A Critical Evaluation of Volcanic Cooling

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Much of this research is available in:

Canty et al., *ACP*, 2013
Mascioli et al., *ACPD*, 2012

30 October 2013

Scientific Echo Chamber: Major volcanic eruptions cause ~0.5°C drop in global mean surface temperature

In terms of surface cooling, the 1991 Mt. Pinatubo eruption in the Philippines, for example, injected about 20 million tons of sulphur dioxide into the stratosphere, cooling the Earth by about 0.5°C for up to a year.

page 11-57, IPCC Physical Science Basis, 2013

There has not been any major volcanic eruption since Mt. Pinatubo in 1991, which caused a one-year RF of about –3.7 W m^{-2},

page TS-21, IPCC Physical Science Basis, 2013

Neither of these statements are true !

There are no papers in the peer reviewed literature that show a 0.5°C drop in globally avg T following Mt. Pinatubo (the commonly cited papers all focus on lower atmospheric T but of course the atmosphere has a lower heat capacity than the surface) and the RF of Mt. Pinatubo is considerably less than 3.7 W m^{-2} if one considers LW trapping of heat together with SW reflection (slide 26)

These are atmospheric observations, <u>not surface observations</u> !

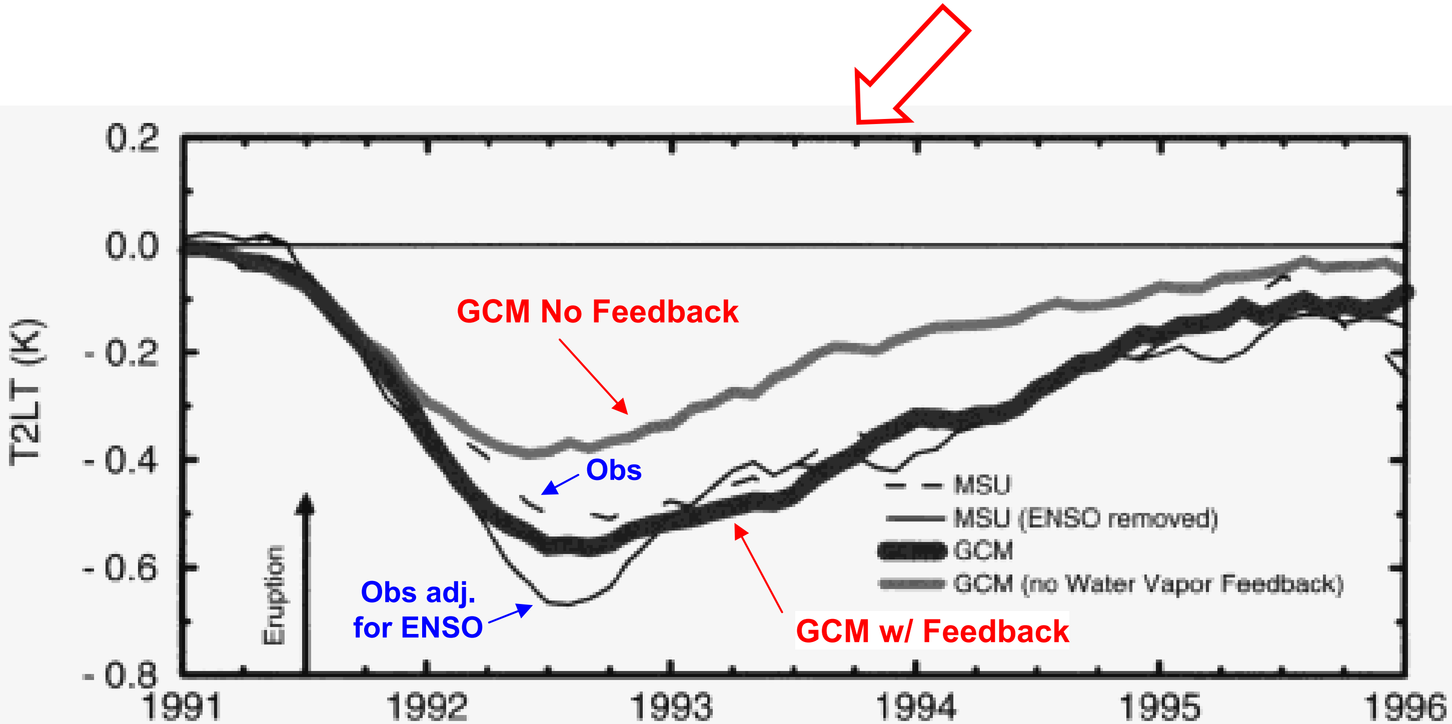
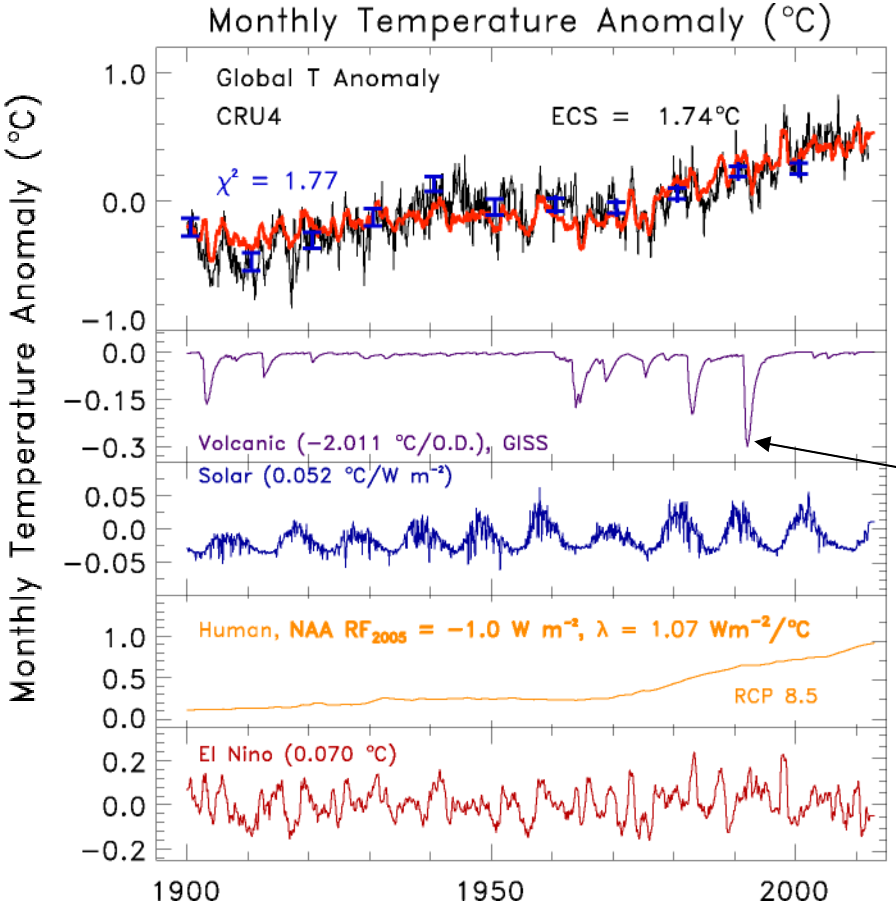
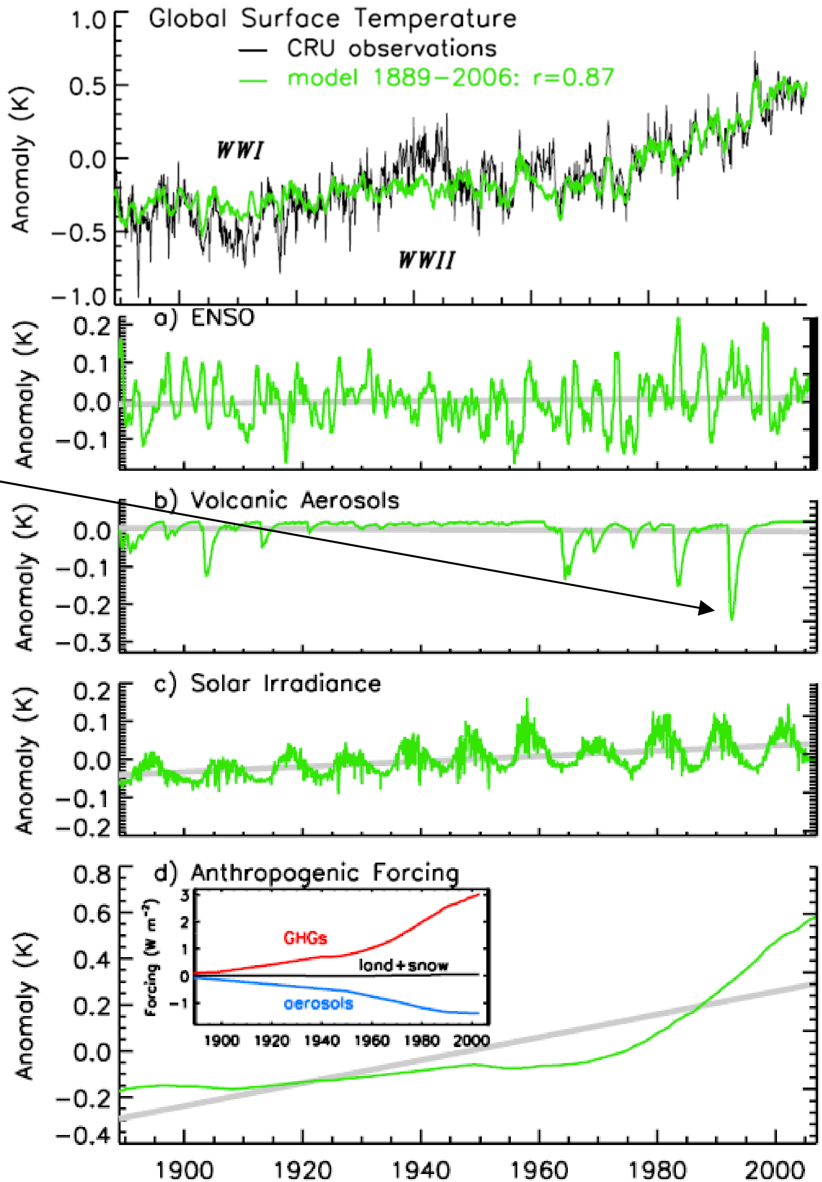


Figure 2. Observations (MSU – Microwave Sounding Unit [*Spencer et al.*, 1990] and MSU (ENSO removed) – with the effects of sea surface temperatures removed) and climate model simulations (GCM – general circulation model). The simulation was only successful with the positive water vapor feedback. (Figure 4 from *Soden et al.* [2002].)

Robock, AGU Geophysical Monograph 139, doi: 10.1029/139GM01, 2003



Canty et al., *ACP*, 2013



Lean and Rind, *GRL*, 2008

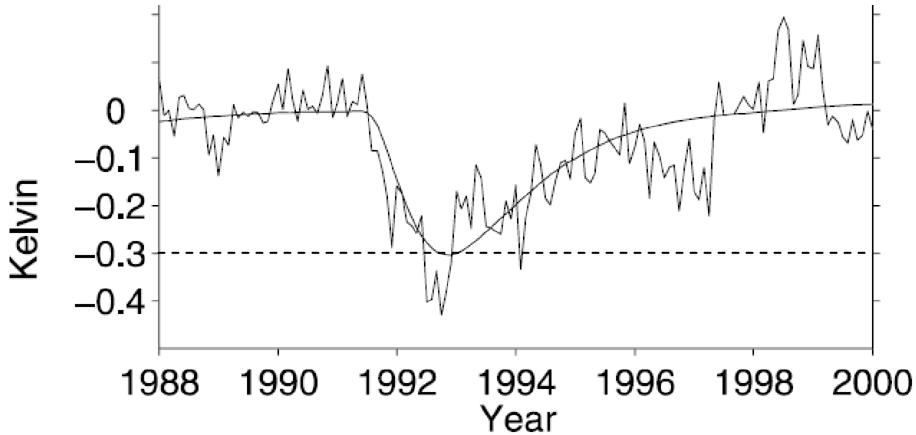
MLR using SOD, TSI, ENSO, & Human RF shows global surface cooling due to Pinatubo ($\Delta T^{PINATUBO}$) was about 0.3°C

JOURNAL OF CLIMATE VOLUME 22

Identifying Signatures of Natural Climate Variability in Time Series of Global-Mean Surface Temperature: Methodology and Insights

DAVID W. J. THOMPSON *et al.*

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado



Thermodynamic model of the response of global surface temperature to volcanic radiative forcing
Fig. 9, Thompson *et al.* (2009)

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. **6** (2011) 044022 (8pp) doi:10.1088/1748-9326/6/4/044022

Global temperature evolution 1979–2010

Grant Foster[1] and Stefan Rahmstorf[2]

[1] Tempo Analytics, 303 Campbell Road, Garland, ME 04939, USA
[2] Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany

Blue: surface T

Regression of SOD vs global surface temperature anomaly
Fig. 3, Foster and Rahmstorf (2011)

RED: lower atmospheric T from MSU

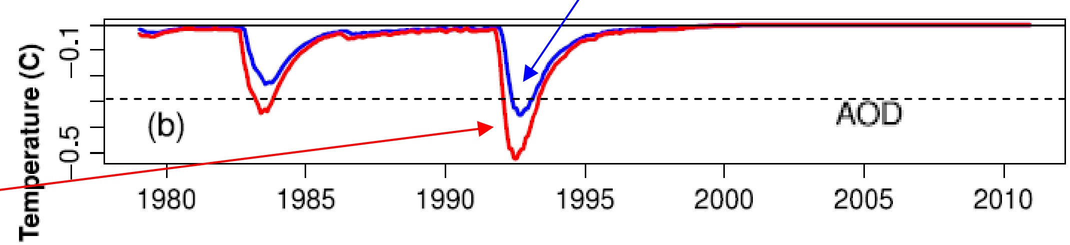
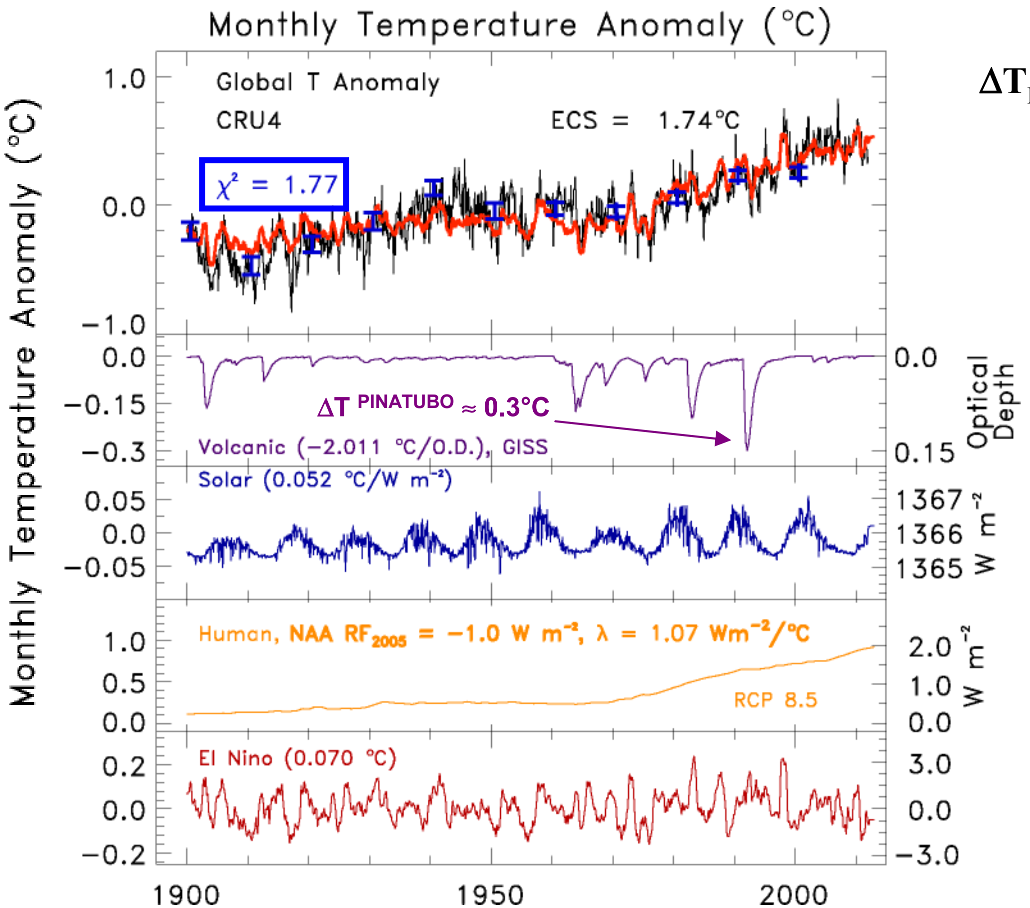


Figure 7. Influence of exogenous factors on global temperature for GISS (blue) and RSS data (red). (a) MEI; (b) AOD; (c) TSI.

Others also estimate $\Delta T^{PINATUBO} \approx 0.3°C$



$$\Delta T_{MDL\,i} = (1+\gamma)\,(GHG\ RF_i + NAA\ RF_i)\,/\,\lambda_{BB} + C_o + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} - Q_{OCEAN\,i}\,/\,\lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ W\ m^{-2}\,/\,°C$

$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters})\,/\,\lambda_{BB}\}^{-1}$

NAA RF = net RF due to anthropogenic aerosols

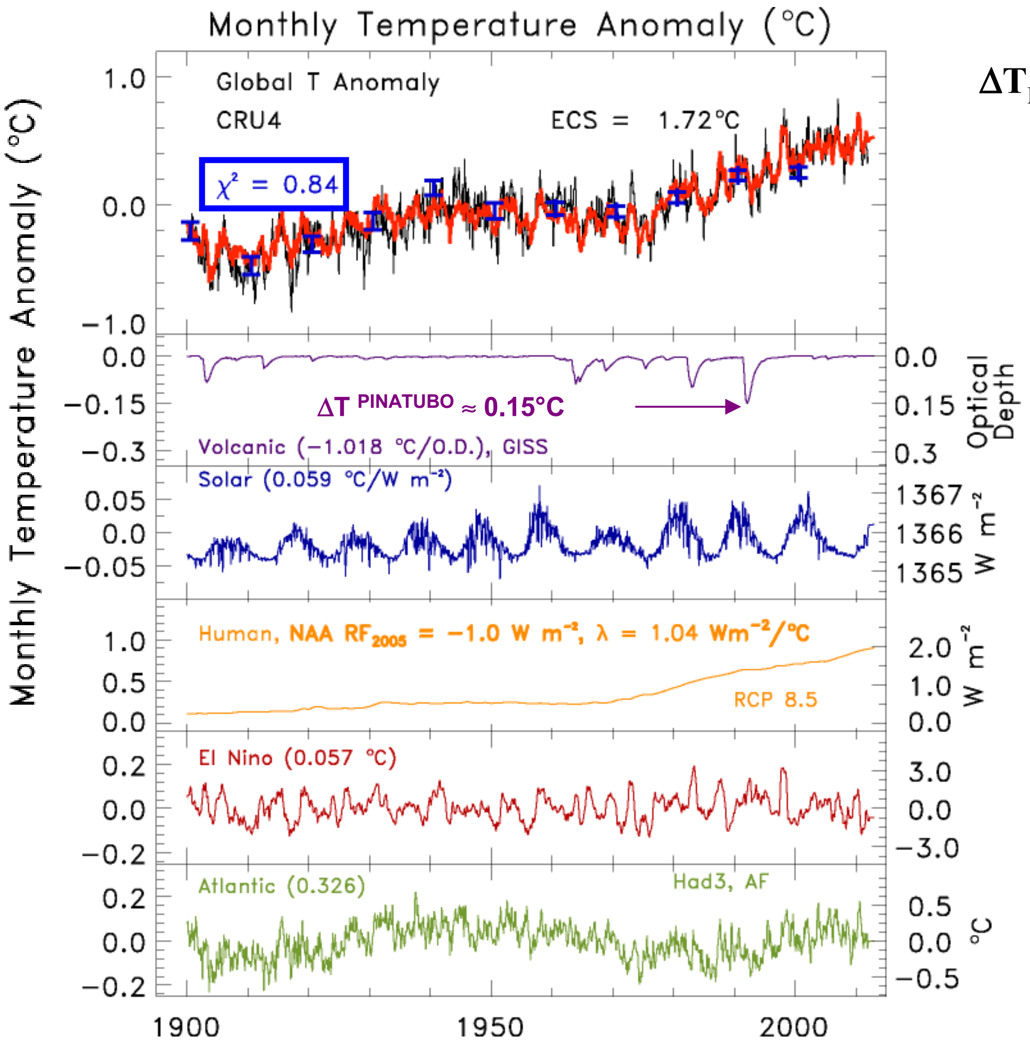
SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = Export of heat from atmosphere to ocean

Canty et al., *ACP*, 2013



$$\Delta T_{MDL\,i} = (1+\gamma)\,(\text{GHG RF}_i + \text{NAA RF}_i)\,/\,\lambda_{BB} + C_o + C_1\times\text{SOD}_{i-6} + C_2\times\text{TSI}_{i-1} + C_3\times\text{ENSO}_{i-2} + C_4\times\text{AMV}_I - Q_{\text{OCEAN}\,i}\;/\,\lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ \text{W m}^{-2}/\,°\text{C}$

$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters})\,/\,\lambda_{BB}\}^{-1}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

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ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = Export of heat from atmosphere to ocean

AMV = Atlantic Multidecdal Variation

Canty et al., *ACP*, 2013

$\Delta T^{PINATUBO}$ drops to ≈ 0.15°C upon consideration of the impact of variations in the strength of the AMOC (Atlantic Meridional Overturning Circulation) on global climate.

Public Discourse

After submission the following comments were posted on ACPD:

I think this paper has fundamental errors, and the conclusion is wrong:

#1. What the authors call the AMO is actually the climate response. So they are just double counting the response. … There is no proof that there is a physical mechanism with a 50-70 year period, because the data record is not long enough.

#2. Equation (2) is wrong. Lambda needs to be multiplied by (1+ gamma) for the aerosols, too.

#3. There are multiple time scale responses to volcanic eruptions, so a simple linear regression like done in this paper does not do a good job of simulating the climate response.

#4. The volcanic lag is wrong. The forcing develops faster than 6 months.

#5. The uncertainty in indirect aerosol forcing is huge. How does this affect the results?

http://www.atmos-chem-phys-discuss.net/12/C10686/2012/acpd-12-C10686-2012.pdf

In the slides to follow we address each of these comments, which led to a greatly improved final paper !

$$\Delta T_{MDL\,i} = \boxed{(1+\gamma)\,(GHG\ RF_{i} + NAA\ RF_{i}) / \lambda_{BB}}$$
$$+ C_{o} + C_{1}\times SOD_{i-6} + C_{2}\times TSI_{i-1} + C_{3}\times ENSO_{i-2}$$
$$+ C_{4}\times AMV_{i} + C_{5}\times PDO_{i} + C_{6}\times IOD_{i}$$
$$- Q_{OCEAN\,i} \quad / \lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ W\ m^{-2} / °C$

$1+\gamma = \{ 1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB}\}^{-1}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = Export of heat from atmosphere to ocean

AMV = Atlantic Multidecdal Variation

Comment #2: Equation 2 is wrong. Lambda needs to be multiplied by (1+ gamma) for the [tropospheric] aerosols, too.

Equation 2 was changed to match the suggested formulation with no impact on volcanic cooling: a reviewer had raised the same point. I'll gladly debate the merits of our original formulation versus the final formulation, but there is no impact on volcanic cooling.

AMOC: Atlantic Meridional Overturning Circulation

Schlesinger and Ramankutty (Nature, 1994):
First identified global, climatic significance of multi-decadal variations of SST in the North Atlantic basin

Schmith and Hansen (J Climate, 2003):
Extended AMOC proxy back to 1820 using shipboard storis (multi-year sea-ice) records

Sutton and Hodson (Science, 2005):
Changes in the Atlantic Ocean, probably related to the thermohaline circulation, have been an important driver of multidecadal variations in summertime climate of both N.A. & western Europe.

Diman and Lohmann (J Climate, 2007):
Offered physical mechanism for ~50 to 70 year variation in the strength of the AMOC, related to SLP anomalies over Pacific and Atlantic basins

Zhang, Delworth, and Held (GRL, 2007):
Used GFL CM2.1 to suggest redistribution of heat in the Atlantic Ocean, with other oceans "free to adjust", would explain multi-decadal variations in NH Mean T similar in phase and magnitude to observation

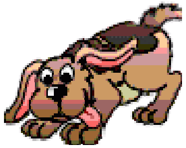
Medhaug & Furevik (Ocean Sci., 2011):
24 A-O GCMs used to assess whether North Atlantic SST serves as a useful proxy for variations in the strength of the AMOC: yes for some models (CCSM3, CSIRO-Mk3.0, ECHO-G) and no for others

Nigam et al. (GRL, 2011):
Atlantic SSTs to be especially influential in forcing multi-year droughts

Srokosz et al. (BAMS, 2012):
Paleoclimatic reconstructions show AMOC's can be highly variable and its mode of operation can change on decadal time scales with significant climate impacts.

Kavvada et al. (Clim. Dynamics, 2013):
CMIP5 GCMs provide poor representation of key oceanic and atmospheric footprints of AMOC

AMOC



← **Decadal time-scale variations in global climate**

Comment #1a: AMO is climate response

These papers (and many others) state otherwise !

AMOC: Atlantic Meridional Overturning Circulation

Stenchikov et al. (JGR, 2009):

GCM simulation suggests volcanic cooling could strengthen the AMOC

Murphy et al. (JGR, 2009)

Empirical relation between enhanced volcanic aerosol and cessation of flow of energy into world's ocean

Booth et al. (Nature Geoscience, 2012):

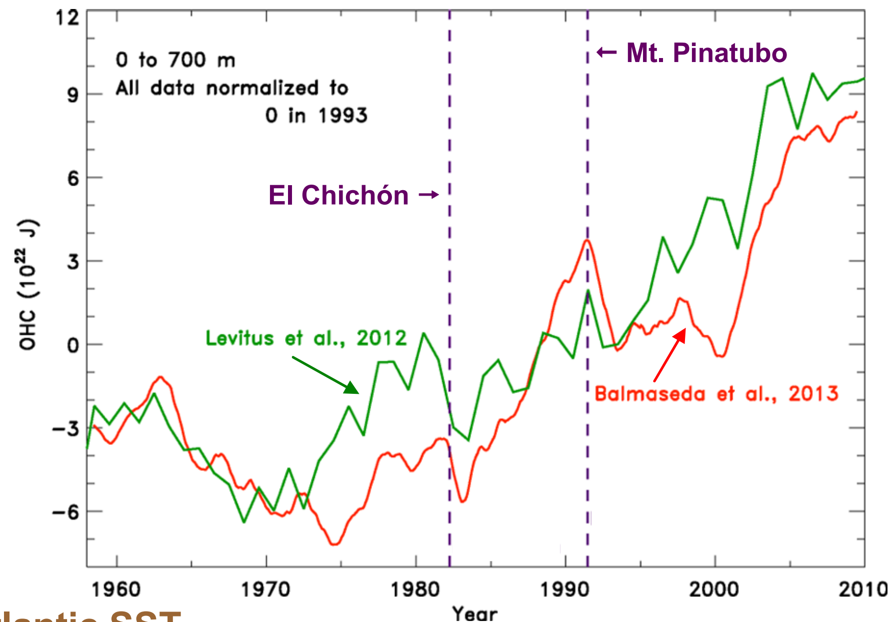
Tropospheric and volcanic aerosols implicated as implicated as a prime driver of 20th century North Atlantic climate variability

Driscoll et al. (JGR, 2012)

NH eruptions induce positive phase of NAO

Balmaseda, Trenberth, and Källen (GRL, 2013):

North Atlantic OHC shows strong drops after major volcanic eruptions



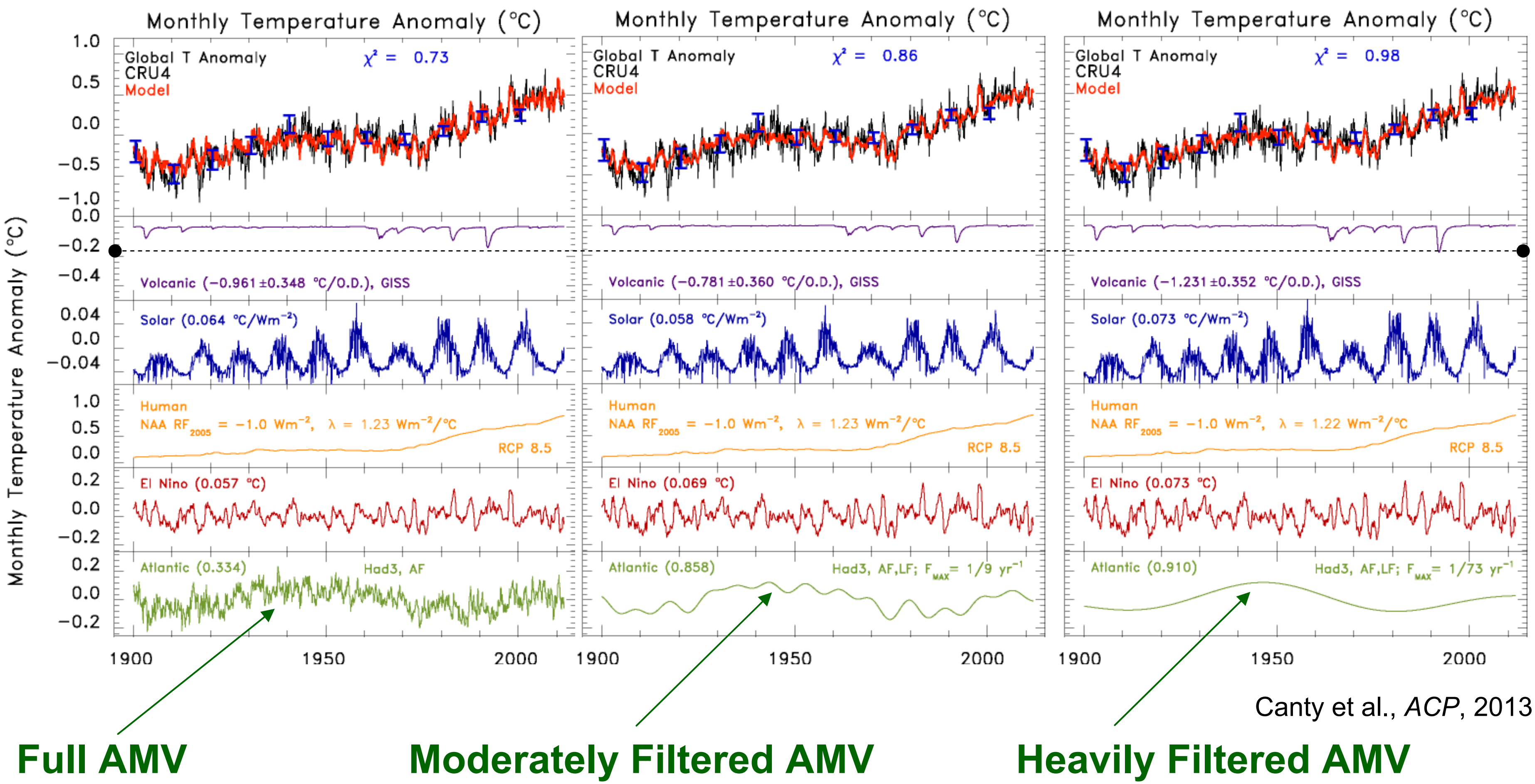
RF due to Volcanic and/or Tropospheric Aerosol

← North Atlantic SST

Comment #1a: AMO is climate response

These papers support this comment !

High Amplitude Low Frequency Component of North Atlantic SST Drives Lower Estimate for Volcanic Cooling

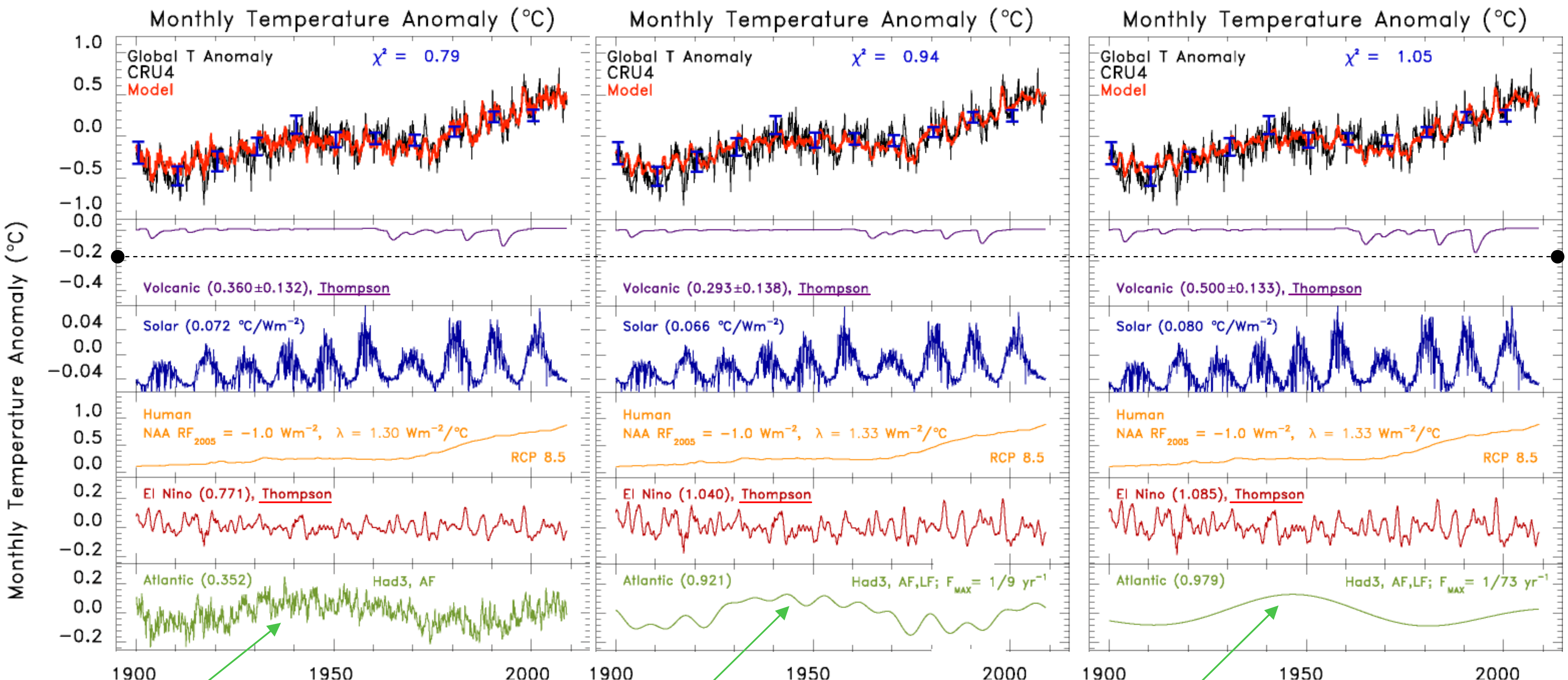


Canty et al., *ACP*, 2013

Comment #1b: Double Counting

Addressed using Fourier Analysis (shown here) & Conditional Regression (slide 14)

Nearly identical results using thermodynamic model of Thompson for volcanic response (his $T_{VOLCANO}$)



Canty et al., *ACP*, 2013

Full AMV **Moderately Filtered AMV** **Heavily Filtered AMV**

Comment #3 & 4 : Multiple Time Scales & Volcanic Lag is Wrong

Addressed using Thompson's thermodynamic response functions for effect of major volcanoes and ENSO on global climate

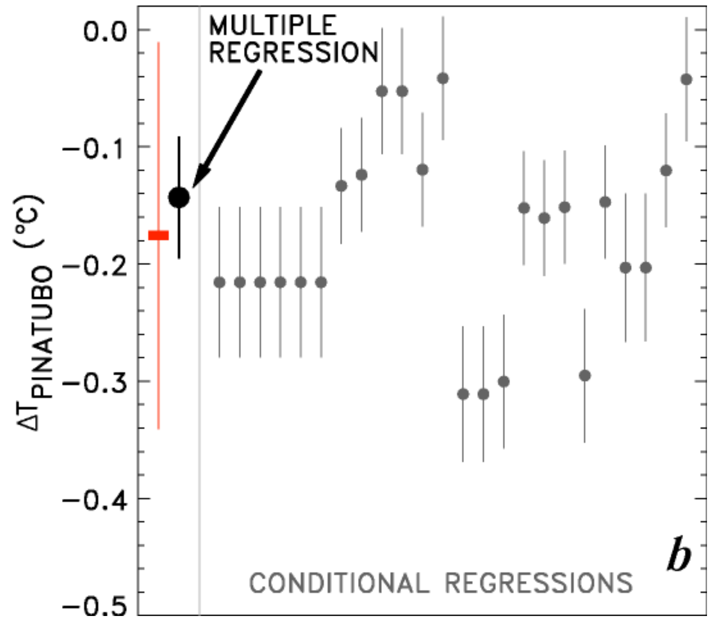


Figure appeared in Canty et al., *ACP*, 2013

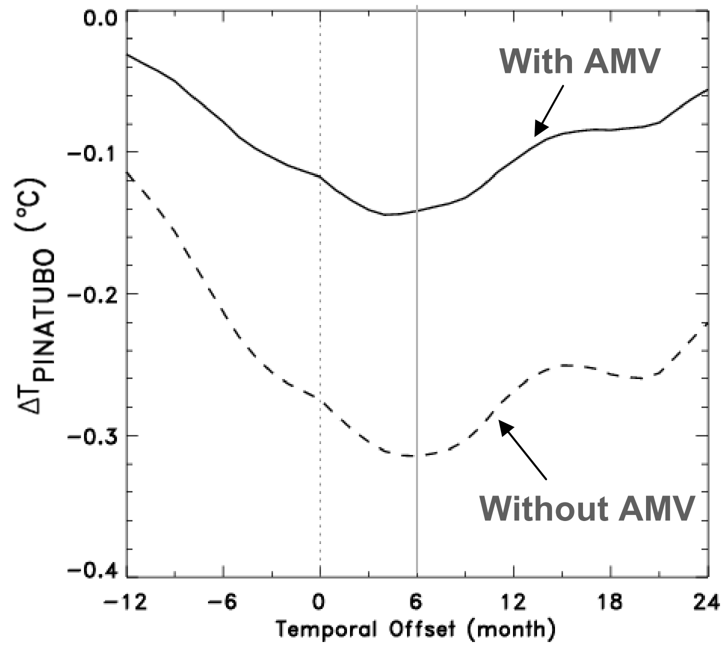


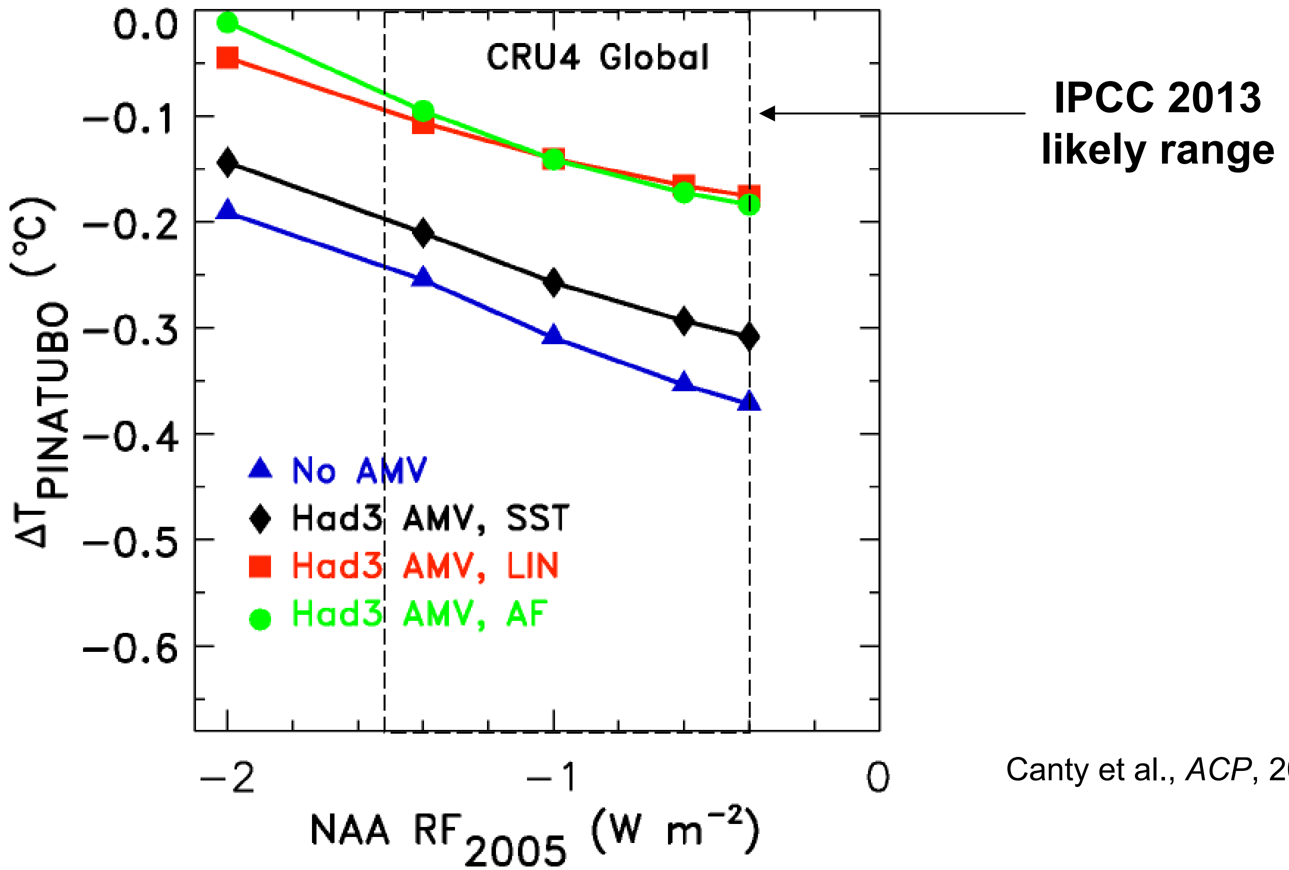
Figure did not appear in Canty et al.

Comment #1b: Double Counting
Addressed using conditional regression

Comment #4 : Volcanic Lag is Wrong
Many others have used a 6 month lag, including Santer et al. (2001), Lean & Rind (2008), Foster and Rahmstorf (2011)

See also Figures 10, S8, S9, and S10 of Canty et al. that show the change in North Atlantic SST proceeded the eruptions of Santa María, El Chichón, and Mt. Pinatubo

$\Delta T^{PINATUBO}$ vs Net Anthropogenic Aerosol Forcing in year 2005 (NAA RF_{2005})



Canty et al., *ACP*, 2013

Comment #5: Uncertainty in indirect aerosol forcing is huge.
How does this affect the results?
Figure above has always been present
(e.g., appeared in submitted and final paper) !

Geoengineering Google Groups Discussion of Canty et al.

24 April 2013:

- Abstract to Canty et al. posted
- The following comment is added to the thread :

  I recommend that you just ignore it and don't take the time to wade through it. It does not prove that the impact of volcanic eruptions is much smaller than previously thought nor that **#6** climate sensitivity is much smaller than commonly accepted.

21 May 2013:

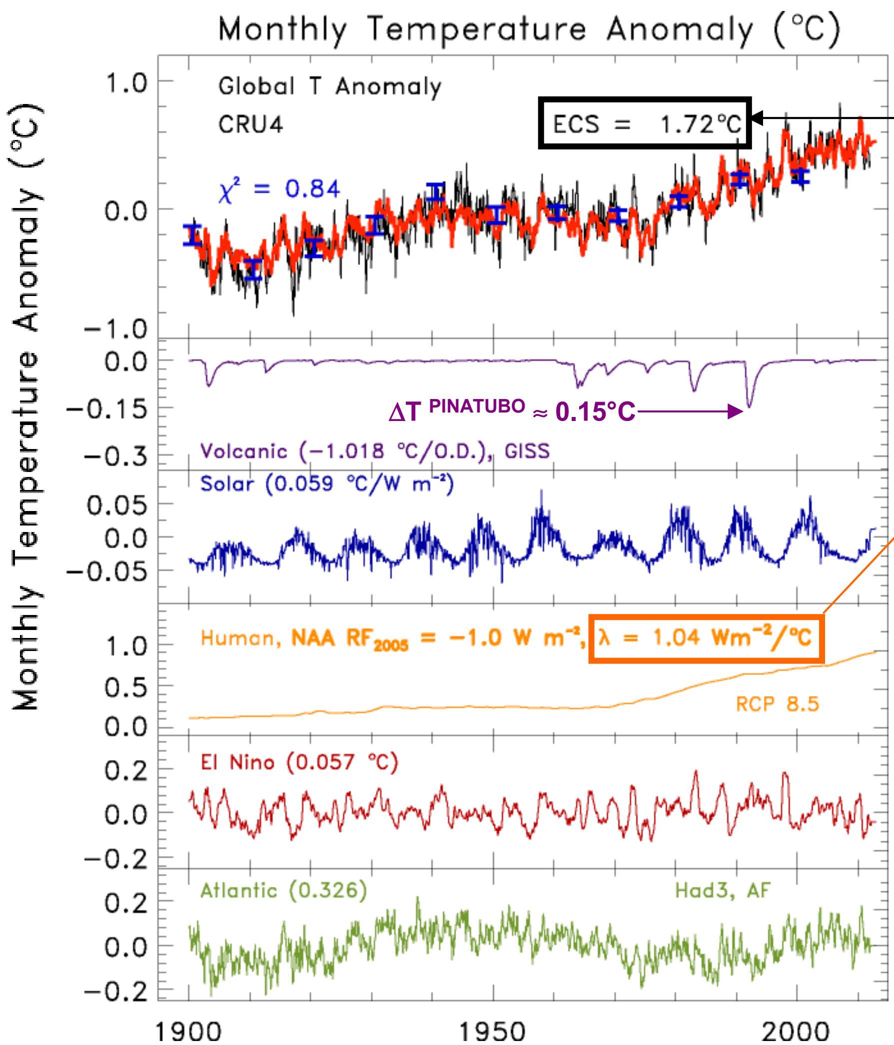
- We reply and the following comments are then posted:

  #7 Canty et al. must have a really serious error in what they've done. There is no way that the Pinatubo-induced cooling signal is only 0.14 degrees C. **The abstract for the paper makes absolutely no sense to me**.

  writer subsequently confirmed he had only read the abstract of the paper

  #8 Why no reference in these papers to other major historic cooling events that coincided with volcanoes, e.g. 1883, 1816, etc...?

https://groups.google.com/forum/#!searchin/geoengineering/canty/geoengineering/qISdZ2rYz5U/N8TPyajWWzgJ



Canty et al., *ACP*, 2013

ECS: Equilibrium Climate Sensitivity

$$\text{ECS} \equiv \{(1+\gamma)\,/\,\lambda_{BB}\} \times 5.35 \ln(2)$$

where

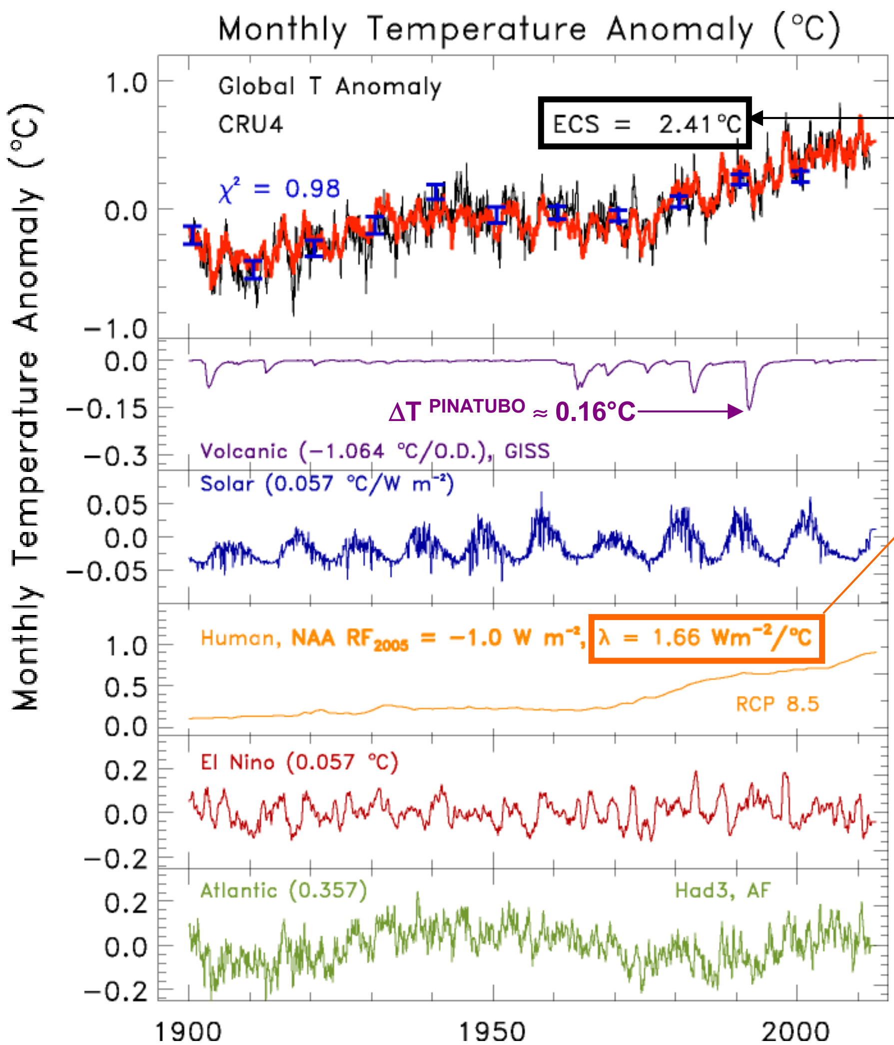
$$1+\gamma = \{\,1 - \Sigma(\text{Feedback Parameters})\,/\,\lambda_{BB}\}^{-1}$$

$$\lambda = \Sigma(\text{Feedback Parameters})$$

$$\lambda_{BB} = 3.21\ \text{W m}^{-2}\,/\,°\text{C}$$

Simulation constrained to OHC record of Levitus et al. (2012) : this OHC record results in a rather low Equilibrium Climate Sensitivity

Comment #6: A colleague takes issue with the low value of ECS in baseline simulation, based on fit to OHC record of Church et al. (2011)



Canty et al., *ACP*, 2013

ECS: Equilibrium Climate Sensitivity

$$ECS \equiv \{(1+\gamma)/\lambda_{BB}\} \times 5.35 \ln(2)$$

where

$$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters})/\lambda_{BB}\}^{-1}$$

$$\lambda = \Sigma(\text{Feedback Parameters})$$

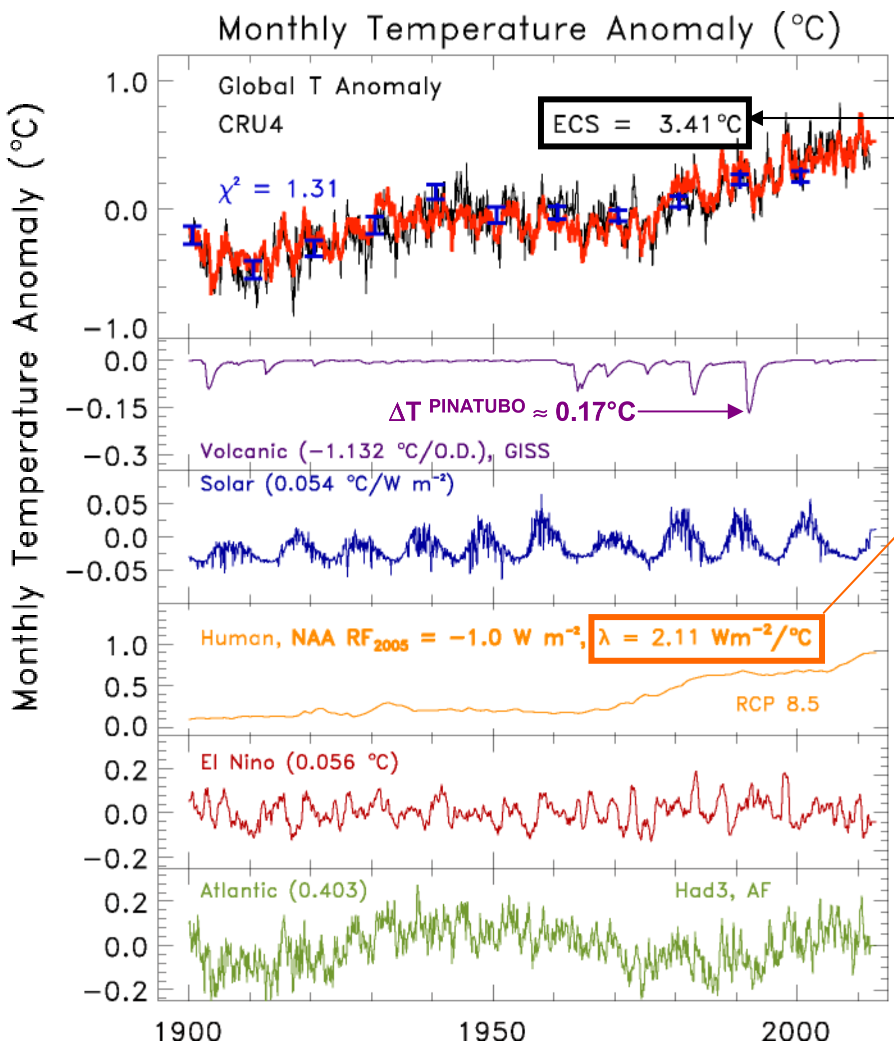
$$\lambda_{BB} = 3.21 \text{ W m}^{-2}/°C$$

Simulation constrained to OHC record of Gouretski & Reseghetti (2010) results in a larger value of Equilibrium Climate Sensitivity

Our model adjusts the climate feedback parameter to match both the T & OHC records

Comment #6: A colleague takes issue with the low value of ECS in baseline simulation, based on fit to OHC record of Church et al. (2011)

When AMV is included as a proxy for variations in the strength of AMOC low values of volcanic cooling are found, even for OHC from other data sources (here Gouretski and Reseghetti, 2010) that result in higher ECS



Canty et al., *ACP*, 2013

ECS: Equilibrium Climate Sensitivity

$$\text{ECS} \equiv \{(1+\gamma) / \lambda_{BB}\} \times 5.35 \ln(2)$$

where

$$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB}\}^{-1}$$

$$\lambda = \Sigma(\text{Feedback Parameters})$$

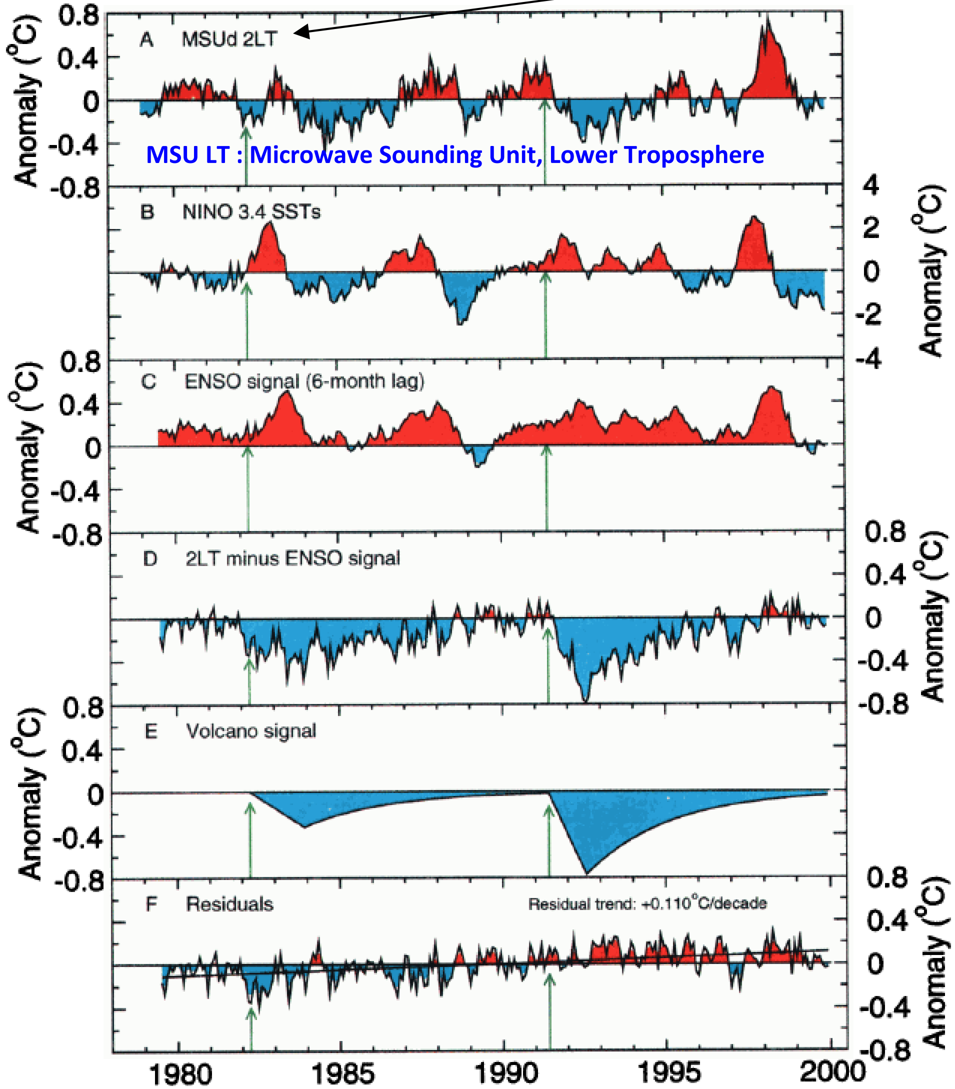
$$\lambda_{BB} = 3.21 \text{ W m}^{-2} / °\text{C}$$

Simulation constrained to OHC record of 2 x Gouretski & Reseghetti (2010) results in a large Equilibrium Climate Sensitivity

Comment #6: A colleague takes issue with the low value of ECS in baseline simulation, based on fit to OHC record of Church et al. (2011)

When AMV is included as a proxy for variations in the strength of AMOC low values of volcanic cooling are found, even for OHC from other data sources (here 2 x Gouretski and Reseghetti, 2010) that result in much higher ECS

MSU Lower Atmospheric Temperature Record



Santer et al., JGR, 2001

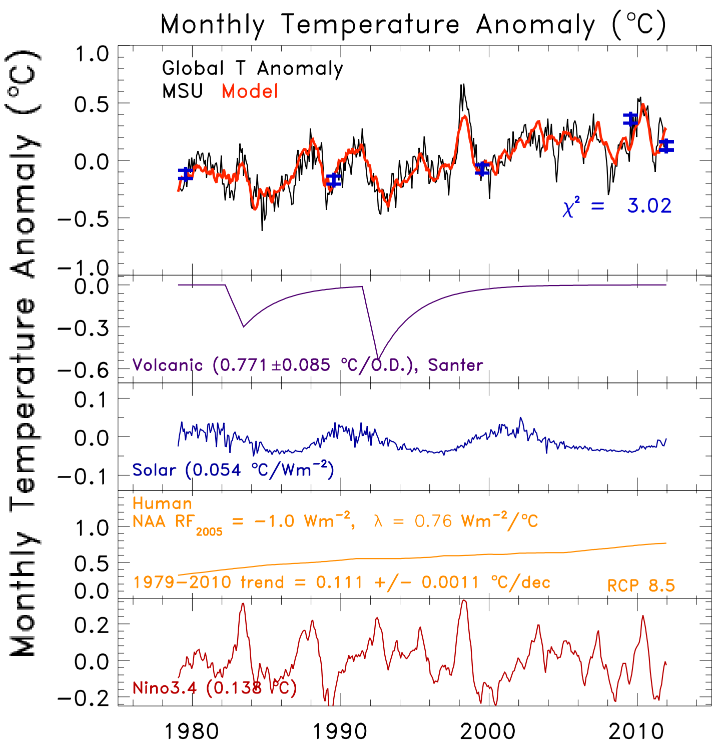
Comment #7: There is no way that Pinatubo-induced cooling is only 0.14 °C

But prior work focused on MSU (lower atmospheric data);

our abstract gave numerical value for surface observations

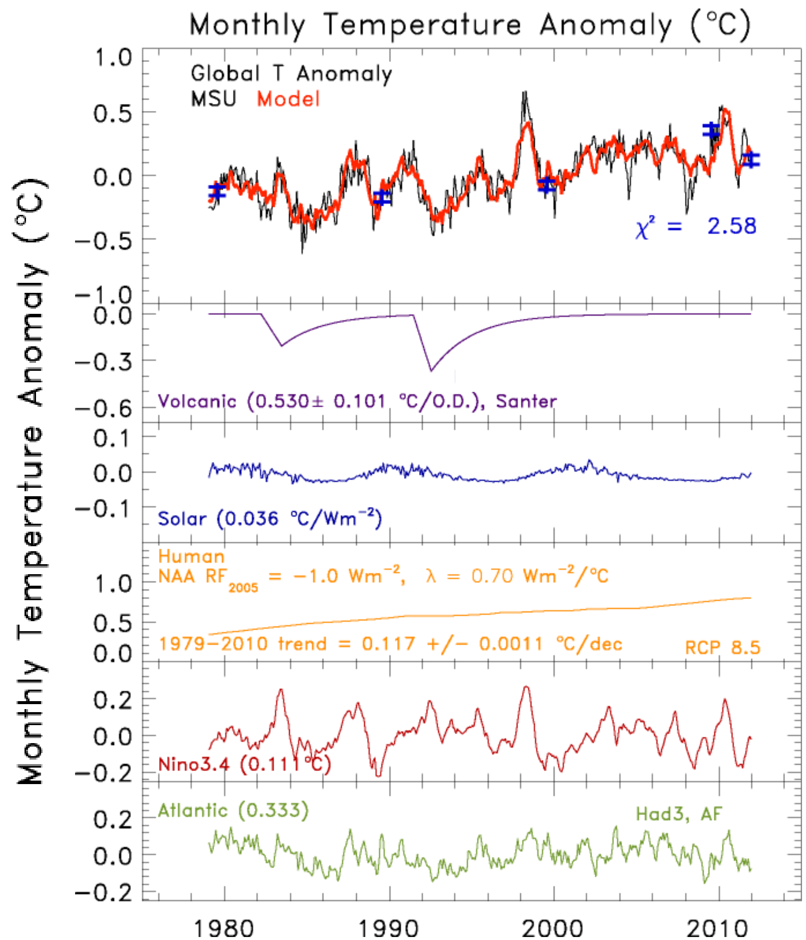
MSU Lower Atmospheric Temperature Record

Our model using Santer's volcanic signal & Niño3.4 and no ocean oscillations



ΔT PINATUBO = 0.536 °C

Our model using Santer's volcanic signal & Niño3.4 **with** ocean oscillations



ΔT PINATUBO = 0.369 °C

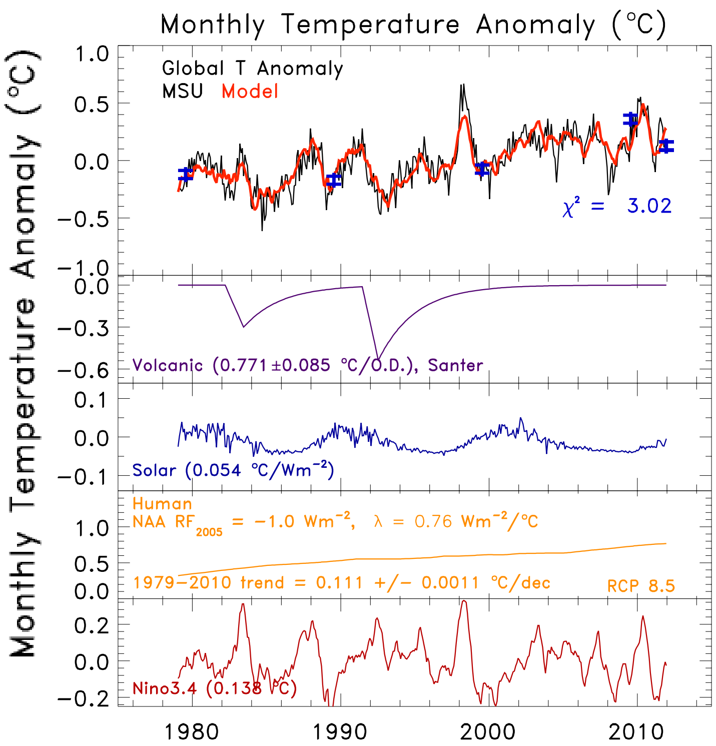
Comment #7: There is no way that Pinatubo-induced cooling is only 0.14 °C

But prior work focused on MSU (lower atmospheric data);

our abstract gave numerical value for surface observations

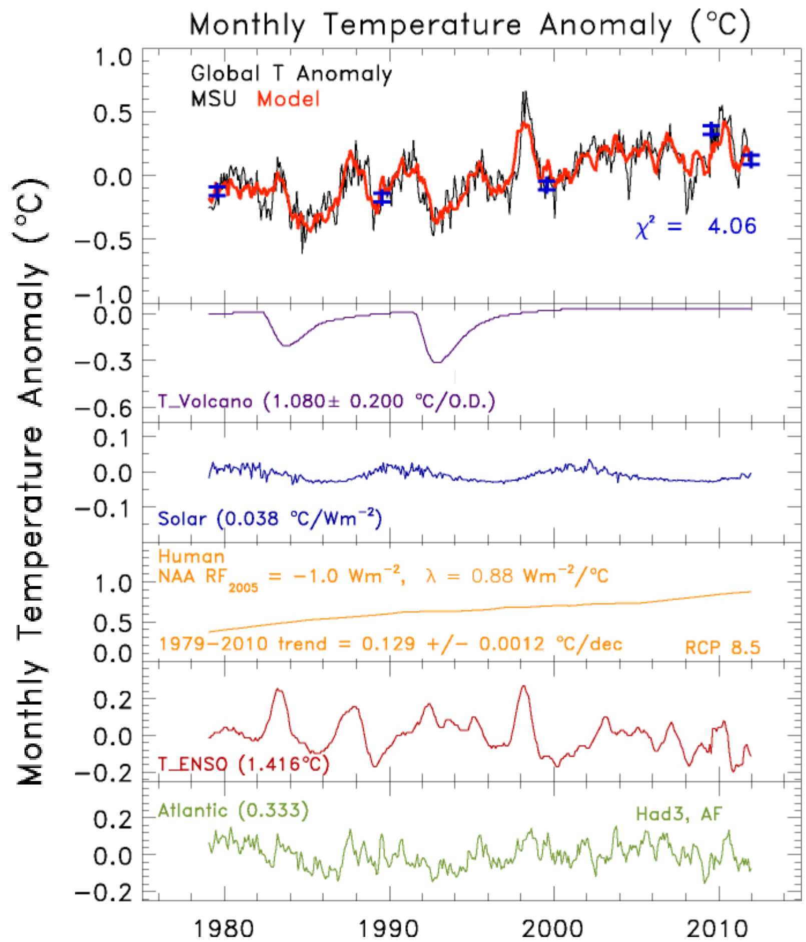
MSU Lower Atmospheric Temperature Record

Our model using Santer's volcanic signal & Niño3.4 and no ocean oscillations



ΔT PINATUBO = 0.536 °C

Our model using **Thompson $T_{VOLCANO}$ & T_{ENSO}** with ocean oscillations



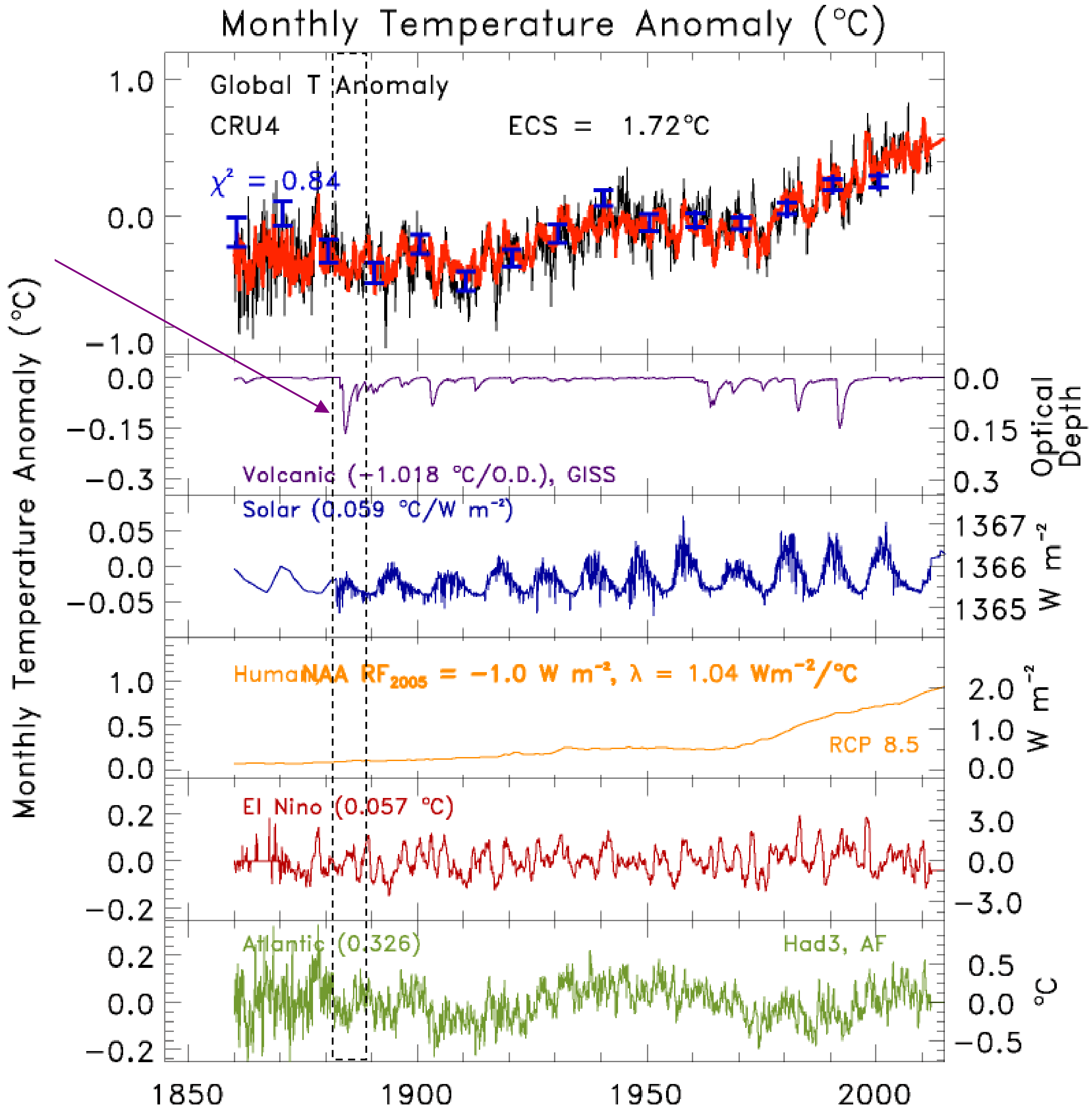
ΔT PINATUBO = 0.346 °C

Comment #7: There is no way that Pinatubo-induced cooling is only 0.14 °C

But prior work focused on MSU (lower atmospheric data);

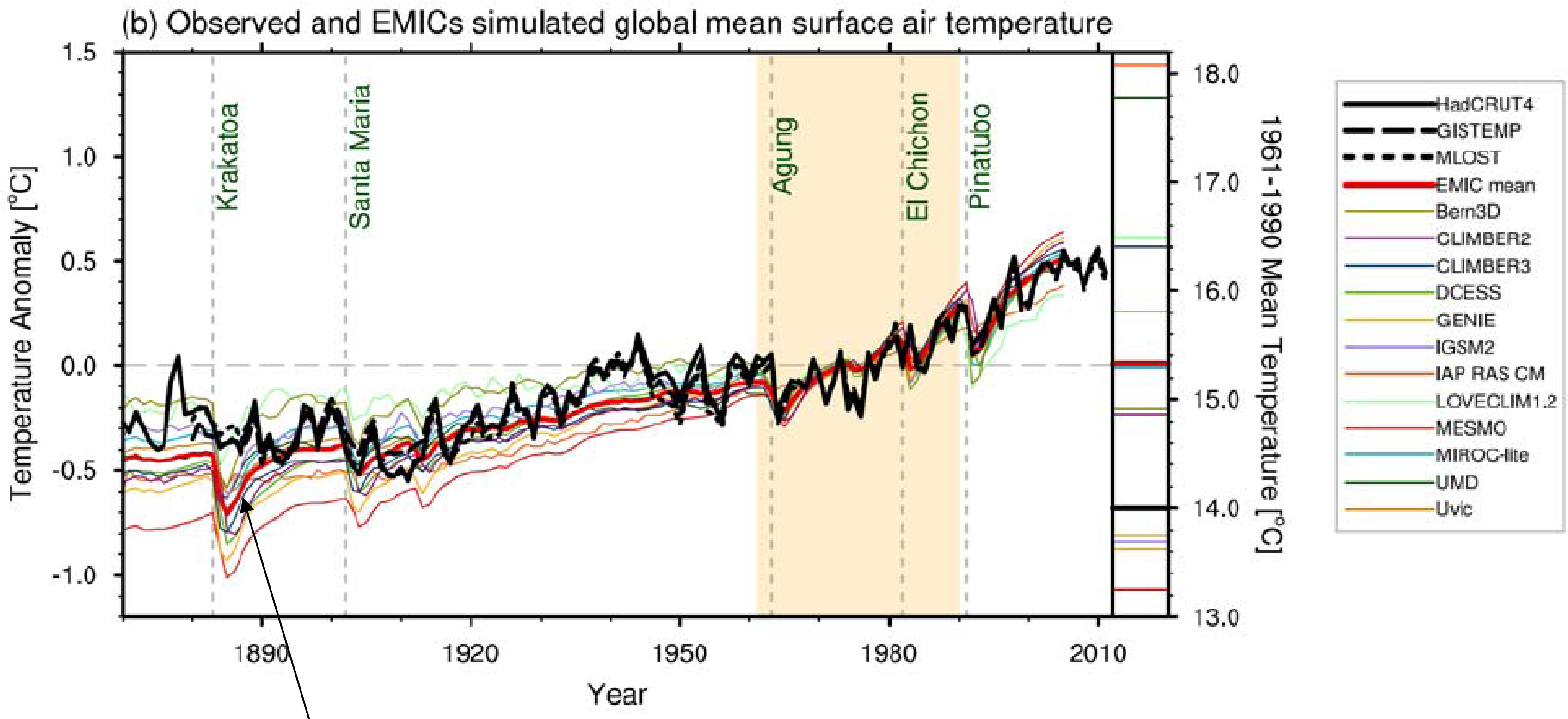
our abstract gave numerical value for surface observations

Krakatao
May 20, 1883



Comment #8: Krakatao

We find modest cooling due to Krakatao if we take our simulation back to 1860

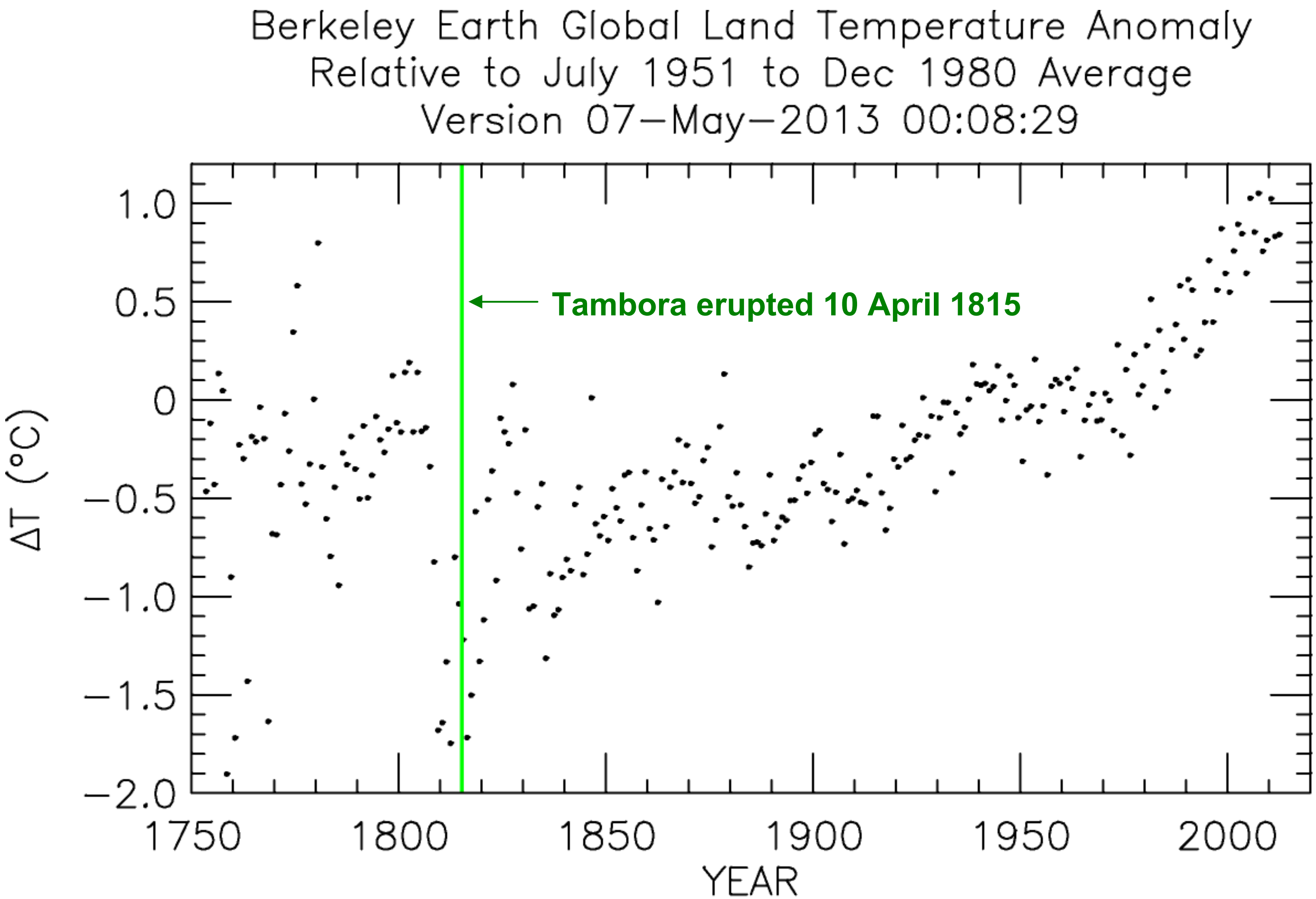


EMIC: Earth-system Models of Intermediate Complexity that include, for instance, interactive biosphere, ice sheets, etc.

Comment #8: Krakatao

IPCC (2013) EMIC simulations provide an especially troubling hindcast of ΔT during the time of Krakatoa

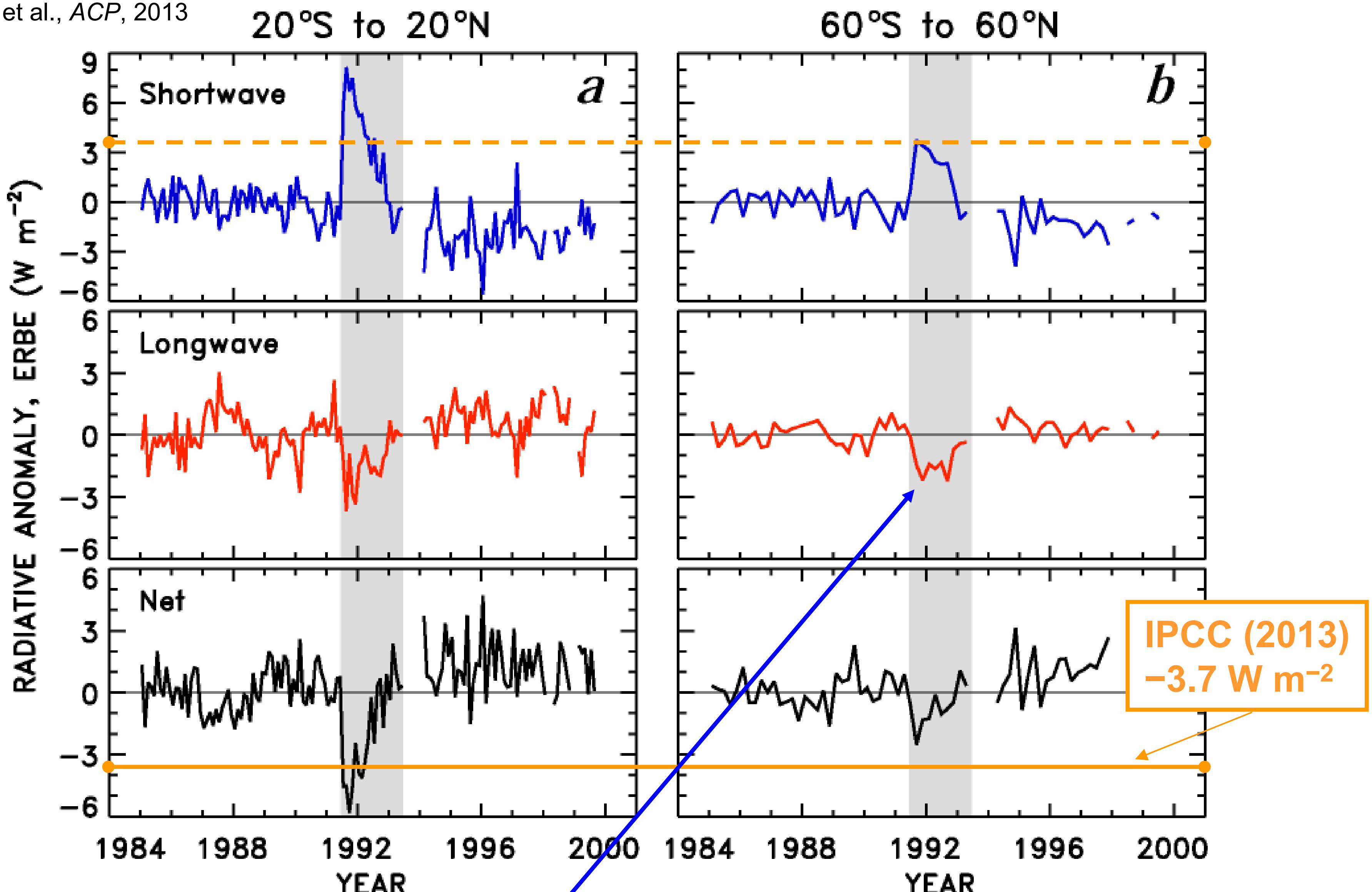
Tambora: The Year Without A Summer



<u>Comment #8</u>: Tambora

Dramatic cooling evident in BEG land surface T anomaly prior to the 10 April 1815 eruption of Tambora

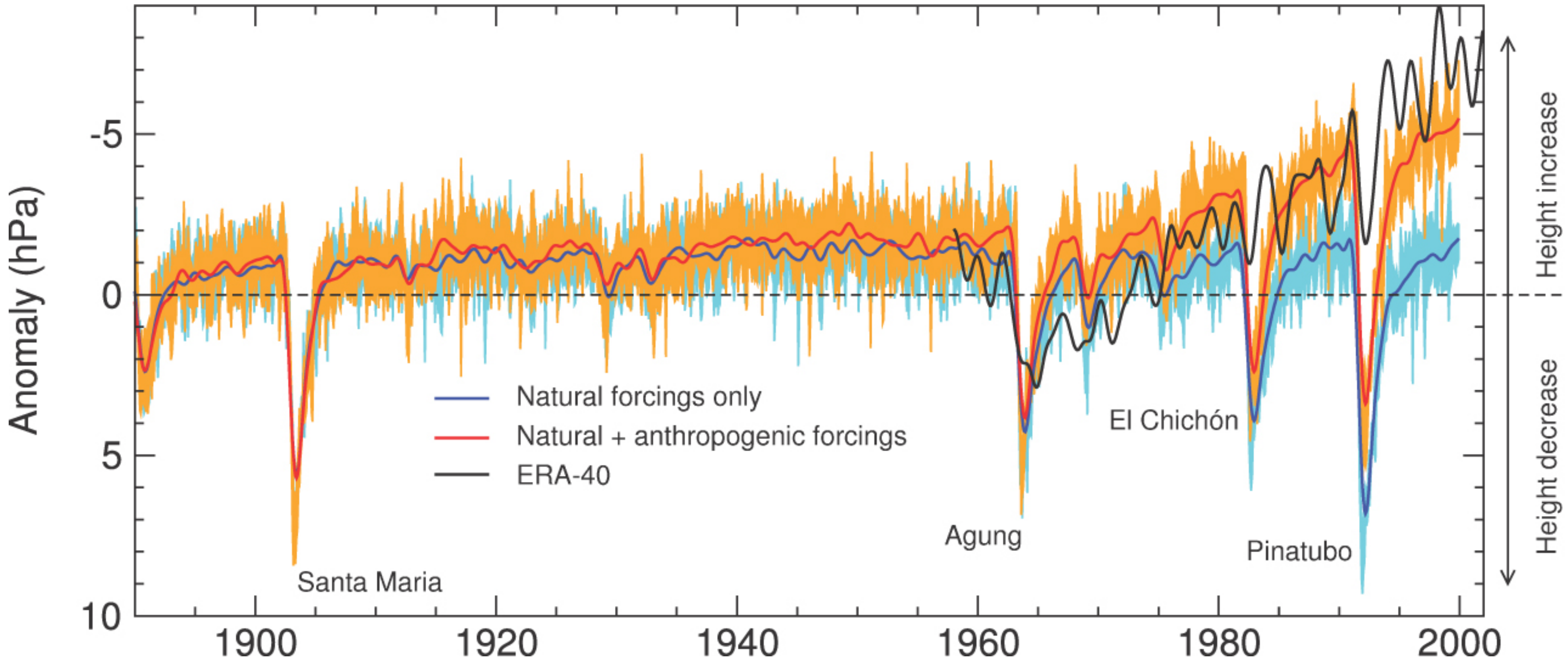
Canty et al., *ACP*, 2013



Problem 1: volcanic aerosols trapped infrared heat, offsetting much of the reflection of sunlight

Problem 2: Climate models tend to collapse the tropopause after major volcanic eruptions, which did not occur in the real atmosphere

perhaps due to placement of volcanic aerosol in the model troposphere: e.g., Figure 6.7 of the June 2010 CCMVal report

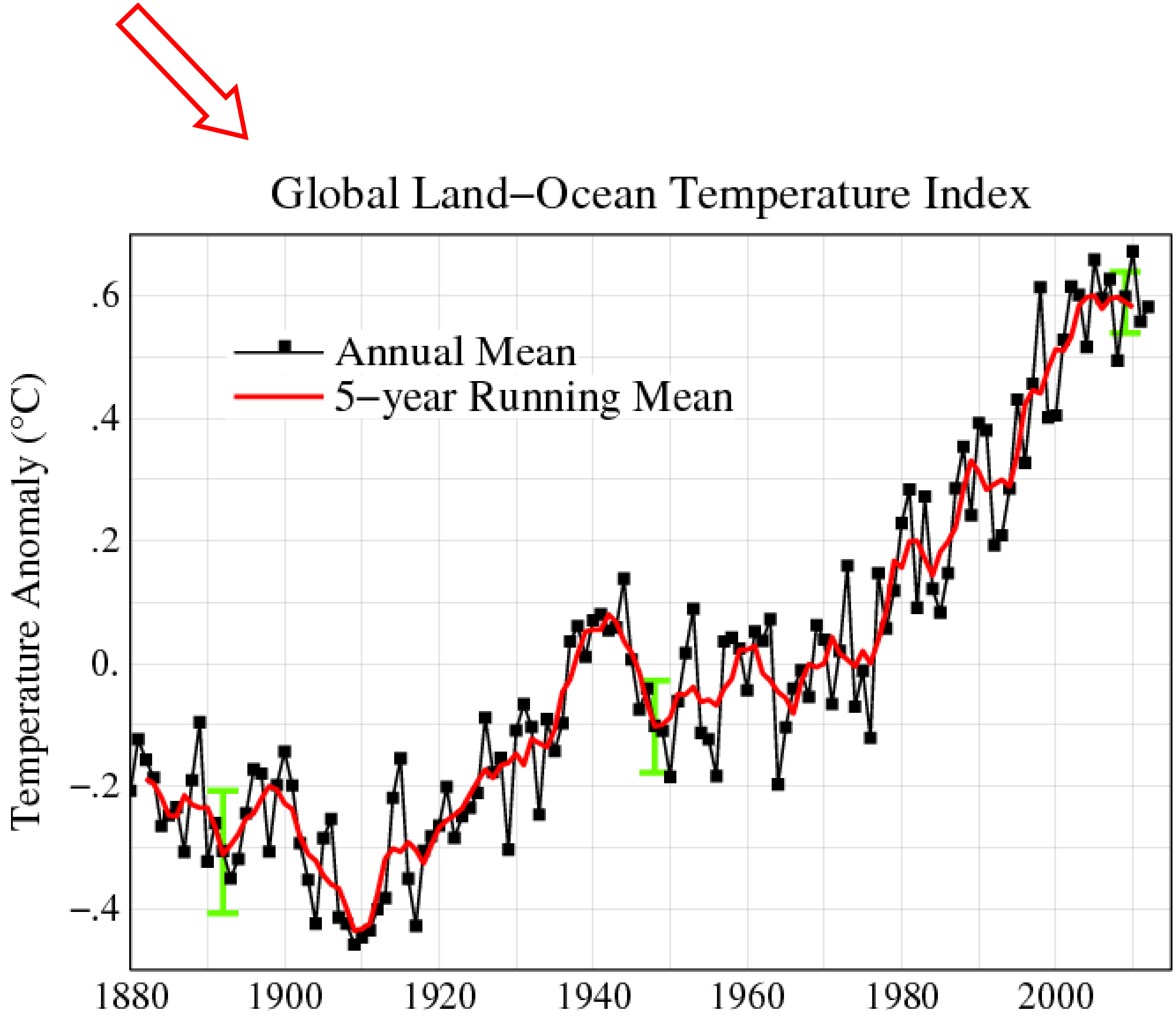


Comparison of reanalysis (BLACK LINE) and modeled global, monthly mean tropopause height anomalies.

IPCC 2007, Fig 9.14

Canty et al. also address a long-standing climate mystery

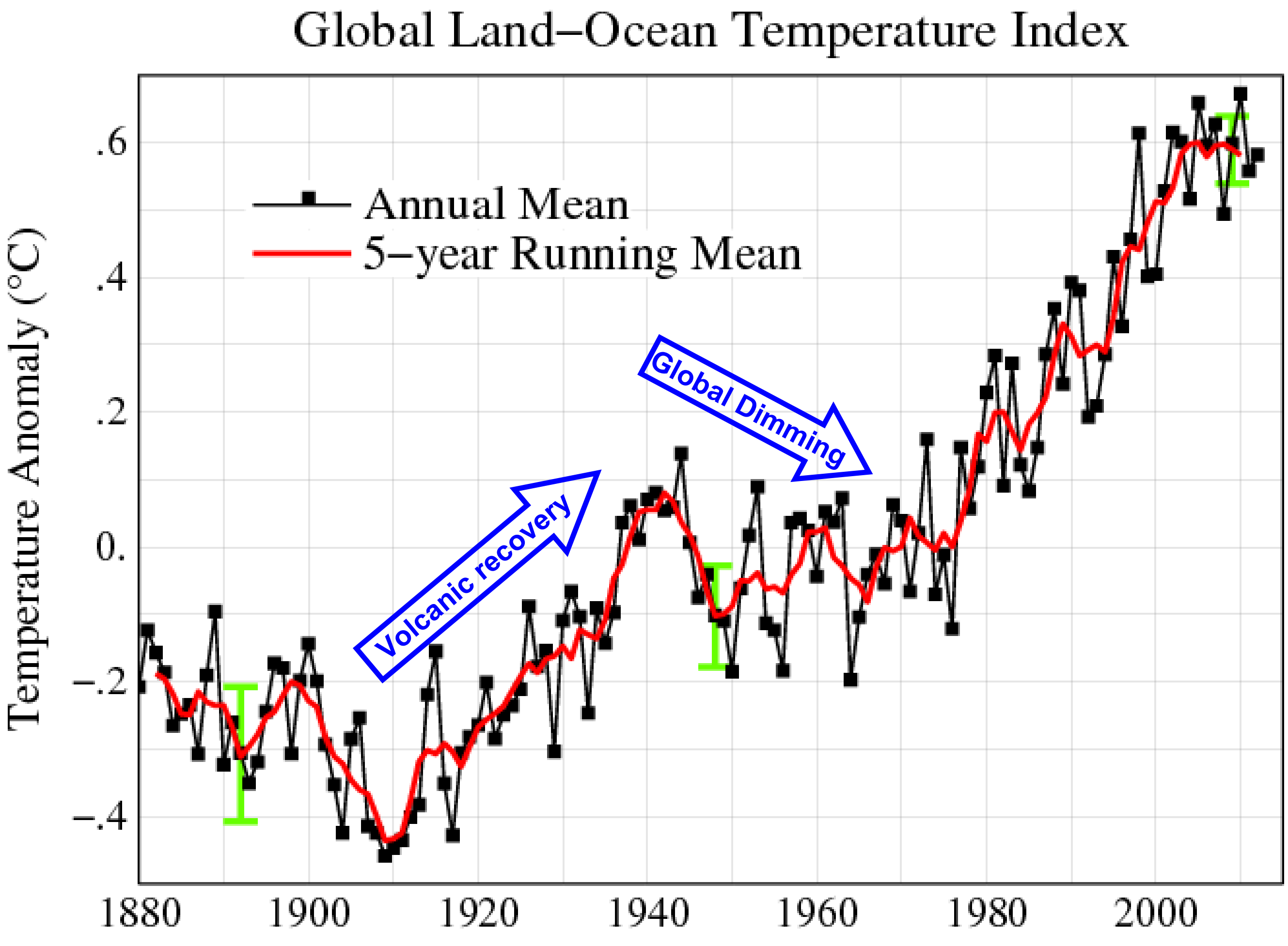
Global averaged surface temperature has <u>not</u> risen in a monotonic fashion:



Canty et al. also address a long-standing climate mystery

Global averaged surface temperature has <u>not</u> risen in a monotonic fashion:

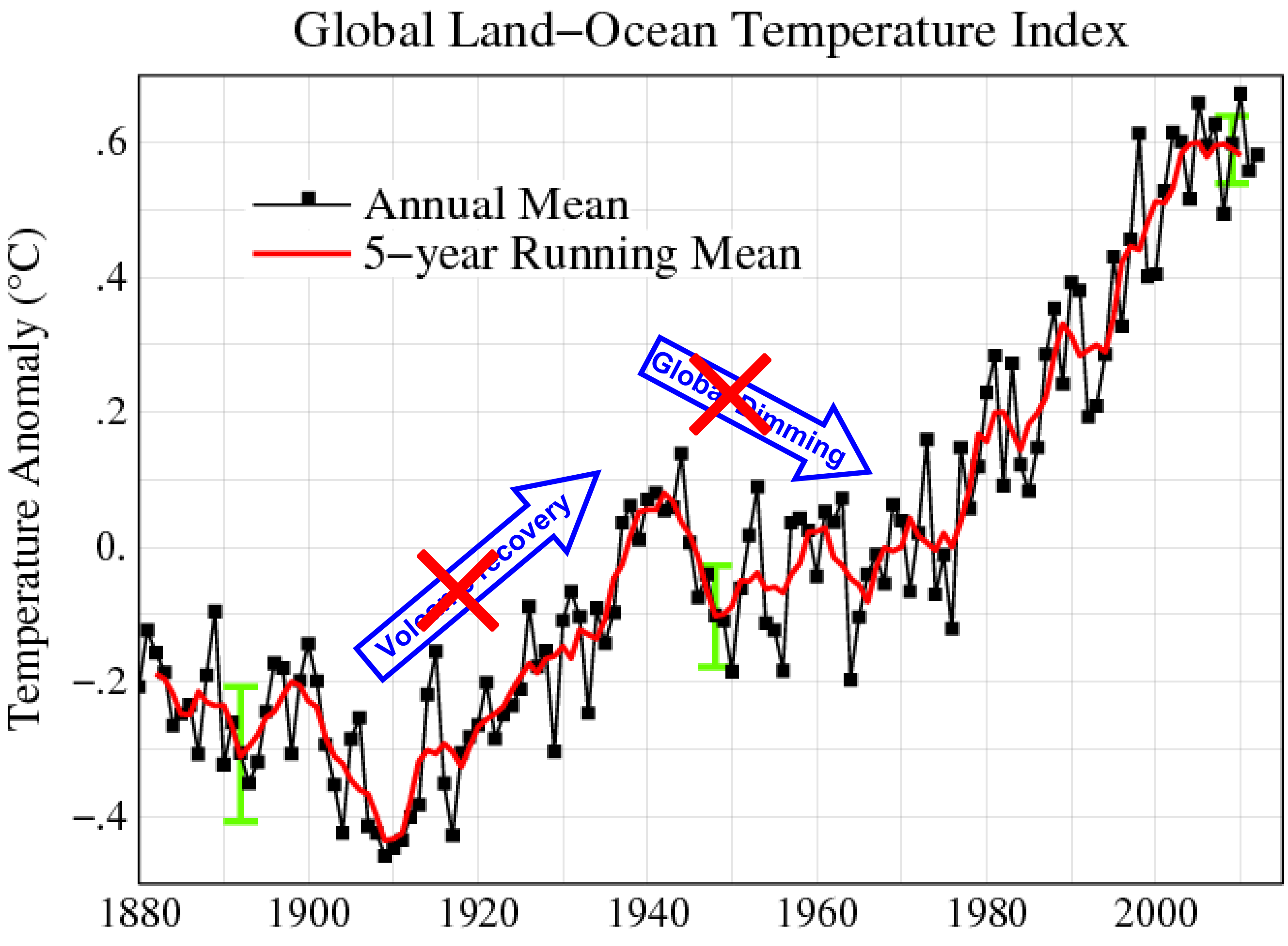
Many others have attributed post WWI warming to "recovery from earlier volcanoes" and post WWII cooling to "global dimming"



Canty et al. also address a long-standing climate mystery

Global averaged surface temperature has <u>not</u> risen in a monotonic fashion:

Canty et al. attribute post WWI warming & post WWII cooling to the influence on global climate of variations in the strength of the AMOC
(see slides 7, 12, 13, 17, 18 and 19)



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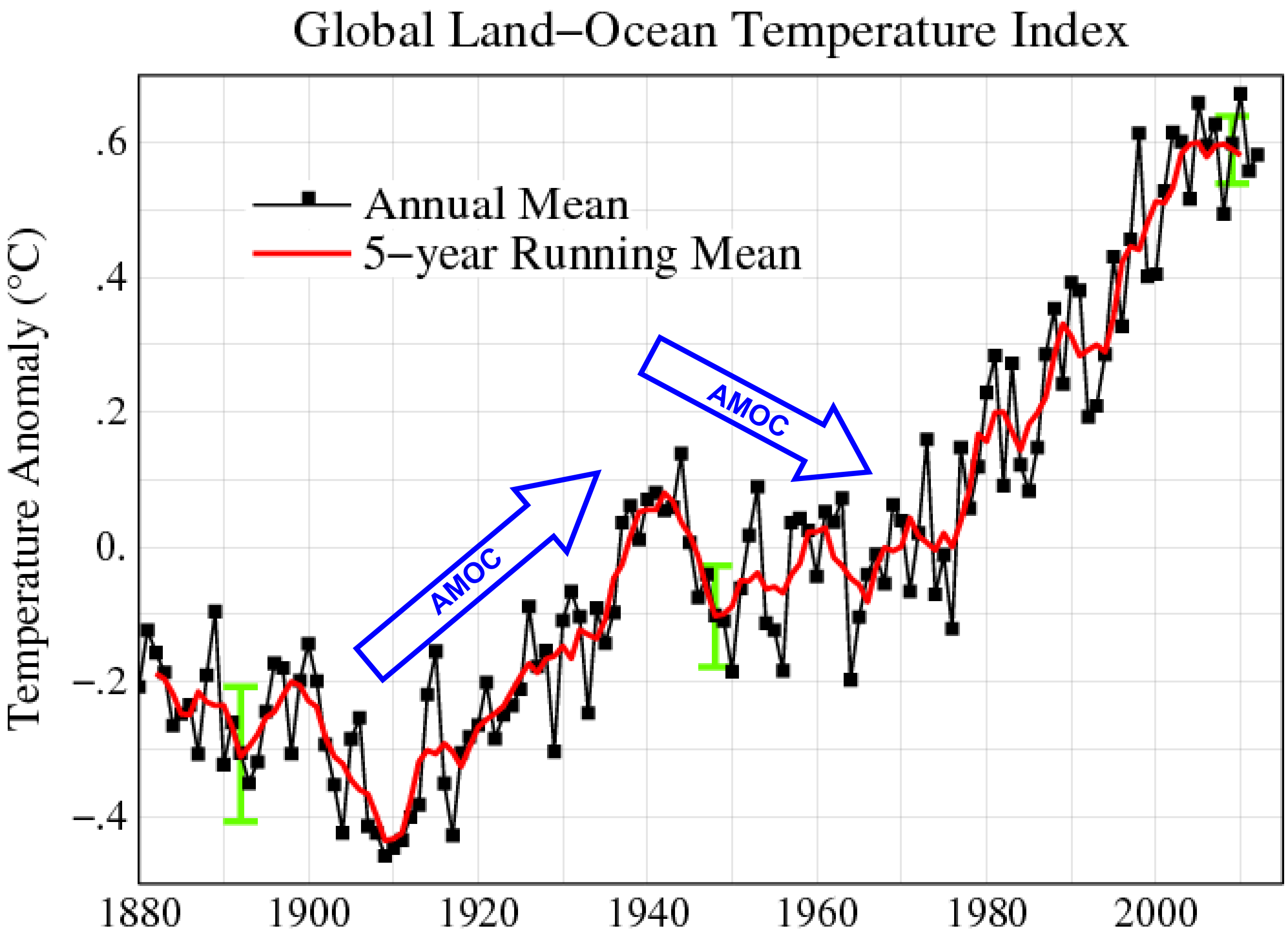
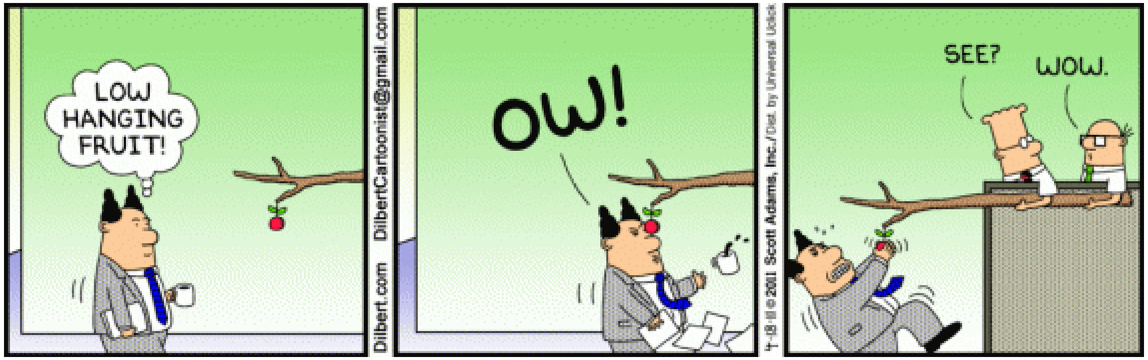
Global averaged surface temperature has not risen in a monotonic fashion:

Canty et al. attribute post WWI warming & post WWII cooling to the influence on global climate of variations in the strength of the AMOC (see slides 7, 12, 13, 17, 18 and 19)



Concluding Thoughts



Adding the AMV to a regression model of global climate was “low hanging fruit”:

- many others are now doing this !
- we did not set out to address volcanic cooling; rather we were curious whether the WWI cooling & WWII warming could be explained by AMOC
- we deemed sensitivity of volcanic cooling to proxy for AMOC to be the *most scientifically compelling aspect of this work*: one for which we have received harsh criticism

The beauty is that the scientific method will reveal the truth no matter the “size of the stick” ☺

Concluding Thoughts

1. **Surface cooled after eruptions of Krakatoa, Santa María, Agung, El Chichón, & Mt. Pinatubo BUT this cooling has probably been overestimated due to neglect of variations in the strength of the AMOC on global climate**
2. **Analysis of volcanic eruptions and geo-engineering should consider longwave trapping of heat as well as shortwave reflection by stratospheric sulfate aerosols**
3. **Analysis of volcanic eruptions and geo-engineering should take care to assure sulfate aerosols are *actually placed in the model stratosphere***
4. **Analysis of response of model tropopause height in response to volcanic or geo-engineering perturbation could reveal insight into a model deficiency:**

   the actual tropopause did not collapse after the eruption of Mt. Pinatubo