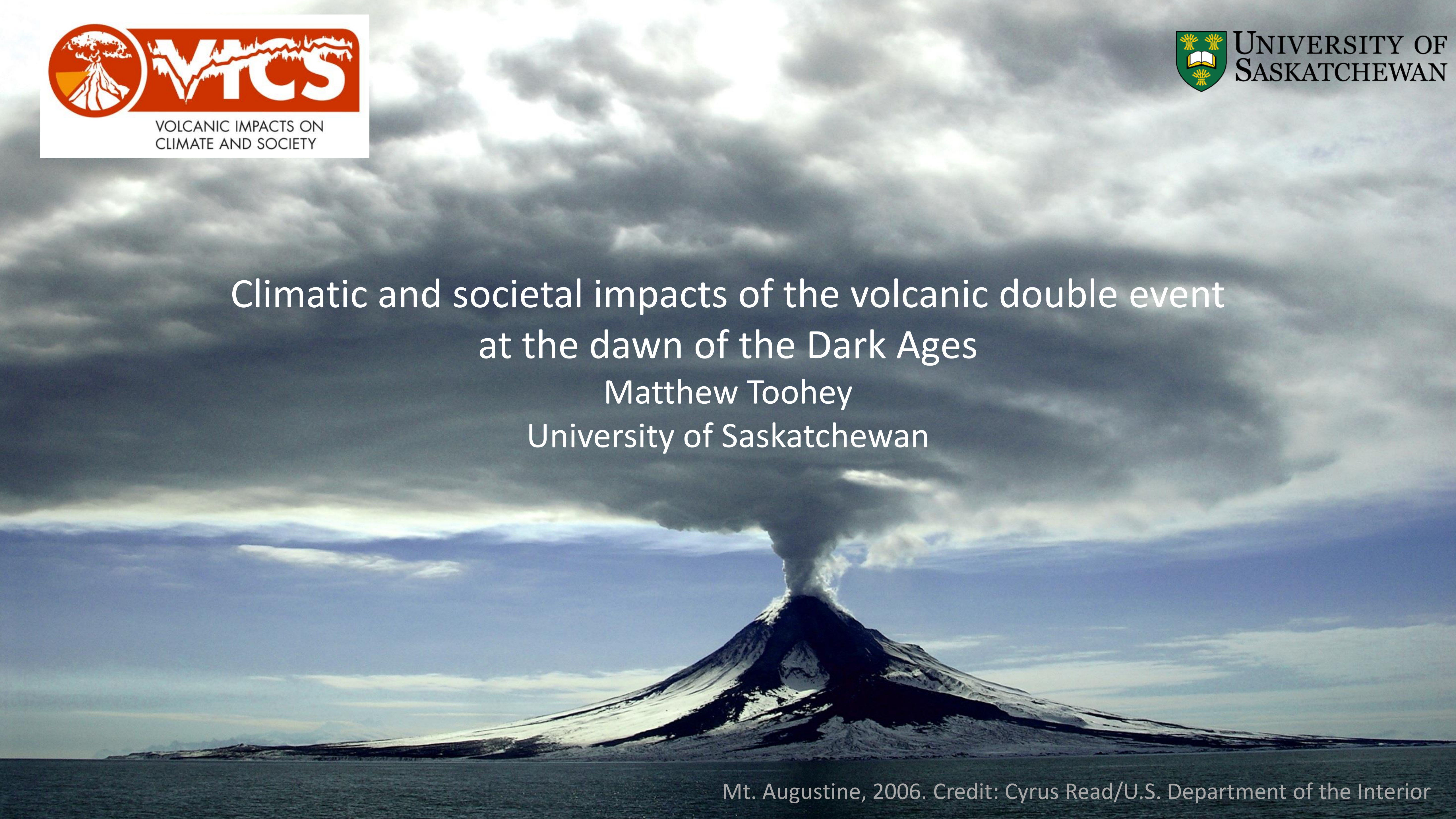


VOLCANIC IMPACTS ON CLIMATE AND SOCIETY

Climatic and societal impacts of the volcanic double event at the dawn of the Dark Ages

Matthew Toohey
University of Saskatchewan

Mt. Augustine, 2006. Credit: Cyrus Read/U.S. Department of the Interior

The mystery cloud of 536 CE

- Procopius (Rome, 42°N):

  The Sun gave forth its light without brightness, like the Moon, during this whole year, and it seemed exceedingly like the Sun in eclipse, for the beams it shed were nor such as it is accustomed to shed.

- Zacharias of Mytilene (Constantinople 41°N):

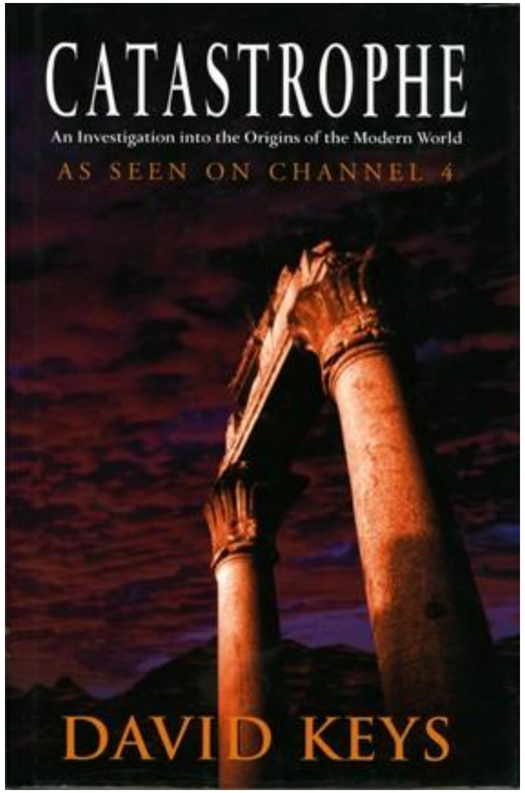
  The Sun began to be darkened by day, and the Moon by night, from the 24th of March in this year till the 24th of June in the following year.

- John of Ephesus (probably, Mesopotamia, 30-37°N)

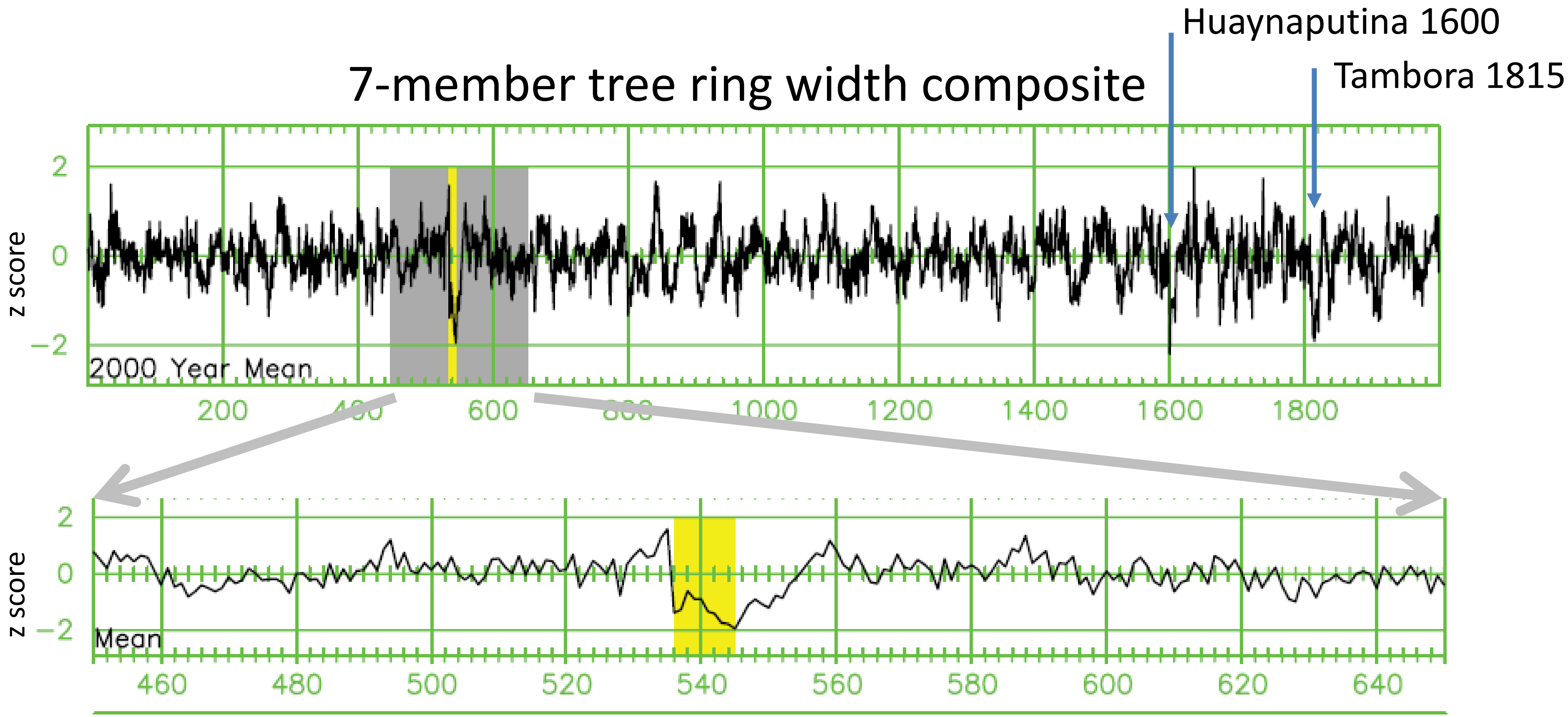
  … the Sun was dark, and its darkness lasted for 18 months; each day it shone for about 4 hours, and still this light was but a feeble shadow… the fruits did not ripen and the wine tasted like sour grapes.

Apparent impacts of the 536 mystery cloud

- “Failure of Bread” in Ireland, 536 and 539 CE
- Extraordinary cold and heavy snowfalls in Baghdad, winters 536 and 537
- In China, reports of summer frosts and snow, widespread famine
- Decline of Teotihuacán and Mayan cities in Mesoamerica
- Reports of crop failures and famines in the Mediterranean (Arjava, 2005)
- The first plague pandemic in Europe began in 541 CE.
- In Scandinavia:
  - large number of abandoned settlements dated to mid 500s
  - sharp decrease in agriculture implied by pollen records
  - Sacrificial gold offerings



Unrivalled cooling after 536 CE



Larsen et al., 2008

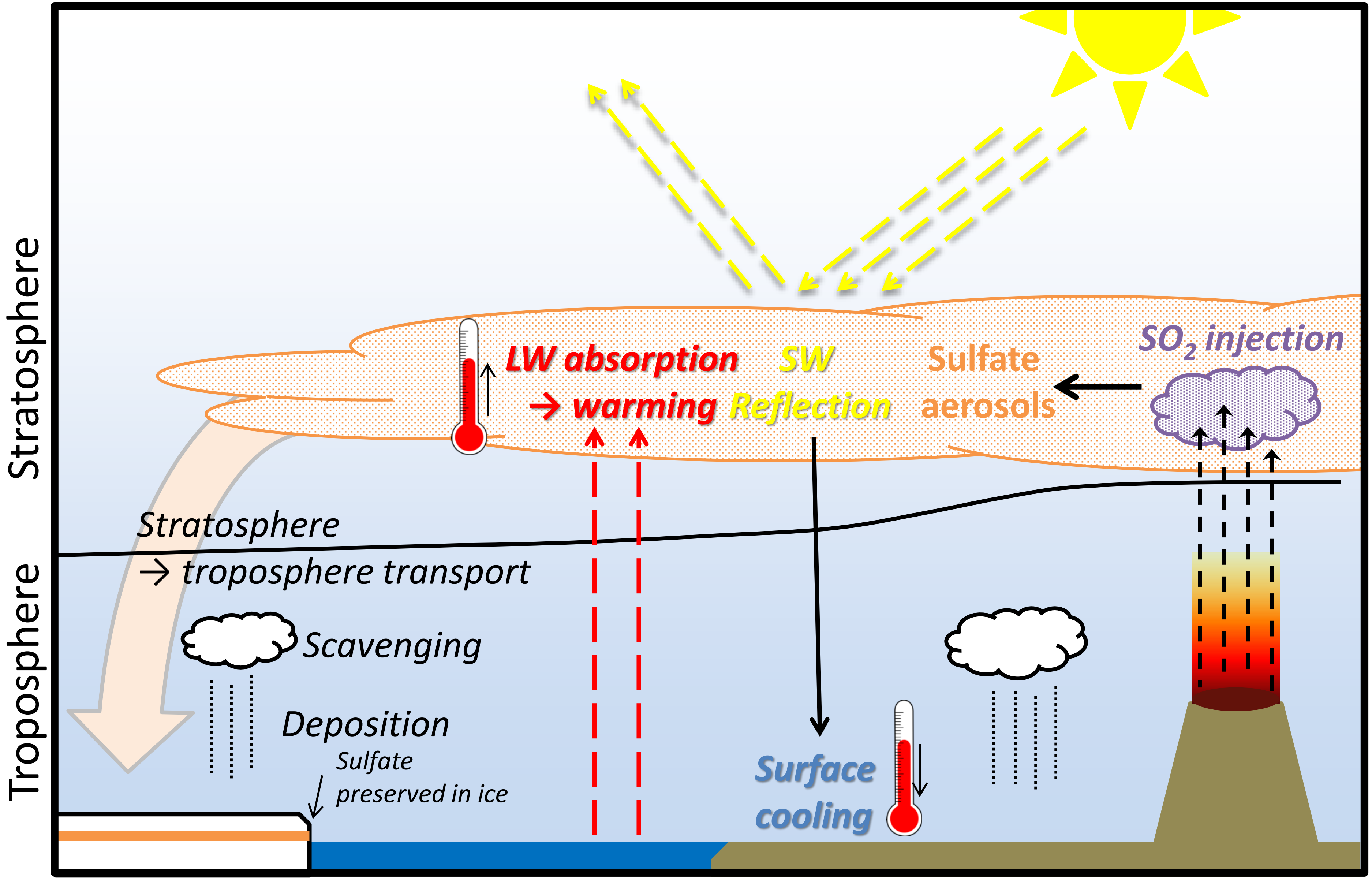
See also: Grudd 2008; Larsen et al. 2008; Esper et al. 2012, D'Arrigo et al. 2001, Salzer and Hughes 2007; Salzer et al. 2013, Stoffel et al. 2015, Büntgen et al., 2016…

What caused the 536 CE mystery cloud?

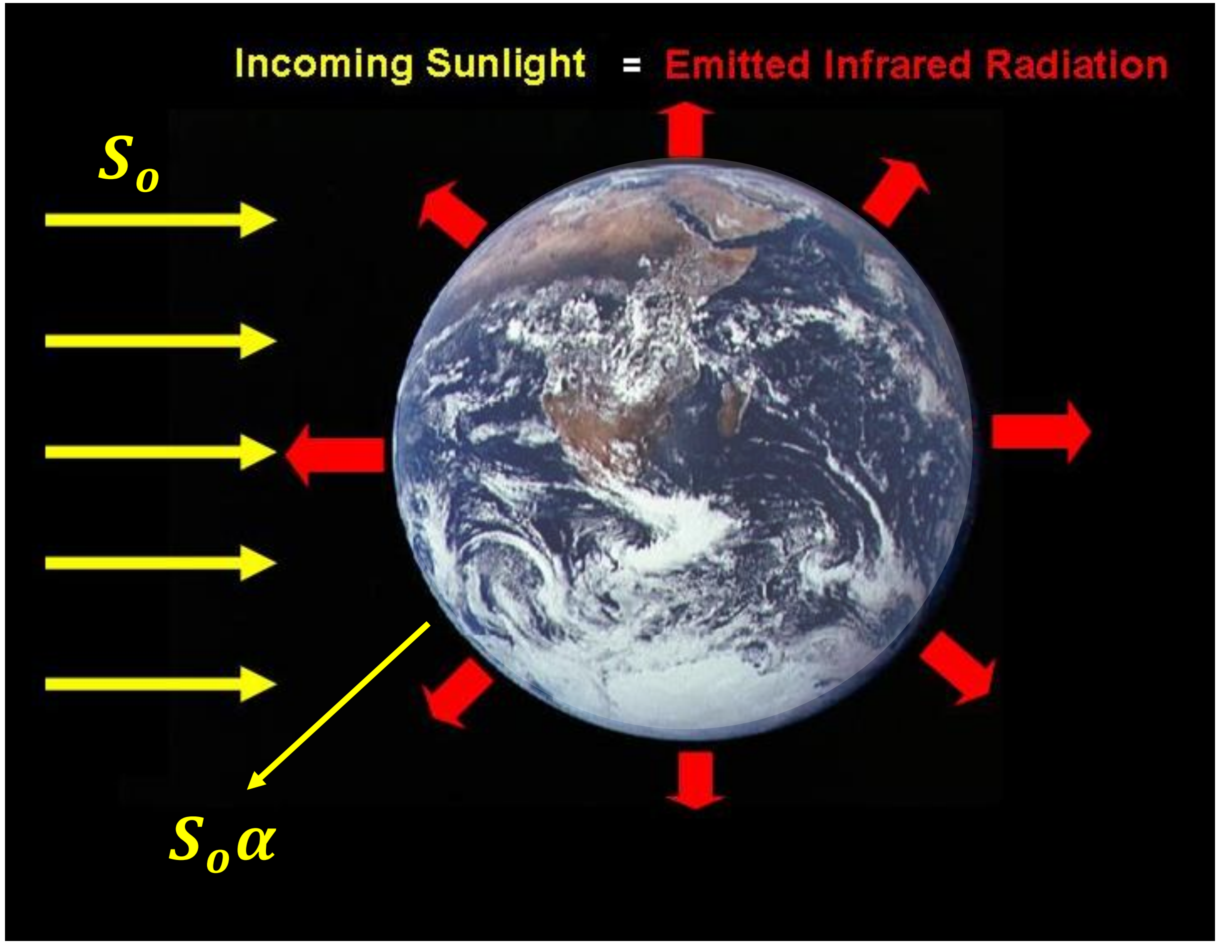
Was the cloud responsible for the climate and societal downturn apparent in the Northern Hemisphere?

What caused the 536 Mystery Cloud?

Volcanic eruptions and climate



Volcanic aerosol and the Earth's albedo



In steady-state, we expect the radiative power collected by Earth (from Sun) to equal the radiative power emitted by Earth.

$$\Phi_{SW} = \Phi_{LW}$$
$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T_e^4$$
$$S_0(1-\alpha) = 4\sigma T_e^4$$
$$T_e = \left(\frac{S_0(1-\alpha)}{4\sigma}\right)^{1/4}$$

S_0 = Solar constant 1361 W/m^2

α = planetary SW albedo (~0.3)

T_e = Earth's effective temperature

σ = Stefan-Boltzman constant

→ A 1% change in albedo leads to a temperature change of 0.3°C

Mt. Pinatubo 1991, by the numbers

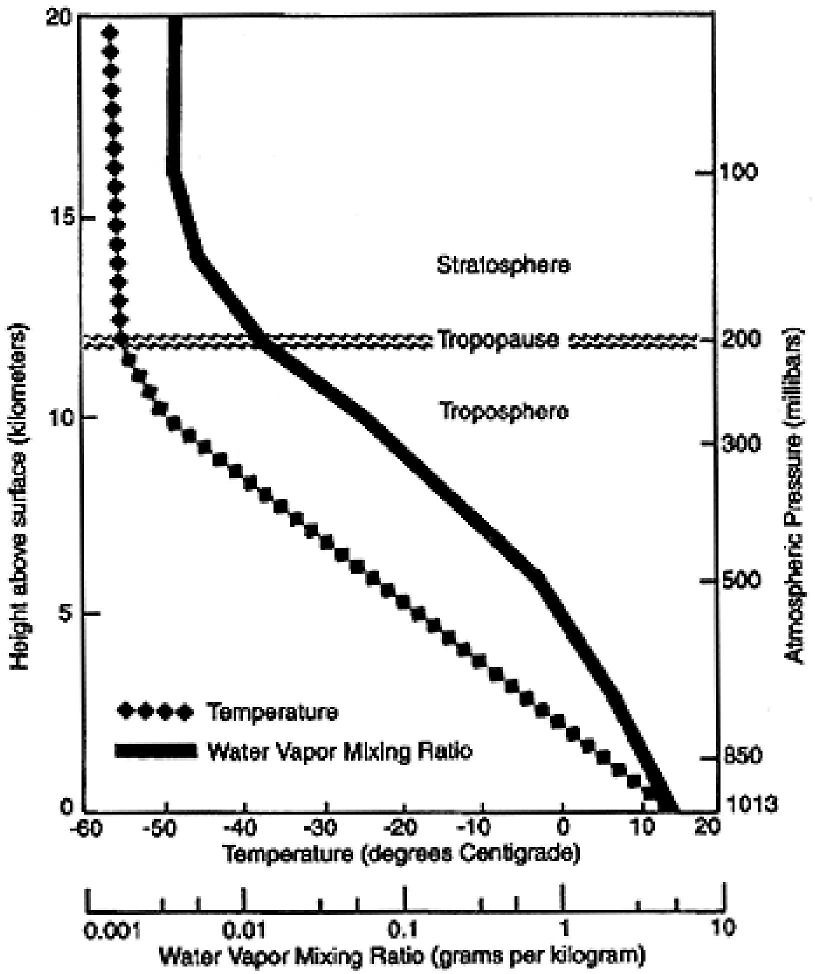
Mt Pinatubo eruption June 1991

- Pinatubo 1991:
  - Ejected 10 km^3 of material
  - >25 km column height
  - Gas emissions
    - 490 Tg H_2O
    - 42 Tg CO_2
    - 17 Tg SO_2
    - 3 Tg Cl

$1\ \mathrm{Tg} = 1 \times 10^{12}\ \mathrm{g}$
$1\ \mathrm{Tg} = 1\ \text{billion kg}$
$1\ \mathrm{Tg} = 1\ \text{million tonnes}$

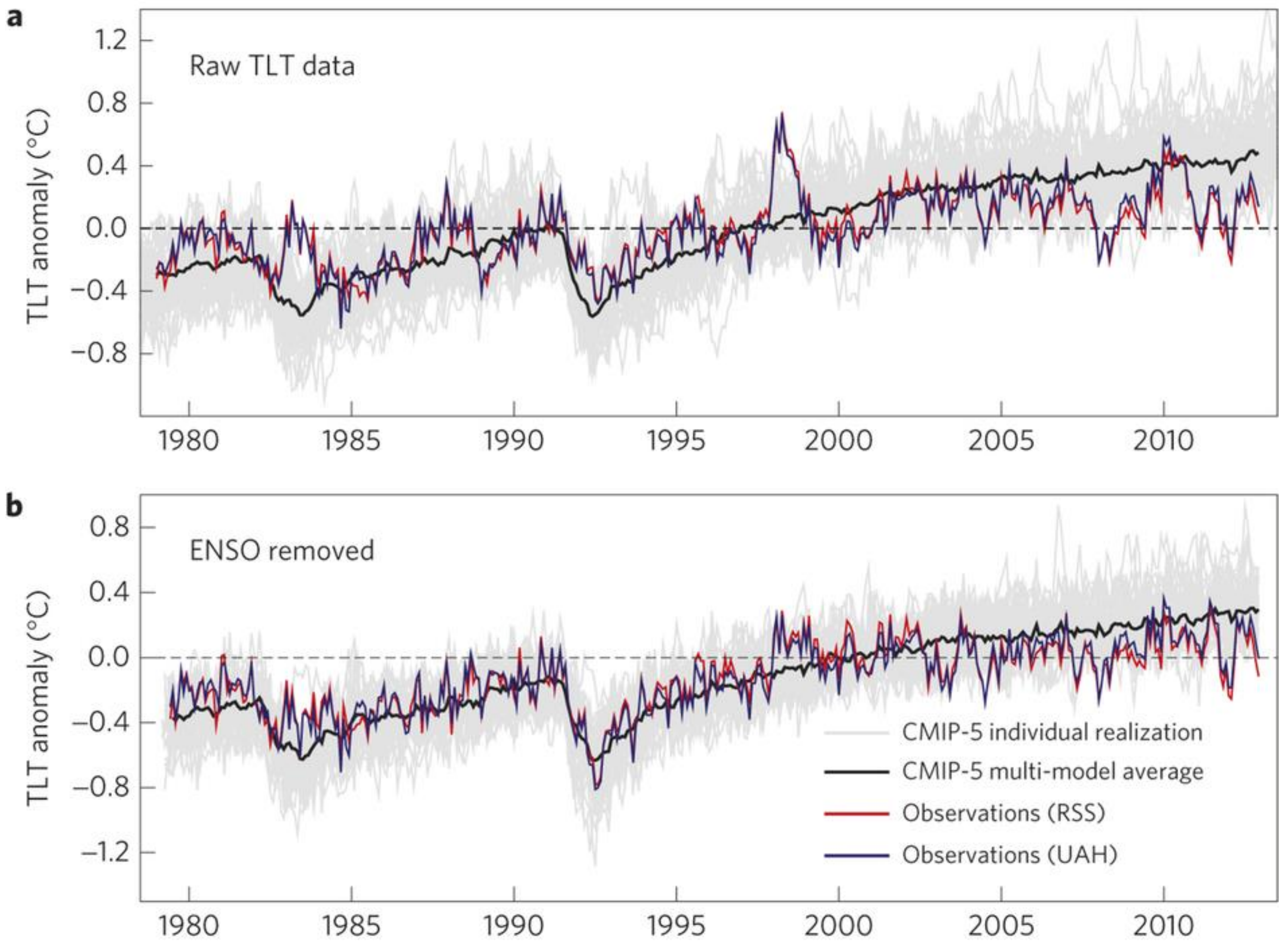
10-20% of modern global annual anthropogenic SO_2 emissions

The stratosphere



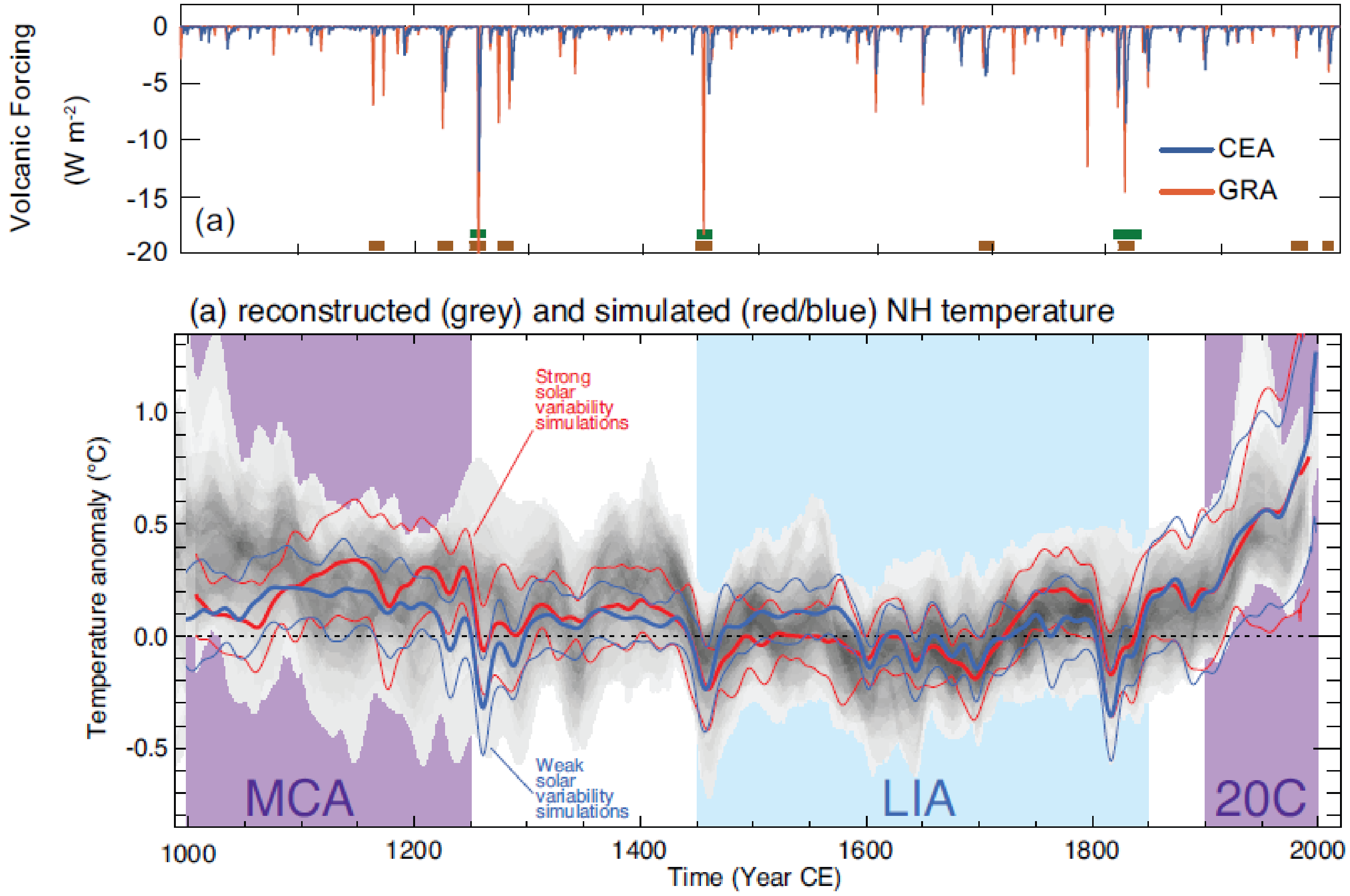
https://www.eso.org/gen-fac/pubs/astclim/espas/pwv/mockler.html

Temperature of the lower troposphere



Santer et al., 2014

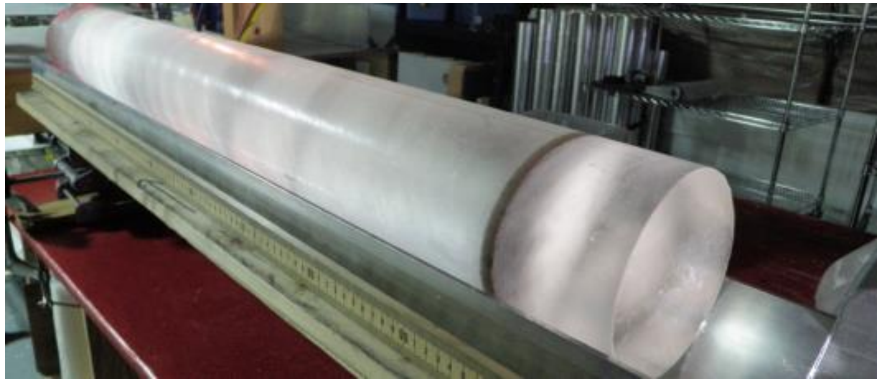
Volcanic forcing and climate variability: last millennium



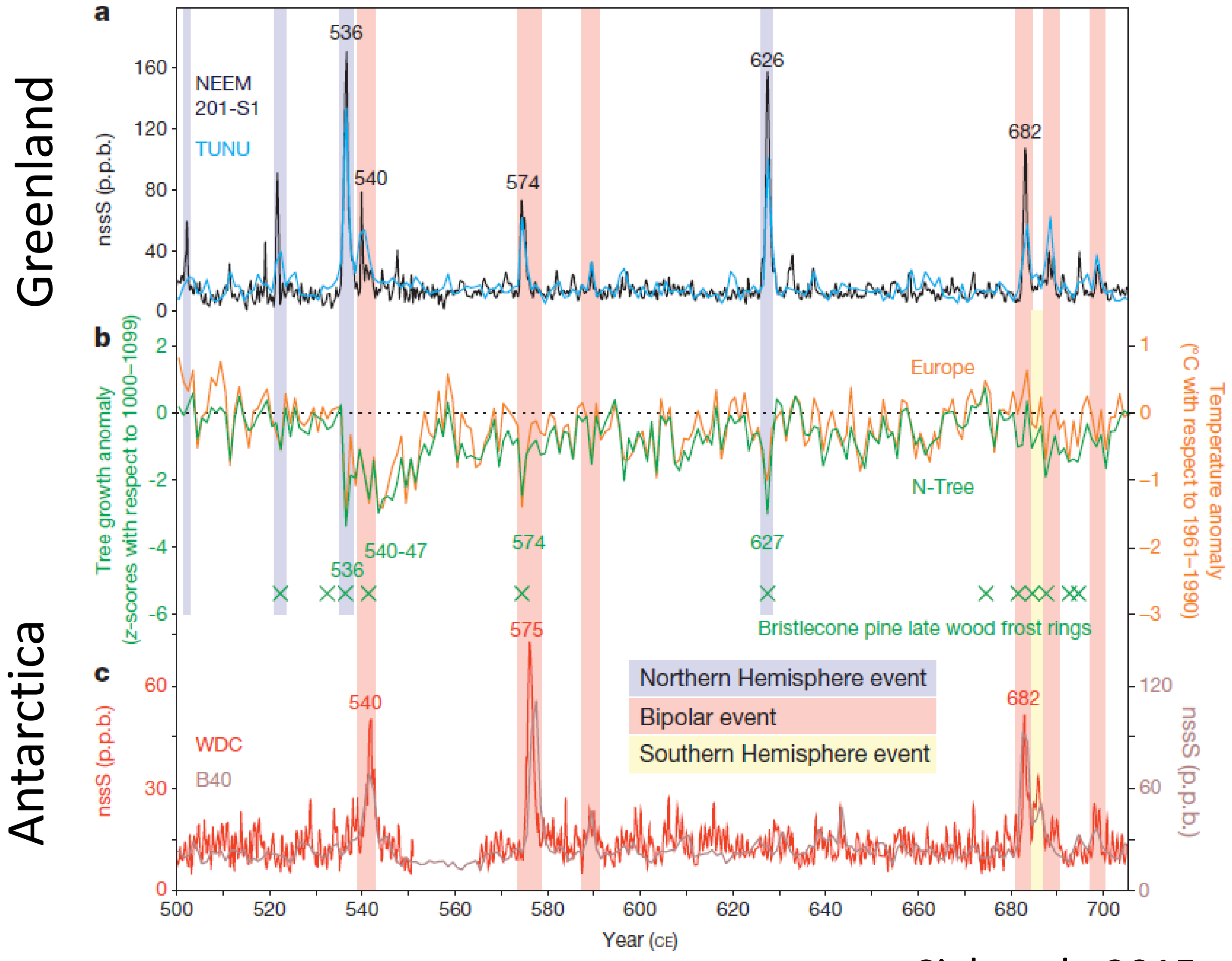
IPCC AR5, 2013

- Volcanic forcing is the main driver of preindustrial interannual-to-decadal temperature variability (Schurer et al., 2013).
- Volcanic forcing main driver of 801-1800 CE negative trend in ocean temperature (McGregor et al., 2015)
- Volcanic forcing linked to NH glacier advances (Sigl et al., 2018)
- Volcanic forcing + ocean and cryospheric feedback the cause of the Little Ice Age (Miller et al., 2012)?

Ice cores confirm a volcanic origin of the 536 CE cloud



- 536 CE eruption was likely in the NH
- Followed by a tropical eruption in 540 CE, and another in 574 CE



Sigl et al., 2015

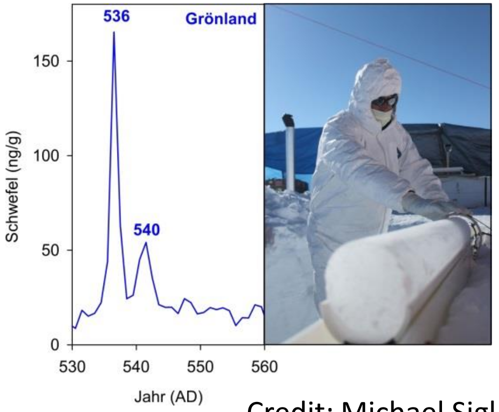
Was the cloud responsible for the climate and societal downturn apparent in the Northern Hemisphere?

How to reconcile reports of widespread catostrophe with the report that in the Mediterranean, the 536 mystery cloud: "caused bad harvests there for one or two years" and people there treated it "as a temporary bad omen, not as the beginning of a long period of unfavorable climatic conditions"

(Arjava, 2005)

Volcanic forcing

Ice core sulfate records



Credit: Michael Sigl

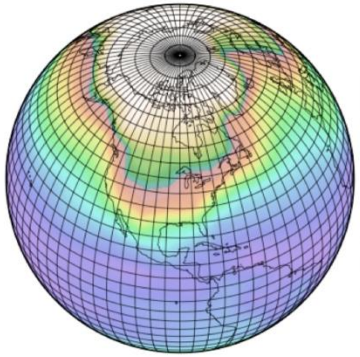
Contemporary chronicles

… the Sun was dark, and its darkness lasted for 18 months…

-- John of Ephesus

Stothers, 1984

Stratospheric aerosol and climate models



Credit: NASA Goddard

?

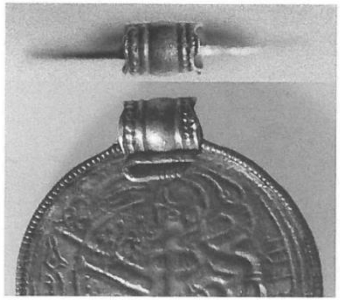
Climate response

Tree ring temperature reconstructions showing extreme cold, 536-545

e.g., Büntgen et al, 2016

Archaeological evidence:

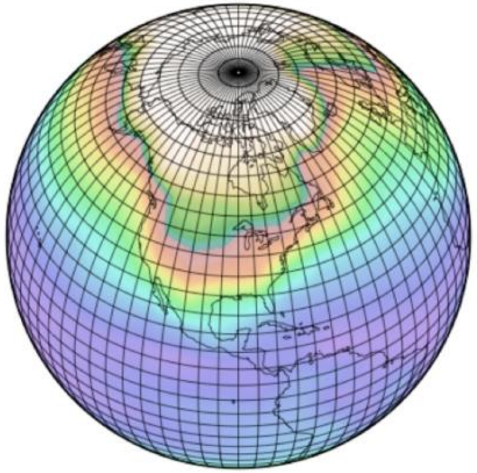
- Agricultural changes
- Population decline
- Sacrificial gold offerings



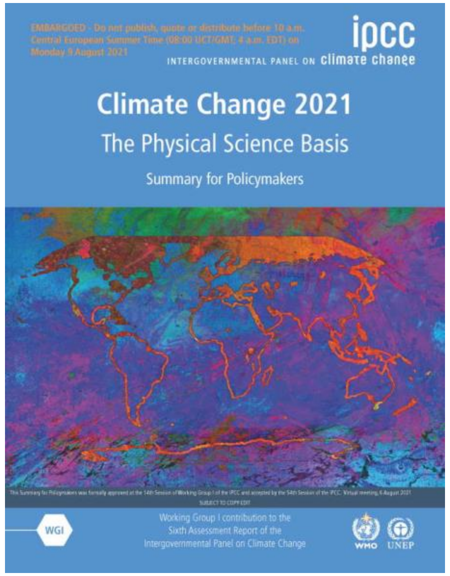
Axboe, 2001

What is a climate model?

- A scientific model seeks to represent empirical objects, phenomena, and physical processes in a logical and objective way.
- All models are simplified reflections of reality that, despite being approximations, can be extremely useful.

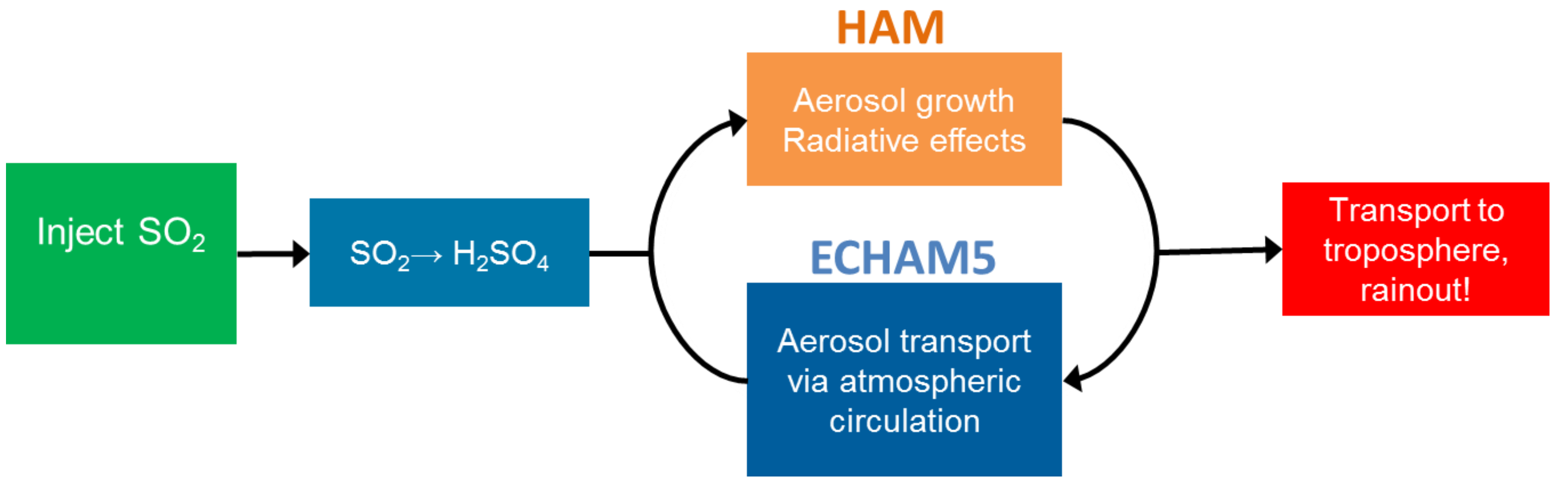


- You've met one! $T_e = \left(\frac{S_0(1-\alpha)}{4\sigma}\right)^{1/4}$
- *Comprehensive* climate models simulate the movement of mass and energy throughout the Earth system in 3 dimensions plus time
  - These models comprise ~1 million lines of code, run on some of the worlds fastest supercomputers
  - Used in climate change projections

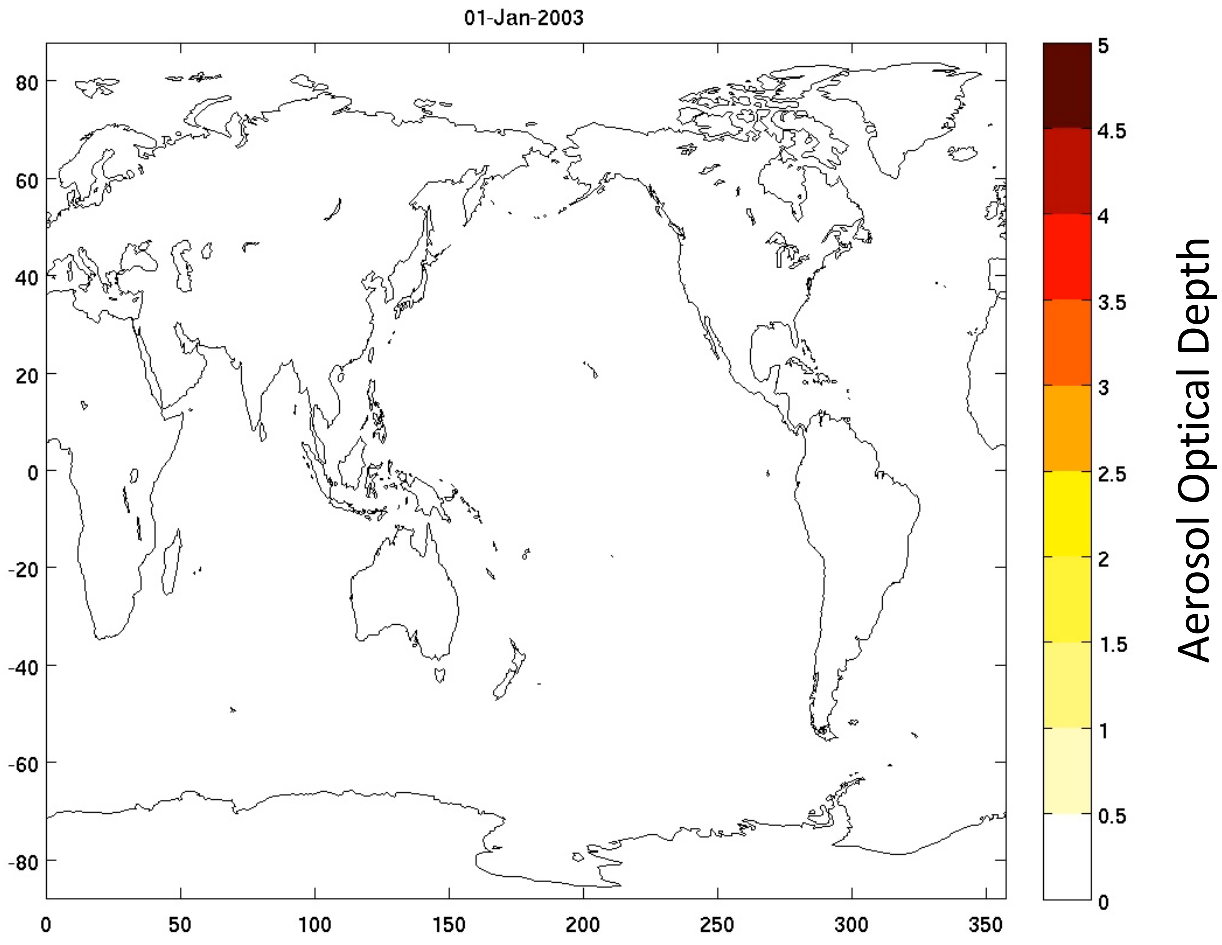


ECHAM5-HAM stratospheric aerosol model

- **ECHAM:** General circulation model (GCM) developed at Max Planck Institute for Meteorology in Hamburg
  - Middle atmosphere version: 39 vertical levels up to 0.01 hPa (~80 km)
- **HAM**: Aerosol microphysical module
  - Models aerosol growth, radiative effects, eventual removal
  - Modified for simulation of stratospheric volcanic aerosols



ECHAM5-HAM stratospheric aerosol simulation



Ice core sulfate -> stratospheric sulfur injection

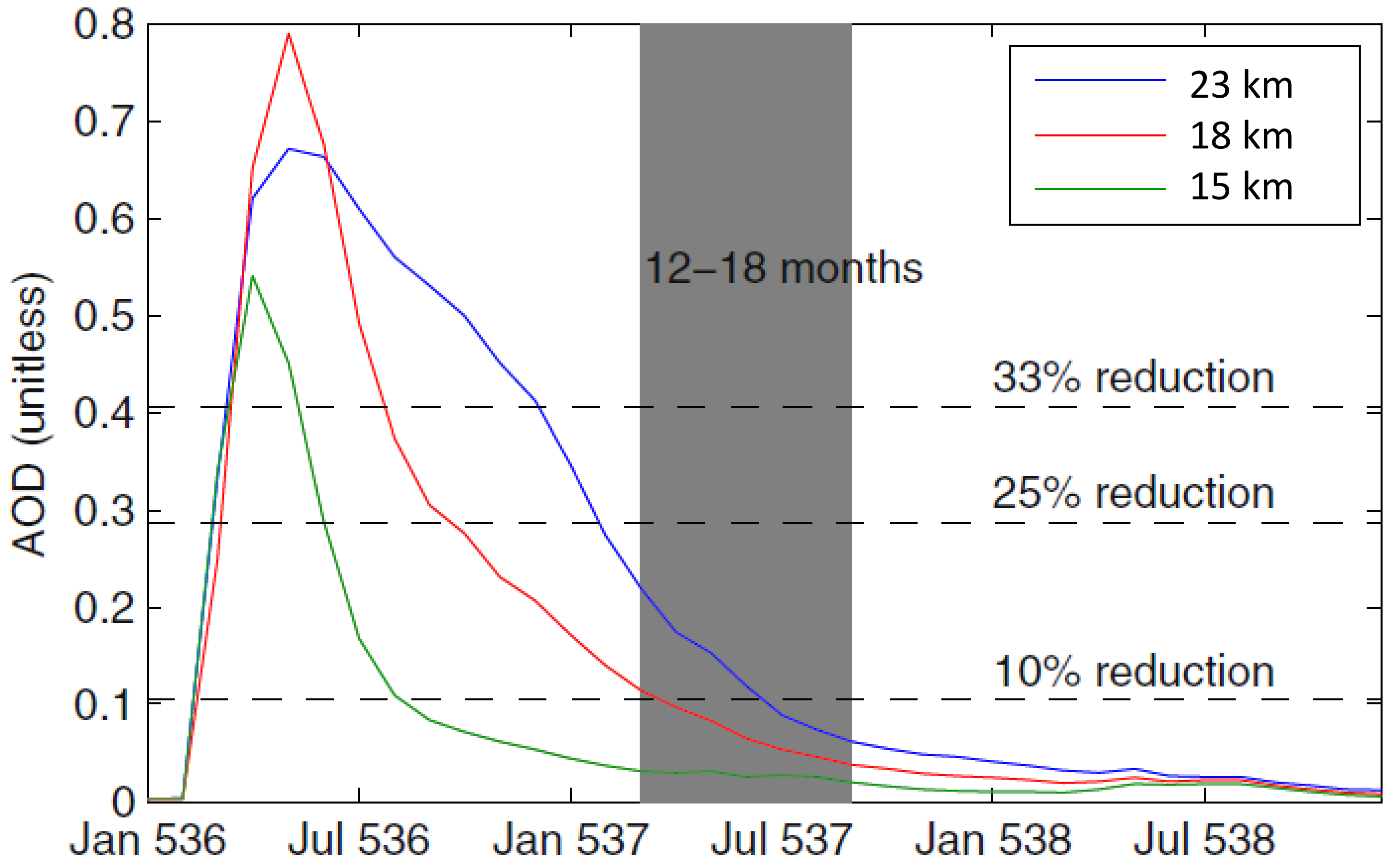
536 is 3rd largest signal in Greenland NEEM core (~2000 years)

	536 CE	540 CE	Tambora
Greenland sulfate flux (kg/km^2)	100.9	71.0	45.3
Antarctic sulfate flux (kg/km^2)	8.3	35.8	58.2
SO_2 injection (Tg) *	32	53	50
Injection latitude †	>45°N	~15°N	~4°S

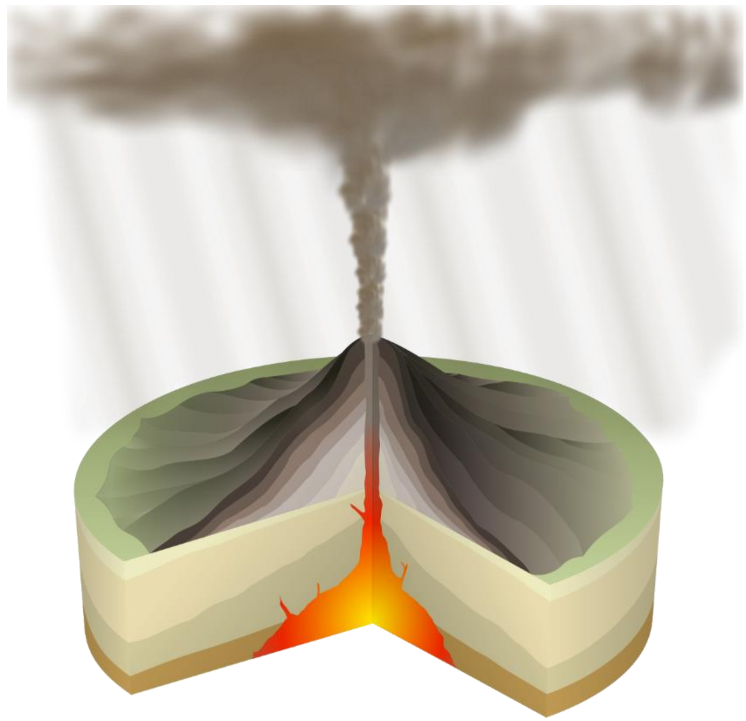
* Using transfer functions of Gao et al. (2007)

† Based on sensitivity study with ECHAM5-HAM

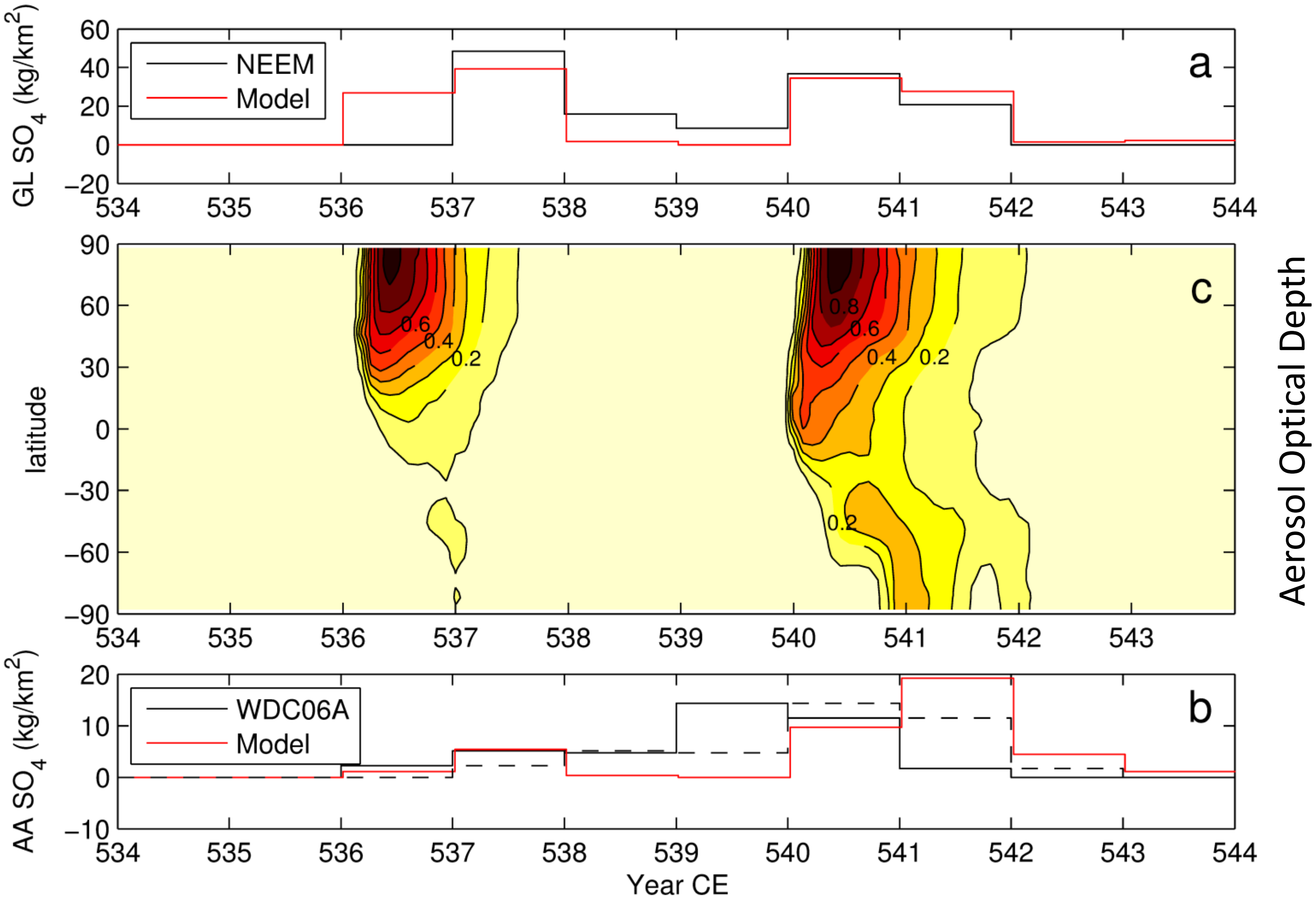
ECHAM5-HAM AOD high-latitude eruptions



Injection altitudes, related to eruption plume height

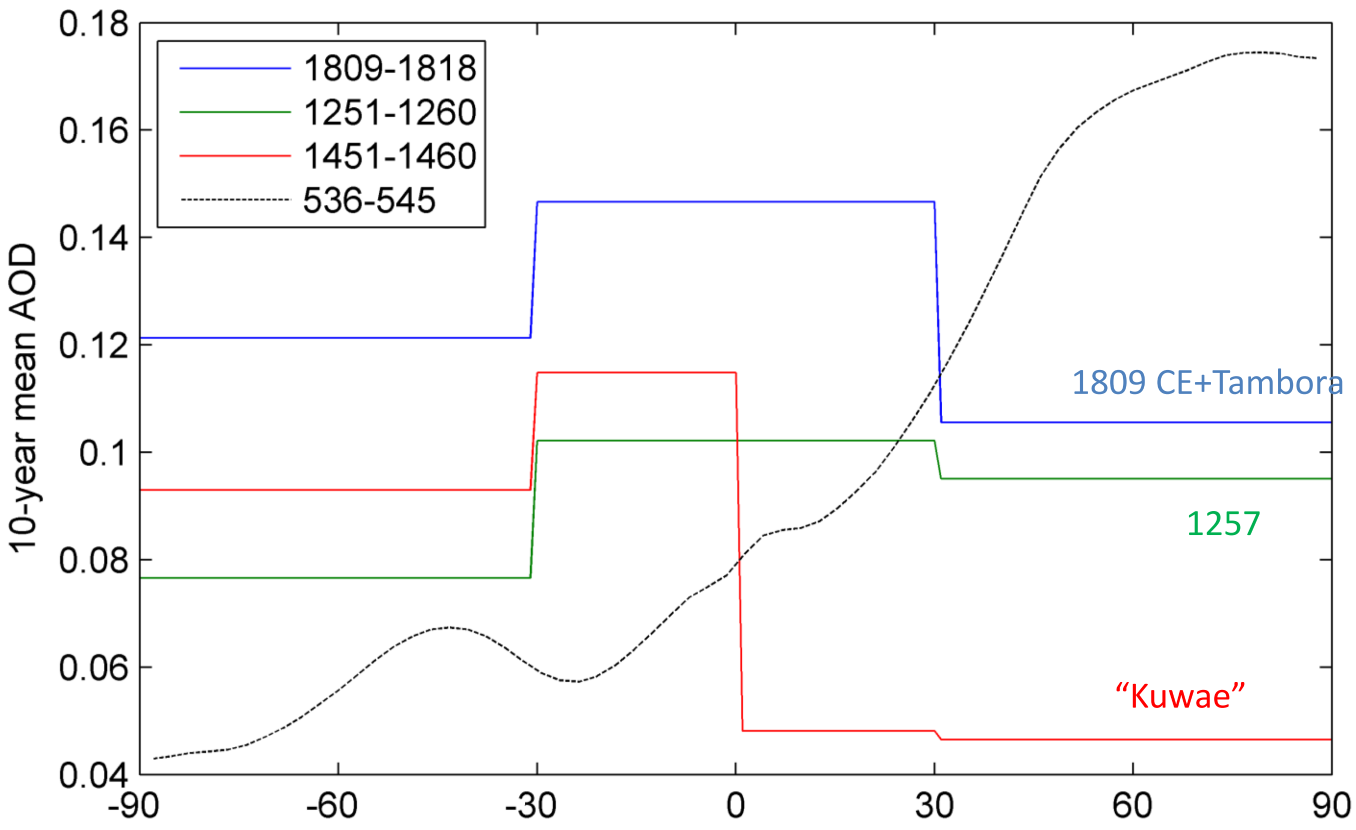


Volcanic radiative forcing from ECHAM5-HAM



Toohey et al., 2016

Decadal mean AOD

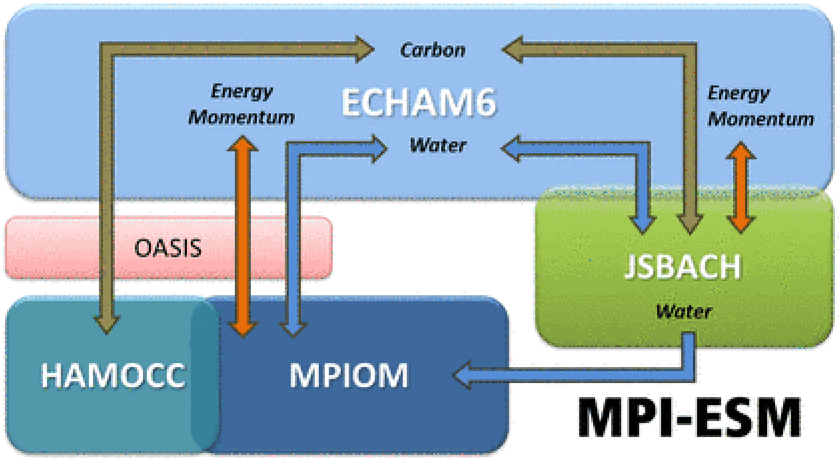


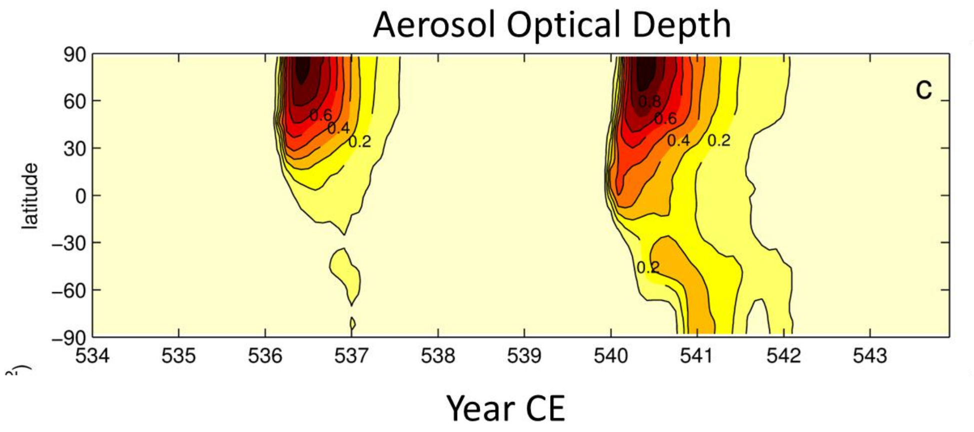
536+540 reconstruction

- In terms of global mean AOD, 536 and 540 CE eruptions would rank 7th and 3rd of past 1200 years.
- In terms of ***Northern Hemisphere, decadal mean*** AOD, 536-545 CE period would rank 1st.

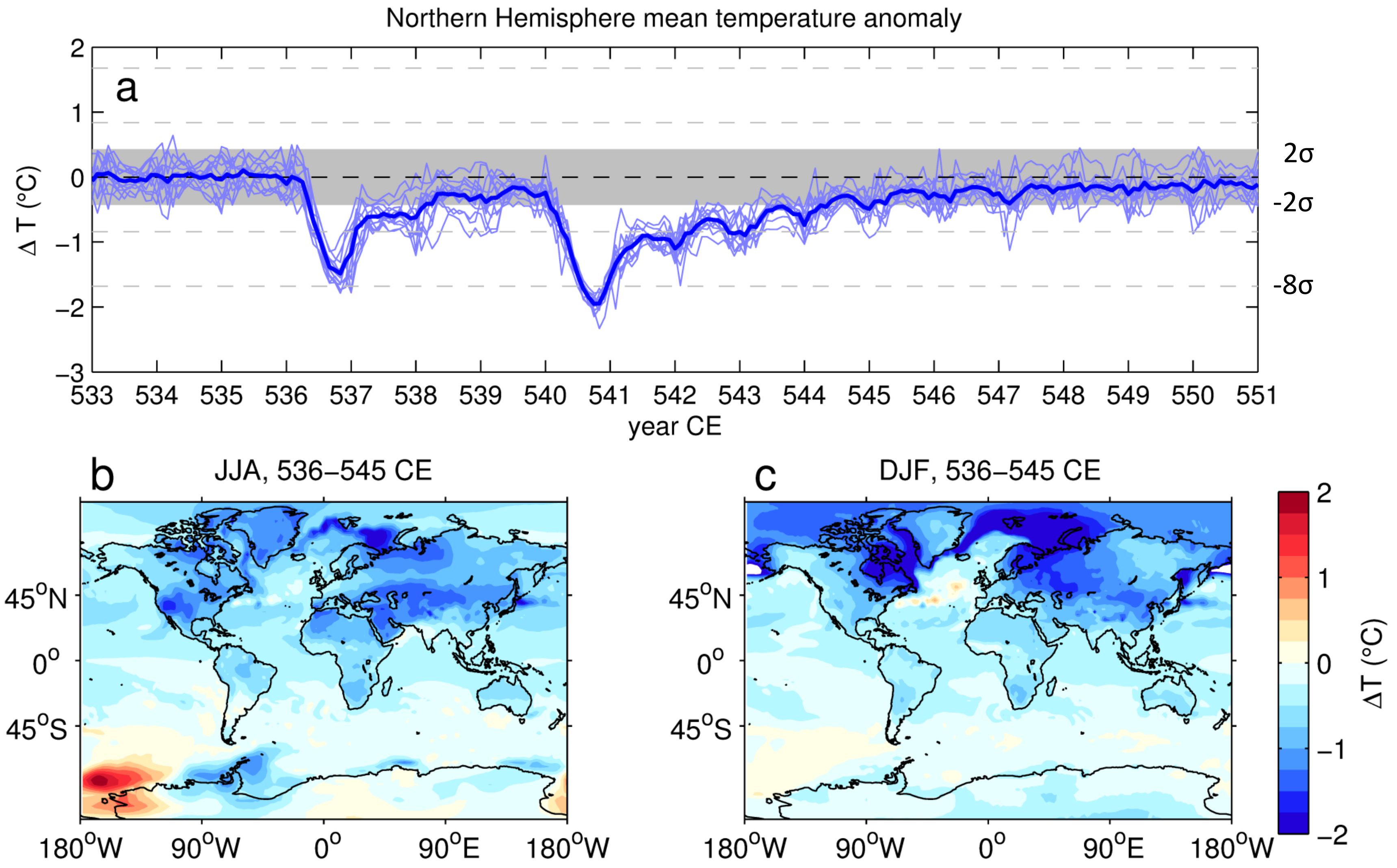
Max Planck Institute ESM

- MPI-ESM: comprehensive Earth system model
  - Atmospheric component ECHAM6.
  - “low resolution” (LR, T63/L47), configuration used here.
- 536 CE simulations:
  - Volcanic aerosols are prescribed from MAECHAM5-HAM reconstruction
  - 12 ensemble members
  - 15 years long, (536-550 CE)
  - Branched from pre-industrial control run (year 1850 conditions)



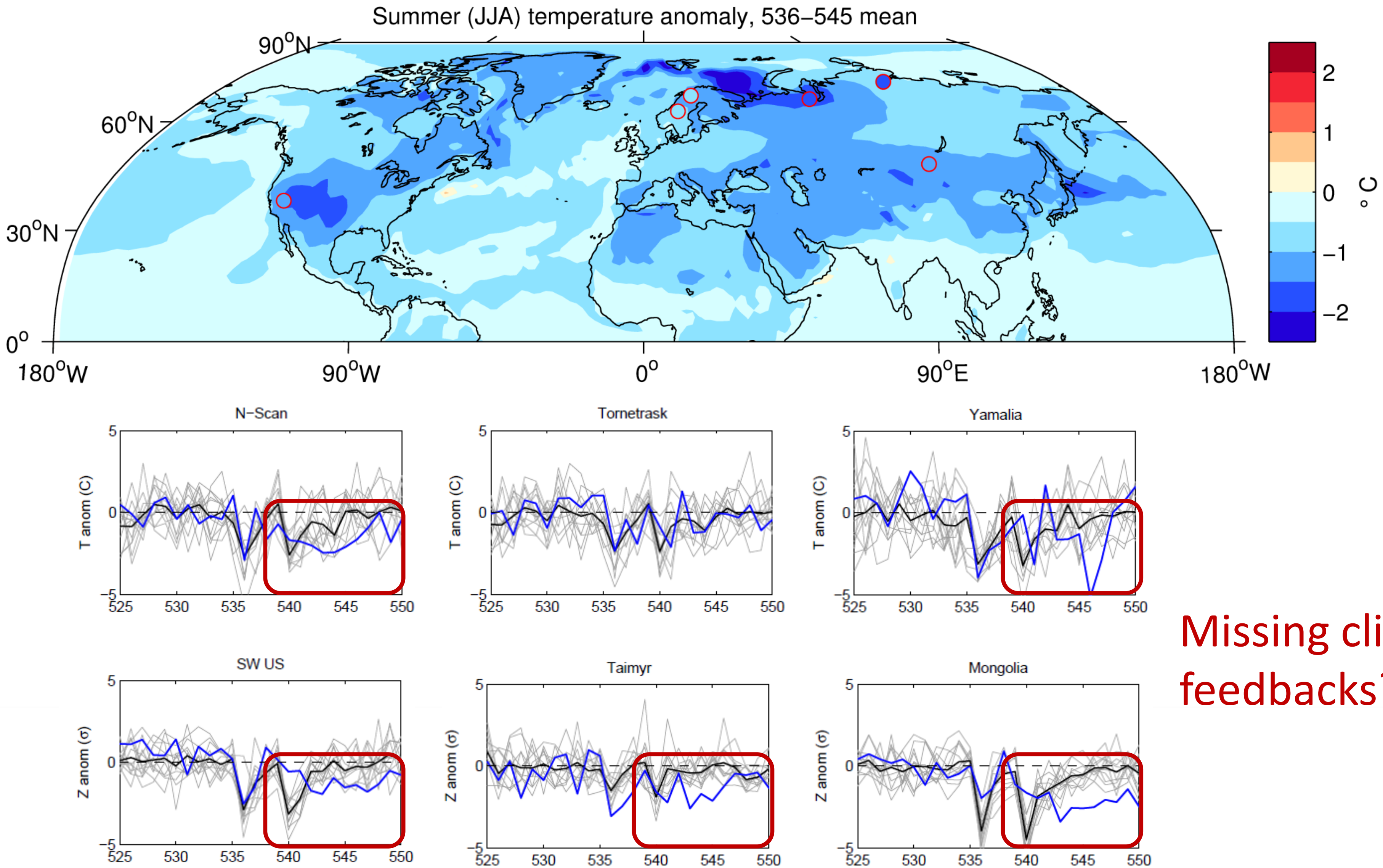


Temperature anomalies from MPI-ESM



Toohey et al., 2016

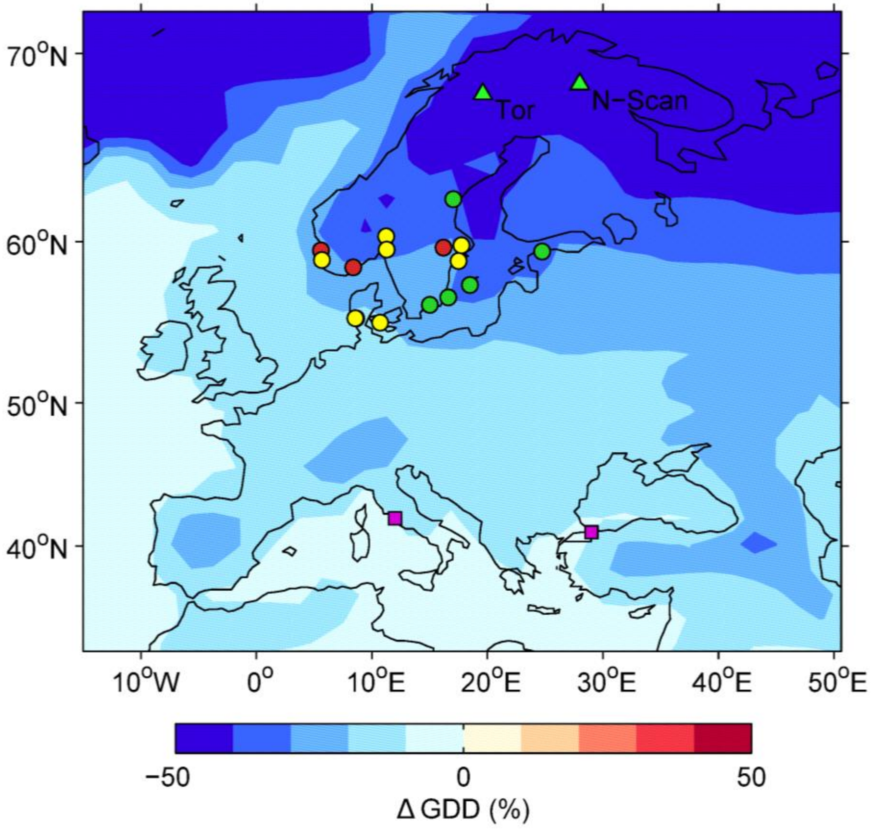
Simulated temperatures vs. tree-ring reconstructions



Missing climate feedbacks?

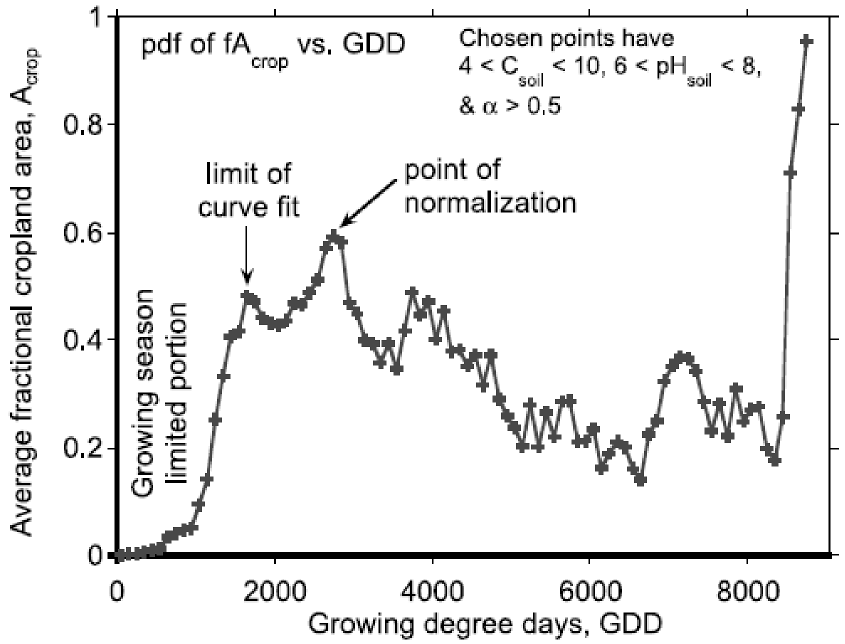
Estimating societal impacts

Simulated Growing Degree Day anomalies: 536 CE



$$GDD = \sum (T_{daily\_mean} - T_{base})$$

Ramankutty et al., 2002

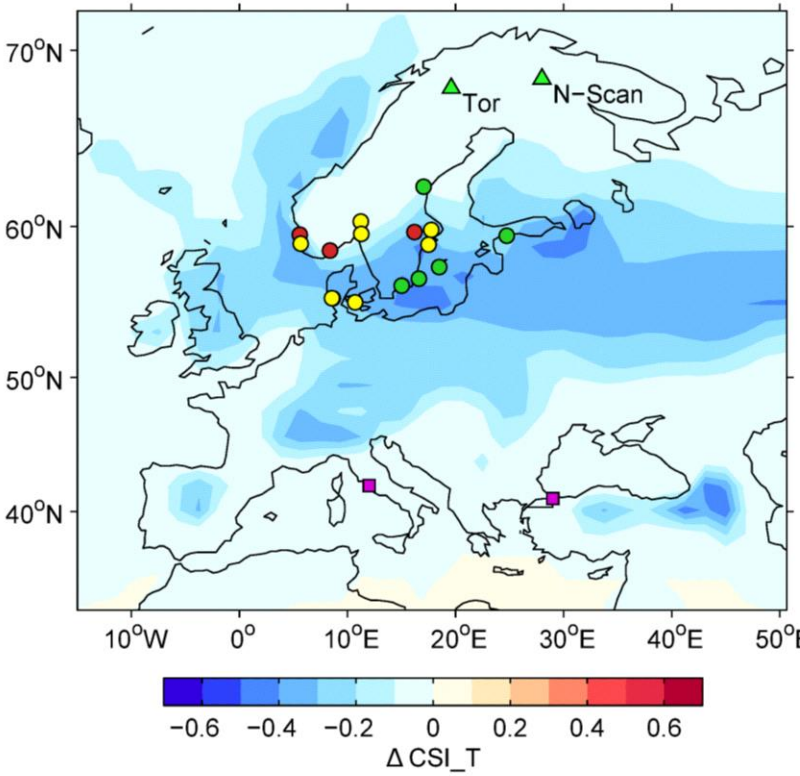


$$CSI_T(GDD) = \frac{1}{[1 + e^{a(b-GDD)}]}$$

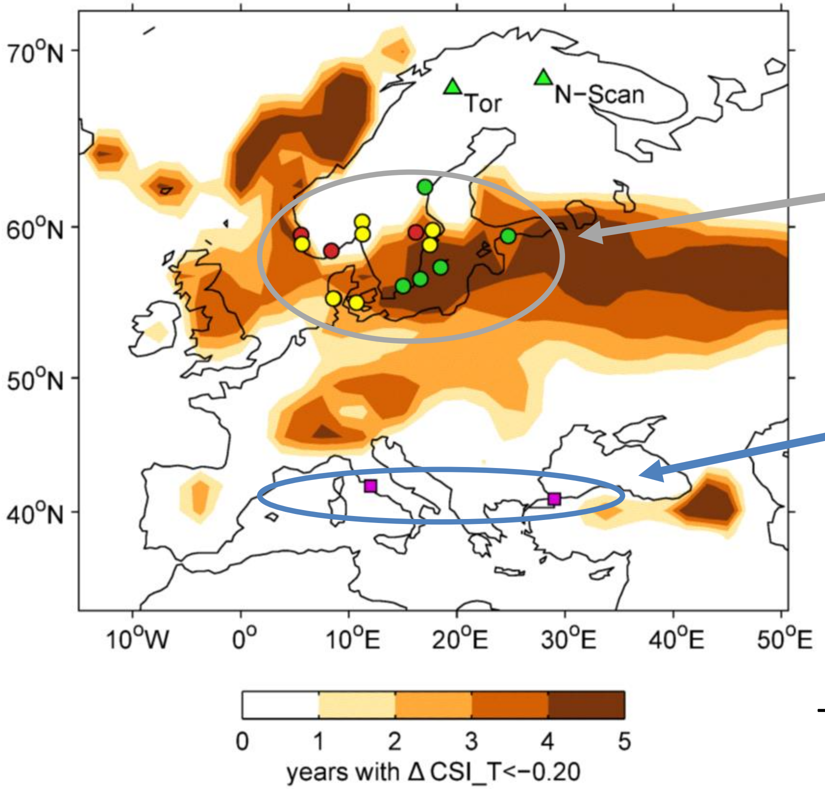
Cultivation Suitability Index due to temperature limitation

Societal impacts: Cultivation Suitability Index (CSI)

Change in CSI_T, 536 CE



Years with ΔCSI_T < -0.2, 536-545



Archaeological evidence for major population loss

Observations of mystery cloud, but no major food crisis

Toohey et al., 2016

- Ongoing collaborative work investigating the impact of 536/540 eruptions on precipitation, sea ice, and spread of malaria in Europe

VICS
VOLCANIC IMPACTS ON CLIMATE AND SOCIETY

Conclusions

- We reconstructed a plausible eruption and radiative forcing history for the 536/540 double event.

  → Based on natural archives and quantitative documentary data

- Climate model simulations using reconstructed forcing lead to:

→ max NH mean T anomalies of about -2°C.

→ Good agreement with available tree ring temperature reconstructions,

- Climate model temperature results interpreted in terms of the impact of temperature changes on agriculture imply:

→ multiple years of crop failure in Scandinavia for marginal agriculture.

→ minimal impact on agriculture in the Mediterranean

To learn more

- Toohey, M., Krüger, K., Sigl, M., Stordal, F. and Svensen, H.: Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages, Clim. Change, doi:10.1007/s10584-016-1648-7, 2016.

Session 4
Environmental history
Thursday am (09:00 - 12:00)

9:00-9:10 EGU Committee on Education: Introduction to the morning
9:10-10:00 Katrin Kleemann (*German Maritime Museum – Leibniz Institute for Maritime History*): Volcano eruptions physical and societal impacts. The case of the 1783 AD Laki eruption
10:00-10:50 Francis Ludlow (*Trinity College Dublin*): Finding Earth System Processes in Ancient Papyri and Medieval Chronicles, and Human History in Tree-Rings and Ice-Cores
10:50-11:10 Break
11:10-12:30 Hands-on activity by The EGU Field Officers team: Climate, Volcanoes and Humans: hands-on for the classroom

Session 5
Ice and ash
Friday pm (14:00 - 17:30)

14:00-14:10 EGU Committee on Education: Introduction to the afternoon
14:10-15:00 Christos Zerefos (*Research Center for Atmospheric Physics and Climatology, Academy of Athens*): Volcanoes, geophysics, climate and art
15:25-15:45 Break
15:45-16:45 Richard Williams (*Steffanson Arctic Institute*): Influence of volcanoes and glaciation on human history
16:45-17:30 EGU Committee on Education: Finale and networking event

VOLCANIC IMPACTS ON CLIMATE AND SOCIETY

https://cp.copernicus.org/articles/special_issue1060.html

Calbuco, Chile, April 2015