Frozen memories of past eruptions reveal the global risks of future ones

Michael Sigl, Climate and Environmental Physics, University of Bern

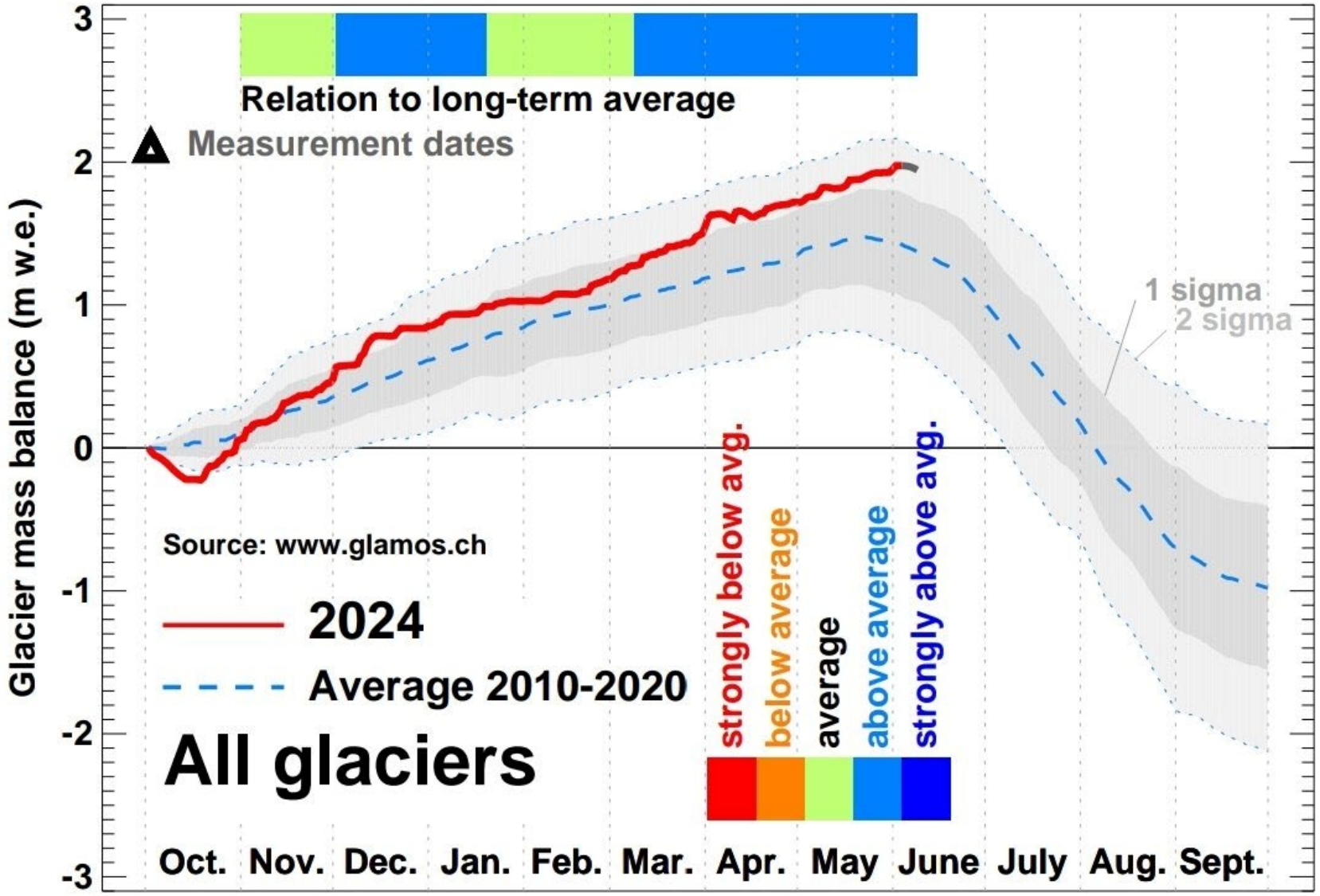
Swiss Polar Day 2024, Fribourg, Switzerland

b
UNIVERSITÄT
BERN

OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

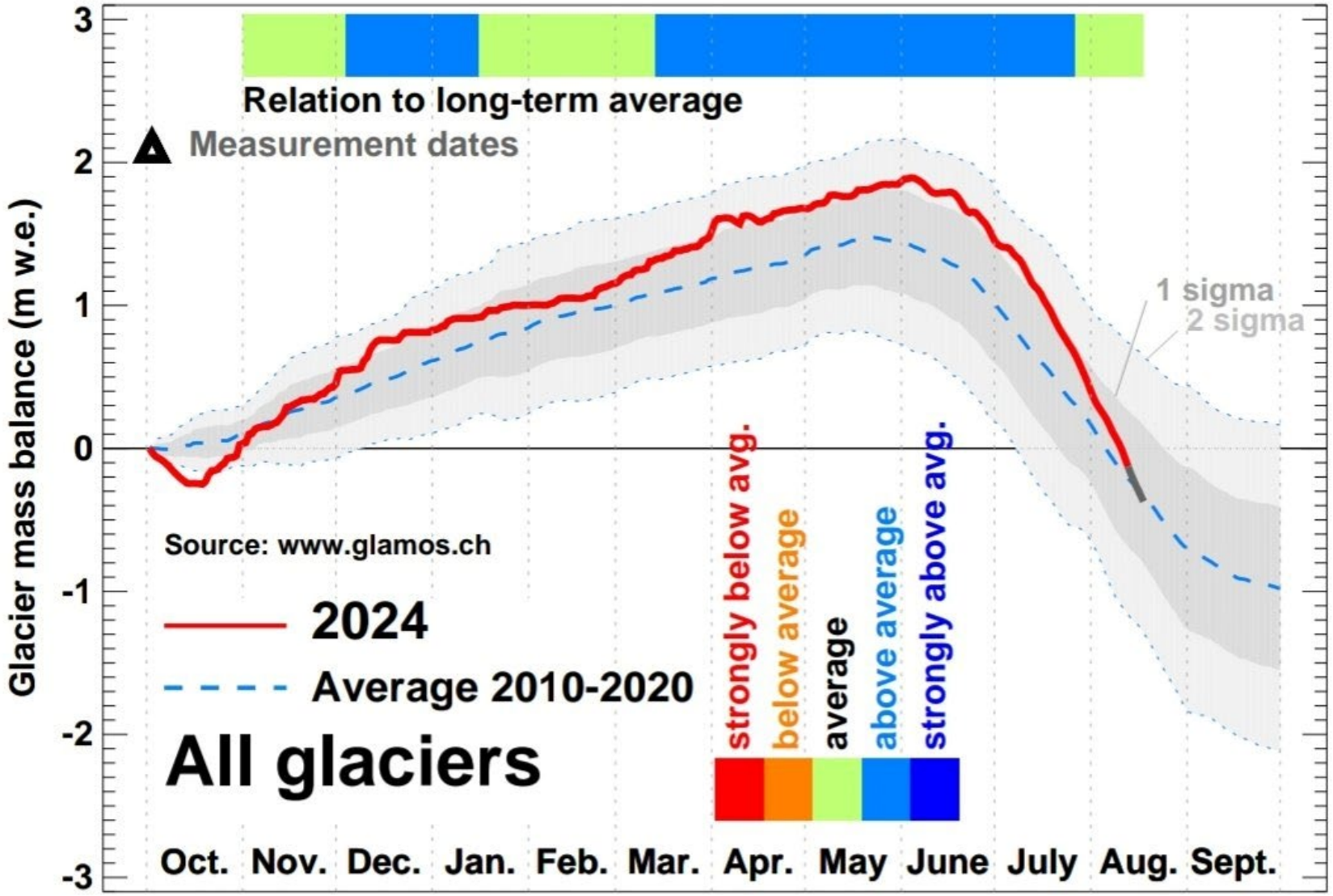
GLAMOS
Glacier Monitoring Switzerland

Summer 2024: How it started…

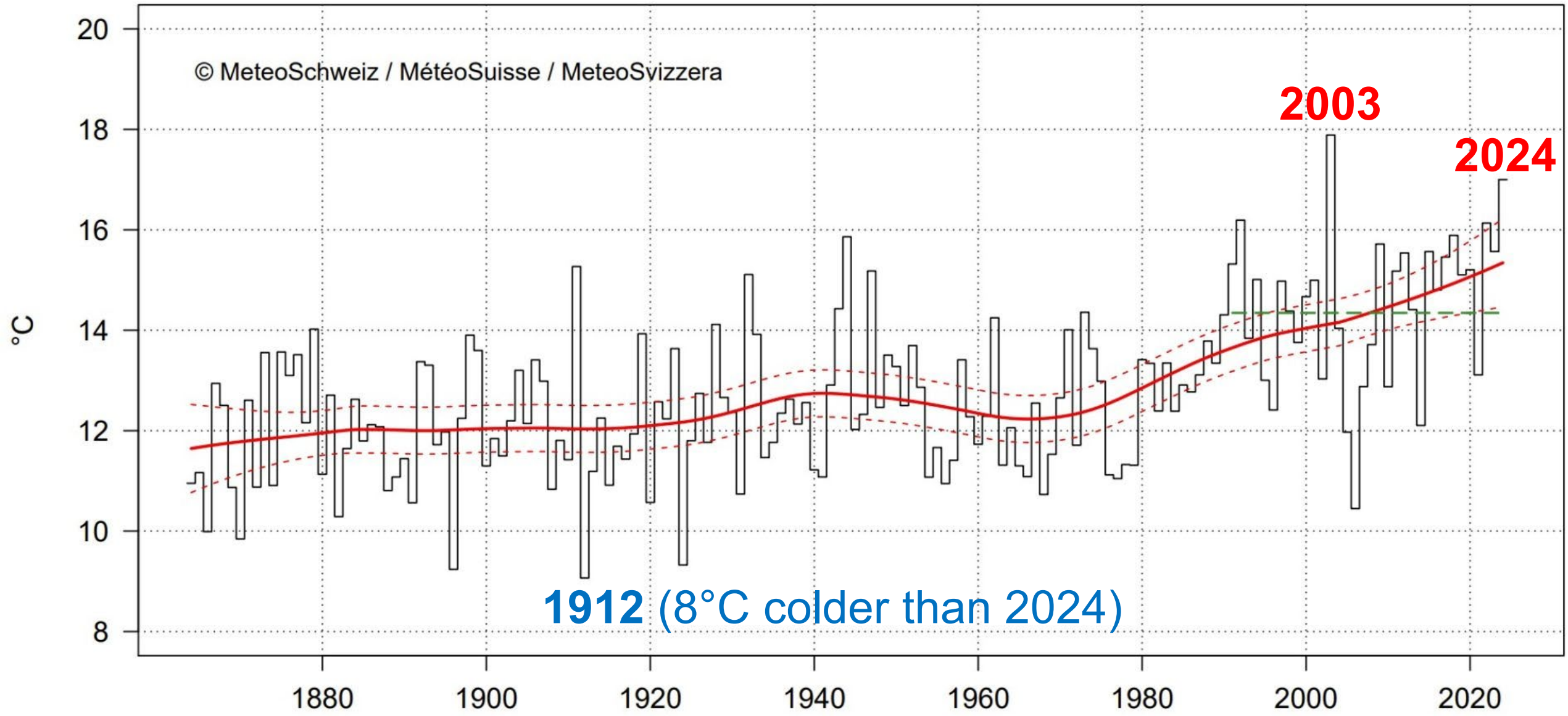


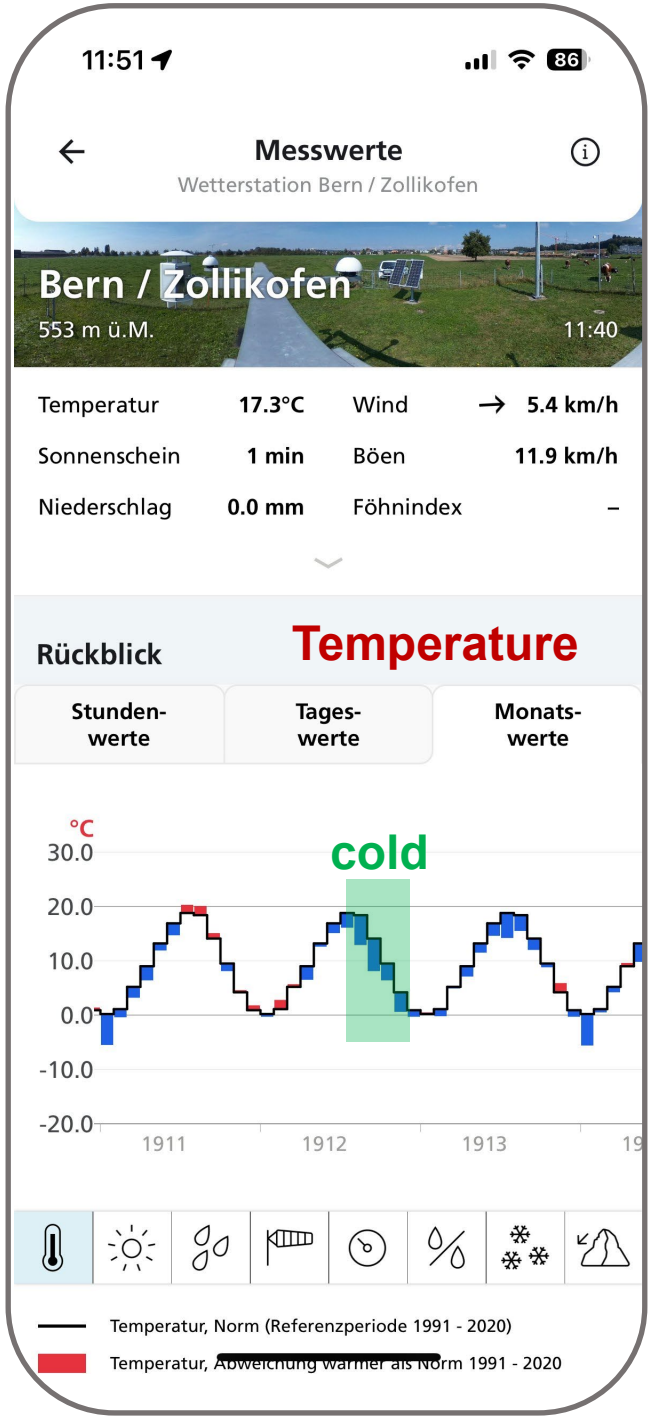
GLAMOS
Glacier Monitoring Switzerland

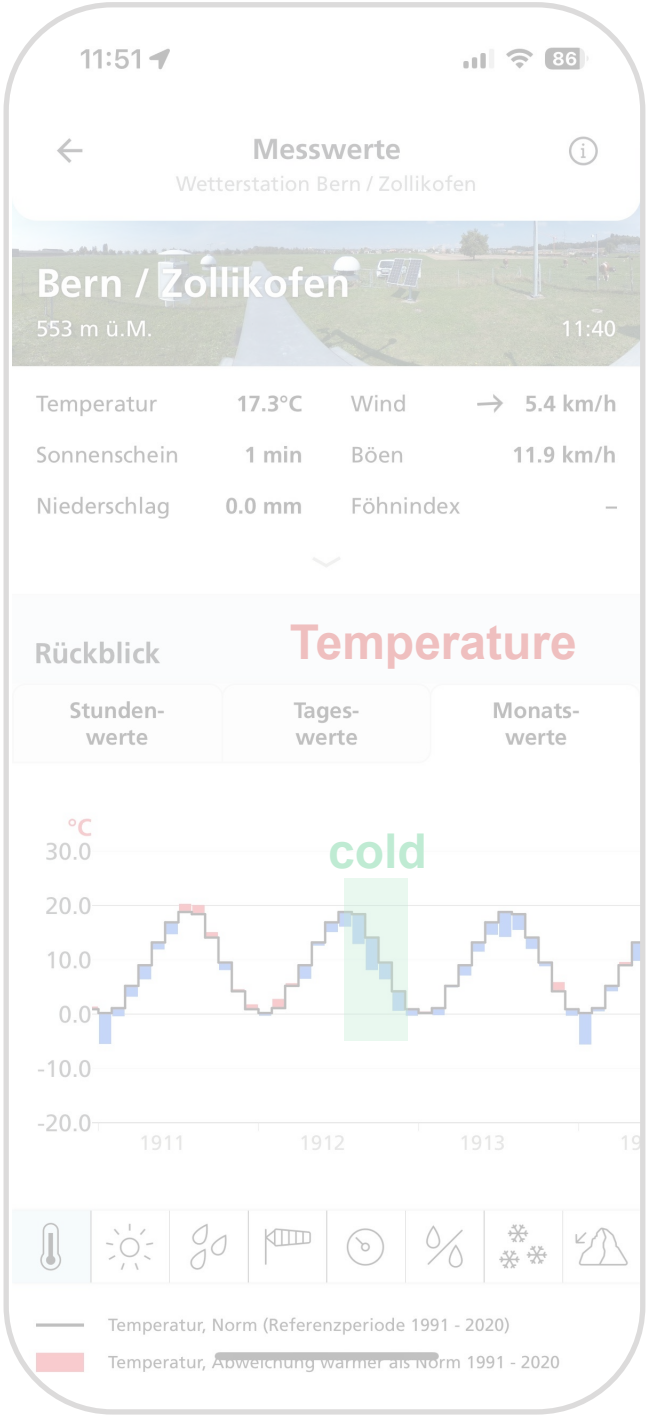
Summer 2024: …how it's going!

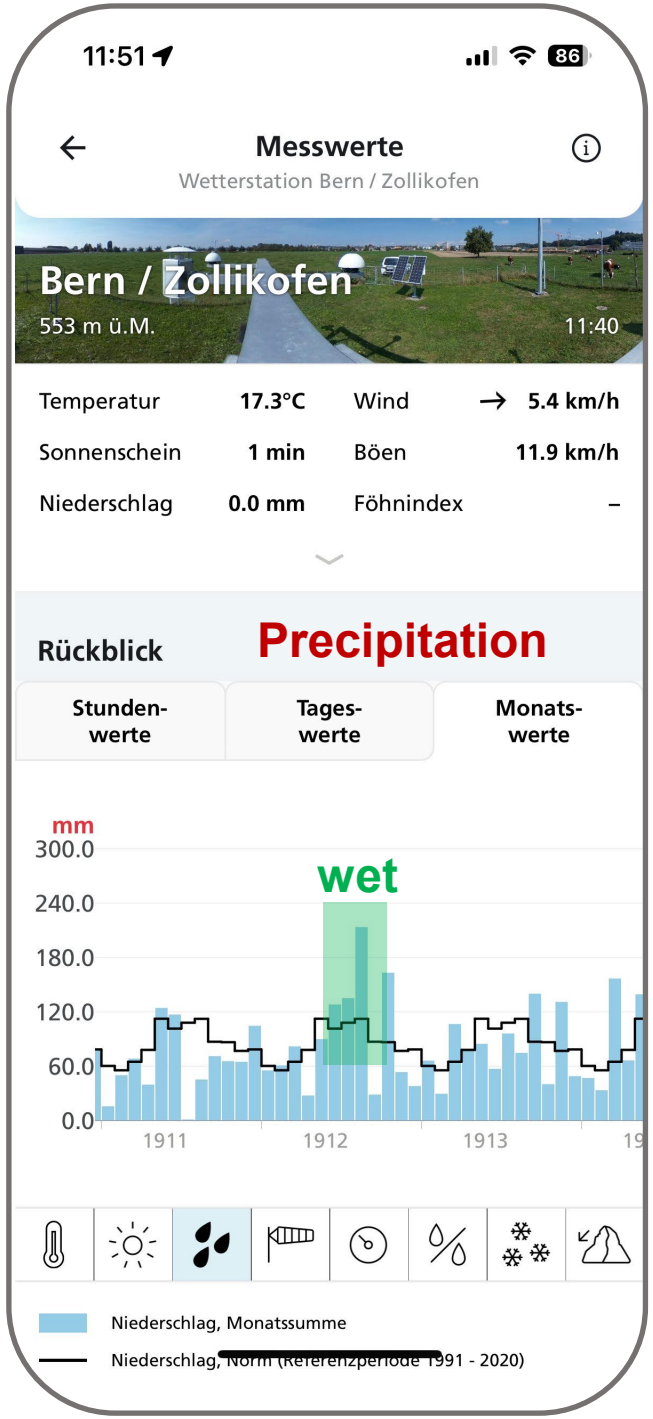


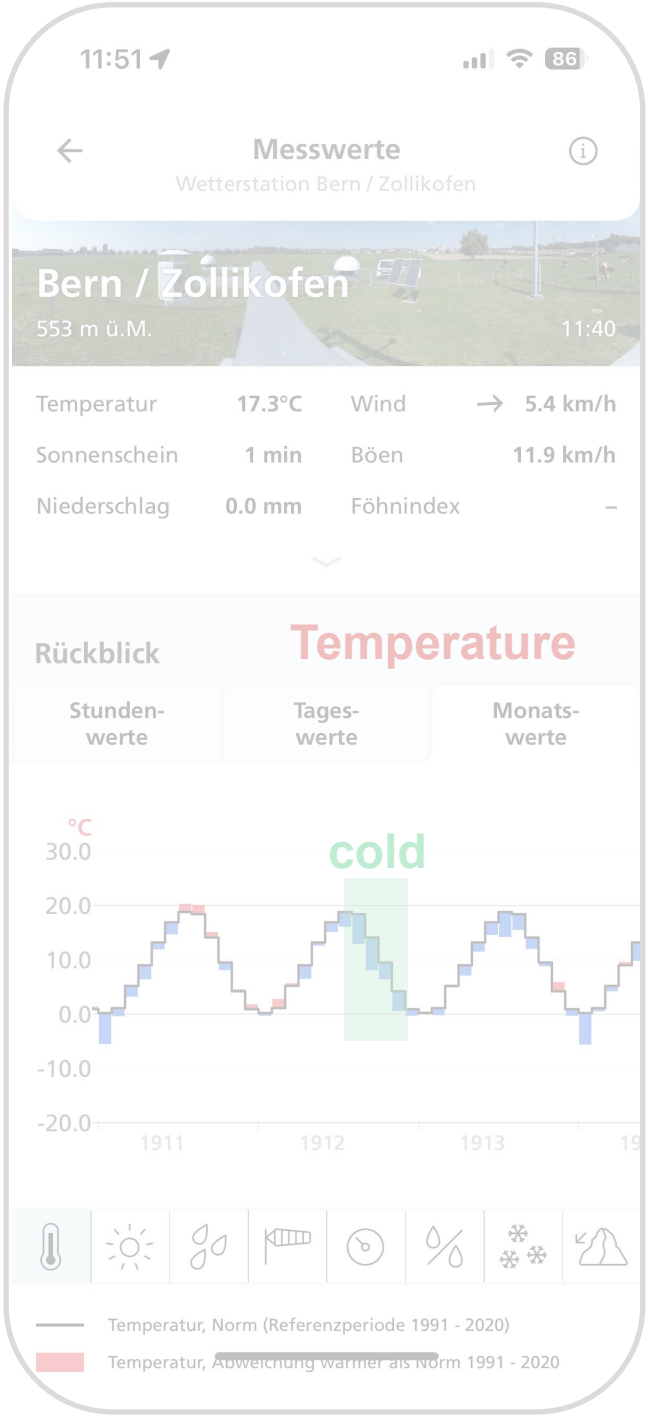
August Temperature Switzerland since 1864

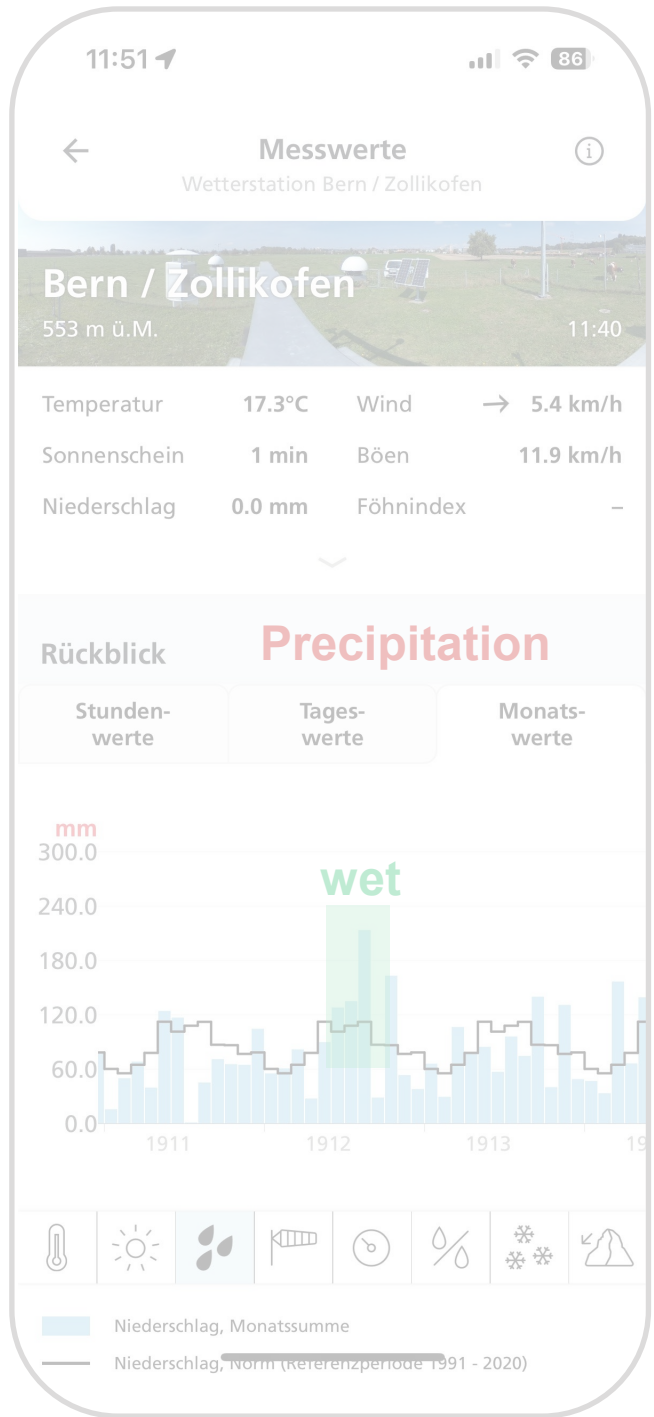


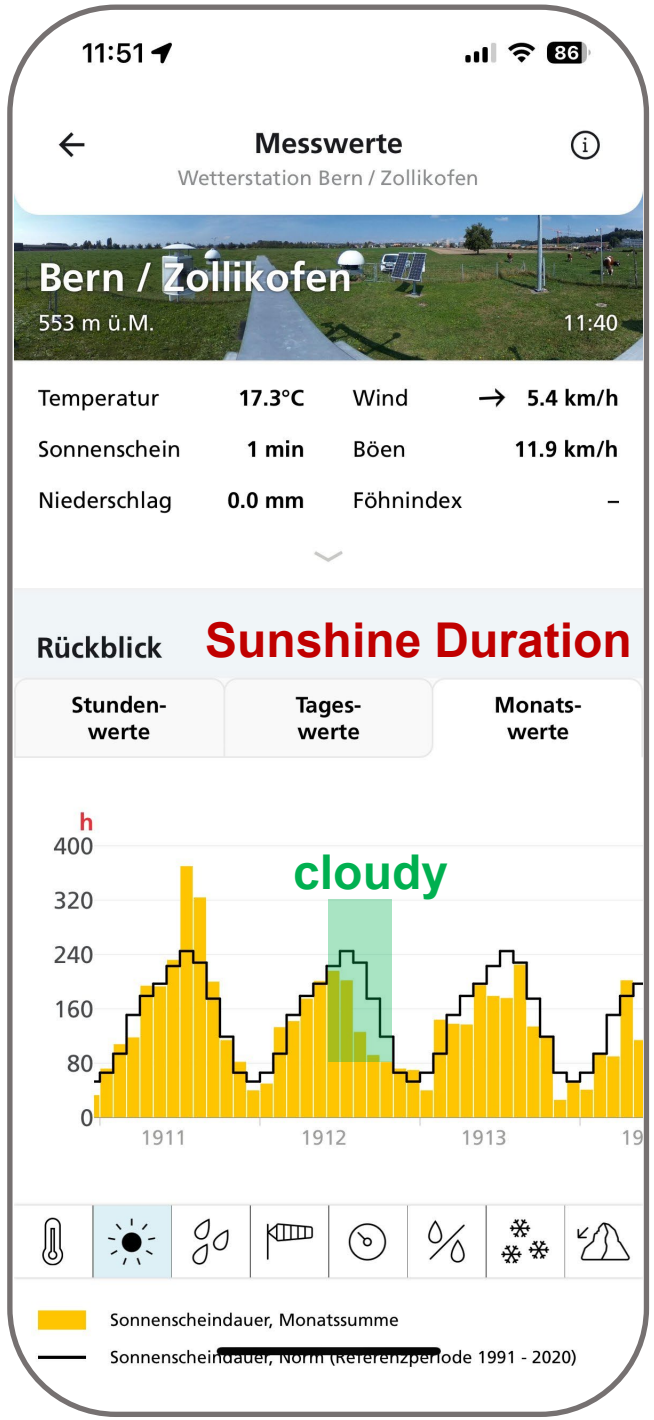

11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Temperature
Stunden-werte
Tages-werte
Monats-werte
°C
30.0
20.0
10.0
0.0
-10.0
-20.0
cold
1911
1912
1913
Temperatur, Norm (Referenzperiode 1991 - 2020)
Temperatur, Abweichung wärmer als Norm 1991 - 2020

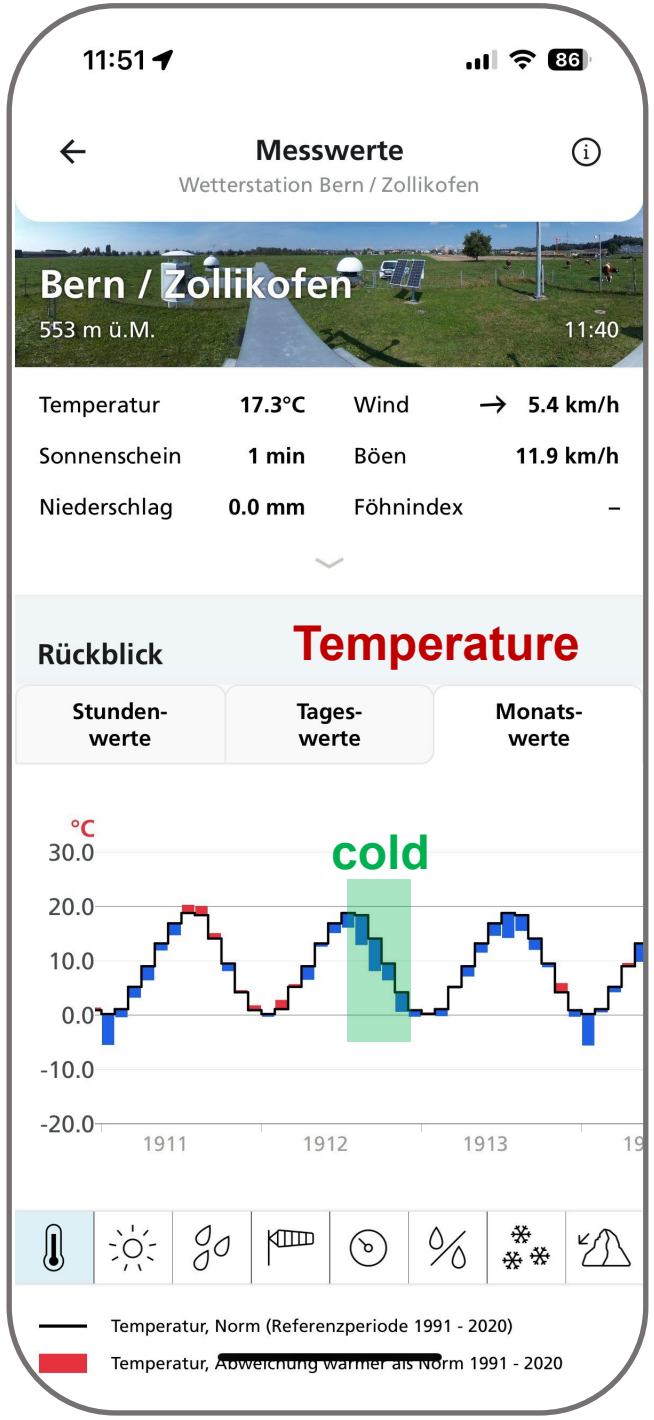

11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Temperature
Stunden-werte
Tages-werte
Monats-werte
°C
30.0
20.0
10.0
0.0
-10.0
-20.0
cold
1911
1912
1913
Temperatur, Norm (Referenzperiode 1991 - 2020)
Temperatur, Abweichung wärmer als Norm 1991 - 2020

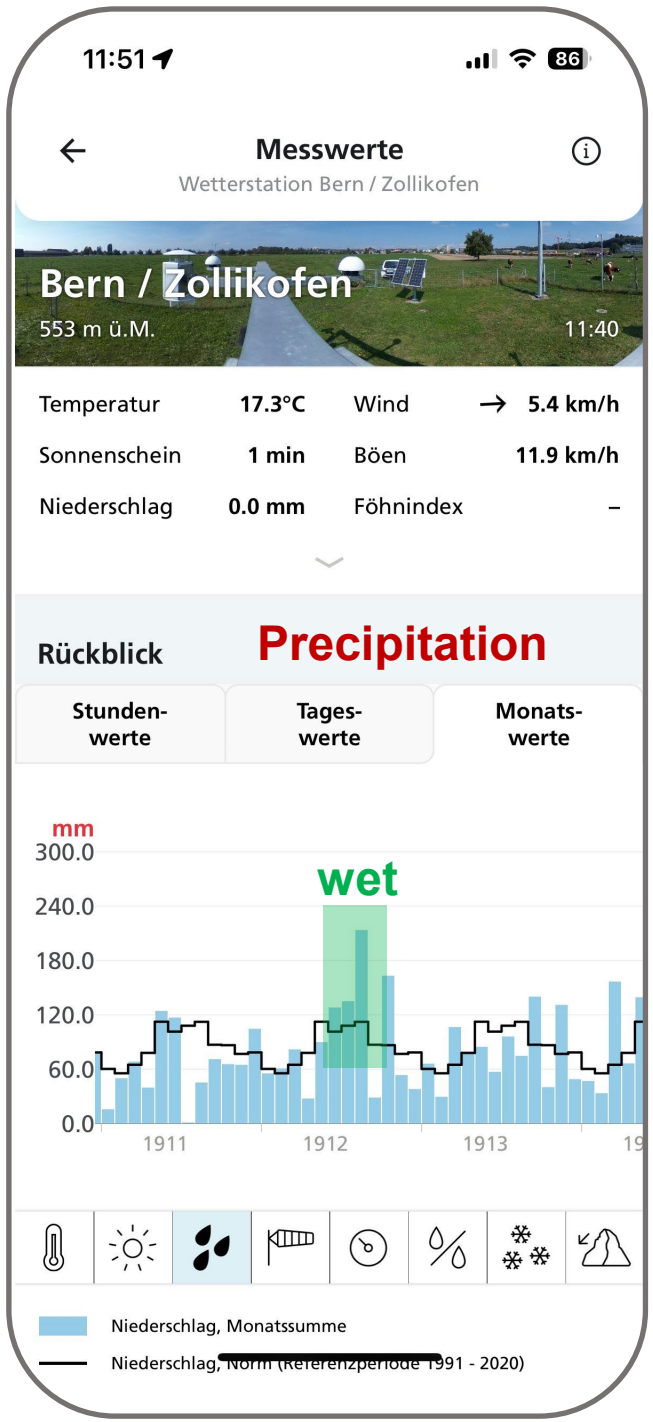

11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Precipitation
Stunden-werte
Tages-werte
Monats-werte
mm
300.0
240.0
180.0
120.0
60.0
0.0
wet
1911
1912
1913
Niederschlag, Monatssumme
Niederschlag, Norm (Referenzperiode 1991 - 2020)

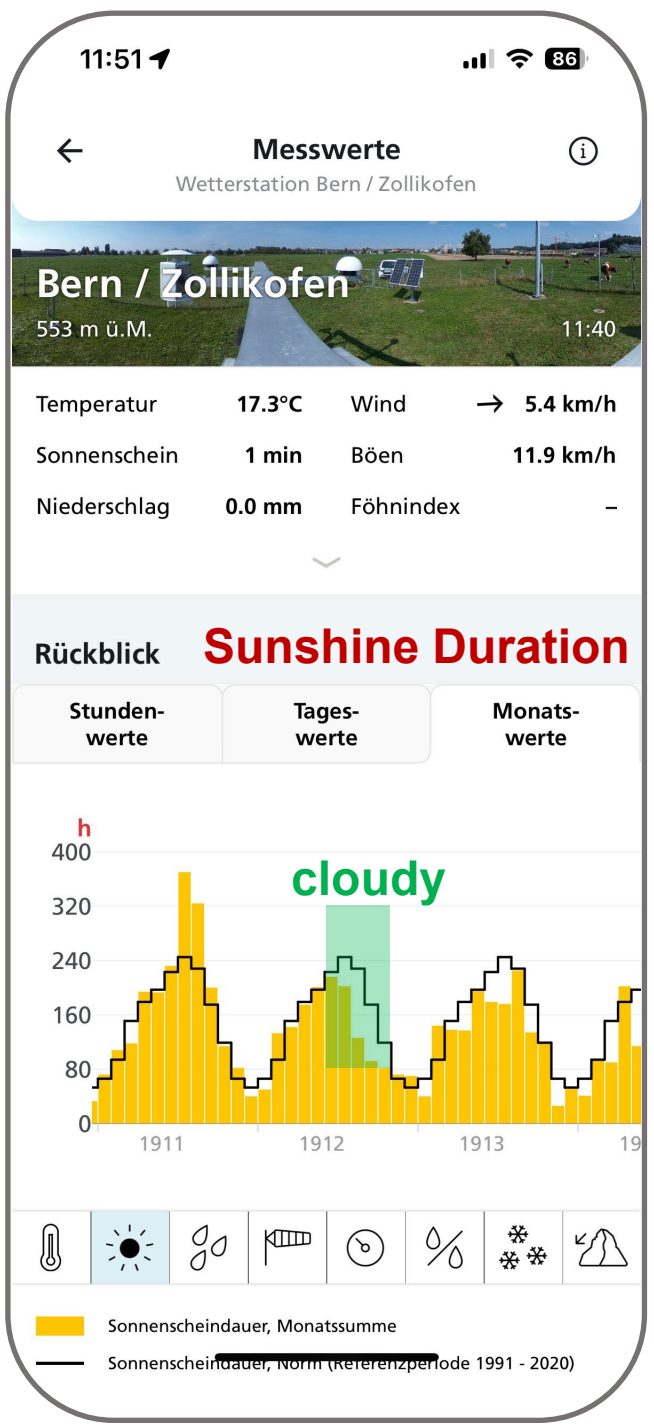

11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Temperature
Stunden-werte
Tages-werte
Monats-werte
°C
30.0
20.0
10.0
0.0
-10.0
-20.0
cold
1911
1912
1913
Temperatur, Norm (Referenzperiode 1991 - 2020)
Temperatur, Abweichung wärmer als Norm 1991 - 2020


11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Precipitation
Stunden-werte
Tages-werte
Monats-werte
mm
300.0
240.0
180.0
120.0
60.0
0.0
wet
1911
1912
1913
Niederschlag, Monatssumme
Niederschlag, Norm (Referenzperiode 1991 - 2020)


11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Sunshine Duration
Stunden-werte
Tages-werte
Monats-werte
h
400
320
240
160
80
0
cloudy
1911
1912
1913
Sonnenscheindauer, Monatssumme
Sonnenscheindauer, Norm (Referenzperiode 1991 - 2020)


11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Temperature
Stunden-werte
Tages-werte
Monats-werte
°C
30.0
20.0
10.0
0.0
-10.0
-20.0
cold
1911
1912
1913
Temperatur, Norm (Referenzperiode 1991 - 2020)
Temperatur, Abweichung wärmer als Norm 1991 - 2020


11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Precipitation
Stunden-werte
Tages-werte
Monats-werte
mm
300.0
240.0
180.0
120.0
60.0
0.0
wet
1911
1912
1913
Niederschlag, Monatssumme
Niederschlag, Norm (Referenzperiode 1991 - 2020)


11:51
86
Messwerte
Wetterstation Bern / Zollikofen
Bern / Zollikofen
553 m ü.M.
11:40
Temperatur 17.3°C
Wind → 5.4 km/h
Sonnenschein 1 min
Böen 11.9 km/h
Niederschlag 0.0 mm
Föhnindex –
Rückblick
Sunshine Duration
Stunden-werte
Tages-werte
Monats-werte
h
400
320
240
160
80
0
cloudy
1911
1912
1913
Sonnenscheindauer, Monatssumme
Sonnenscheindauer, Norm (Referenzperiode 1991 - 2020)

„It was an **unusally wet summer**; during their stay (22 June -31 July) it rained on one day out of three."

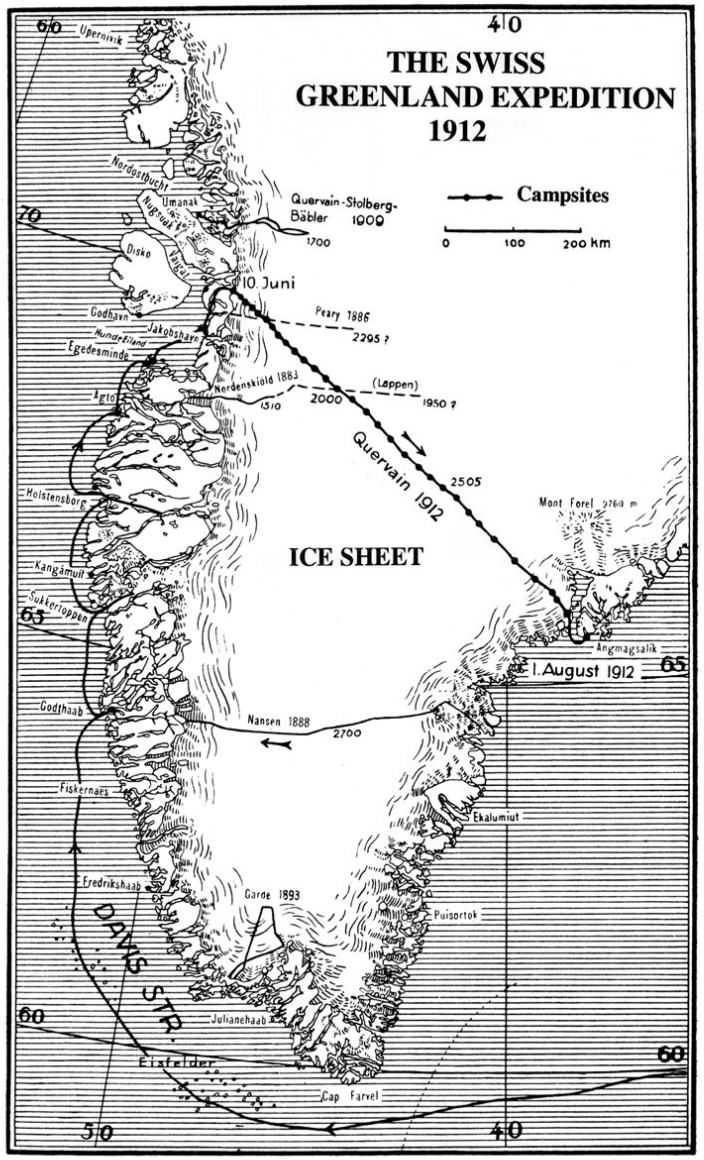
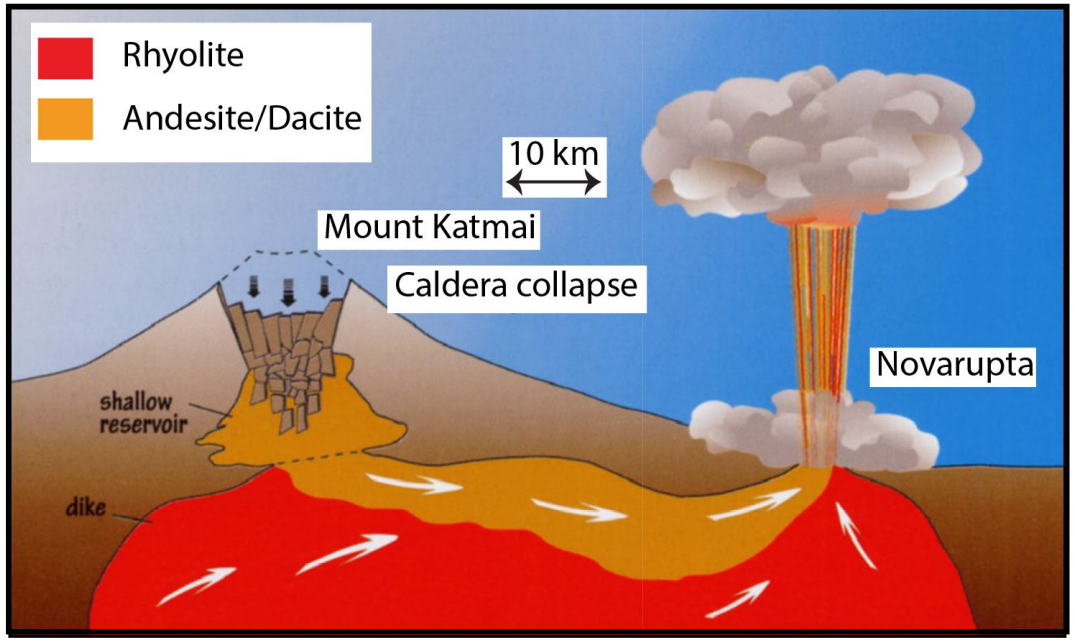
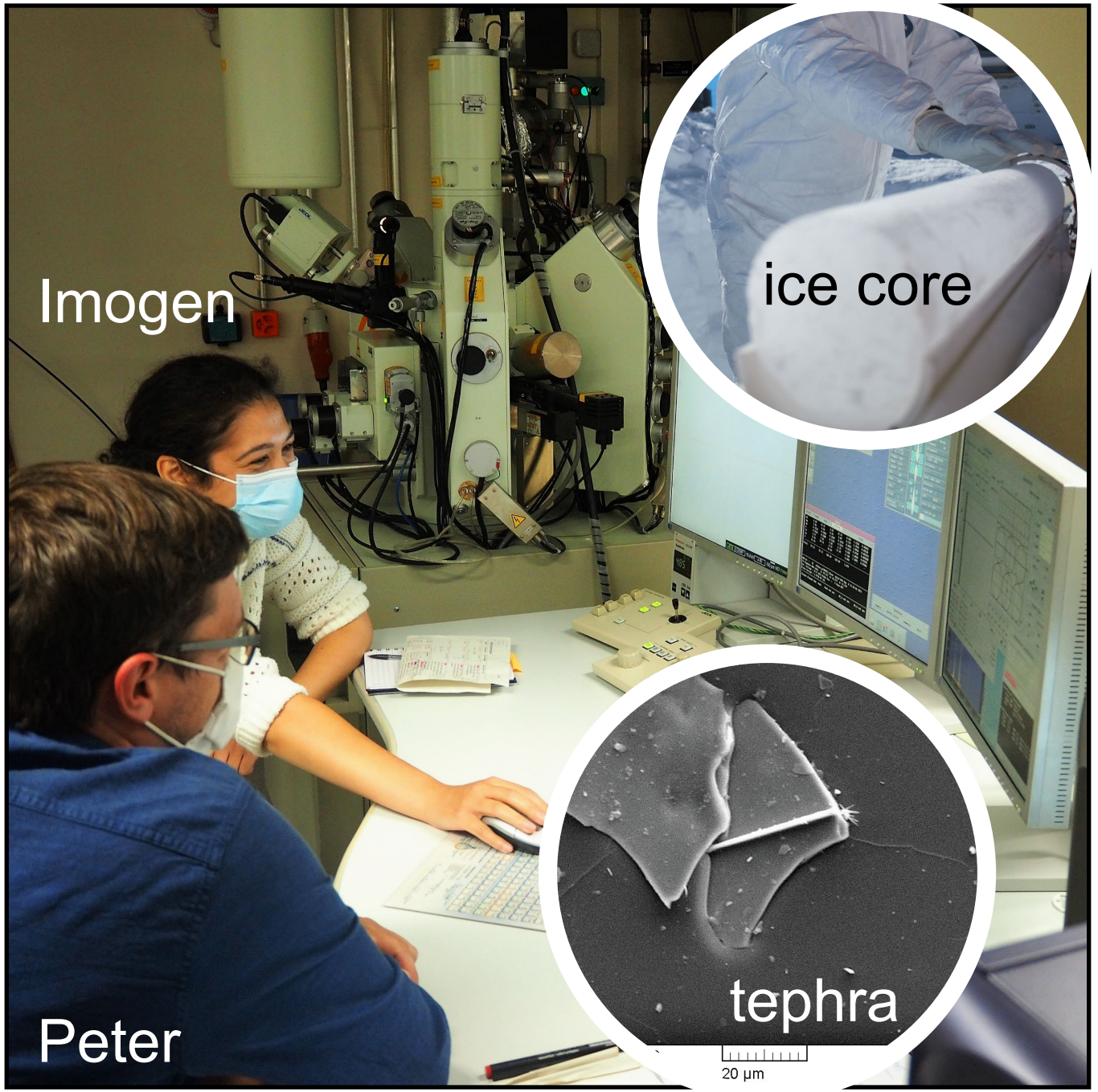


Fig. 2. Map showing routes of de Quervain's 1909 and 1912 expeditions, and of various earlier expeditions on the Greenland ice cap (based on map in de Quervain 1914).

W. Barr (2015): Alfred de Quervain's Swiss Greenland expeditions, 1909 and 1912

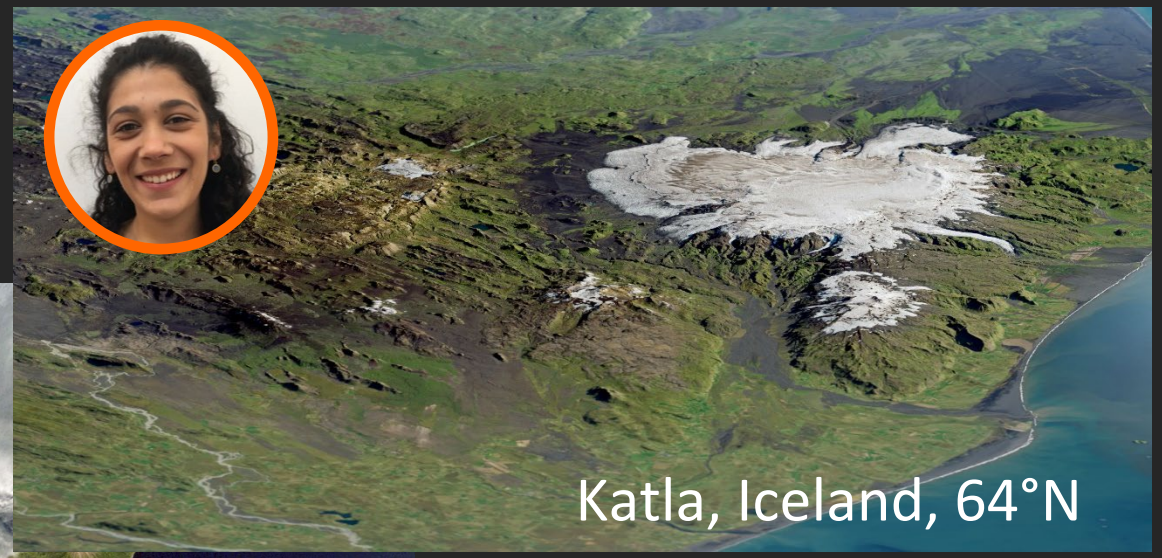

Katmai/Novarupta (VEI=6)
6 June 1912


Rhyolite
Andesite/Dacite
10 km
Mount Katmai
Caldera collapse
Novarupta
shallow reservoir
dike


Imogen
ice core
tephra
20 µm
Peter

Volcanic Eruptions (VEI, M)

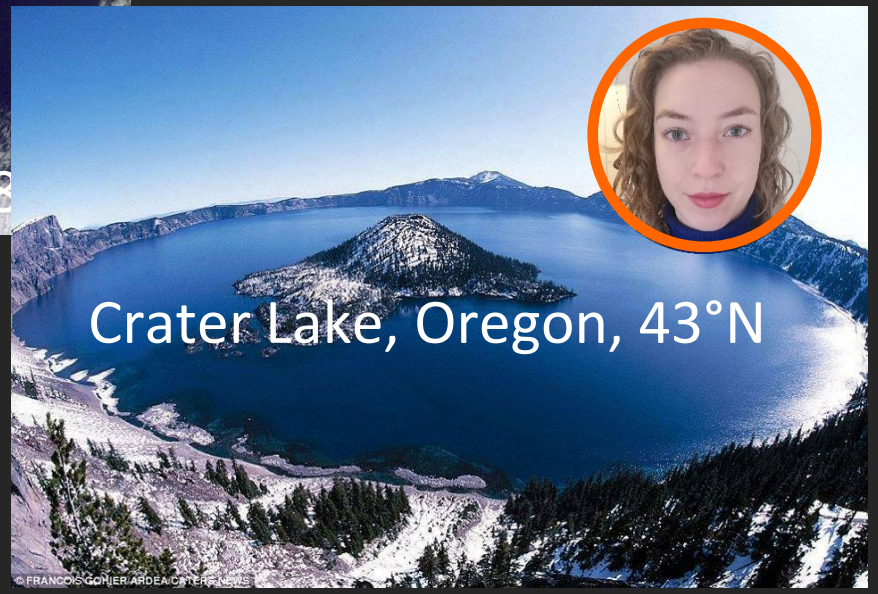
Scale	Volume of volcanic ejecta
0	0.00001 km^3
1	0.001 km^3
2	0.01 km^3
3	0.1 km^3
4	1 km^3
5	10 km^3
6	100 km^3
7	

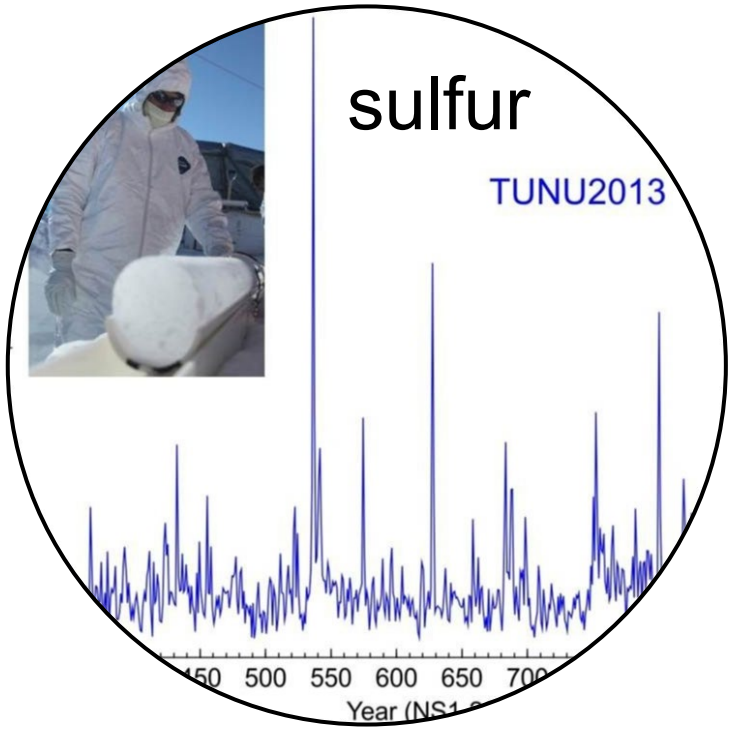


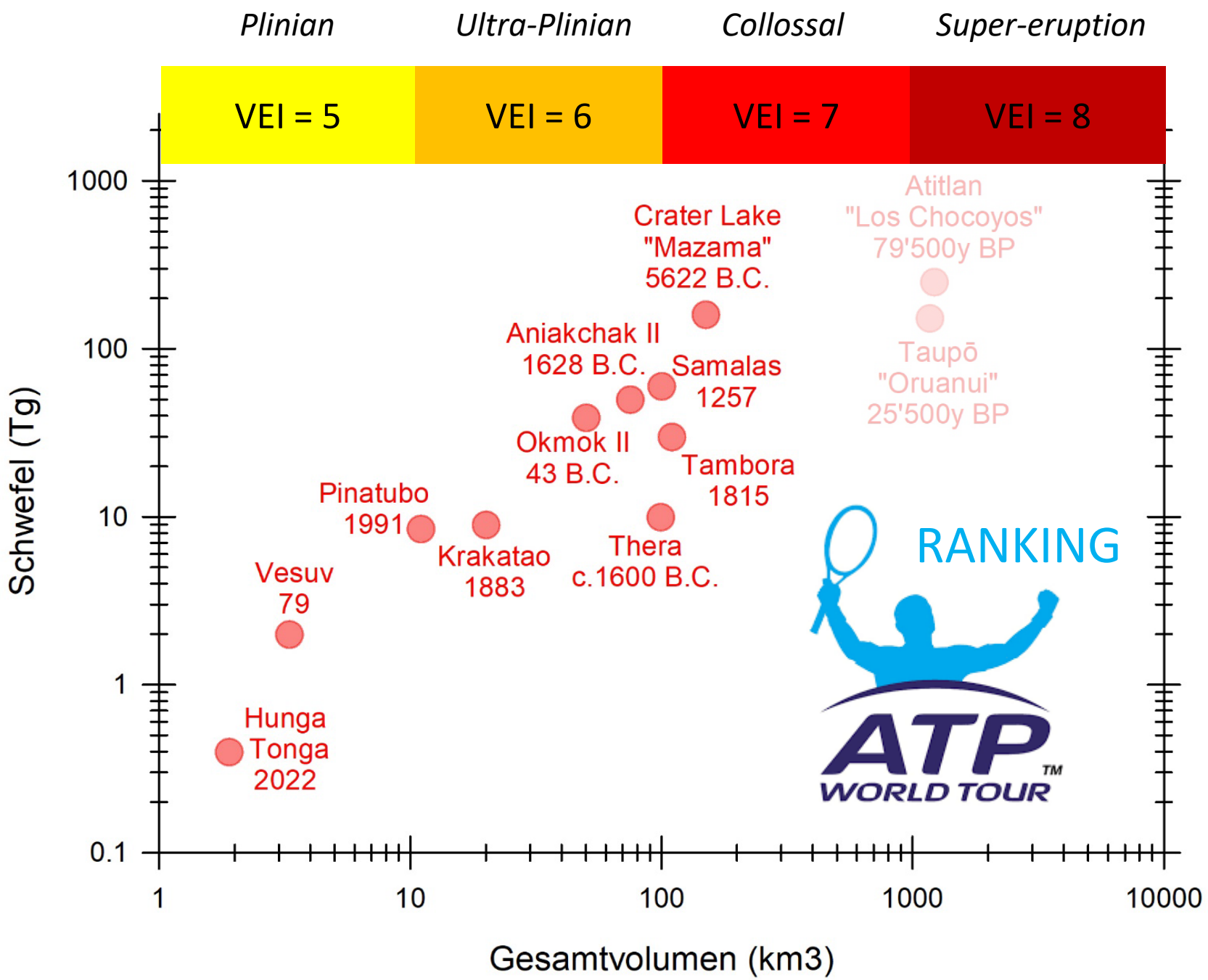
Hrafnkatla, 763 CE

Zavaritskii, 1831 CE

Mazama, Crater Lake 5622 BCE




sulfur
TUNU2013
500
550
600
650


Plinian
Ultra-Plinian
Collossal
Super-eruption
VEI = 5
VEI = 6
VEI = 7
VEI = 8
Schwefel (Tg)
1000
100
10
1
0.1
1
10
100
1000
10000
Gesamtvolumen (km3)
Crater Lake
"Mazama"
5622 B.C.
Atitlan
"Los Chocoyos"
79'500y BP
Taupō
"Oruanui"
25'500y BP
Aniakchak II
1628 B.C.
Samalas
1257
Okmok II
43 B.C.
Tambora
1815
Pinatubo
1991
Krakatao
1883
Thera
c.1600 B.C.
Vesuv
79
Hunga
Tonga
2022
RANKING
ATP
WORLD TOUR

Name: Katmai

Region: Alaska

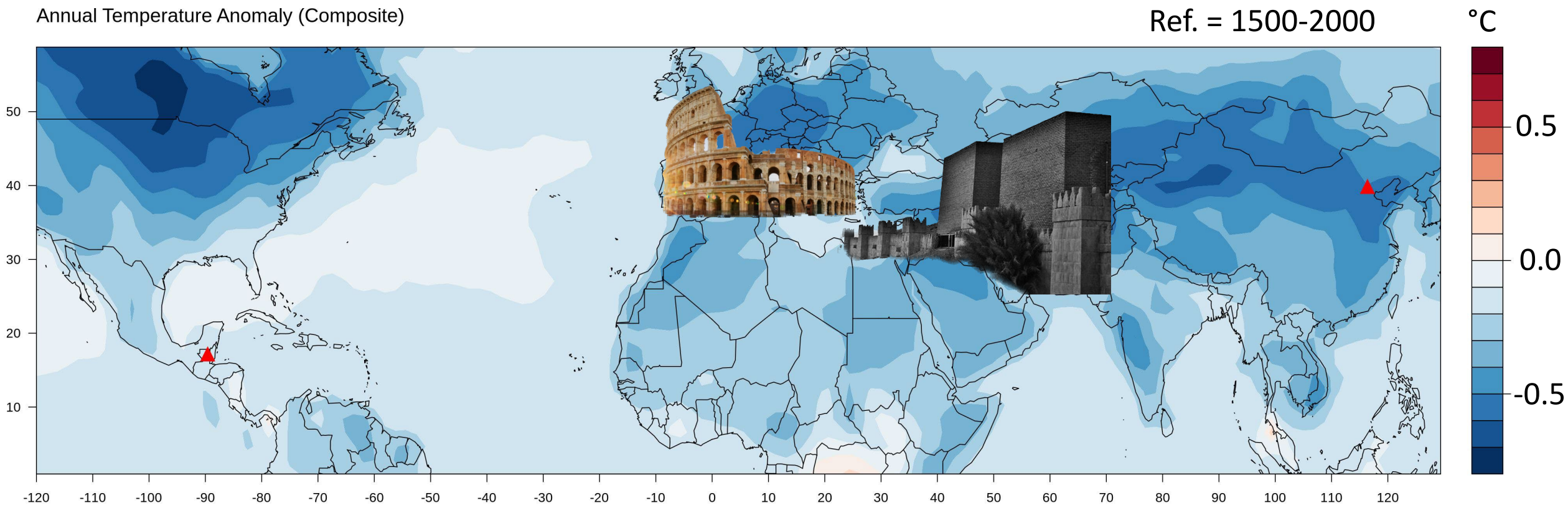
Year: 1912

S (Tg): 5

ATP#: 330

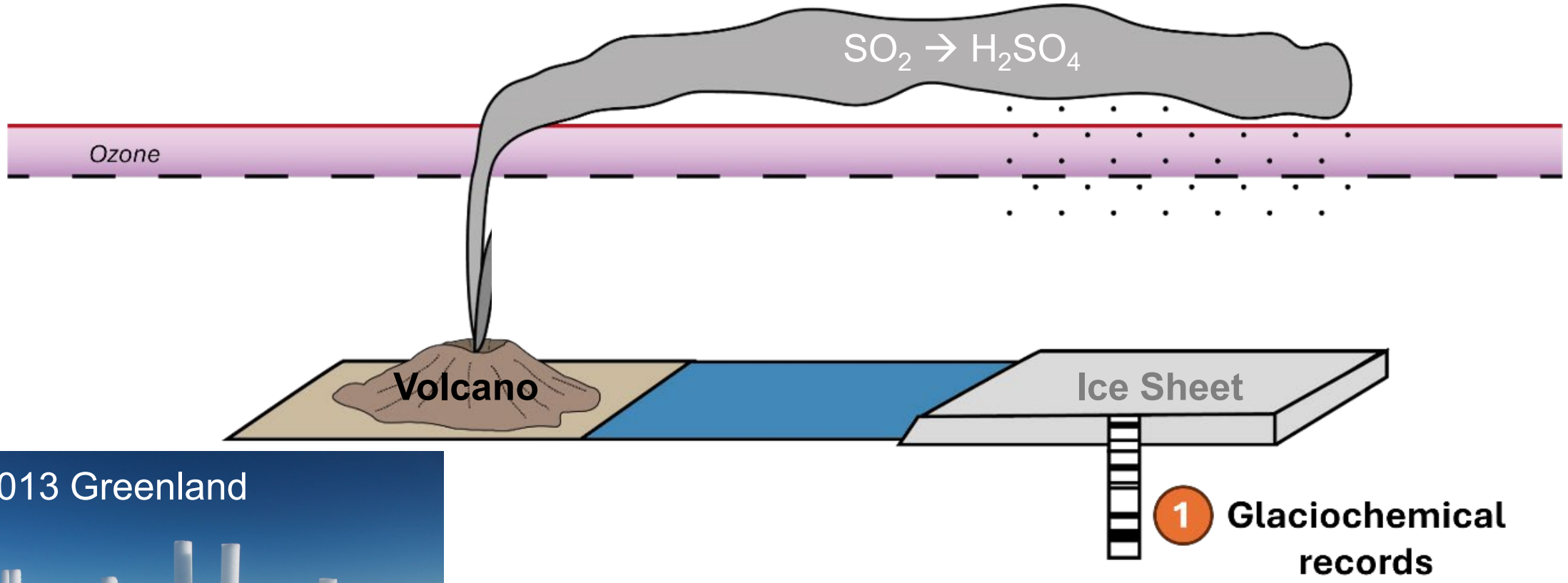
RANK 330

Average 2-yr annual temperature response to the 18 largest volcanic eruptions since 1400 CE

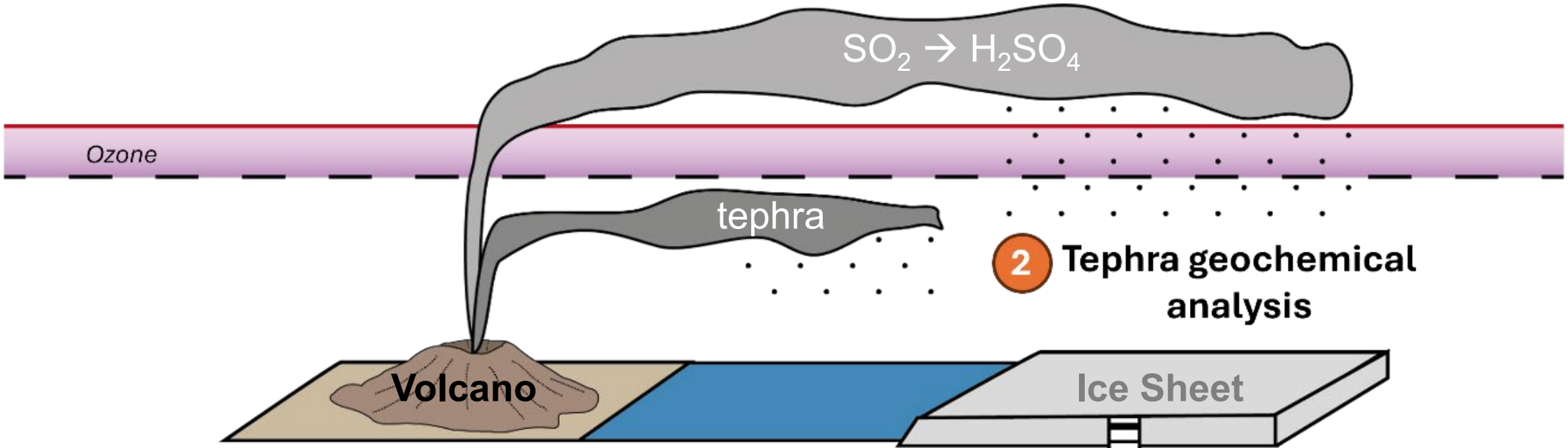


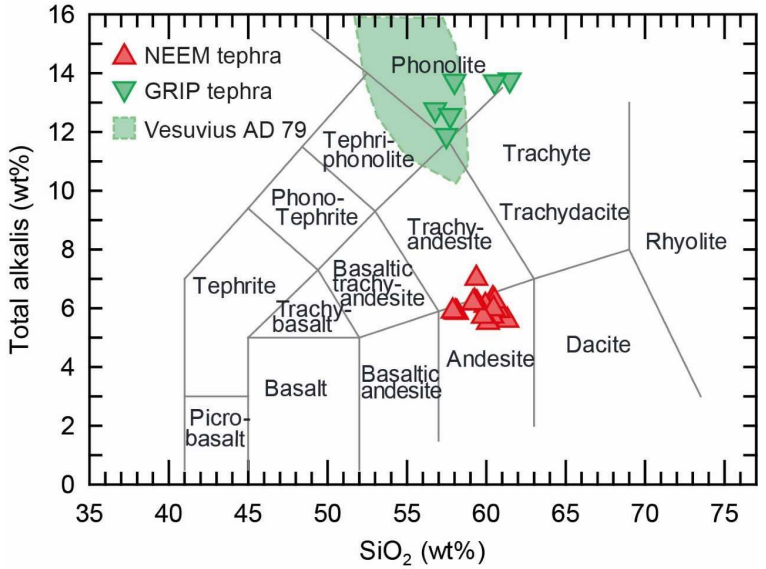
Data from Valler et al. 2024, *SciData*

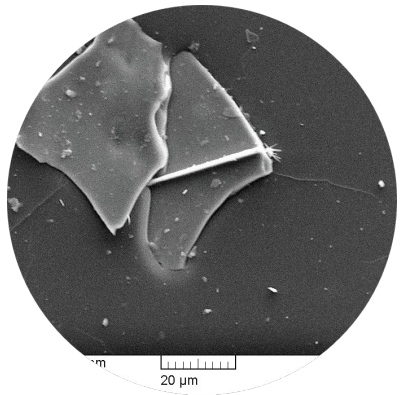
Stratosphere (lifetime 1-3 yrs)



Stratosphere (lifetime 1-3 yrs)







Stratosphere (lifetime 1-3 yrs)

Mass Independent Fractionation

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

3 Sulfur isotope analysis

$SO_2 \rightarrow H_2SO_4$

Ozone

tephra

Mass Dependent Fractionation

$\Delta^{33}S = 0$

2 Tephra geochemical analysis

Volcano

Ice Sheet

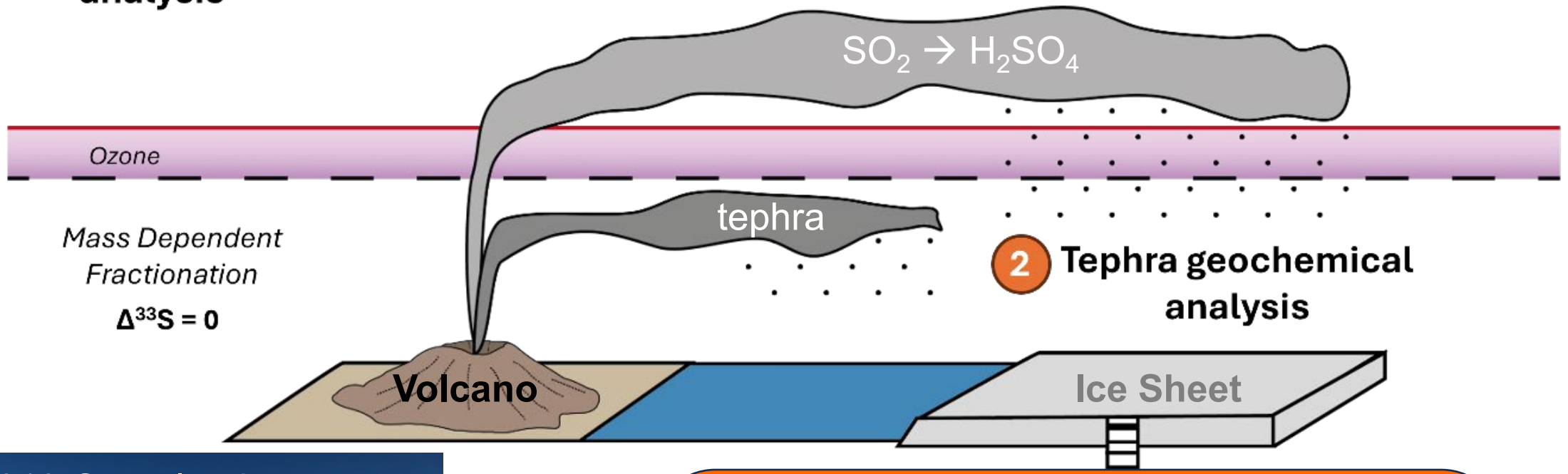
1 Glaciochemical records

Stratosphere (lifetime 1-3 yrs)

3 **Sulfur isotope analysis**

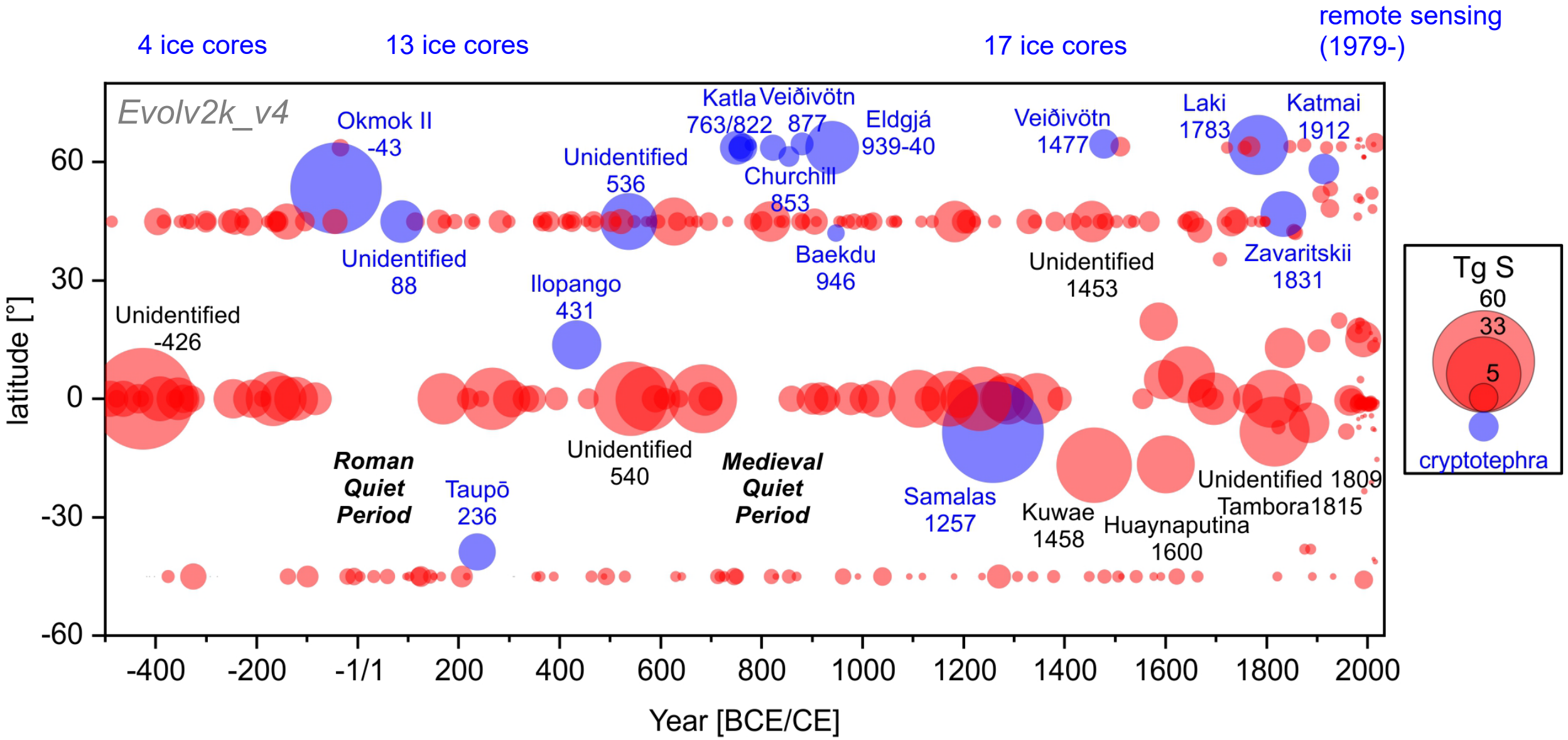
Mass Independent Fractionation

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



- ✓ **When** did the eruption occur?
- ✓ **Where** did it happen?
- ✓ How much **SO_2** was injected?
- ✓ How much into the **stratosphere**?

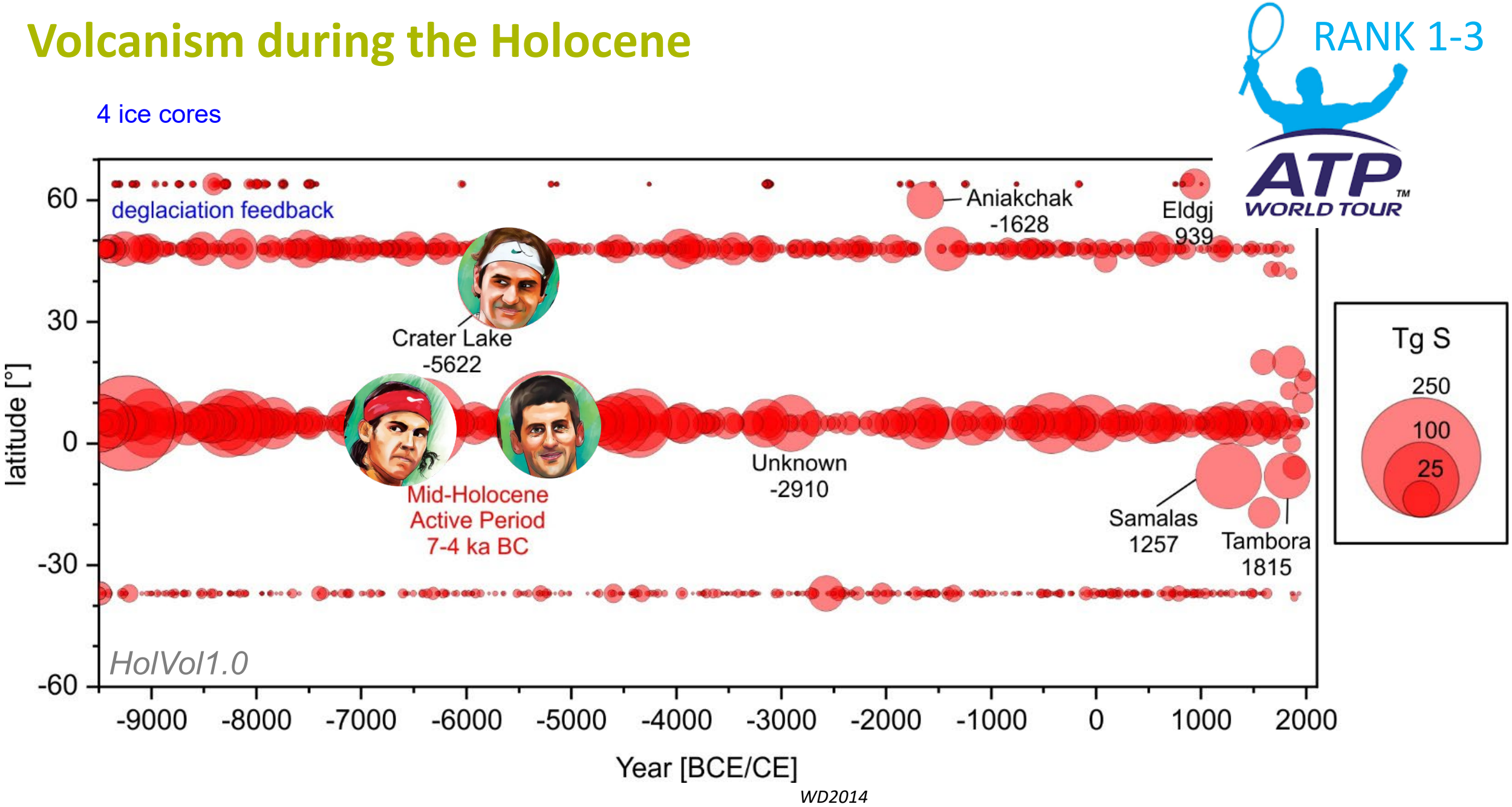
Volcanism during the Common Era



Sigl et al. 2015, *Nature*; Toohey & Sigl 2017, *ESSD*; McConnell et al., 2020, *PNAS*; ….; Sigl & Toohey 2024, *PANGAEA*

Volcanism during the Holocene

RANK 1-3



Sigl et al. 2022, *ESSD*; Pearson et al., 2022 *PNAS Nexus*; Sigl & Toohey, 2021; *PANGAEA*

Name:

Region:

Year:

S (Tg):

ATP#:

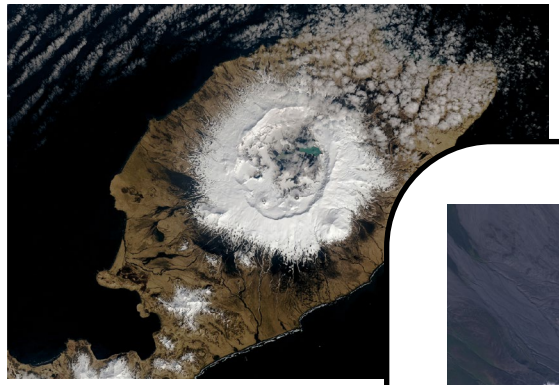
Name: Hraf

Region: Ic

Year:

S (Tg): 5

ATP#: 366



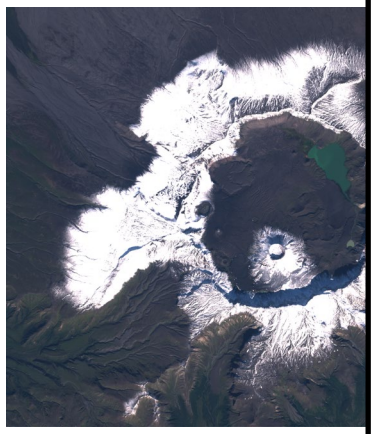
Name: Ok

Region: A

Year: 4

S (Tg):

ATP#:



Name: Ania

Region: A

Year: 1628 B.C.

S (Tg): 52

ATP#: 18

Name: Crater Lake

Region: Oregon

Year: 5622 B.C.

S (Tg): 162

ATP#: 2

Name: Zavaritskii

Region: Kurils

Year: 1831

S (Tg): 13

ATP#: 152

Zavaritskii caldera (Simushir Island), Kurils

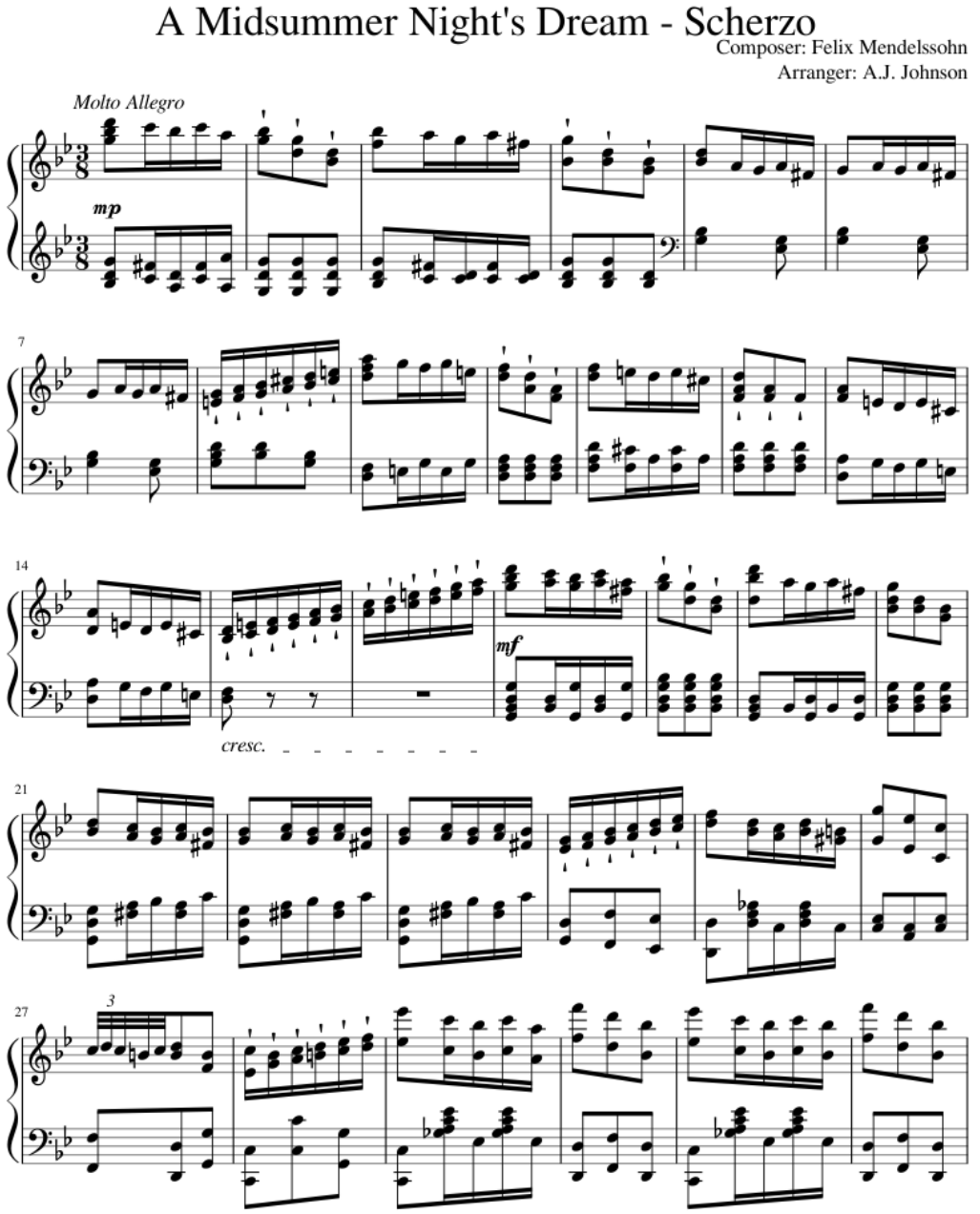
- ✓ **Largest** eruption in the past 200 years, since Tambora 1815
- ✓ Youngest eruption seen in ice cores not linked to a **source volcano**
- ✓ Droughts, crop failures & **famines** in Africa, India & Japan
- ✓ **Extreme weather** in the Alps
- ✓ **Glacier advances** (Little Ice Age)

Hutchison et al., in review

Jakob Ludwig **Felix Mendelssohn** Bartholdy

* 3. Februar 1809 in Hamburg

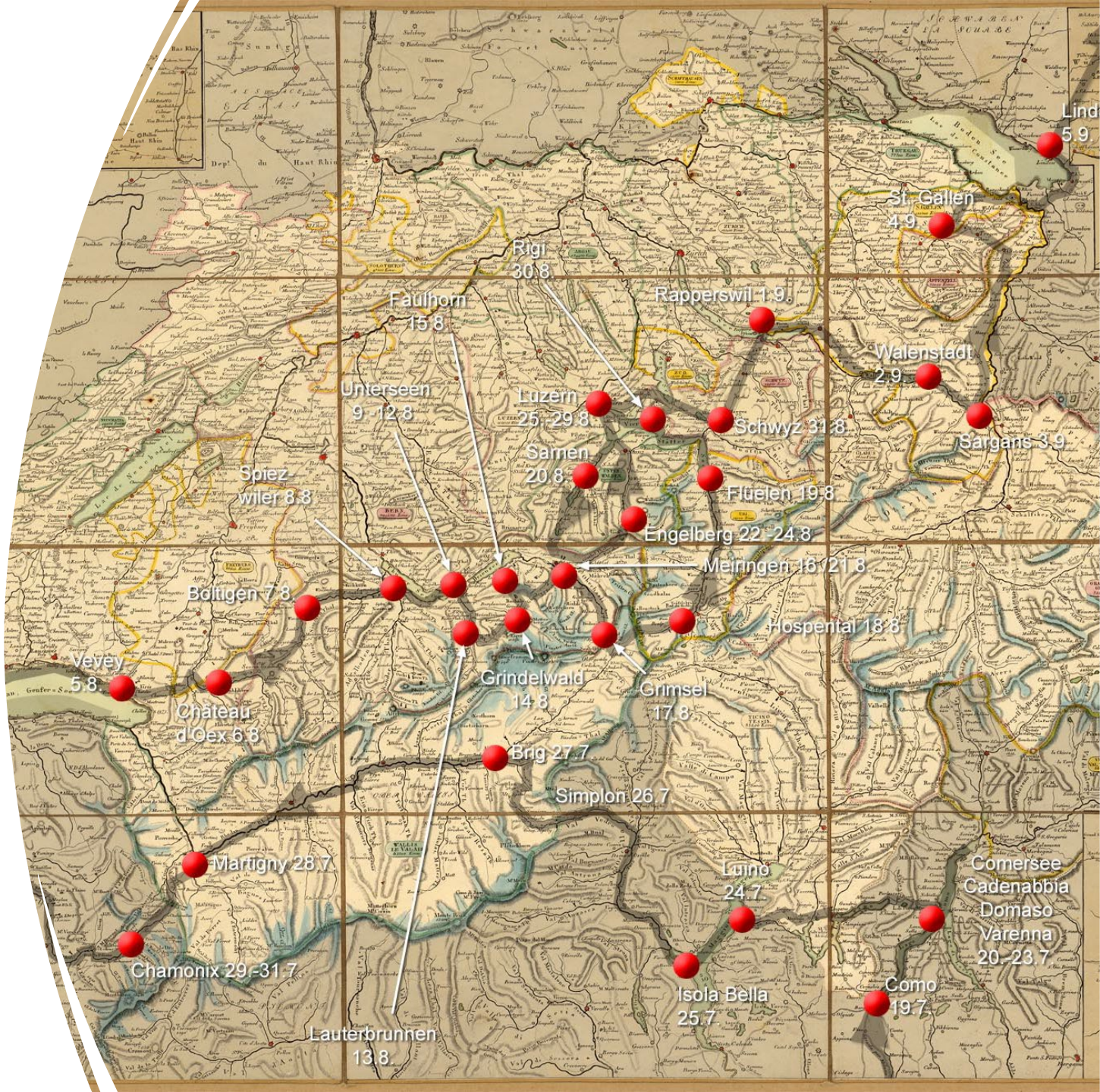
† 4. November 1847 in Leipzig



Felix Mendelssohn's Alpenreise 1831

19.7. – 5.9.

Walter Bersinger, pers. communications



«Desolate weather, it has rained again all night and all morning, it is as cold as in winter, there is already deep snow on the nearest hills…

….

Good night, it strikes eight o'clock in F minor and rains and storms in F-sharp minor or G-sharp minor in all possible sharp keys.»

(Sargans, Switzerland, September 3rd 1831)

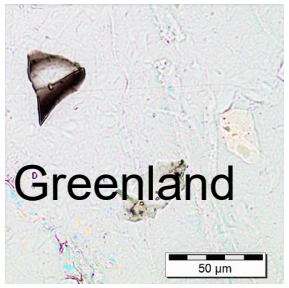
Name: Hrafnkatla

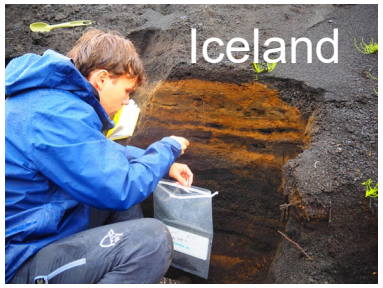
Region: Iceland

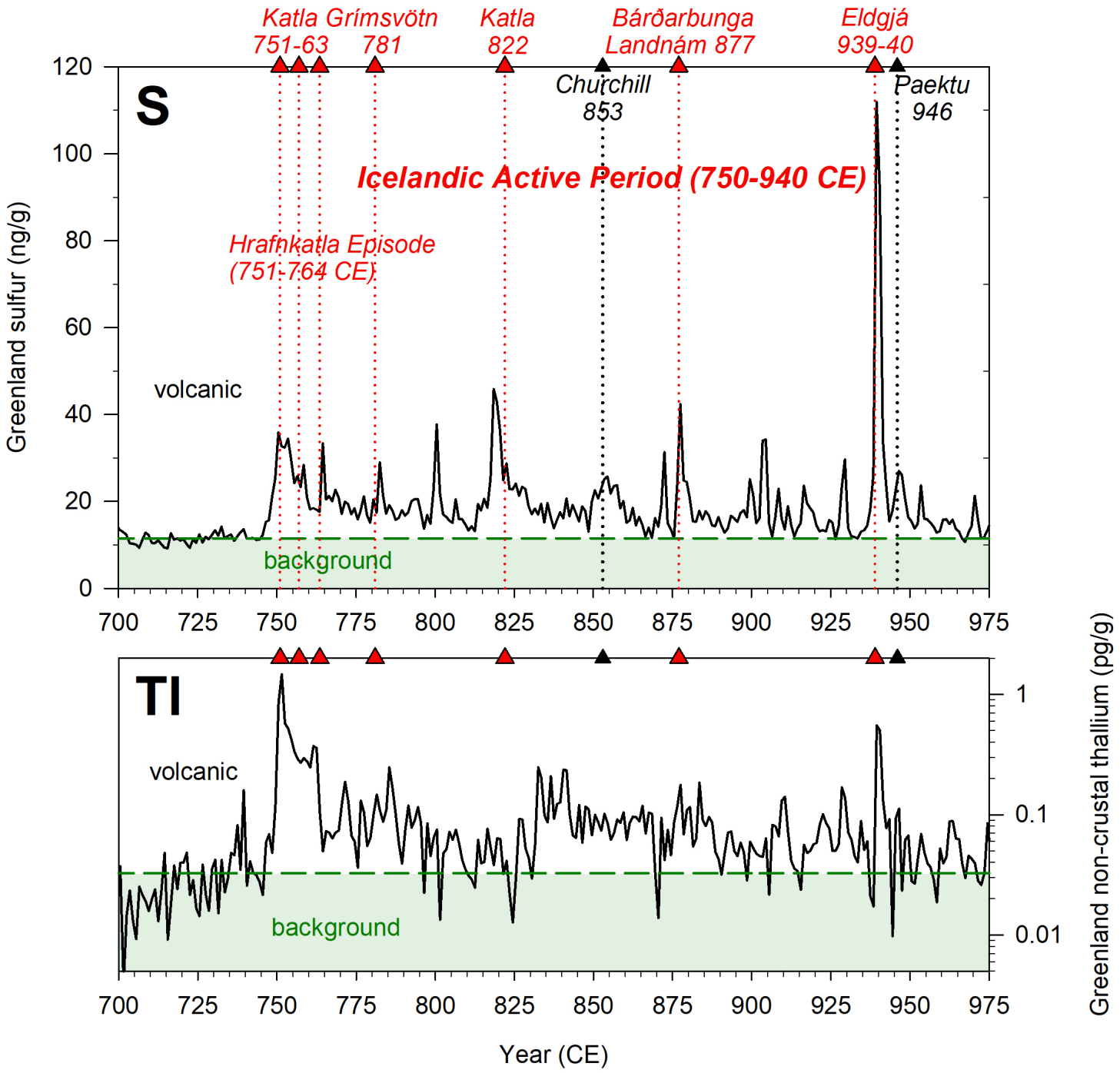
Year: 763

S (Tg): 5

ATP#: 366



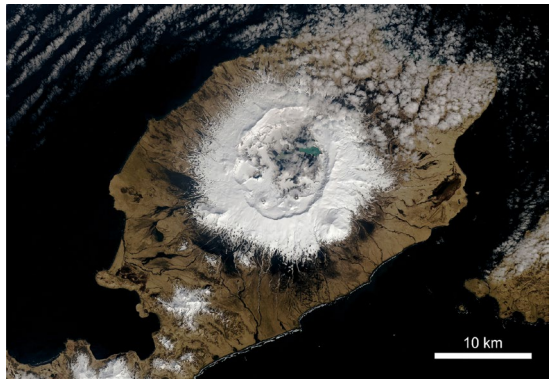




Hrafnkatla 763

Gabriel et al., 2024 *Communications Earth & Environment*

Disproportionately strong forcing from extratropical eruptions



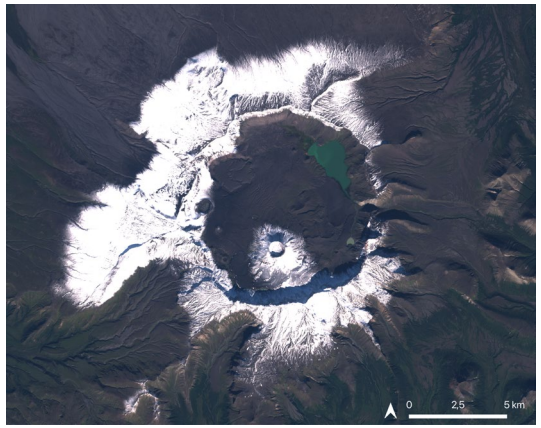
Name: Okmok II

Region: Alaska

Year: 43 B.C.

S (Tg): 48

ATP#: 21



Name: Aniakchak

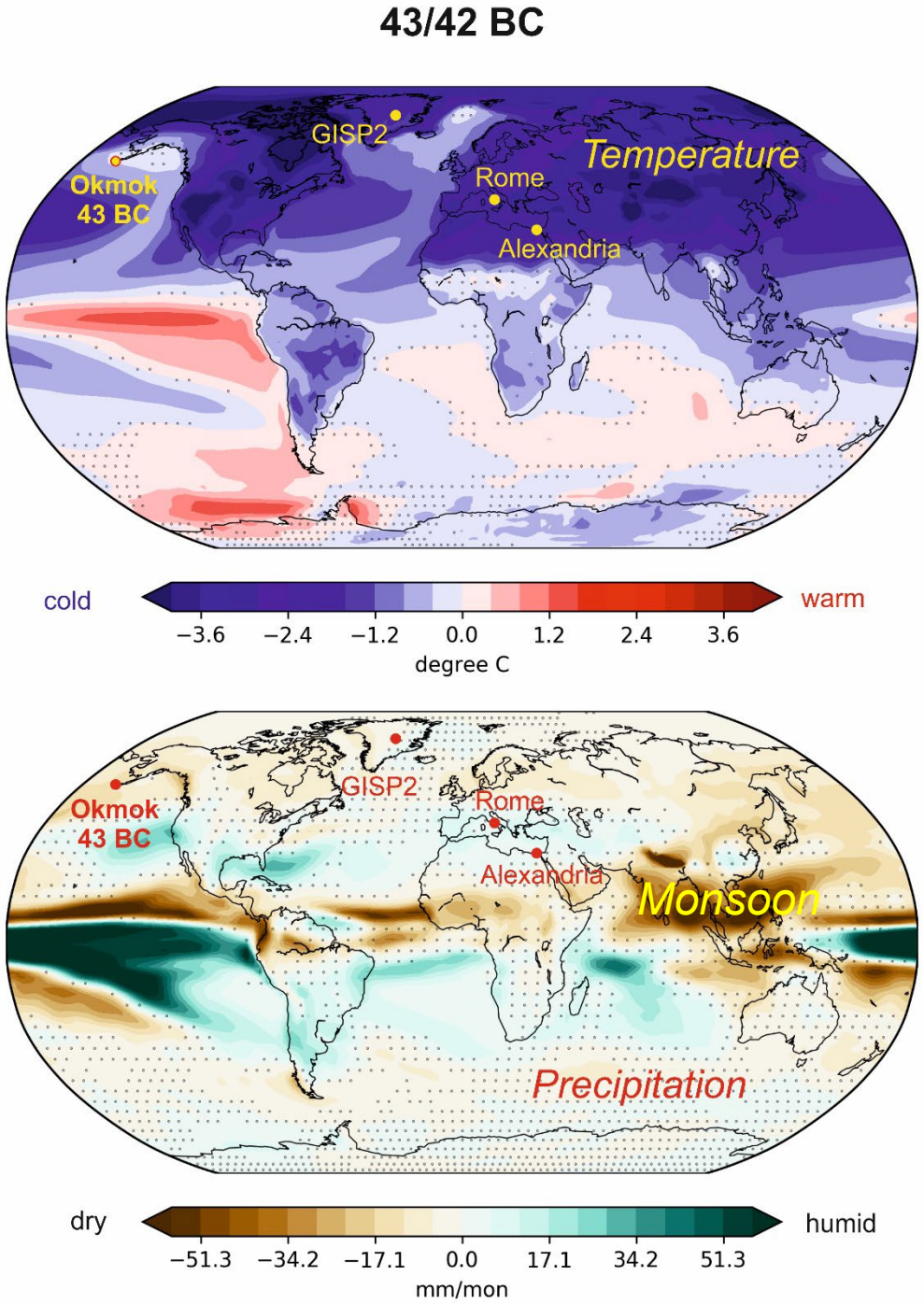
Region: Alaska

Year: 1628 B.C.

S (Tg): 52

ATP#: 18

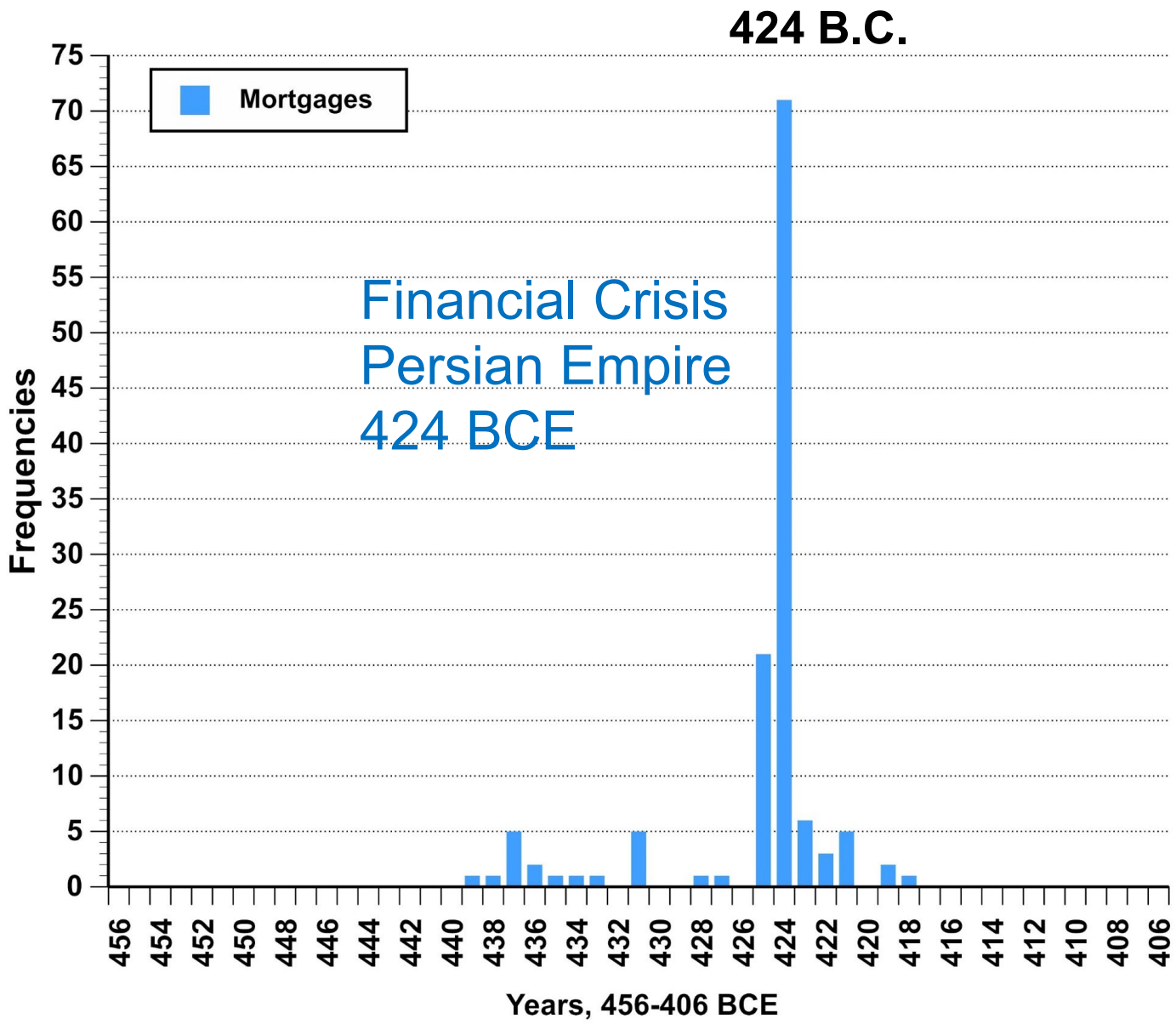
Toohey et al. 2019, *Nat. Geosci.;* McConnell et al. 2020, *PNAS*, Pearson et al. 2022; *PNAS Nexus;* Burke et al. 2020, *PNAS.*



Manning et al. 2017; *Nature Communications;* McConnell et al. 2020, *PNAS*

Volcanic impacts on monsoon, streamflow, agriculture and ancient societies

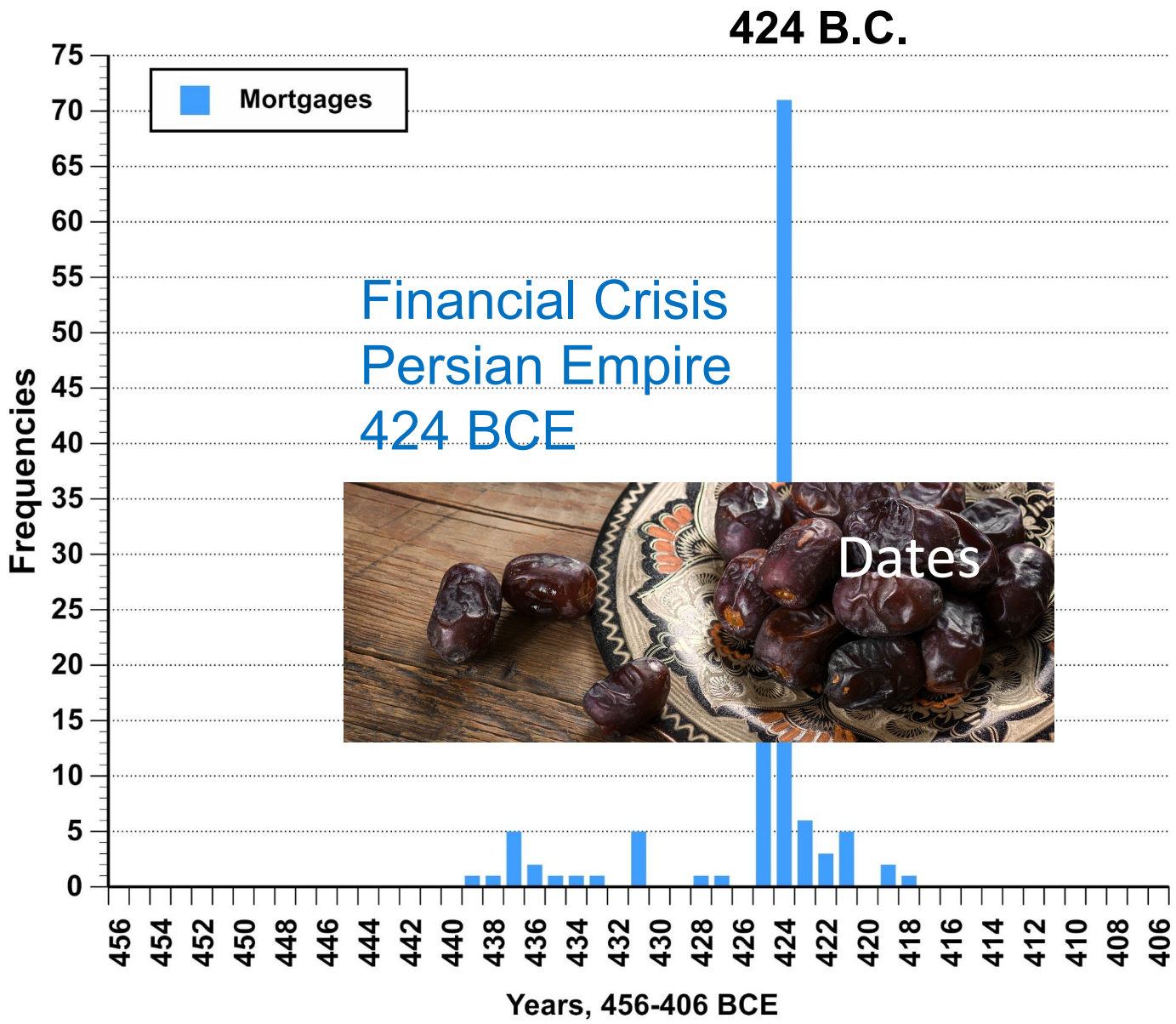
Manning et al. 2017; *Nature Communications;* McConnell et al. 2020, *PNAS*; Gao et al. 2021 *Commun. Earth Environ.*



Number of dated mortgages per year in the Murašû archive, 456 – 406 BCE. Based on M.W. Stolper, *Entrepreneurs and Empire: The Murašû Archive, the Murašû Firm, and Persian Rule in Babylonia*

*"If the [Murašû] Archive presents a fair picture of the firm's business, it is plain that the change was not gradual and evolutionary; **it was sudden and dramatic**. It needs to be explained by a **short-term cause** and the cause of these circumstances must have been **external** to the business."*

Matthew W. Stolper, *Entrepreneurs and Empire*.



?

Name: Unknown

Region: Tropics

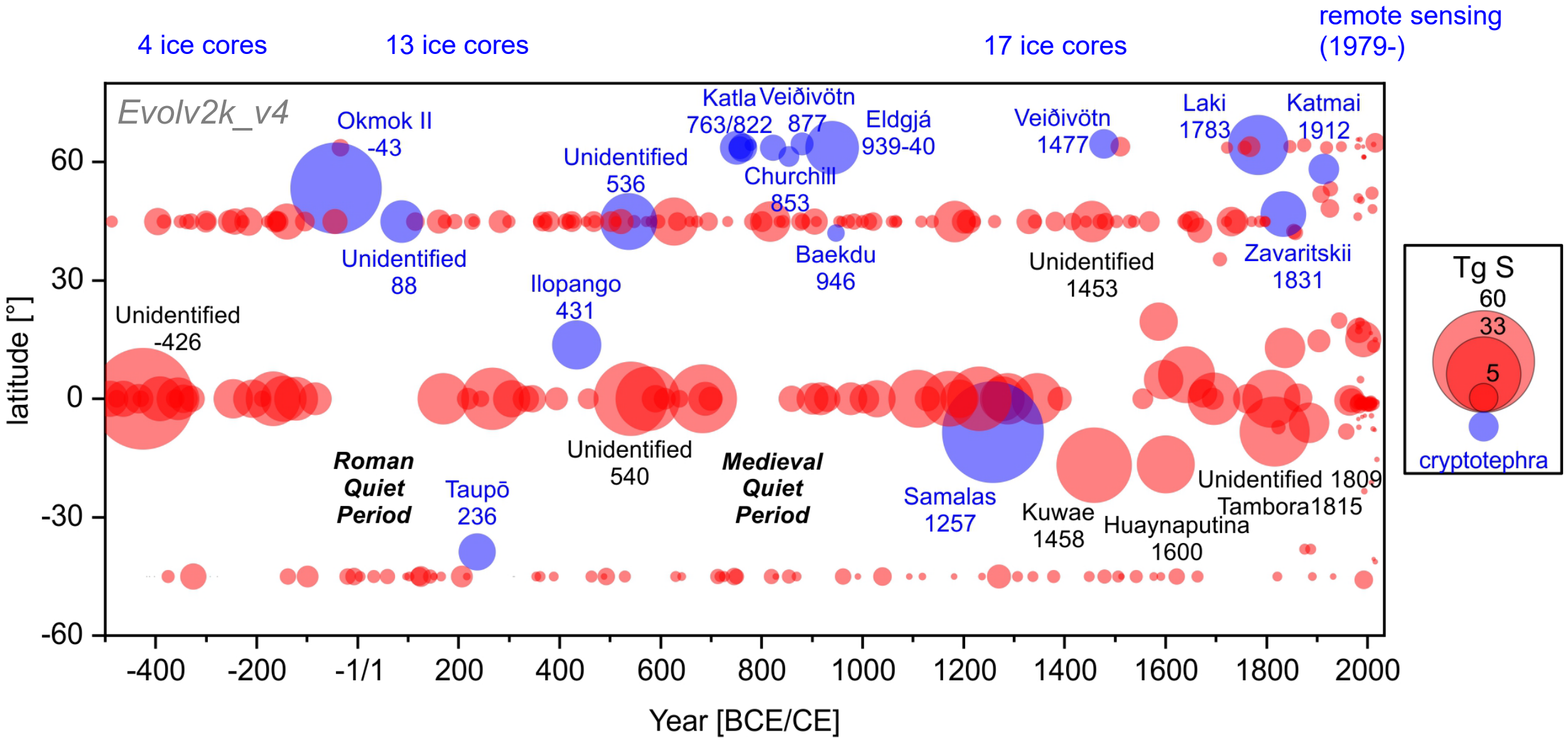
Year: 426 B.C.

S (Tg): 62

ATP#: 11

Number of dated mortgages per year in the Murašû archive, 456 – 406 BCE. Based on M.W. Stolper, *Entrepreneurs and Empire: The Murašû Archive, the Murašû Firm, and Persian Rule in Babylonia*

Volcanism during the Common Era



Sigl et al. 2015, *Nature*; Toohey & Sigl 2017, *ESSD*; McConnell et al., 2020, *PNAS*; ….; Sigl & Toohey 2024, *PANGAEA*

Mazama (Crater Lake) – the Greatest of all time?

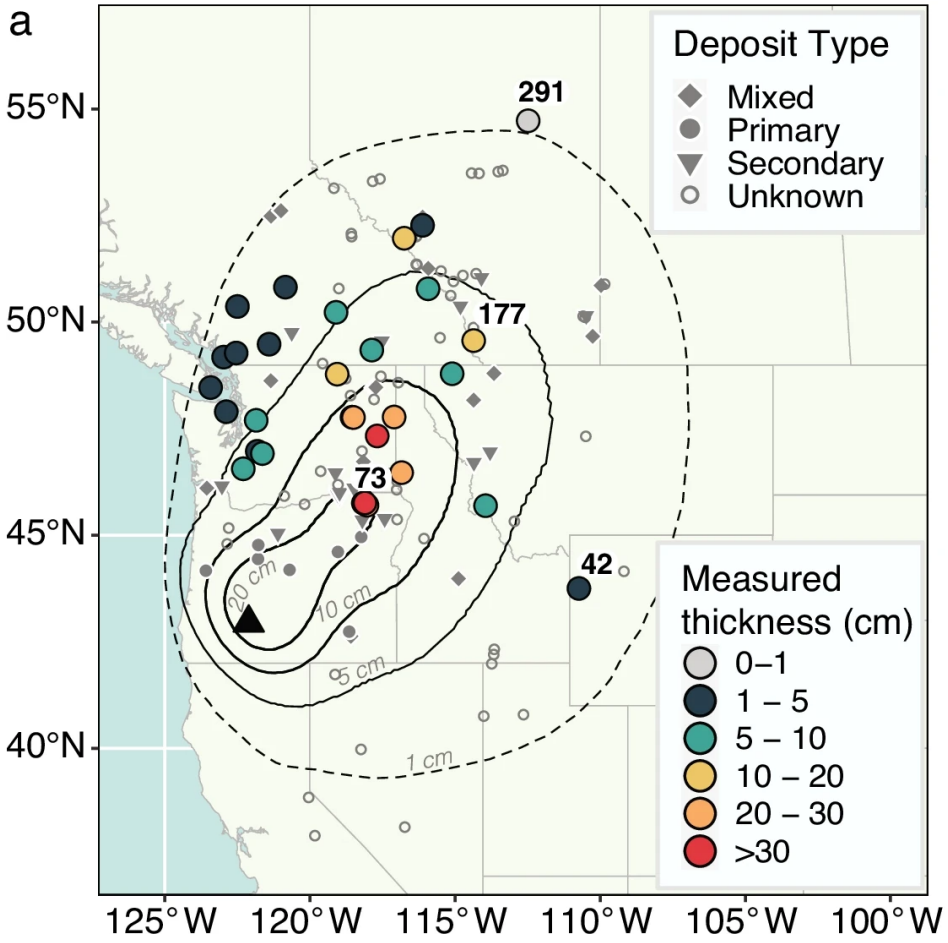
Name: Crater Lake

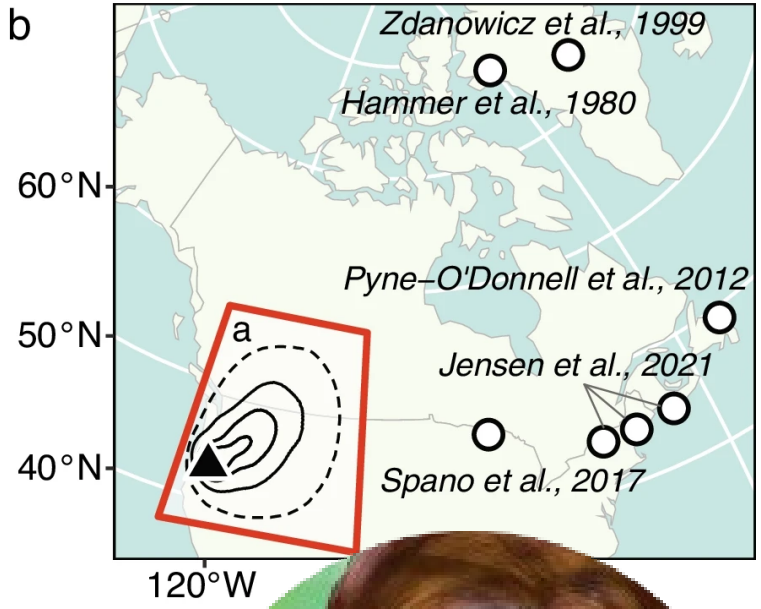
Region: Oregon

Year: 5622 B.C.

S (Tg): 162

ATP#: 2

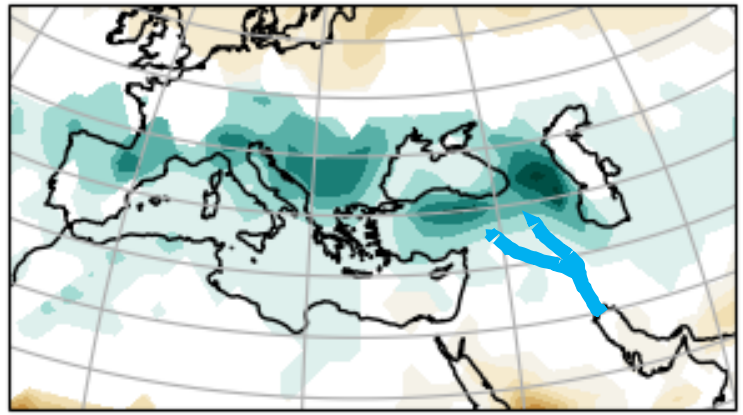




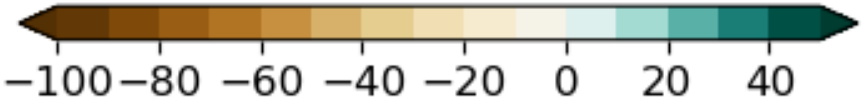
Annual

DJF

JJA



Euphrates/Tigris

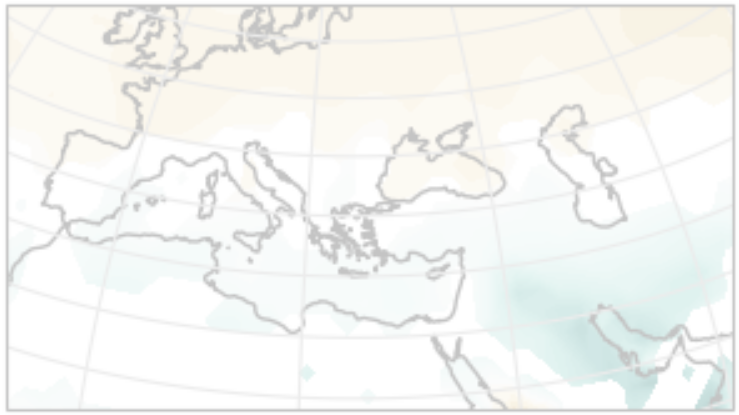


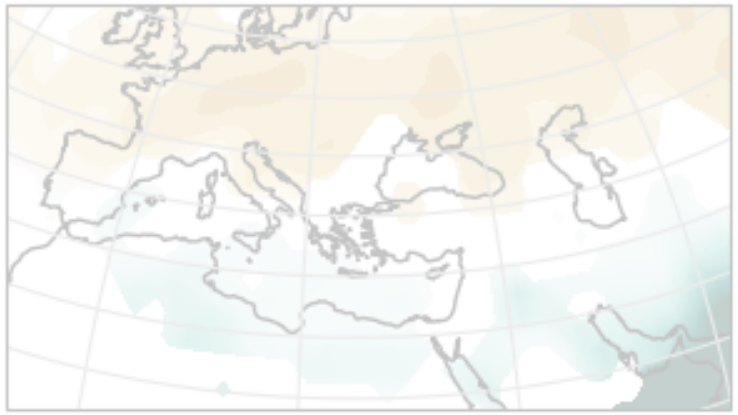
Precipitation anomaly [mm/month]

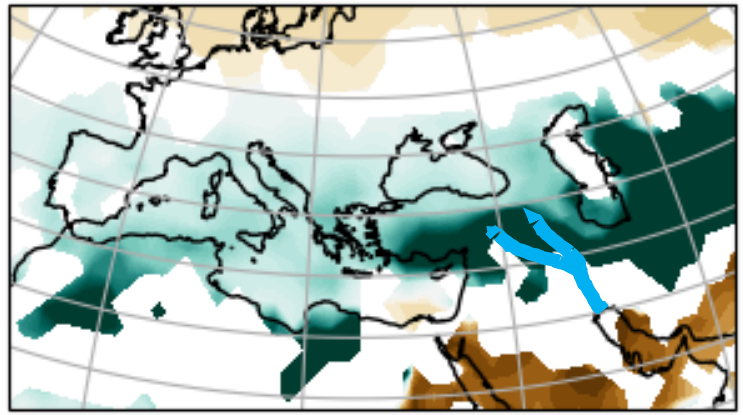
Annual

DJF

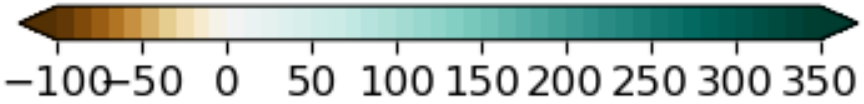
JJA



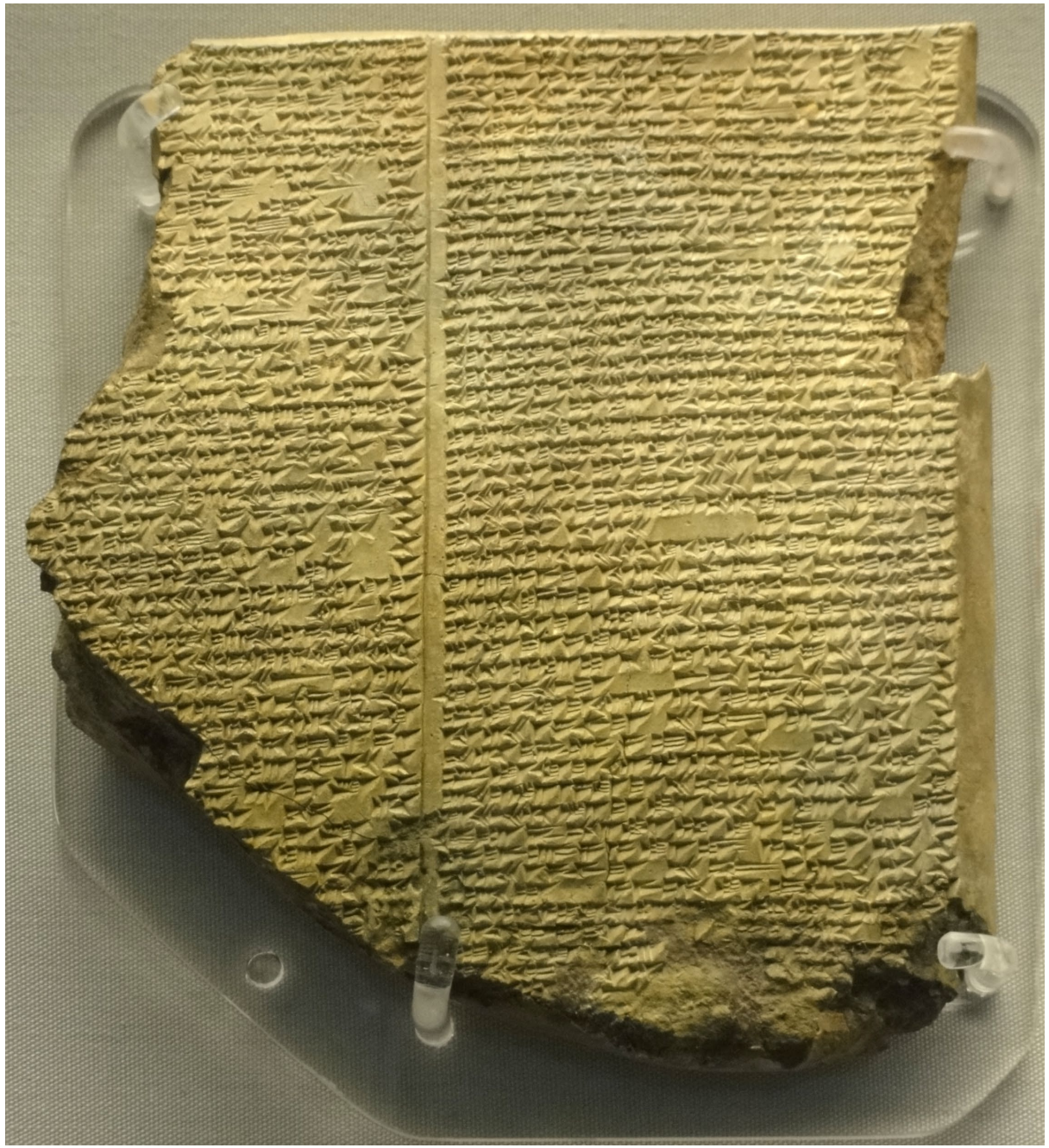




Euphrates/Tigris



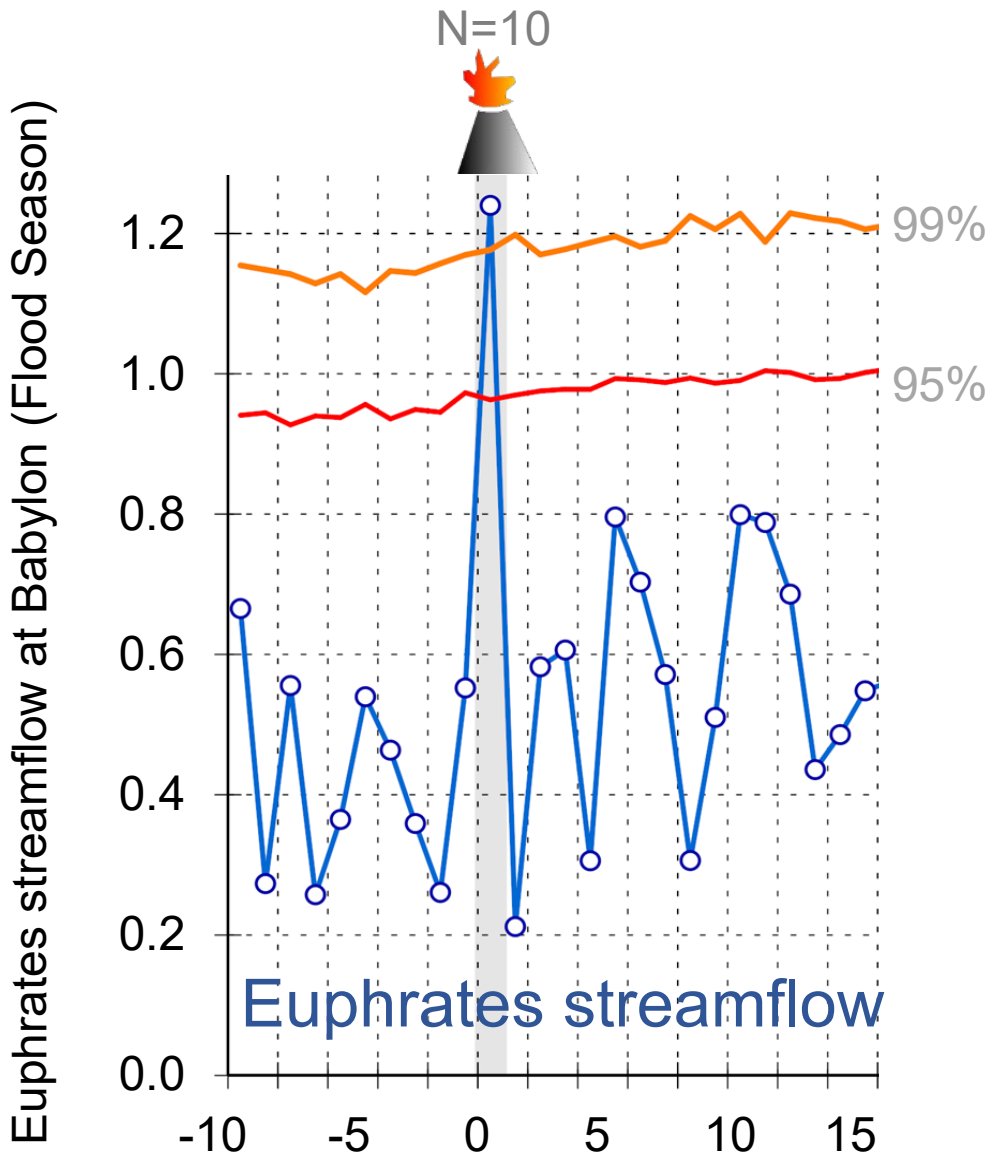
Precipitation anomaly [%]

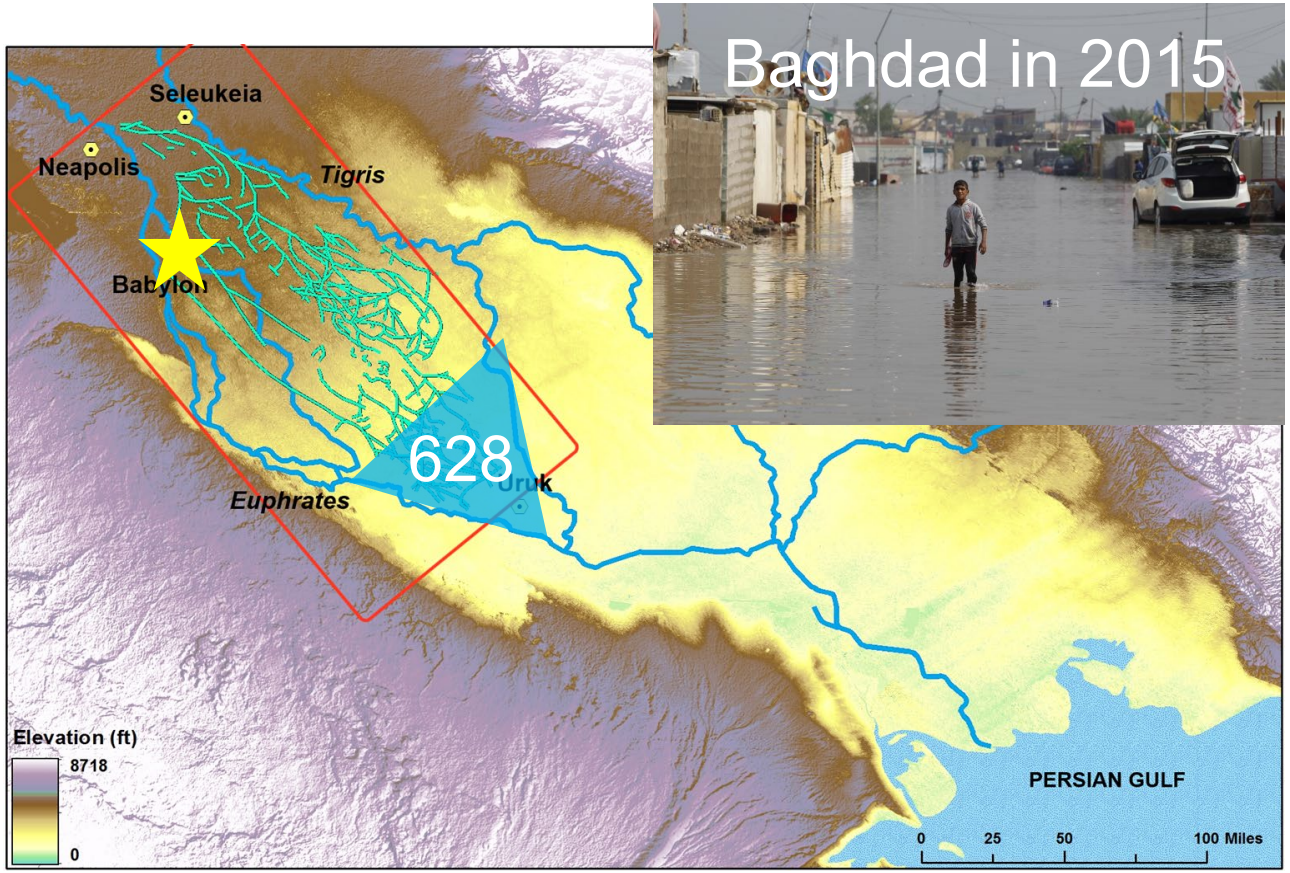


Gilgamesh is the semi-mythic King of Uruk the hero of *The Epic of Gilgamesh* (c. 2150-1400 BCE)

Gilgamesch, by Walter Jonas 1943

Ludlow et al., EGU 2020

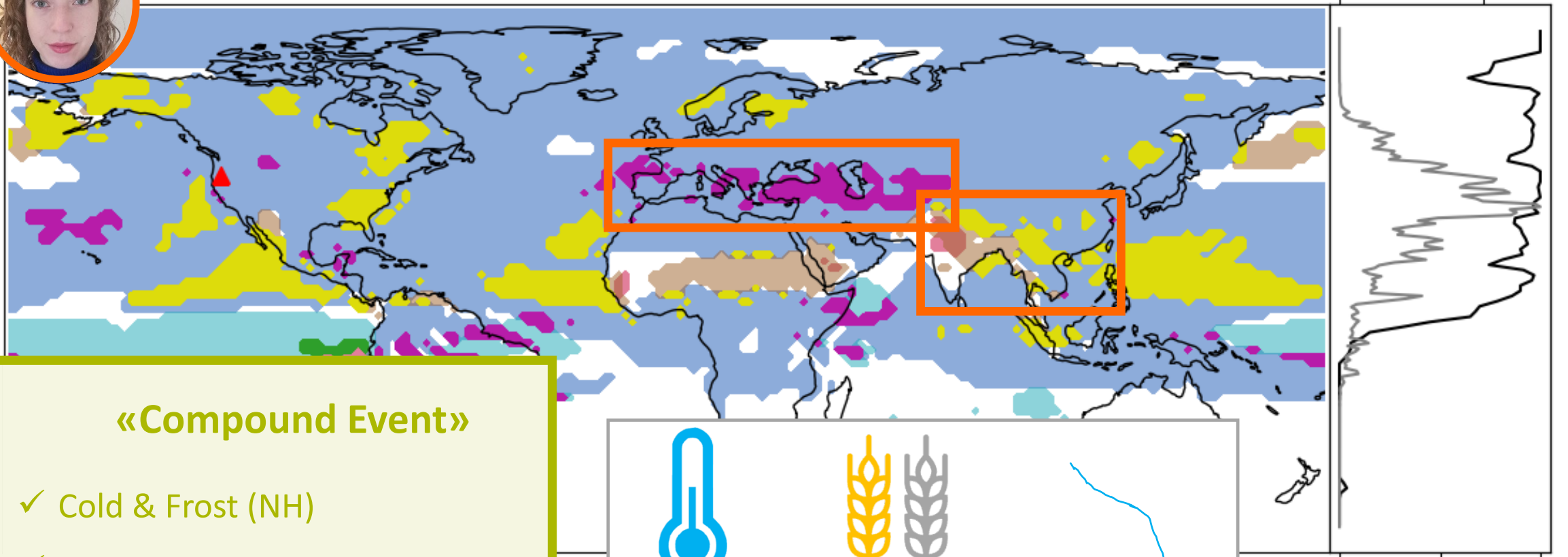




Arid Mesopotamia ("land between the rivers") is heavily dependent upon the Tigris and Euphrates rivers, with intense innovation in irrigation networks (canals, dykes, basins).

The region is prone to floods e.g. in 628 CE to the south of Wāsit, following a large volcanic eruption from October 626-27 CE.

June-August (Y_{+0}, Y_{+1}, 2-sigma Anomalies)



«Compound Event»

- ✓ Cold & Frost (NH)
- ✓ Droughts (Sahel, SE-Asia)
- ✓ Floods (Near East)
- ✓ El Nino (Pazific)
- ✓ **Simultaneous, widespread, severe, persistent hazards**

Cold
Frost

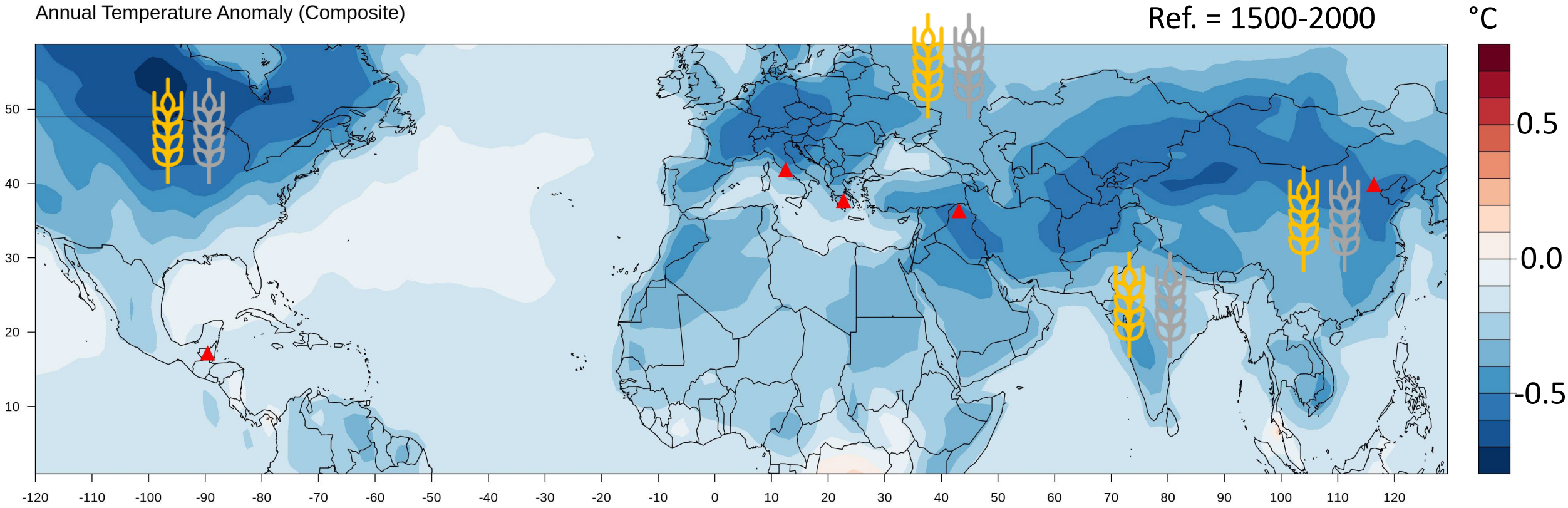
Drought
Flood

Streamflow
(Nile, Euphrates)

cold | wet | **cold + wet** | warm + wet

warm | **dry** | **cold + dry**

40-60% of global crop production (wheat, soybean, rice, maize) are from China, India, U.S.A. & Russia



Average 2-yr annual temperature response to the 18 largest volcanic eruptions since 1400 CE

ModE-RA data, *Valler, Franke et al., (2024)*

Risk = Impact x Frequency

Sigl et al. (2022)

Global Population Density

The height of the spikes relates to the number of people living in an area - roughly 2km x 2km

Compound Volcanic Weather Hazards

2 ZERO HUNGER

Eruption Frequency

Simultaneous Global Breadbasket Failures

✓High Impact
✓High Exposure
✓High Probability
= High Risk

Data: GHS_POP_EU
Software: Aerialod
Author: Alasdair Rae


Global catastrophic risk from lower magnitude volcanic eruptions,
Mani et al., 2021, Nature Communications
Aviation
Global Warming
Energy
Communication
Infrastructure
Agriculture
Transportation

Learning from the Past

(1) “More must be done to **forecast** and try to **manage** globally disruptive volcanic eruptions. The risks are greater than people think!” (Cassidy & Mani, *Nature* 2022)

(2) Volcanic eruptions are more than just a “year without a summer”

(3) Often, it’s not the prominent “**celebrity volcanoes**” that matter (e.g. Thera, Vesuvius) but previously under-researched volcanoes (e.g. Katla, Okmok, Aniakchak)

THERA

Timing of Holocene Volcanic Eruptions and Radiative Aerosol Forcing

European Research Council
Established by the European Commission

European Research Council

Established by the European Commission

THERA

Timing of Holocene Volcanic Eruptions and Radiative Aerosol Forcing

Frozen memories of past eruptions reveal the global risks of future ones

Michael Sigl, Peter Abbott, Imogen Gabriel, Evelien Van Dijk

Klima- und Umweltphysik & Oeschger-Zentrum für Klimaforschung, Universität Bern

michael.sigl@unibe.ch @THERA_4ever

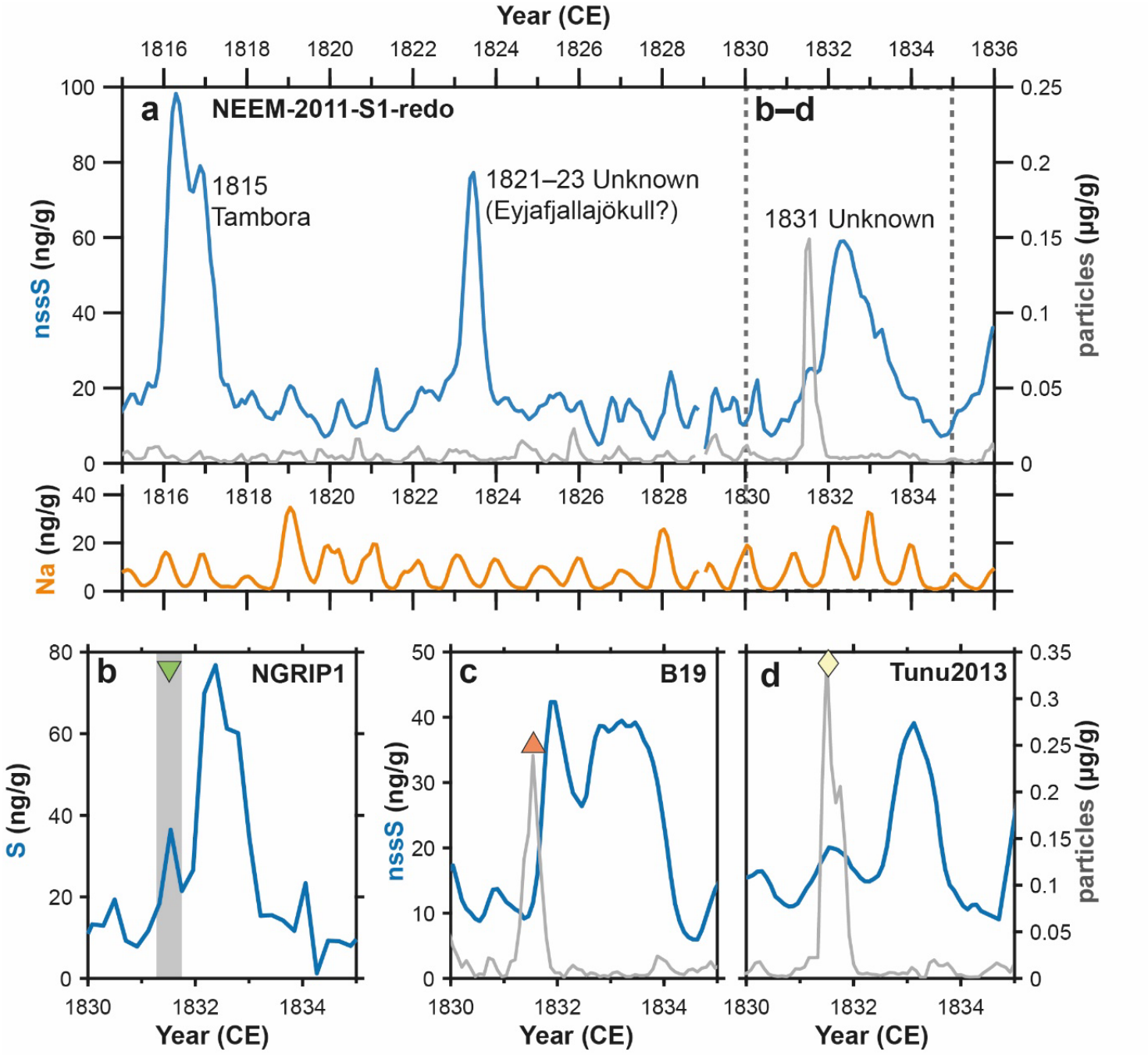
b UNIVERSITÄT BERN

OESCHGER CENTRE CLIMATE CHANGE RESEARCH

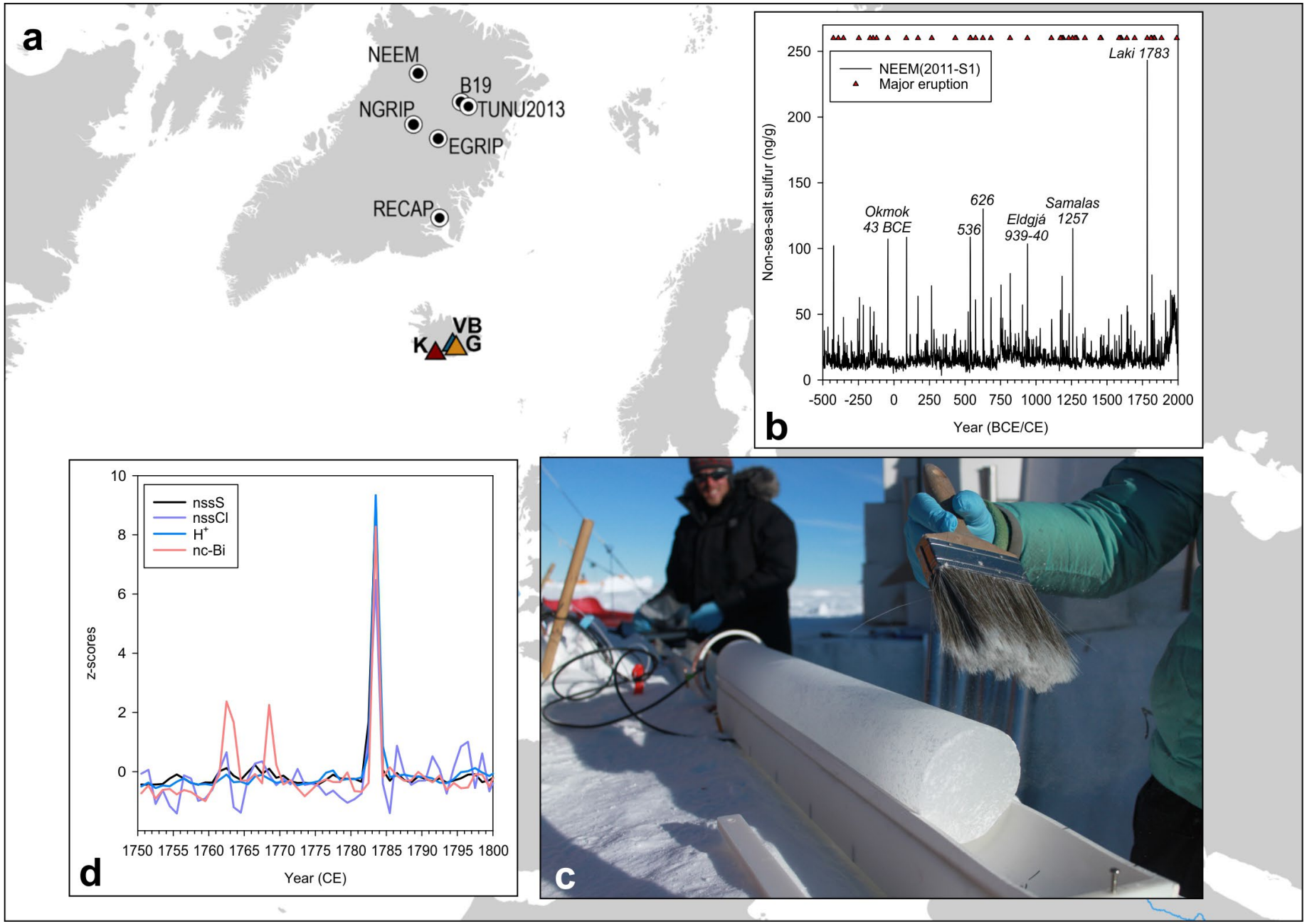
Witterungsberichte Schweiz 1910 – 1919

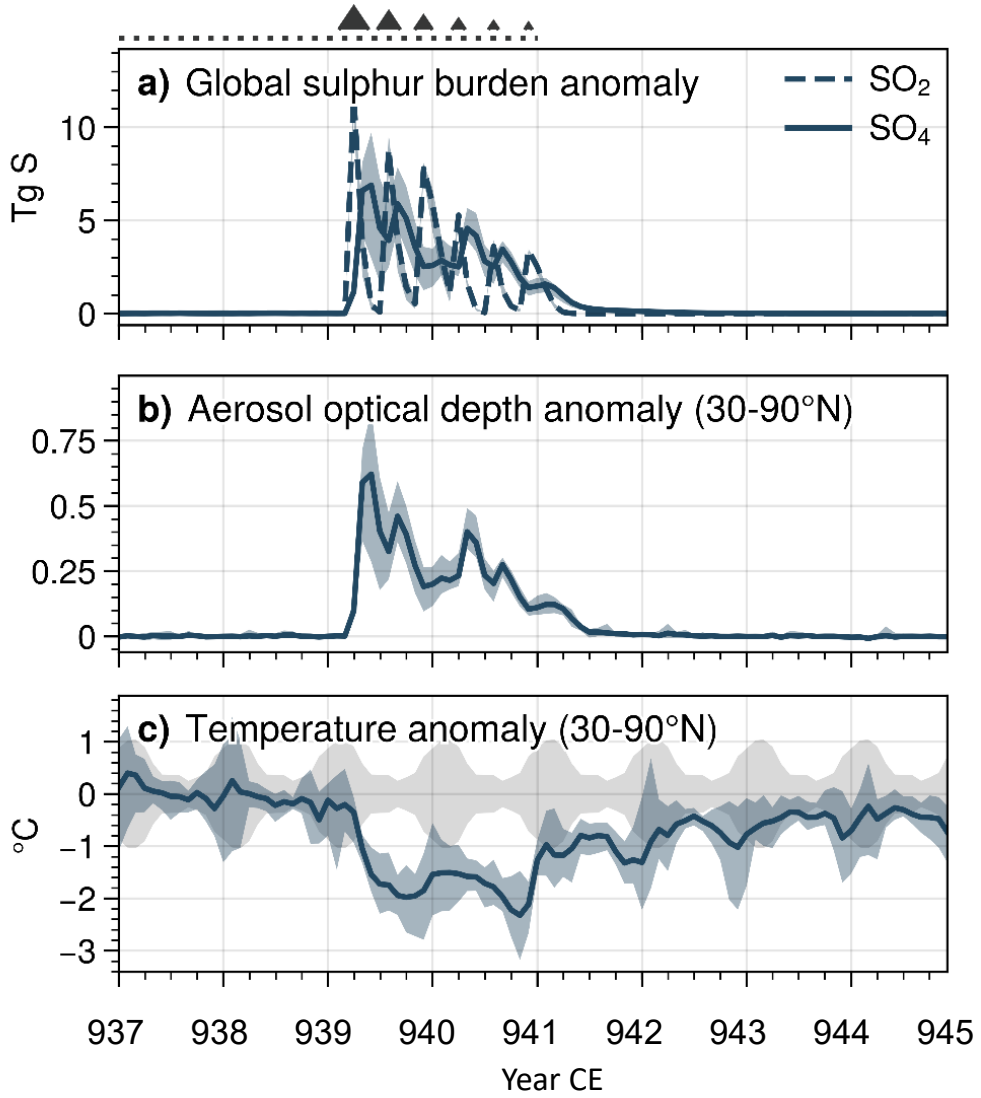
Witterung im August

Der August war äussert trüb, kühl und niederschlagreich. Hinsichtlich der Temperatur ist er mit einem Wärmeausfall von über 3 Graden der kälteste August unserer annähernd 50jährigen offiziellen Beobachtungsreihe; nur im äussersten Südwesten des Landes (Genf), wo das Defizit etwas geringer war, lässt sich ein gleich kalter August (1896) nachweisen. (p. 4) Die Niederschlagsmengen betragen das 1 ½ bis 2 fache der langjährigen Mittelwerte; viel besser als durch die Niederschlagssummen wird die Witterung des diesjährigen Augustmonats aber charakterisiert durch die Niederschlagshäufigkeit: nur drei Tage blieben völlig niederschlagsfrei. Auch in Bezug auf die Bevölkerung stellte der Monat einen Rekord dar: er ist der trübste Augustmonat; das Mittelland hatte keinen einzigen hellen Tag. (p. 4) Die kältesten Tage waren diejenigen vom 7. - 9., am 7. schneite es bis auf zirka 1500 m herunter. (p. 4)

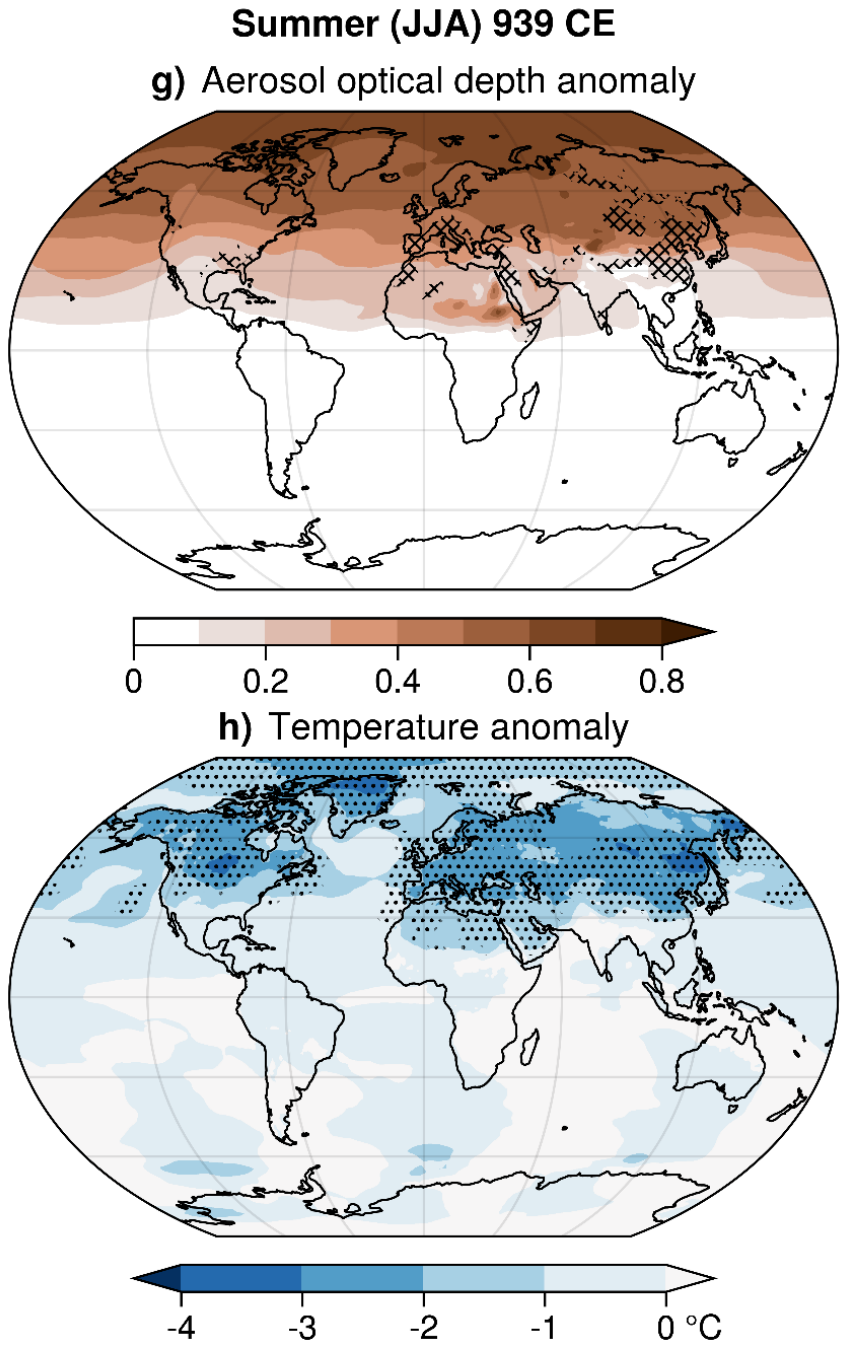


Largest eruption in the past 200 years


a
NEEM
B19
NGRIP
TUNU2013
EGRIP
RECAP
VB
K
G
b
NEEM(2011-S1)
Major eruption
Laki 1783
Okmok
43 BCE
626
536
Eldgjá
939-40
Samalas
1257
Non-sea-salt sulfur (ng/g)
Year (BCE/CE)
c
d
nssS
nssCl
H+
nc-Bi
z-scores
Year (CE)

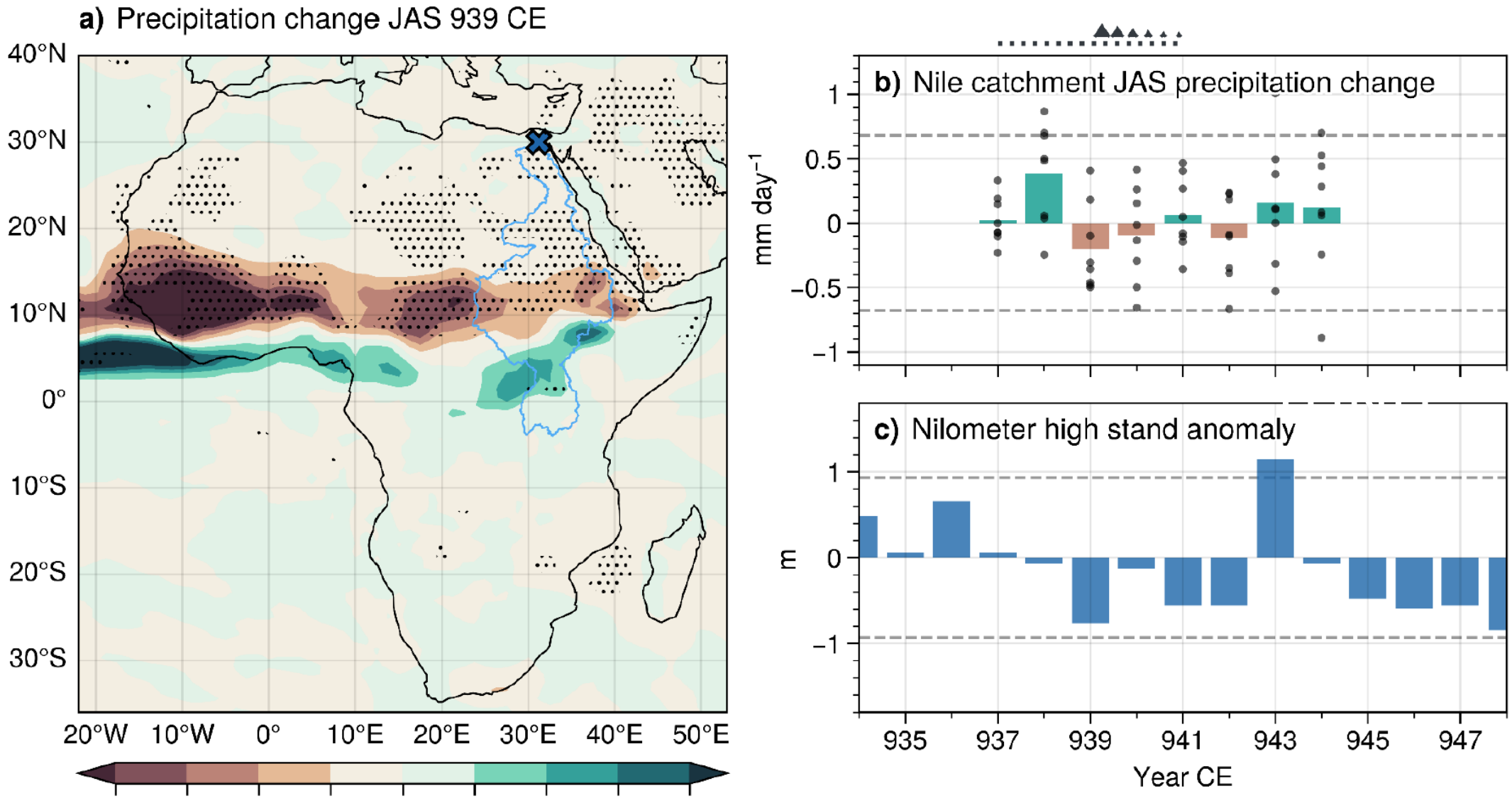


Volcanic Emission Scenario



Gabriel et al. 2024 *Commun. Earth Environ.*
Hutchison et al. *in review;* Fuglestvedt et al. *in review*

CESM2.1.3
WACCM6

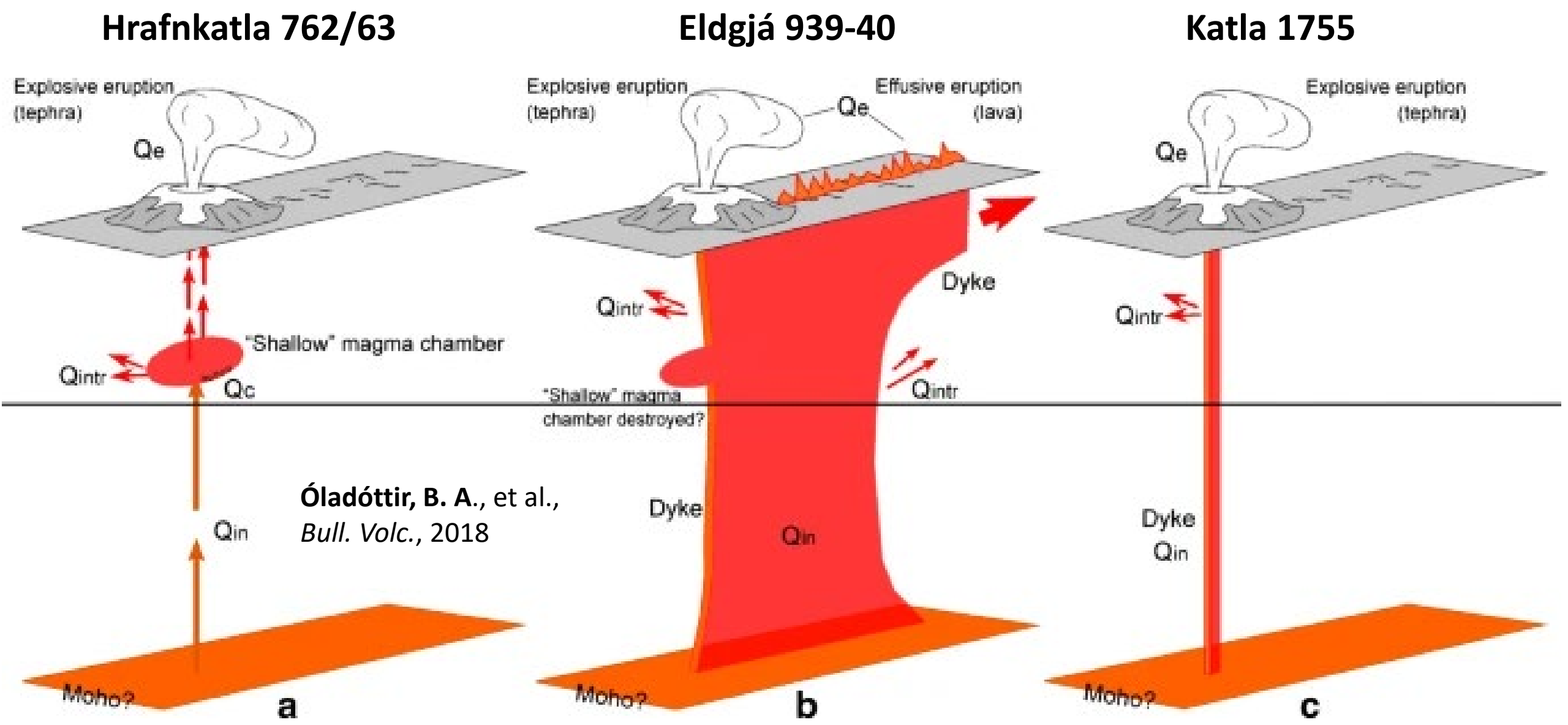


Fuglestvedt et al. *in review*

0.3 km^3 DRE

3 km^3 DRE on land / century

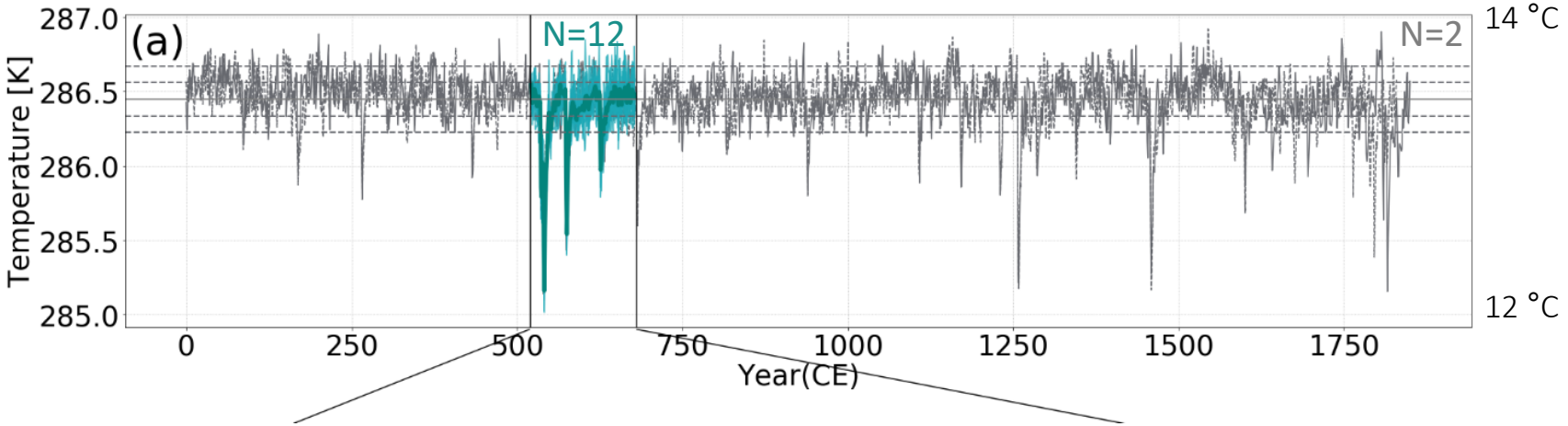
0.3 km^3 DRE on land / century



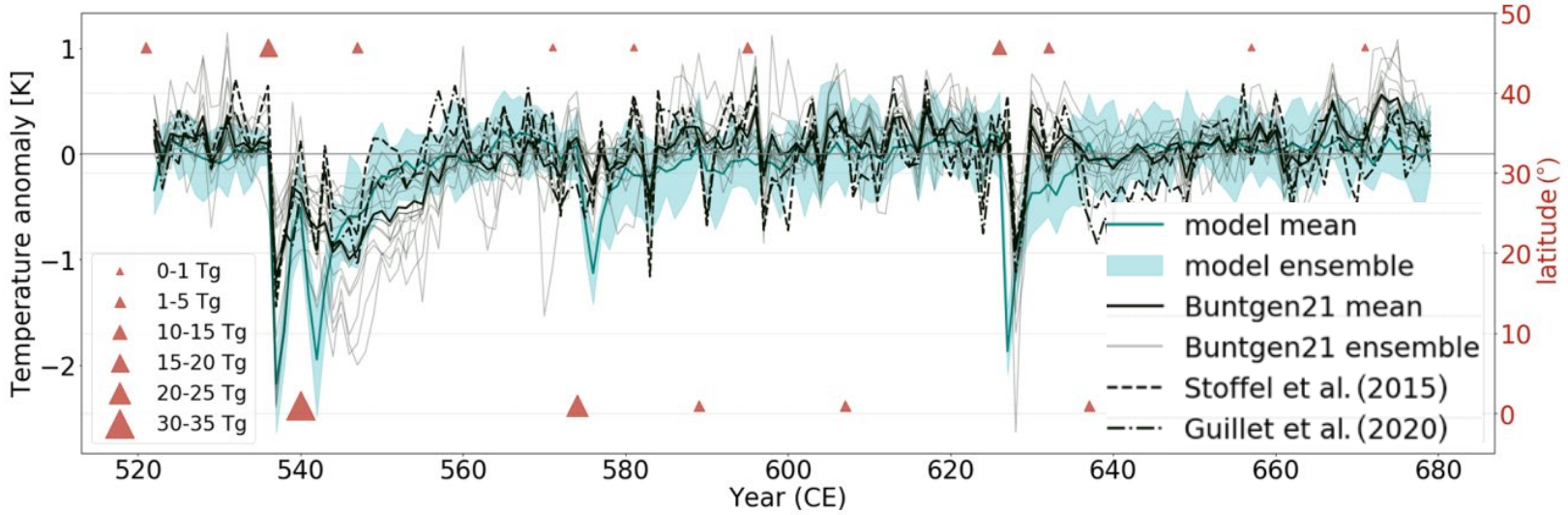
Óladóttir, B. A., et al., *Bull. Volc.*, 2018

Multi-decadal cooling following large eruptions

MPI-ESM Model w PMIP4 volcanic forcing – NH 2m air temperature



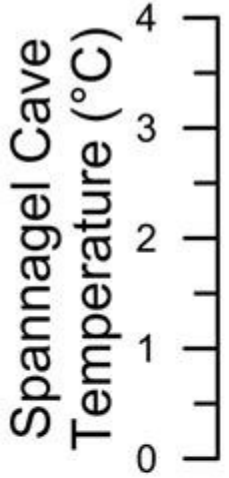
Northern Hemisphere land 40-75 N, JJA, 2m air temperature anomaly wrt 0-1850 CE

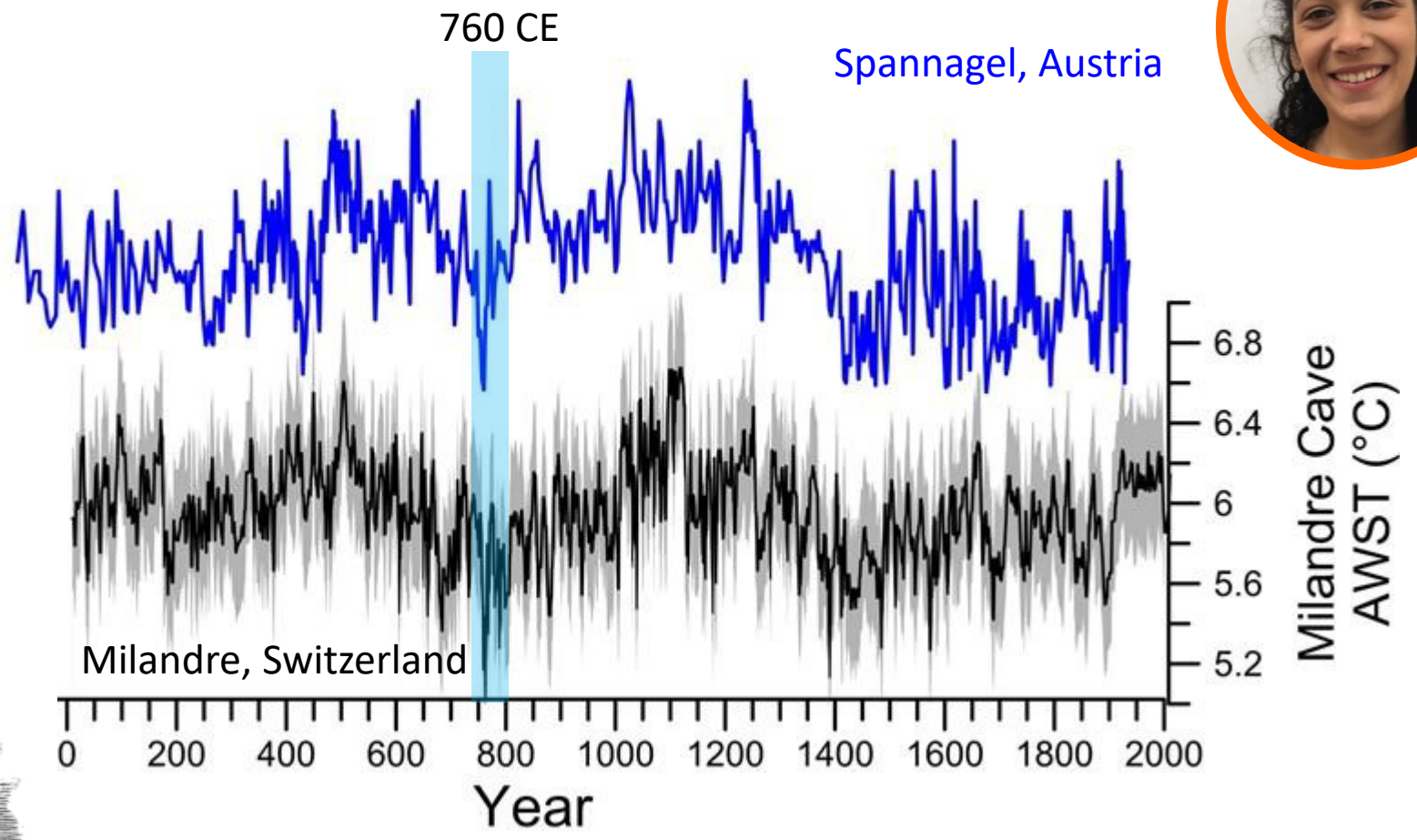


van Dijk et al (2022 *Climate of the Past)*

Case Study 2: Winter is coming with a black raven

Hrafnkatla
762 or 763
Iceland

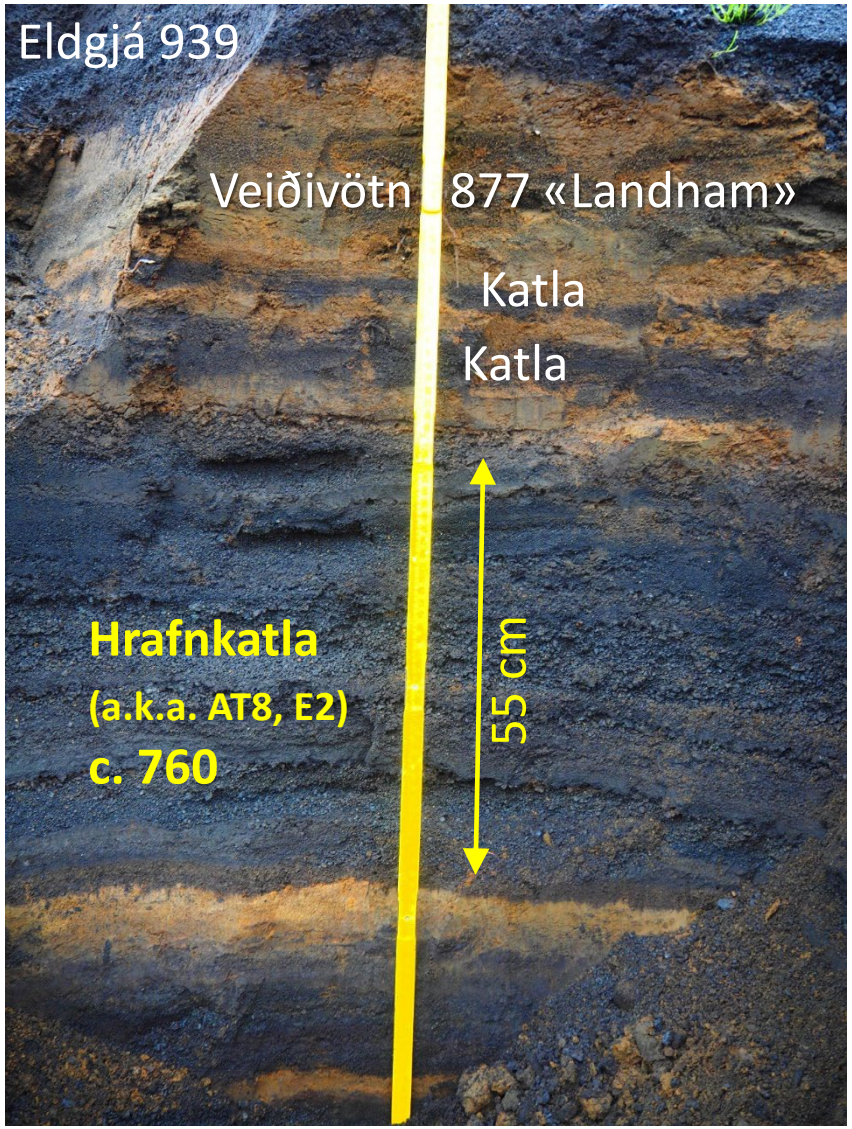




"Here was the big winter" *Anglo-Saxon Chronicle*, 763-764.
"A great snowfall which lasted almost three months." *Annals of Ulster*, 764.
"A great scarcity, and famine." *Annals of Ulster*, 764.
"An abnormally great drought." *Annals of Ulster*, 764.

Iceland

Atley, 10 km E of Katla

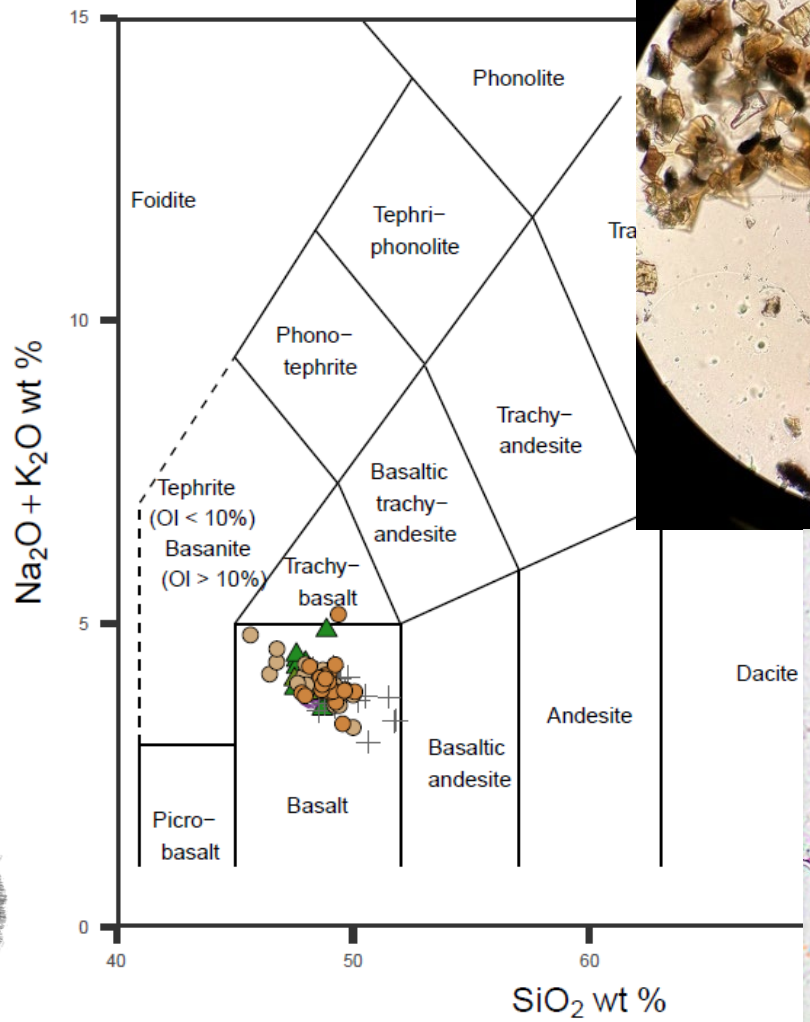


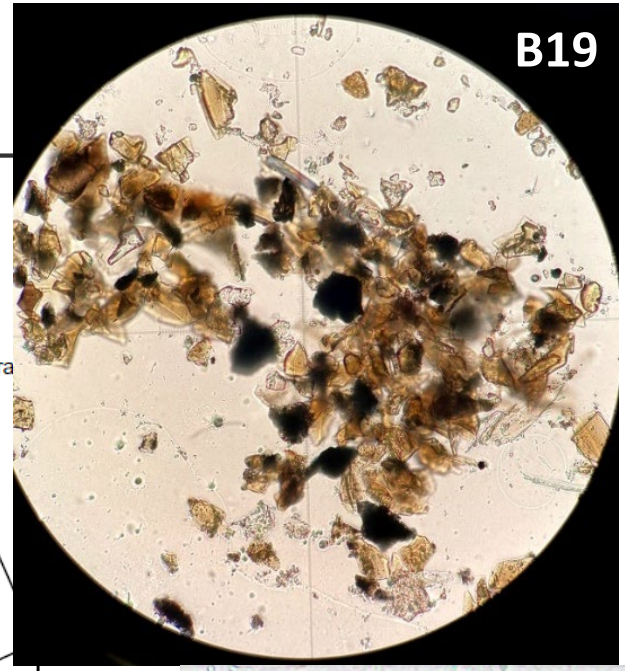
Gabriel et al. 2024 *Commun. Earth Environ.*

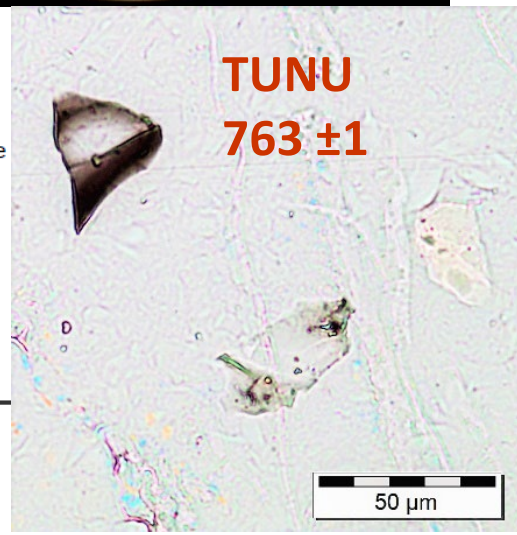
Óladóttir, B. A., et al., *Bull. Volc.*, 2011

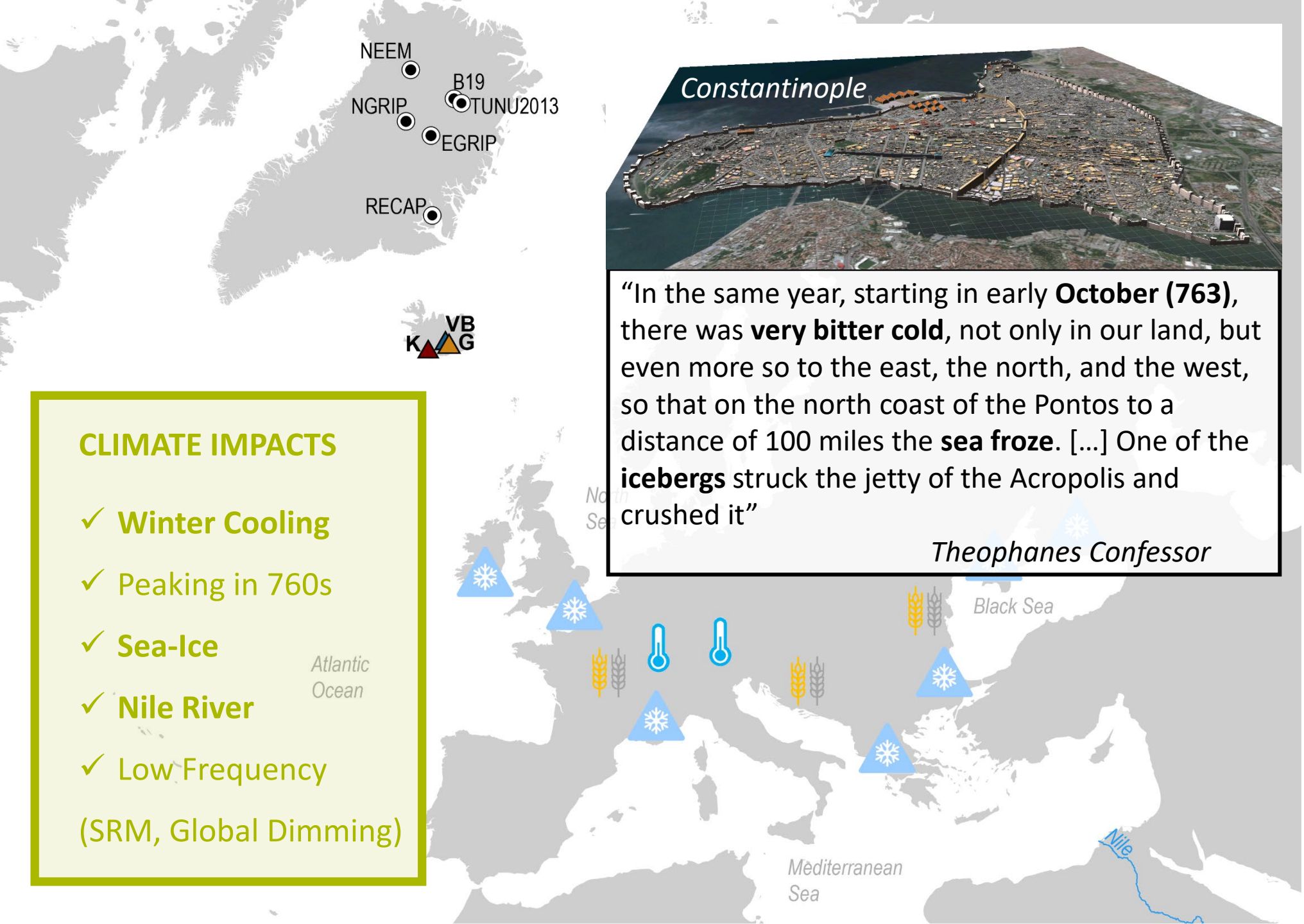
Ice Cores

TUNU, B19, RECAP









"In the same year, starting in early **October (763)**, there was **very bitter cold**, not only in our land, but even more so to the east, the north, and the west, so that on the north coast of the Pontos to a distance of 100 miles the **sea froze**. […] One of the **icebergs** struck the jetty of the Acropolis and crushed it"

Theophanes Confessor

CLIMATE IMPACTS

- ✓ **Winter Cooling**
- ✓ Peaking in 760s
- ✓ **Sea-Ice**
- ✓ **Nile River**
- ✓ Low Frequency

(SRM, Global Dimming)

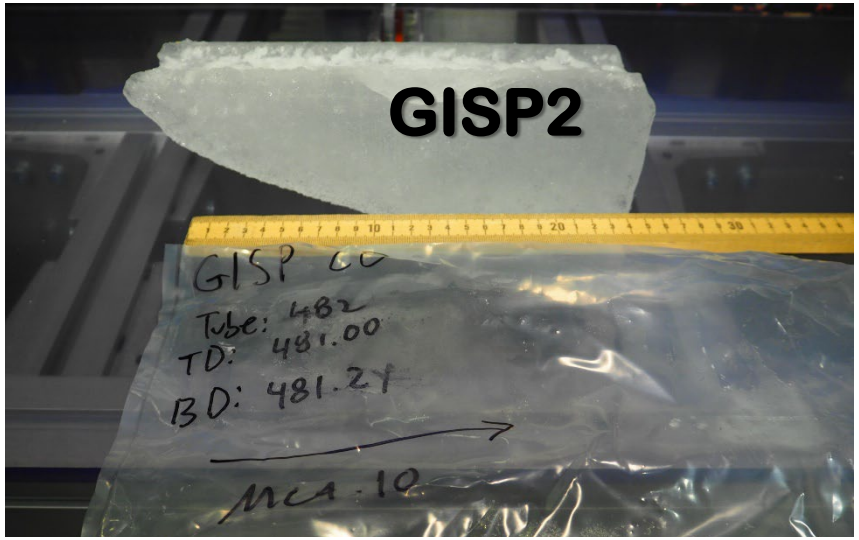
COLD

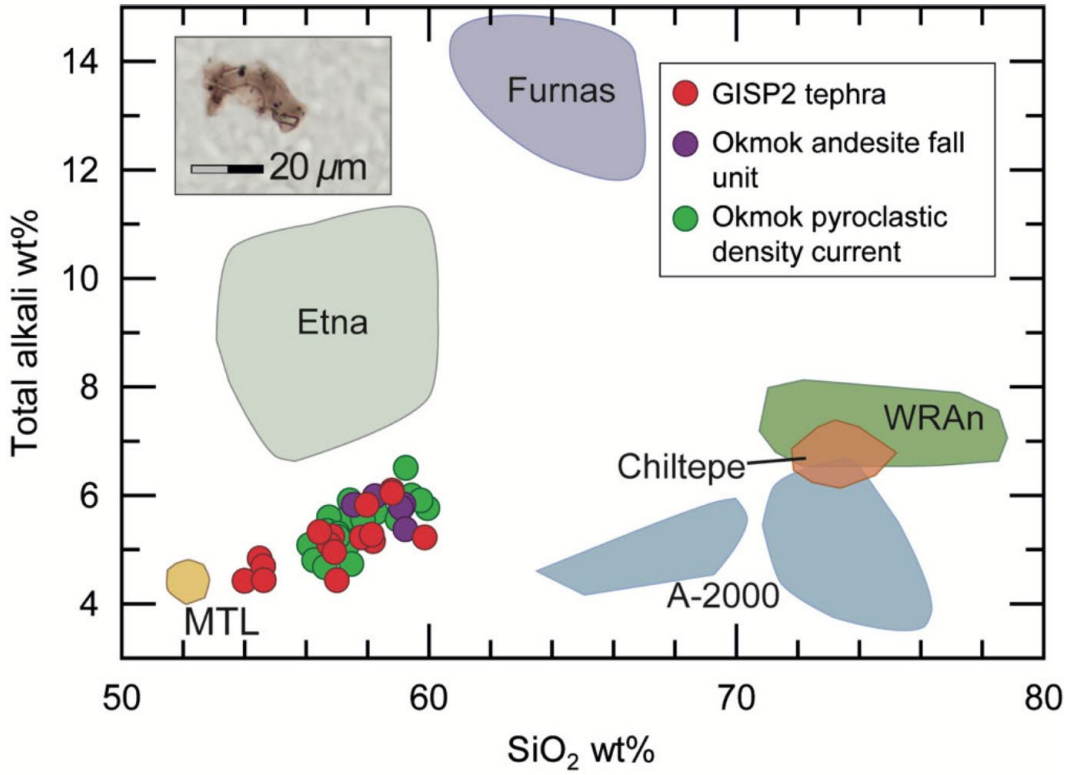
SNOW SEA-ICE

FAMINE

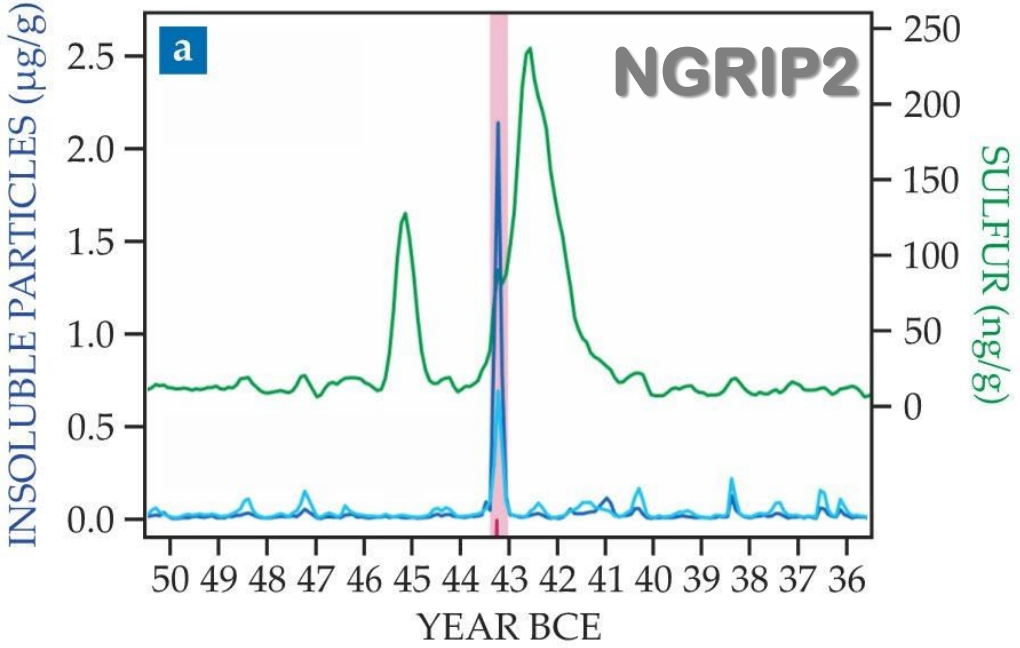
STREAM FLOW

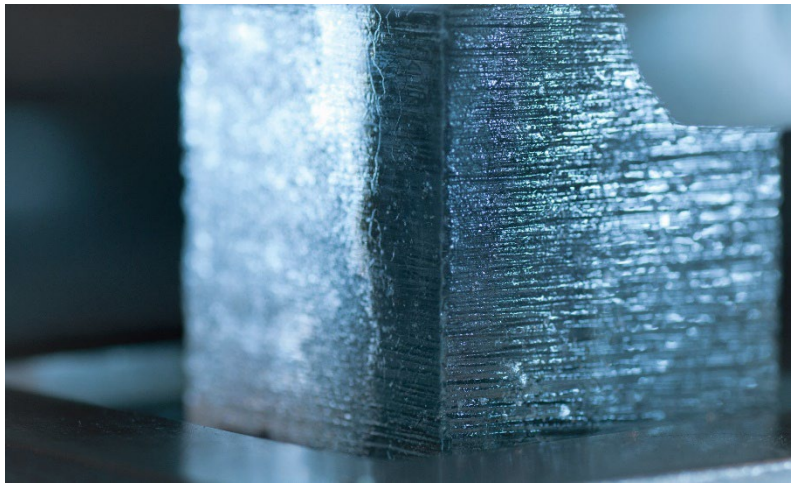
Gabriel, et al., 2024





Okmok



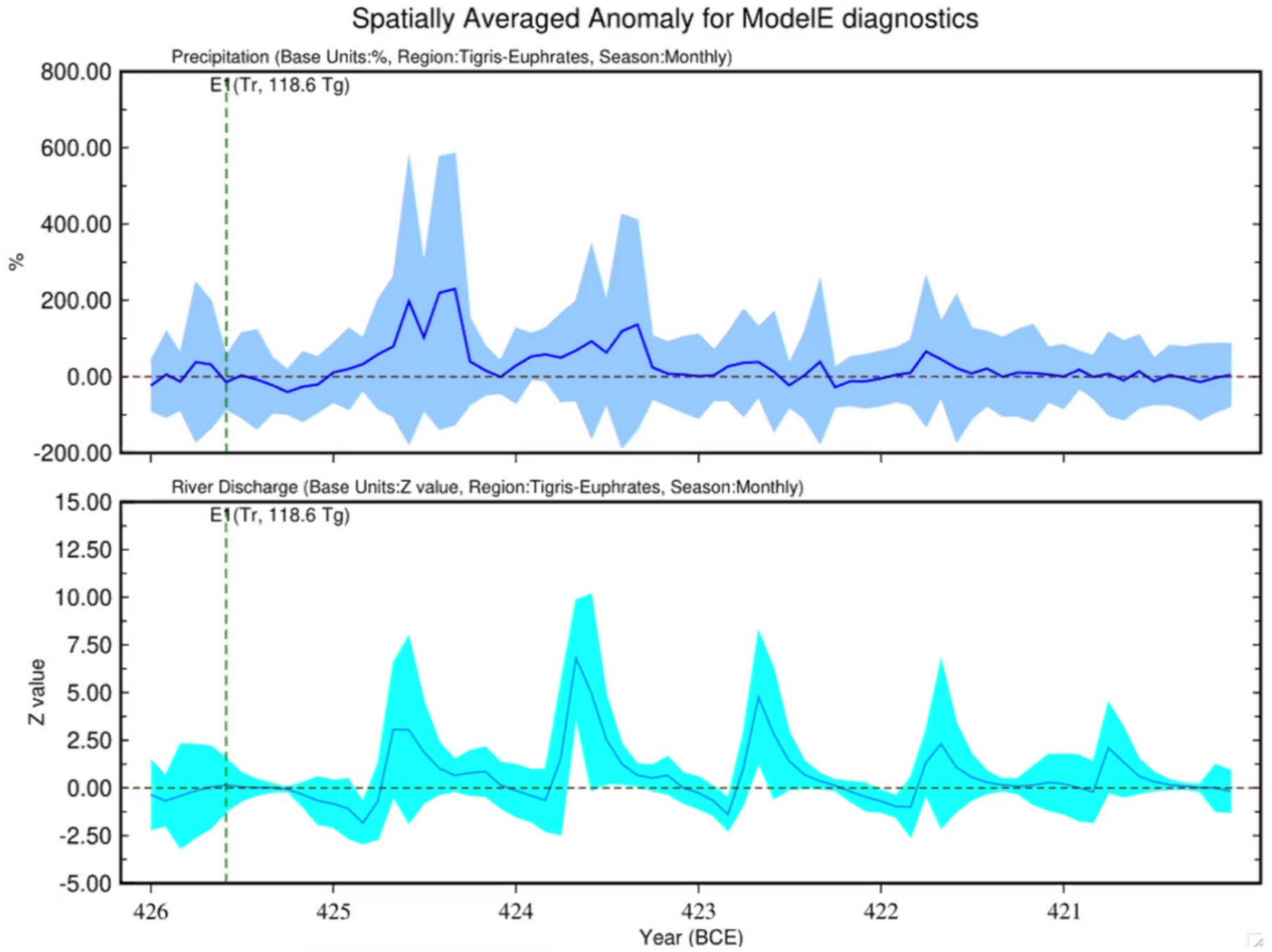


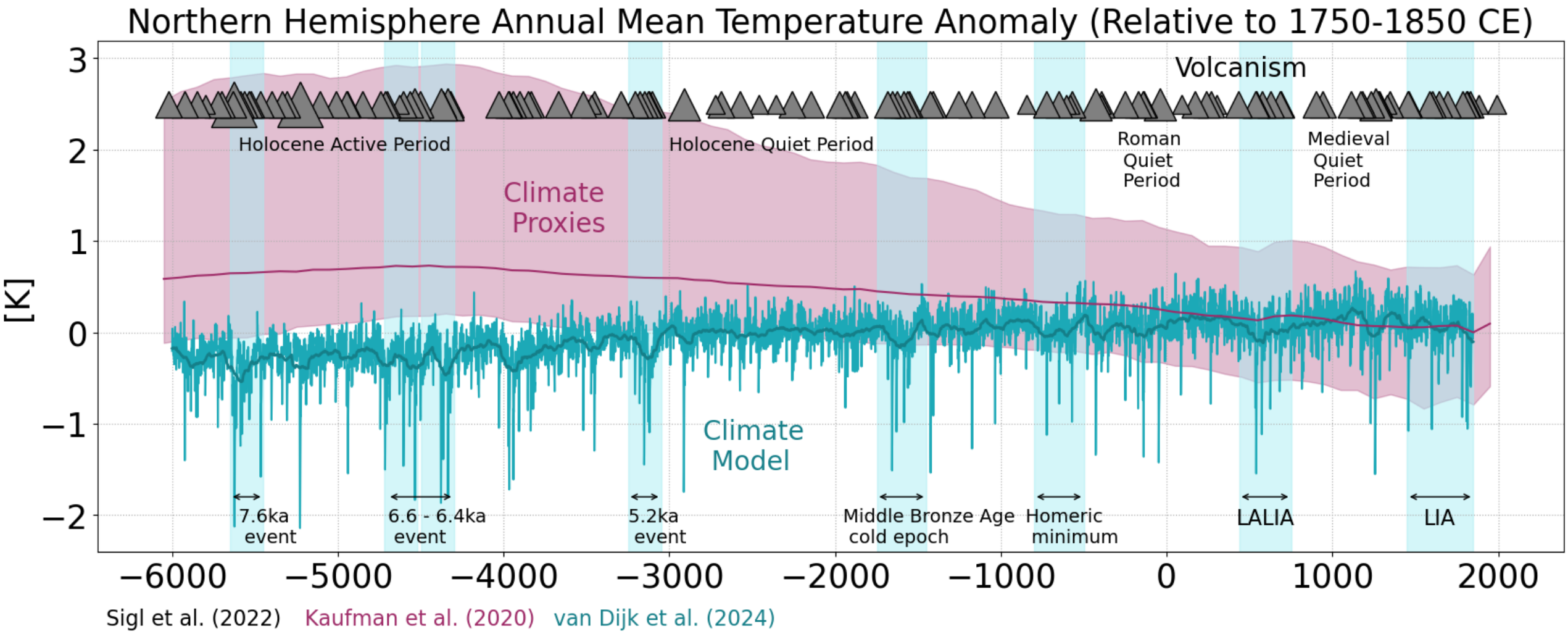
DRI
Desert Research Institute

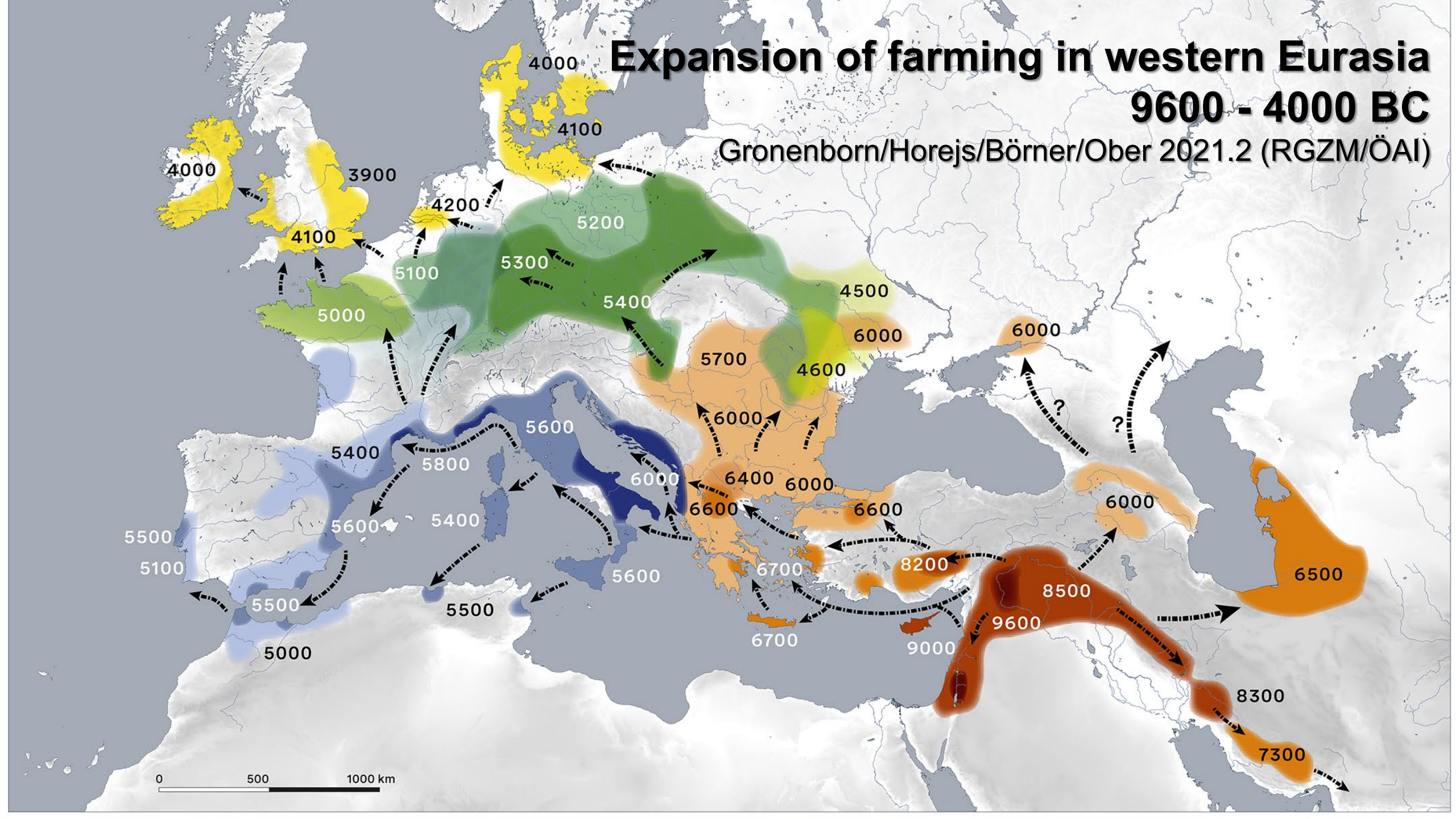
ModelE Results:
Annual River flow change

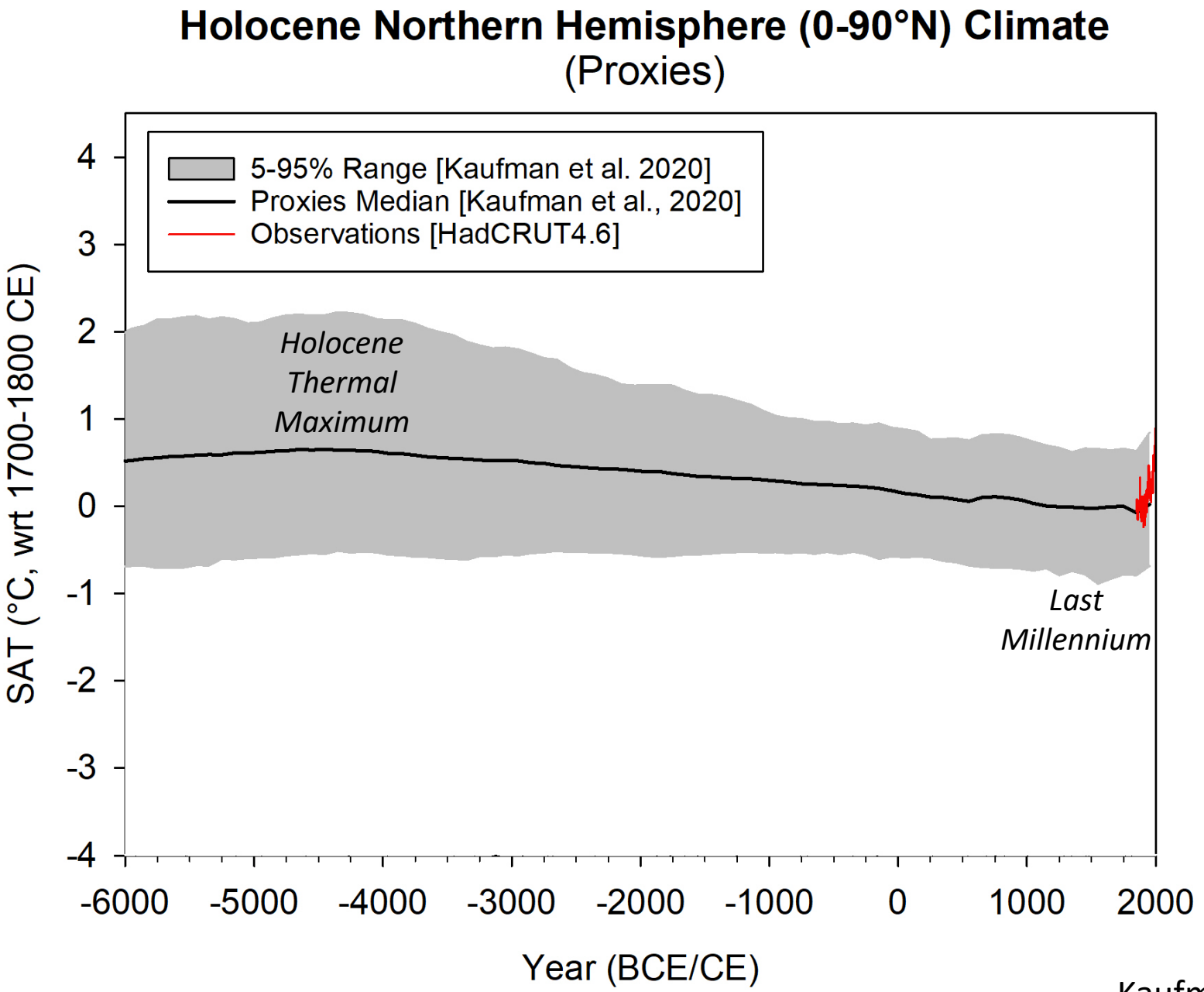
Mean Increase in rainfall up to 200% and 100% after the for year 1 and 2 respectively over the T-E river basin

River flow increase upto 2.5 to 5 Z value (times of σ)

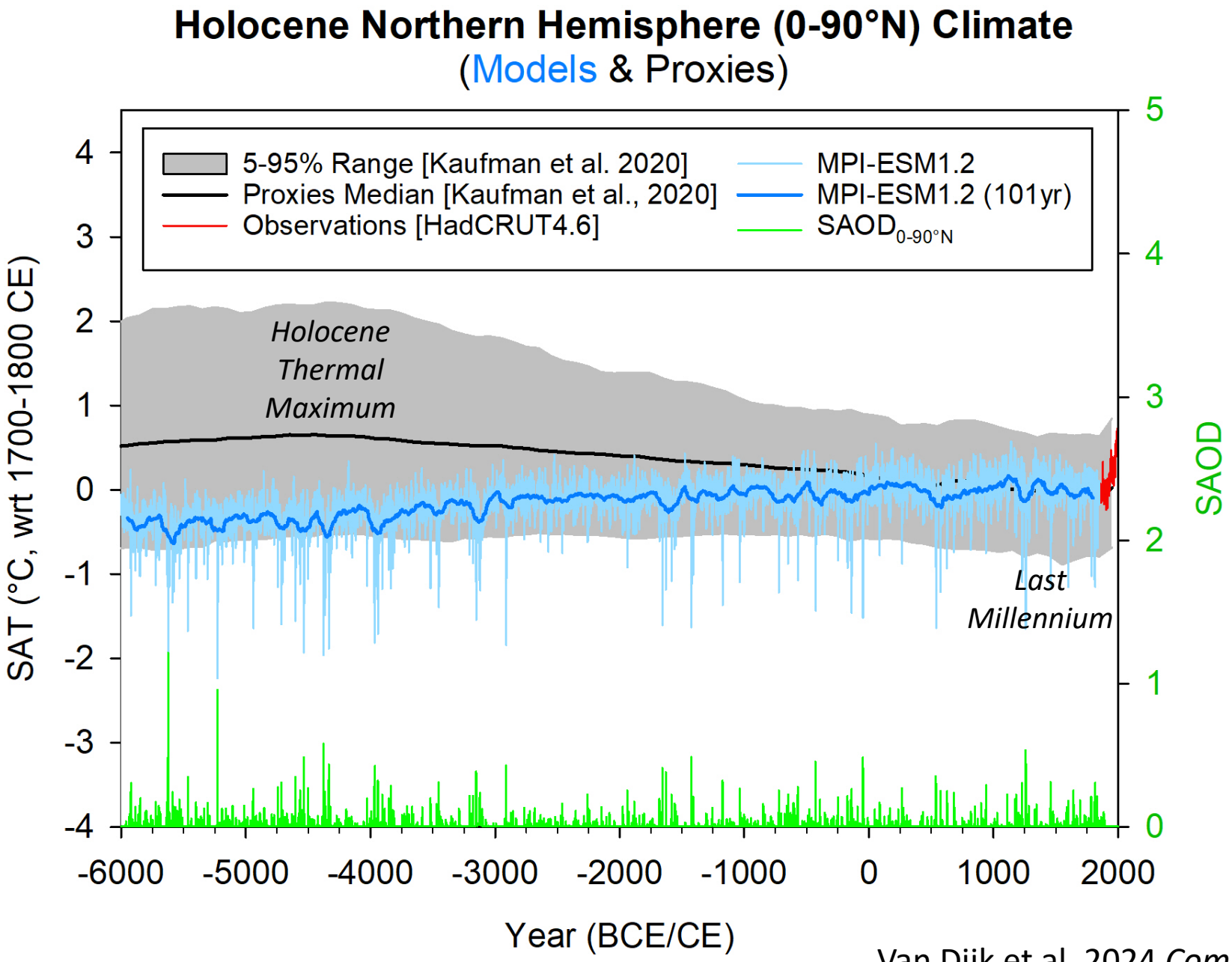



Northern Hemisphere Annual Mean Temperature Anomaly (Relative to 1750-1850 CE)
[K]
3
2
1
0
−1
−2
−6000
−5000
−4000
−3000
−2000
−1000
0
1000
2000
Volcanism
Holocene Active Period
Holocene Quiet Period
Roman Quiet Period
Medieval Quiet Period
Climate Proxies
Climate Model
7.6ka event
6.6 - 6.4ka event
5.2ka event
Middle Bronze Age cold epoch
Homeric minimum
LALIA
LIA
Sigl et al. (2022)
Kaufman et al. (2020)
van Dijk et al. (2024)


Expansion of farming in western Eurasia
9600 - 4000 BC
Gronenborn/Horejs/Börner/Ober 2021.2 (RGZM/ÖAI)
4000
4100
4000
3900
4200
4100
5200
5300
5100
5400
5000
4500
6000
5700
4600
6000
6000
?
?
5600
5400
5800
6000
6400
6000
6600
6600
6000
5600
5400
5500
5100
5500
5600
6700
8200
6500
8500
5600
5500
9600
6700
9000
5000
8300
7300
0
500
1000 km

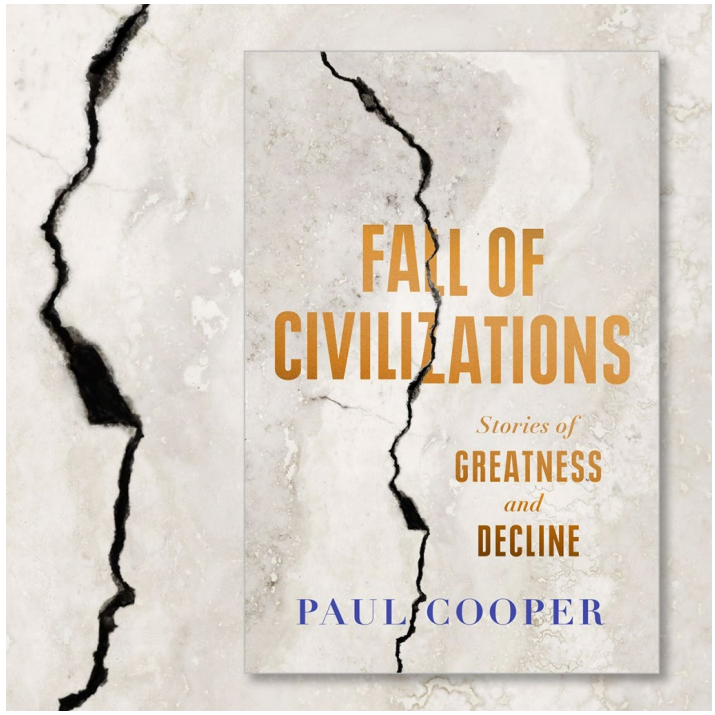


Kaufman et al. 2020 *Sci. Data*

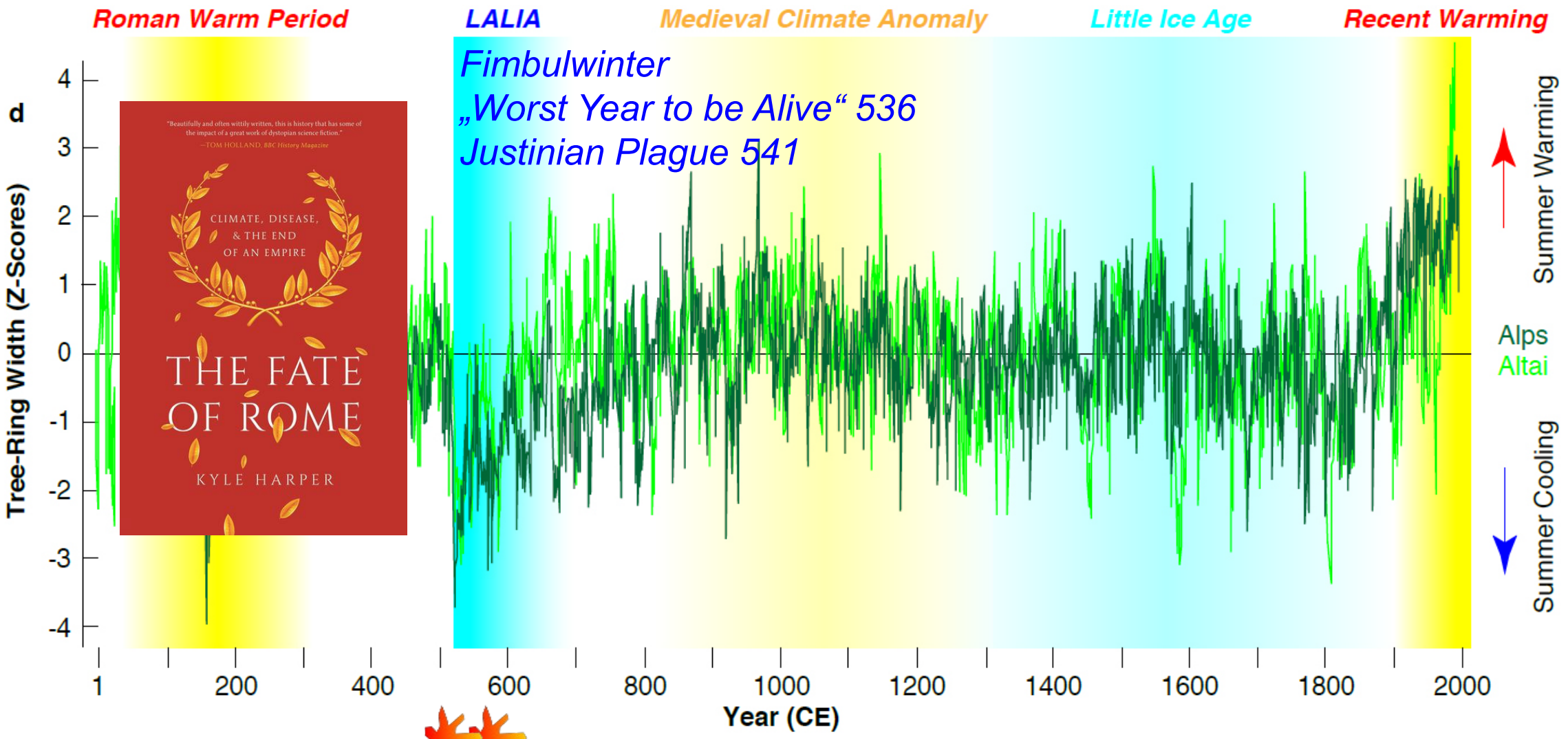


Van Dijk et al. 2024 *Commun. Earth Environ.*

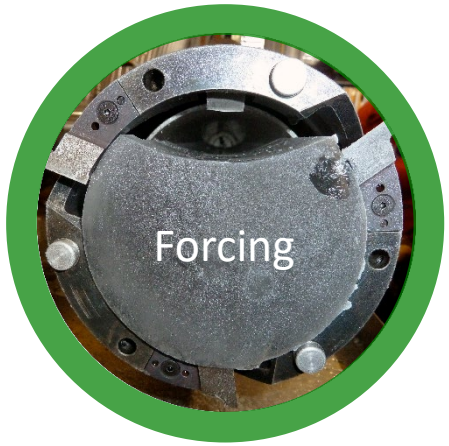
Late Holocene Northern Hemisphere: Climate & Volcanism

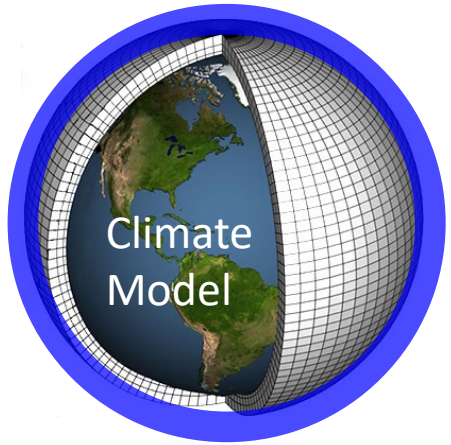


#4 Late Antique Little Ice Age (536-660) and Justinian Plague (from 541)

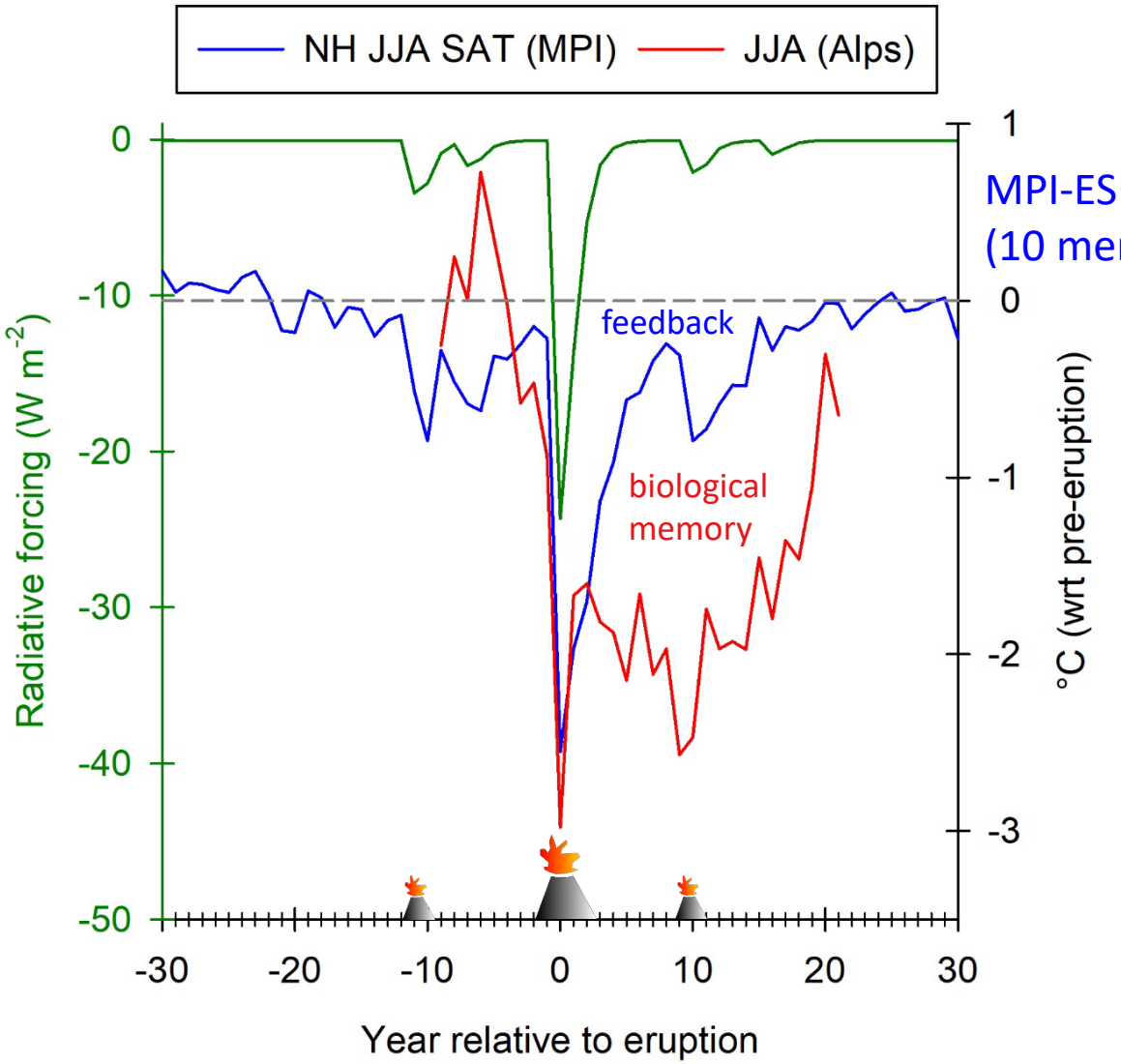


Gräslund & Price 2012, *Antiquity*
Dijk et al., 2022, 2023, *ClimPast;*
Büntgen et al. 2016; *Nat. Geosci.;* Toohey et al. 2016; *Clim. Ch.*; Harper 2019; Van
Büntgen 2022, *Sci. Bull.;* Mordechai et al., 2019, *PNAS;* Riede et al. 2020, *JVGR*





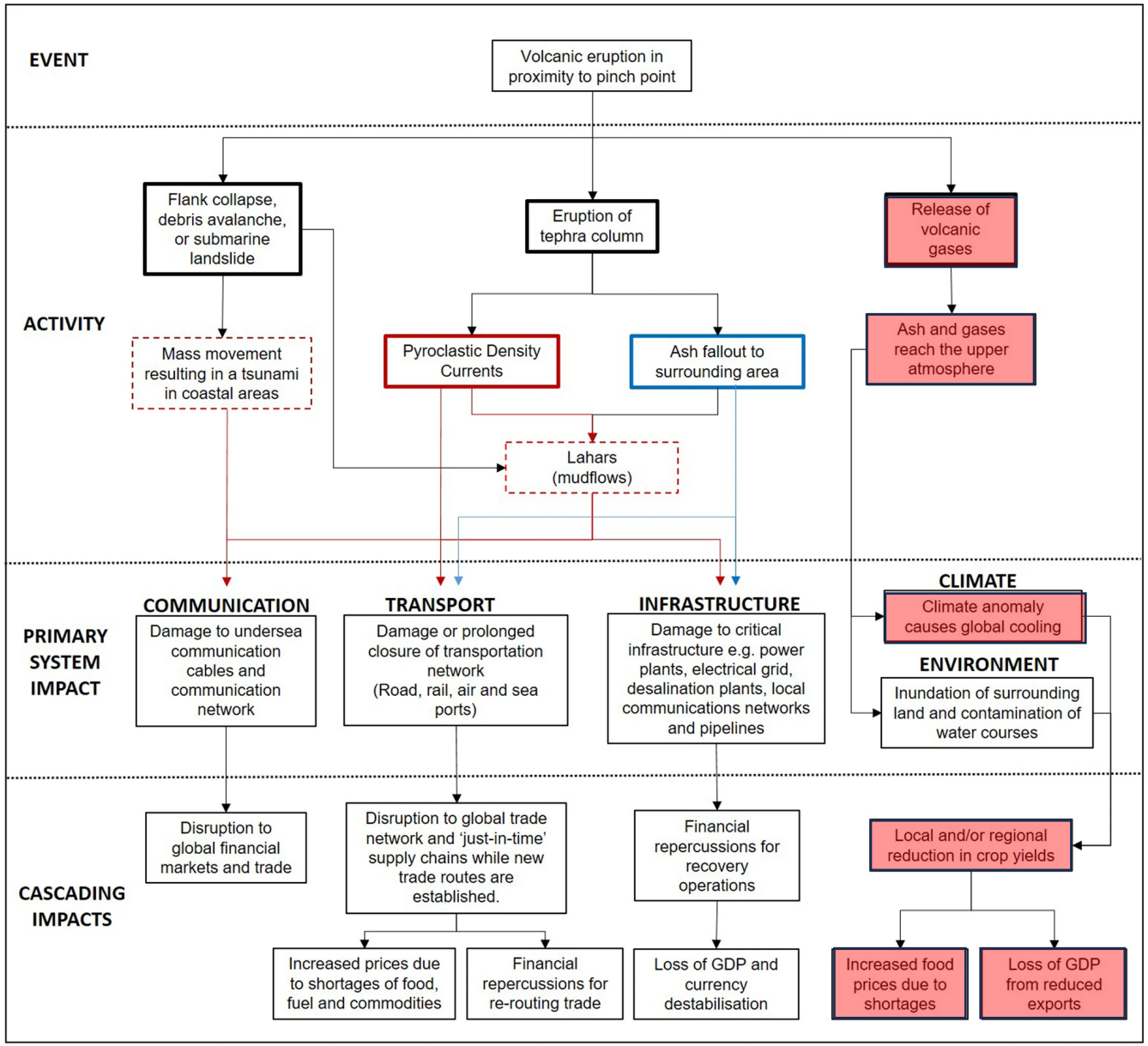
Crater Lake "Mazama", USA
VEI=7, VSSI=140 TgS
c. 5620s BCE

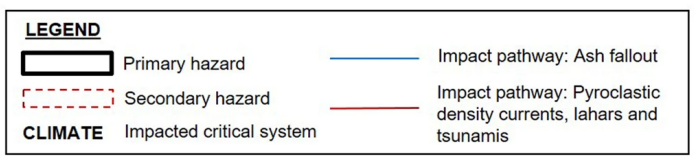


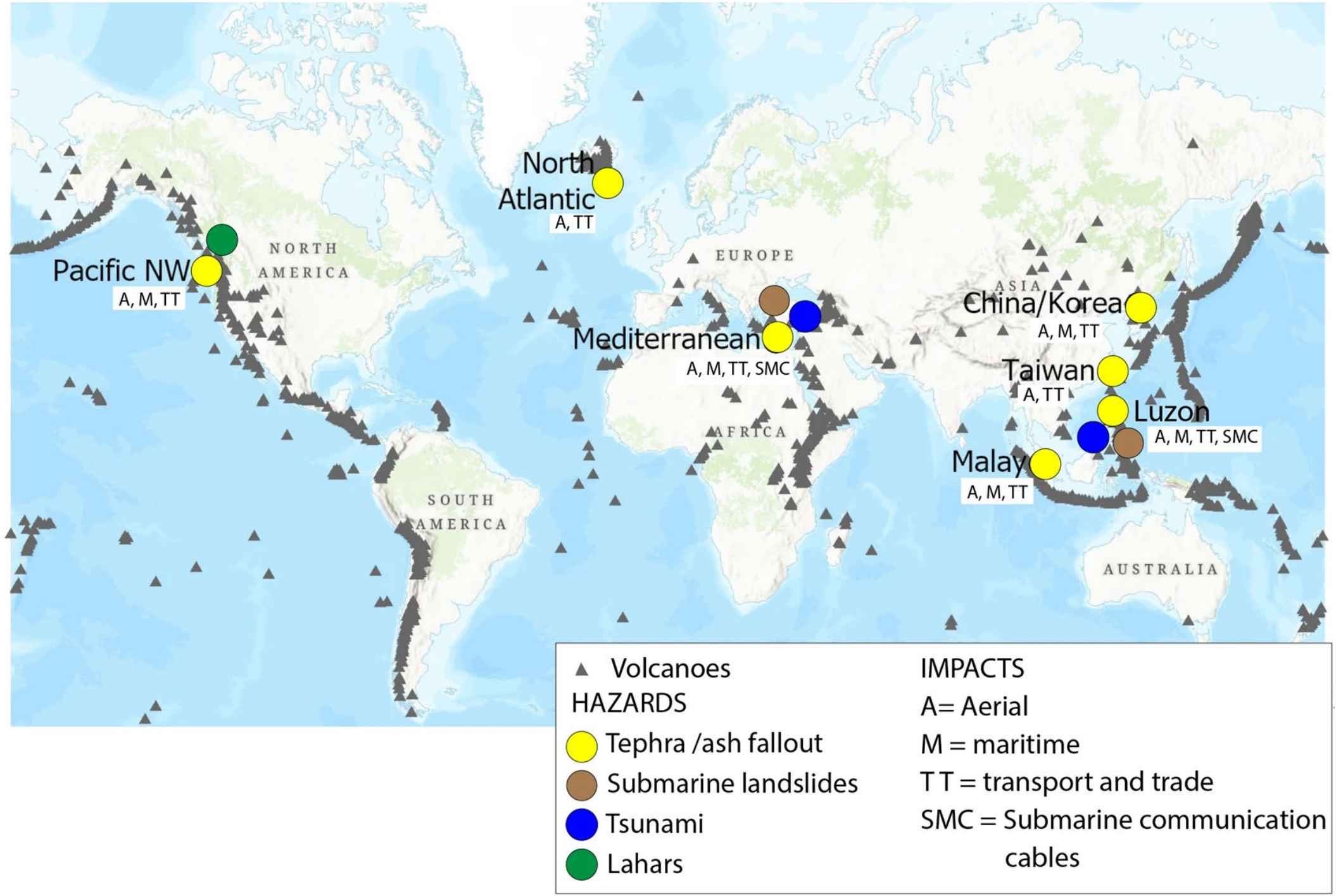
MPI-ESM 1.2
(10 member ensemble mean)

- -3°C max cooling
- lasting up to 20 yrs
- temporal clustering

➢ chronological anchor with annual precision


EVENT
Volcanic eruption in proximity to pinch point
ACTIVITY
Flank collapse, debris avalanche, or submarine landslide
Eruption of tephra column
Release of volcanic gases
Mass movement resulting in a tsunami in coastal areas
Pyroclastic Density Currents
Ash fallout to surrounding area
Ash and gases reach the upper atmosphere
Lahars (mudflows)
PRIMARY SYSTEM IMPACT
COMMUNICATION
Damage to undersea communication cables and communication network
TRANSPORT
Damage or prolonged closure of transportation network (Road, rail, air and sea ports)
INFRASTRUCTURE
Damage to critical infrastructure e.g. power plants, electrical grid, desalination plants, local communications networks and pipelines
CLIMATE
Climate anomaly causes global cooling
ENVIRONMENT
Inundation of surrounding land and contamination of water courses
CASCADING IMPACTS
Disruption to global financial markets and trade
Disruption to global trade network and 'just-in-time' supply chains while new trade routes are established.
Financial repercussions for recovery operations
Local and/or regional reduction in crop yields
Increased prices due to shortages of food, fuel and commodities
Financial repercussions for re-routing trade
Loss of GDP and currency destabilisation
Increased food prices due to shortages
Loss of GDP from reduced exports


LEGEND
Primary hazard
Secondary hazard
CLIMATE Impacted critical system
Impact pathway: Ash fallout
Impact pathway: Pyroclastic density currents, lahars and tsunamis


North Atlantic
A, TT
Pacific NW
A, M, TT
NORTH AMERICA
EUROPE
ASIA
China/Korea
A, M, TT
Mediterranean
A, M, TT, SMC
Taiwan
A, TT
Luzon
A, M, TT, SMC
AFRICA
Malay
A, M, TT
SOUTH AMERICA
AUSTRALIA
Volcanoes
HAZARDS
Tephra /ash fallout
Submarine landslides
Tsunami
Lahars
IMPACTS
A= Aerial
M = maritime
T T = transport and trade
SMC = Submarine communication cables