Atmospheric emissions from explosive eruptions:
how well do we understand the environmental effects?

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Sunday morning, May 18, 1980 – near Ephrata, Washington….

The Yellowstone supervolcano is the ultimate eruption waiting to happen

By Riff Bentham / November 5, 2018

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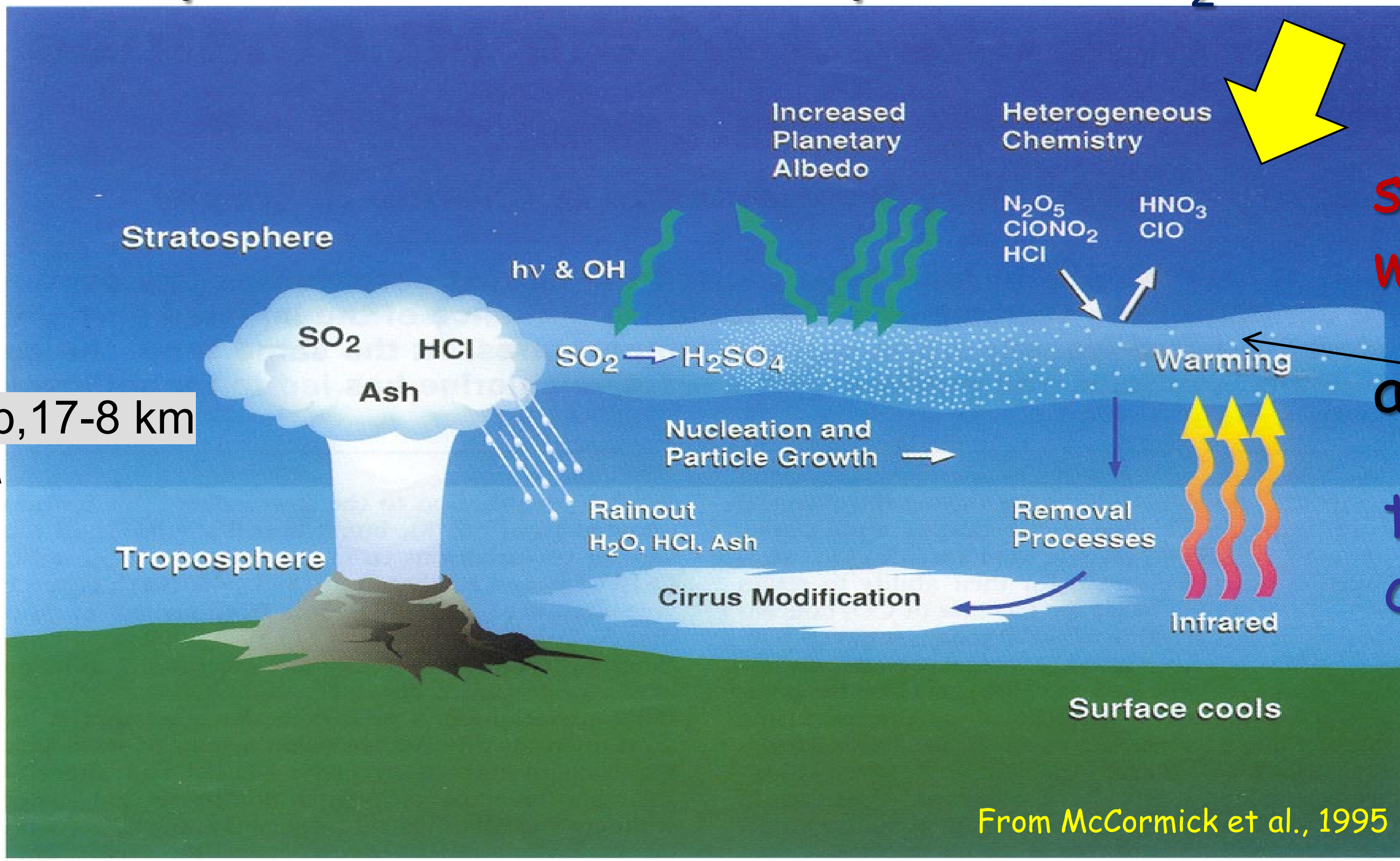
Volcanoes are cool. But they're also bad. While many of us don't live with the fear that they may ruin our livelihoods, other of us do. But beyond those few small volcanoes that threaten us

Atmospheric effects of eruptions: SO_2 and aerosols



Sulfur dioxide gas combines with water + OH from the atmosphere and the volcanic cloud to produce tiny droplets of sulfuric acid - *sulphate aerosols (complex reactions)*

- **Stratospheric aerosols have residence times of 2-3 years (could be longer in some cases?)**

- **Tropospheric aerosols have very short residence times (but can be transferred to stratosphere if in upper troposphere)**

- Ash has very short residence times (days – weeks, max), but effects are relatively unexplored

Are big volcanic SO_2 releases "over the limit"?

Post-eruption cooling not linearly related to aerosol mass [Rampino & Self, 1982]

Pinto et al. [1984] – explained this by "self-limiting process" using an atmospheric chemistry model.

For larger releases of SO_2, bigger aerosol particles form quicker, fall-out faster; have smaller radiative effect

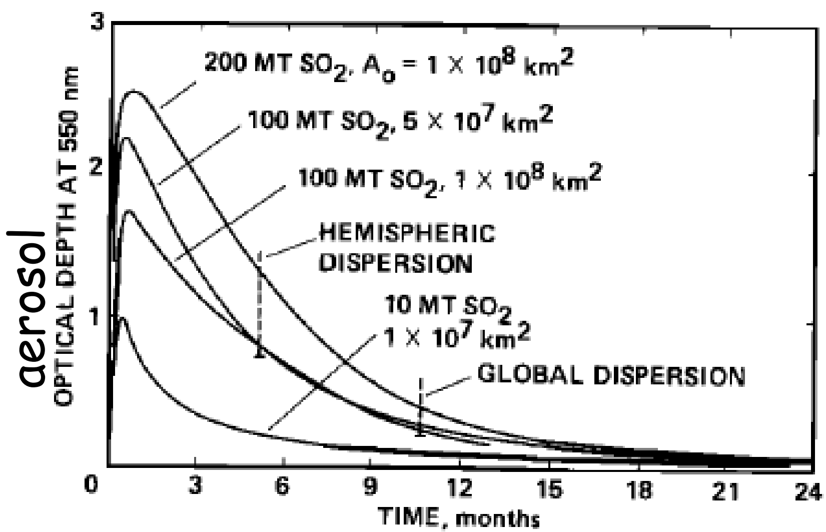


Fig. 2. Calculated optical depths as a function of time from various size injections of SO_2. Areas beside the injection rates refer to the initial area of the cloud over which oxidation is assumed to occur. [Pinto, Toon, & Turco JGR, 1984]

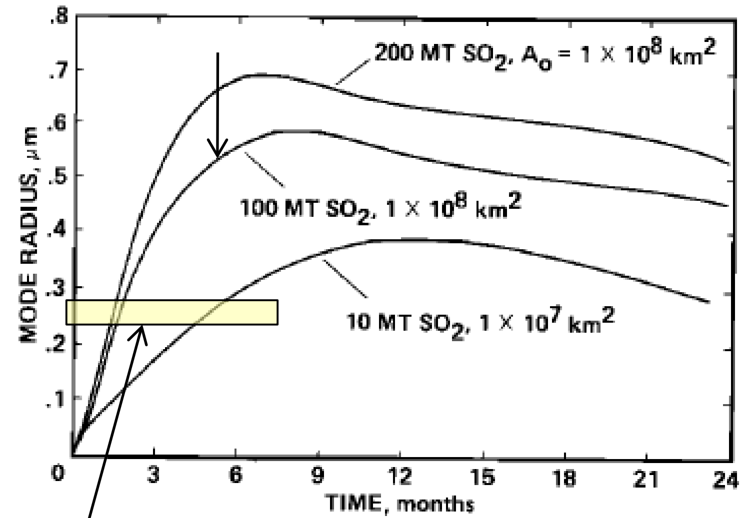
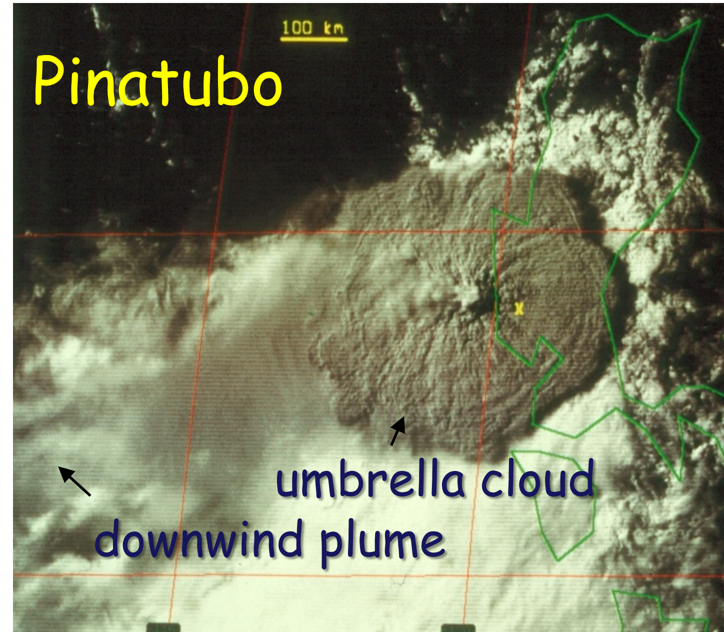


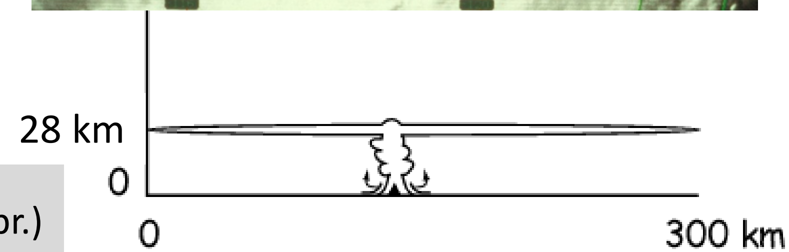
Fig. 3. The lognormal mode radius of the aerosol number size distribution for the SO_2 injections shown in Figure 2, as a function of time.

Most radiatively effective at 0.2-0.3 microns

Tambora 1815

Tambora eruption, Sumbawa (4°S), April 5-11, 1815





Duration of climactic phase: ~ 18 hrs (10-11 Apr.)

Height of eruption cloud @ ~ 35 km; main disc spreads at 25-28 km

Was this essentially a co-ignimbrite cloud - and why does it matter? If it was, then much tropospheric H_2O also injected, *cf.* much less if the eruption column was Plinian *[see Pinatubo example, ~ 5 km^3 magma.]*

33-45 km^3 magma, mostly in the ash fall

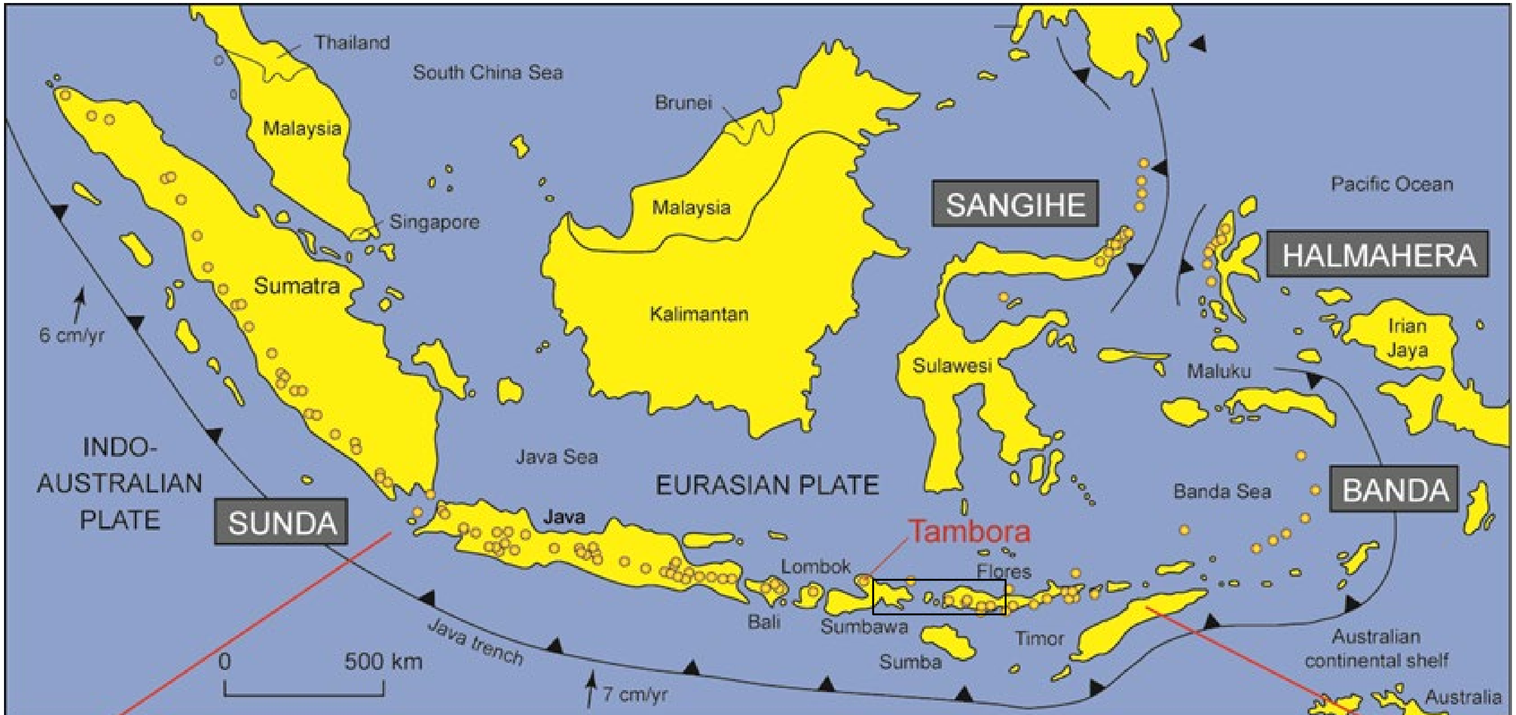
Umbrella cloud spreads radially; rotates; crosses equator [Baines et al. 2009]

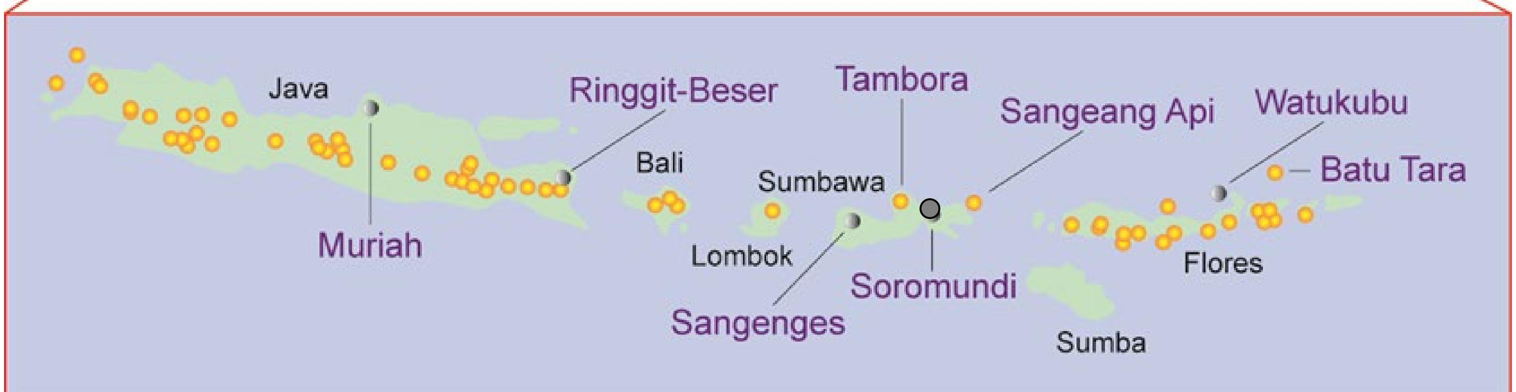
Bicentenary of the great Tambora eruption

Bern, Switzerland, 7-11 April 2015!

- Raible et al., 2015, *Tambora 1815 as a test case for high-impact volcanic eruptions: Earth system effects* (WIRES)
- Brönimann et al., 2015, *Bicentenary of the Great Tambora Eruption: Implications for Stratosphere-Troposphere Processes* (SPARC)

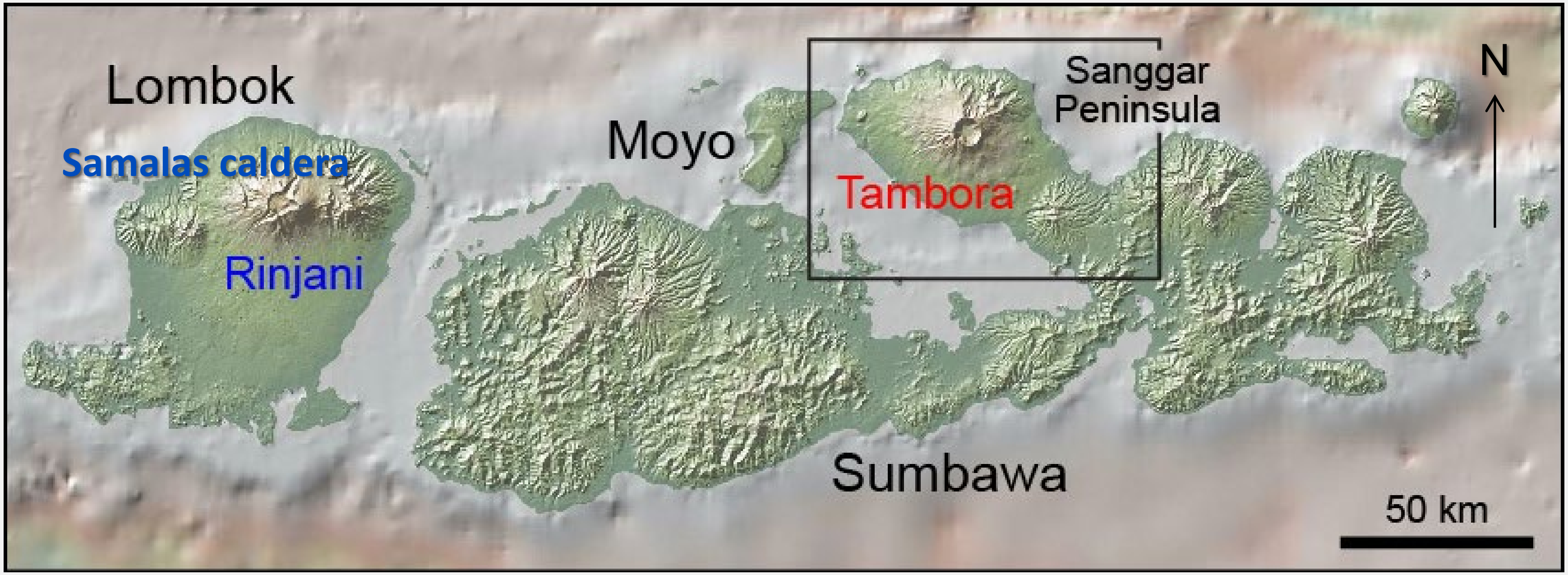
The Indonesian volcanic arc





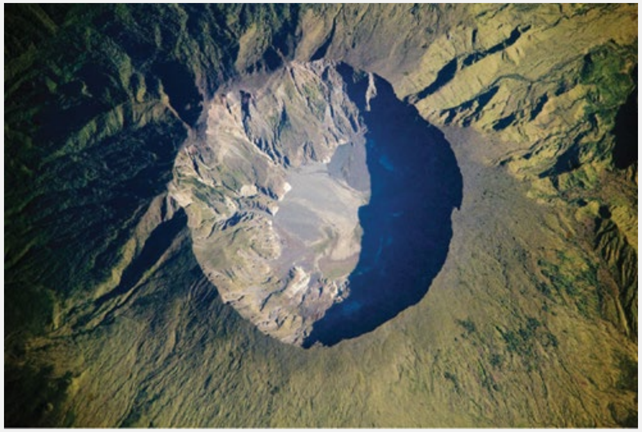
- Potassic (K-rich) alkaline volcanoes in the Java-Flores sector, Sunda arc. Tambora erupted essentially phonolite in 1815.

Tambora volcano, Sumbawa (4°S), 2850 m high



[Gertisser and Self, 2015]

Satonda Isl.



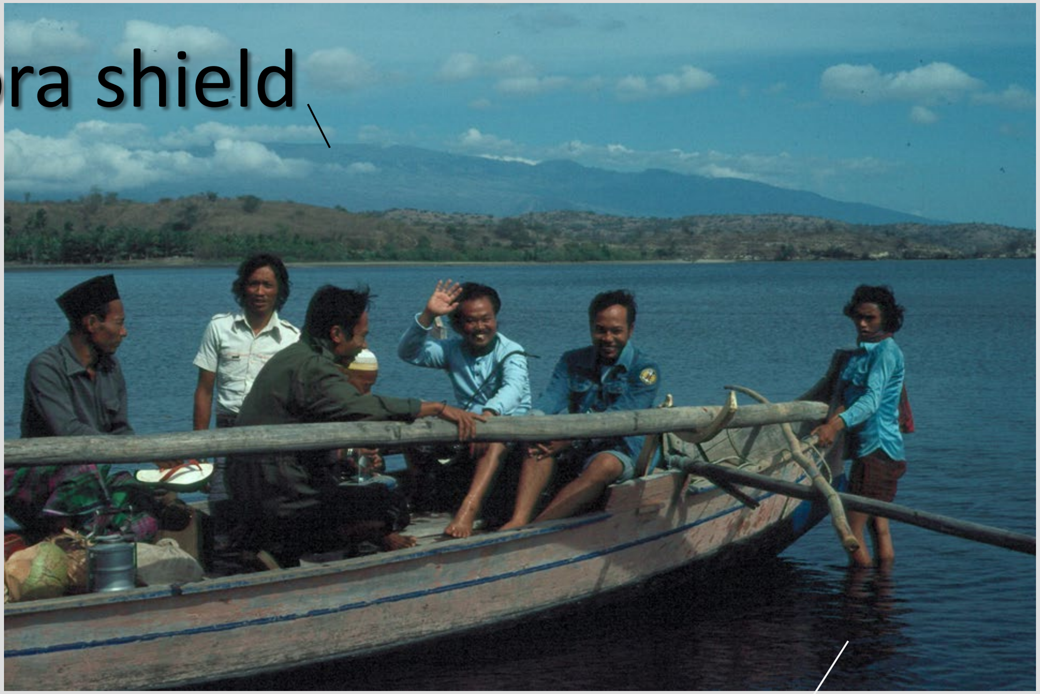
[SPOT image]

6 x 7-km diameter caldera; 1.2 km deep

Moyo,
Mojo

[NASA image, courtesy C.A. Wood]

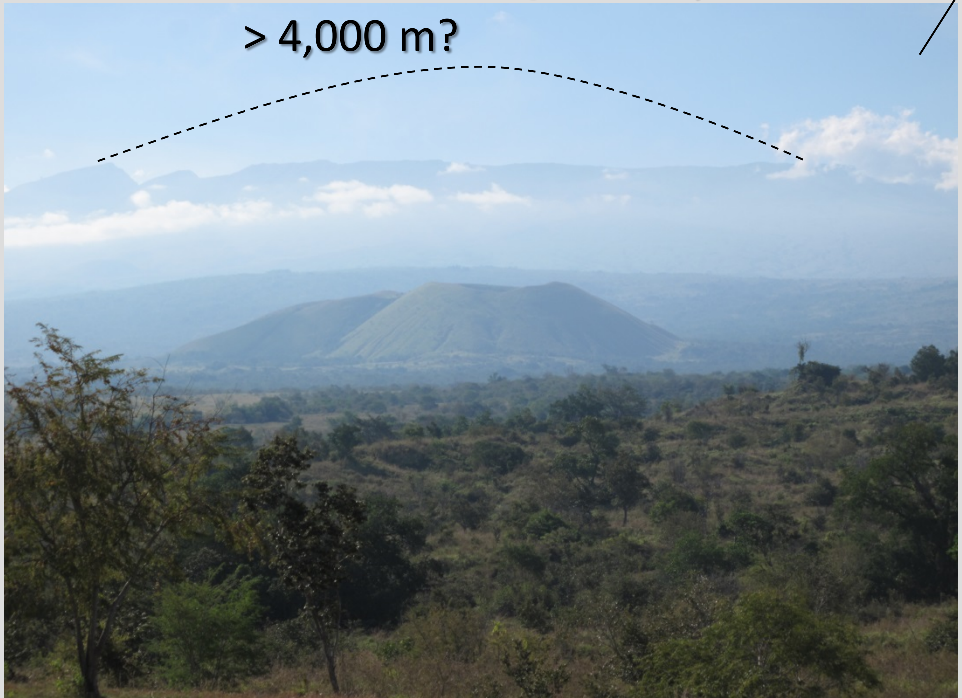
Tambora shield



[Photos by S. Self, R. Gertisser]

Crater Lake, Oregon, USA

[www.pinterest.com]

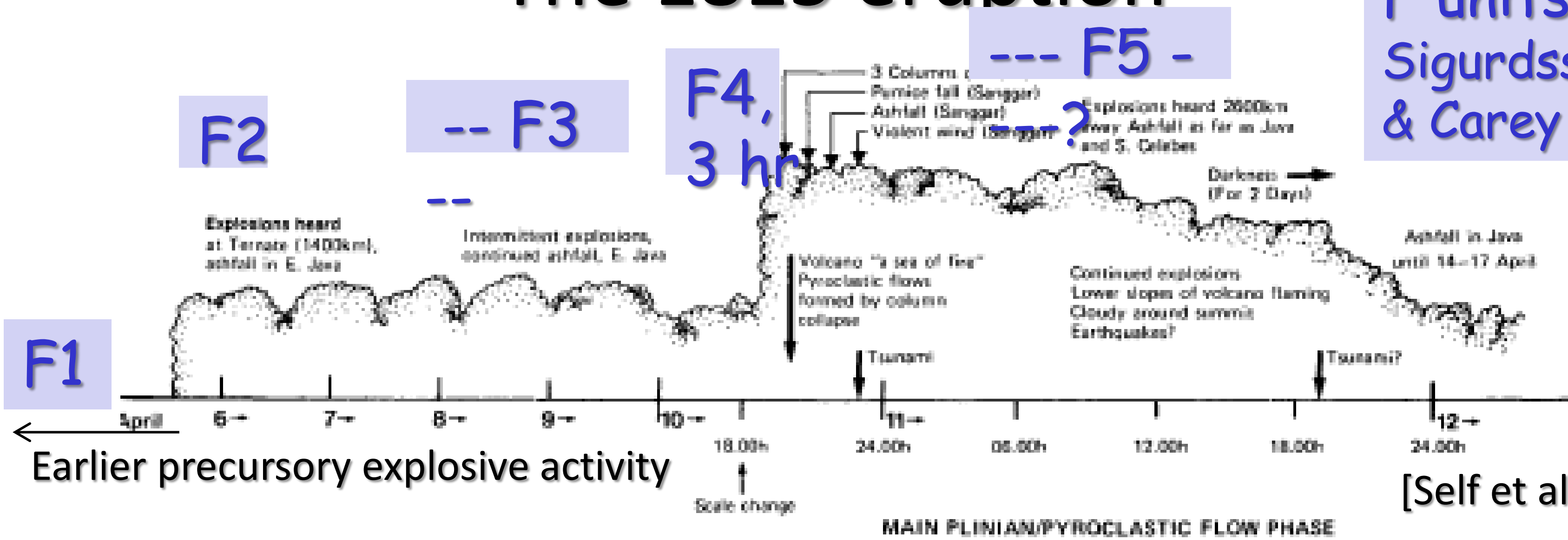


Tambora 1815 caldera

[Photos by K. Preece and R. Gertisser]

The 1815 eruption

F units, Sigurdsson & Carey [1989]



Earlier precursory explosive activity

[Self et al., 1984]

Figure 2. Chronology of 1815 eruption using evidence from contemporary reports combined with pyroclastic stratigraphy.

Caldera + "missing" cone volume = 35 km^3 (dense rock)

Fall deposit ~ 27 km^3
Flow deposits ~ 3-6 km^3

Total magma volume;
~ 30-33 km^3 [originally 50 km^3]
[Self et al., 1984, 2004; Stothers, 1984]
~ 45 km^3 according to Kaldelbaur and Sparks [2014]

Pinatubo 1991: 3.5 hr climax
Tambora 1815: 18 - 24 hr climax;

- at the Pinatubo mass eruption rate, 24 hrs of activity would produce 26 km^3 of magma

Tambora 1815 and Pinatubo 1991 - a comparison

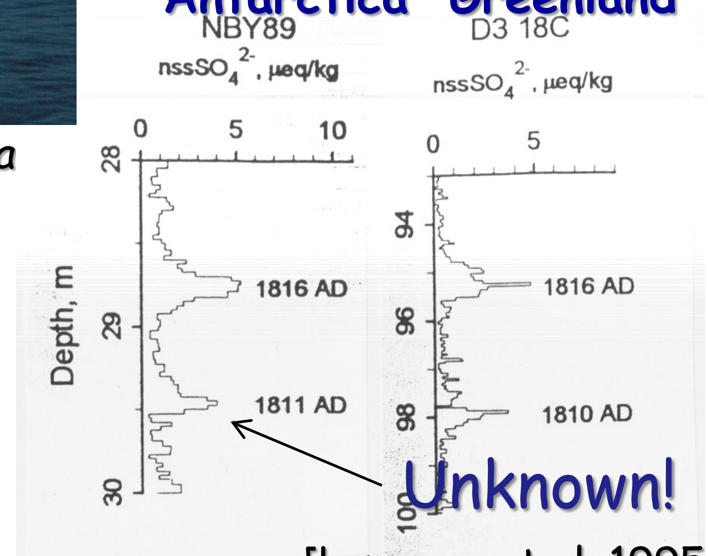
En route to Tambora

Tambora: 18-24? hr climax;
Pinatubo: 3.5-5 hr climax

- at the Pinatubo mass eruption rate, 24 hrs of activity would produce ~ 26 km^3 of magma

Bi-polar acidity spikes

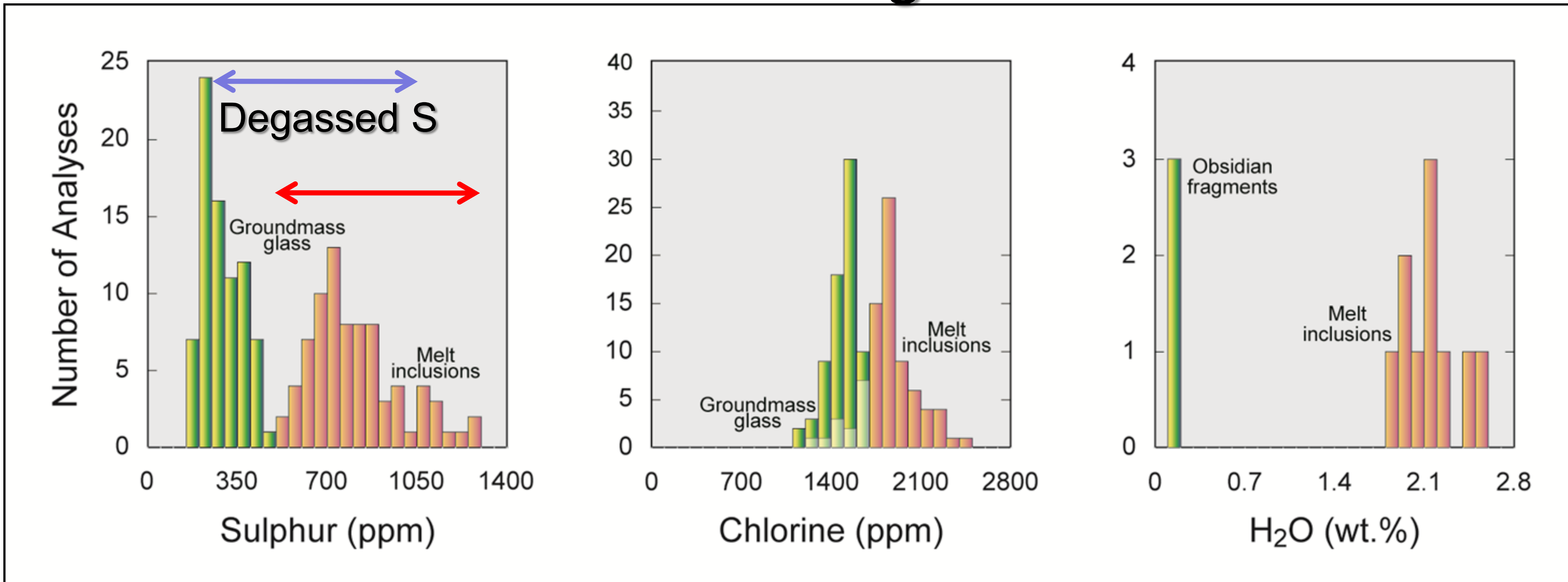
Antarctica **Greenland**



[Langway et al. 1995]

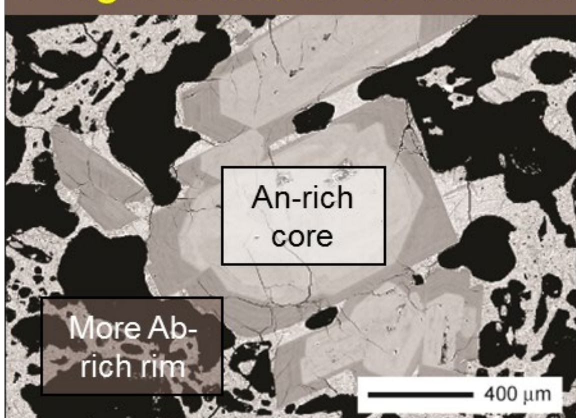
- **Both were tropical eruptions ® aerosols with global dispersal (ice core record)**
- **Both produced pyroclastic flow deposits and Plinian/co-ignimbrite fallout** [Self et al., 1984, 2004; Sigurdsson & Carey, 1988]

Melt (glass) inclusion and groundmass glass compositions in 1815 magma

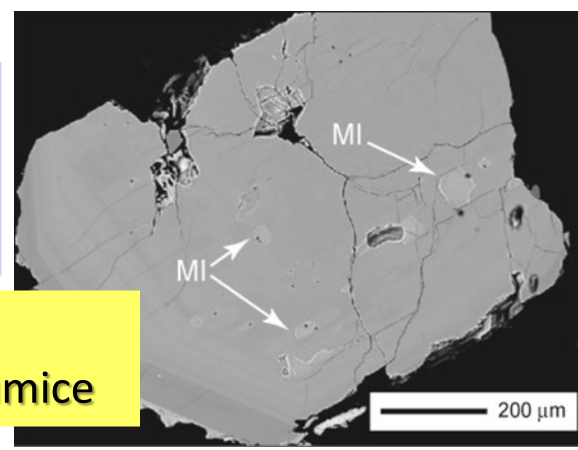


[Electron microprobe data, Gertisser et al., 2010; Self et al., 2004]

Plagioclase, 1815 Tambora pumice

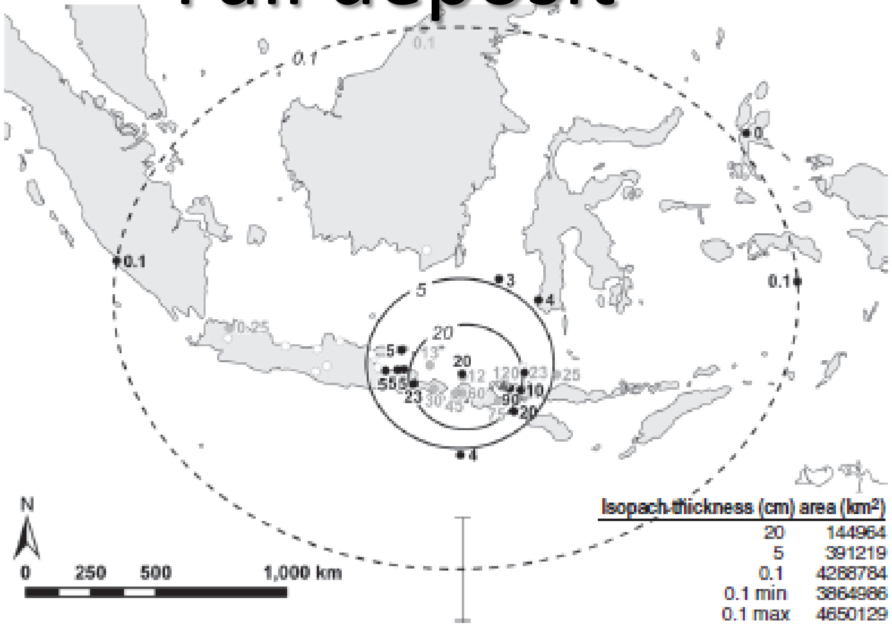


Mass SO_2 released
= min. 53 Tg; max. 58 Tg,
based on 33 km^3 magma

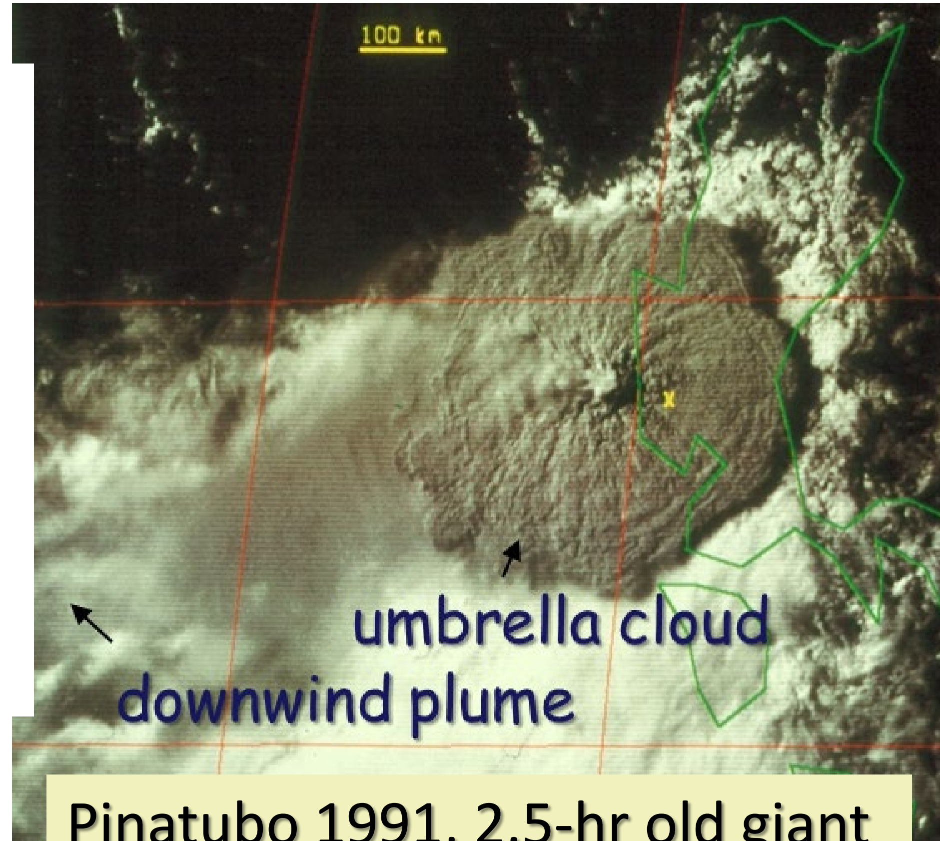


Glass (melt) inclusions in plagioclase from 1815 pumice

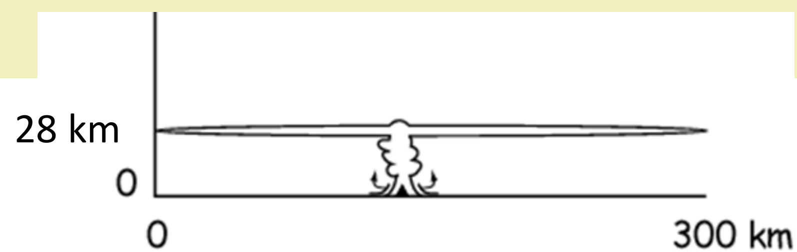
Fall deposit



[Kandelbaur and Sparks, 2014]



Pinatubo 1991, 2.5-hr old giant umbrella cloud

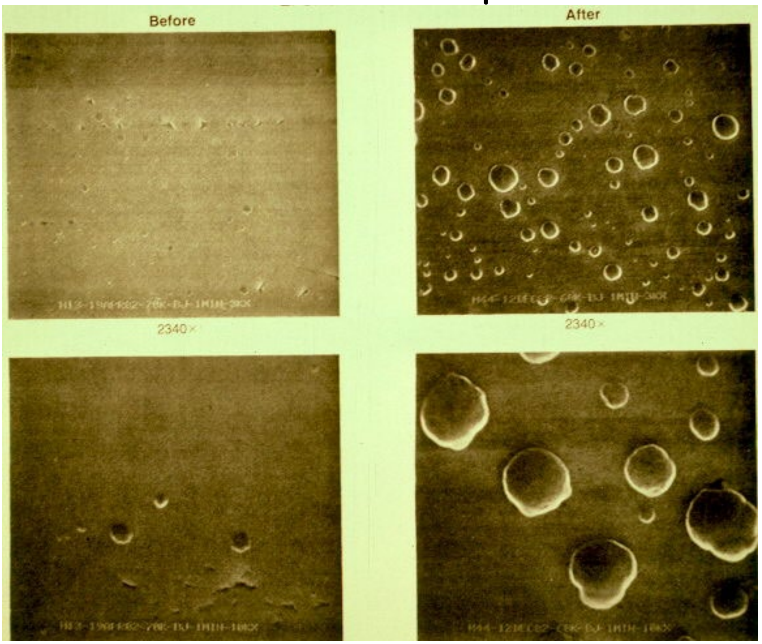


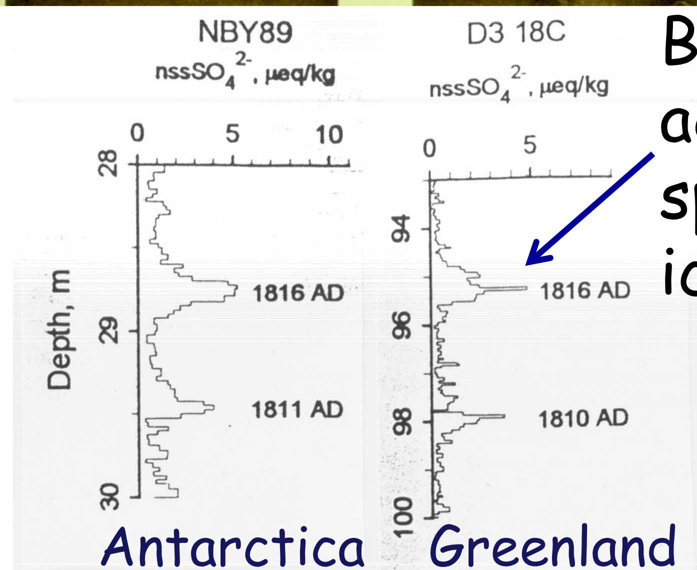
Fall deposit ~ 27 km^3; flow deposits ~ 3-6 km^3. F5 ash was proposed to be co-ignimbrite, which means the ignimbrite volume must have been significantly more – BUT if there was no separate ignimbrite-producing phase, then the distal ash is both Plinian and co-ignimbrite [Self et al., 2004]

Many large eruptions are being re-interpreted this way – from Pinatubo to super-eruptions

Estimate of mass of sulfate aerosols created by Tambora sulfur gas release

El Chichon aerosol particles





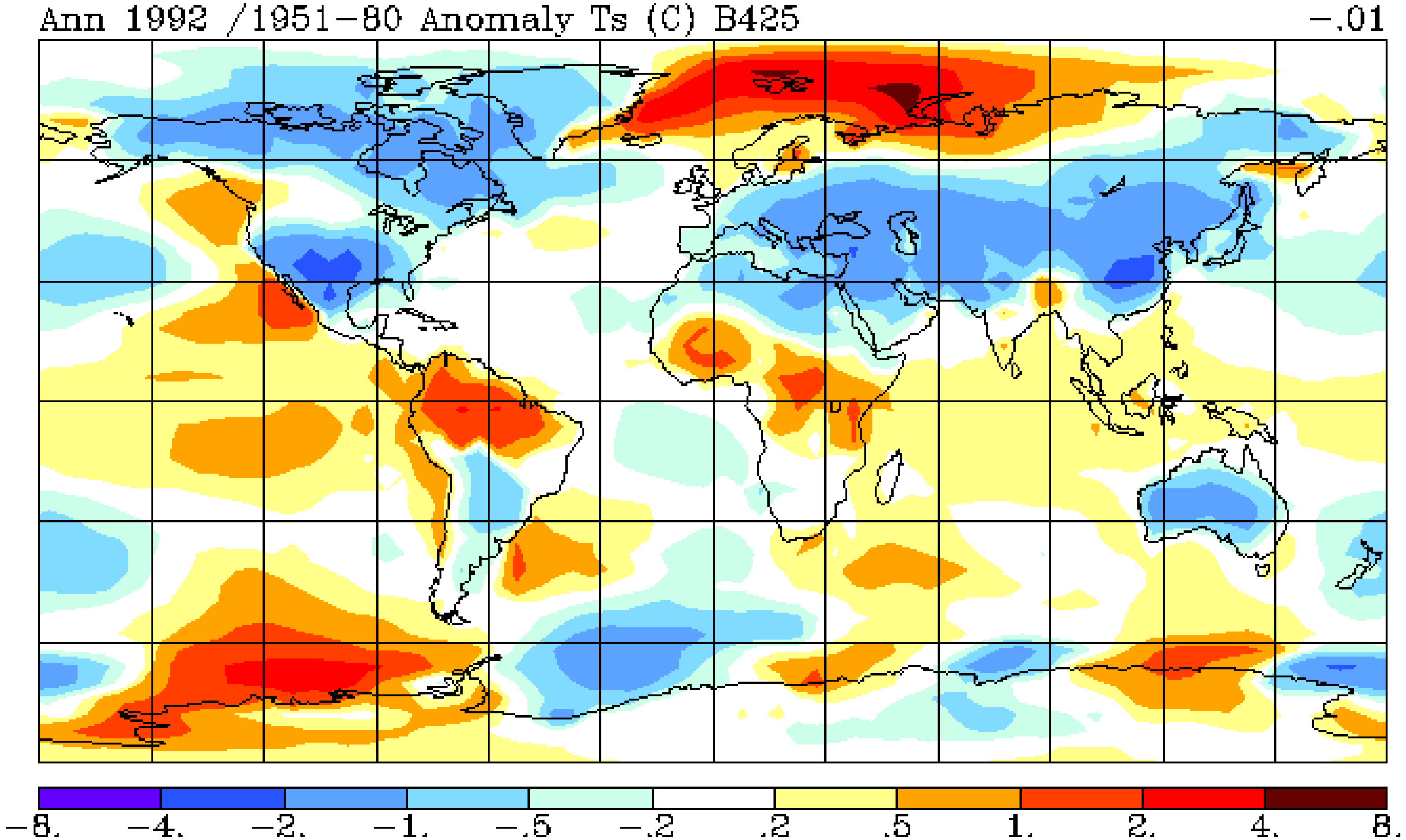
Bi-polar acidity spikes in ice-cores

From mass SO_2, 58 Mt, [Self et al., 2004]
theoretical max. = 118 Mt
or
using Pinatubo ratio **= 102 Mt**

Tambora estimate is @ 3 x the Pinatubo aerosol mass; **may have been over the limit of "most efficient" mass of SO_2 for aerosol impact?**

Tambora's magma was moderately S rich, and there was a lot of magma!

Climatic and radiative effects of Tambora aerosols in 1815-16

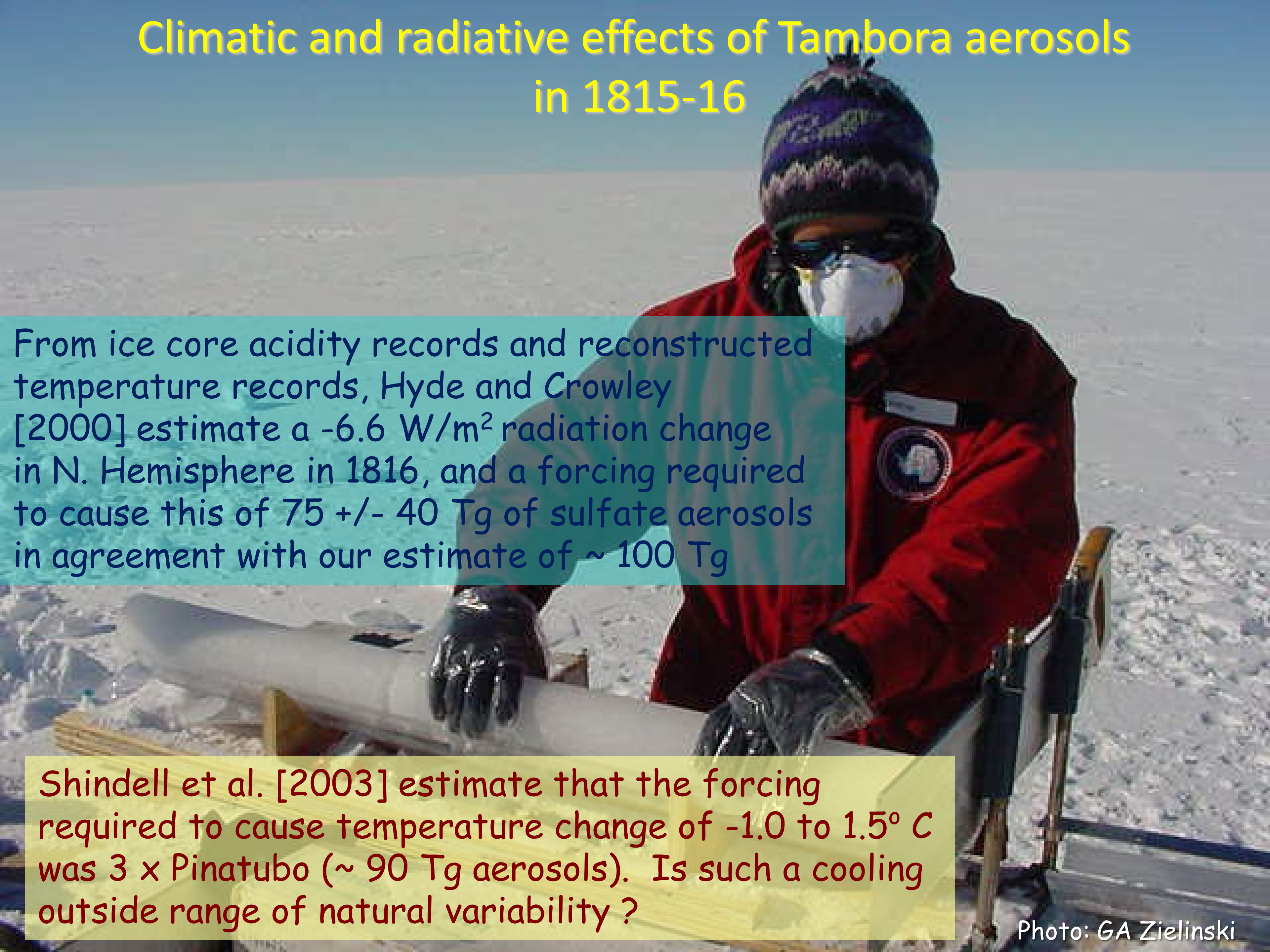


NASA - GISS climate model results for cooling after a 2 x Pinatubo eruption (Hansen, Rampino et al., unpublished)

Temperature measurements were few in 1815 but most compilations show N Hemisphere average ΔT was -1.0 to -1.5° C [e.g., Mann et al. 1998]; cold 1810 – 1820 decade due to combined cooling from ?1809 and Tambora [Cole Dai, 2008].

[ENSO cycle can mask radiative effects of aerosols if in El Nino phase.]

Climatic and radiative effects of Tambora aerosols in 1815-16

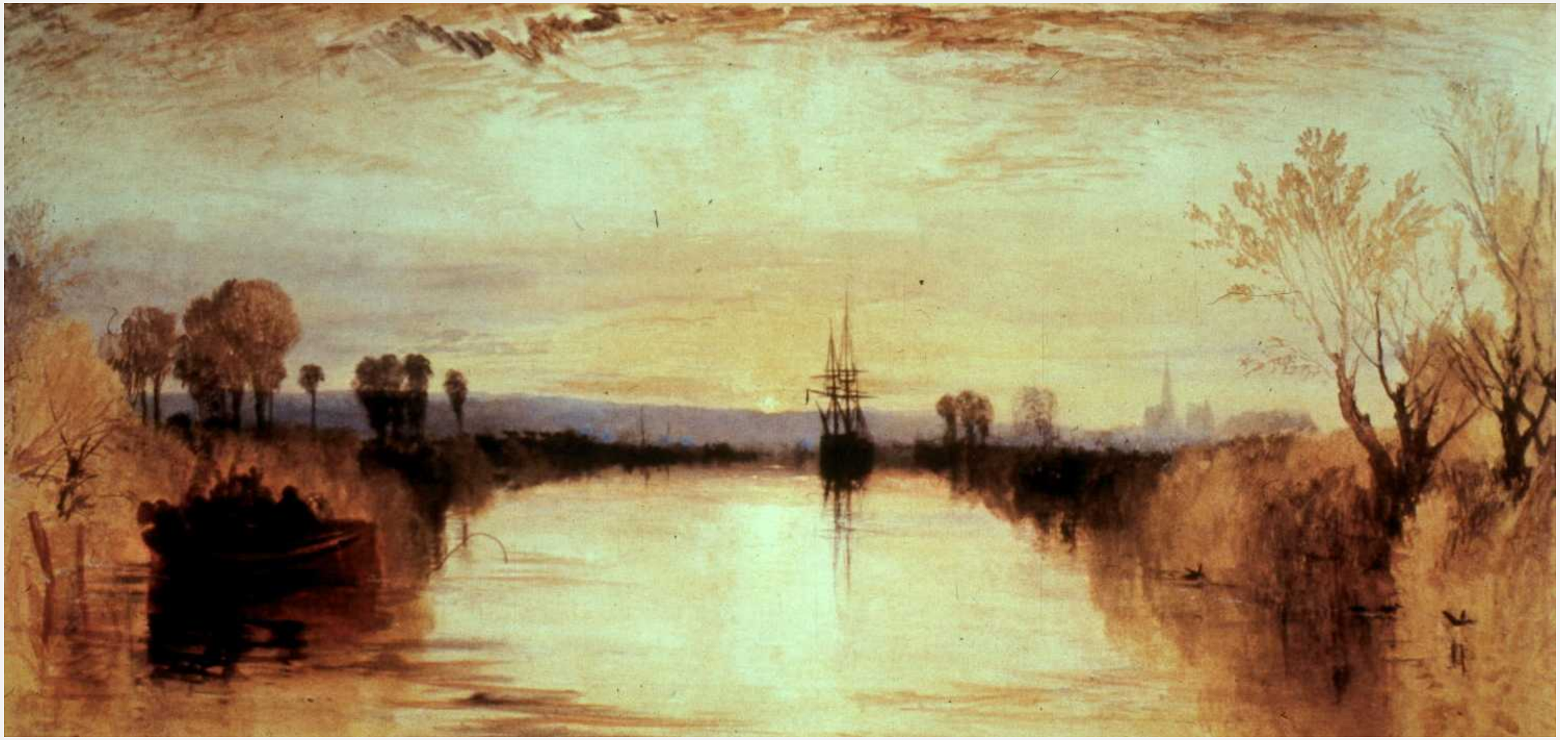


From ice core acidity records and reconstructed temperature records, Hyde and Crowley [2000] estimate a -6.6 W/m^2 radiation change in N. Hemisphere in 1816, and a forcing required to cause this of 75 +/- 40 Tg of sulfate aerosols in agreement with our estimate of ~ 100 Tg

Shindell et al. [2003] estimate that the forcing required to cause temperature change of -1.0 to 1.5° C was 3 x Pinatubo (~ 90 Tg aerosols). Is such a cooling outside range of natural variability ?

Photo: GA Zielinski

Environmental effects in 1816 attributed to Tambora aerosols

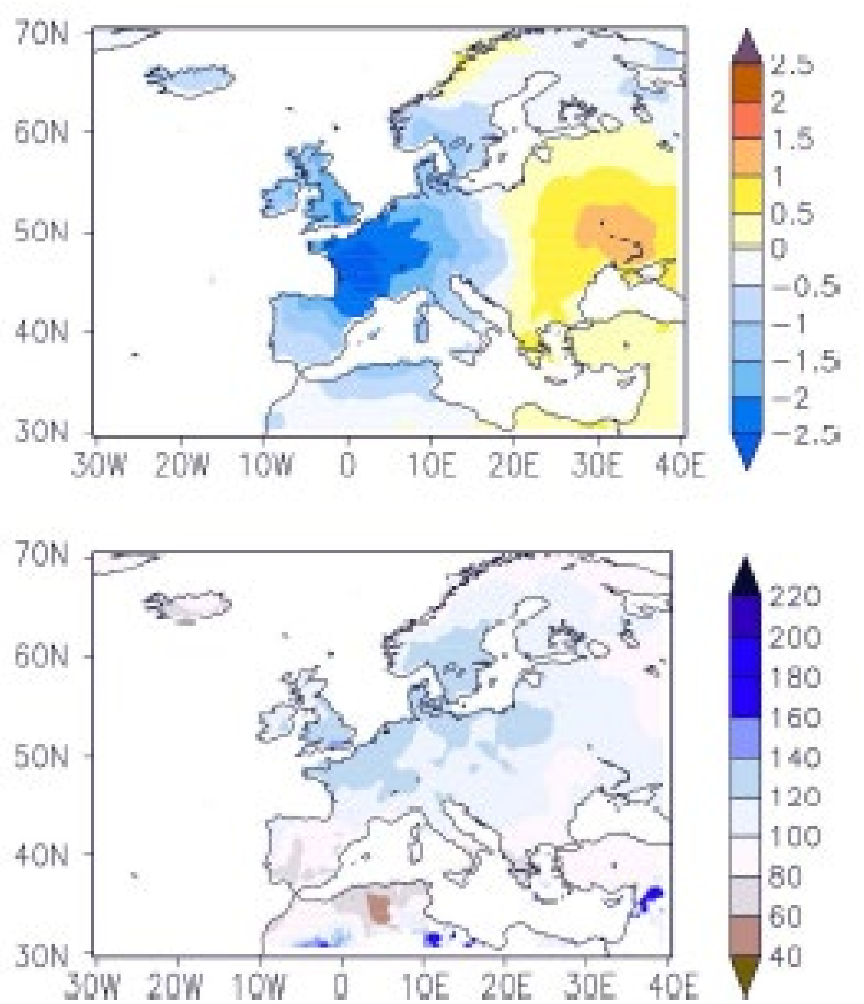


J.M.W. Turner, 1828

- England: London 5 - 8 º C cooler; crop yield down by one-third
  “1800 and froze to death”; >100,000 died
- Ireland: famine led to typhoid epidemic
- Switzerland: food shortages — cats eaten!
- France: food shortages led to “grain insurrections”
- “Year without a summer” in northeastern North America ®
  the great expansion to the western states
- “The last great subsistence crisis of the Western World” (Post, 1985)

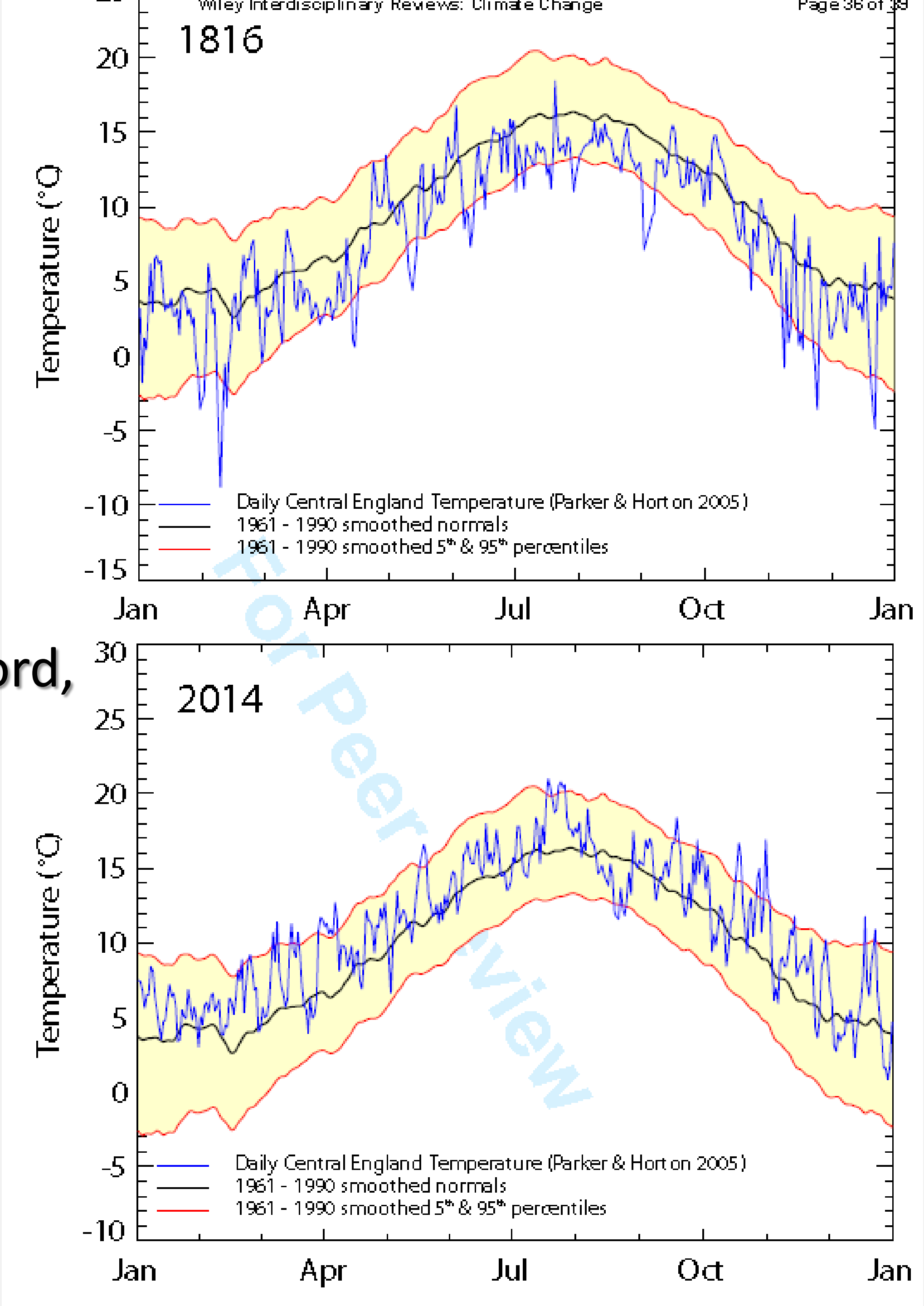
European climate 1816,

instrumental records



(Top): **temperature anomalies (in °C)**, and
(Bottom): **precipitation anomalies (in mm)** for summer 1816 statistically reconstructed using station series only. Temperature and precipitation reconstructions in the outer margins of Europe and the Mediterranean are less certain due to the lack of meteorological station information for those areas. Anomalies are with respect to the mean from 1961-1990.
[Brönnimann et al., 2015, after J. Luterbacher, unpublished.]

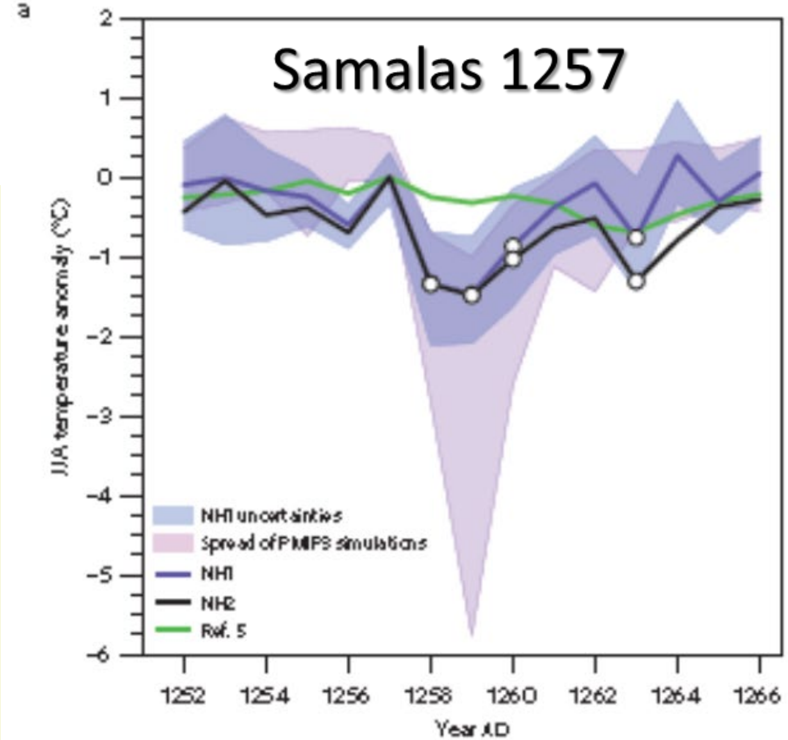
Central England temperature anomalies, instrumental record, 1816 and 2014



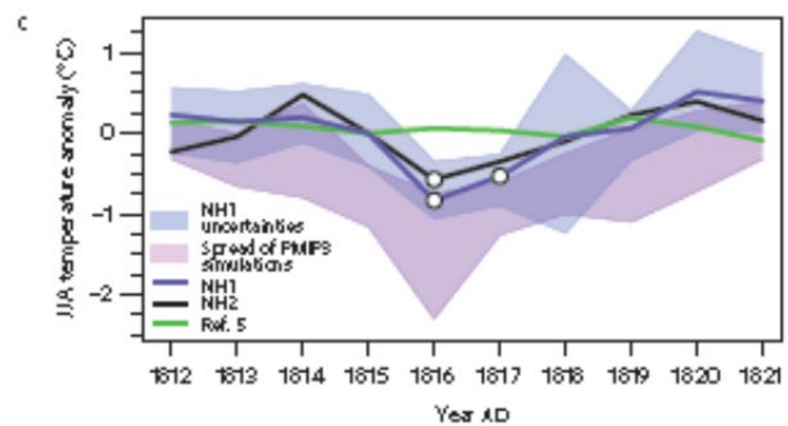
Latest modelling paper on Tambo

Tree-ring reconstructions and climate simulations are in agreement, with a mean Northern Hemisphere extra-tropical summer cooling over land of 0.8 to 1.3 C in 1816 for the eruption of Tambora 1815 (bottom), and in 1258 for Samalas 1257 (top)

[Stoffel et al., Nat Geo, Oct., 2015]



Tambora 1815



Summary on Tambora

Climate models respond to prescribed Tambora-like forcing with *a strengthening of the wintertime stratospheric polar vortex, global cooling and a slow-down of the water cycle, weakening of the summer monsoon circulations, a strengthening of the Atlantic Meridional Overturning Circulation, and a decrease of atmospheric* CO_2.

The 2015 conference also addressed future undertakings of the scientific community to study volcanic effects on climate with a consistent modeling protocol. The VolMIP initiative (Model Intercomparison Project on the climatic response to Volcanic forcing) was started and advertised at the meeting. VolMIP is endorsed by CMIP6, the latest Climate Modeling Intercomparison Project.

SPARC Report – 2015 Tambora meeting [Brönnimann et al., 2015]

Pinatubo 1991

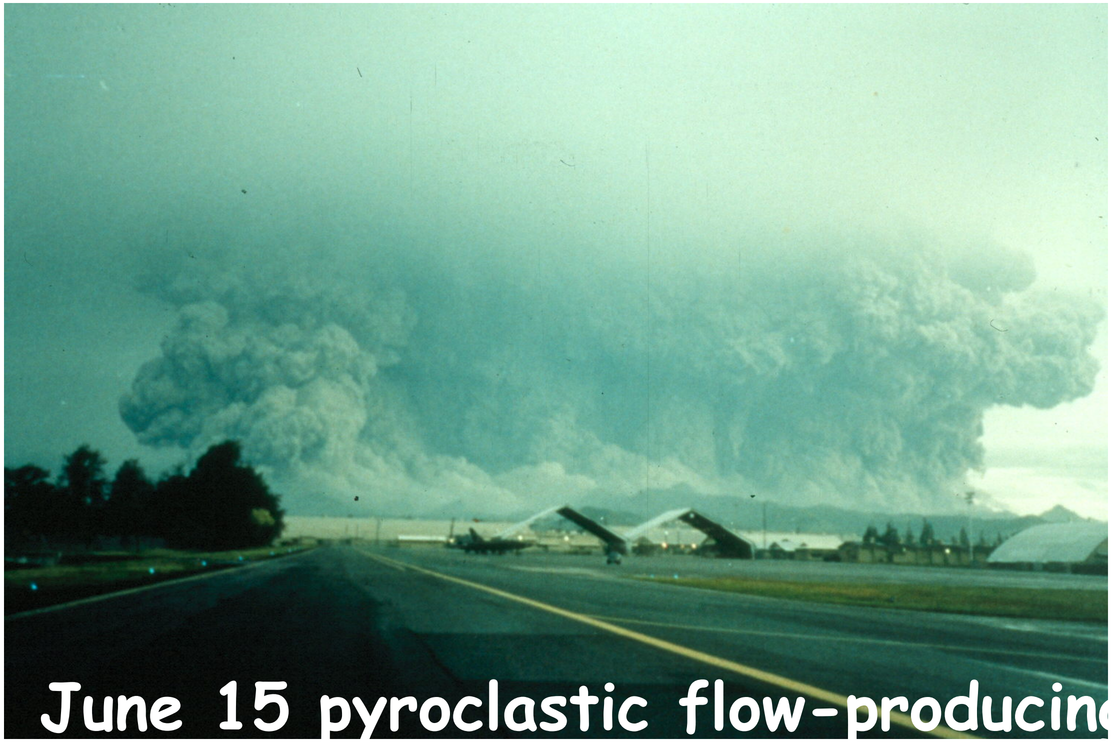
Pinatubo 1991 eruption: a small eruption & caldera

• volume of PFD deposit is well constrained

caldera + “missing” volume = ~ 3.5 km^3 (*cf.* 3.5-5.5 km^3 DRE from the deposits); second biggest eruption of 20thCentury, VEI 5-6, yet we don’t know the volume precisely! What about the bigger ones?

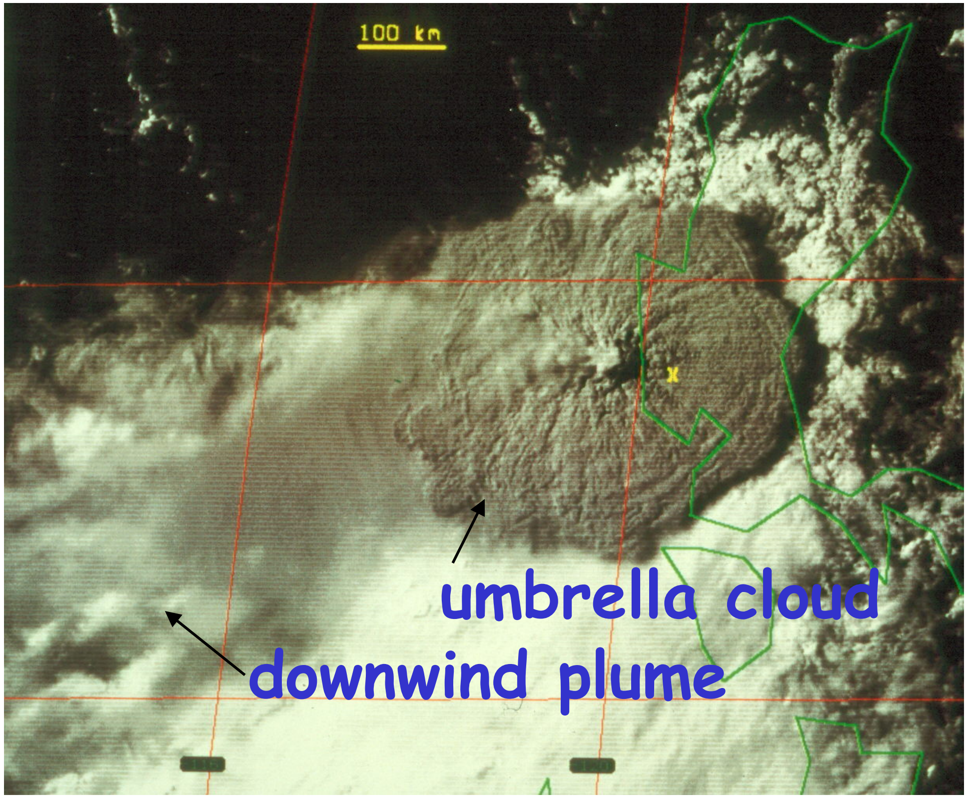
• volume of fall deposits is not

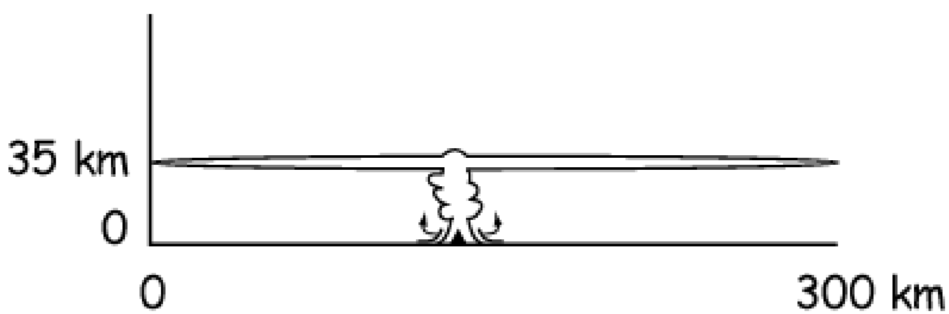
Global effects of Pinatubo 1991 eruption



- Magma volume: 4 km^3 PFD + 1.5 km^3 fall = 5.5 km^3 ($\cong$ 1.2 x 10^{13} kg)
- Mass eruption rate: $\cong$ 8 x 10^8 kg^3 s^{-1} (3.5 hr)
- Dacite magma; highly oxidizing; excess sulfur*

Pinatubo eruption cloud and gas injection





Height of eruption cloud ≅ 35 km; main disc spreads at 23-28 km

Is this essentially a co-ignimbrite cloud - and why does it matter?

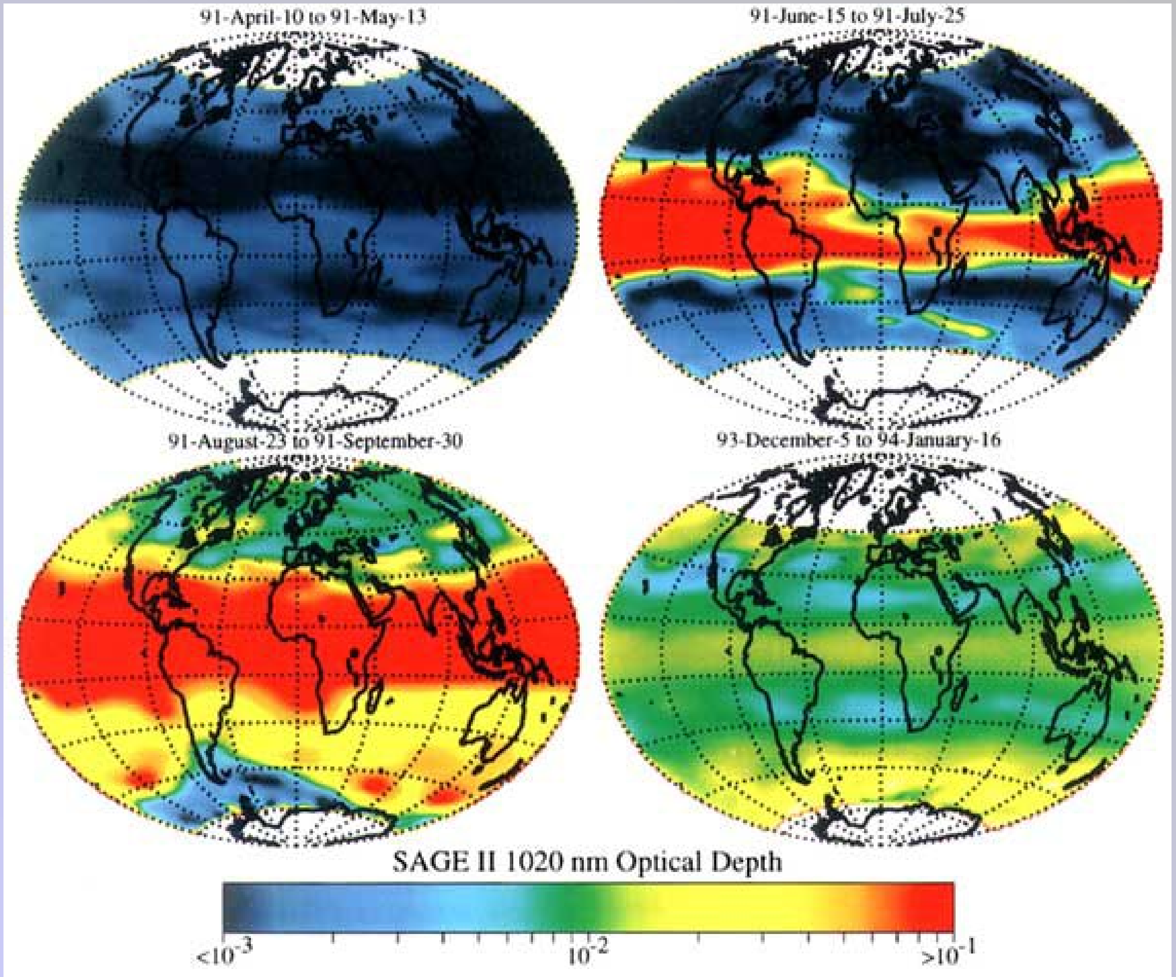
If it is, then 2520 Tg tropospheric H_2O also injected, *cf.* w/ 540 Mt if the eruption column was Plinian

Extra $H_2O \rightarrow$ more efficient S gas-aerosol conversion in stratosphere

- synchronous column collapse and Plinian column [Scott et al. 1996]
- co-ignimbrite ash recycled into umbrella cloud
- high column due to this fact, ? *cf.* Toba (YTT)

Pinatubo caldera, 2000, IAVCEI field

Widespread effects from Pinatubo aerosol clouds



Pinatubo's eruption in 1991 released ~ 18 Tg of sulfur dioxide (SO_2) gas [1 Tg = 1 x 10^{12} g], which generated about 30 Tg of aerosols

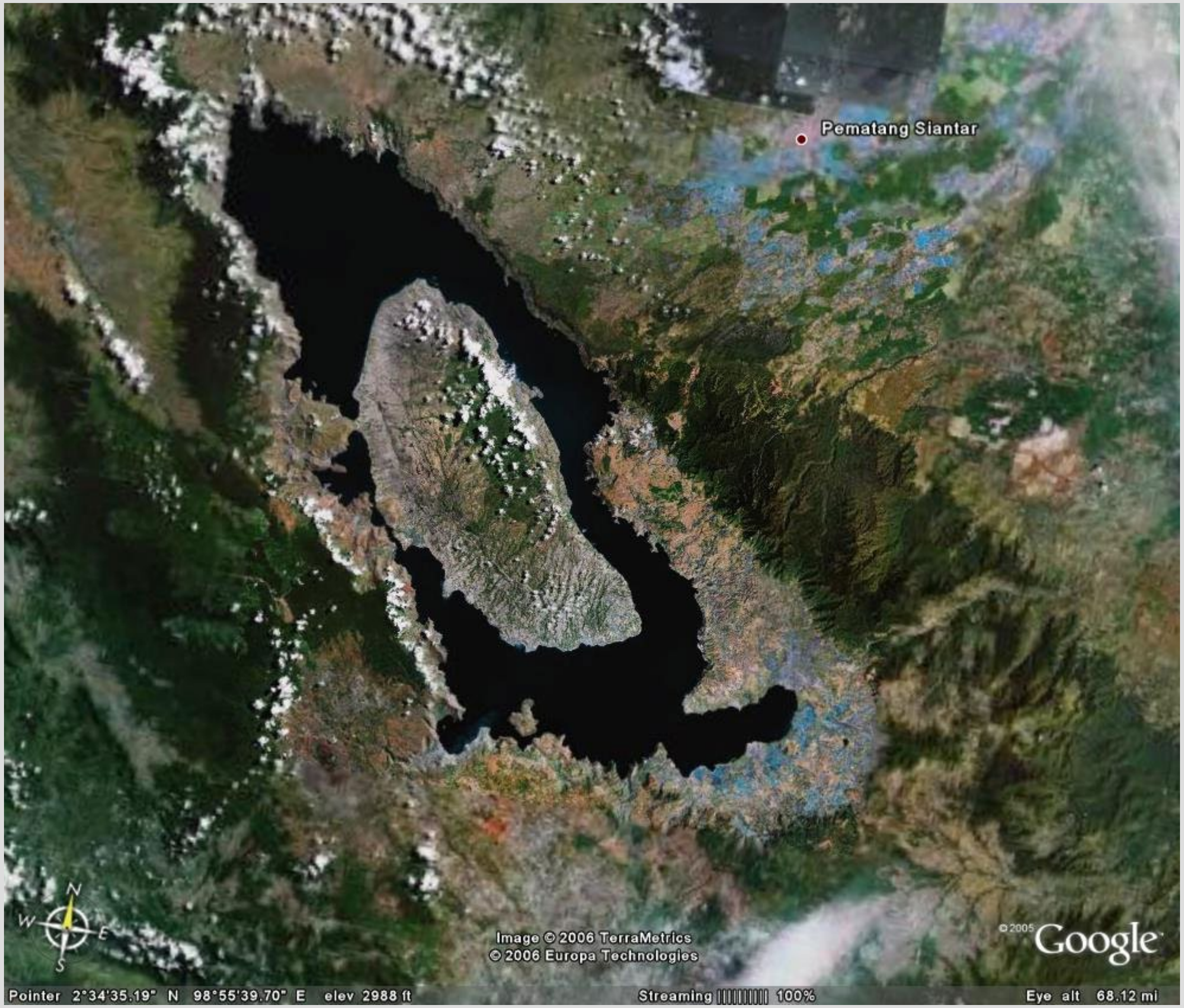
The post-Pinatubo aerosol cloud (~ 30 Tg) cooled Earth's surface temperature by 0.5 C and halted global warming for 2-3 years

Pinatubo aerosol cloud photographed from Space Shuttle (NASA)

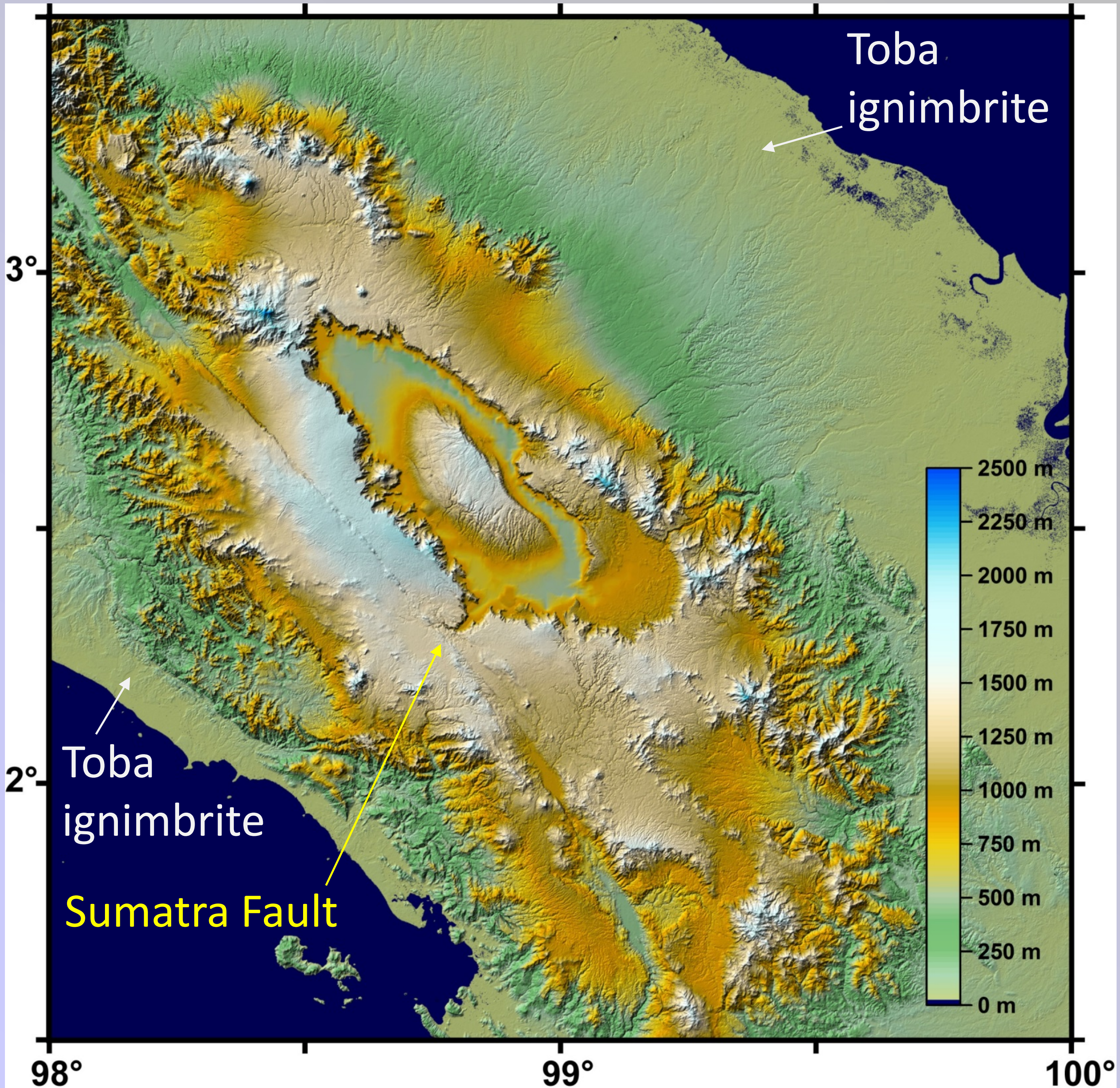
Toba, 73.98 ka ago

Largest super-eruption (Mag 8-9) is Toba (Young Toba Tuff, YTT), Sumatera

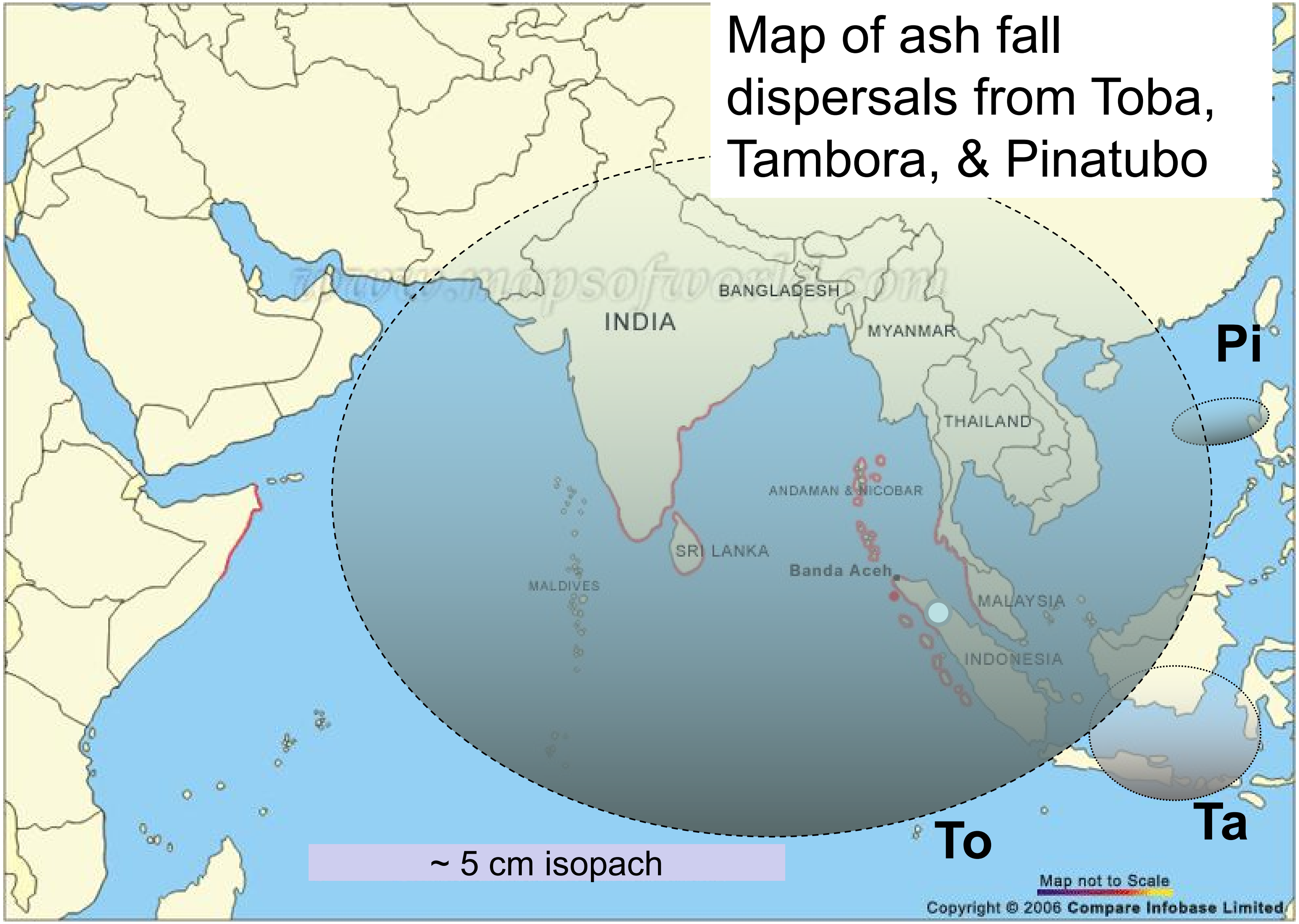
- Complex caldera
- 3 major eruptions; YTT is youngest at 74,000 ka
- Size is > 100 km x 40 km

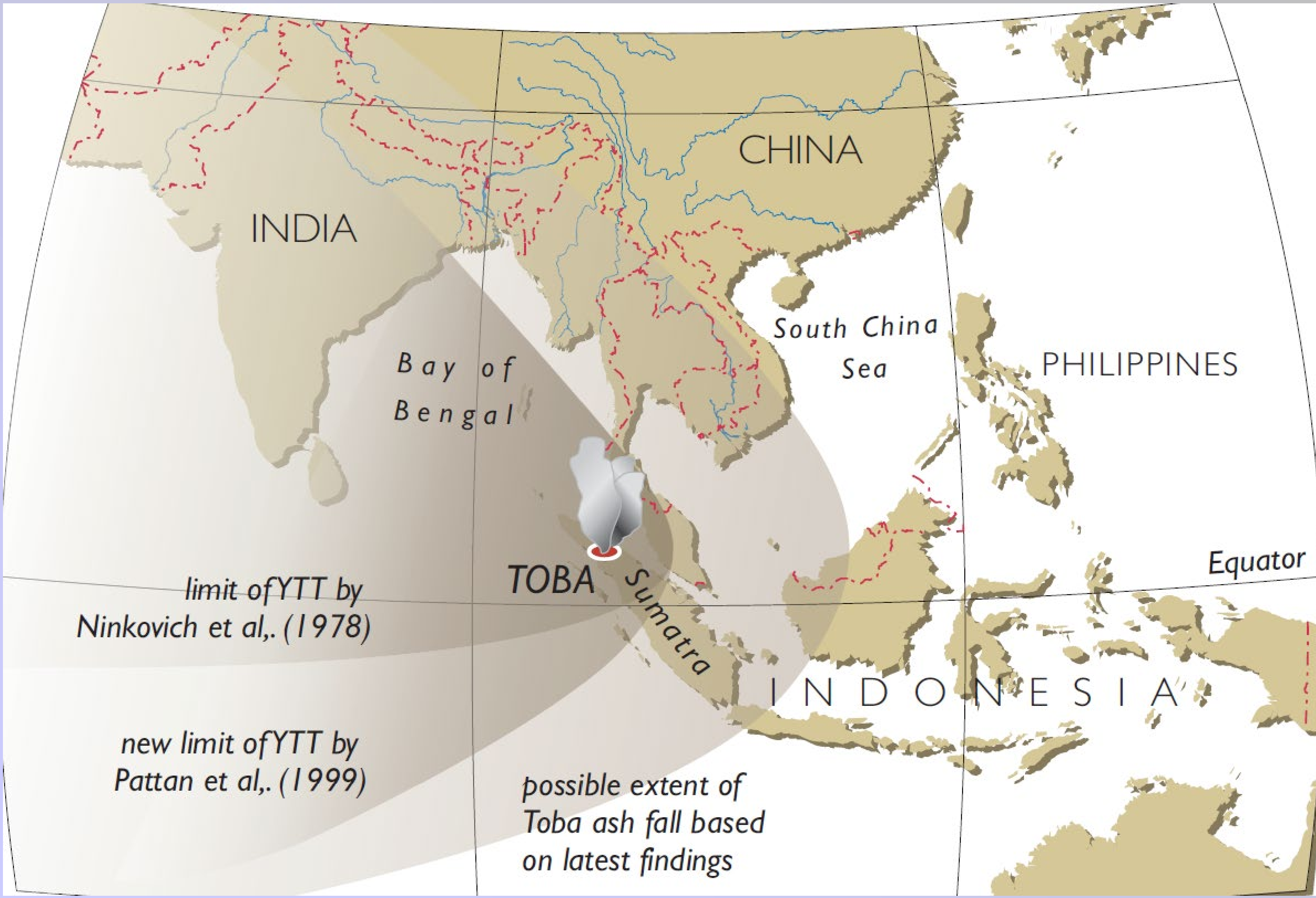


Toba, DEM from NASA Shuttle radar data, courtesy of C. Chesner

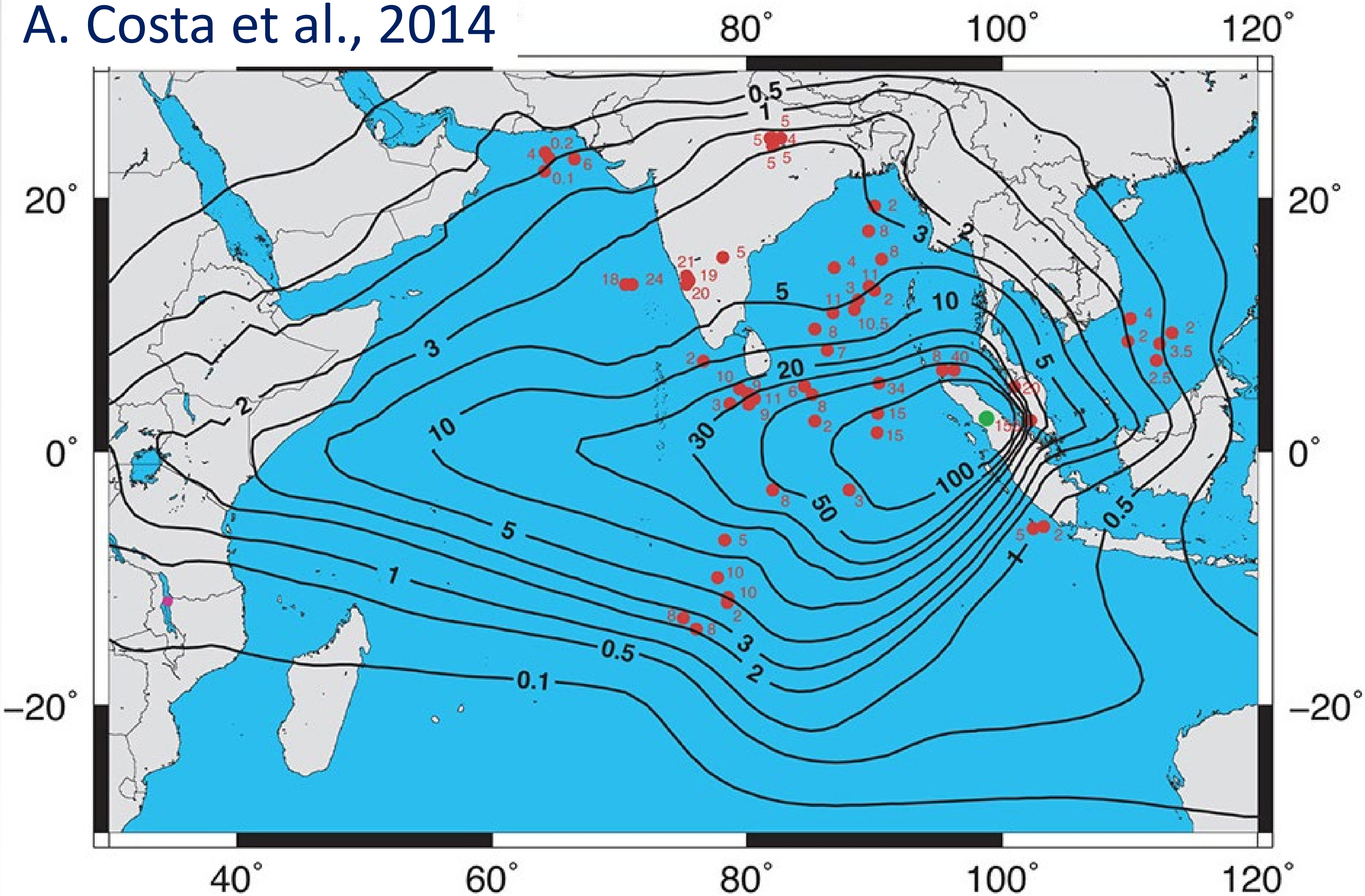


Size of super-eruptions, To = YTT




CHINA
INDIA
Bay of Bengal
South China Sea
PHILIPPINES
Equator
TOBA
Sumatra
INDONESIA
limit of YTT by Ninkovich et al,. (1978)
new limit of YTT by Pattan et al,. (1999)
possible extent of Toba ash fall based on latest findings

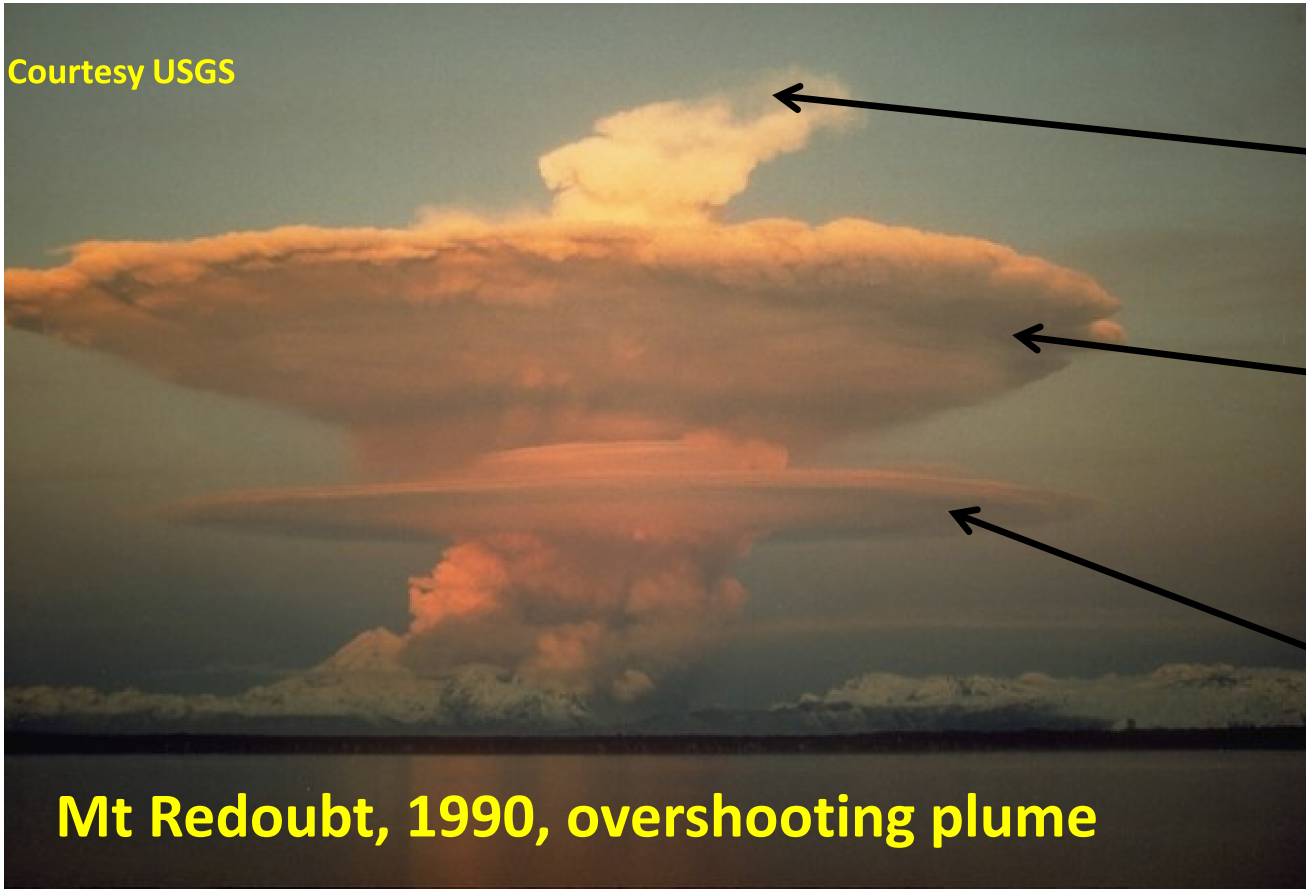
A. Costa et al., 2014



Toba ash re-calculated with various wind dispersal models – best fit for the ash fall alone totals 3800 km^3 DRE; with ignimbrite at 1,500 km^3 = **5,300 km^3**

Fits with occurrence of Toba ash in Lake Malawi (E Africa) and now on South Coast of S Africa (both papers in Nature, 2018). The volume is growing! No proper estimate is too small!

Neutral buoyancy height vs. maximum height



Maximum height

Neutral buoyancy height Plinian

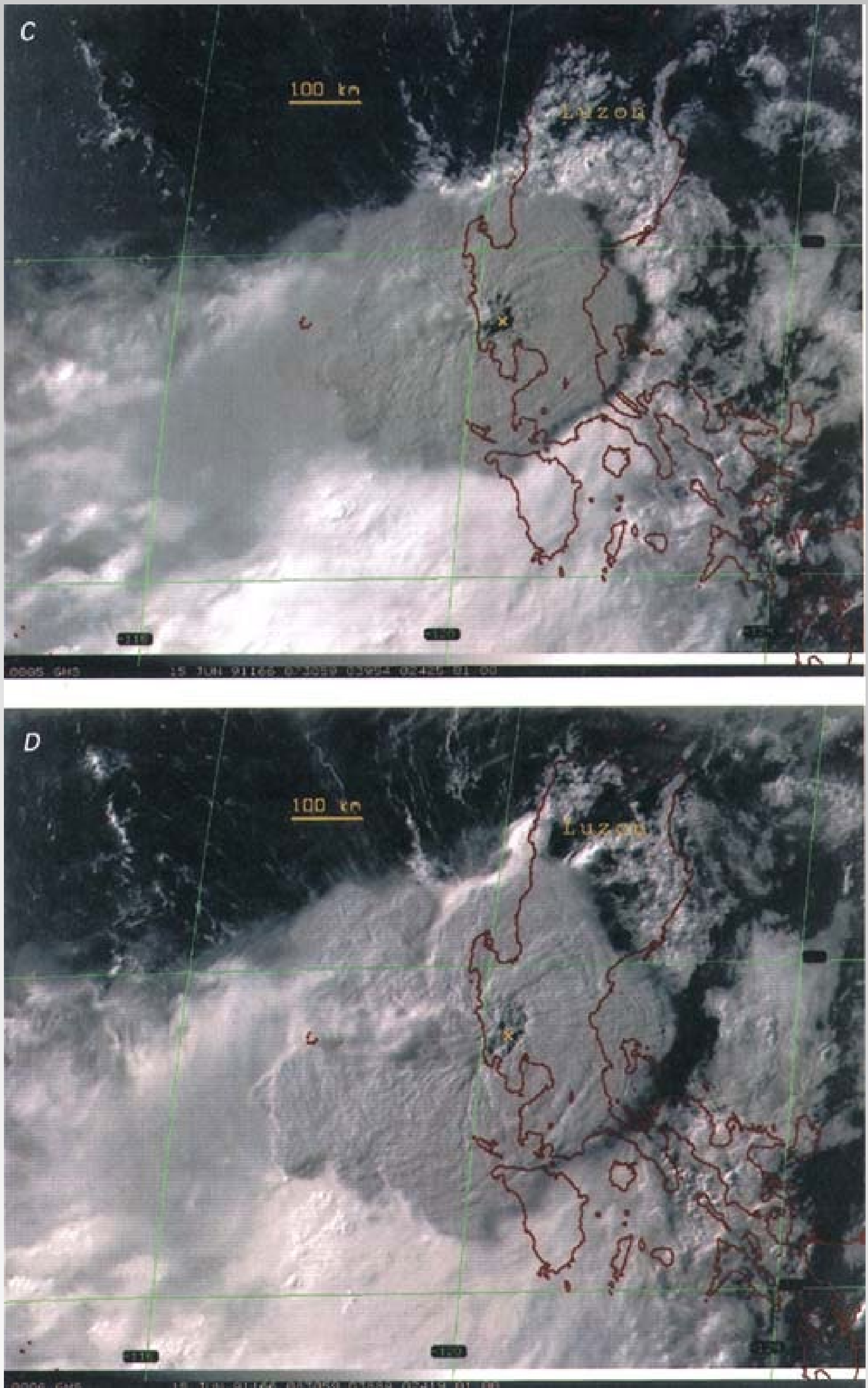
NBH of co-ign (phoenix) cloud

Quite often it seems that maximum heights are reported, but the main injection level is NBH. Overshooting means that the vertical momentum is big enough that the NBH is exceeded, but most of the material will fall back from maximum height to NBH, forcing the spread of the umbrella.

Growth of Pinatubo umbrella cloud

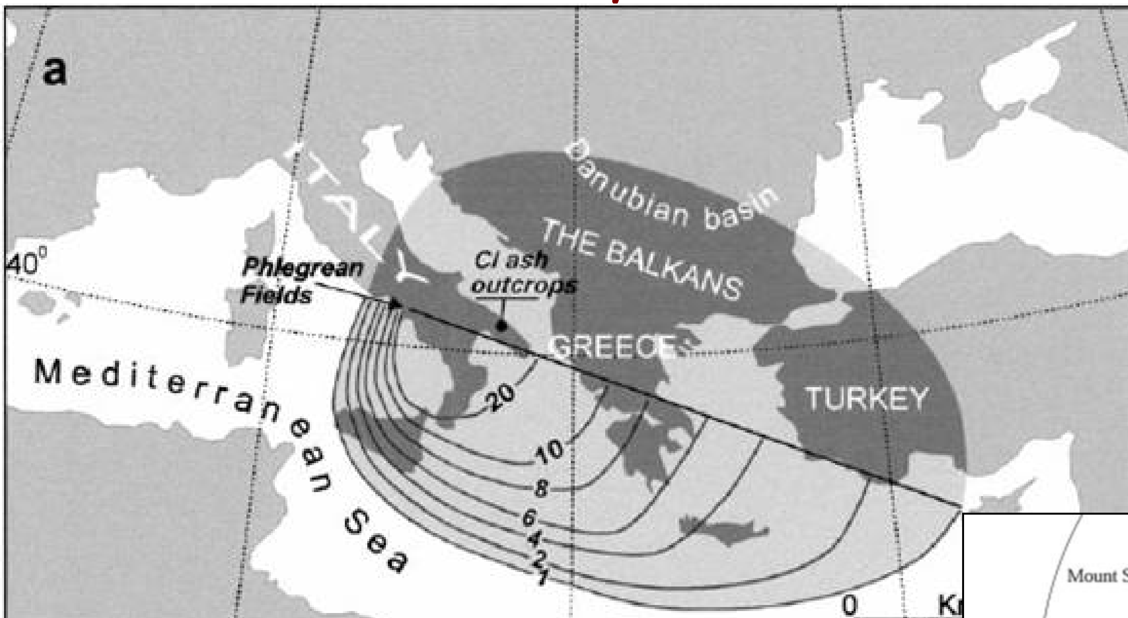
The best place to watch
an eruption from ...
a satellite or space station!

A Toba-scale cloud would spread from the NBH, and gain size very quickly? Pinatubo got to 1000 km diameter in 3 hrs!



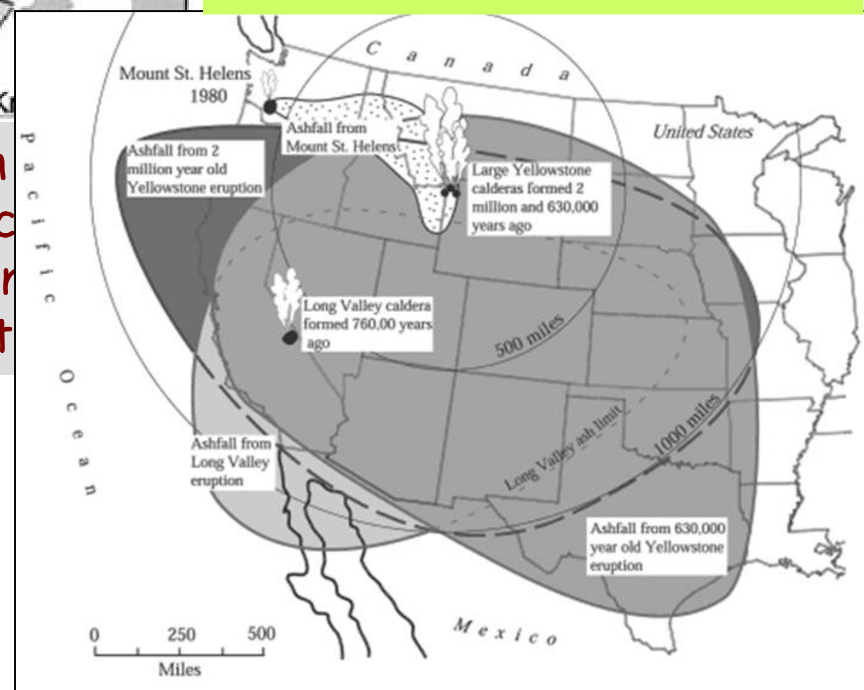
Mount St Helens blast umbrella cloud, – 29 km
in 4 mins! May 18, 1980; tracked by radar and other
methods.

Other large ash fall deposits [accumulate in a few hours to days]



Ash fall blanket from Campanian eruption
200-300 km^3; lines of equal thickness in c
Fedele et al., 2002). Areas receiving ever
ash would be severely affected by fallout

Yellowstone ash falls

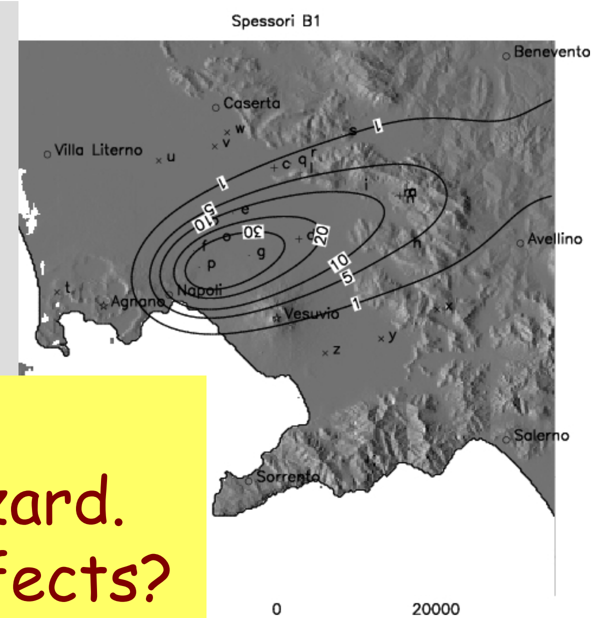


The amount of ash fall would be sufficient to cover the area of California with a layer 1.25 m (> 4 ft) thick!

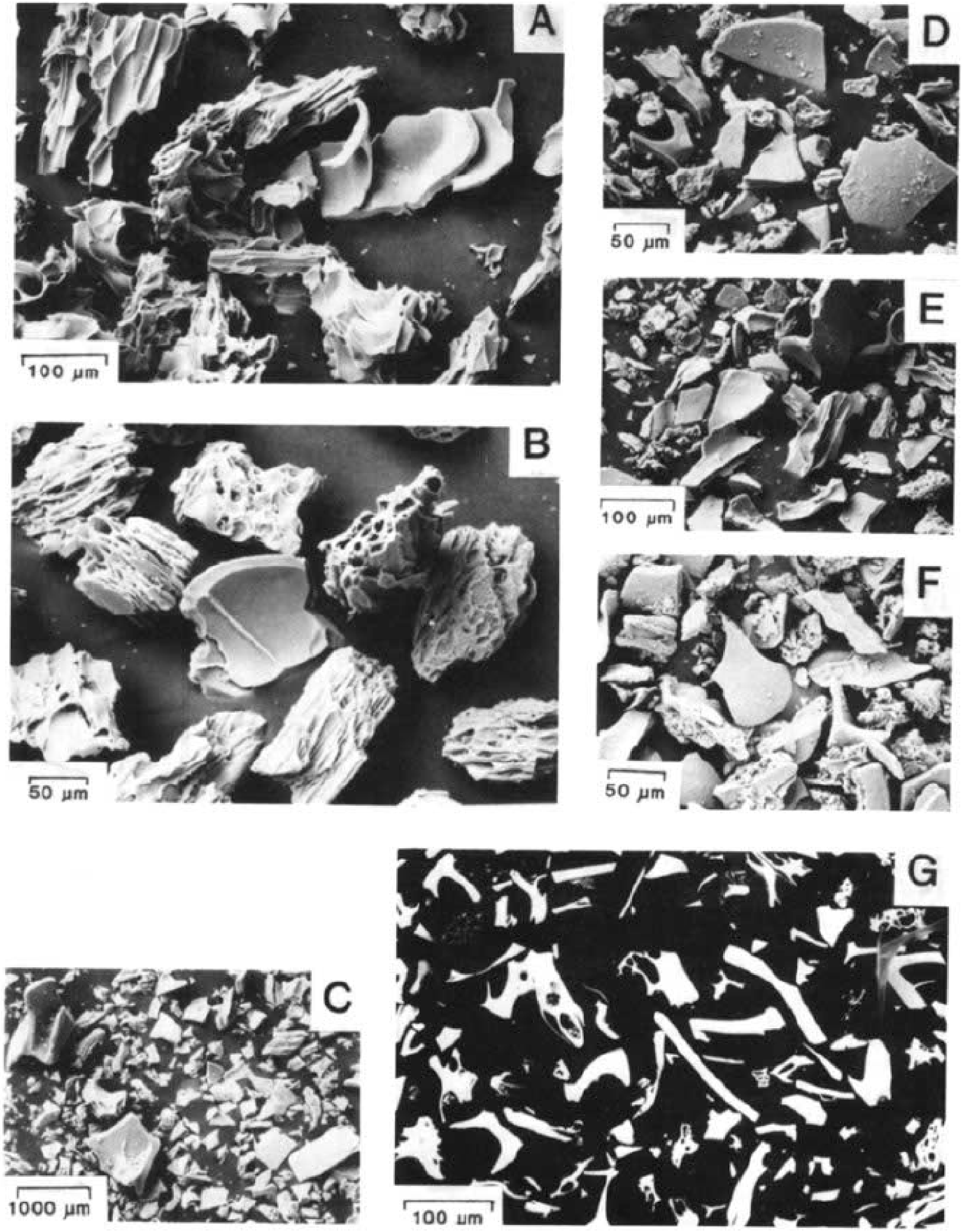
Ash fallout!

after Pinatubo, ~ 3 cm of ash

Volcanologists are developing better predictive models for ash fall, such as this one for an eruption from Campi Flegrei



Airborne ash is an aircraft hazard;
on the ground it's a respiratory health hazard.
Ash on sea surface may have profound effects?



Rose and Chesner

GEOLOGY, October 1987

Distal Toba ash from deep sea cores (C-F)

Figure 3. SEM photomicrographs of Toba materials. A, B: Crushed pumice from Toba ignimbrite samples T63A1 and T97A2, respectively. C–F: Distal ashes from Toba in order of increasing distance. C is upper fine layer and D is basal coarse layer of core RC17-145, about 500 km from Toba. E is sample RC17-128, 2000 km away; F is sample S-44, 3100 km away. G: Polished mount of sample RC17-128 showing view analyzed by image processor.

YTT ash effects – what might they be?

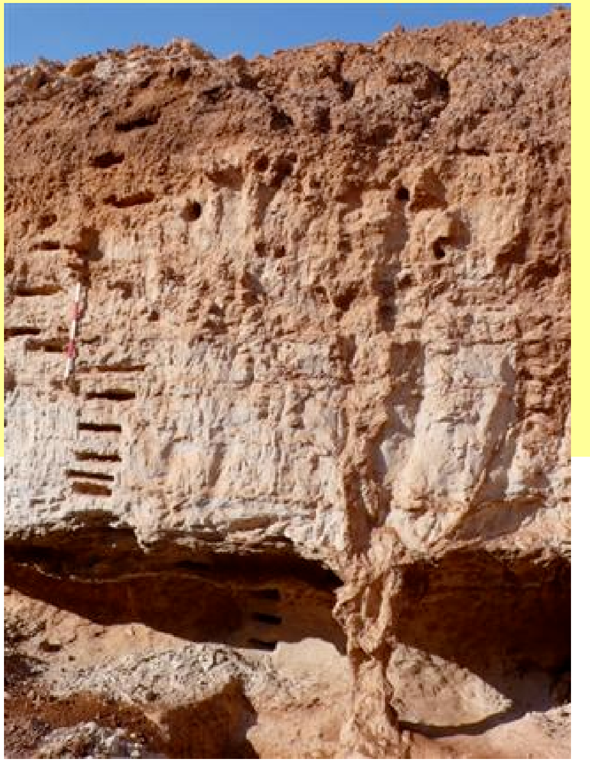
Toba ash (and aerosol) effects

Two opinions: Williams et al. [2008, 2010] – considerable effect on vegetation (palynology); Ambrose et al. [several papers] – "bottleneck" in numbers of early humans (genetics)

Petraglia et al. [2008] no effect on early humans living in India, based on stone tools (anthropology)

These studies suffer from a "cause-and-effect timing" issue

We must question how well we understand the impacts of Toba. Such super-eruptions are so rare that society should be more concerned about smaller ones (M7)

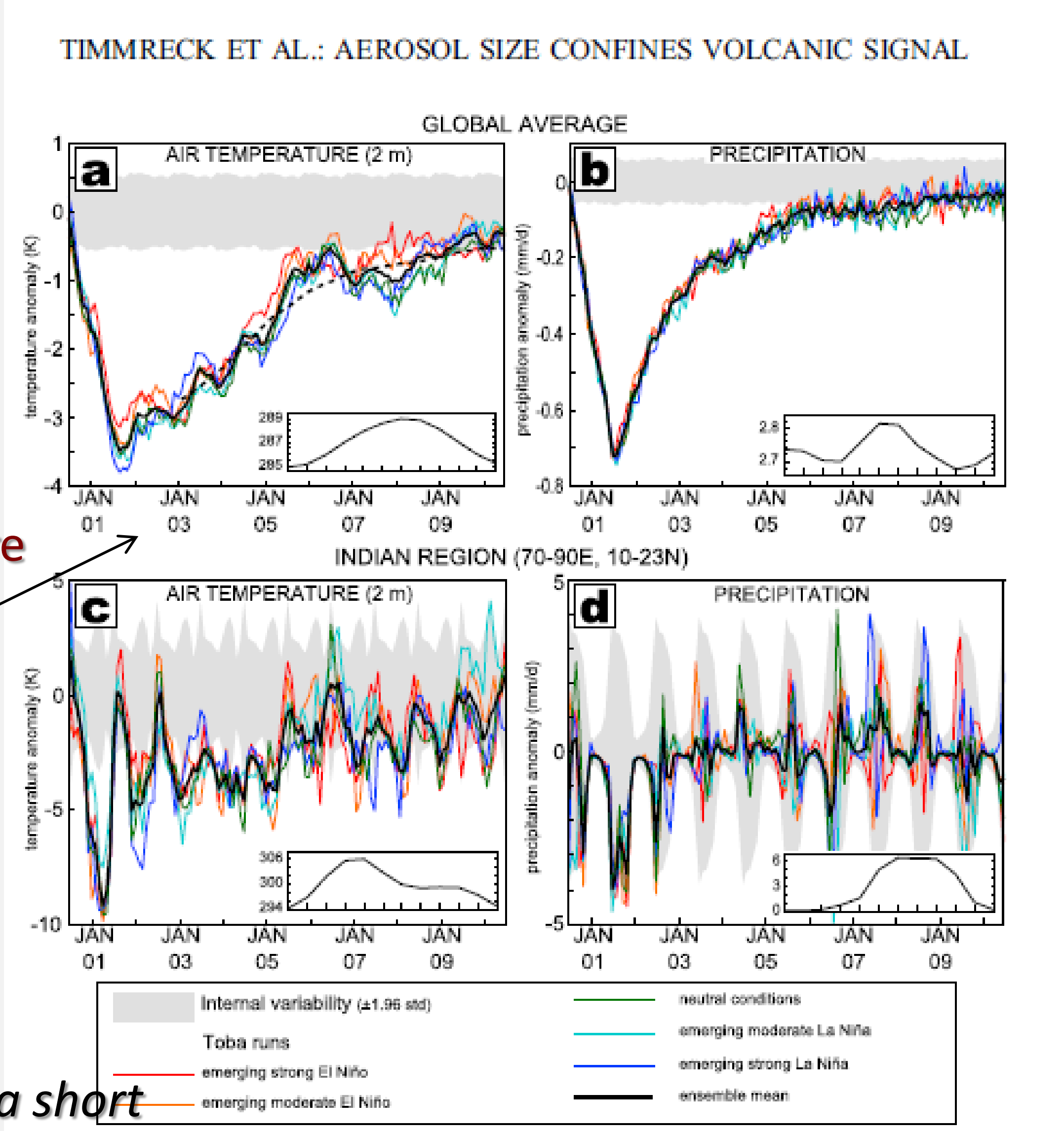


Toba ash in India – no details!

Limited climatic impact of large volcanic aerosol masses

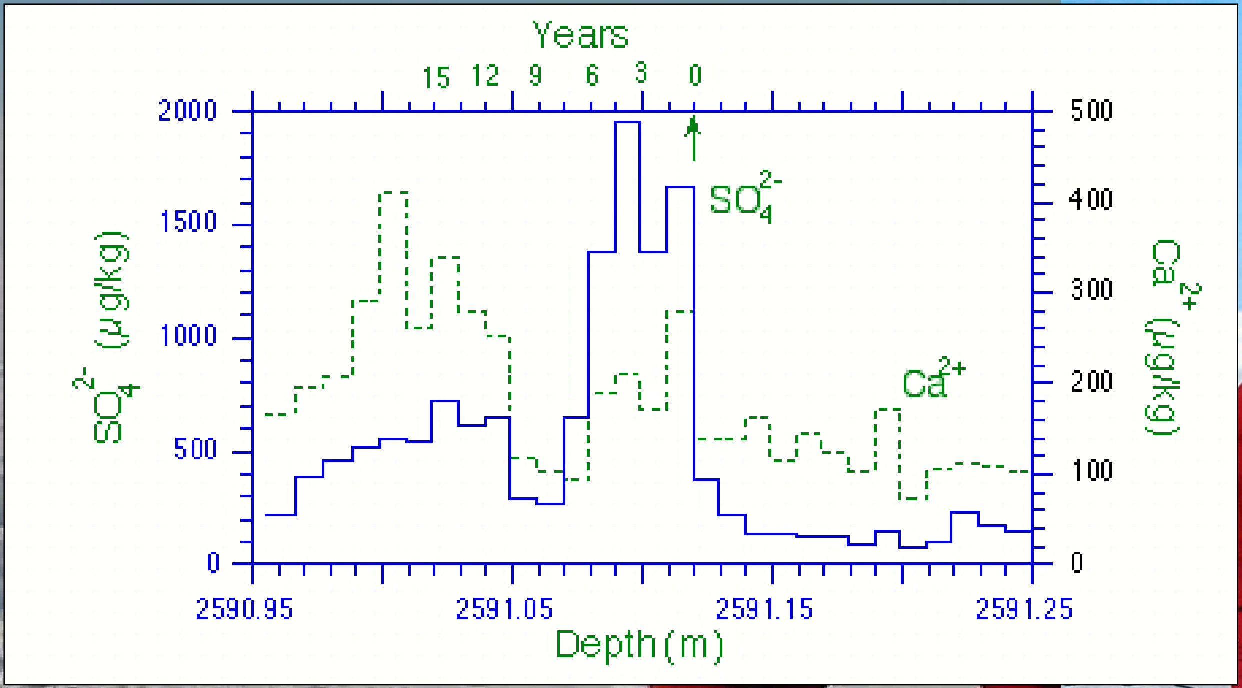
Samalas (Unknown) eruption, AD 1257: temp. response less than expected from huge "sulfate acidity spike" in ice core [Timmreck et al., 2009]

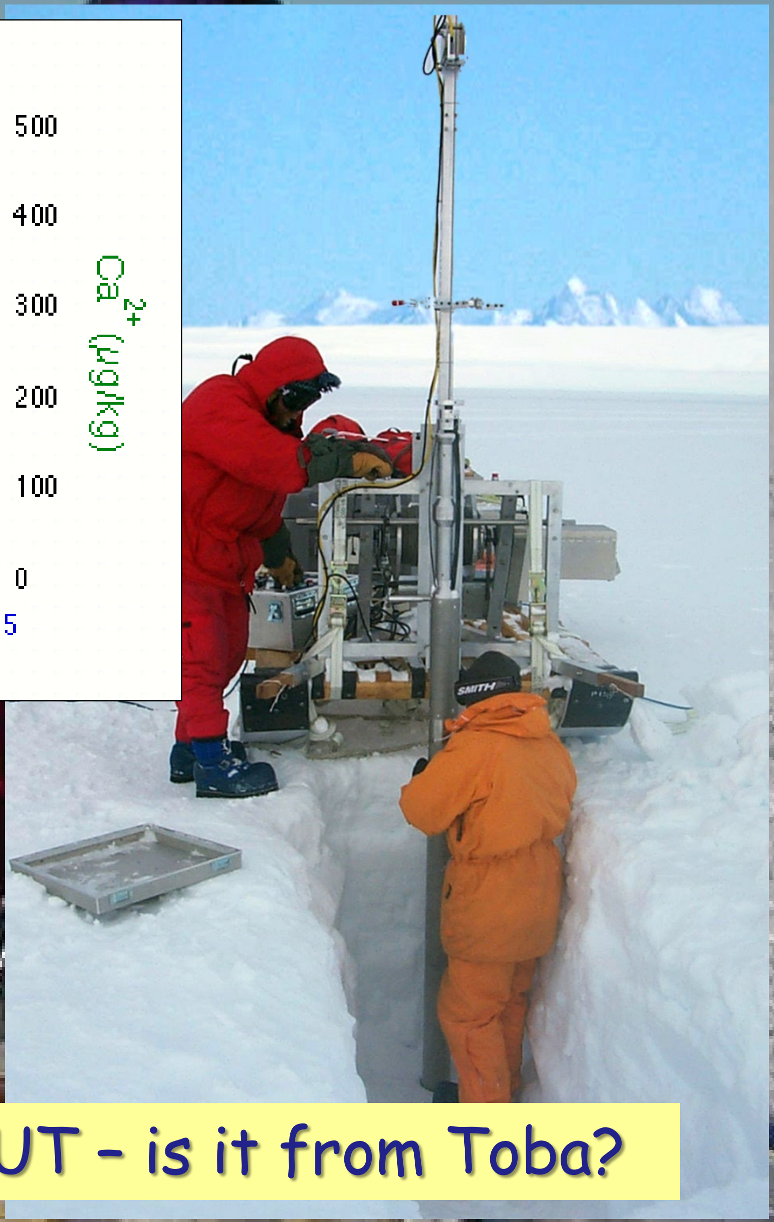
Expected **climatic response from super-eruptions** (*if they release S*) would be muted [Timmreck et al., 2010; for 100 x Pinatubo SO_2 case]



Tambora's ~ 60 Tg SO_2, formed from a short paroxsysmal burst, could still cause optical depths of 1-2 and give the range of observed and modelled global cooling.

The Toba ice-core record? (Zielinski, 1997)

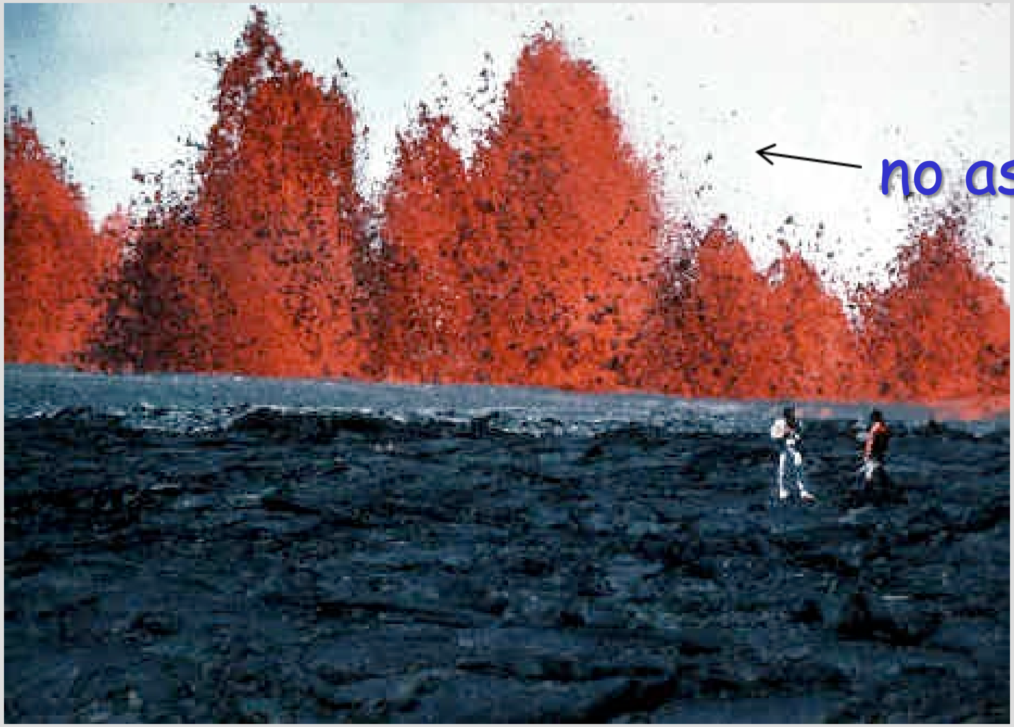




Ice core peak is 71,000 yrs old, BUT – is it from Toba?

Basaltic eruptions

Gas release from basaltic eruptions



no ash

much ash

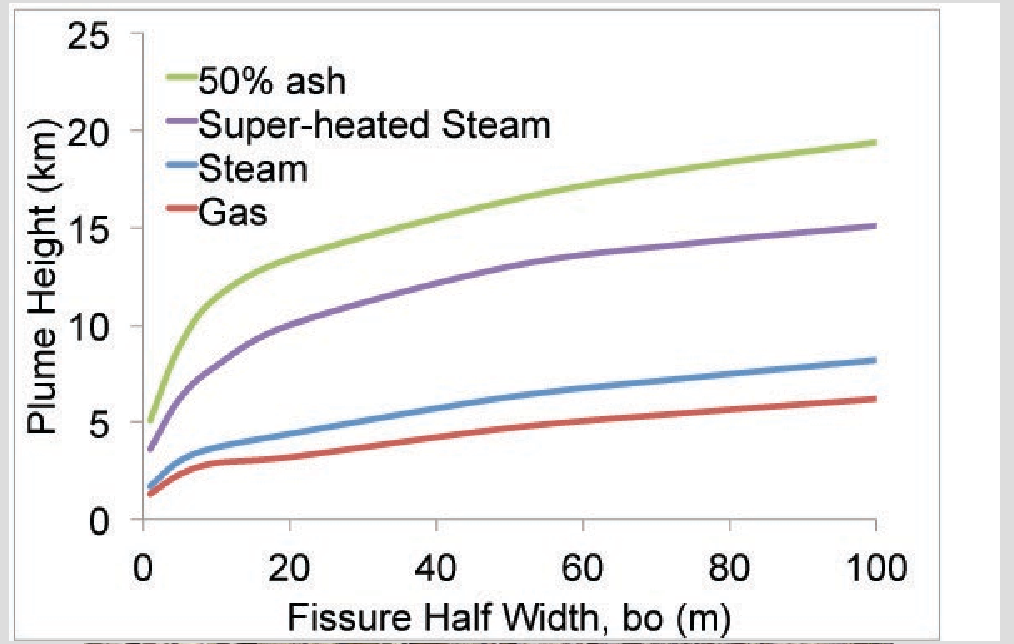
Many basaltic eruptions produce ash – difficult to find in flood basalt provinces, but is there in CFB provinces in minor amounts. Many locations examined are far from source vents; ash dispersal also dependent on wind directions, thus it's rare.

Plumes above lava curtains

- "Ash-poor" plumes have H_2O + CO_2 + SO_2 + other gases
- Increasing temperature can drive buoyancy
- **Inclusion of dilute ash increases plume height** (solids have higher specific heat)
- Evidence for ash deposits

around flood basalt vents is slim but they exist; example from Roza lava, ~ 2 km from axis of fissure (CRB)

[Glaze et al., 2015}



Summary of knowledge on S emissions from basaltic flood volcanism

- Basalts have relatively high S concentration*!

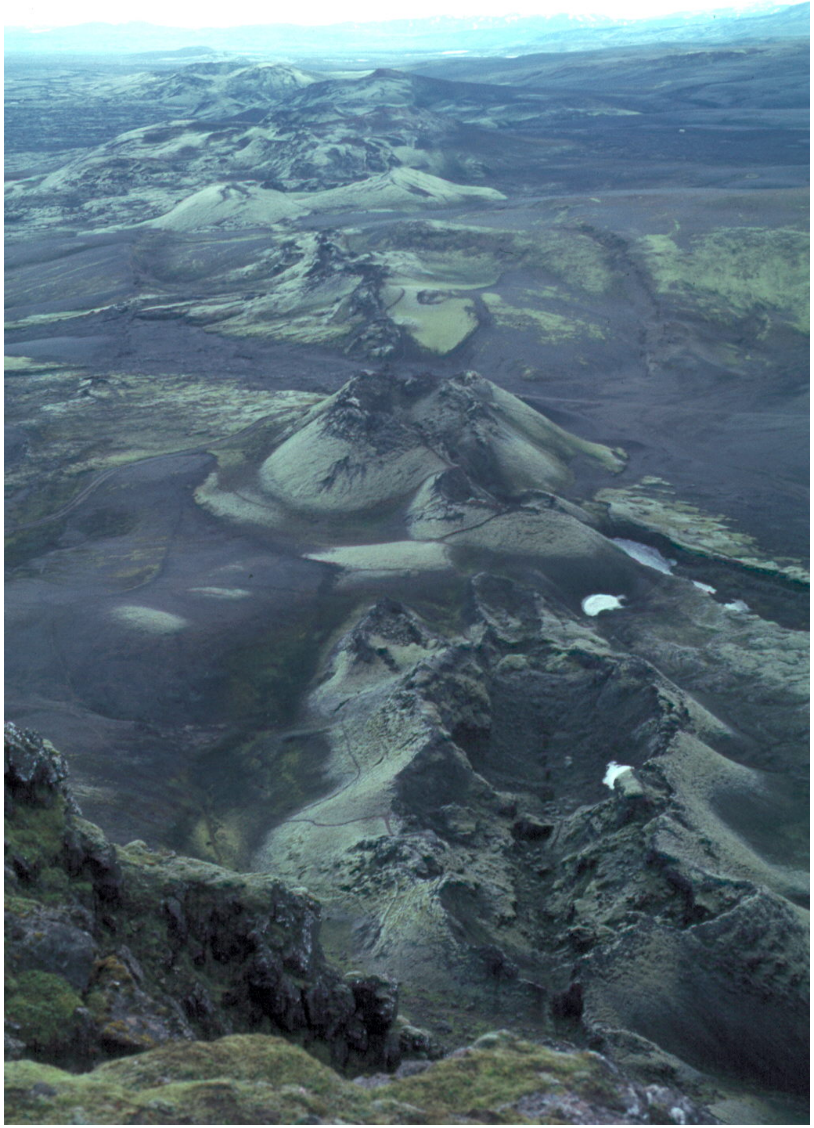
- Studies from Iceland, CRB, Deccan, Siberian Traps suggest typical eruptions yielded from ~ 3,000 – 10,000 Mt (Tg) SO_2

- Yield per km^3 of magma of 3-10 Mt SO_2; release rates from a few to 10s of Mt per year likely, dependent on magma output rate

- Historic flood eruptions had similar emissions – Laki, Lanzarote

[Thordarson & Self, 1996; Self et al., 2008; Blake et al. 2010; Black et al. 2012; Davis, Wolff & Rowe – up to 1900 ppm S in main-phase CRB eruptions [Geology, 2018]

Laki eruption, 1783-84: capability from Iceland ~ M 6.8

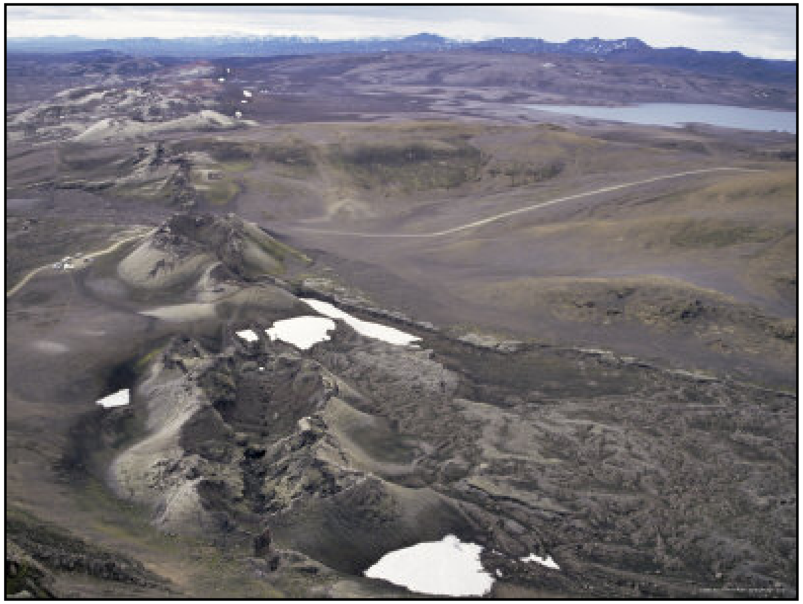


Laki fissure and craters

- Volume of magma: 15 km^3 (M 6.6) (***incls. 0.5 km^3 ash fall deposit***)
- Duration: 8 months; **peak in first 3 months (June – Aug.)**
- Eruption rate: 3 x 10^3 m^3/s (8.3 x 10^6 kg/s) for 44 days
- Eruption column heights: 13 km (max); 7-9 km (mean)

Fire-fountain > 1 km high, Izu-Oshima, 1986

Lanzarote 1730-36 fissure eruption smaller (M > 6.3) but similar effects



Laki eruption (1783): only 4-5 km length of 23 km-long fissure was active at any one time

Plume above Pu'u O'o vent, 1986

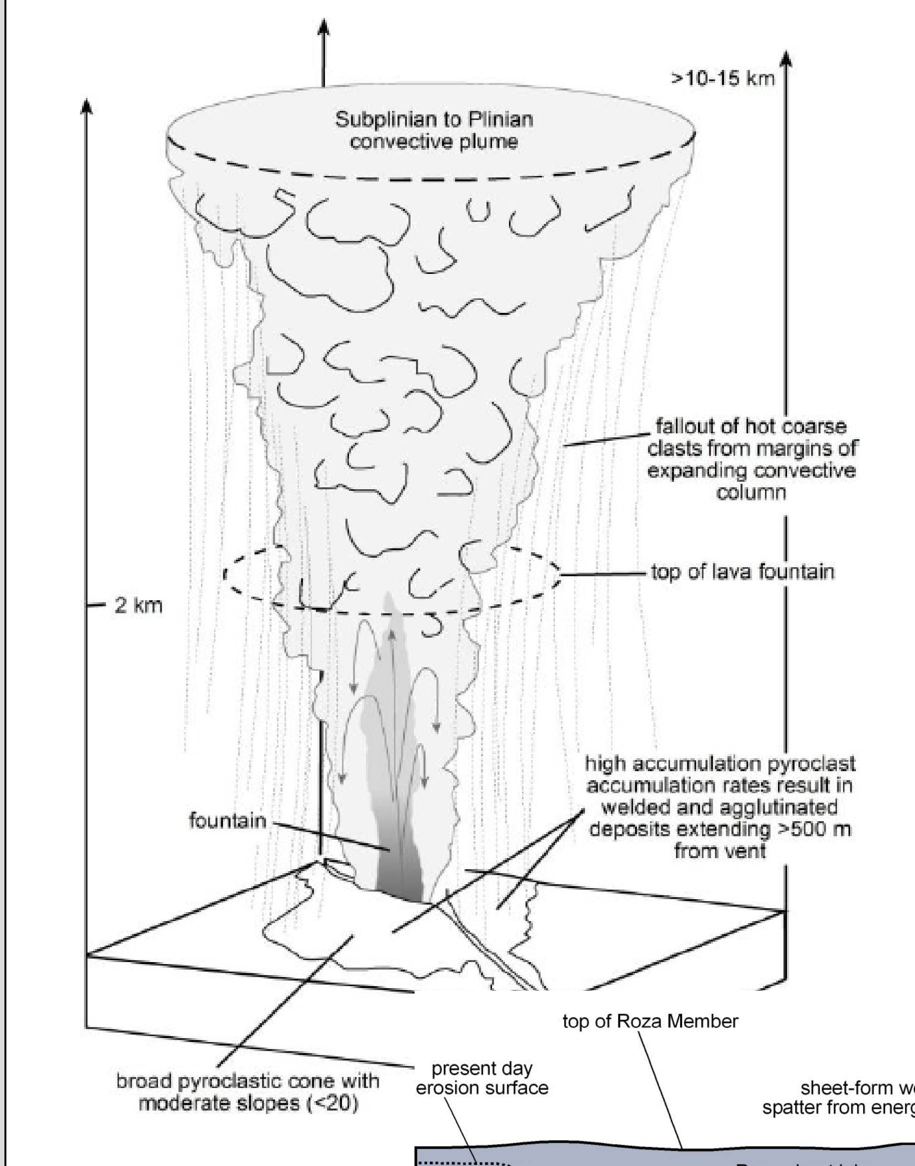
Plume/column height depends on:

- Eruption rate (MOR) → vent size & velocity
- Magma volatile content (composition and wt%) & temp
- Ambient atmosphere density (function of T and P)
- Amount of ash (may reflect local environmental condits)

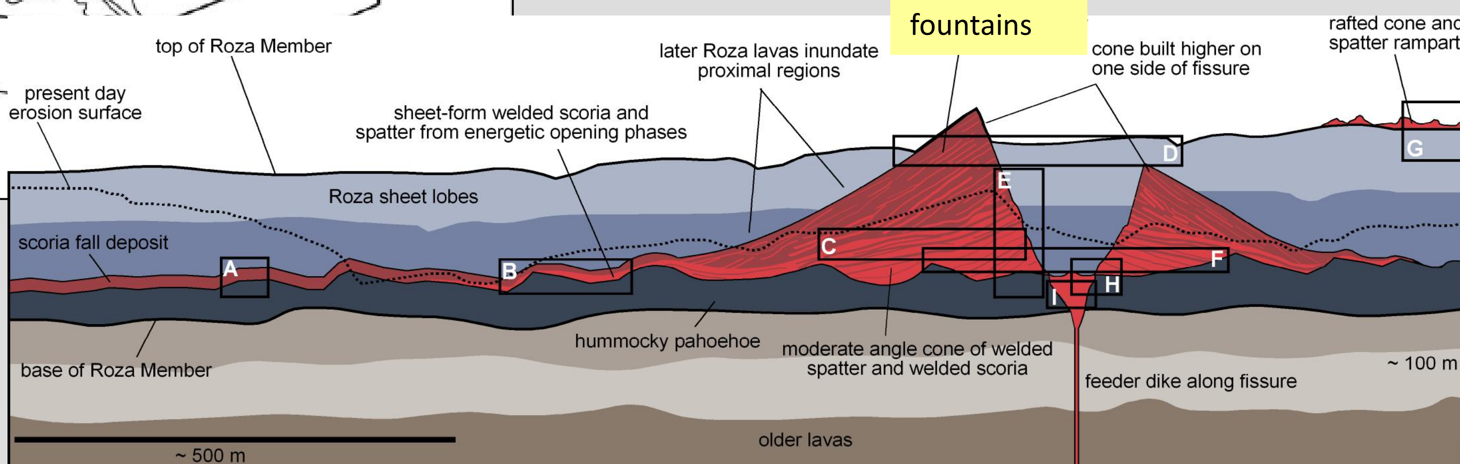
Basaltic vent deposits and eruption columns

Based on study of Roza vent system, CRB

- No question that plumes can reach stratosphere sometimes during FB eruptions; often in upper troposphere.

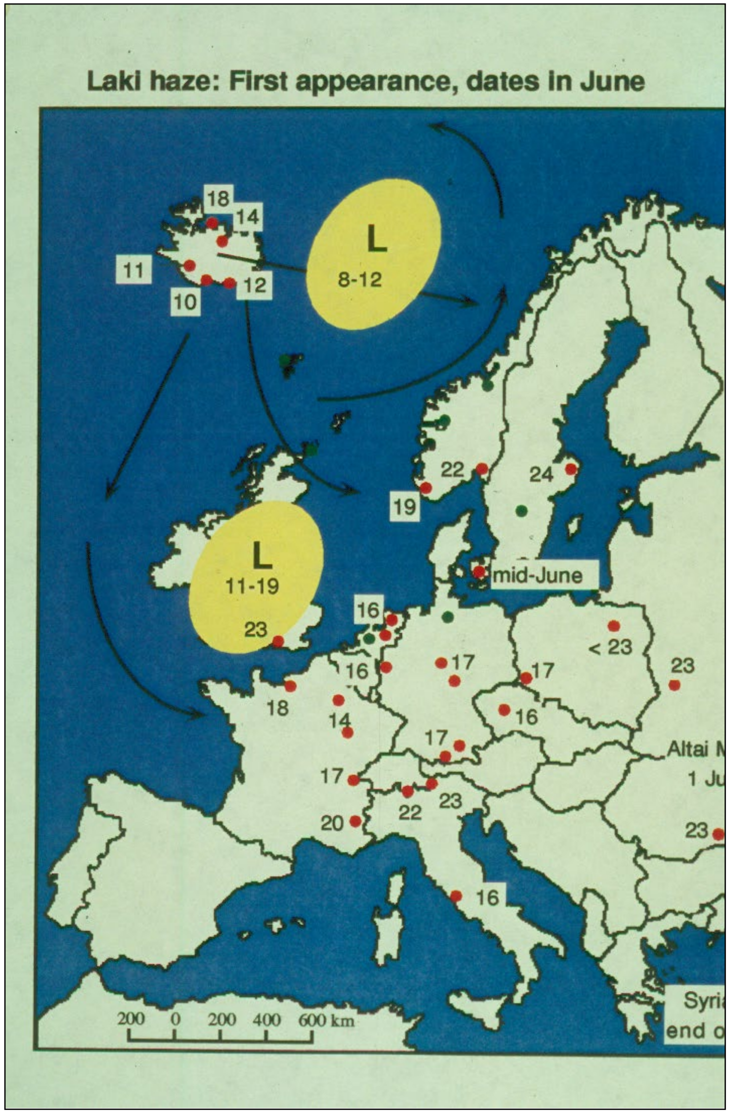


Spatter cone from high sustained fountains



Brown et al., 2014

Environmental impacts of the Laki eruption



Laki dry fog, June 1783

[Thordarson & Self, 2003]

- Dry fog over Europe and Asia; ash fall?
- Acid haze and precipitation killed crops
- Haze famine in Iceland (25% population and 75% livestock died)
- Crop failure and famine in Ireland, Scotland, France and Switzerland
- Increased mortality in UK and France**
- Anomalously warm in parts of western Europe during height of eruption**, then very cold in Europe for 1 year
- Lowest winter temperatures ever recorded in NE USA & Alaska** (tree-ring evidence)
- Mississippi River froze at New Orleans in 1783-4, ice floes in Gulf of Mexico
- Breakdown of the Asian and African monsoon →drought in 1784-85 [Oman et al. 2006]

But was Laki the cause? ** [Zambri et al., 2019]

Model simulations of Laki aerosol cloud and impacts:

[Oman et al., 2006a, b]

OMAN ET AL.: LAKI VOLCANIC AEROSOL CLOUD

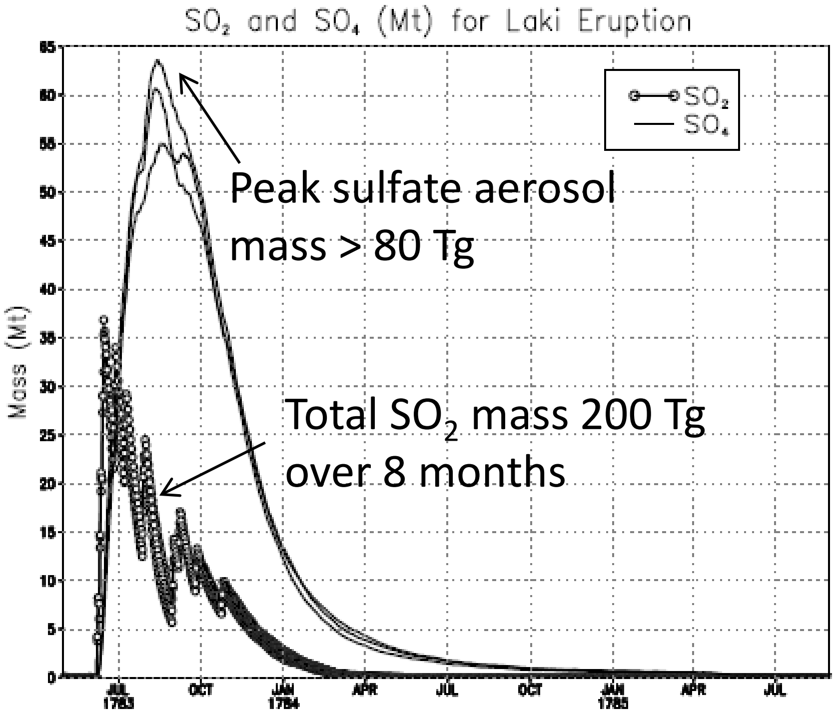


Figure 5. Daily mass loading of SO_2 and SO_4 (Mt) for the three simulations of the Laki eruption with the background loadings removed. The Laki simulations are from May 1783 through August 1785.

Modeled radiative effect of Laki aerosols:

Short—lived late summer-winter 1783 cooling of 1-3 deg C over NH land masses [Oman et al., 2006b]

Aerosols and effects limited to > 35 deg N

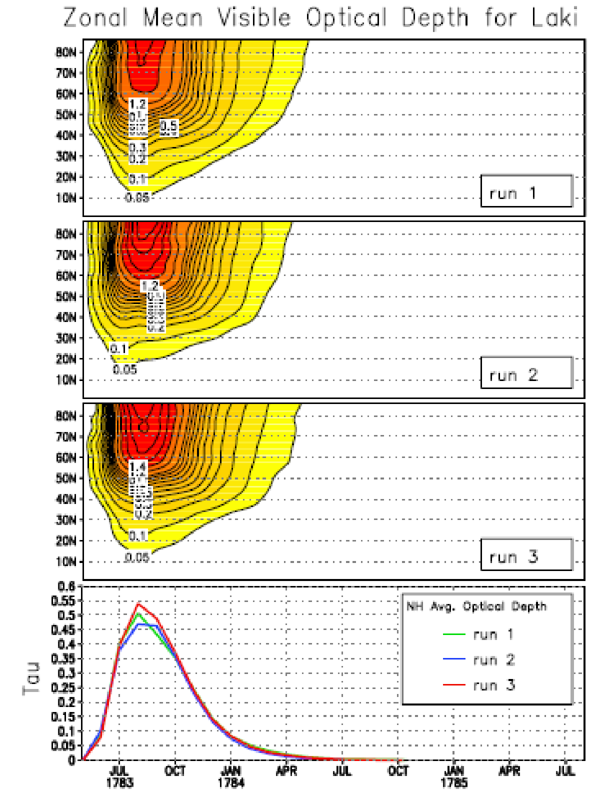


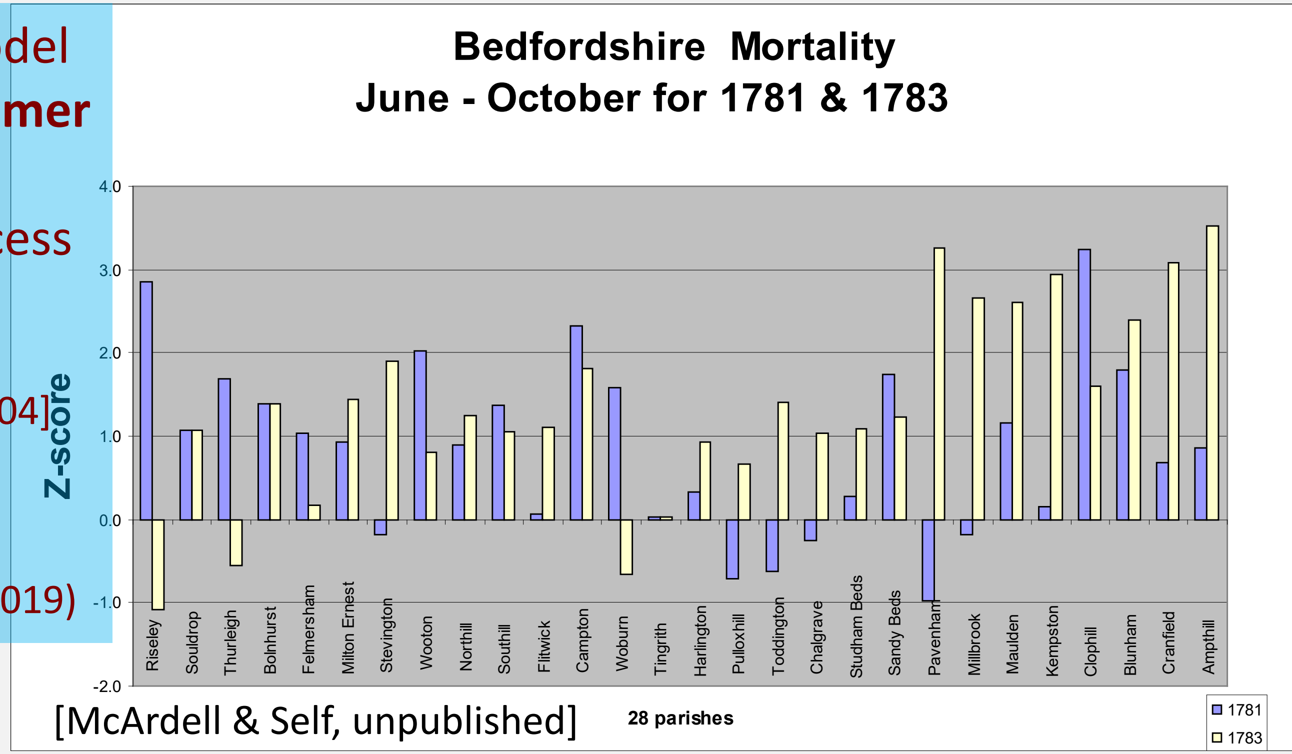
Figure 6. Zonal mean sulfate optical depth for Laki from three modelE simulations with backgrounds ...d. The bottom panel is Northern Hemisphere average optical depth for the three individual runs. The optical depths are from May 1783 through August 1785.

Limited by rapid aerosol growth/ fall-out?

Alternative explanations of “Laki” climatic/health effects

Laki forcing in climate model does not explain **hot summer of 1783** [Oman, 2006b] ;
role of hot summer in excess mortality in 1783?
Grattan, many papers;
Whitham and Oppenheimer, 2004]

Now “know” this is NOT a Laki effect (Zambri et al., 2019)



[McArdell & Self, unpublished]

Cold post-Laki 1783-84 winter [D’Arrigo et al., 2011]:

simulations support our hypothesis that a combined, negative NAO-ENSO warm phase was the dominant cause of the anomalous winter of 1783–1784, and that these events likely resulted from natural variability unconnected to Laki. Citation: D’Arrigo, R., R. Seager, J. E.

Lanzarote, Canary Islands, 1730-36

AD 1730s event was the 3rd largest known basaltic fissure eruption of past 1000 years (after Laki 1783 & Eldgja 934)

- <u>Minimum</u> 7 km^3 (M6.3) of magma erupted from ~30 vents
- Lava & ash covered half of the island causing widespread destruction; subsequent famine led to abandonment of island ~ 1732
- Magma compositions range from basanite (~ 43 wt% SiO_2) to alkali basalts
- 5 main eruption phases, 1-3 episodes in each phase

Lanzarote 1730-31: Phase I & II explosive activity

Fountain heights 1.5 km; column heights 9 km

- Violent Strombolian fire fountains provided mechanism for injection of SO_2 to atmosphere; total SO_2 released during Phase I & II = 30 Mt

- Average mass eruption rate (Phase I) = 600 m^3/s (~1.4×10^6 kg/s); this is 60 × > current Kilauea eruption but < Laki peak eruption rates

- Eruption column heights = 9-13 km dry atmos.; 12-16 km wet atmos.

- At Lanzarote latitudes this implies upper tropospheric-lower stratospheric heights [Sharma et al., in prep.]

Lanzarote 1730-31: Ice core estimate of SO_2 released

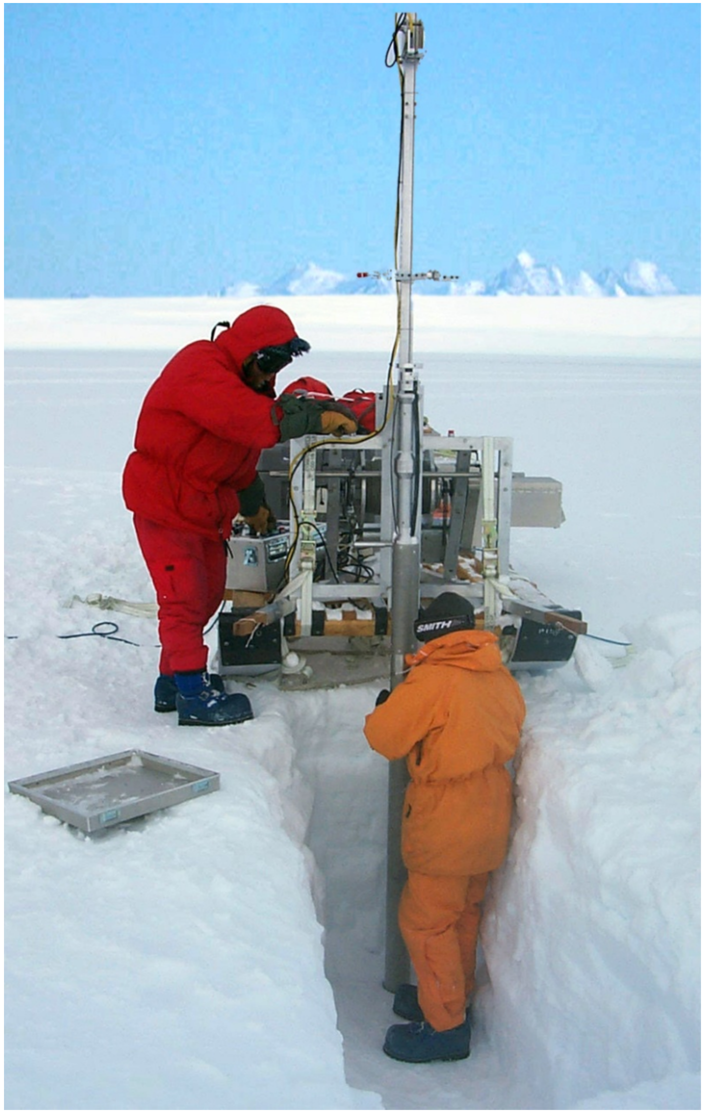
- A 1731 sulphate peak is recorded in GISP-2 Greenland ice core [Zielinski et al., *J. Geophys. Res.*, *100*, 1995]

- Other eruptive activity in 1729-1730 not significant enough to cause acidity peak in 1731 [Simkin & Siebert 1995]

- Zielinski suggests maximum total atmospheric loading of H_2SO_4 aerosols (assumes stratospheric transport) = ~ 30 Mt [1×10^{12} g = 10^9 kg = 1 Mt]

- ~18-20 Mt of SO_2 required to generate this amount of aerosols (as much as Pinatubo 1991)

- **Transport by surface winds in winter takes air masses west & then north**; trajectories towards Greenland feasible.



Lanzarote 1730-31: Climate & Environmental Effects

- Marked decrease (- 0.3°C) in average Northern Hemisphere temperature in 1732 - 1734 (Mann et al., 1999)

- Tree ring records from North America indicate moderately severe decline in summer temperatures in 1732 (Jones et al., 1995), as do whole Northern Hemisphere records (Briffa et al., 1998)

- Icelandic historical records describe anomalously cold weather conditions and "haze" (*cf.* Laki 1783) in the years following the Lanzarote eruption

What might be the effects of a repeated eruption like this?

Putting basaltic emissions into perspective

- Presently, anthropogenic emissions of SO_2 are 130-160 Mt/yr (most into boundary layer)
- Natural emissions (volcanism and others) are ~ 50 Mt/yr; most into mid-tropopause to lower stratosphere. [Total > 200 Mt/yr]
- In the geologic past, natural only, thus **CFB emissions** are >> natural; 500 – 1000s Mt/yr *cf.* 50, or even 200 Mt/yr.
- This level of emission may have led to an enhanced optical depth, but we do not know by how much, or for how long!
- **Acid rain must increase, but over what area?**

Pu'u O'o 1983-86, Hawaii

Will the SO_2 generate stratospheric aerosols?

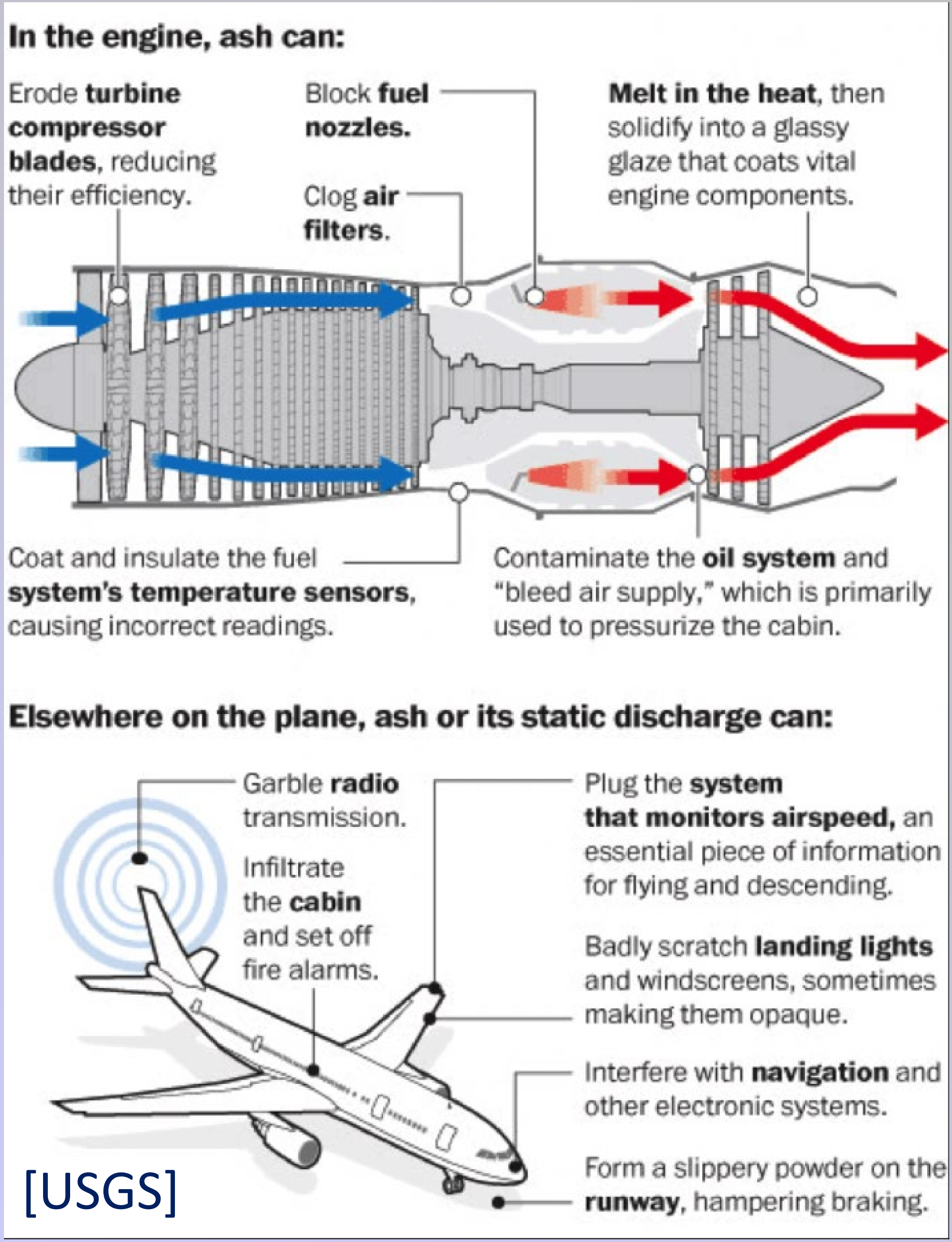
- Dependent on output rate at vents – and this depends on duration of eruptions, and other factors such transfer to stratosphere (Nabro)
- Duration must be long enough to accommodate sheet lobe growth (10,000s SLs per eruption), suggests last decades to centuries
- Laki analogy and modelling suggests columns will be 10-15 km high
  [Laki's peak rate maintained for 10 yrs > ~1,500 km^3 magma]
- Laki (and Roza) vents were << 5 km long; also supports high columns, but output rate must be highly variable.
- Also greatly helped by ash generation in conduit and vent

General considerations and questions

What would a large eruption do to our lives?

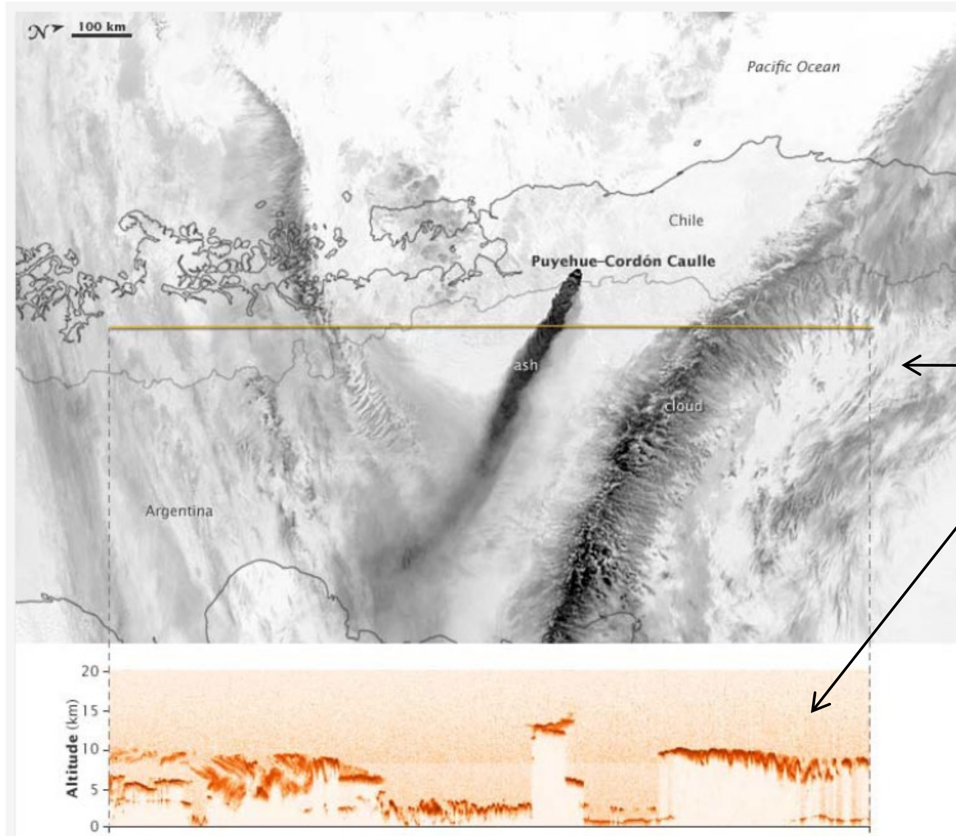
- Sudden changes in climate & weather
- Ozone depletion
- Reduced light levels
- Food shortages, especially in the grain belts and other climatically fragile areas
- Atmospheric boundary layer pollution and water quality issues
- Air (and other) transport disruptions
- Communication disruptions / satellite receivers
- many more ……

Ash vs jet engines



[USGS]

Possible behavior of ash from a Tambora-like eruption



June 2011 **Puyehue** ash cloud, MODIS and CALYSPO images [www.Earth-observatory.nasa.gov]

Many unknowns!

Global circumnavigation in two weeks, spreading latitudinally

Residence time and *distal dispersal* of fine ash – a big?

Altitude initially will be above commericial flight paths (10-11 km)

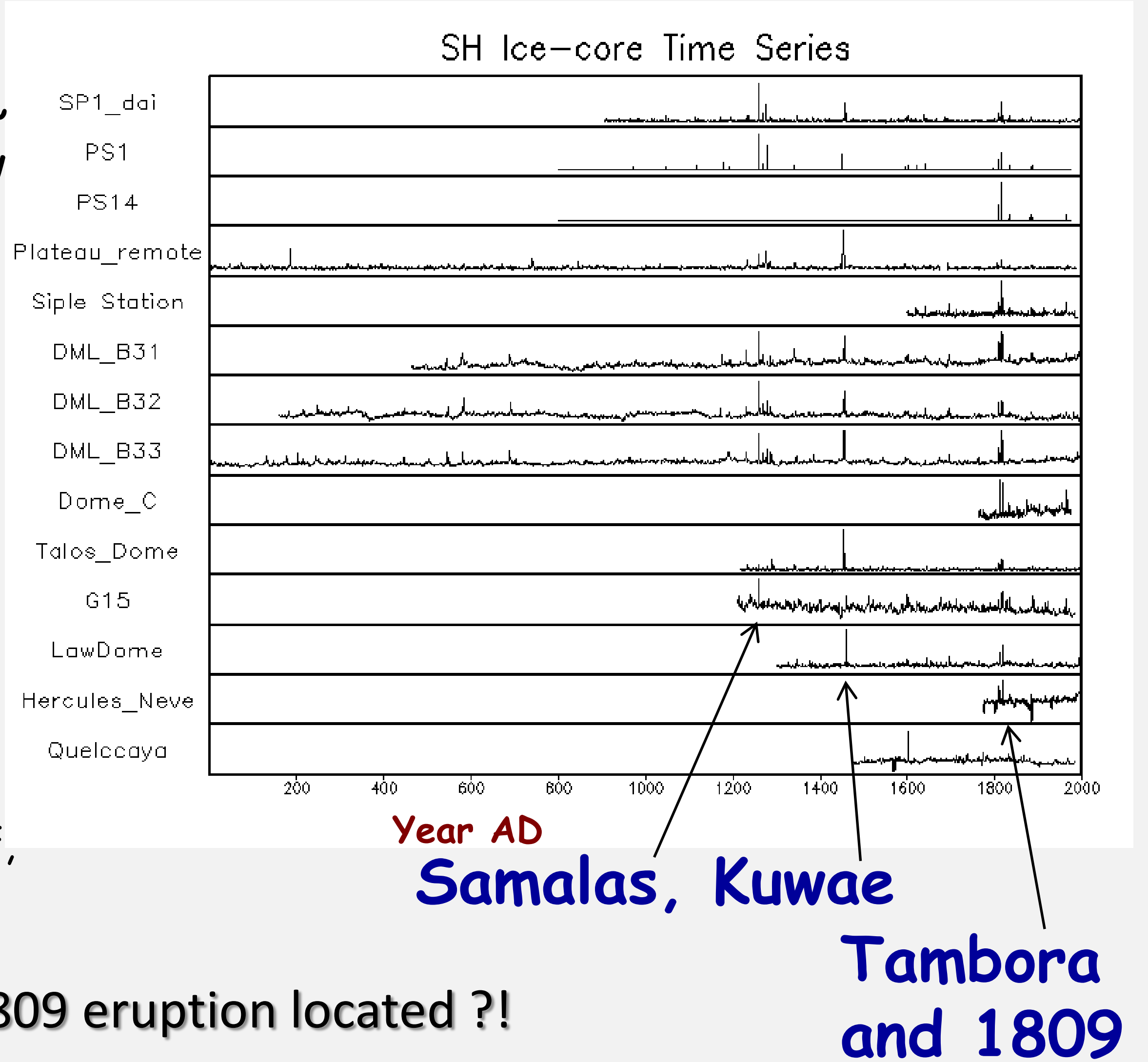
Would ash stay aloft long enough to impact flights in high latitudes?

- + aerosol cloud ….. effects on aircraft? [Bernard & Rose, 1989: Post-El Chichón aerosol effects on aircraft acrylic windows was "epidemic" and very costly]

Other important eruptions about which we need to know more:

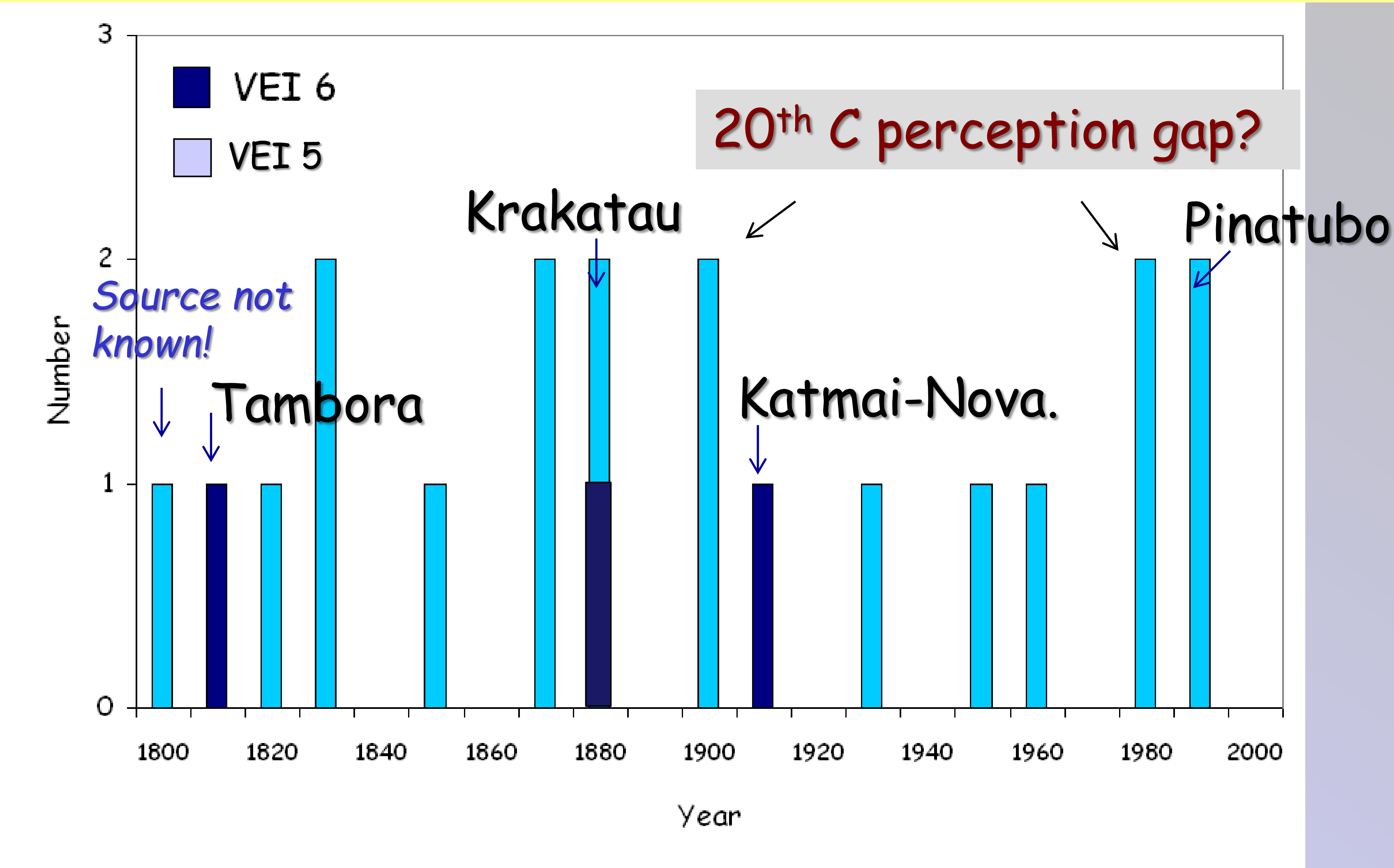
- **Kuwae (16 S), AD 1452**: 40-60 km^3 magma?
- caldera 12 km diameter, ~ 2 x size of Tambora's, now largely under sea
- Bigger acid fallout mass (from ice core records) than Tambora
- Suspected to have generated 160-200 Tg of aerosols compared to Tambora's 100 Tg

[Gao et al., 2006; Witter and Self, 2006]



Where the hell was the 1809 eruption located ?!

Our present view of volcanic activity is distorted by a benign past: too few VEI/M > 5 events in past 200 years to put large eruptions on our “radar screens”. Several big eruptions were in very remote areas; no M 7 eruptions *(Tambora 1815 = M 6.9)*. Considering the under-reporting, we should strive to understand the range of effects of M 7 eruptions better …… *as with Tambora*



The future – 2: predicting large eruptions

Table 1. Large Holocene eruptions with a VEI of 7 or a magnitude > 6.8 (data sources: Global Volcanism Program – Volcanoes of the World; Global database on large magnitude explosive volcanic eruptions – LaMEVE). The dates in brackets for the Changbaishan and Taupo eruptions are from newer studies. [Gertisser and Self, 2015]

Volcano	**Country**	**Date** *
Tambora	Sumbawa, Indonesia	AD 1815
Kuwae	Vanuatu	AD 1452
Samalas (Rinjani)	Lombok, Indonesia	AD 1257
Changbaishan	China / North Korea	AD 1000 ± 40 (946 ± 3)
Taupo Ignimbrite	New Zealand	AD 233 ± 13 (232 ± 5)
Santorini (Minoan)	Greece	1610 ± 14 BC
Aniakchak	Alaska, USA	1645 ± 10 BC
Cerro Blanco	Argentina	2300 ± 160 BC
Kikai	Kyushu, Japan	~ 5350 BC
Mt. Mazama (Crater Lake)	Oregon, USA	5677 ± 150 BC
Kurile Lake	Kamchatka, Russia	6437 ± 23 BC

*Could add Unknown 1809?

Known from ice cores

How incomplete is this record? What is the return period for Tambora-size eruptions? *Very difficult to say…….*

We are “discovering” Mag 7s all the time….

- 3980 ybp, Deception Island (Antoniades et al., 2018; Sci Reps 8(1))

- 4200 cal ybp, Cerro Blanco (Argentina) (Fernandez-Turiel et al., 2019; Estud. Geol. 75 (1))

The climatic impact of supervolcanic ash blankets

Morgan T. Jones · R. Stephen J. Sparks ·
Paul J. Valdes

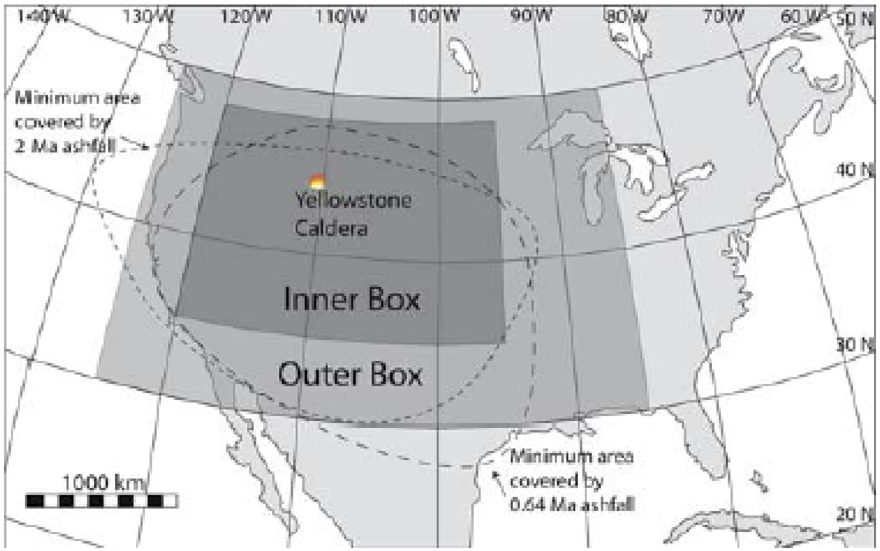
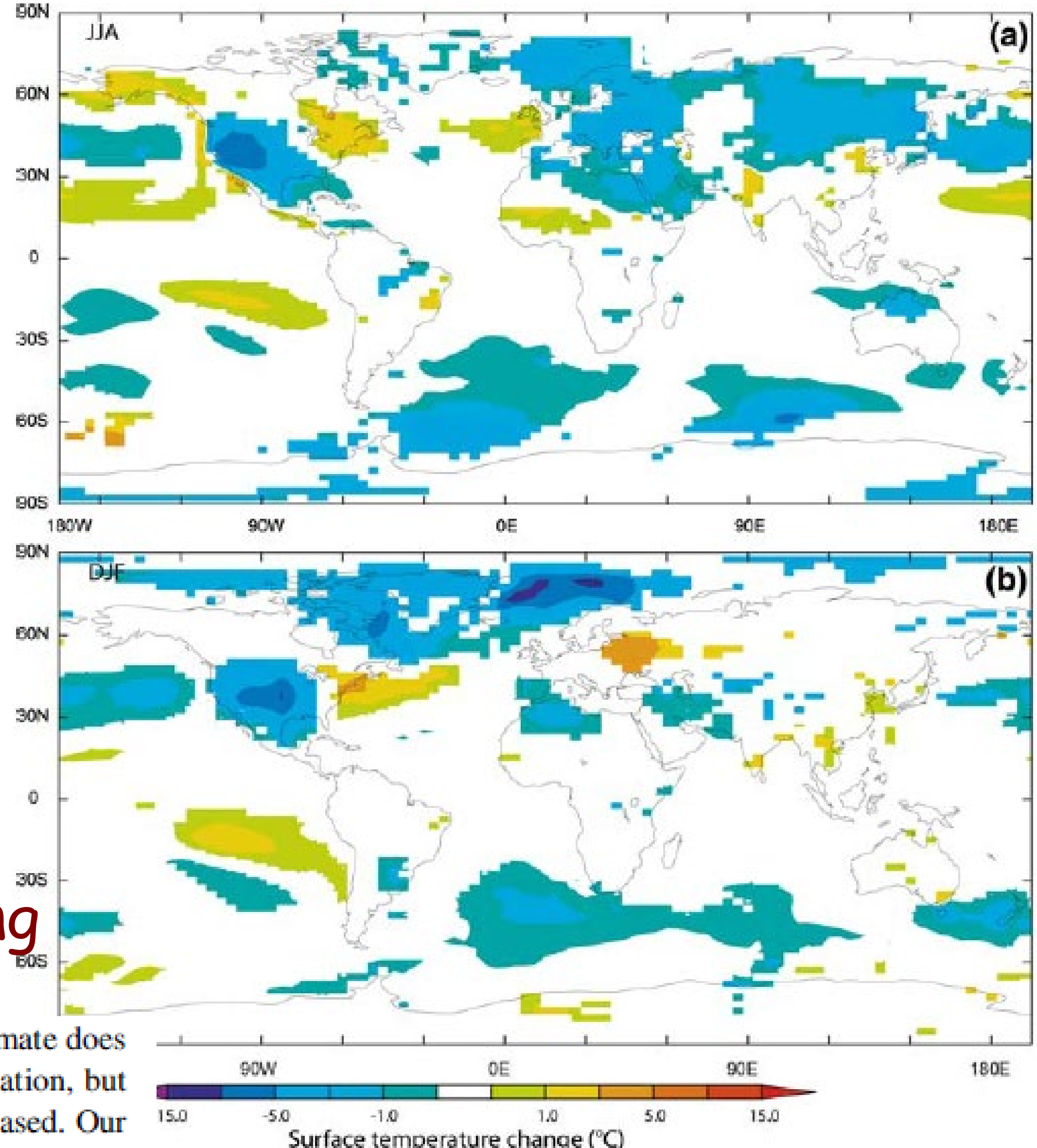


Fig. 1 Map of North America illustrating the known ashfall from two eruptions of Yellowstone and the affected area in the ash blanket simulation. The *shaded areas* show the 'two box' configuration assumed by the model. For the *inner box*, total destruction of vegetation is assumed. The soil values in the model are replaced with the physical properties of ash. The distal *outer box* suffers a 50% reduction in flora. Soil properties for the outer box are an average between ash and the original soil. The two *dashed lines* enclose sites where previous ash deposits have been recognized (e.g. Sparks et al. 2005). The actual area covered by ash is likely to have been significantly larger

Effects could last up to 10 yrs;
increases in ENSO cycle;
slight effects on precipitation

How big an impact compared with aerosol effects?

Fig. 3 Comparisons of surface air temperature between the ash-affected simulation and the control run (°C), showing anomalies exceeding the 95% statistical confidence level using the student's *t* test. **a** Show the global temperature changes for JJA and **b** highlights the temperature difference during DJF



Globally, < 0.1 C cooling

impact on atmospheric circulation. The global climate does not change significantly in the ash-affected simulation, but seasonal climatic variability is substantially increased. Our findings, such as the change in ENSO variability and magnitude, are significant enough to impact climatic responses to other volcanogenic forcings.

Summary on Magnitude 6-7 explosive eruptions:

- Effects of past historic and semi-historic explosive eruptions in Mag 6-7 range (Tambora, Kuwae, ?1809, [Laki]) on climate were due to sulfate aerosols (100-200 Tg)

- Effects were limited to a few degrees centigrade cooling over land masses in NH (< in SH, but 90 % of world's population lives in NH) – but sufficient to offset global warming

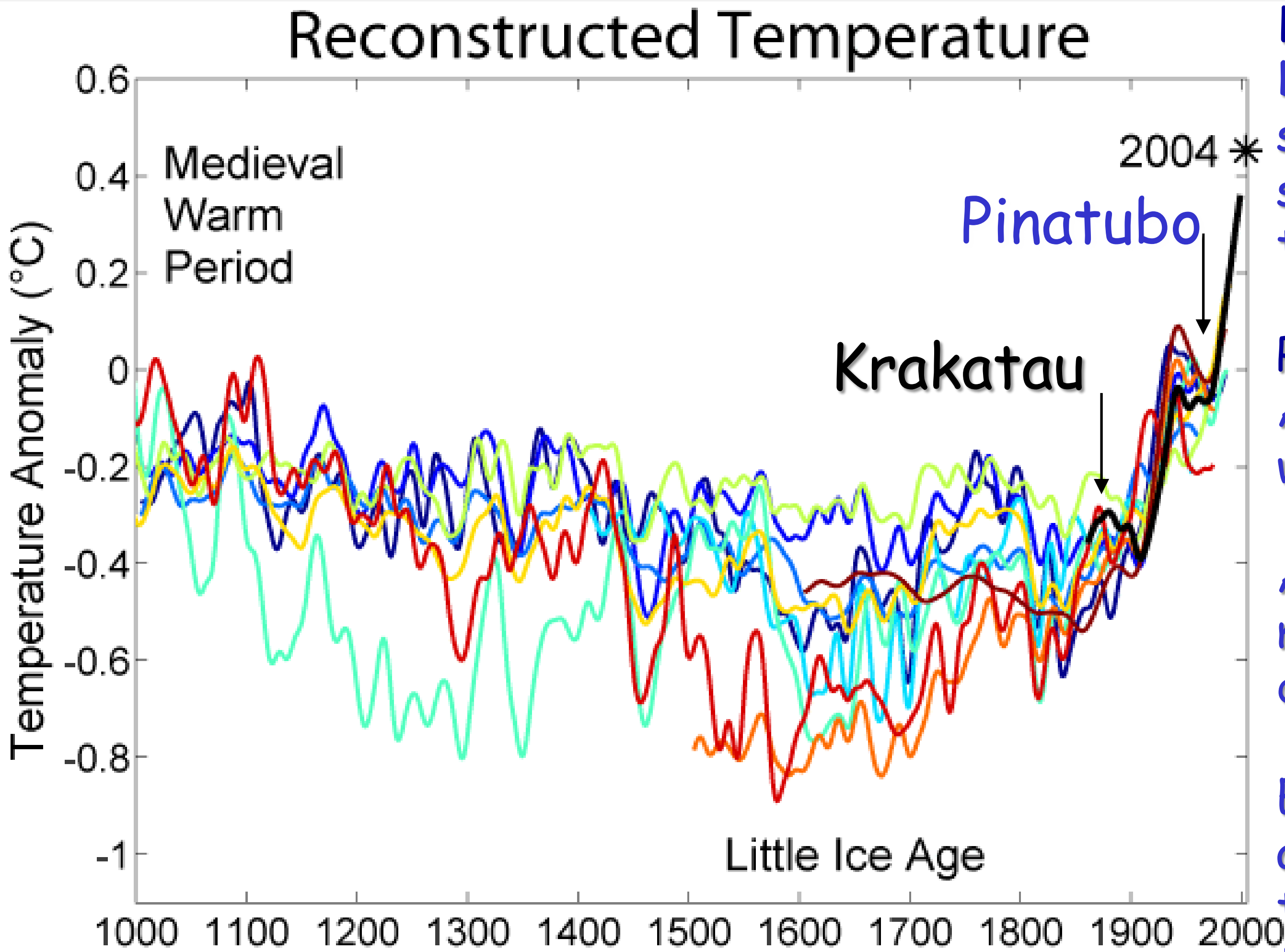
A 50-100 Tg S gas release may yield the maximum long-lasting aerosol clouds, due to the self-limiting effects

Occurrence rate: 1-2 per century; effects will have wide reach compared to those, e.g., of a major earthquake or tsunami

Tambora caldera, A. Spicak

A future M7 eruption with modest-S release would be expected to cause a similar, limited climatic impact to Tambora depending on location, season, and state of the QBO *- thus there's interest in when will we get our next Tambora or Krakatau!*

A comment about global warming:



Krakatau 1883:
Did this cool the sea surface temps sufficiently for them to be still lagging?

Pinatubo 1991:
Aerosols halted global warming for 2 years

Ash fall on sea surface may cause CO_2 decrease (Fe effect)

Eruptions might pose an important offset to the present warming trend?

[From Michael Mann: various publications 2004; black is measured record]

Initial fate of fine ash and sulfur from large volcanic eruptions

U. Niemeier[1], C. Timmreck[1], H.-F. Graf[2], S. Kinne[1], S. Rast[1], and S. Self[3] Atmos. Chem. Phys., 2010

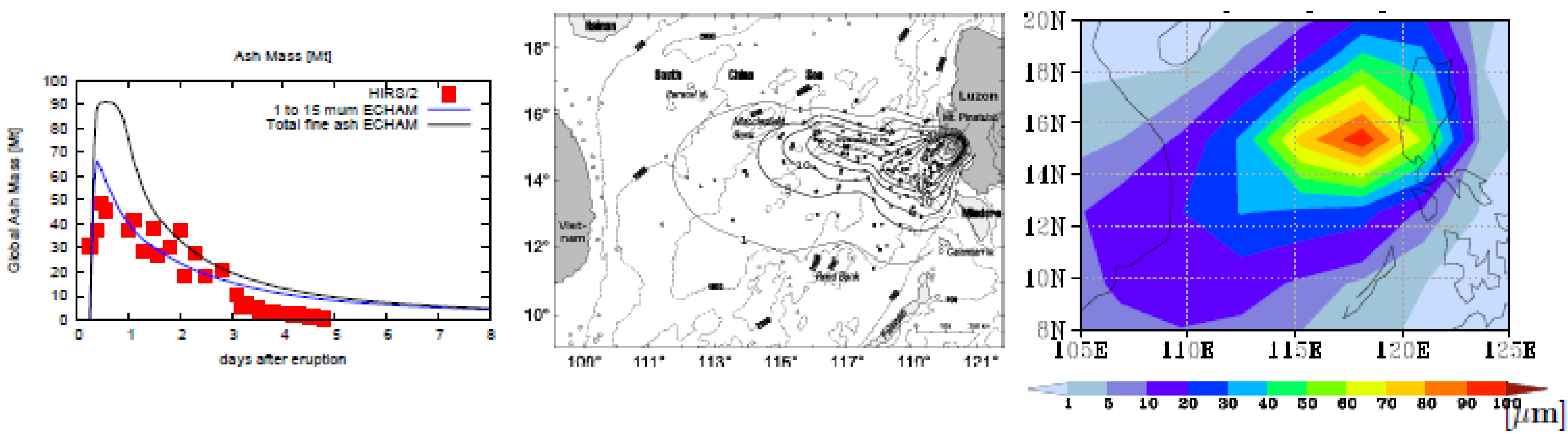


Fig. 1. Left: Evolution of the global mass of fine ash in the first days after the Mt. Pinatubo eruption. The red squares show results of satellite measurements in the size range of 1 µm to 15 µm (Guo et al., 2004), the curves give model results of the total fine ash amount (black) and the amount of fine ash in the 1 µm to 15 µm size interval. (Mass & size < rapidly in first 3 days.)
Right: Measured fine ash fall out [mm] after Wiesner et al. (2004) (middle) and simulated fine ash fall out [µm] in the first month after the Mt. Pinatubo eruption.

Winter vs summer (Pinatubo being a summer eruption):

of ash. The heating rates are increased due to ash, causing a slightly stronger winds and westerly transport of the volcanic cloud. The changing horizontal wind direction from easterly to westerly winds between 10° N and 20° N assist the temporary development of areas with anticylonic rotation in the ash containing cloud, keeping the cloud more condense. The overall impact of the ash is similar to the summer case and the main transport of the cloud without ash does not differ strongly from the pattern with ash.

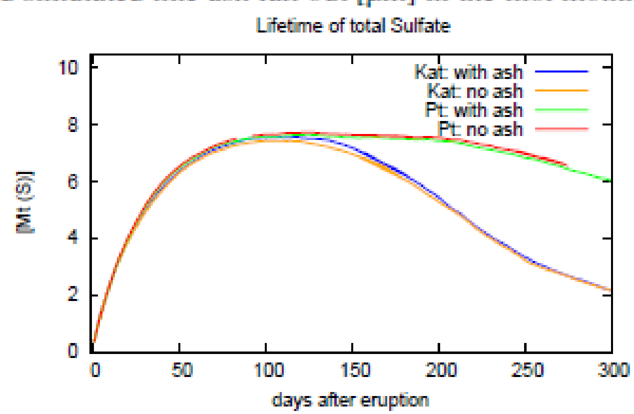


Fig. 16. Global total sulfate concentration kg(S)/kg for 300 days after the eruption in the simulation Pt1 and Kat1.

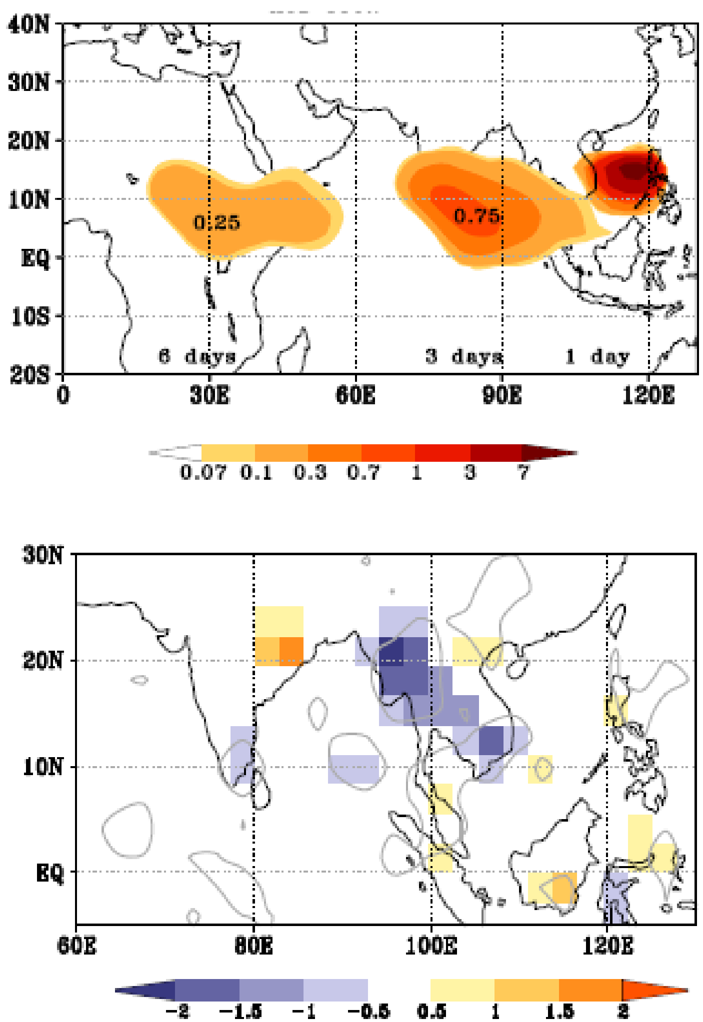


Fig. 5. Development of the aerosol optical depth of fine ash over the first week after the Mt. Pinatubo eruption (top) and differences in the 2m-temperature [K] comparing the simulation with and without ash (bottom) at the 3rd day after the eruption at noon local time (Case Pt1_ens). The grey line denotes the 99% significance level.

Local cooling and heating due to ash

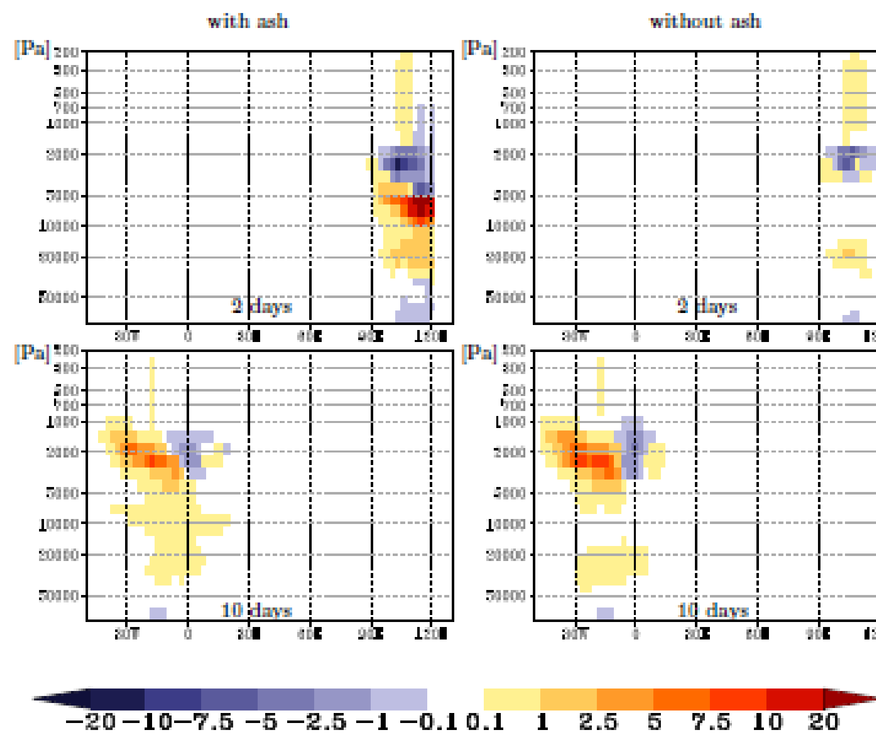


Fig. 6. Total radiative heating rates [K/day] as a daily mean two days (top) and ten days (bottom) after the Mt. Pinatubo eruption in a simulation including fine ash (left) and without fine ash (right). A vertical cross section along 15° N is shown. (Case Pt1_ens)

Ash causes heating in lower stratosphere-upper troposphere for a few days; this causes the SO_2 - sulfate cloud to propagate around the Earth faster; bigger effect for bigger ash masses (but aggregation ignored)

Also, **Yellowstone** and **Toba** magmas [Chesner, 2012] are predicted to yield extremely low S gas releases: so, Huckleberrry Ridge 2,500 km^3 eruption ≈ 200 Tg, or “only” 20 times Pinatubo’s release, unless excess S was involved [Self and Blake, Elements, 2008]

Yellowstone geyser basin

All eruptions are somewhat predictable, but they are unstoppable and potentially long-lasting; large eruptions will have widespread effects that may last years, and pose a considerable long-term “risk” factor

What about CO_2 release?

Present mass in atmosphere: ~ 3 x 10^{15} kg (3000 Gt)

A 1000 km^3 eruption (releasing ~ 0.5 wt % CO_2) would yield ~ 1.2 x 10^{13} kg to the atmosphere (could double this?)
– that's 0.004 (1/250) of the amount in the present atmosphere, a miniscule perturbation. Such eruptions have a very low frequency!

It is difficult to see how explosive eruptions could have had a direct effect on the atmosphere via CO_2

This is for eruptive degassing, I am not considering passive degassing here – but this is important during flood basalt province formation!