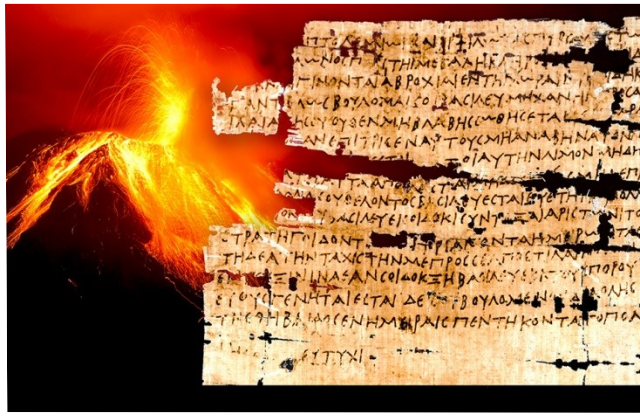
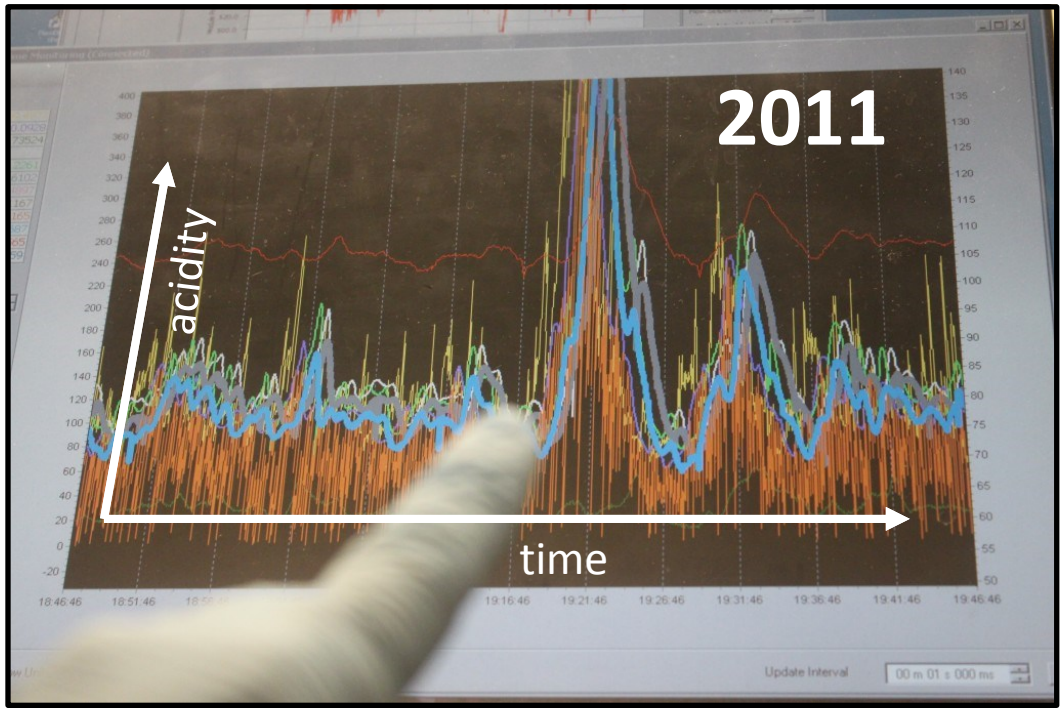
Shedding Light on Earth's Volcanic Past

How Common is Present-Day Volcanism in a Multi-Millennial Context?



Michael Sigl

Paul Scherrer Institute & Oeschger Center for Climate Change Research, University Bern



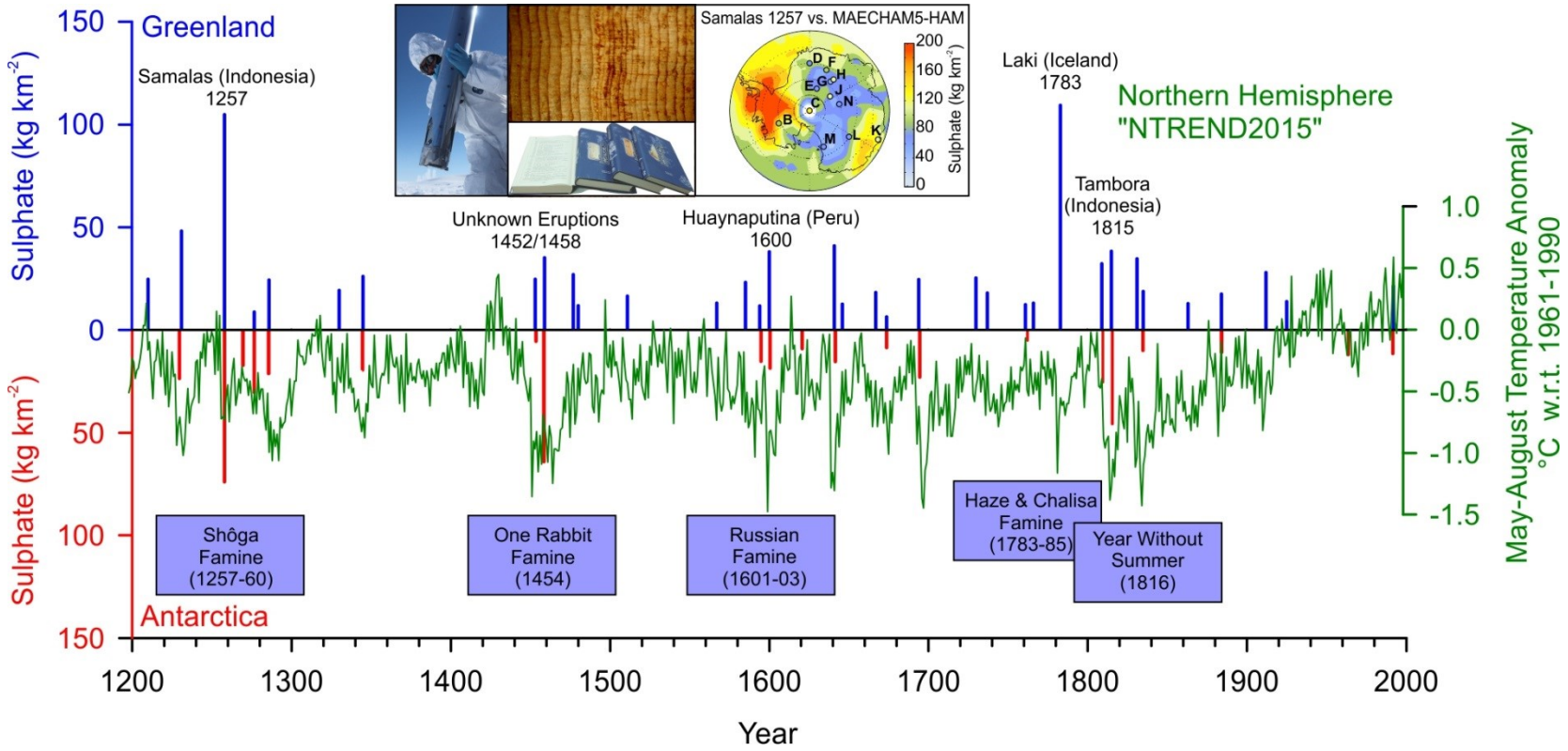
How I got interested in volcanoes…

(left): Volcanic event is observed as a massive increase in the conductivity of the melted ice – in many different ice cores!

Tool to align and evaluate ice-core chronologies.

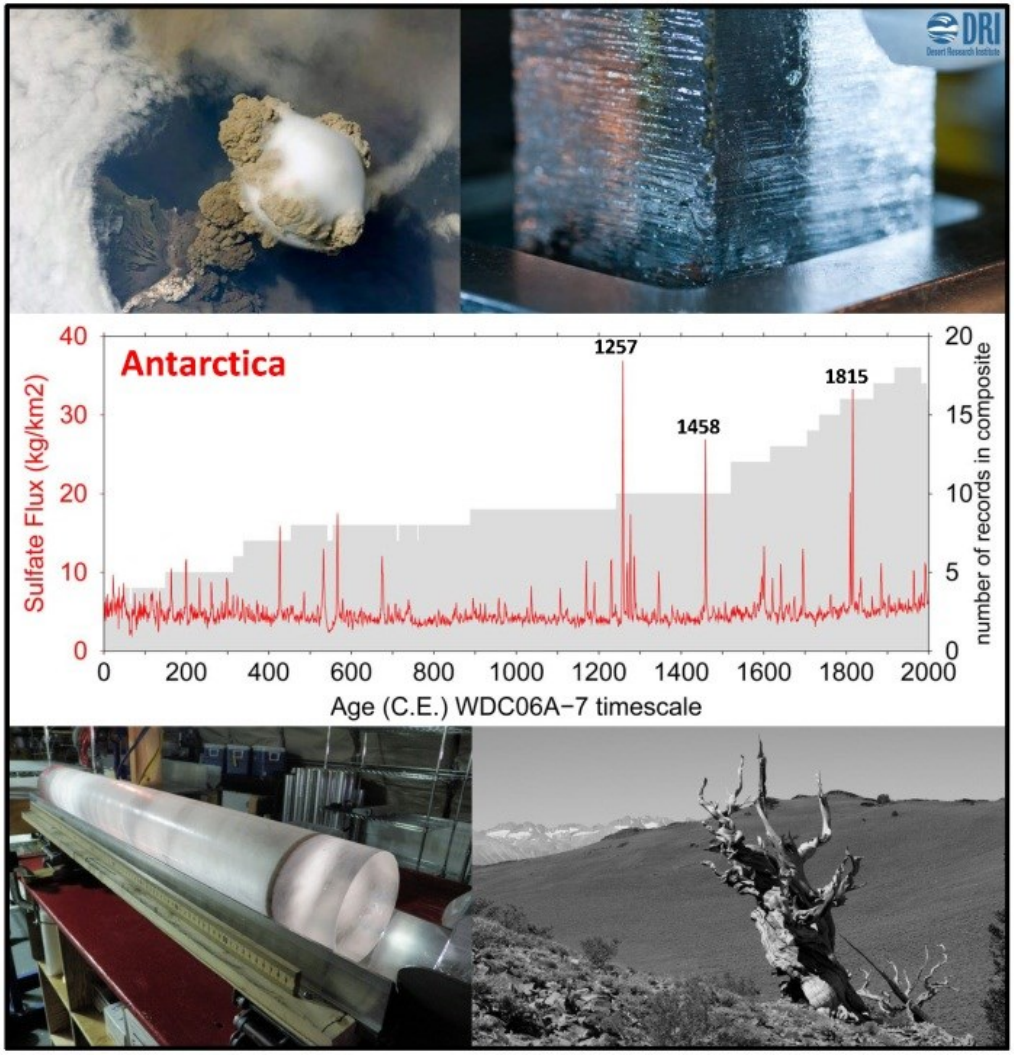
PAGES
PAST GLOBAL CHANGES

VOLCANIC IMPACTS ON CLIMATE AND SOCIETY



Outline

5) Post-Pinatubo



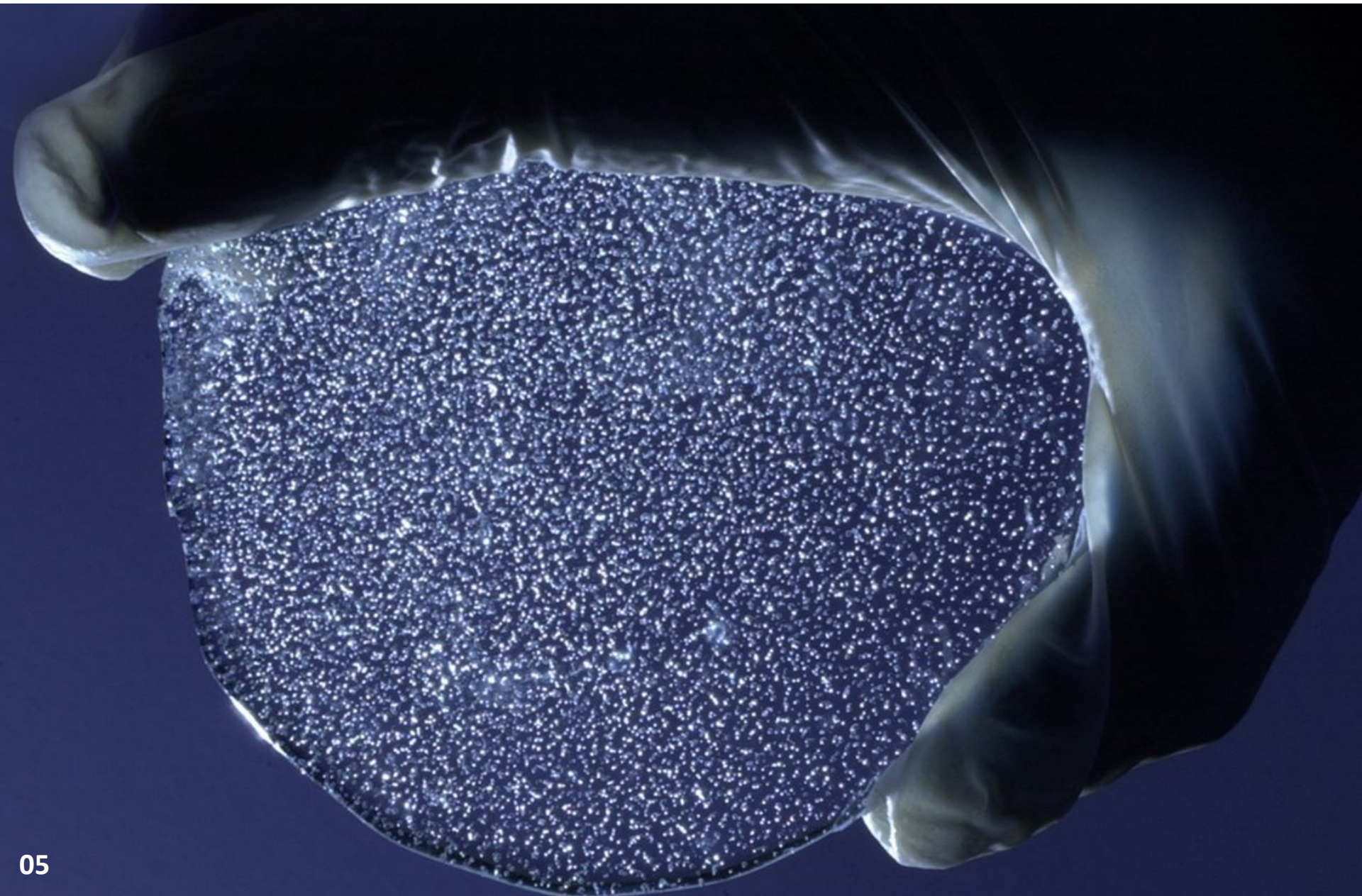
1) Ice Cores

2) Past Volcanism

4) New Proxies

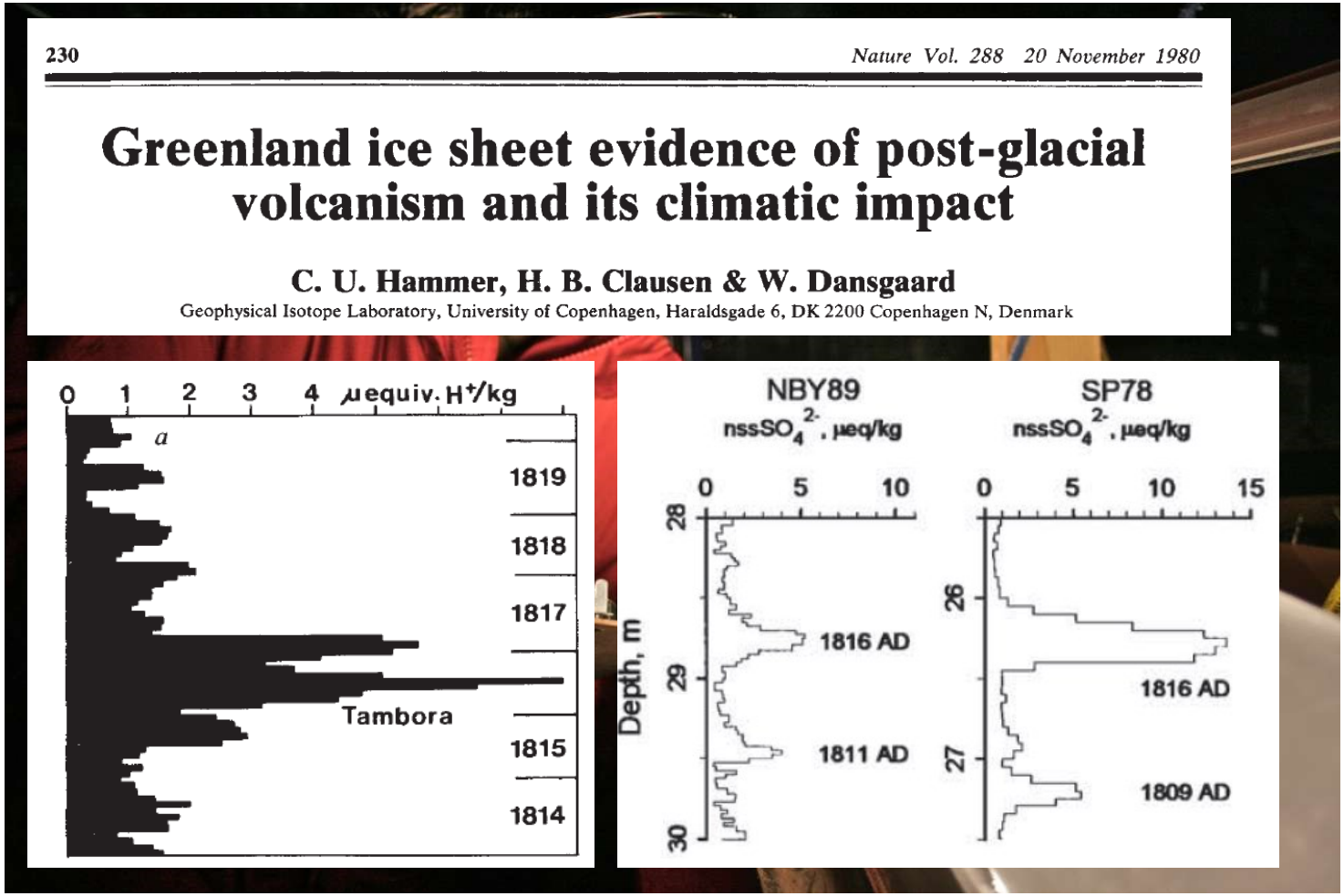
3) Climate

Ice Cores



Ice Cores

Ice Cores



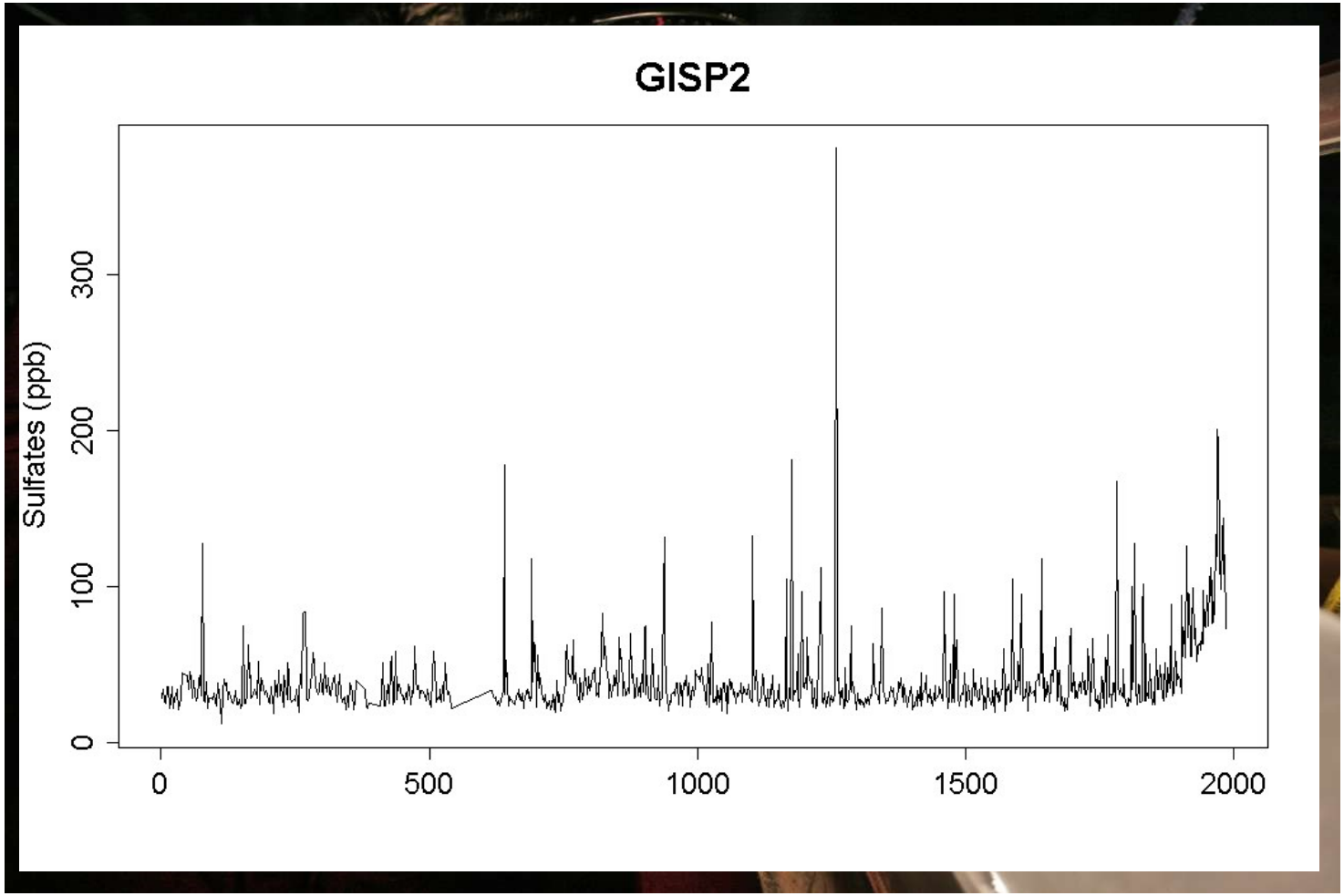
230 Nature Vol. 288 20 November 1980

Greenland ice sheet evidence of post-glacial volcanism and its climatic impact

C. U. Hammer, H. B. Clausen & W. Dansgaard
Geophysical Isotope Laboratory, University of Copenhagen, Haraldsgade 6, DK 2200 Copenhagen N, Denmark

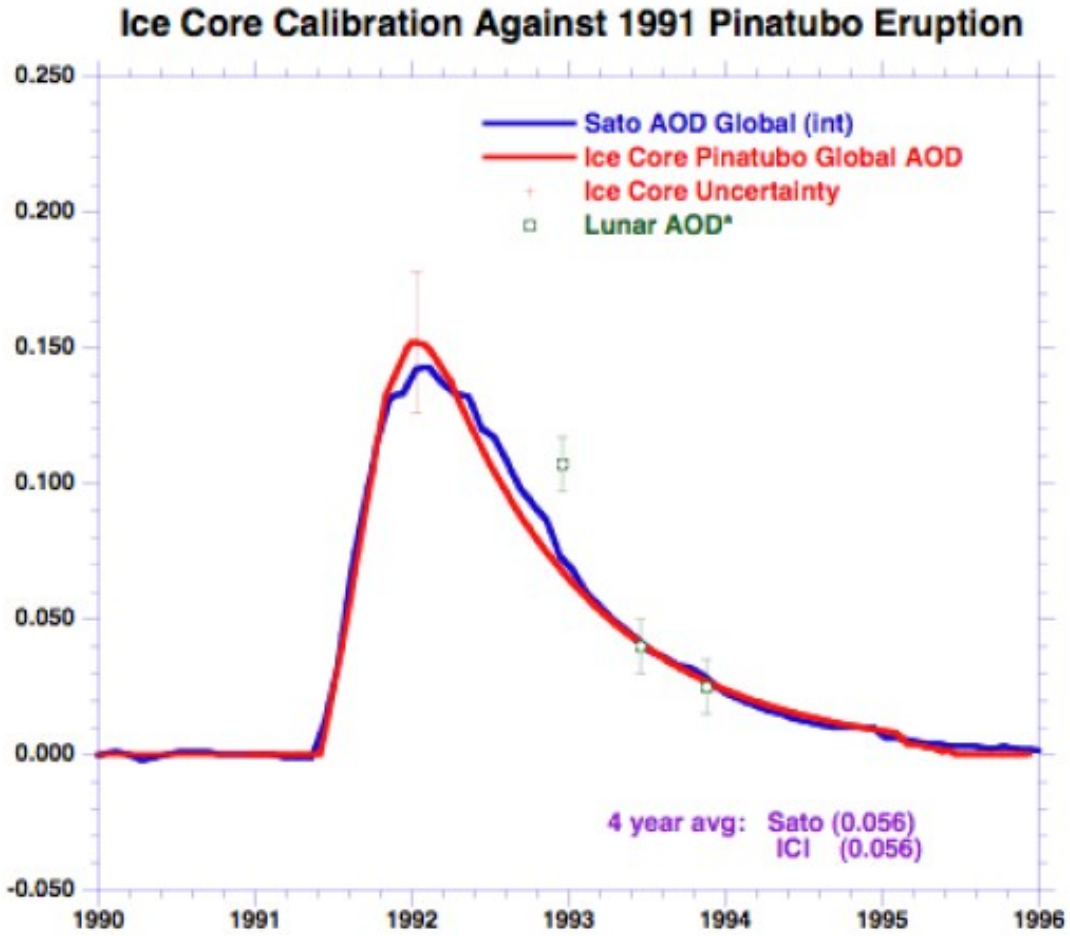
Hammer et al., 1980, Nature; Langway et al., J Geophys Res Atmos; 1995; Zielinski et al., 1994, Science

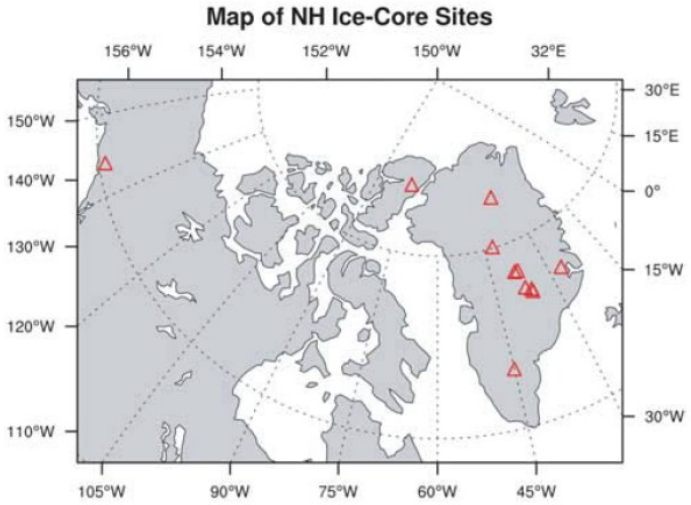
Ice Cores

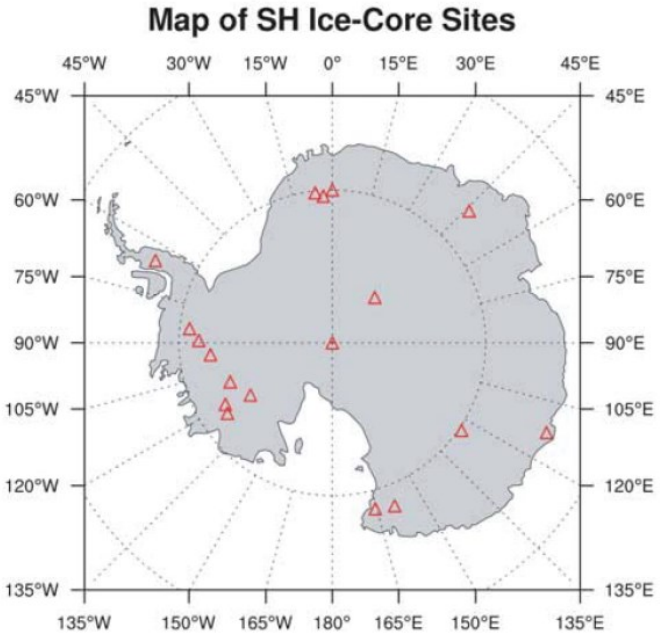


Hammer et al., 1980, Nature; Langway et al., J Geophys Res Atmos; 1995; Zielinski et al., 1994, Science

Ice Cores

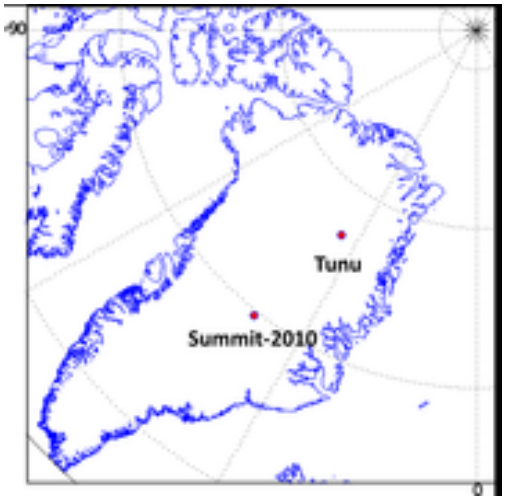




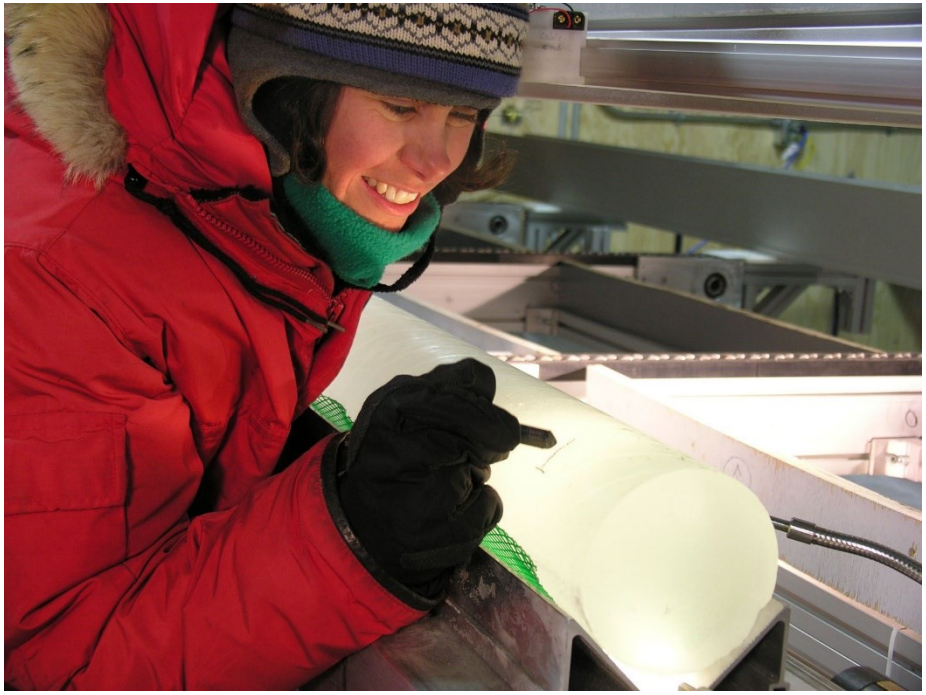


Robock & Free, 1995; J Geophys Res Atmos; Crowley, 2000, Science; Gao et al., 2008, J Geophys Res Atmos; Crowley & Unterman 2013; Earth System Science Data

Ice Cores

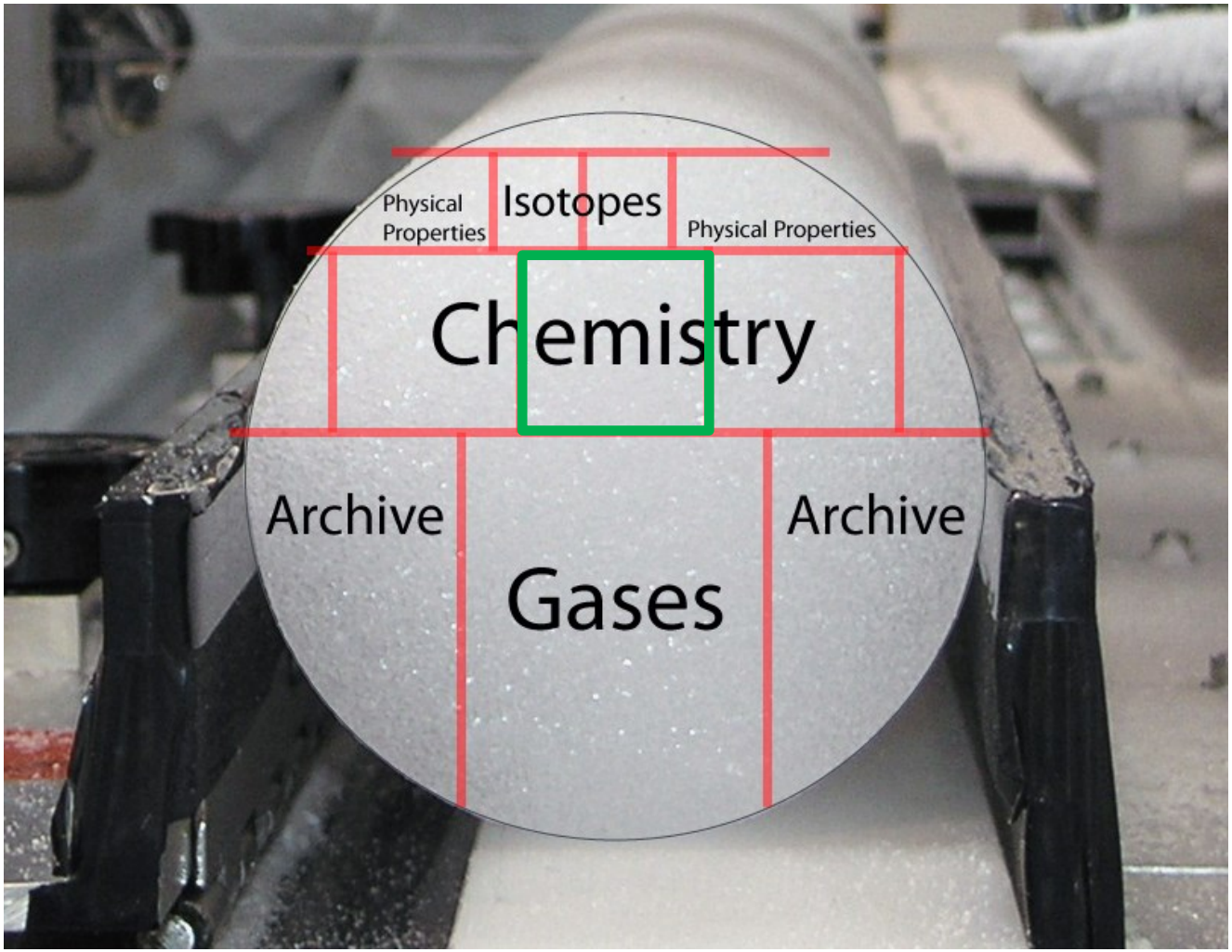


Ice Cores

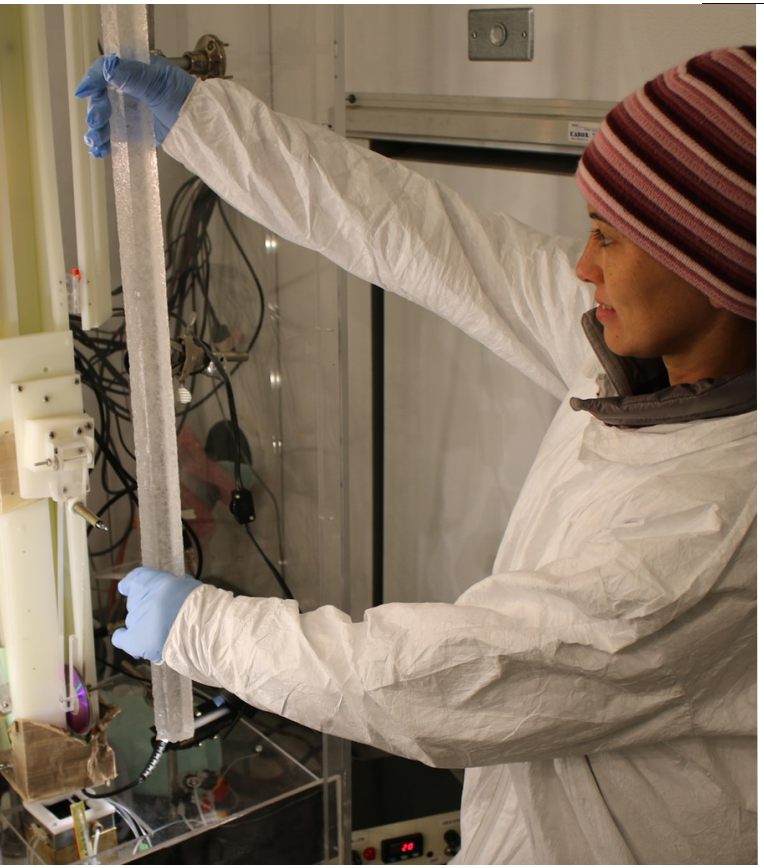


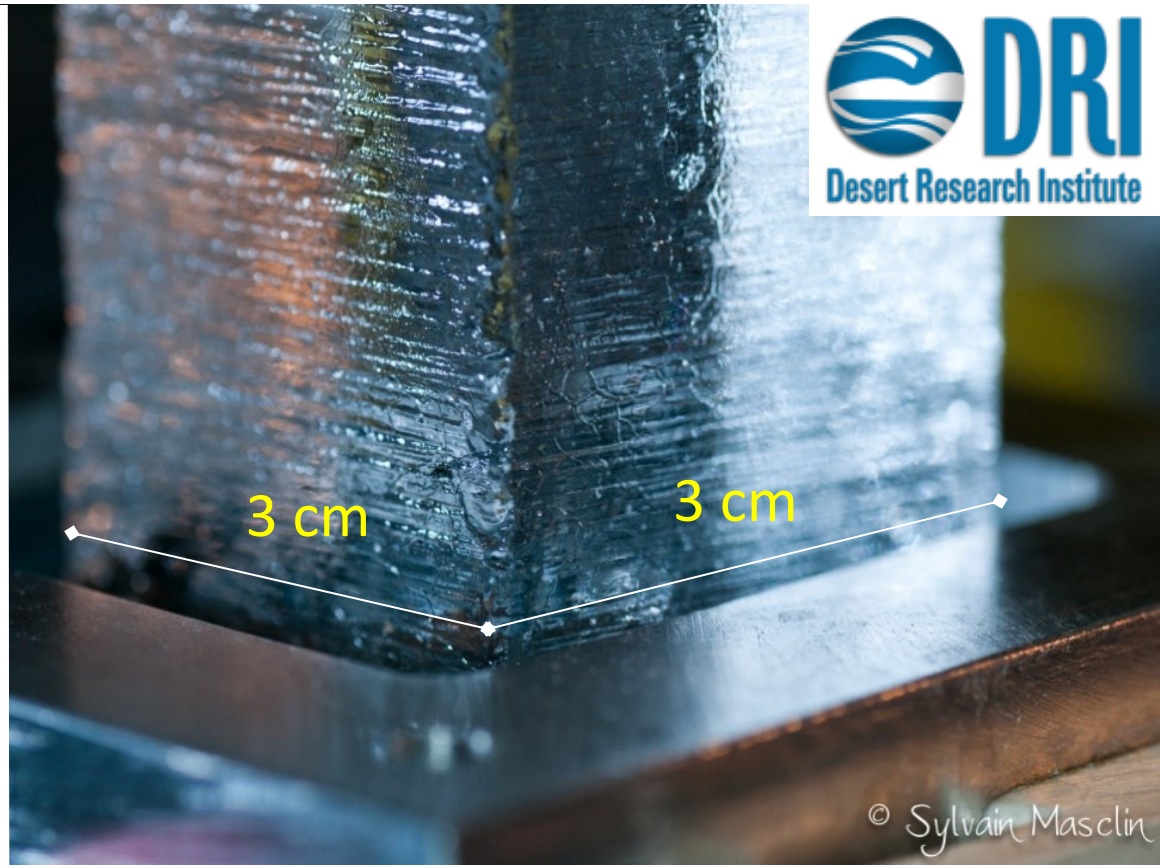
West Antarctic Ice Sheet Divide Ice Core

Ice Cores


Physical Properties
Isotopes
Physical Properties
Chemistry
Archive
Gases
Archive

Real-time ultra trace analyses





By using new, real-time, high-resolution measurement techniques we could develop a history of sulfate deposition for Antarctica and Greenland for the past 2,500 years.

DRI's Analytical System

Melter Head

Instrumented Melter Stand
Capacity 1.6 m Core
Melt Rate Measured
Continuously

Cold Lab

DEP I

DEP II

Na, Al, Rb, Sr, Y, In, Cd, I, Sb, Cs, Ba, La, Ce, Nd, Sm, Eu, Gd, Dy, Tl, Pb, Bi, Th, U

HR-ICP-MS II (Low Res)

Acidified Internal In Standard

Na, Mg, Al, P, S, Cl, Ca, V, Cr, Mn, Fe, Cu, Br, Rb, Sr, Y, In, La, Ce, Nd, Pb

HR-ICP-MS I (Med Res)

Inner Ring

Acidified External Y Standard

Middle Ring

CFA

Part Cnt

NO_3^- NH_4^+ Liq Cond Acidity

NO_3^-

DOC

Water Isotopes

Liq Cond

Single Particle Soot Photometer

Liq Cond

Black Carbon

Liq Cond

Gas/Water Seperator

CH_4

Clean Lab

Wet La

KRAKEN

McConnell et al., 2017, Proc. Natl. Acad. Sci. U.S.A

DRI's Analytical System

Melter Head

Instrumented Melter Stand
Capacity 1.6 m Core
Melt Rate Measured
Continuously

Cold Lab

DEP I

DEP II

Na, Al, Rb, Sr, Y, In, Cd, I, Sb, Cs, Ba, La, Ce, Nd, Sm, Eu, Gd, Dy, Tl, Pb, Bi, Th, U

HR-ICP-MS II (Low Res)

Acidified Internal In Standard

Na, Mg, Al, P, S, Cl, Ca, V, Cr, Mn, Fe, Cu, Br, Rb, Sr, Y, In, La, Ce, Nd, Pb

HR-ICP-MS I (Med Res)

Inner Ring

Acidified External Y Standard

Middle Ring

CFA

Part Cnt

NO_3^- NH_4^+ Liq Cond Acidity

NO_3^-

DOC

Water Isotopes

Liq Cond

Single Particle Soot Photometer

Liq Cond

Black Carbon

Liq Cond

Gas/Water Seperator

CH_4

Clean Lab

Wet La

KRAKEN

McConnell et al., 2017, Proc. Natl. Acad. Sci. U.S.A

DRI's Analytical System

Melter Head

Instrumented Melter Stand
Capacity 1.6 m Core
Melt Rate Measured
Continuously

Cold Lab

DEP I

DEP II

Na, Al, Rb, Sr, Y, In, Cd, I, Sb, Cs, Ba, La, Ce, Nd, Sm, Eu, Gd, Dy, Tl, Pb, Bi, Th, U

HR-ICP-MS II (Low Res)

Acidified Internal In Standard

Na, Mg, Al, P, S, Cl, Ca, V, Cr, Mn, Fe, Cu, Br, Rb, Sr, Y, In, La, Ce, Nd, Pb

HR-ICP-MS I (Med Res)

Inner Ring

Acidified External Y Standard

Middle Ring

CFA

Part Cnt

NO_3^- NH_4^+ Liq Cond Acidity

NO_3^-

Liq Cond

Gas/Water Seperator

CH_4

DOC

Water Isotopes

Liq Cond

Single Particle Soot Photometer

Liq Cond

Black Carbon

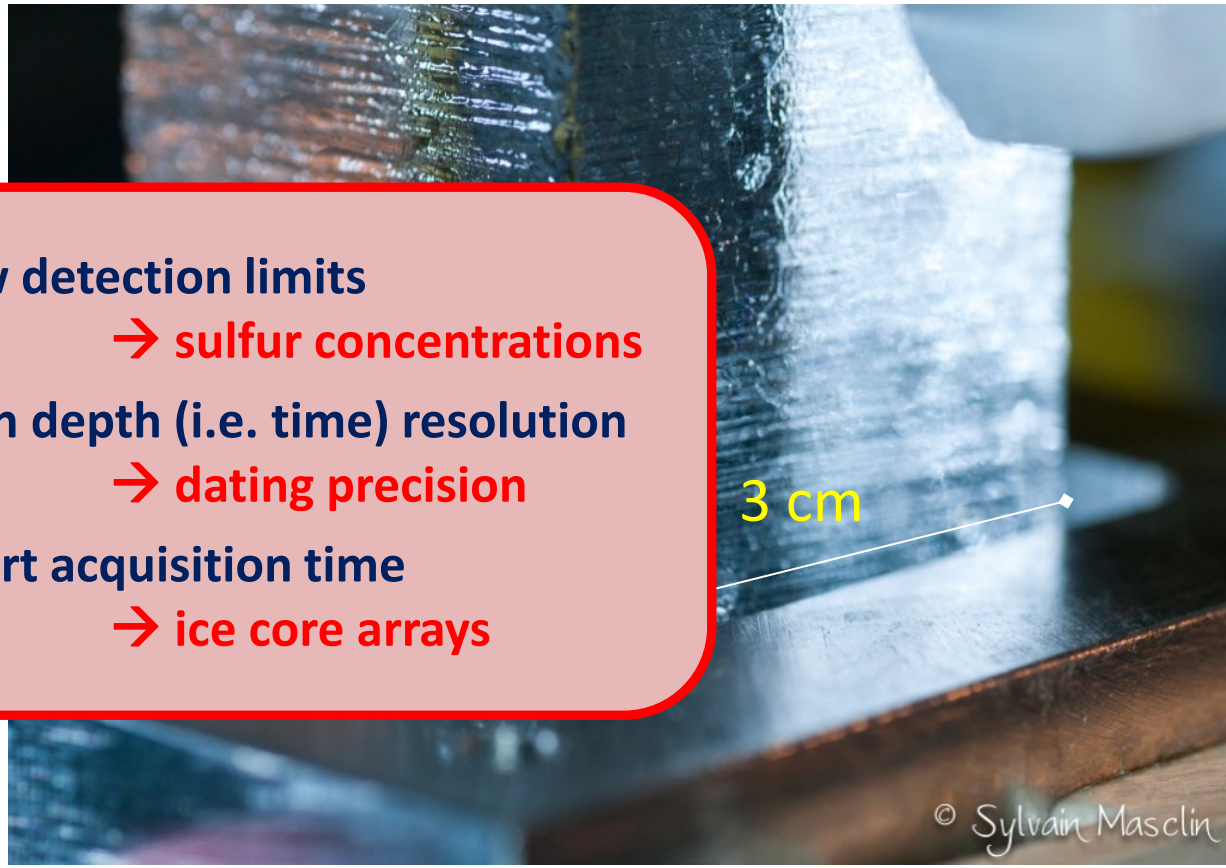
Clean Lab

Wet La

KRAKEN

McConnell et al., 2017, Proc. Natl. Acad. Sci. U.S.A

Real-Time Ultra-Trace Analysis



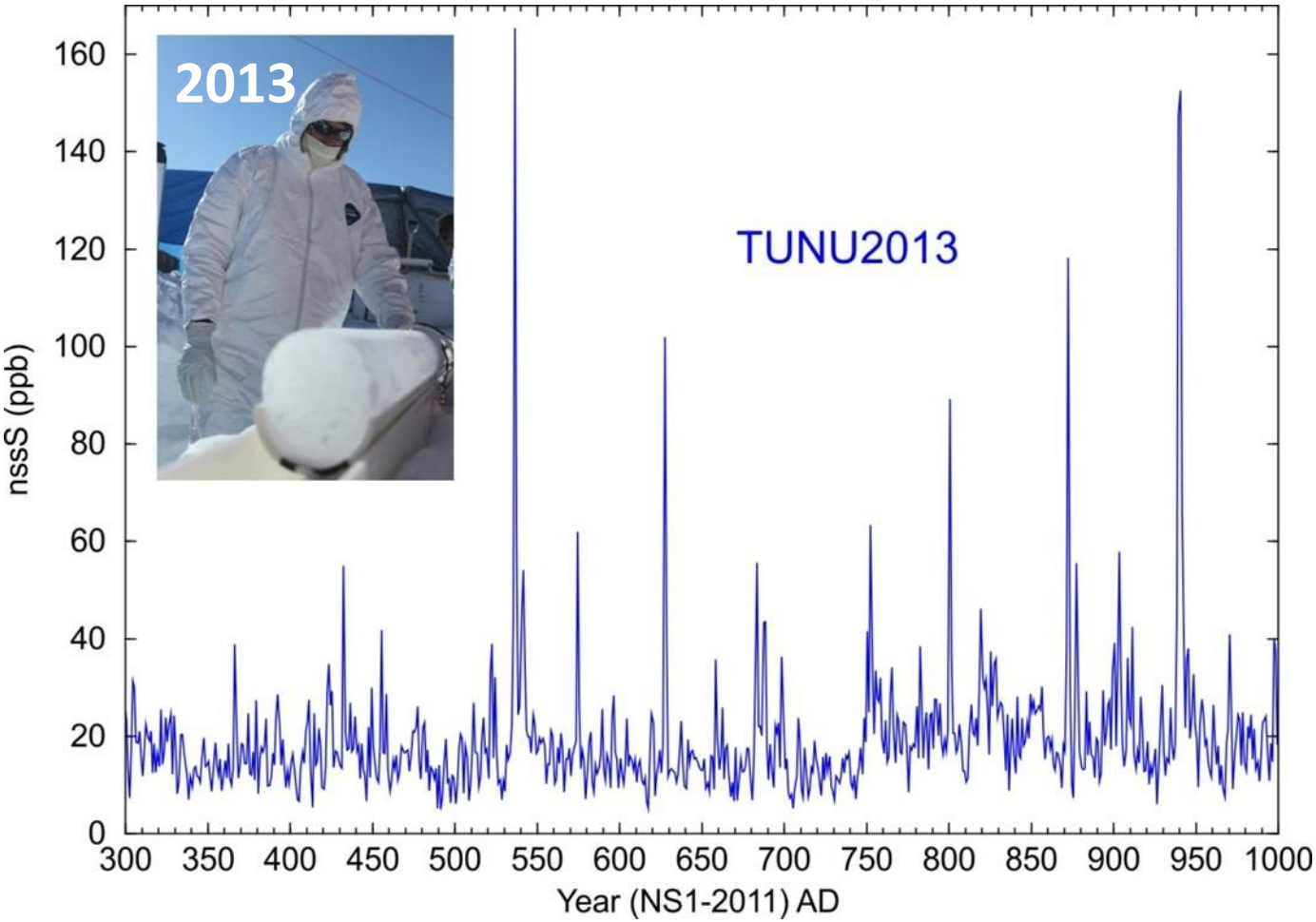
Low detection limits
→ **sulfur concentrations**

High depth (i.e. time) resolution
→ **dating precision**

Short acquisition time
→ **ice core arrays**

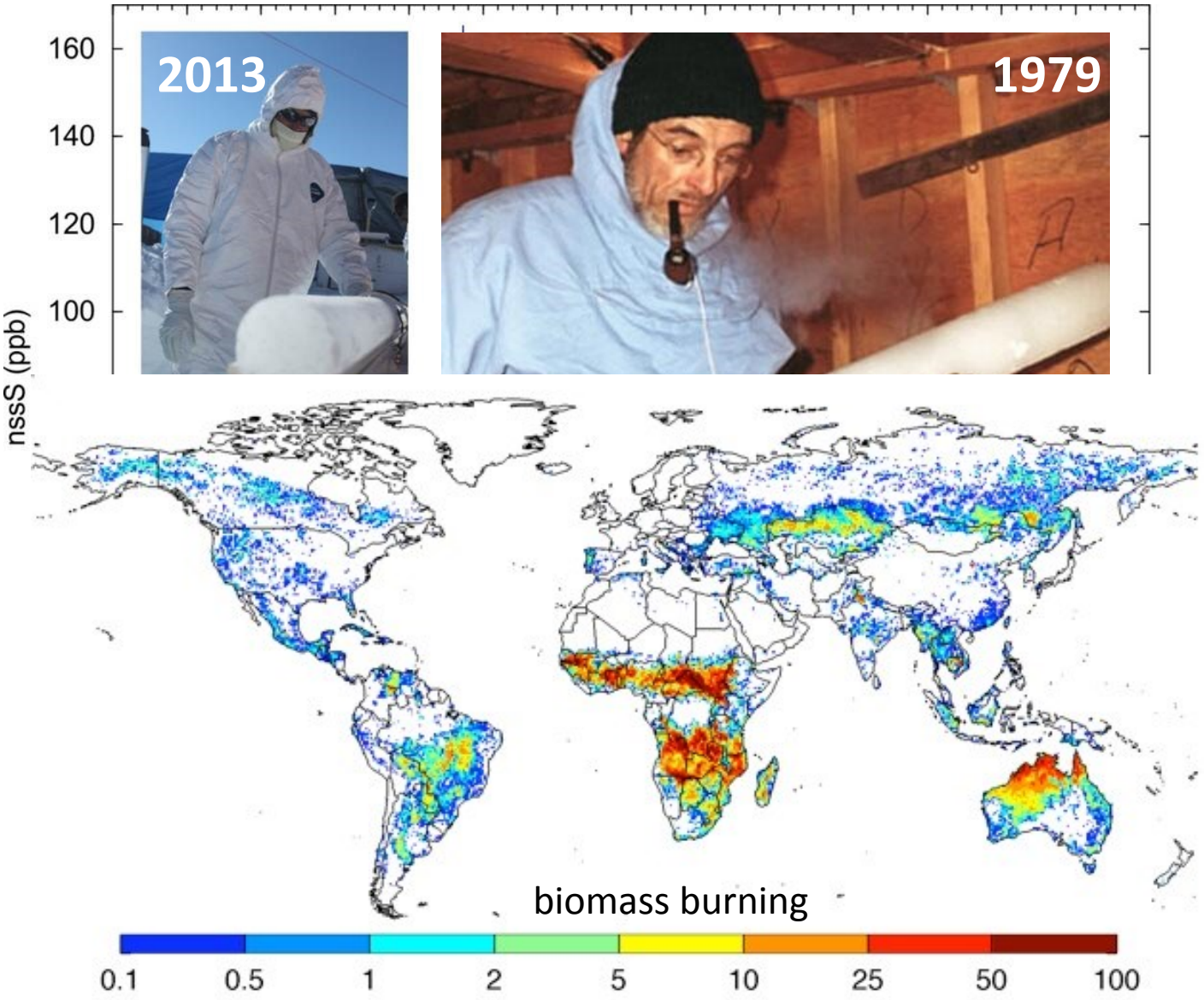
By using new, real-time, high-resolution measurement techniques we could develop a history of sulfate deposition for Antarctica and Greenland for the past 2,500 years.

Ice Core Dating

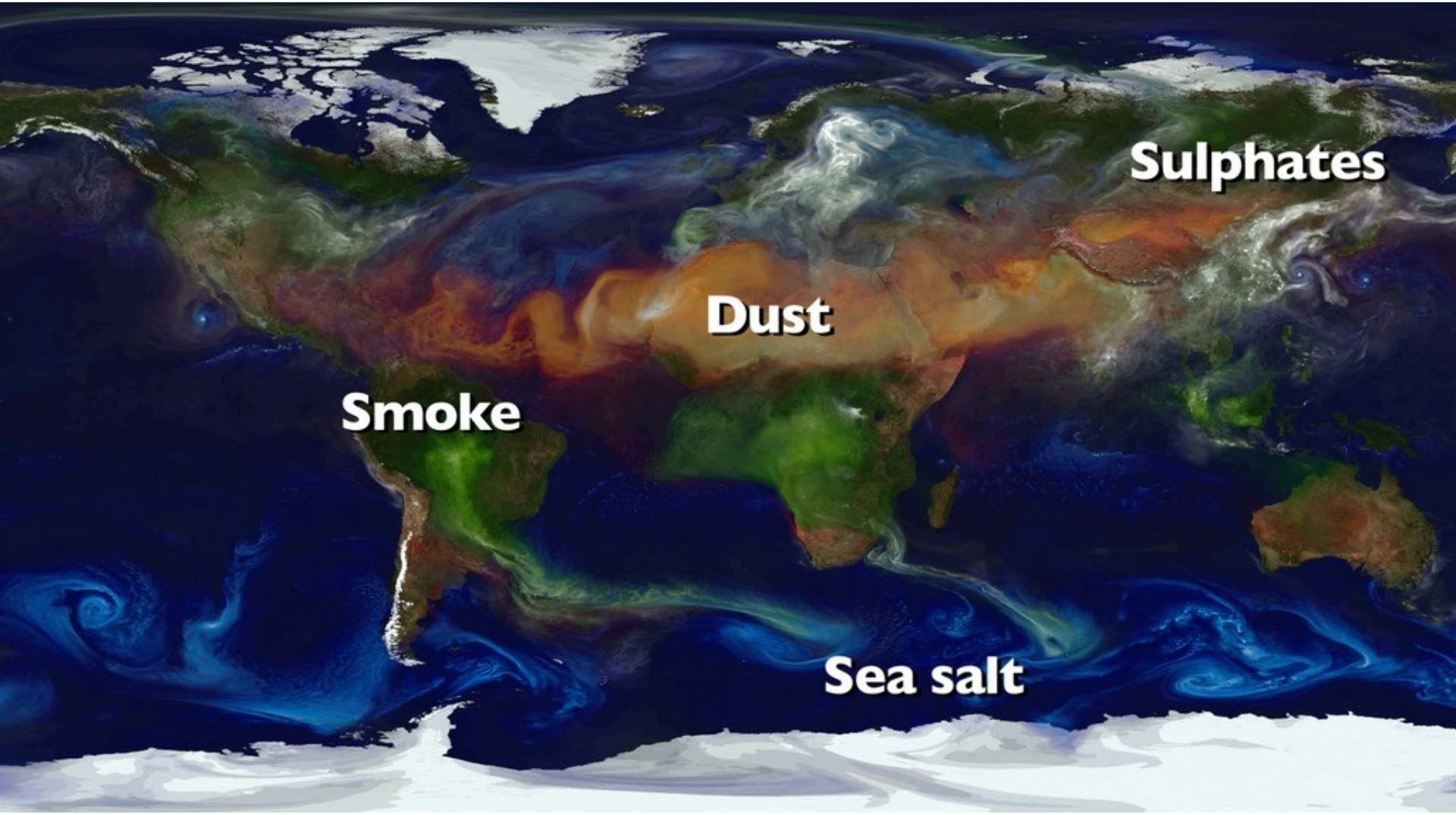


Sigl et al. 2015, Nature

Ice Core Dating

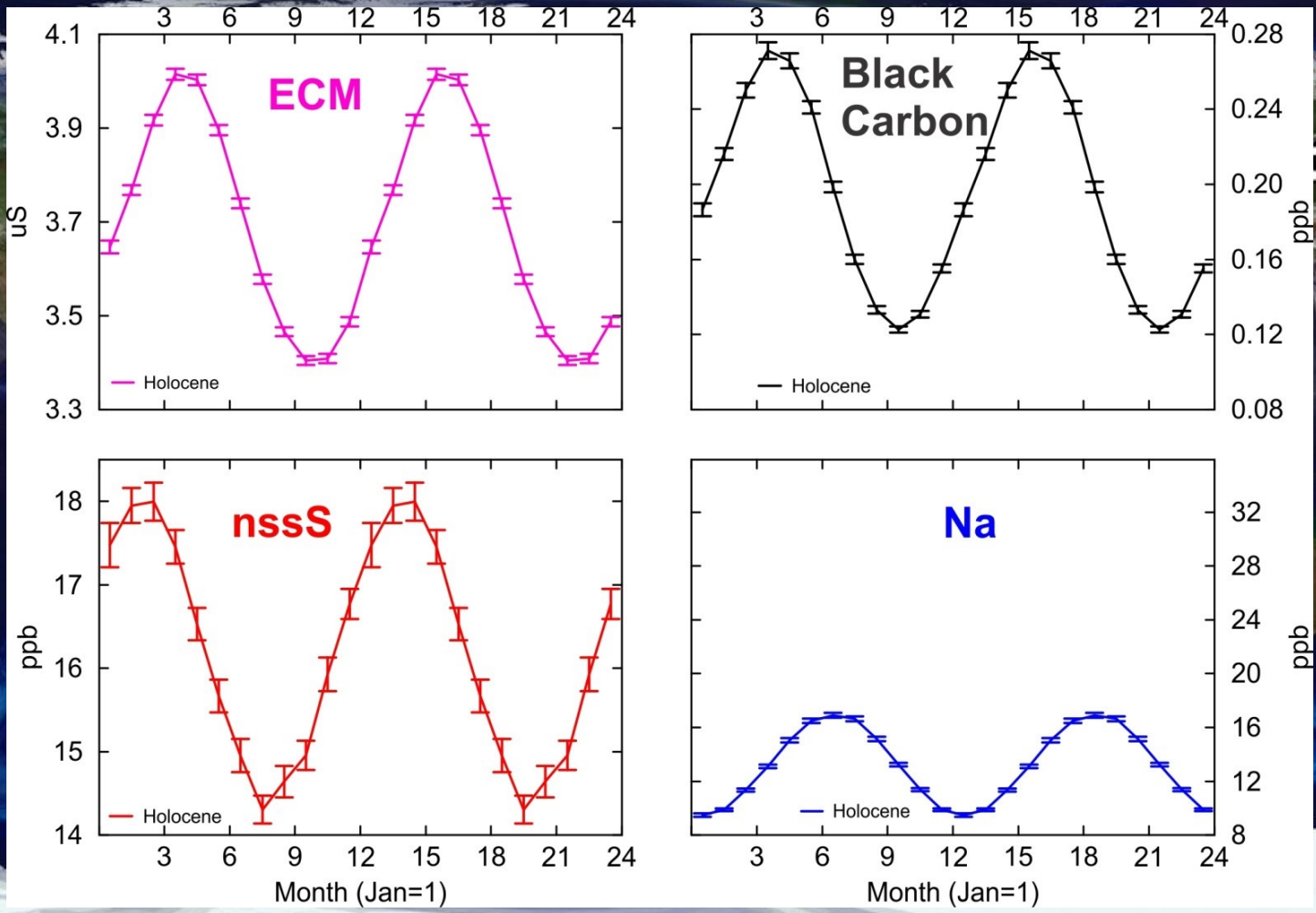


Ice Core Dating



Source: NASA

Ice Core Dating

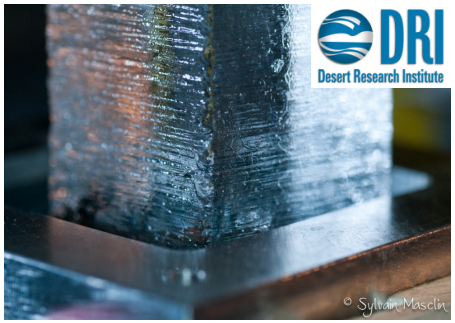


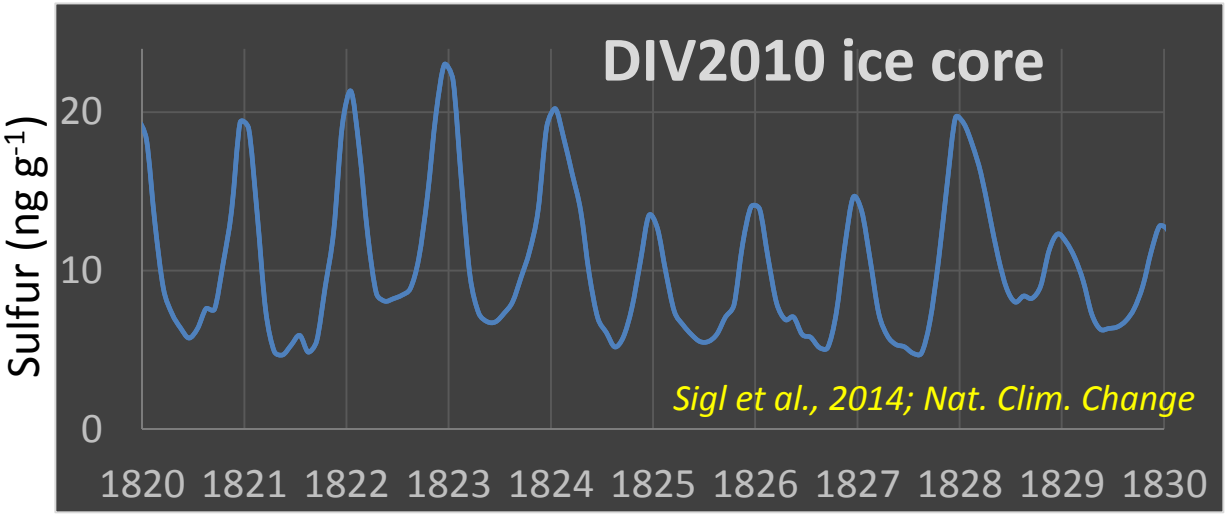
Source: NASA

Sigl et al., 2016; Clim. Past

Ice Core Dating

High-accumulation + high-resolution = high-precision





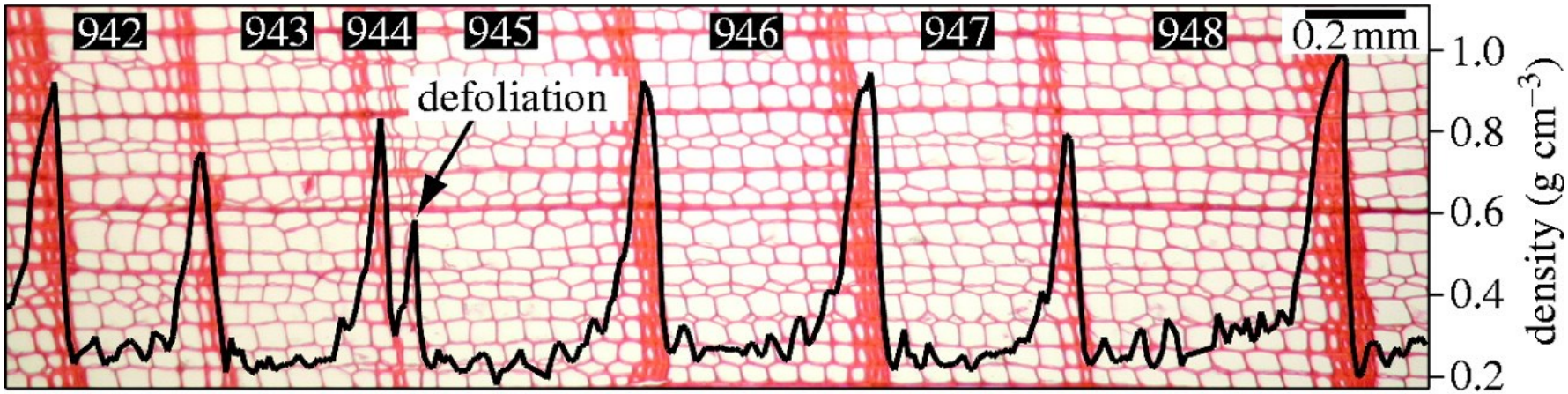
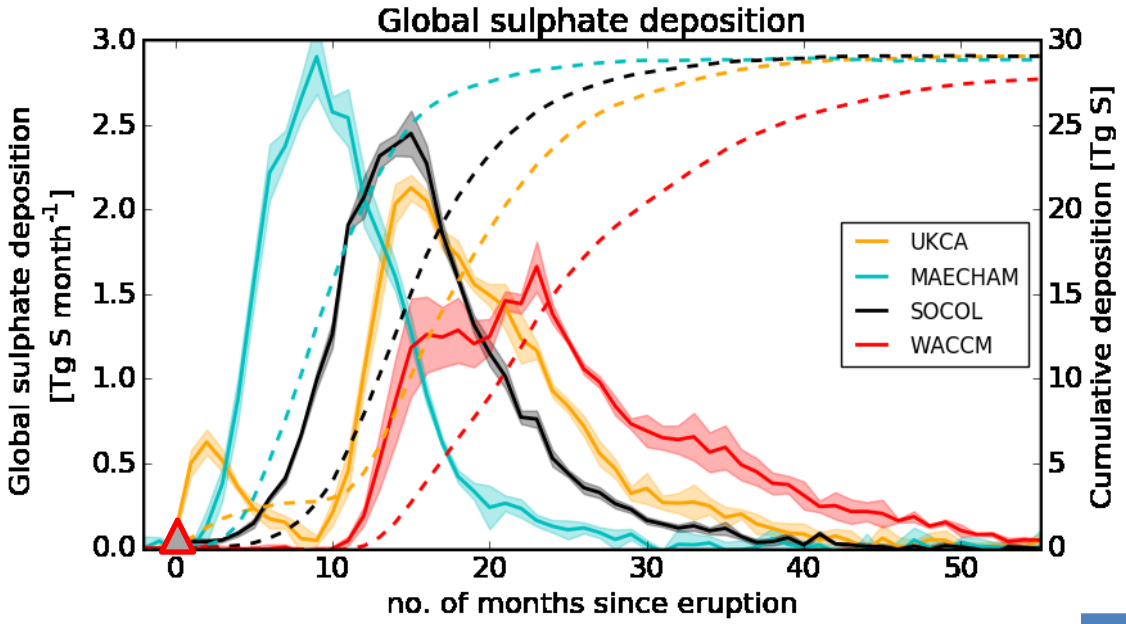
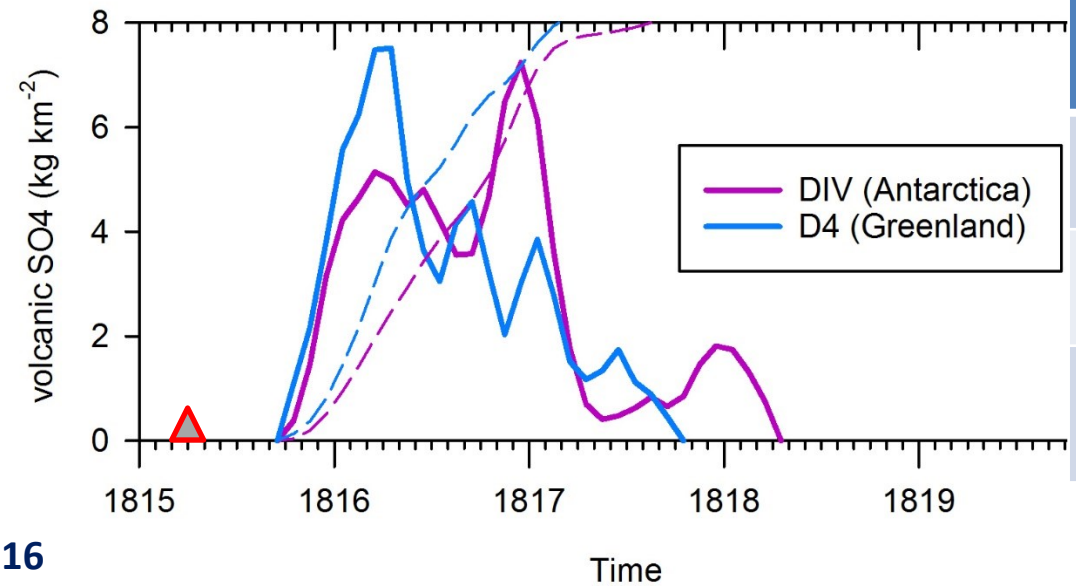


Photo: Jan Esper

Tambora 1815: Ice cores and climate models





Months since eruption (Apr. 1815)

Volc. SO_4	Greenland (D4 core)	Antarctica (DIV core)
Start	6	6
Peak	12	20
Duration (start-end)	24	30

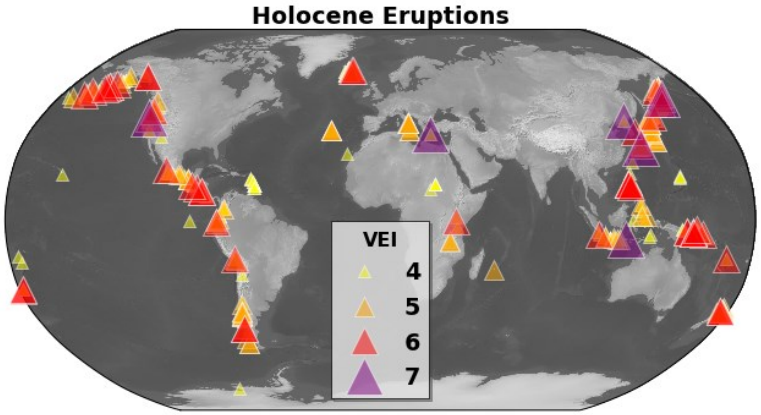
Marshall et al., 2018, Atmospheric Chem. Phys

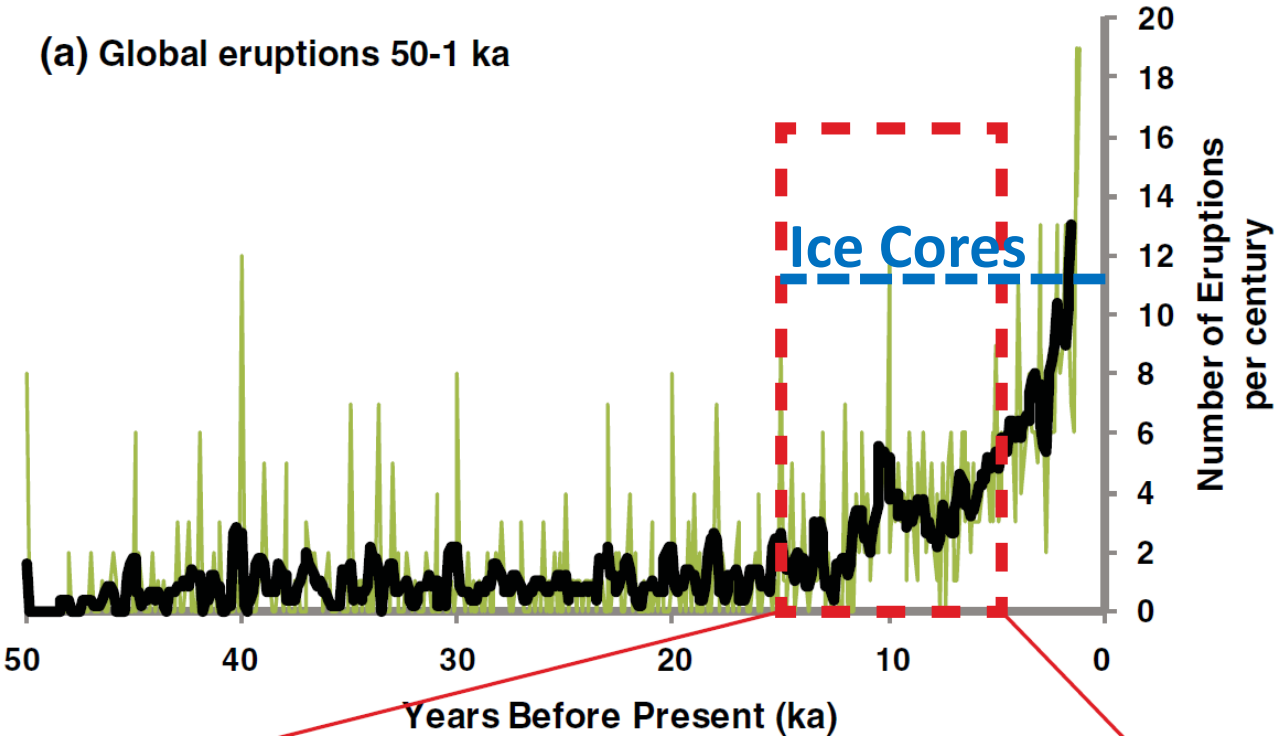
Past Volcansim

Geologic eruption records are incomplete!

Global recording rate:

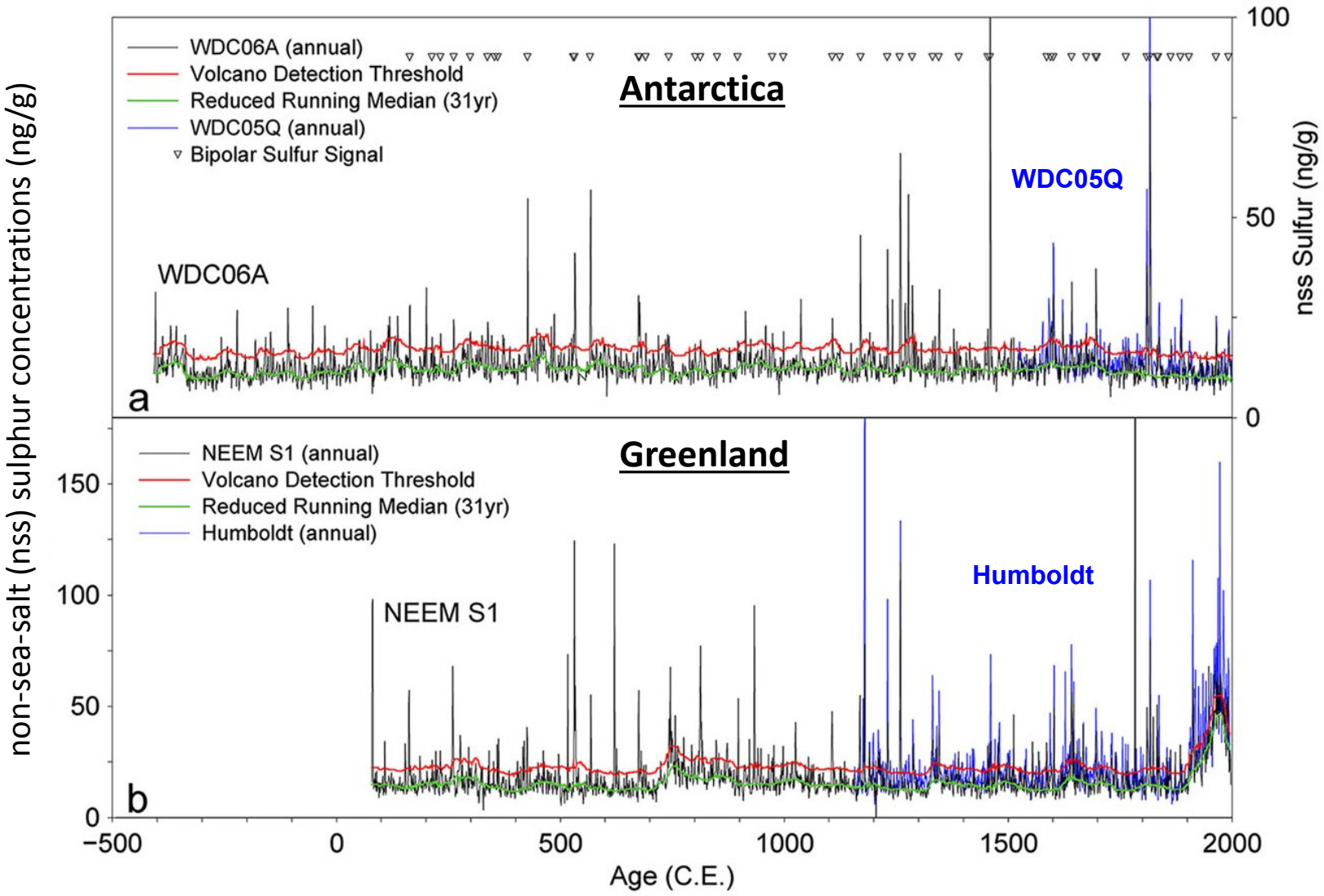
- ❑ before 1600 AD: **<50%**
- ❑ before 1100 AD: **< 20%**





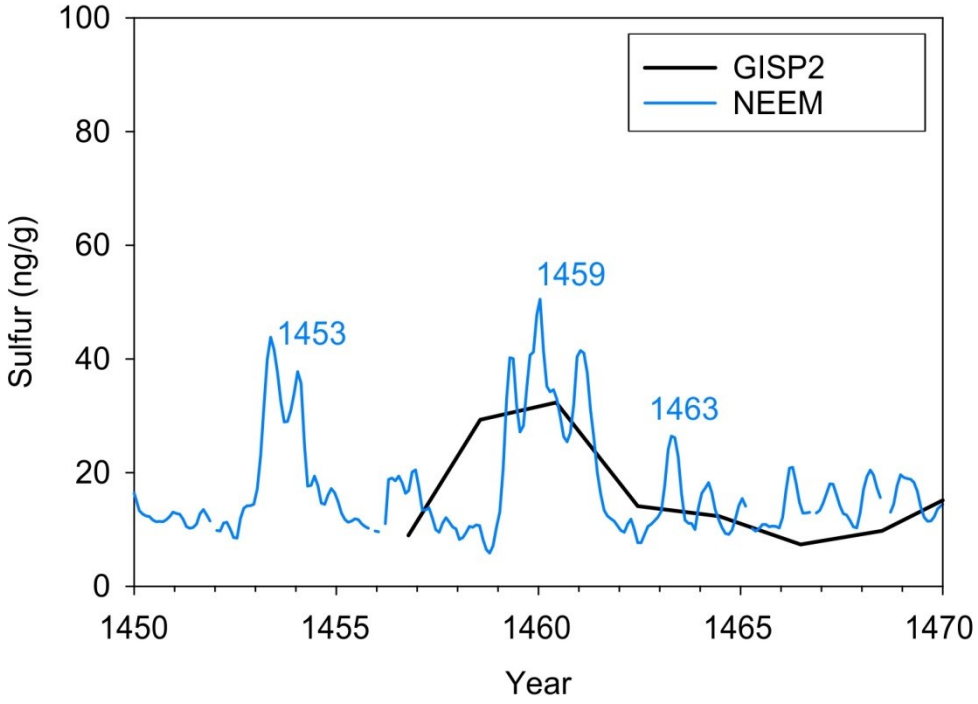
Brown et al., 2014, Journal of Applied Volcanology

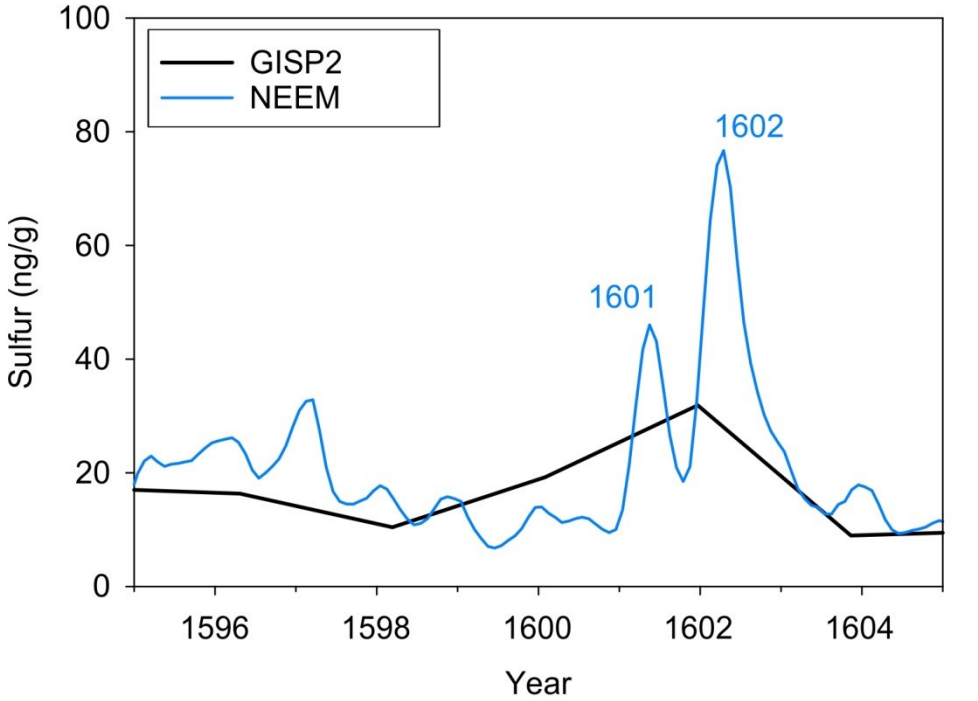
From single ice cores…



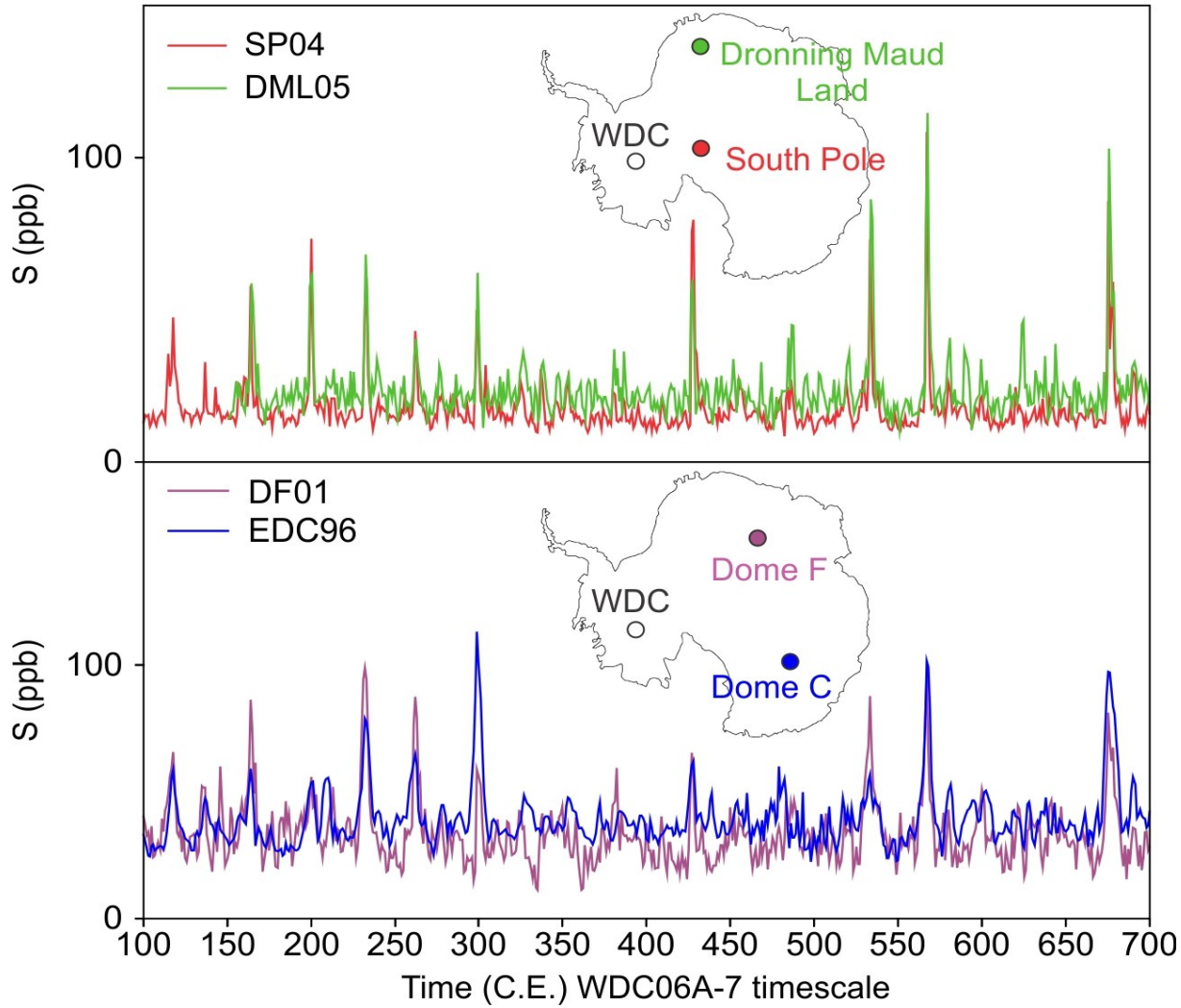
Due to the bipolar sulfate distribution about 50 volcanic eruptions dated and attributed to tropical eruptions, indicated by the triangles.

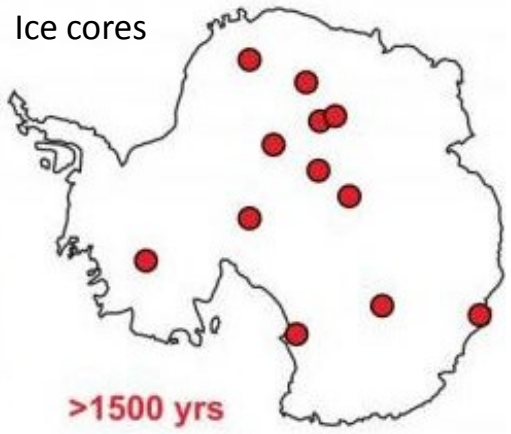
Sigl et al. 2013, J Geophys Res Atmos


GISP2
NEEM
1453
1459
1463
Sulfur (ng/g)
Year
0
20
40
60
80
100
1450
1455
1460
1465
1470


GISP2
NEEM
1601
1602
Sulfur (ng/g)
Year
0
20
40
60
80
100
1596
1598
1600
1602
1604

…towards a composite reconstruction

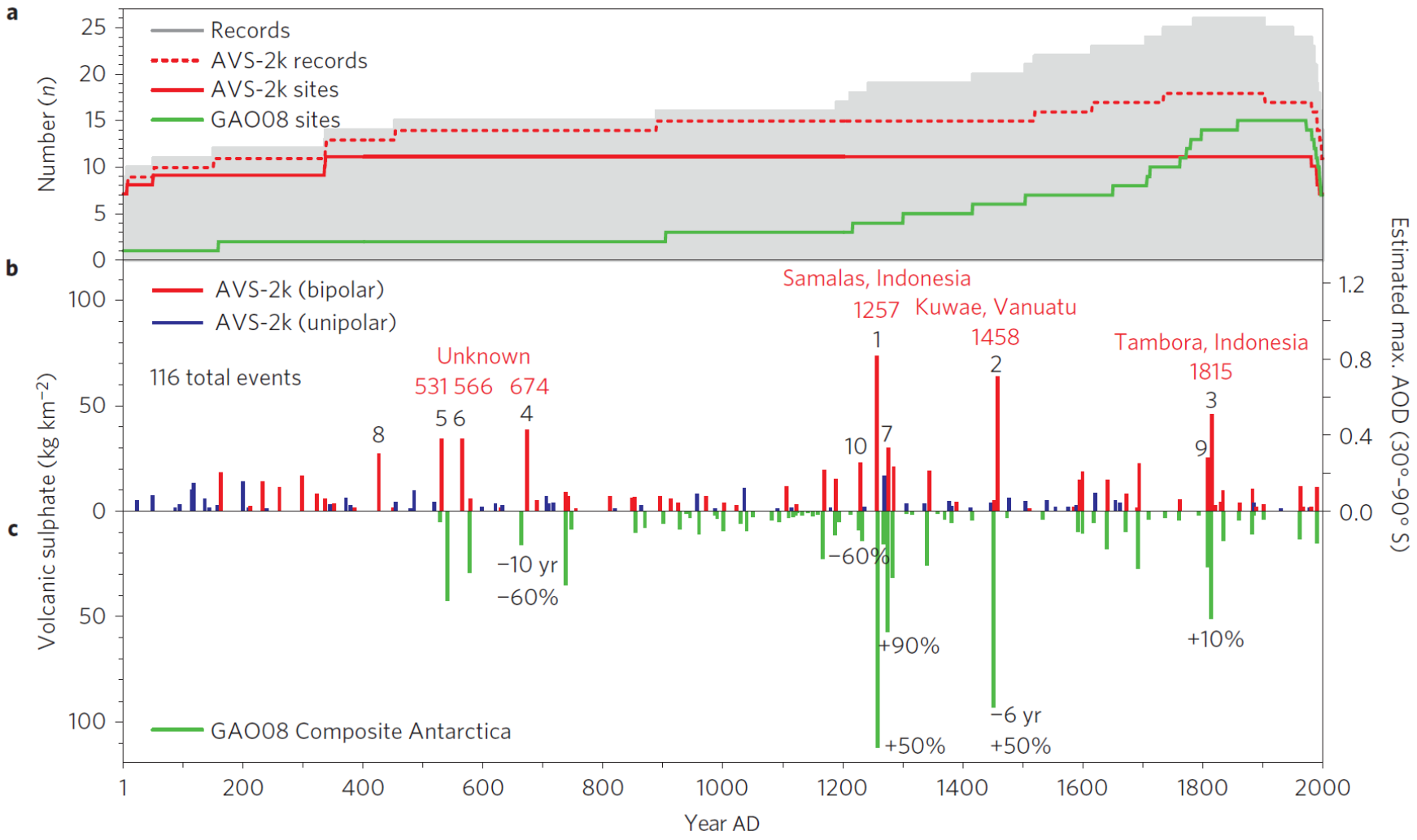




With 12 records covering the past 1,500 years, we can reconstruct robust estimates of sulfate deposition on larger spatial scales.

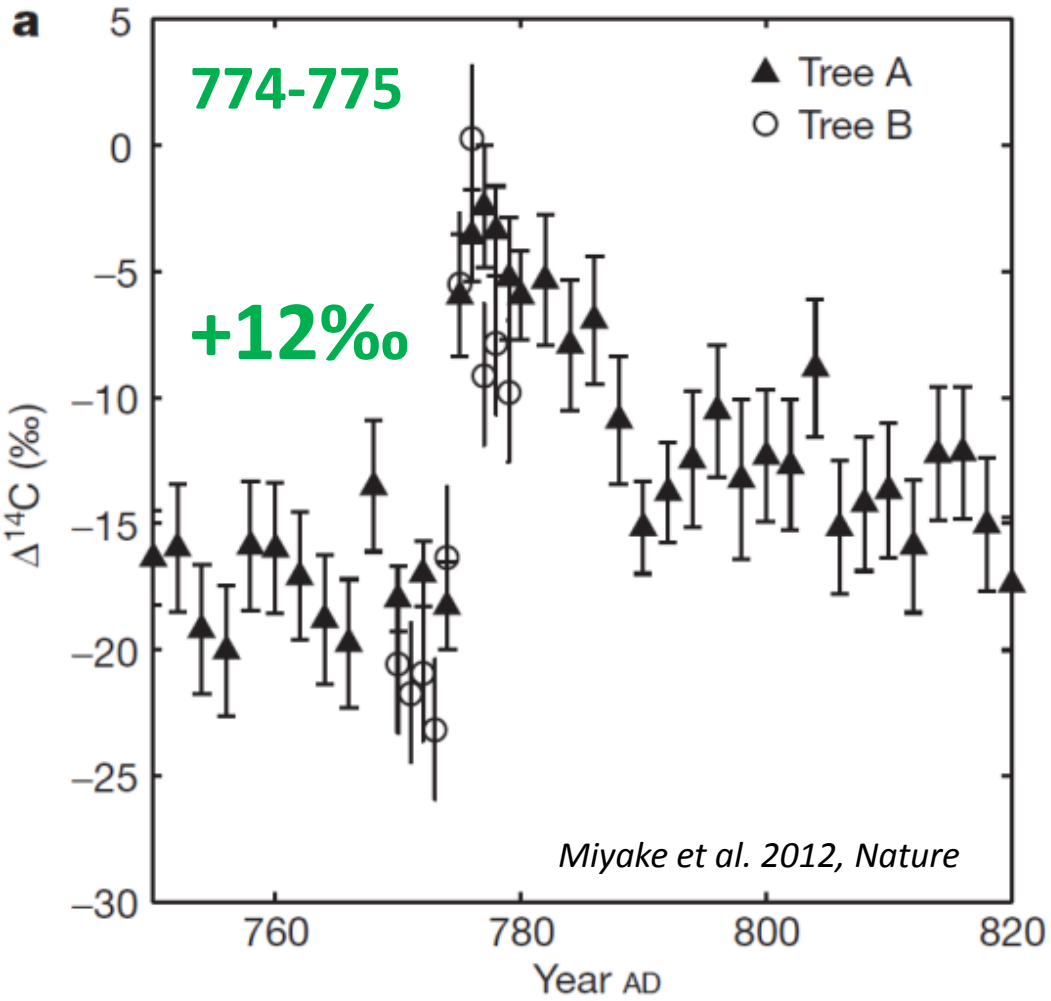
Sigl et al. 2014, Nat. Clim. Change

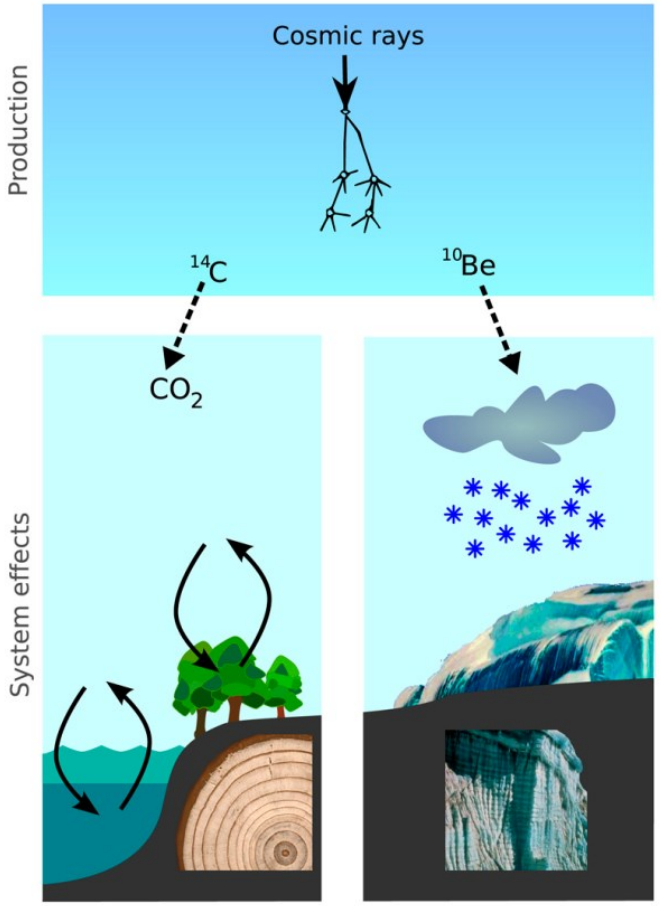
Stratospheric aerosol loading in the S. Hemisphere



Sigl et al. 2014, Nat. Clim. Change

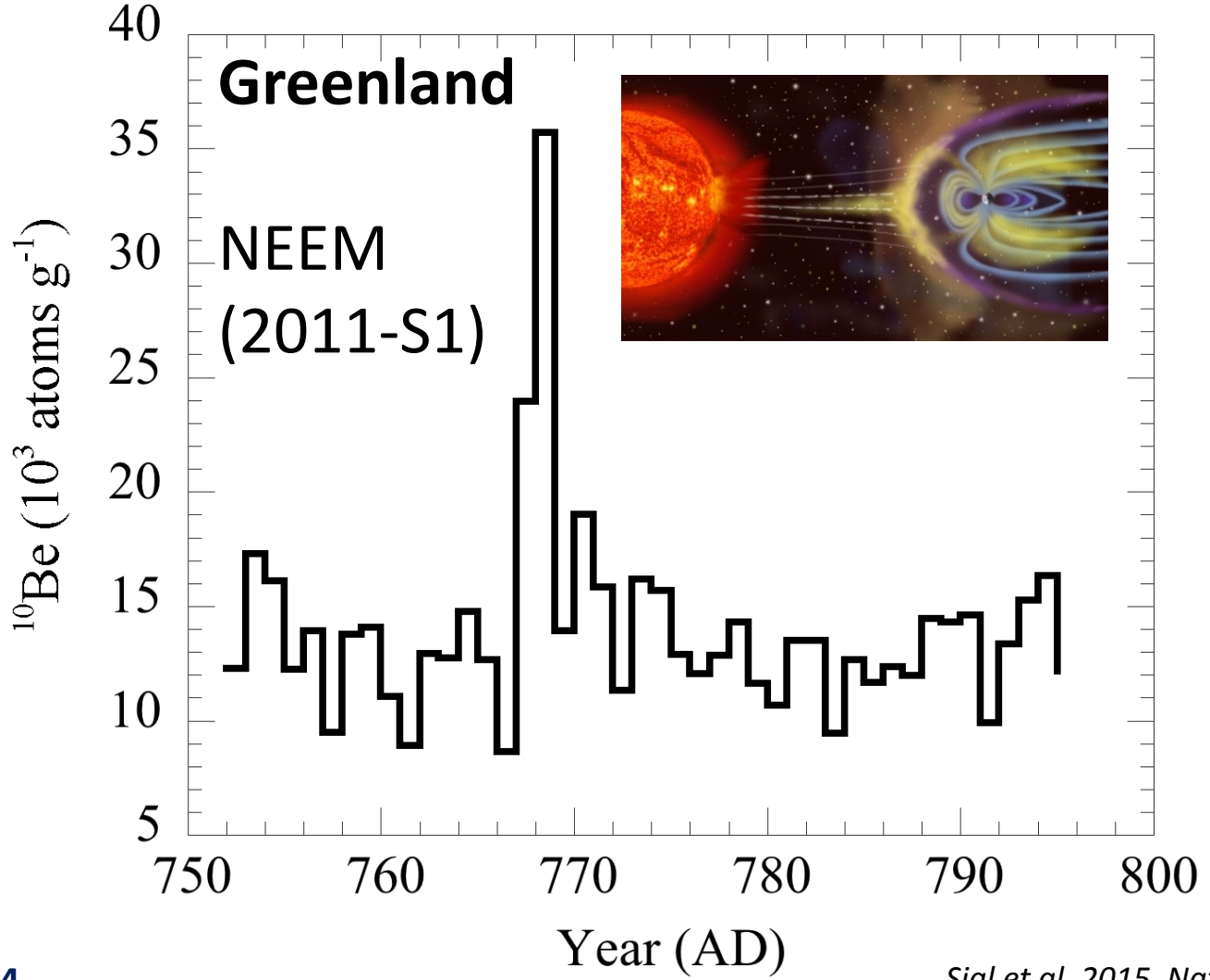
Global Age Marker in 775 AD in tree-rings…

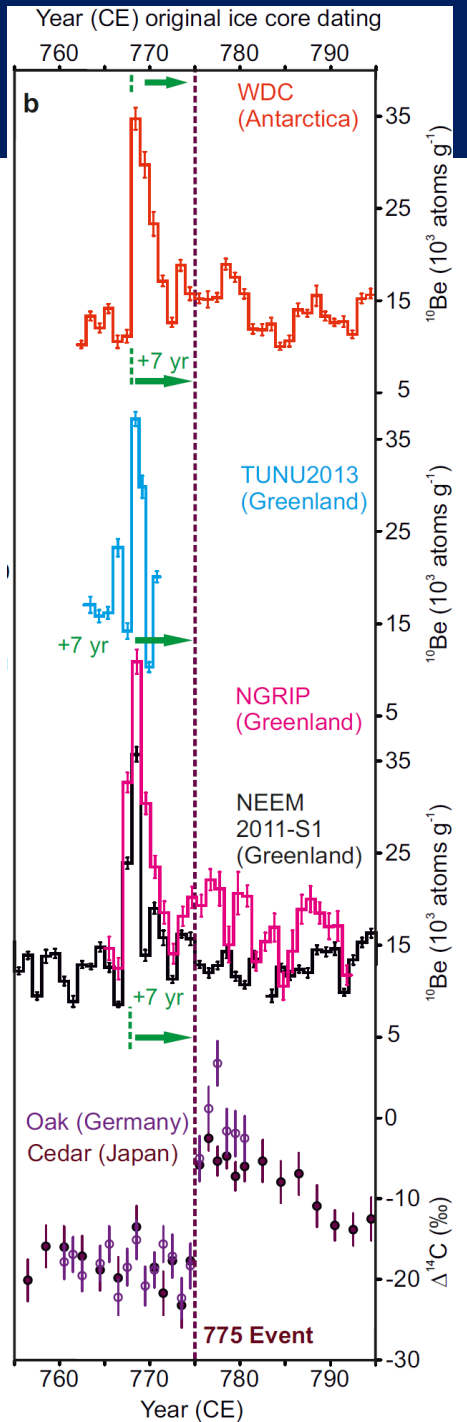




For the timing of eruptions some refinements on the dating have recently become available with the **discovery** of an unique, global-scale **time marker** by the **"solar energetic particle"** event in the **year 775 CE**: rapid increase of ^{14}C content in tree rings and of ^{10}Be in ice cores…

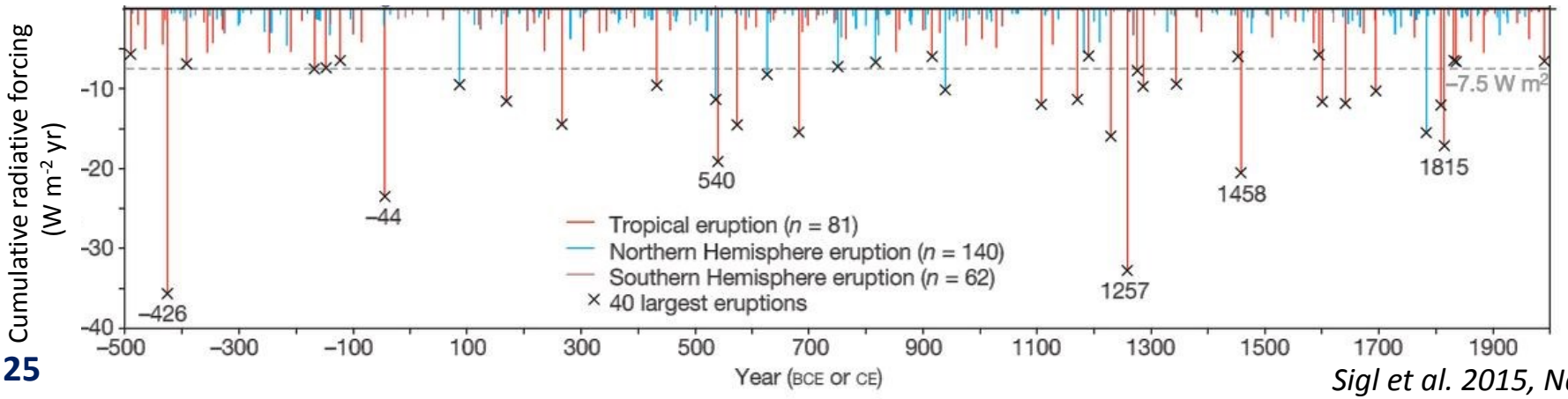
…and in ice cores





Sigl et al. 2015, Nature

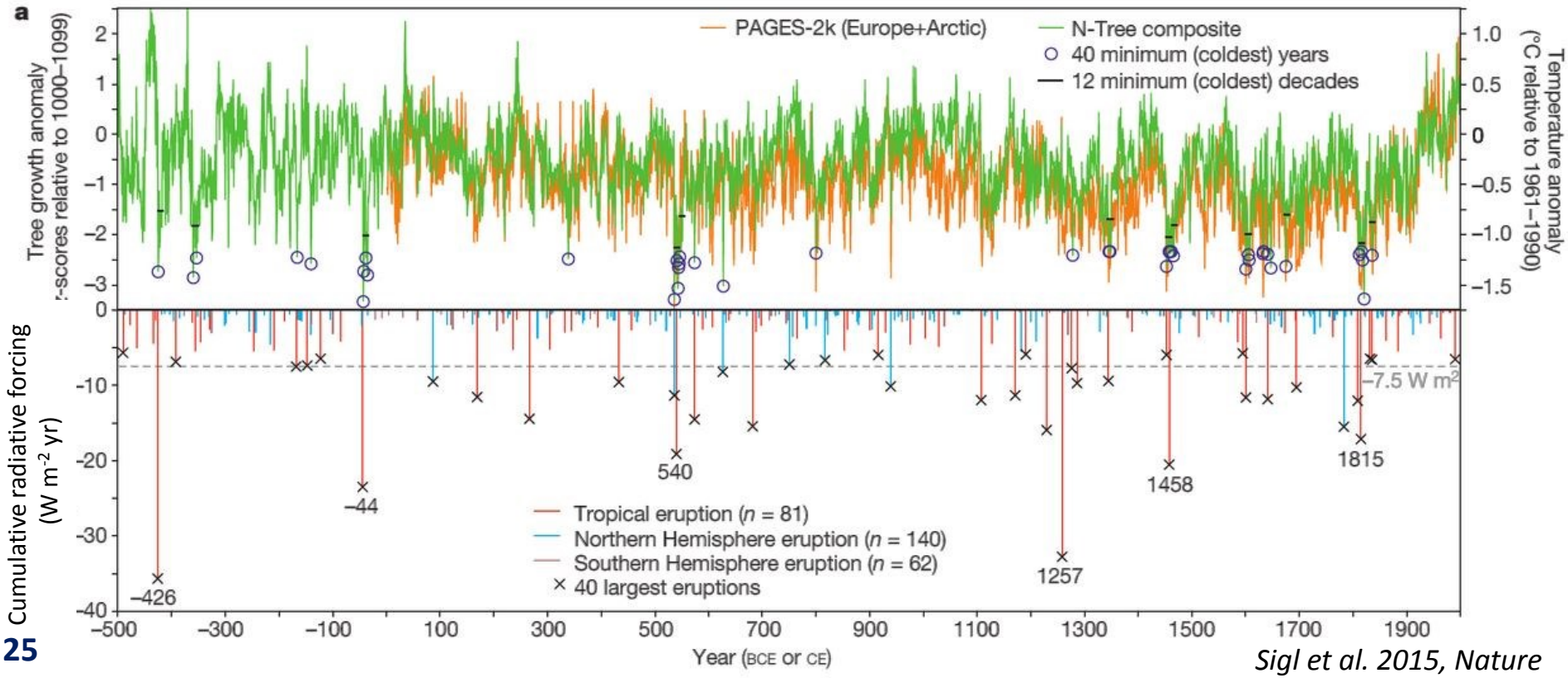
Volcanic forcing of the past 2,500 years



Sigl et al. 2015, Nature

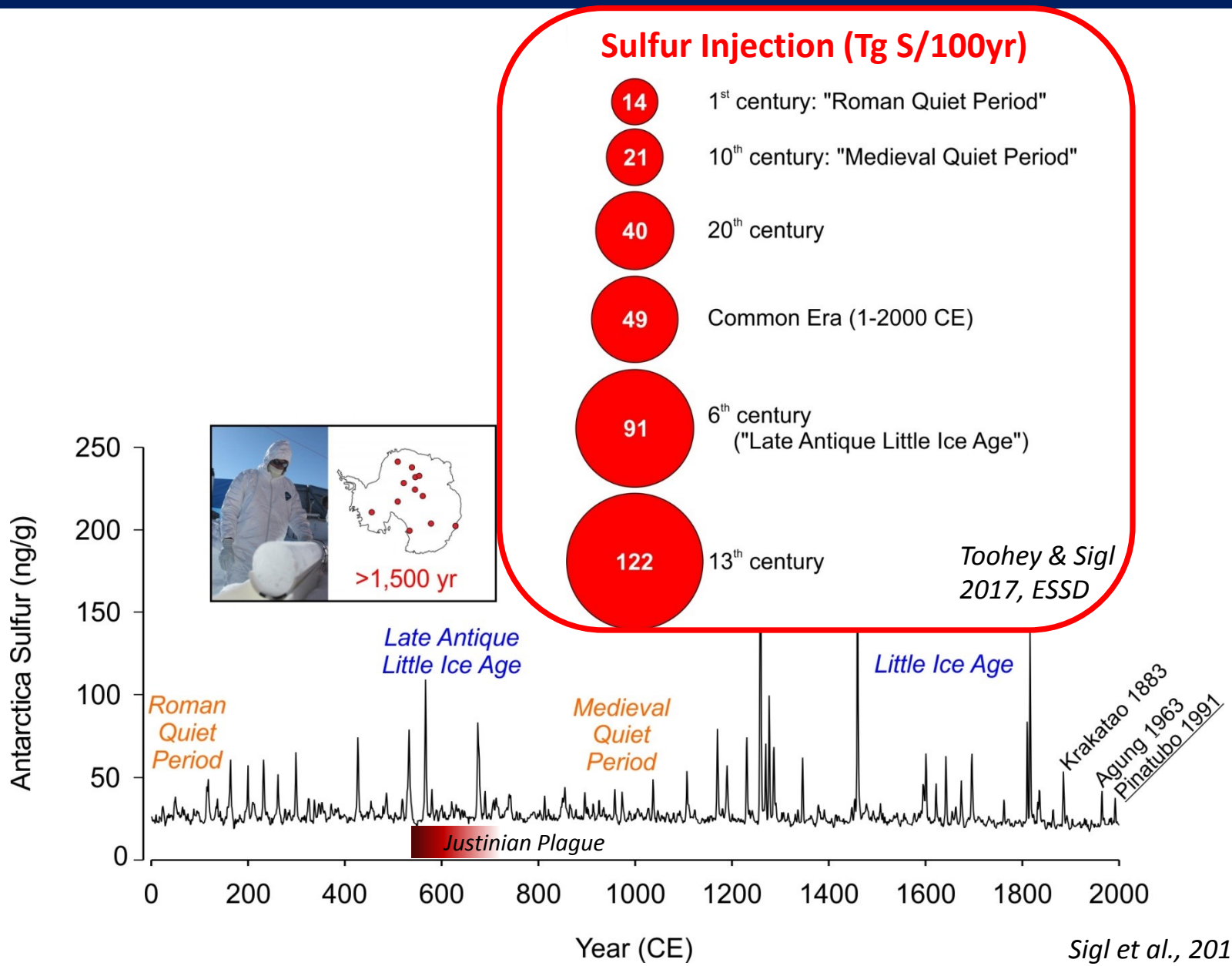
Volcanic forcing of the past 2,500 years

	≥ Tambora	≥Pinatubo
Number	6	35
Recurrence time:	400 yrs	70 yrs
NH Cooling (5 yrs):	**-1.0°C**	**-0.5°C**



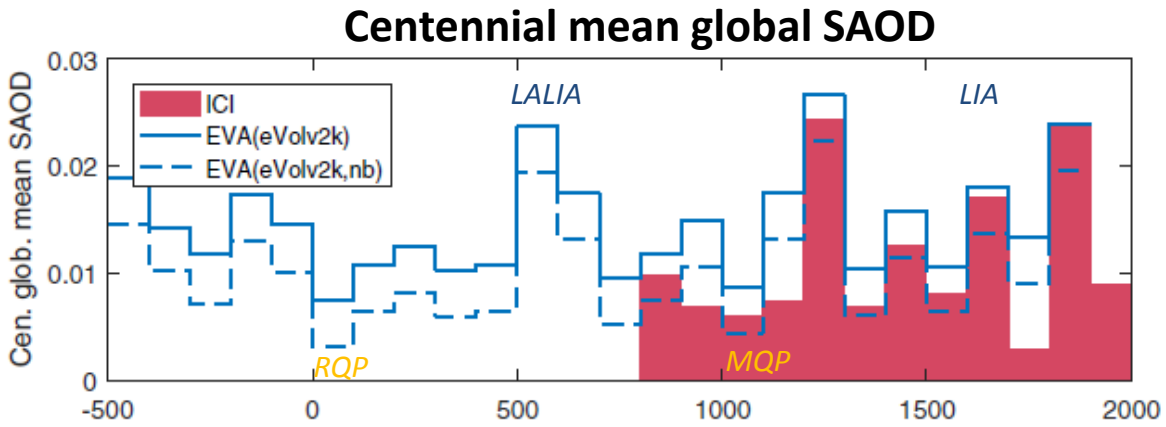
Sigl et al. 2015, Nature

Long-term variability

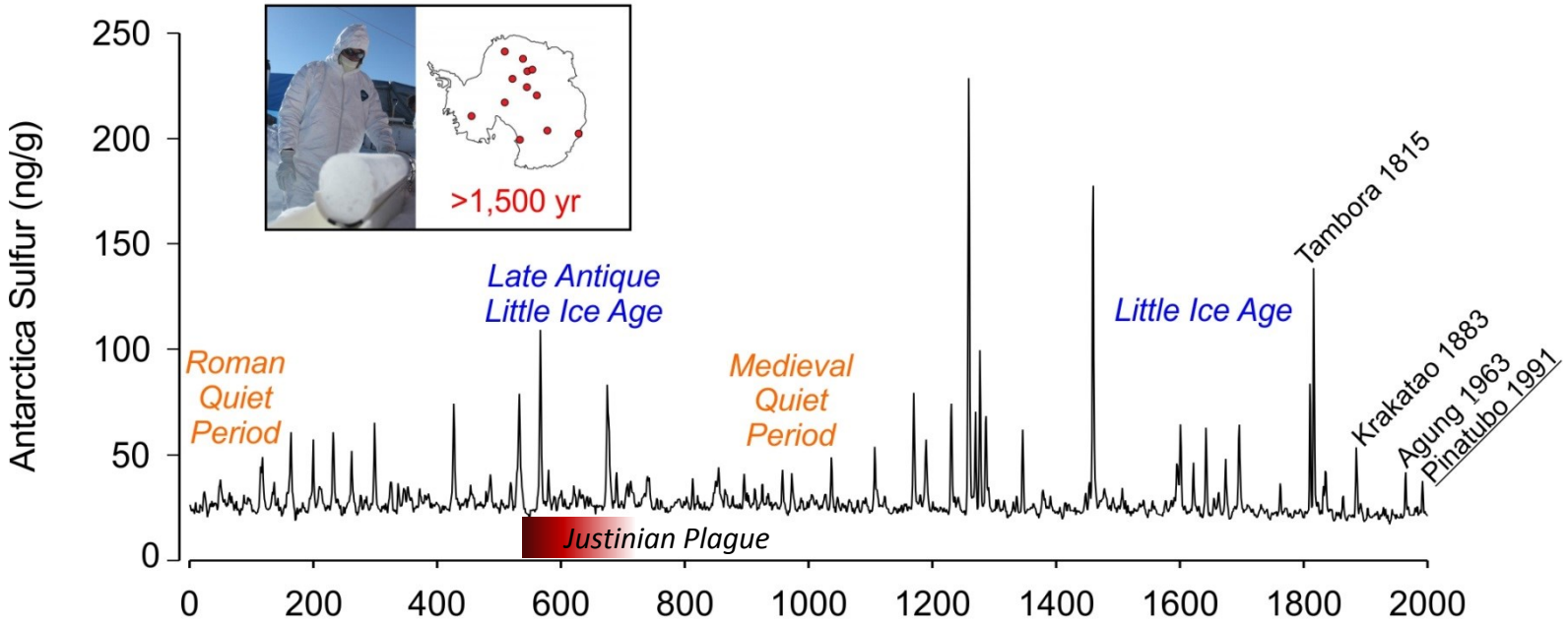


Sigl et al., 2015, Nature

Long-term variability

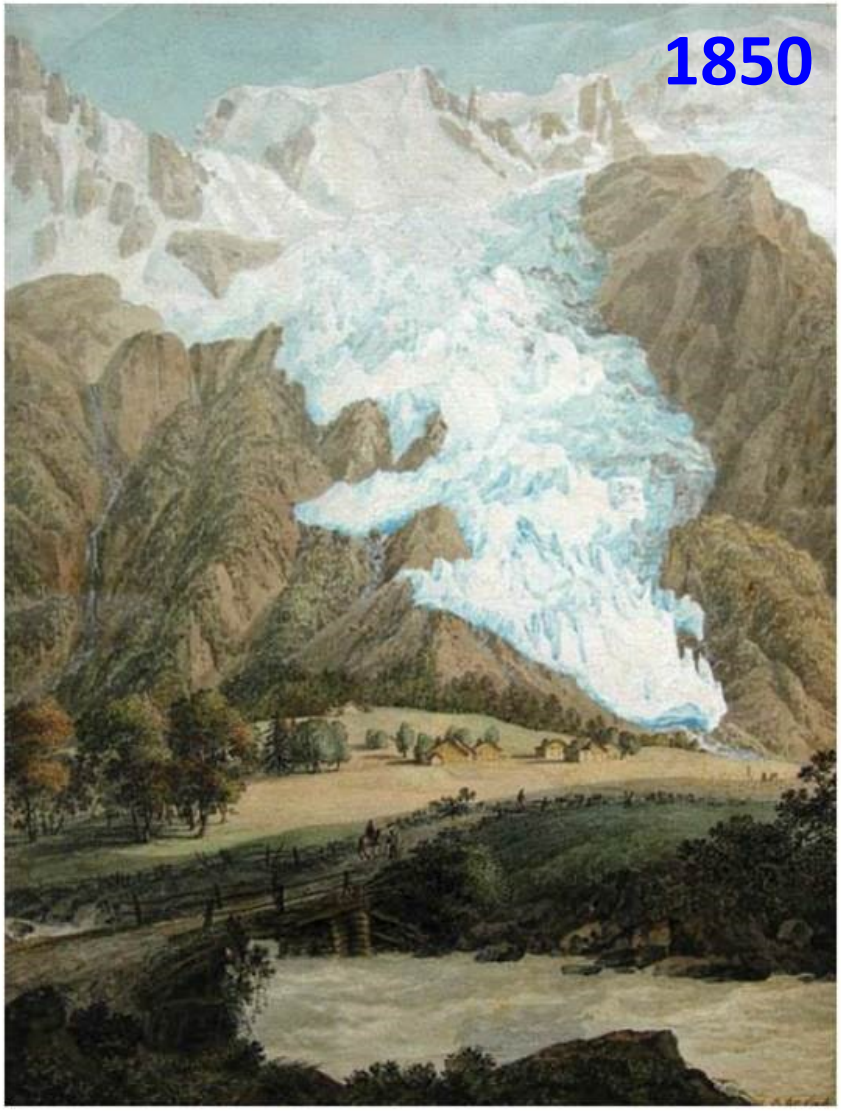


Toohey & Sigl, 2017, ESSD



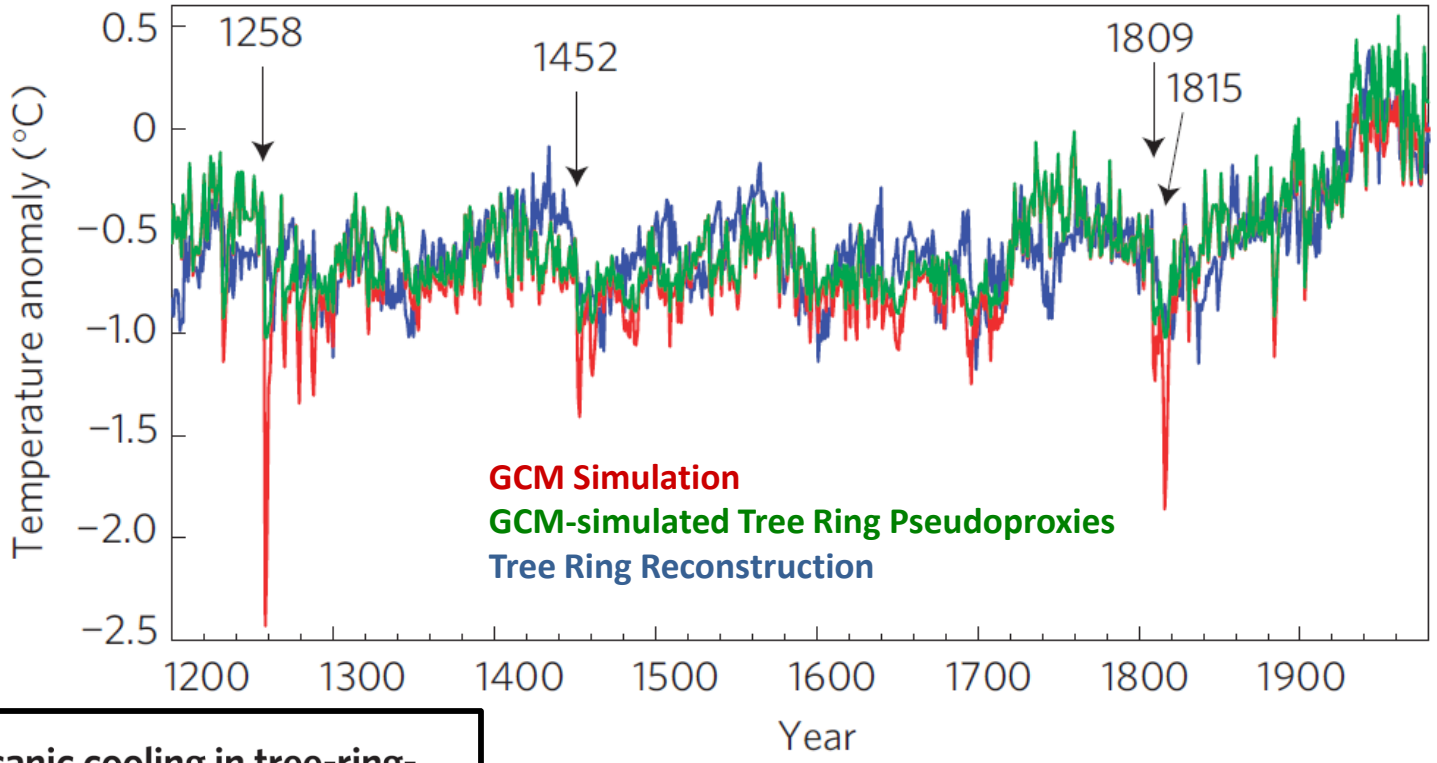
Sigl et al., 2015, Nature

Climate



Sigl et al. 2018, The Cryosphere Discuss.

Model/Data Mismatches in Climate Response



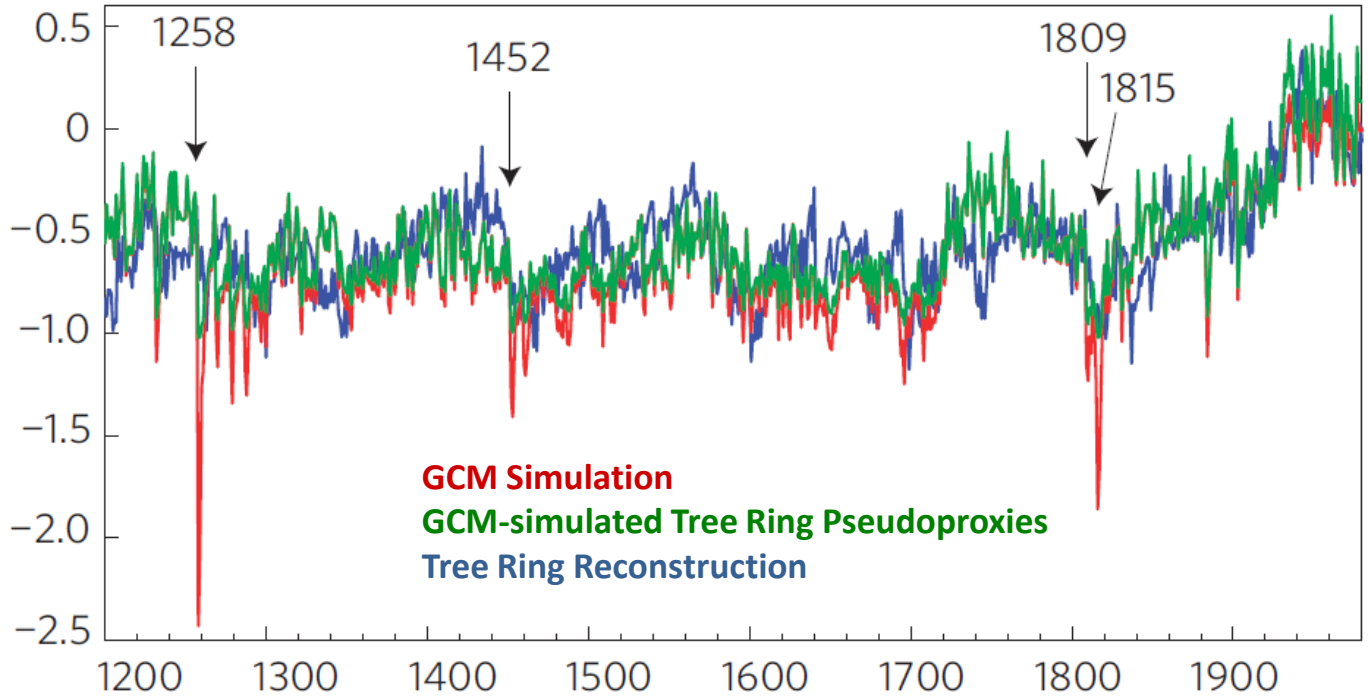
Underestimation of volcanic cooling in tree-ring-based reconstructions of hemispheric temperatures

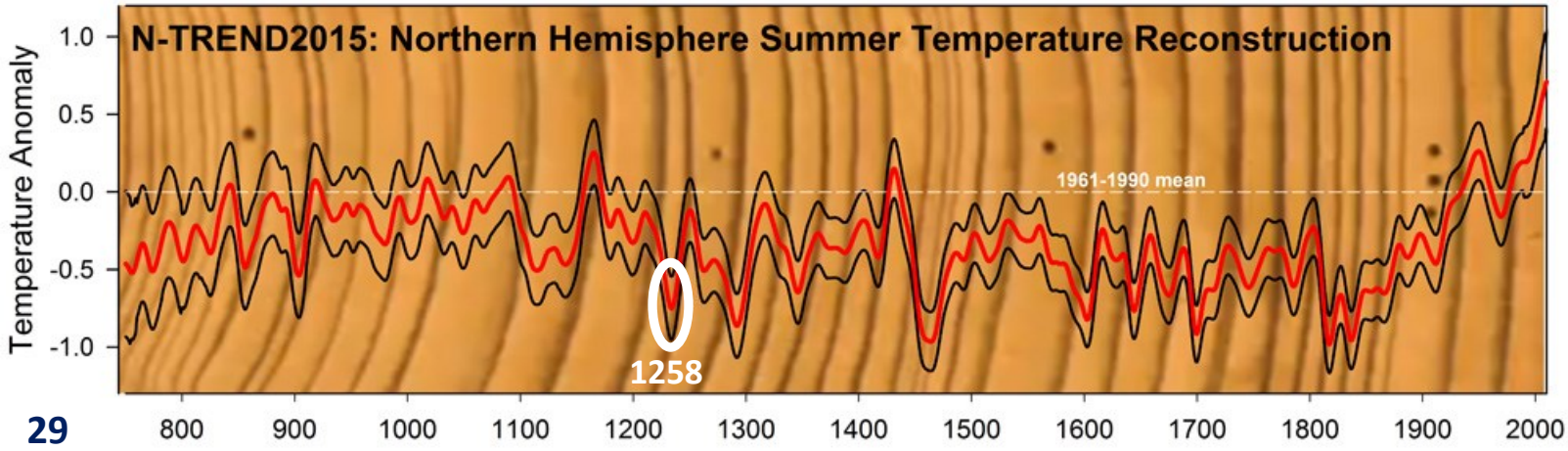
Michael E. Mann[1]*, Jose D. Fuentes[1] and Scott Rutherford[2]

Mann et al. 2012, Nature Geoscience

Model/Data Mismatches in Climate Response

Lavigne al. 2013
Proc. Natl. Acad. Sci. U.S.A

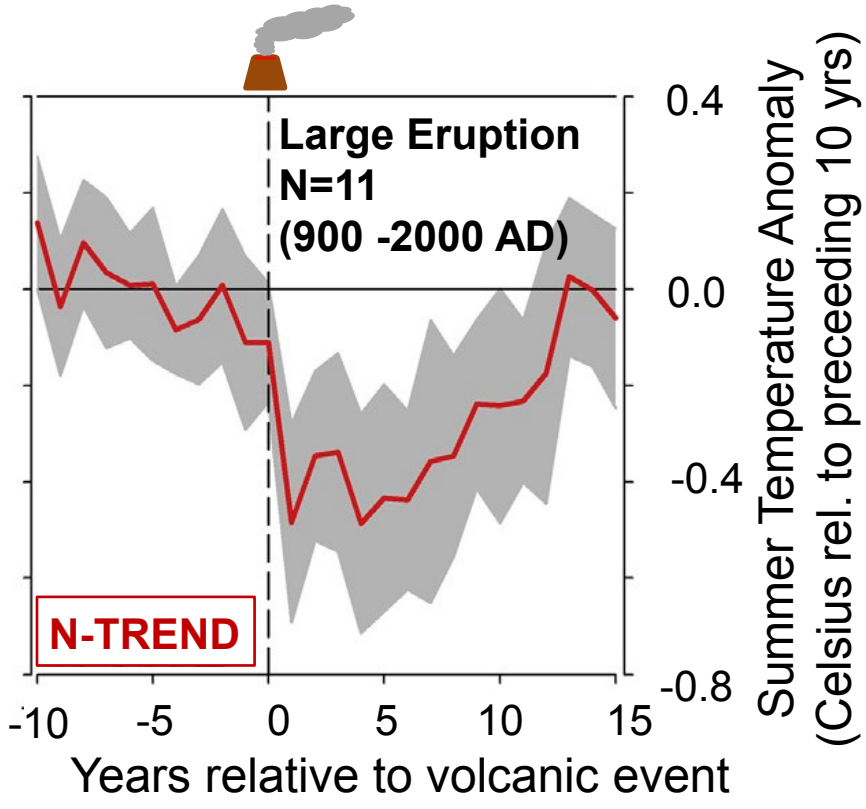


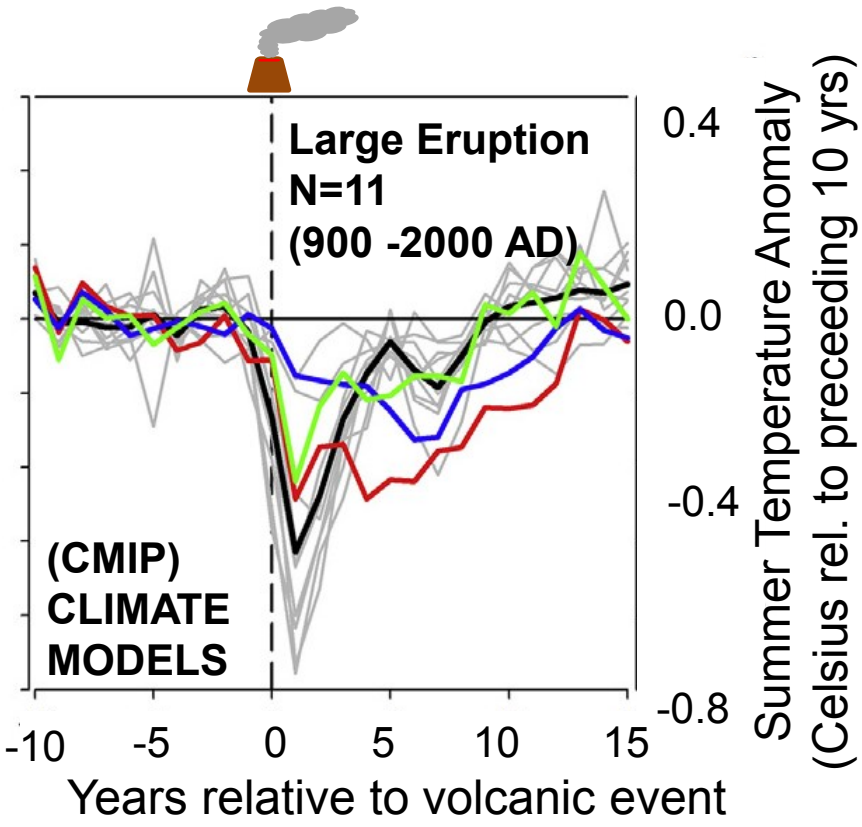


Wilson et al. 2016
Quat. Sci. Rev

Model/Data Mismatches in Climate Response

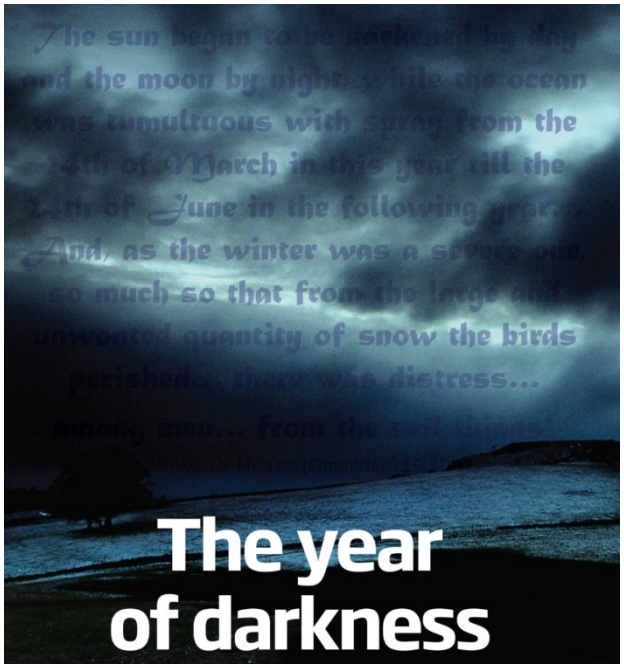
Ring Width (D'Arrigo et al., 2006)
Mixed (Wilson et al., 2016)
MXD (Schneider et al., 2015)





Wilson et al. 2016, QSR

536 AD: The year of darkness



"And it came about during this year that a most dread portent took place. For 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 not clear nor such as it is accustomed to shed"

PROCOPIUS (Wars, 4.14.5)

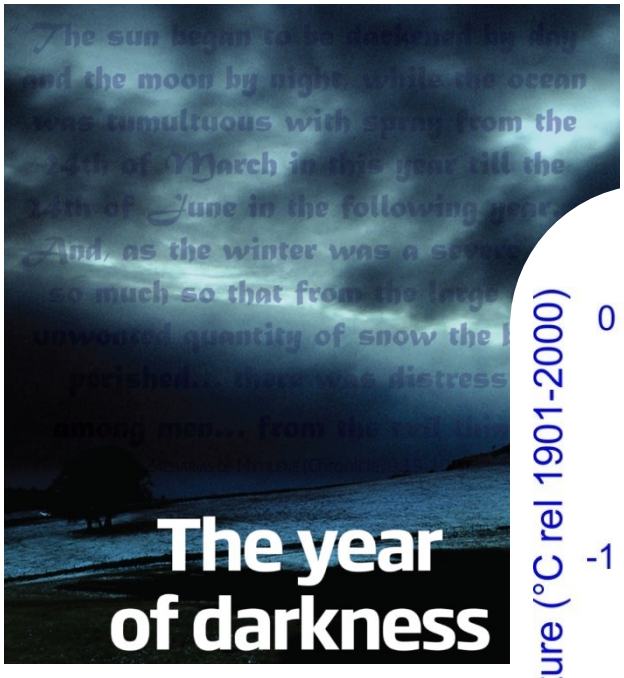
Tree Rings-Frost Starting in Early 536 A.D.

Damaged tree rings 536-538 A.D.

D'Arrigo et al., 2001; Geophys. Res. Lett

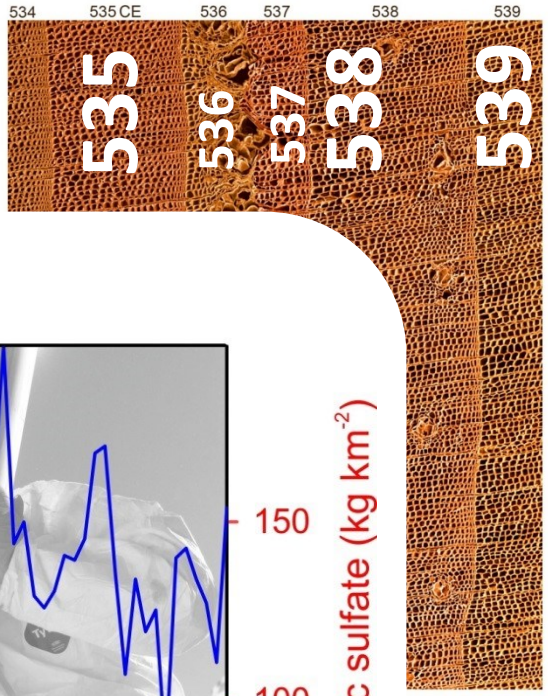
Stothers 1986, Nature

536 AD: The year of darkness



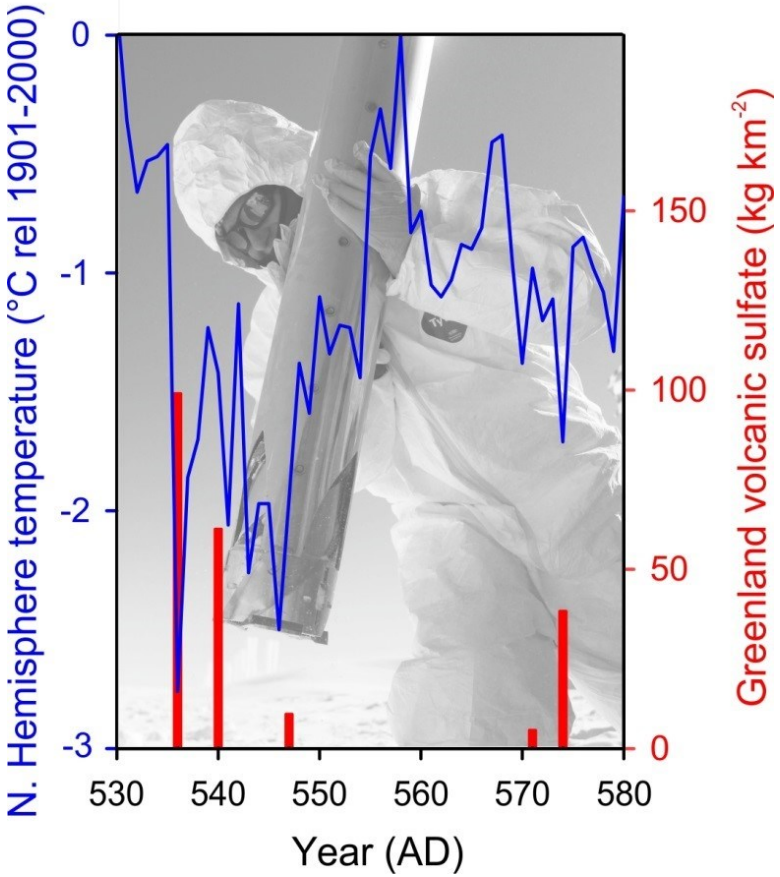
"And it came about during this year that a most dread portent took place. For the sun gave forth its light without brightness, like the moon, during this whole year, and it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear nor such as it is accustomed to shed"

PROCOPIUS (Wars, 4.14.5)



Tree Rings-Frost Starting in Early 536 A.D.

Damaged tree rings 536-538 A.D.

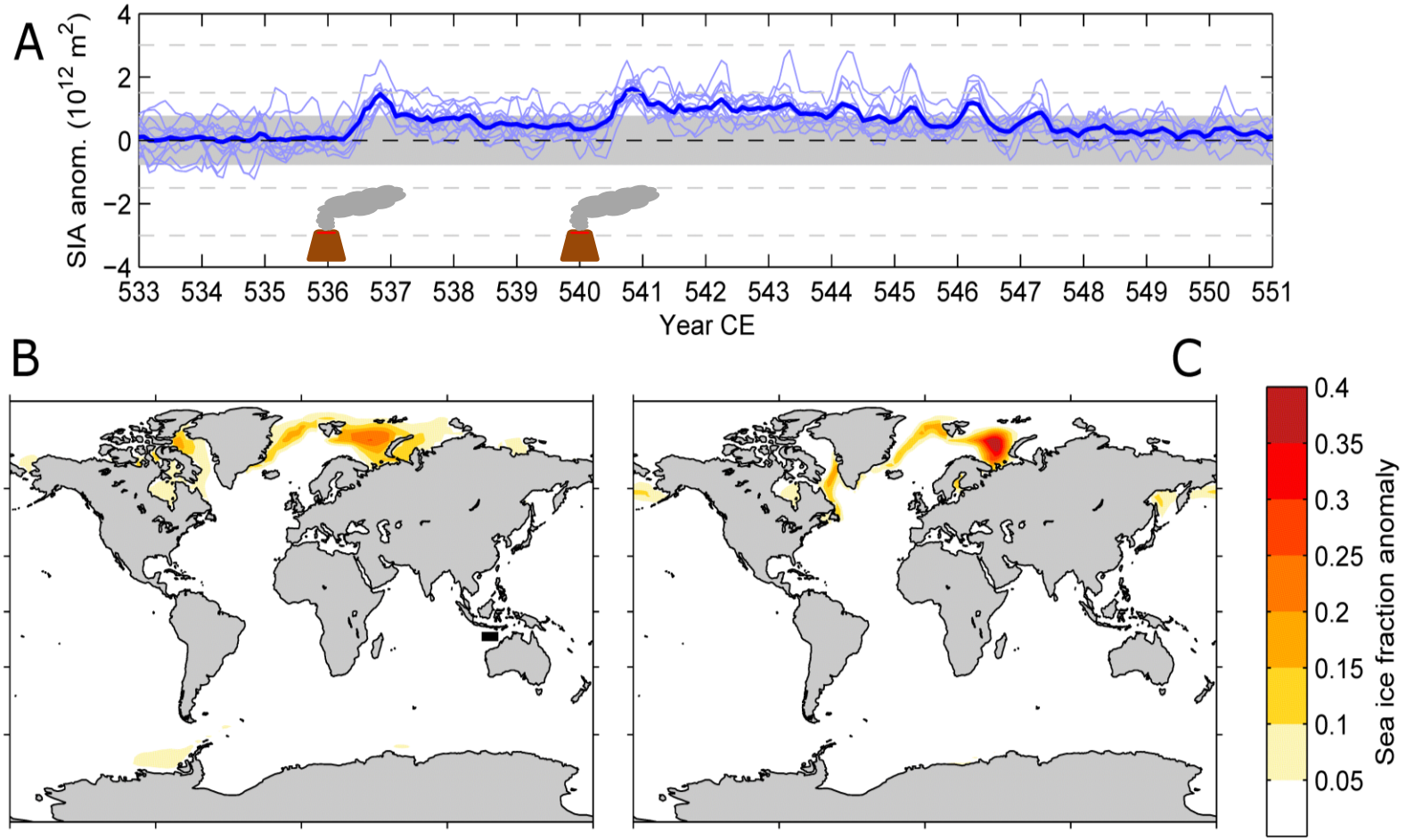


Stothers 1986, Nature

Sigl et al., 2015, Nature

D'Arrigo et al., 2001; Geophys. Res. Lett

536/540



Toohey et al., 2016, Clim. Change

Asymmetric Aerosol Forcing…

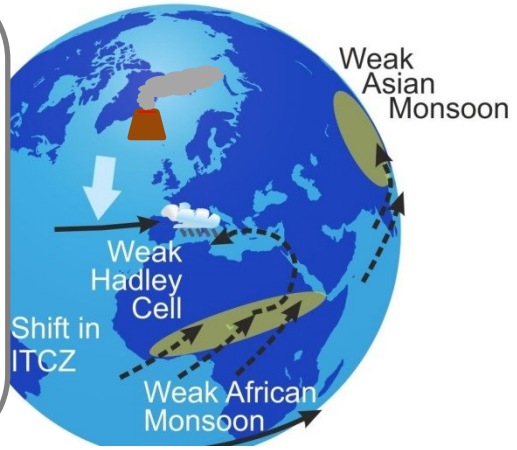
ARTICLE

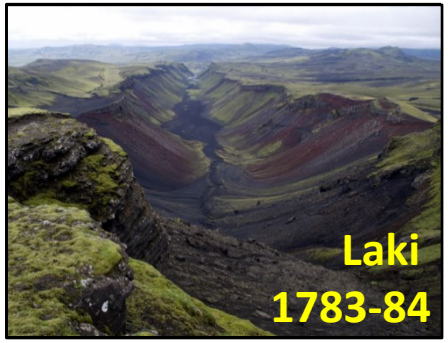
DOI: 10.1038/s41467-017-00957-y

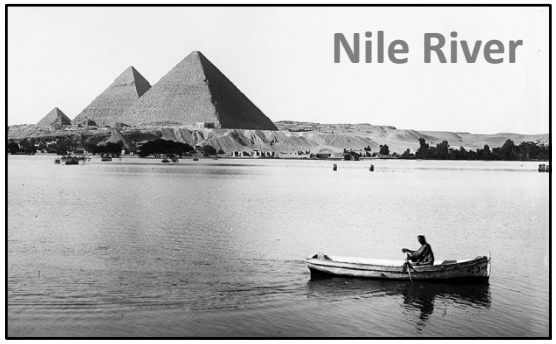
nature COMMUNICATIONS

Volcanic suppression of Nile summer flooding triggers revolt and constrains interstate conflict in ancient Egypt

Joseph G. Manning[1,2], Francis Ludlow[3,4], Alexander R. Stine[5], William R. Boos[6,7], Michael Sigl[8] & Jennifer R. Marlon[9]



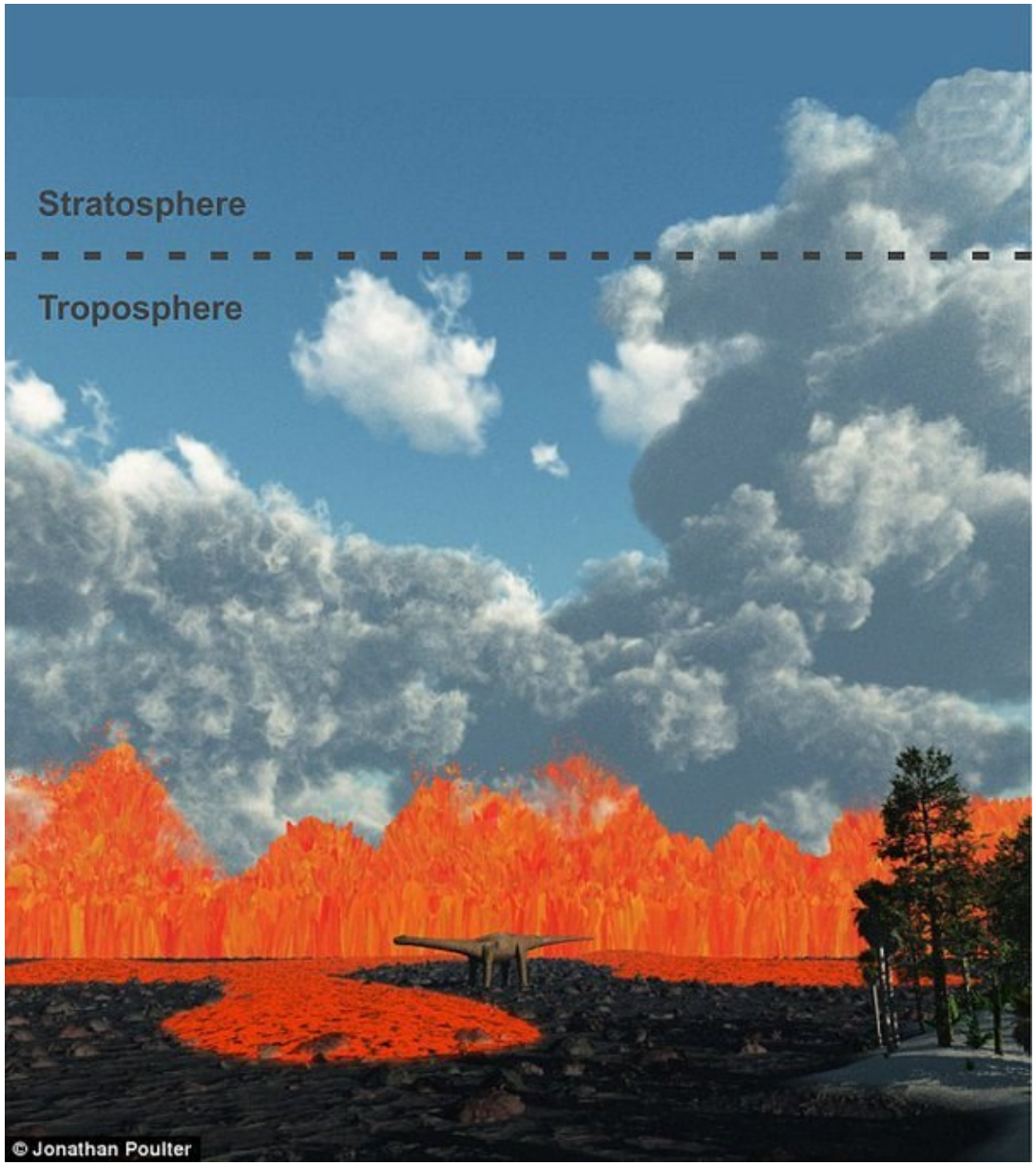




…causes monsoon failure and riverflow reduction

Manning, et al., 2017, Nat. Commun.

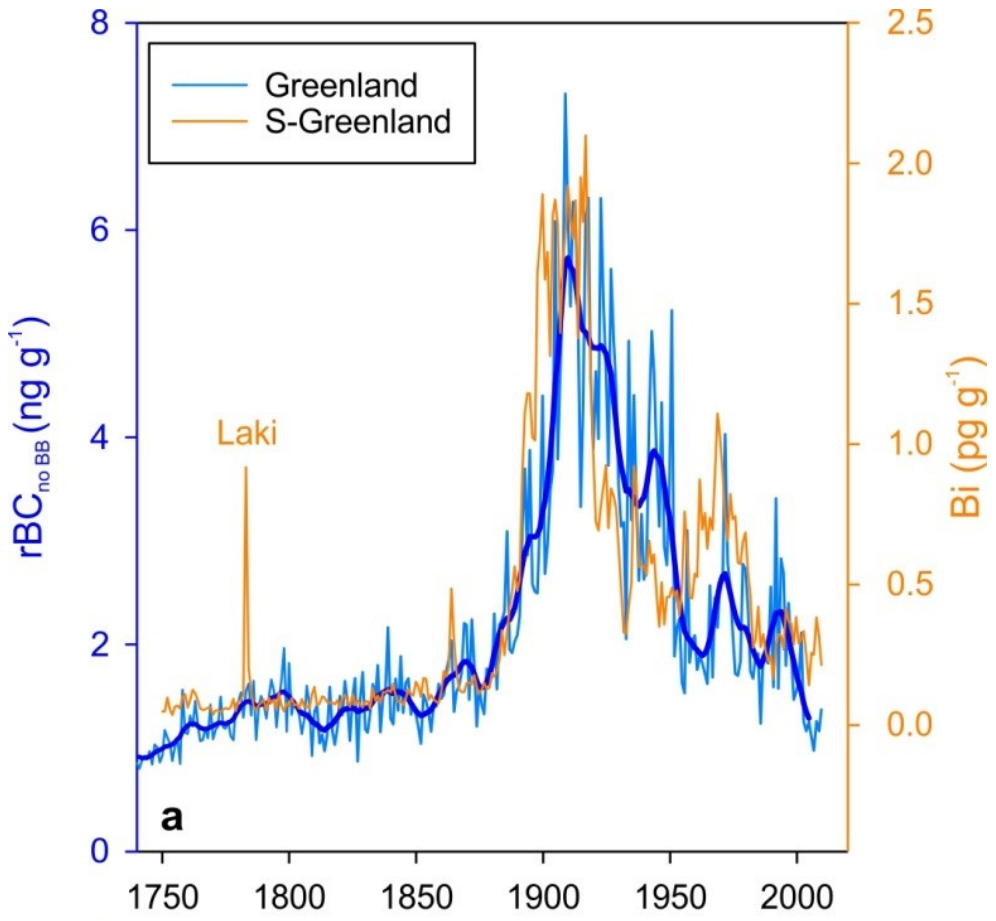
New Proxies



Credit: Jonathan Poulter

Constraining eruption source parameters

Diagnostic signatures in ice cores



Chellman et al., 2017, Environ. Sci. Technol.
Sigl et al. 2018, The Cryosphere Discuss.

Thallium as a Tracer for Preindustrial Volcanic Eruptions in an Ice Core Record from Illimani, Bolivia

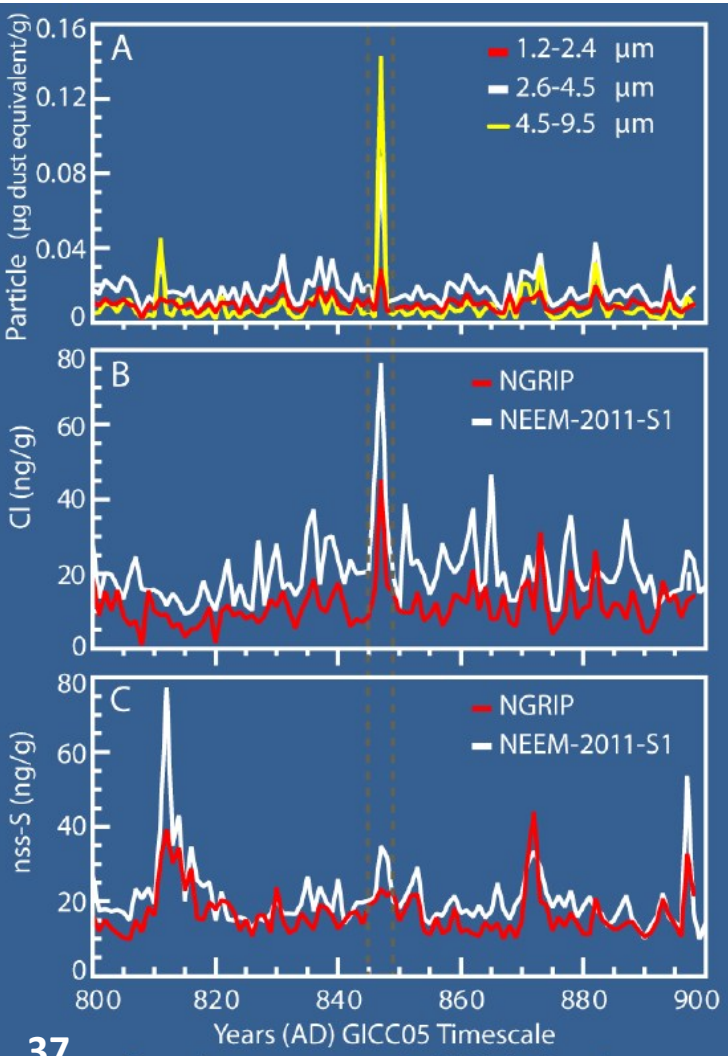
THOMAS KELLERHALS,[*,†,‡] LEONHARD TOBLER,[‡] SABINA BRÜTSCH,[‡] MICHAEL SIGL,[†,‡] LUKAS WACKER,[§] HEINZ W. GÄGGELER,[†,‡] AND MARGIT SCHWIKOWSKI[‡,∥]

Department of Chemistry and Biochemistry, University of Bern, Switzerland, Paul Scherrer Institut, Villigen, Switzerland, Institute for Particle Physics, ETH Zürich, Switzerland, and Oeschger Centre for Climate Change Research, University of Bern, Switzerland

Kellerhals et al., 2009, Environ. Sci. Technol.

Constraining eruption source parameters

A diagnostic signature for tephra in ice cores



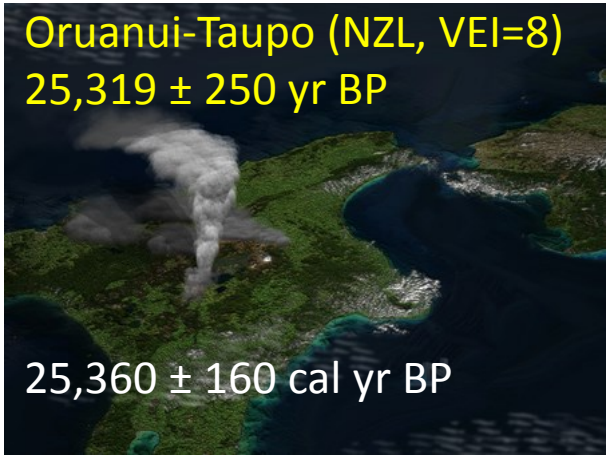
after Jensen et al. 2014 *Geology*

Sources of data

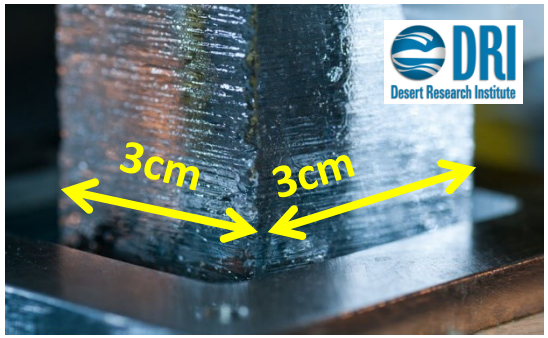
Changbaishan 946
White River Ash 853

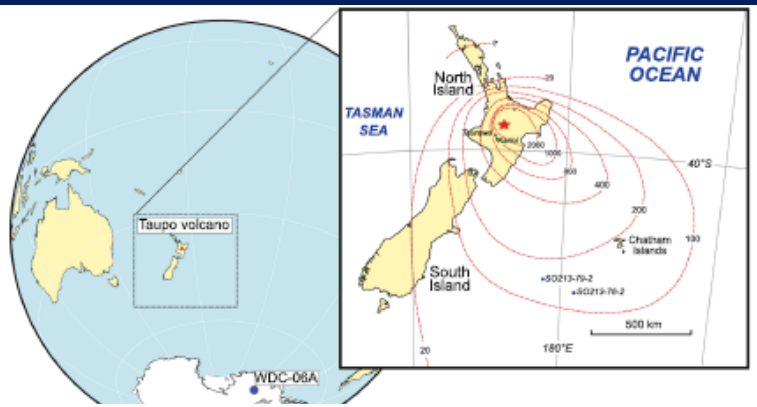
Sun et al., 2014, Geophys. Res. Lett

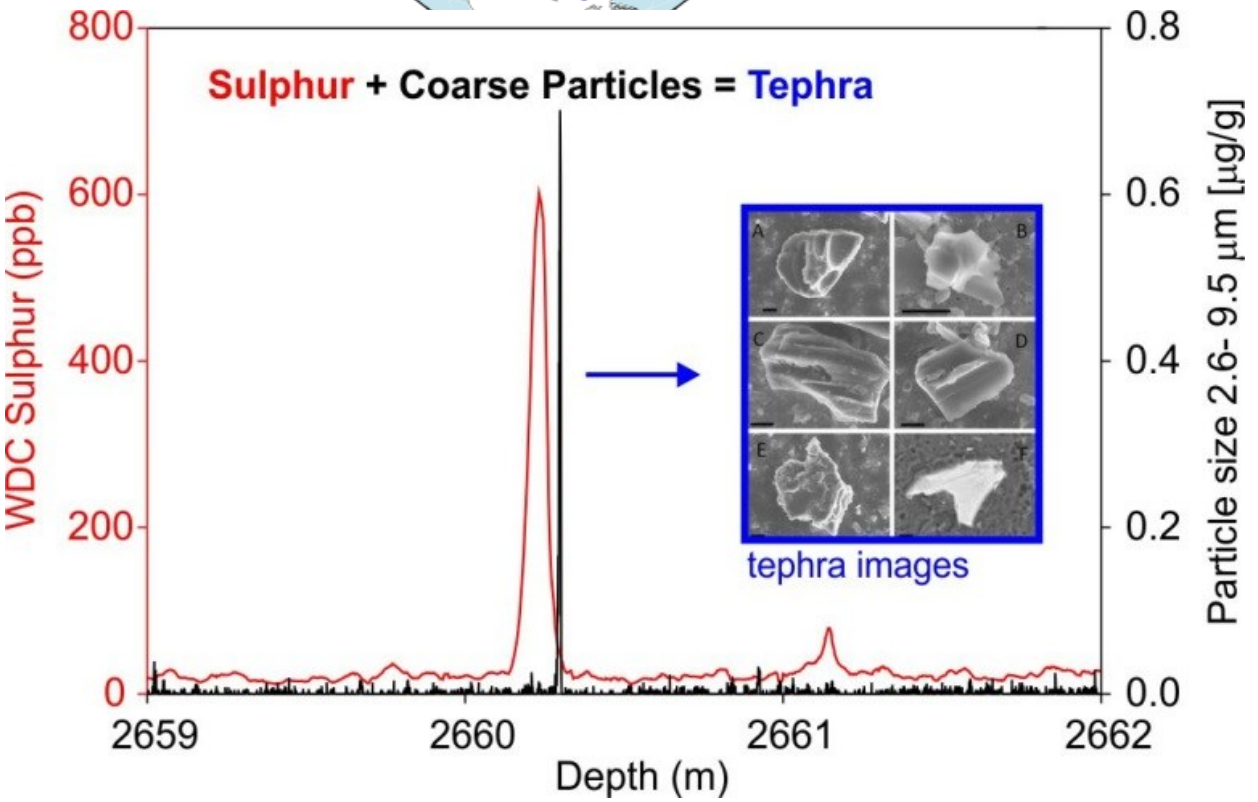
Taupo-Oruanui Super-eruption



Sigl et al., 2016, Clim. Past
Vandergoes et al., 2013, Quat. Sci. Rev



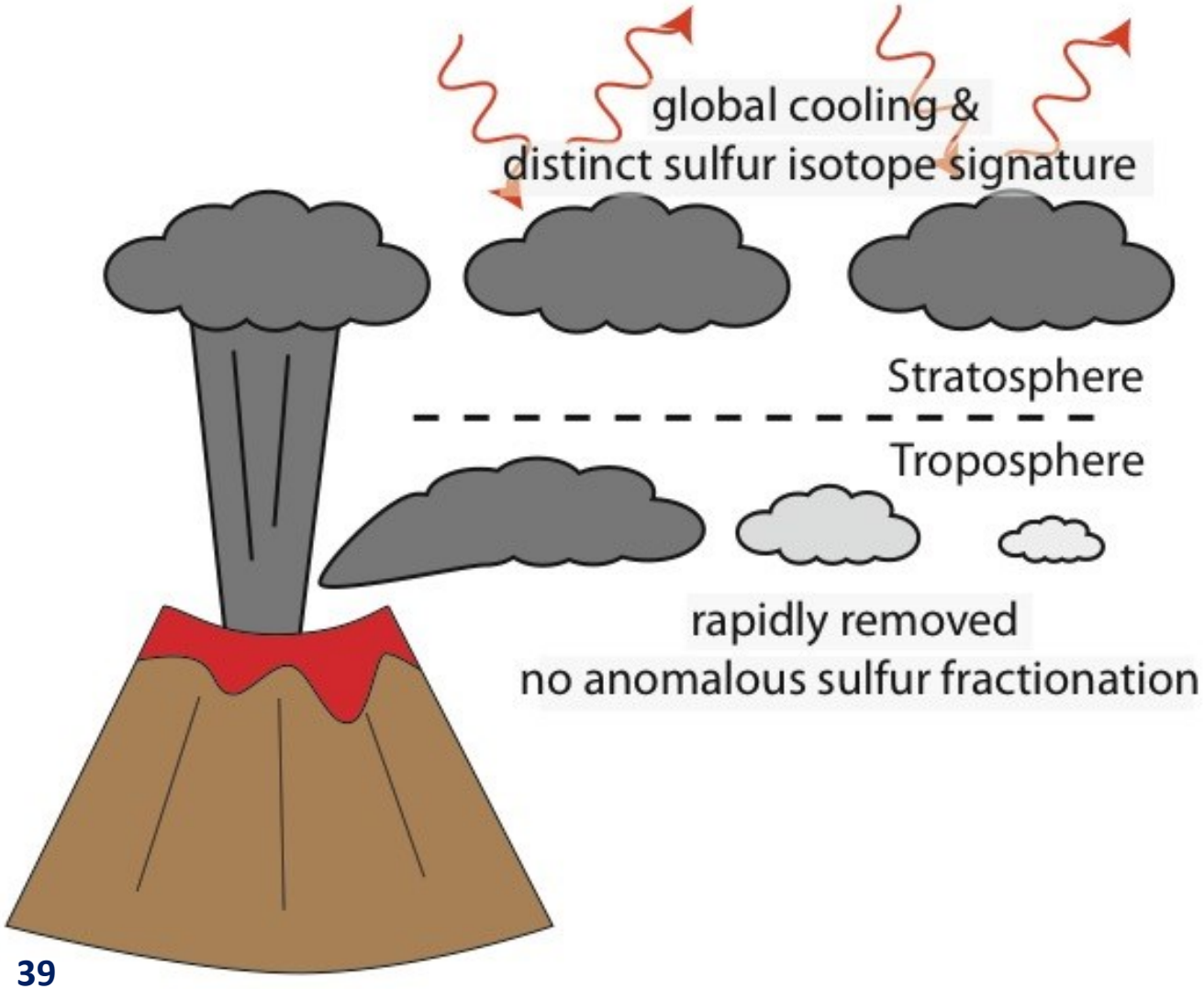




Dunbar et al., 2017, Sci Rep.

Can we constrain the injection height ?

Injection height + Location → Atmospheric lifetime of sulphate aerosols



$\Delta^{33}S \neq 0$

$\Delta^{33}S = 0$

After Baroni et al., 2007, Science

A novel method for sulfur isotopes

- ^{32}S, ^{33}S, and ^{34}S isotope measurements in sulfate by *Neptune Plus* MC-ICP-MS
- **0.1‰ precision** on sulfur isotope ratios

A novel method for sulfur isotopes

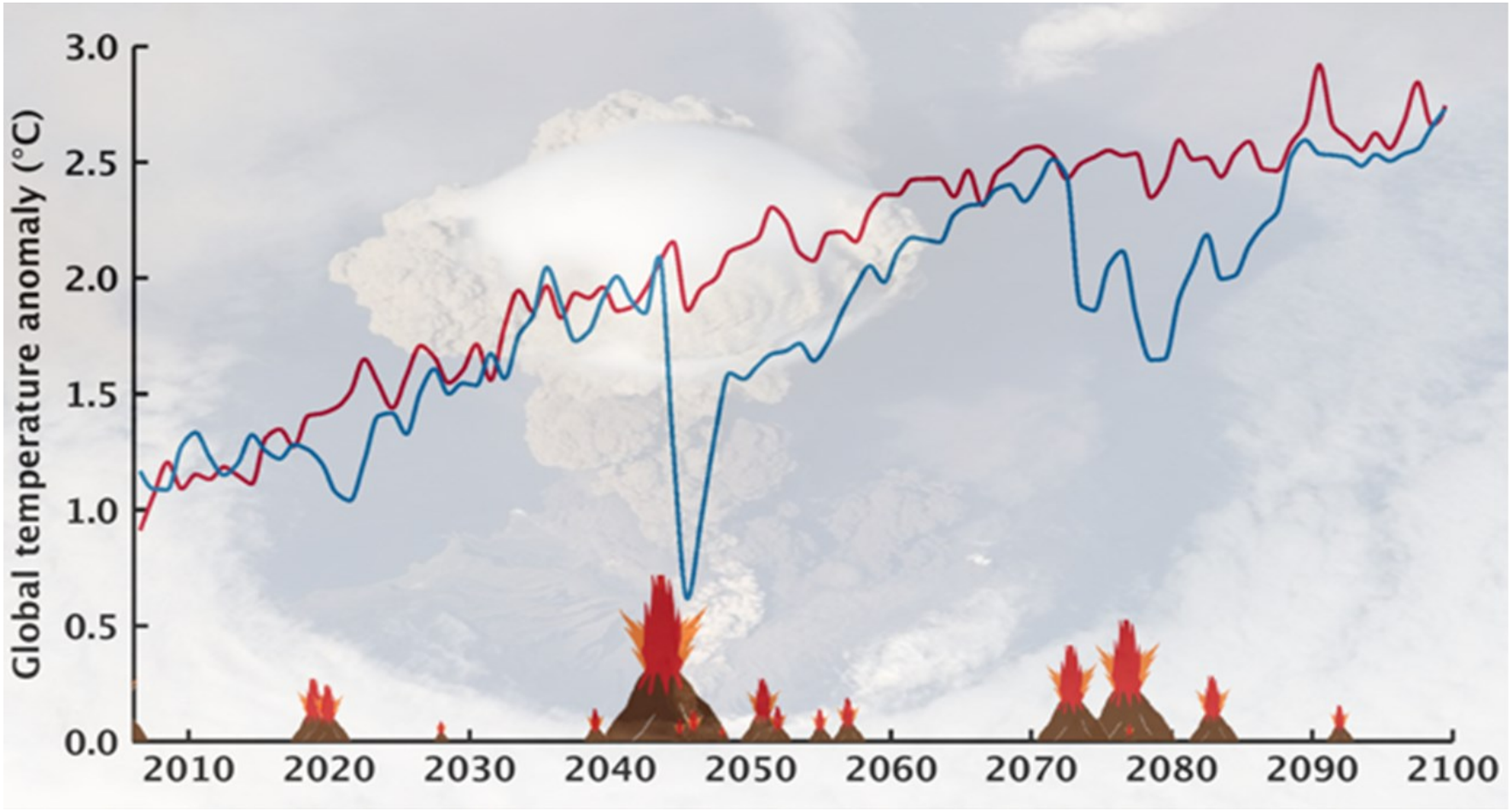
- ^{32}S, ^{33}S, and ^{34}S isotope measurements in sulfate by *Neptune Plus* MC-ICP-MS
- **0.1‰ precision** on sulfur isotope ratios

µmols of sulfate:
several months/years of ice accumulation

nmols of sulfate:
bi-monthly resolution

Paris et al., 2013, Chem. Geol.
Paris et al., 2014, Science

Volcanism in the Post-Pinatubo Era



Summit
2010

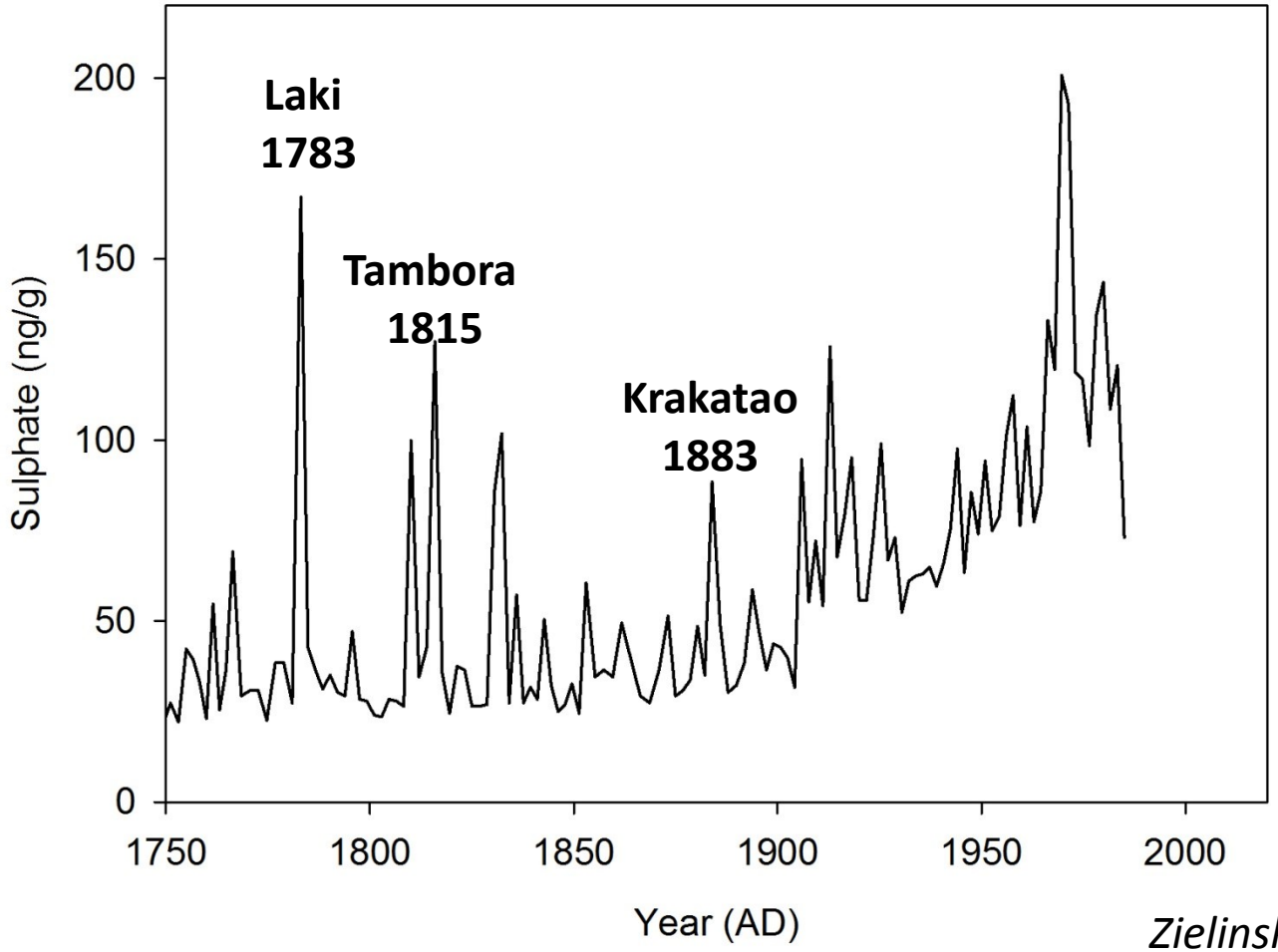
GISP2
(ends 1985 AD)

Sigl et al., 2011, Quaternary International

Aerosols in Air (daily)

Greenland, Summit 3200m

Aerosols in Snow (weekly)



Summit
2010

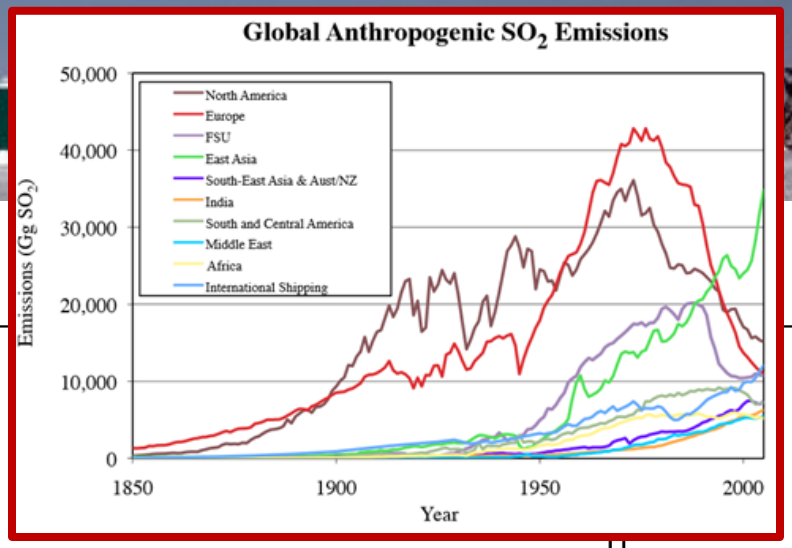
GISP2
(ends 1985 AD)

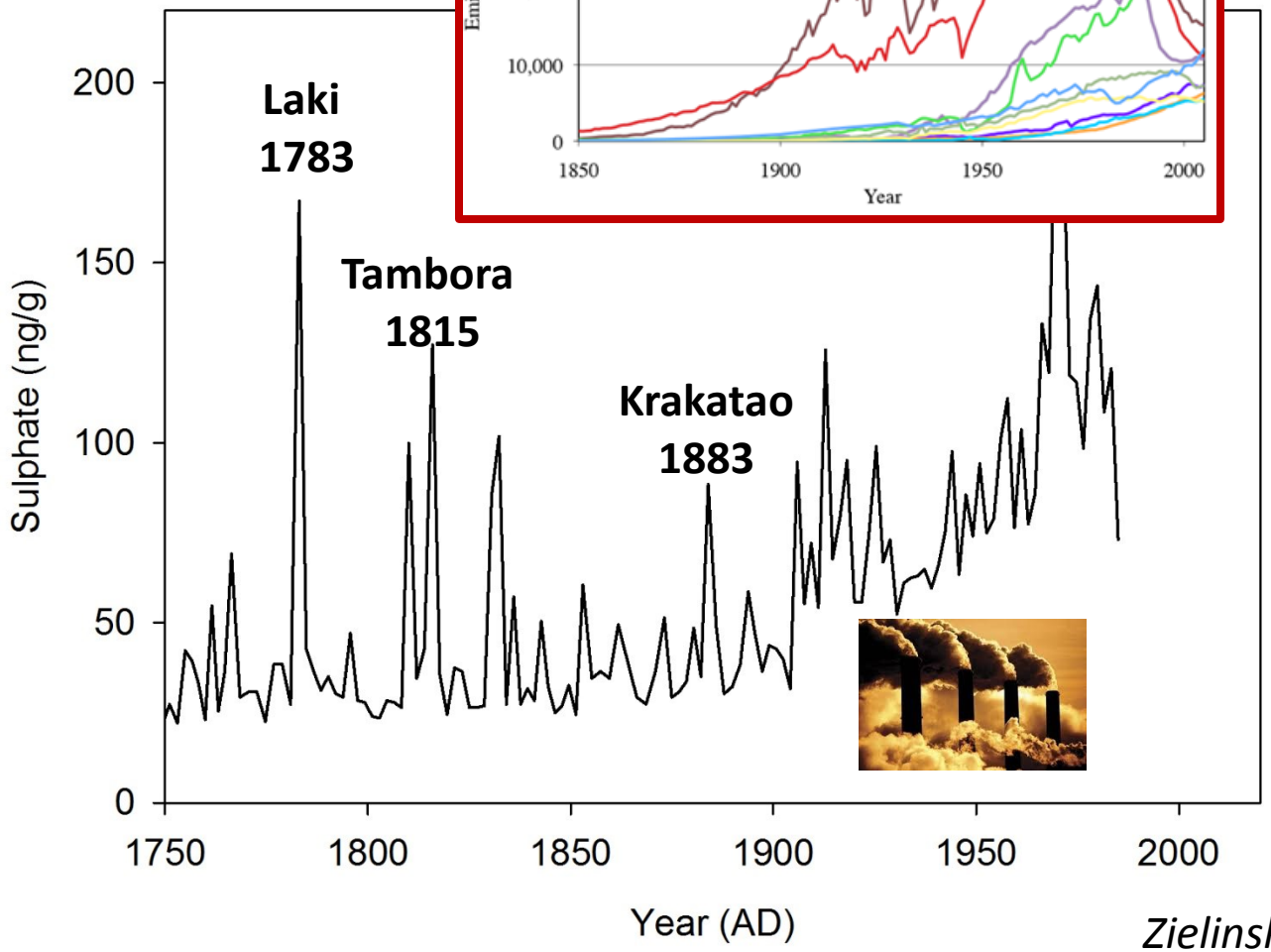
Zielinski et al., 1994, Science

Aerosols in Air (daily)

Greenland, Summit 3200m

Aerosols in Snow (weekly)





Summit
2010

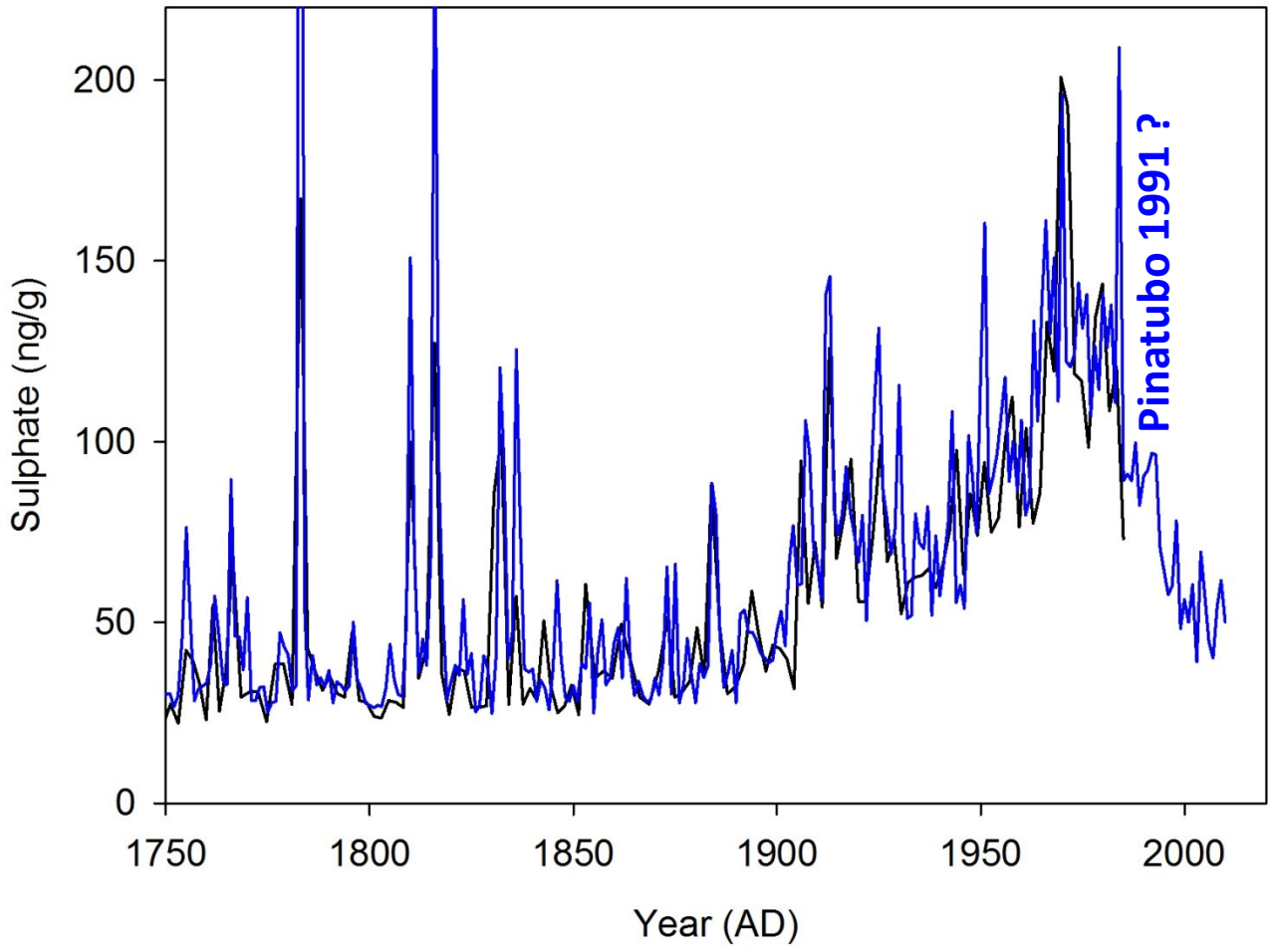
GISP2
(ends 1985 AD)

Zielinski et al., 1994, Science

Aerosols in Air (daily)

Greenland, Summit 3200m

Aerosols in Snow (weekly)



Summit 2010

GISP2

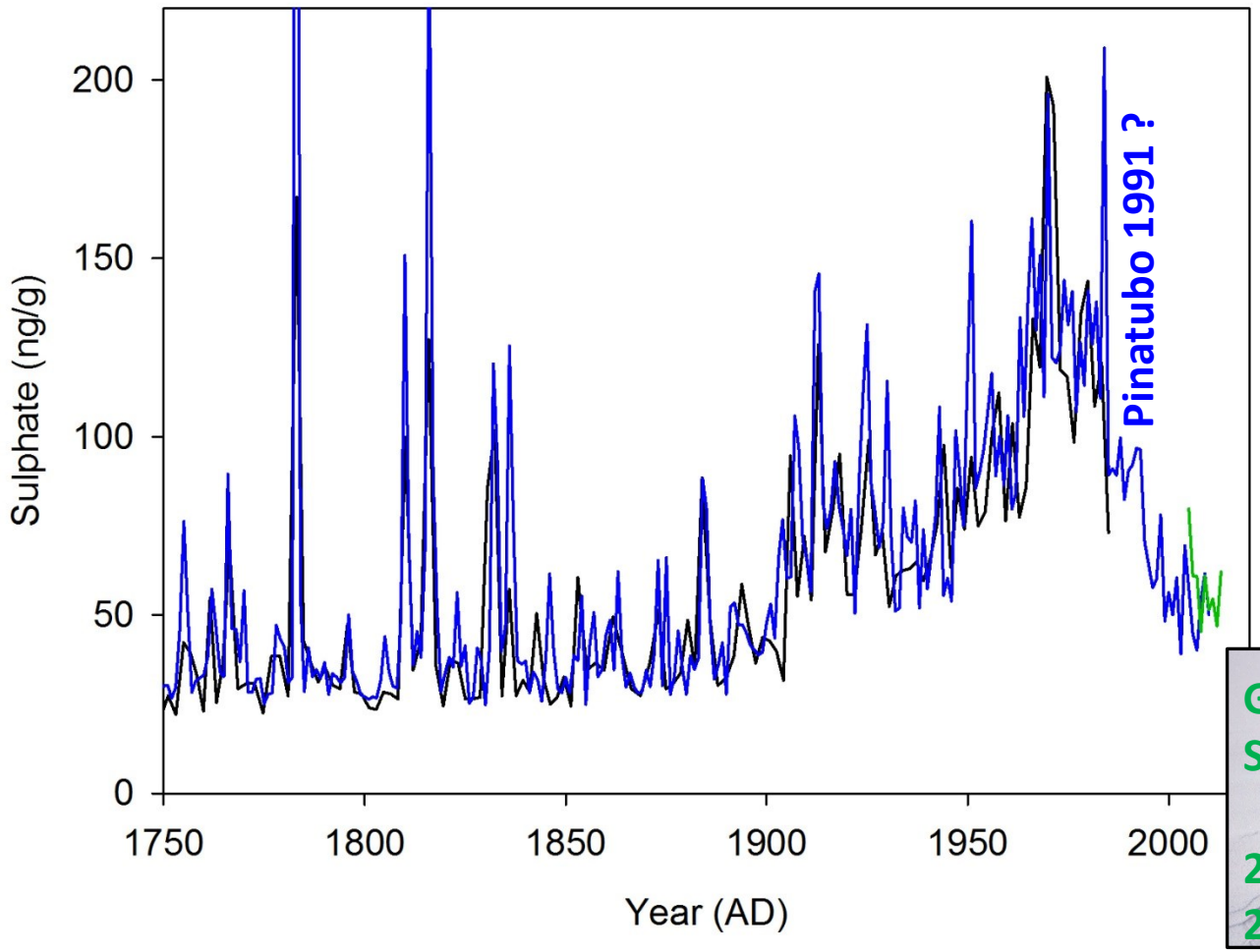
(ends 1985 AD)

Keegan et al., 2014 Proc. Natl. Acad. Sci. U.S.A.

Aerosols in Air (daily)

Greenland, Summit 3200m

Aerosols in Snow (weekly)



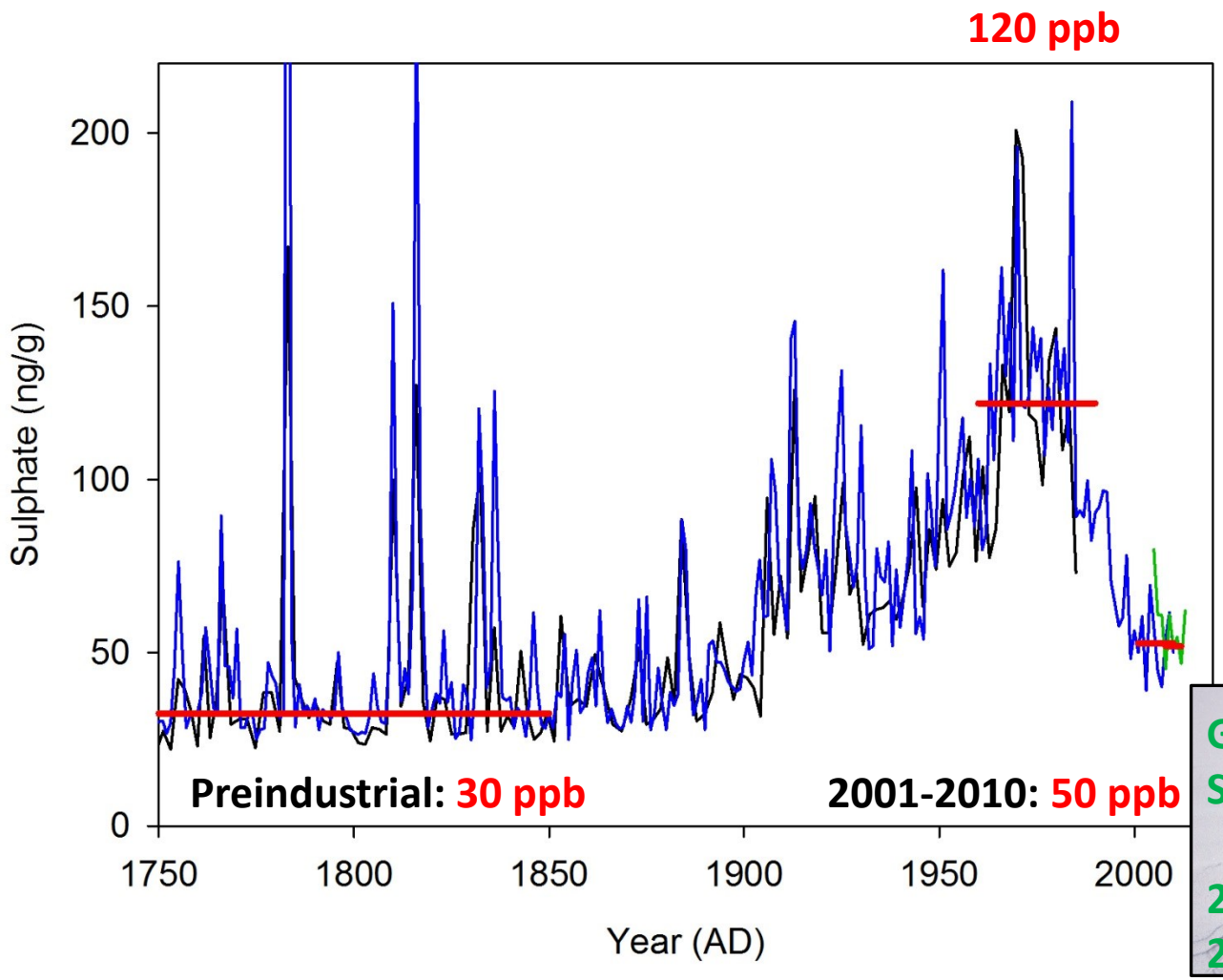
Summit 2010

GISP2

Aerosols in Air (daily)

Greenland, Summit 3200m

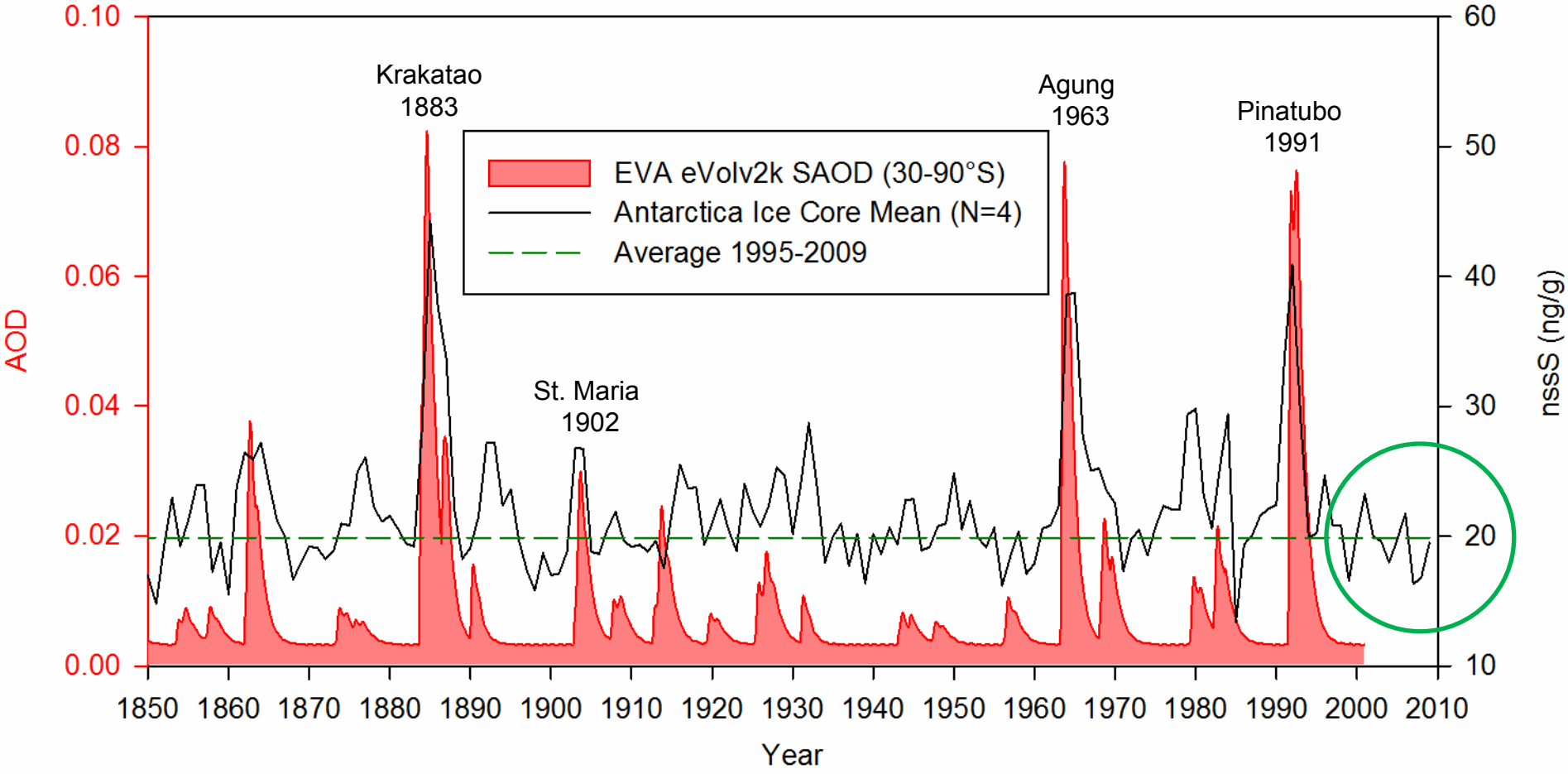
Aerosols in Snow (weekly)



Summit 2010

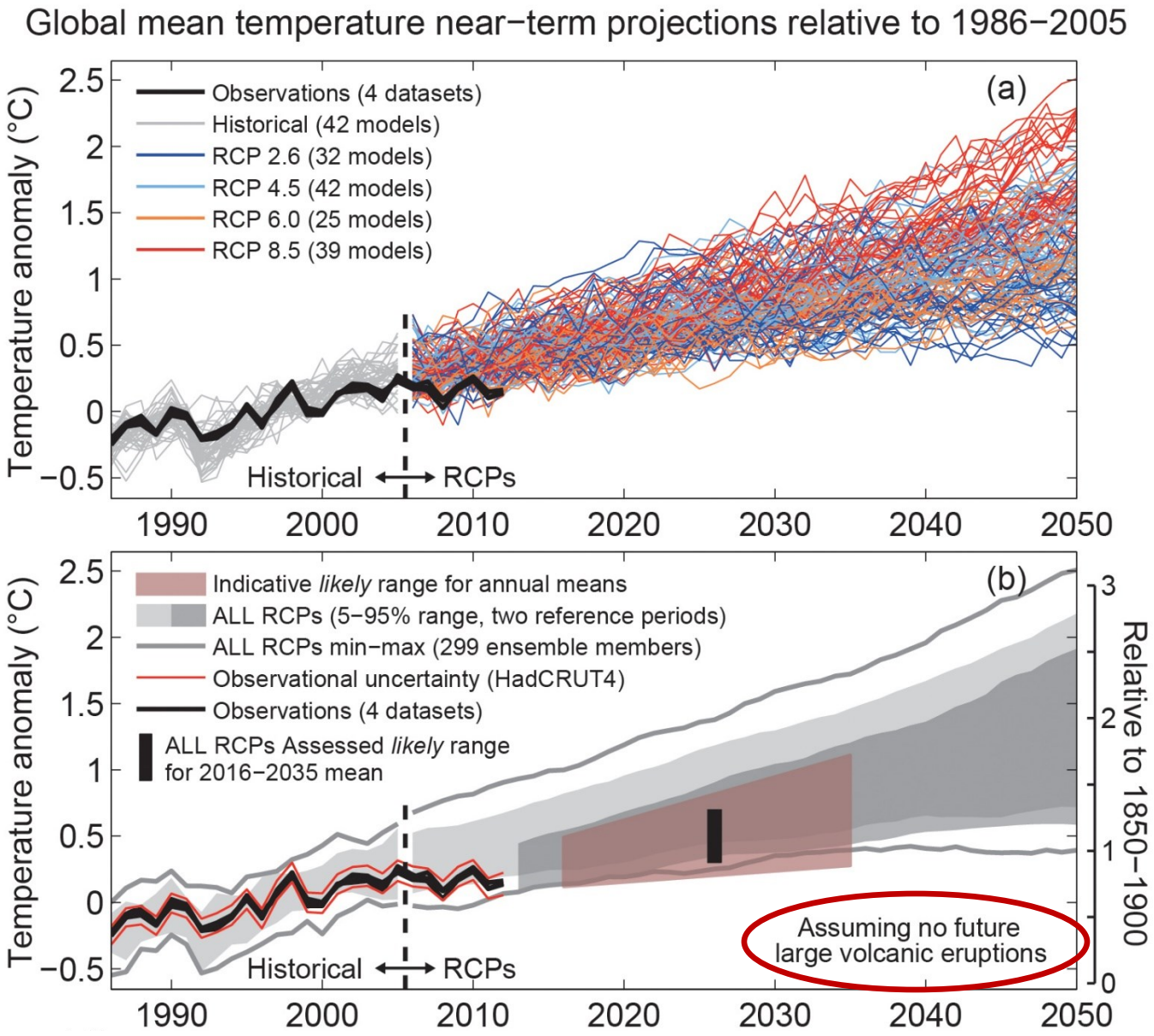
GISP2

No increase in background sulfur in Antarctica



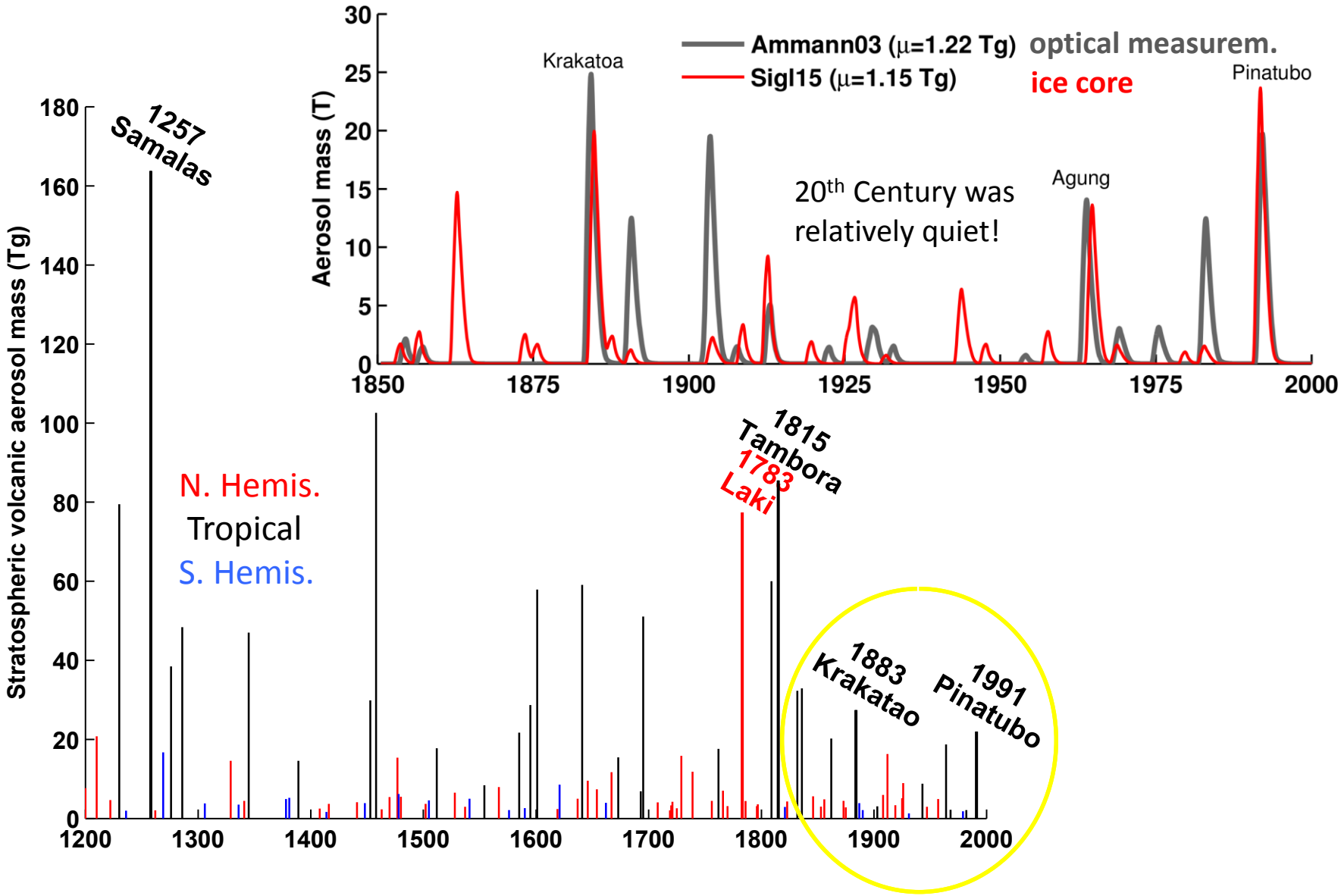
Sigl et al. 2014, Nat. Clim. Change
Toohey & Sigl, 2017, ESSD

Future Climate



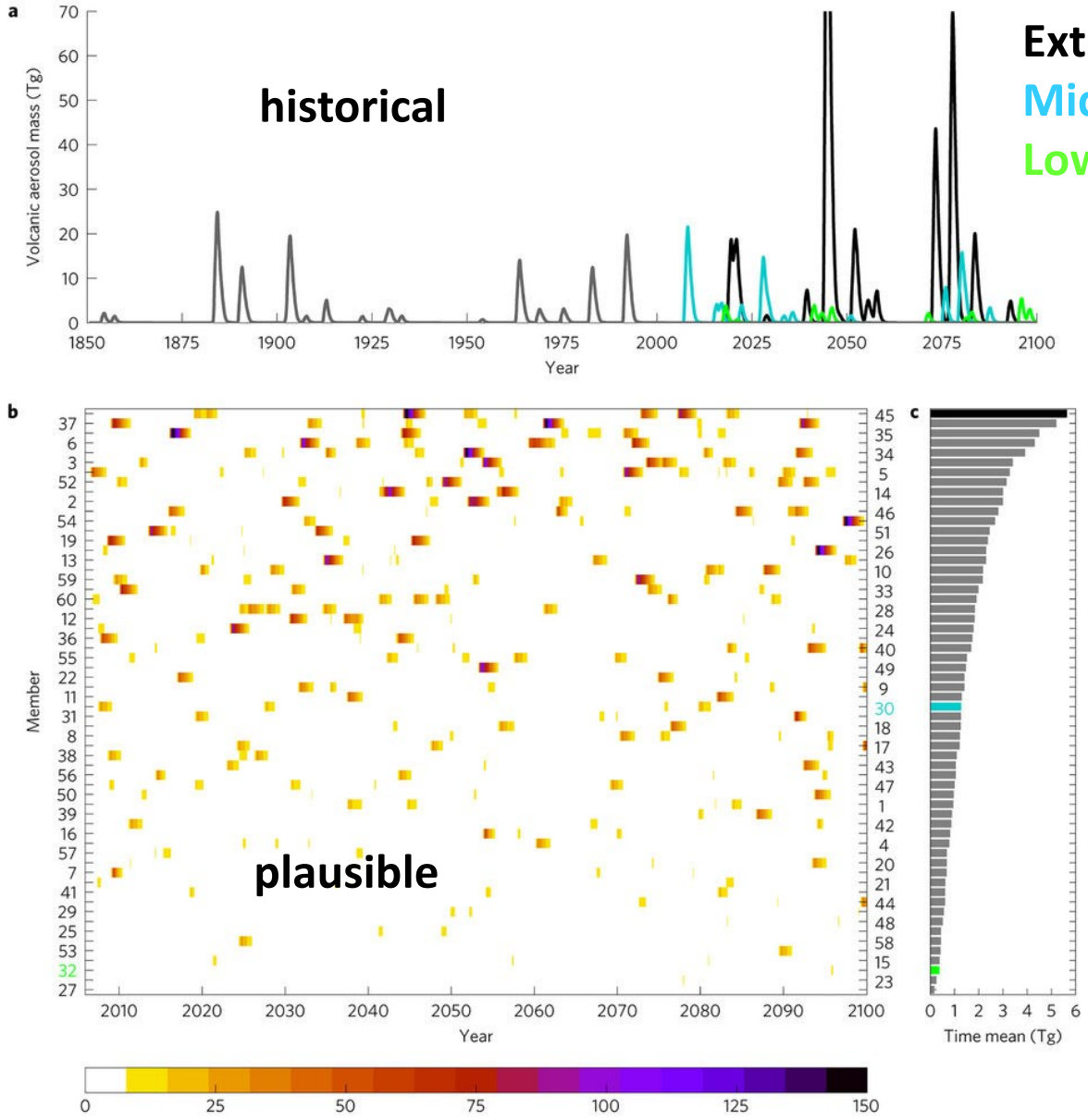
IPCC, 2014: Climate Change 2014: Synthesis Report.

Volcanic activity since the Preindustrial



Bethke et al., 2017, Nat. Clim. Change

Future volcanic eruption pathways

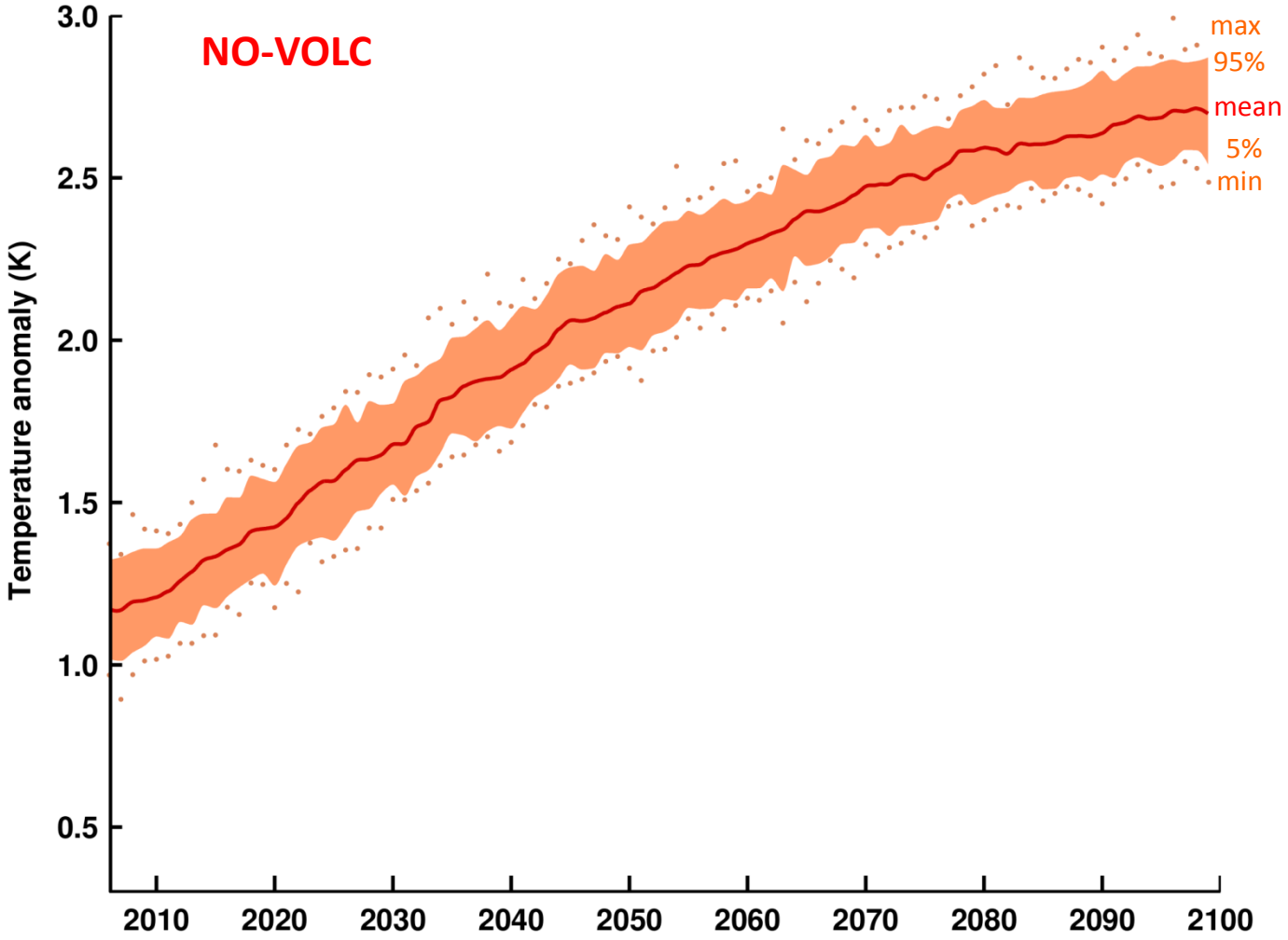


Extreme (>98%)
Mid (50%)
Low (5%)

NorESM
60-member
RCP4.5

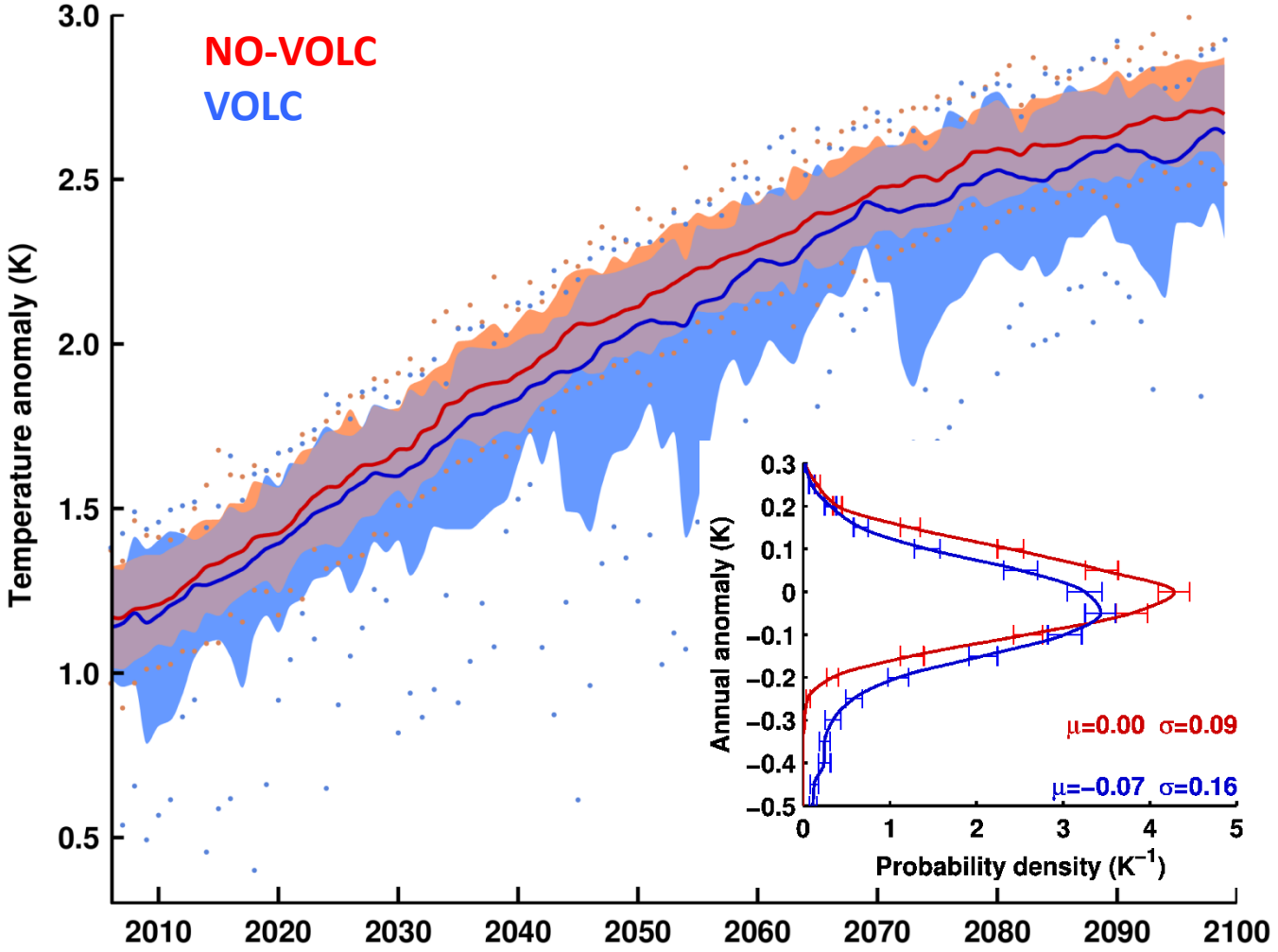
Bethke et al., 2017, Nat. Clim. Change

Projected Global Mean Surface Air Temperature



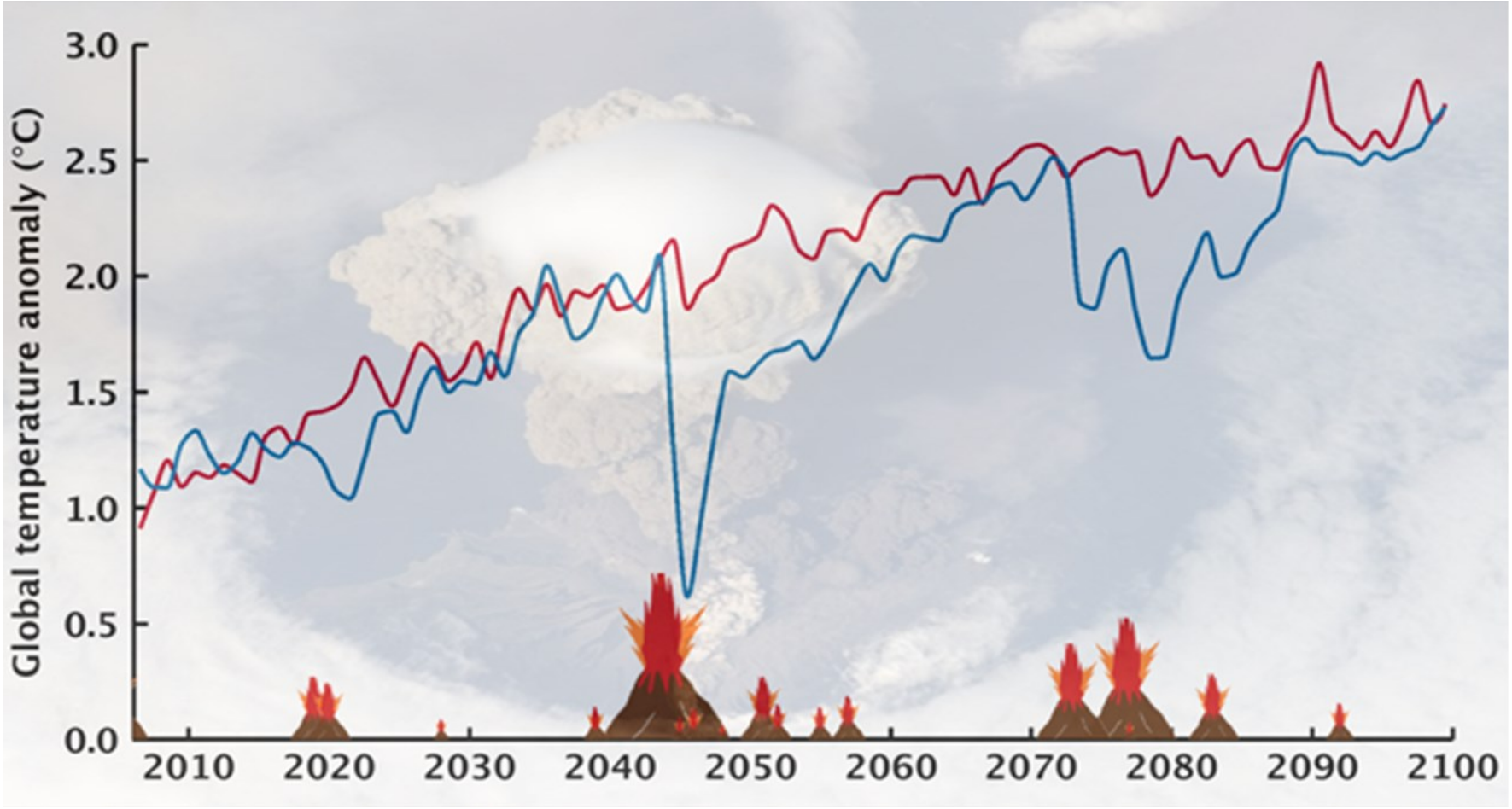
Bethke et al., 2017, Nat. Clim. Change

Projected Global Mean Surface Air Temperature



Bethke et al., 2017, Nat. Clim. Change

Projected Global Mean Surface Air Temperature

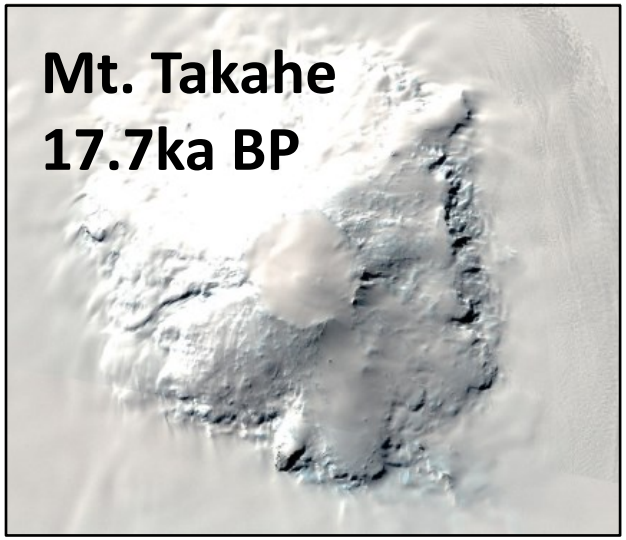


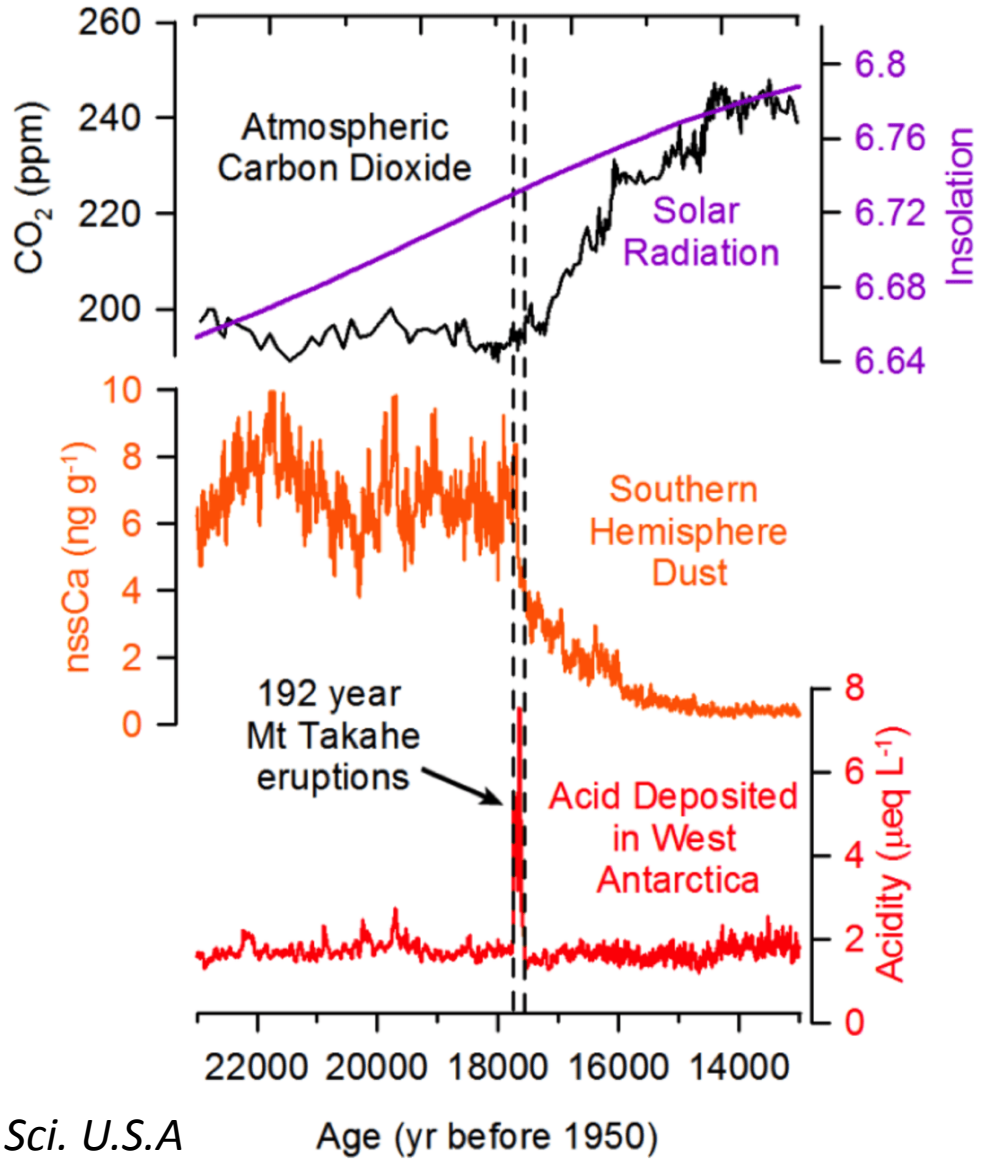
Bethke et al., 2017, Nat. Clim. Change

A 192-yr long eruption & the deglaciation

Mt. Takahe (Antarctica)

- ✓ Duration: **192 years!**
- ✓ Age: 17.7 ka BP (deglaciation)





McConnell et al., 2017, Proc. Natl. Acad. Sci. U.S.A

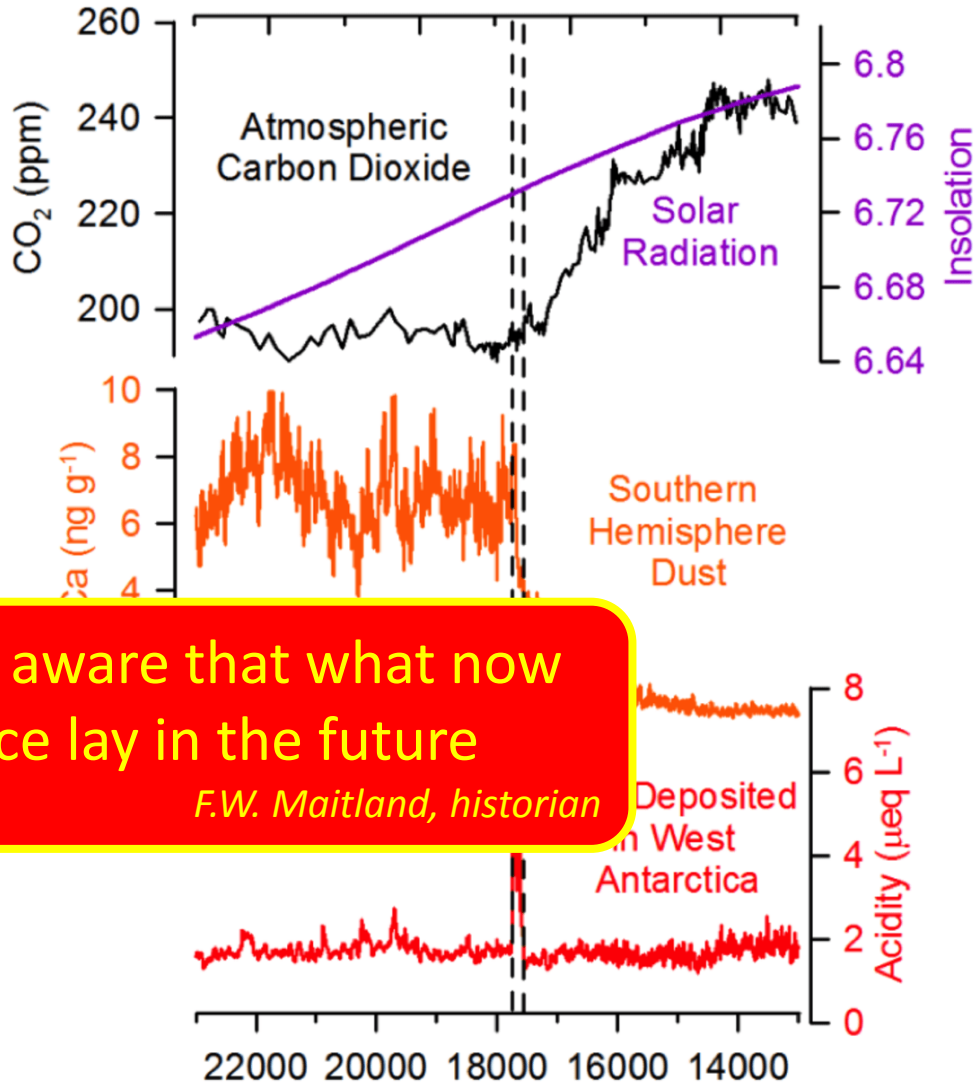
A 192-yr long eruption & the deglaciation

Mt. Takahe (Antarctica)

- ✓ Duration: **192 years!**
- ✓ Age: 17.7 ka BP (deglaciation)

We should always be aware that what now lies in the past once lay in the future

F.W. Maitland, historian



McConnell et al., 2017, Proc. Natl. Acad. Sci. U.S.A.


The End

Co-author list

M. Toohey, (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)
I. Bethke (Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway)
J.R. McConnell, O.J. Maselli, L. Layman; N. Chellman (Desert Reseach Insitute, Reno, USA)

K. Anchukaitis (University of Arizona, Tucson, USA)
U. Büntgen (University of Cambridge)
A. Burke, R. Wilson (University of St. Andrews, St. Andrews, UK)
J. Cole-Dai, D. Ferris (South Dakota State University, Brookings, USA)
N. Dunbar, N. Iverson (New Mexico Tech, Socorro, USA)
K. Krüger, (University of Oslo, Norway)
F. Ludlow (Trinity College, Dublin, Ireland)
J. Manning (Yale University, New Haven, USA)
L. Marshall (University of Leeds, UK)
R. Mulvaney (British Antarctic Survey, Cambridge, UK)
R. Muscheler (Lund University, Sweden)
G. Plunkett (Queen's University, Belfast, UK)
M. Severi (University of Florence, Florence, Italy)
A. Stine (San Francisco State University, USA)
K. Welten (University of California, Berkeley, USA)
M. Winstrup (University of Copenhagen, Denmark)

References

Baroni M. et al., *Science* **315**, 84-87 (2007).

Bethke I. et al., *Nat Clim Change* **7**, 799-805 (2017).

Brown S.K. et al., *Journal of Applied Volcanology* **3**, 5 (2014).

Burke A. et al., *Geophysical Research Abstracts* 18, 15260 (2016).

Chellman N. et al., *Environ Sci Technol* **51**, 4230-4238 (2017).

Crowley T., *Science* **289**, 270-277 (2000).

Crowley T. & Unterman M., *Earth Syst. Sci. Data*, **5**, 187-197 (2013).

D'Arrigo R. et al., *Geophys Res Lett* **28**, 543-546 (2001).

Dunbar N.W. et al., *Sci Rep-Uk* **7**, 12238 (2017).

Esper J. et al., *B Volcanol* **79**, 41 (2017).

Gao C.C. et al., *J Geophys Res-Atmos* **113**, D23111 (2008).

Hammer C.U. et al., *Nature* **288**, 230-235 (1980).

IPCC, Climate Change 2014: Synthesis Report (2014).

Jensen B.J.L. et al., *Geology* **42**, 875-878 (2014).

Keegan K.M. et al., *P Natl Acad Sci USA* **111**, 7964-7967 (2014).

Kellerhals T. et al., *Environ Sci Technol* **44**, 888-893 (2010).

Langway C. et al., *J Geophys Res-Atmos* **100**, 16241-16247 (1995).

Lavigne F. et al. 2013, *P Natl Acad Sci USA* **110**, 16742-16747 (2013).

Mann M.E. et al., *Nat Geosci* **5**, 202-205 (2012).

Manning J.G. et al., *Nat Commun* **8**, 900 (2017).

Marshall L. et al., *Atmos. Chem. Phys.* **18**, 2307-2328 (2018).

McConnell J.R. et al., *P Natl Acad Sci USA* **114**, 10035-10040 (2017).

Miyake F. et al. *Nature* **486**, 240-242 (2012).

Paris G. et al., *Chem Geol* **345**, 50-61 (2013).

Paris G. et al., *Science* **346**, 739-741 (2014).

Robock A. & Free M.P., *J Geophys Res-Atmos* **100**, 11549-11567 (1995).

Sigl M., *Quatern Int* **279-280**, 449 (2012).

Sigl M. et al., *J Geophys Res-Atmos* **118**, 1151-1169 (2013).

Sigl M. et al., *Nat Clim Change* **4**, 693-697 (2014).

Sigl M. et al., *Nature* **523**, 543-549 (2015).

Sigl M. et al., *Past Global Changes Magazine* **23**, 48-49 (2015).

Sigl M. et al., *Clim Past* **12**, 769-786 (2016).

Sigl M. et al., *The Cryosphere Discuss.* (in review).

Sun C.Q. et al., *Geophys Res Lett* **41**, 694-701 (2014).

Stothers R.B., *Nature* **307**, 344-345 (1984).

Toohey M. et al., *Climatic Change* **136**, 401-412 (2016).

Toohey M. & Sigl M., *Earth Syst. Sci. Data* **9**, 809-831 (2017).

Wilson R. et al., *Quaternary Sci Rev* **134**, 1-18 (2016).

Zielinski G. et al., *Science* **264**, 948-952 (1994).