mean

Dash: 50th percentile

Using DARDAR-Nice retrievals

Observed Changes in Ice Microphysics



Unperturbed period
Volcanic period

Shading area: 1 std dev

Ash-rich scenario

- N_i decreases by 60-80% (60-80 L^{-1});
- r_{eff} increases from 17um to 20um (~12% increase);
- Indicative of heterogeneous freezing on ash suppressing homogeneous freezing;

"Negative Twomey effect"

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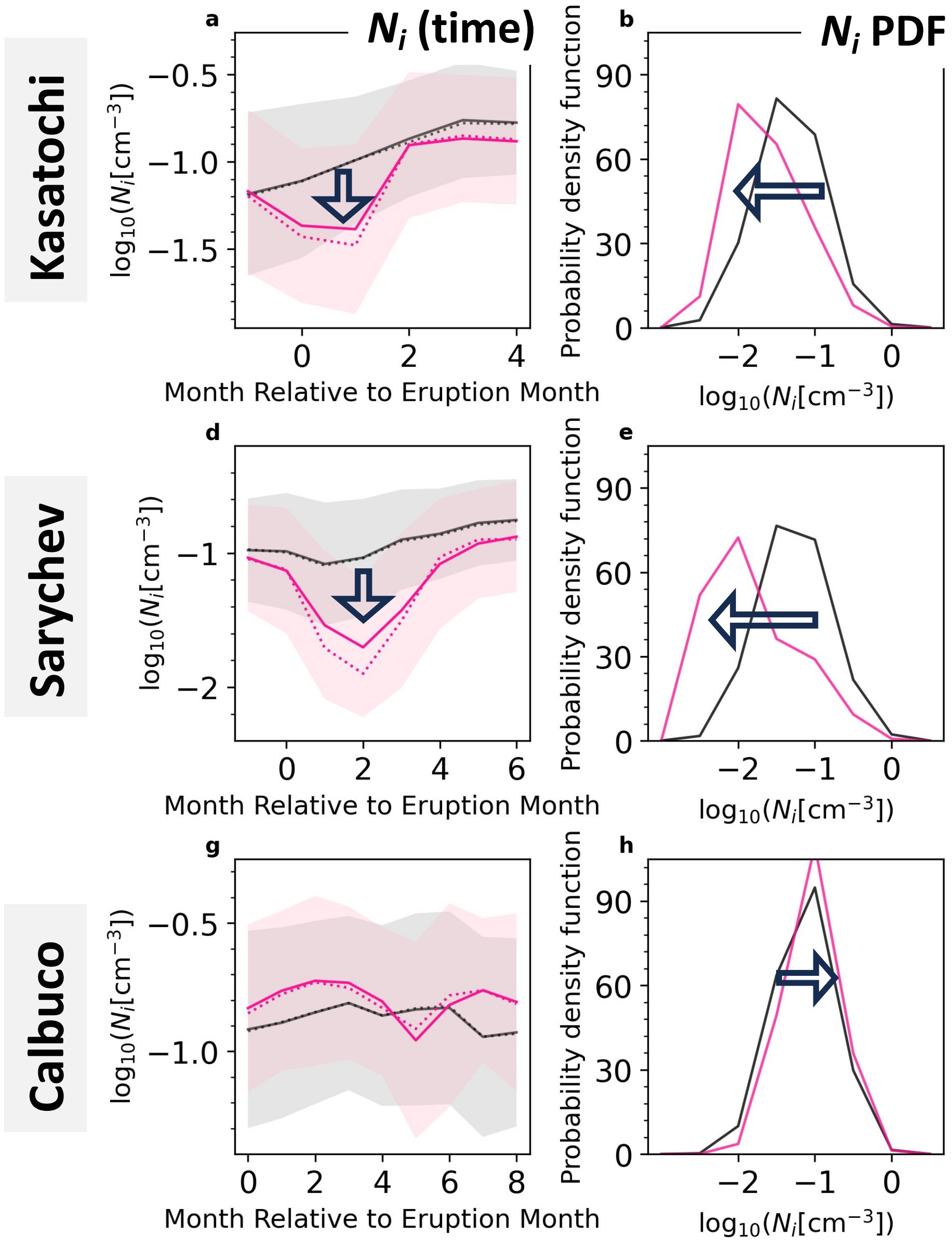

Unperturbed period
Volcanic period

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"Negative Twomey effect"

Ash-poor scenario

- N_i increases slightly by about 26% (~30L^{-1}) (within 1σ range);
- r_{eff} remains unchanged;
- Indicative of homogeneous freezing of enhanced sulfate produced by eruption;

Model configuration & Experiment setup

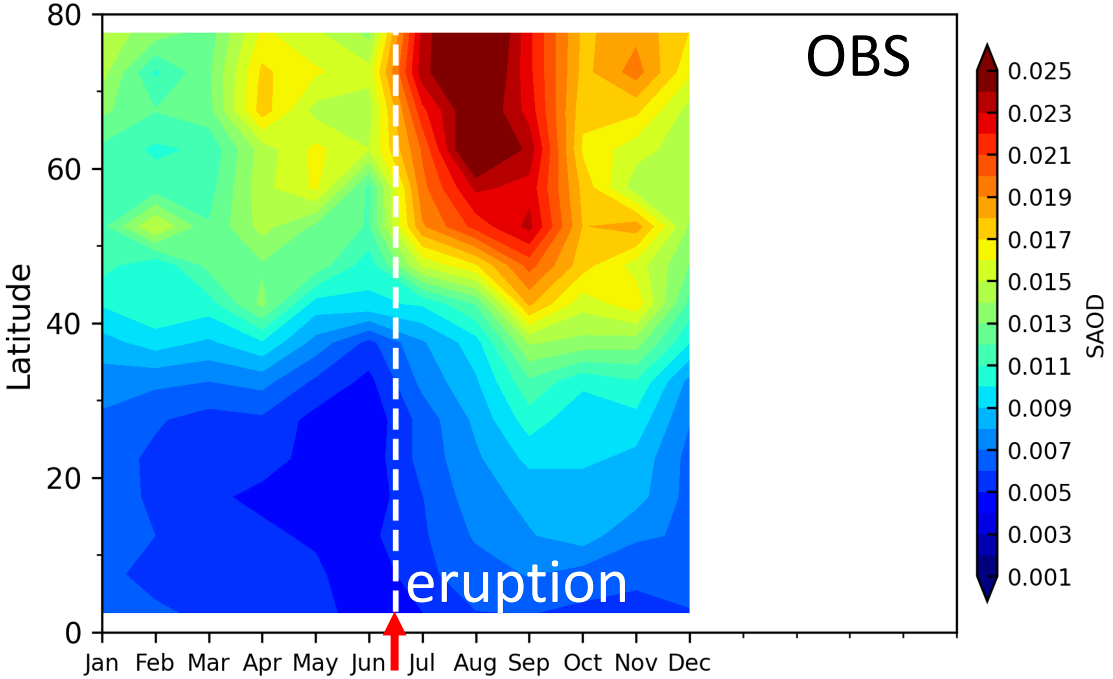
Based on our observational findings, we examine the response of cirrus cloud microphysics to volcanic aerosol emissions in CESM2.

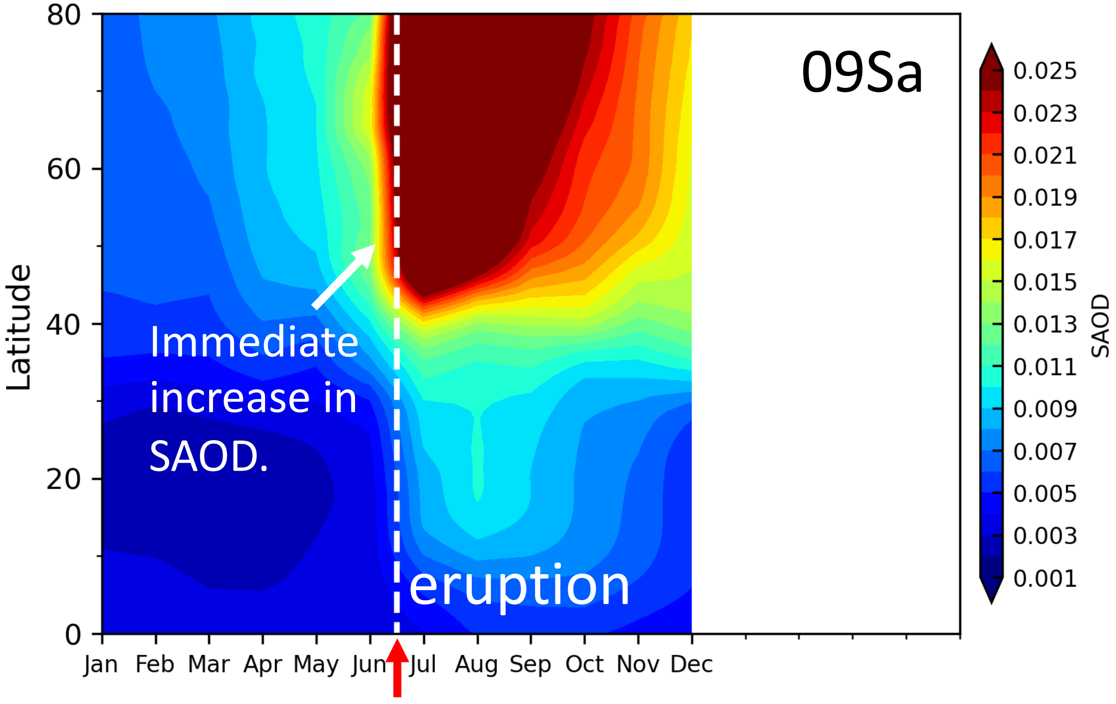
Experiment	Setup	Notes	Configuration
09Sa	**CESM2.2 + WACCM6**	Historical emission file	0.9° x 1.25° horizonal resolution; 88 vertical layers; Nudged u,v, temperature;
09Saoff		Same as 09Sa except that 2009 Sarychev volcanic SO_2 emission is excluded	
15Ca		SSP245 emission file	
15Caoff		Same as 15Ca except that 2015 Calbuco volcanic SO_2 emission is excluded	

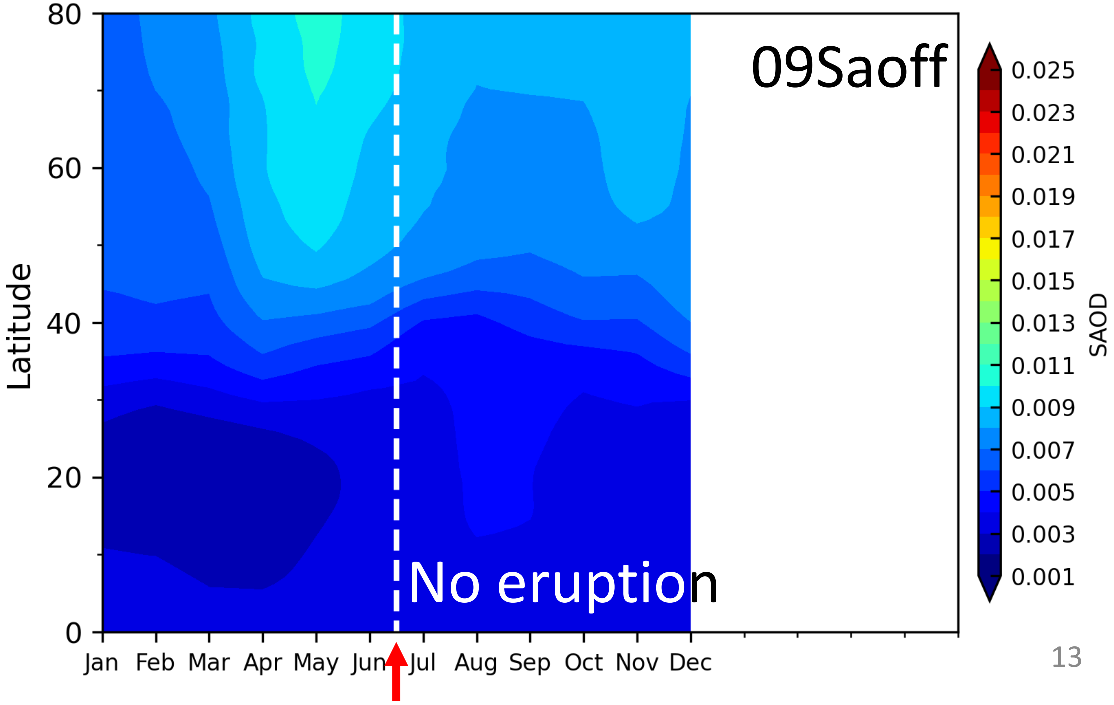
Note: all model simulations now do NOT consider volcanic ash emission.

2009 Sarychev eruption Stratospheric aerosol optical depth (SAOD)

Simulated meridional SAOD distribution as time, compare with CALIPSO L3 Stratospheric aerosol profile product

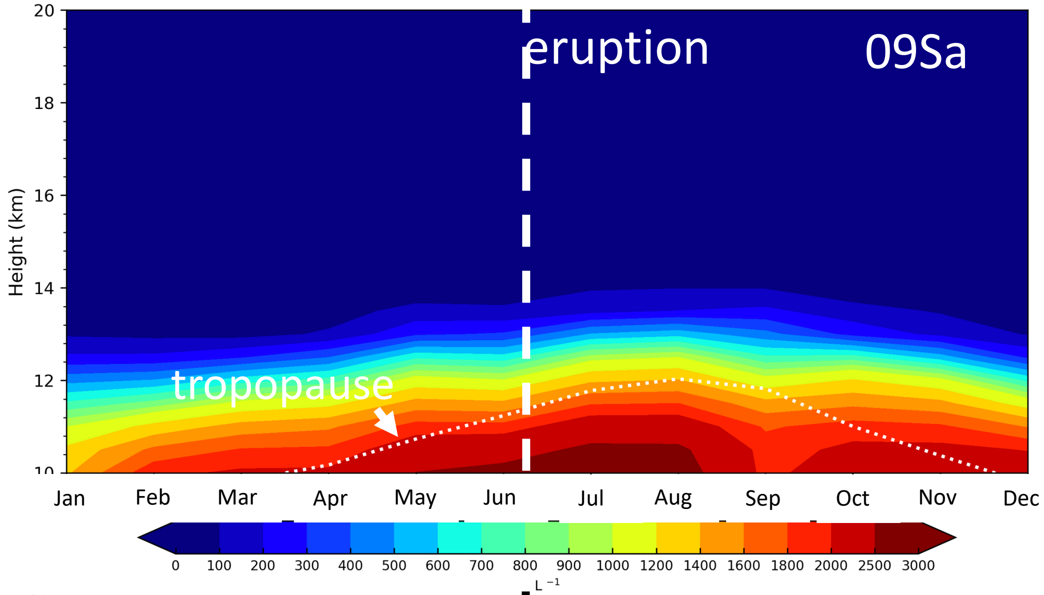


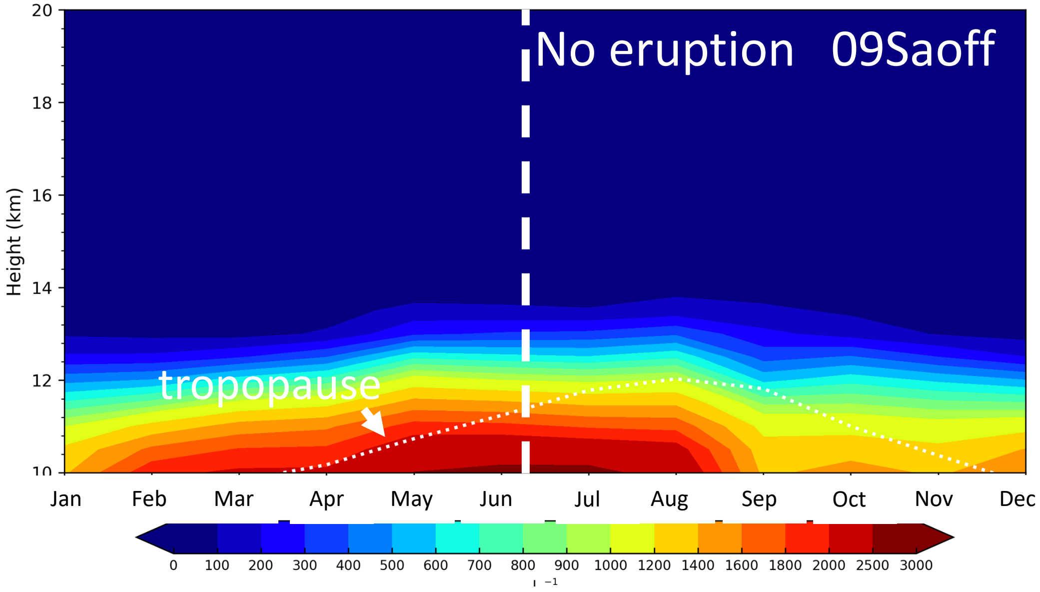


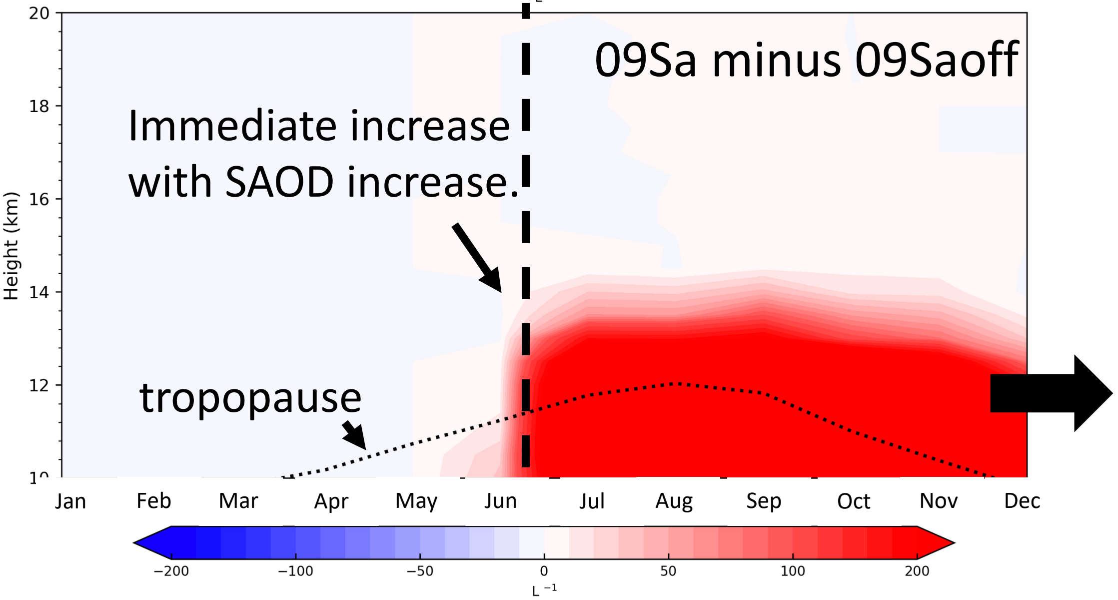


Cloud signature after 2009 Sarychev eruption(ash-rich case)

Simulated ice crystal number (Ni)







Increase by 20-120% in N_i after 09Sa eruption.

Cloud signature after 2009 Sarychev eruption(ash-rich case)

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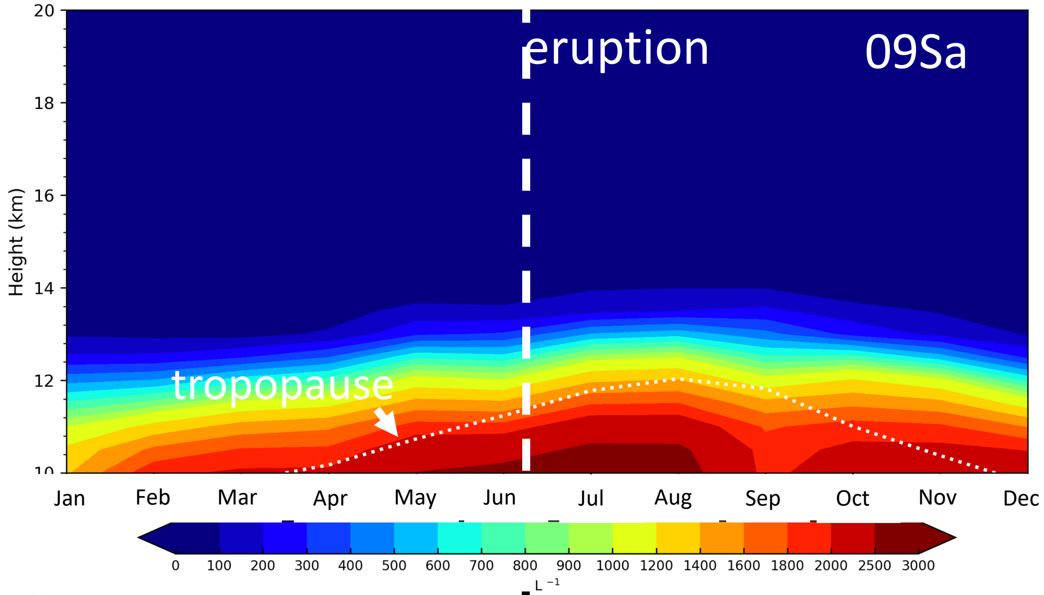
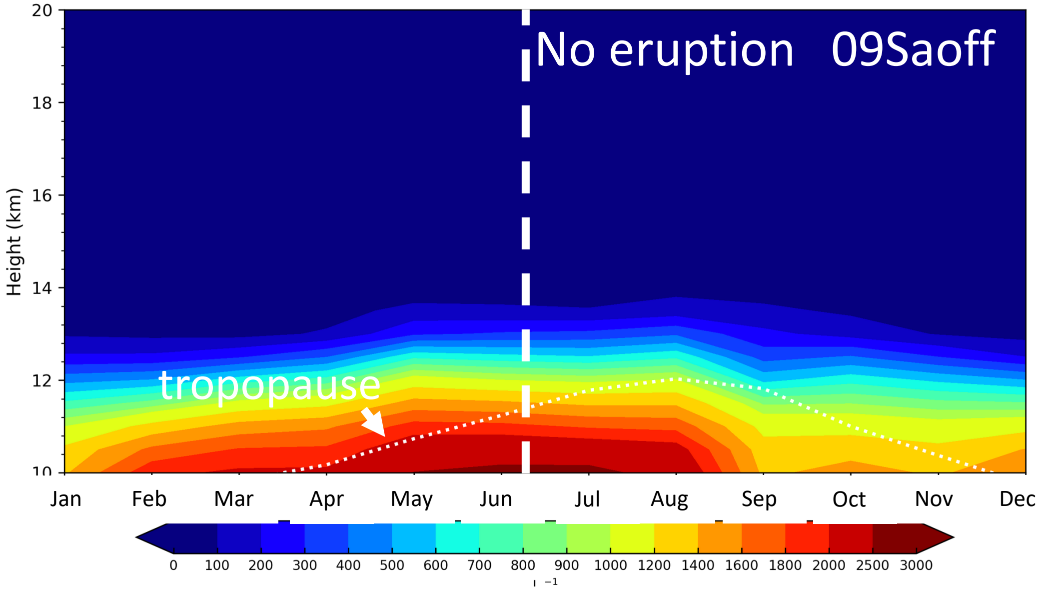
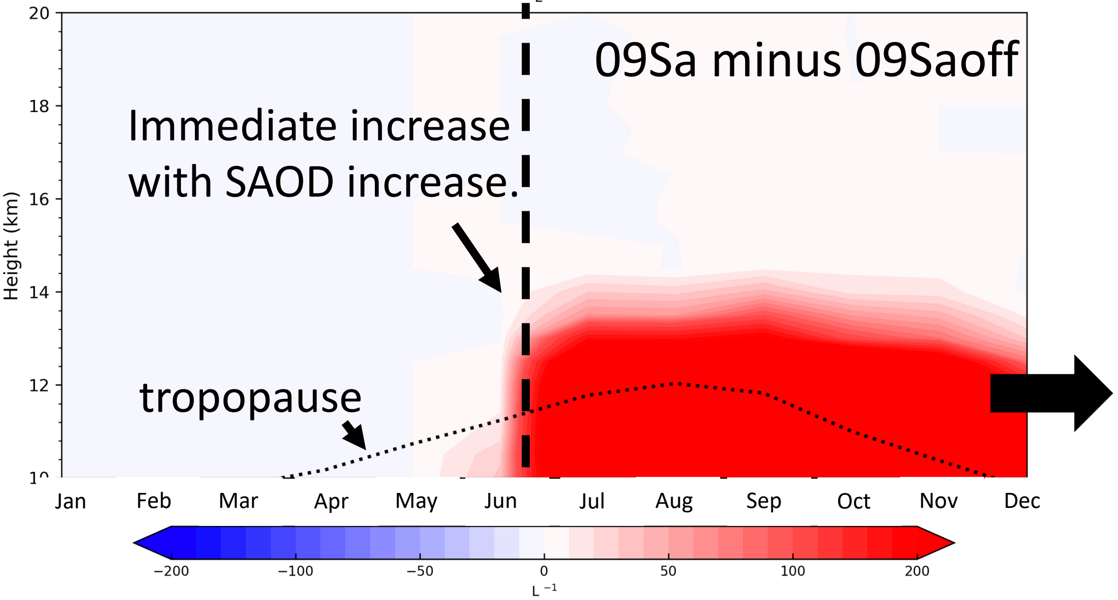






Increase by 20-120% in N_i after 09Sa eruption.

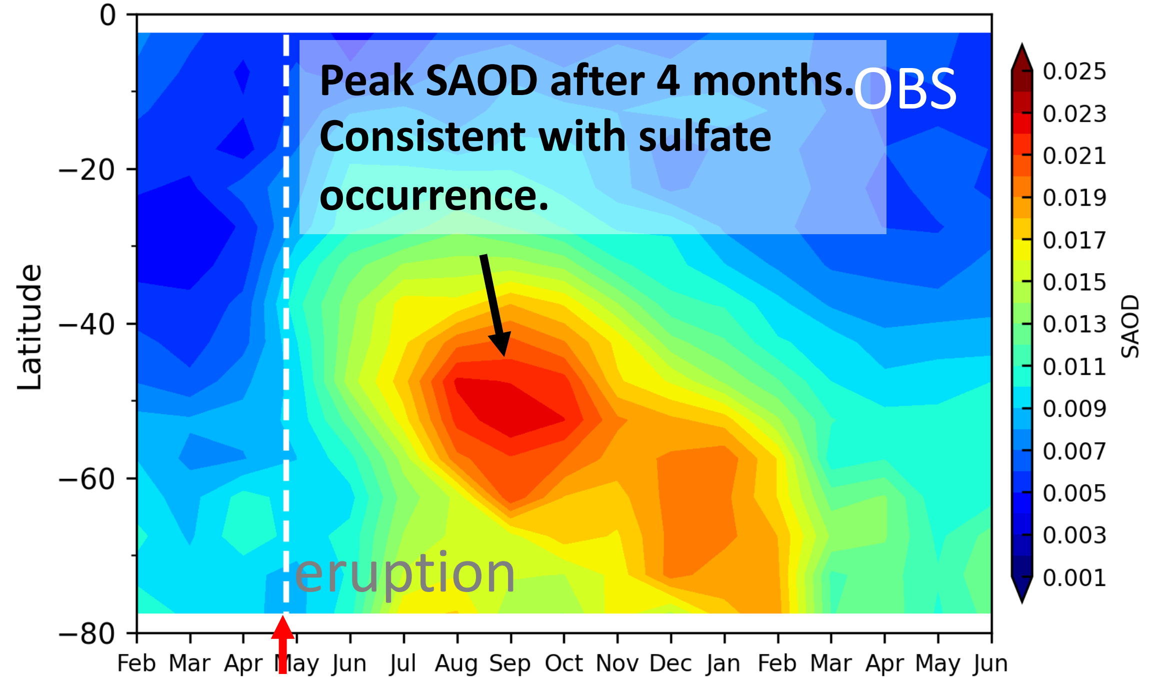
Observations show decreases in N_i after 09Sa, due to volcanic ash particles.

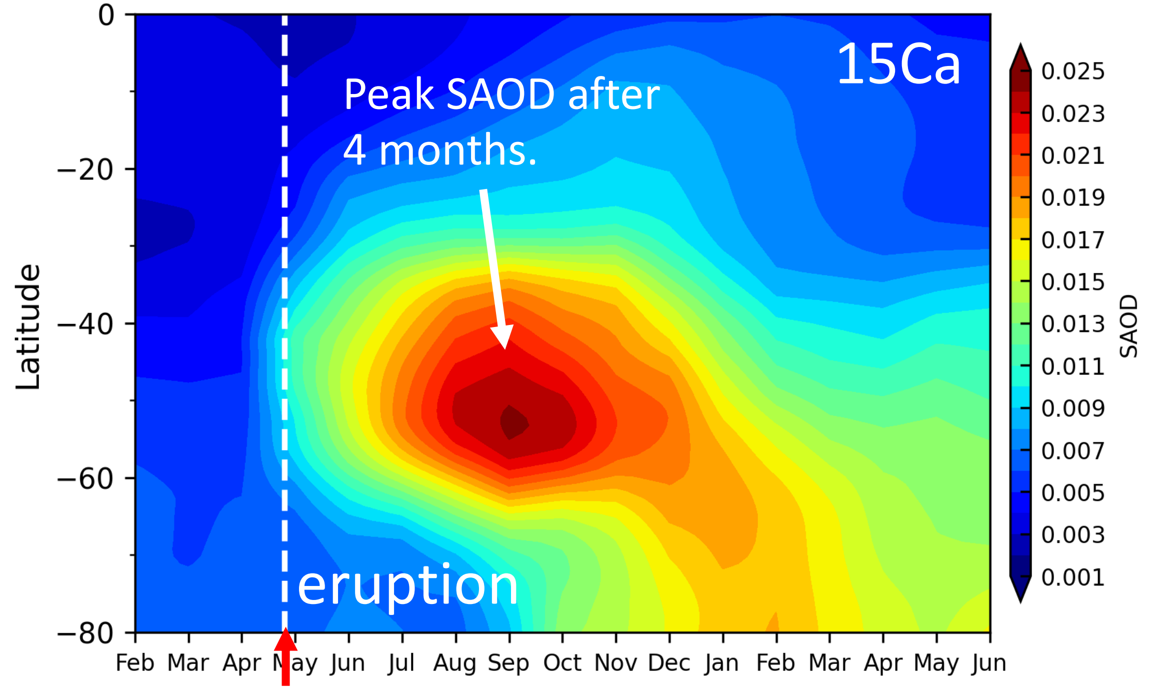
We speculate that without volcanic ash, the model fails to reproduce observations.

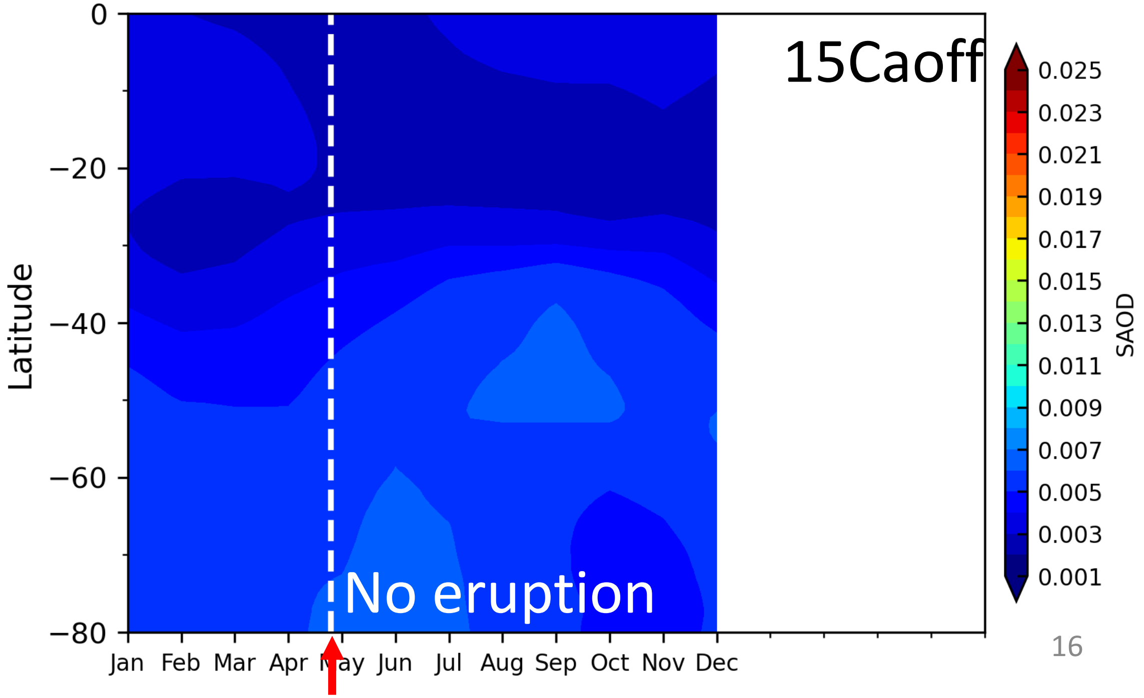
It is imperative to incorporate volcanic ash in simulating impacts of eruption on clouds.

2015 Calbuco eruption Stratospheric aerosol optical depth (SAOD)

Simulated meridional SAOD distribution as time, compare with CALIPSO L3 Stratospheric aerosol profile product

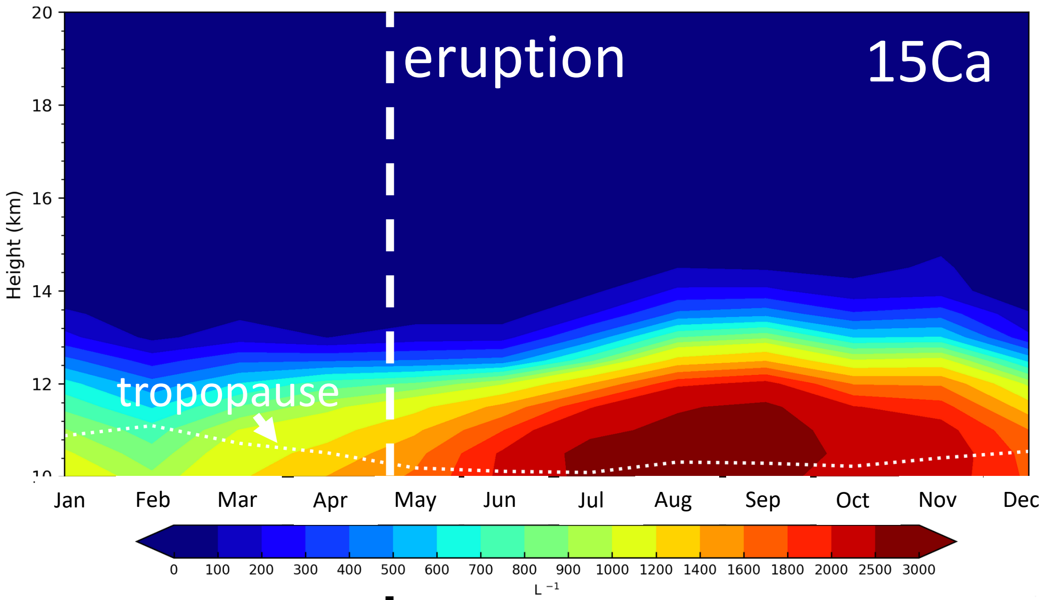


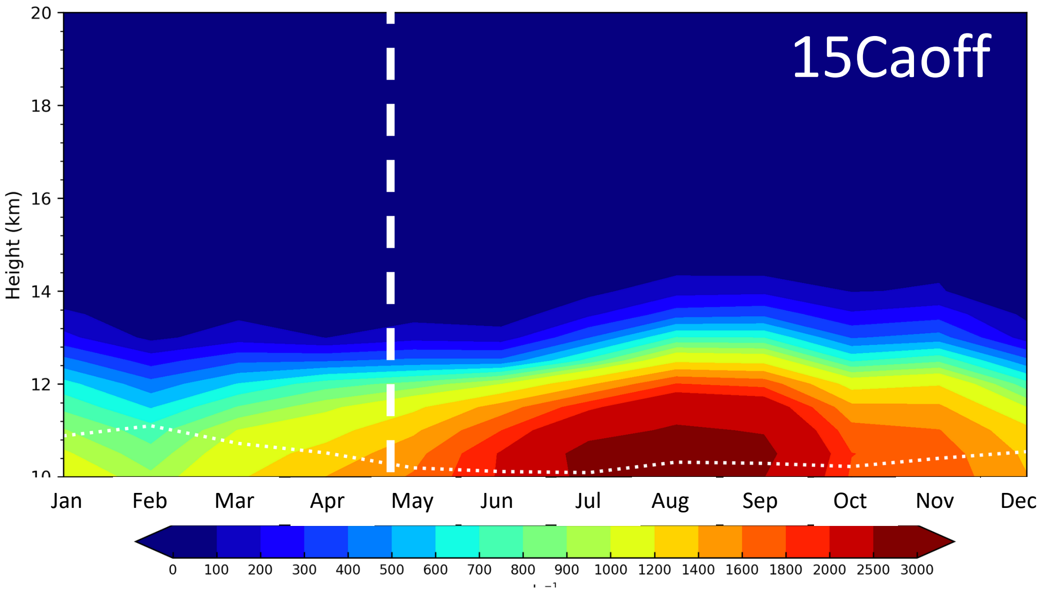


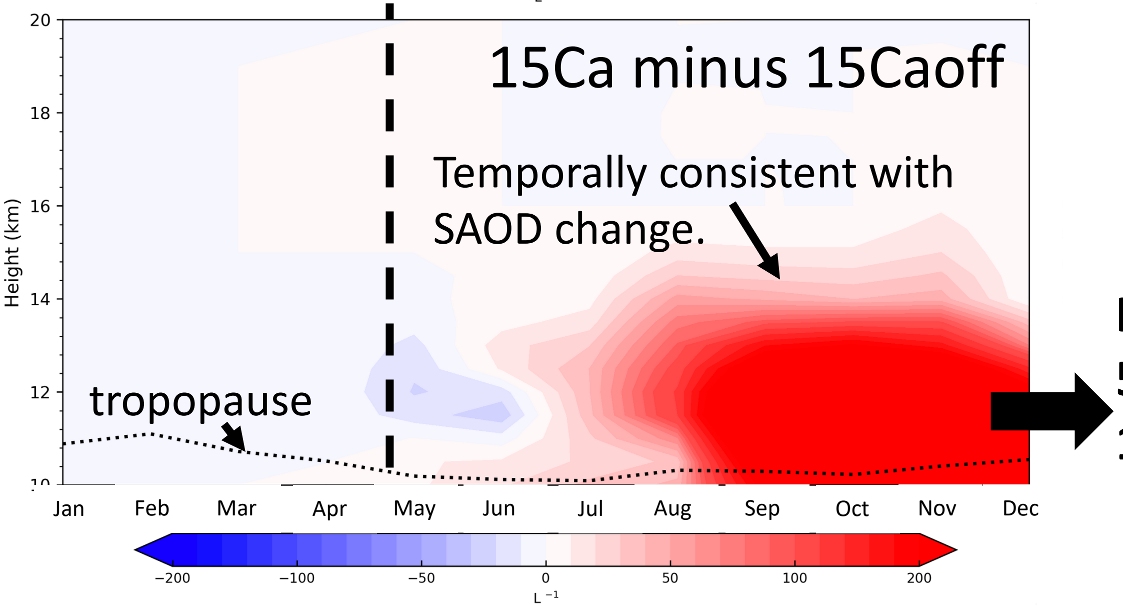


Cloud signature after 2015 Calbuco eruption(ash-poor case)

Simulated ice crystal number (Ni)







Increase by 20-50% in N_i after 15Ca eruption.

Observations show ~26% increases in N_i after 15Ca (volcanic ash-poor).

Absent volcanic ash emission.
Model results are qualitatively consistent with observations.

%

Summary & Discussion & Outlook

- Satellite observations show
  - (1) **a substantial drop (60-80%) in N_i for the ash-rich case**: heterogeneous ice nucleation of volcanic ash suppresses homogeneous ice nucleation of sulfate to reduce total number of N_i (negative Twomey effect);
  - (2) **a slight (~26%) increase in N_i for the ash-poor case**: enhanced homogeneous freezing of sulfate with weak sensitivity.

- Model simulated volcanic aerosol indirect effect from the 2015Ca case (ash-poor) qualitatively agree with observations, while from the 2009Sa case (ash-rich) **disagrees** with observations

- Incorporate volcanic ash in GCMs as INPs to account for the missing ice nucleation mechanism and estimate cloud radiative forcing change in response to eruptions.

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- Lin L., Liu X. et al., 2023: Abrupt changes in post-eruption cirrus microphysics reveal ice nucleation on volcanic ash, in prep.
- Lin L., Liu X. et al., 2023: Examining the response of cirrus cloud microphysics to volcanic aerosol emissions in CESM2 against satellite observations, in prep.