Global volcanic aerosol properties and volcanic forcing of global climate change since 1980

Anja Schmidt & Michael Mills

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Andrew Conley, Piers M. Forster, Andrew Gettelman,
Susan Solomon, and Owen B. Toon

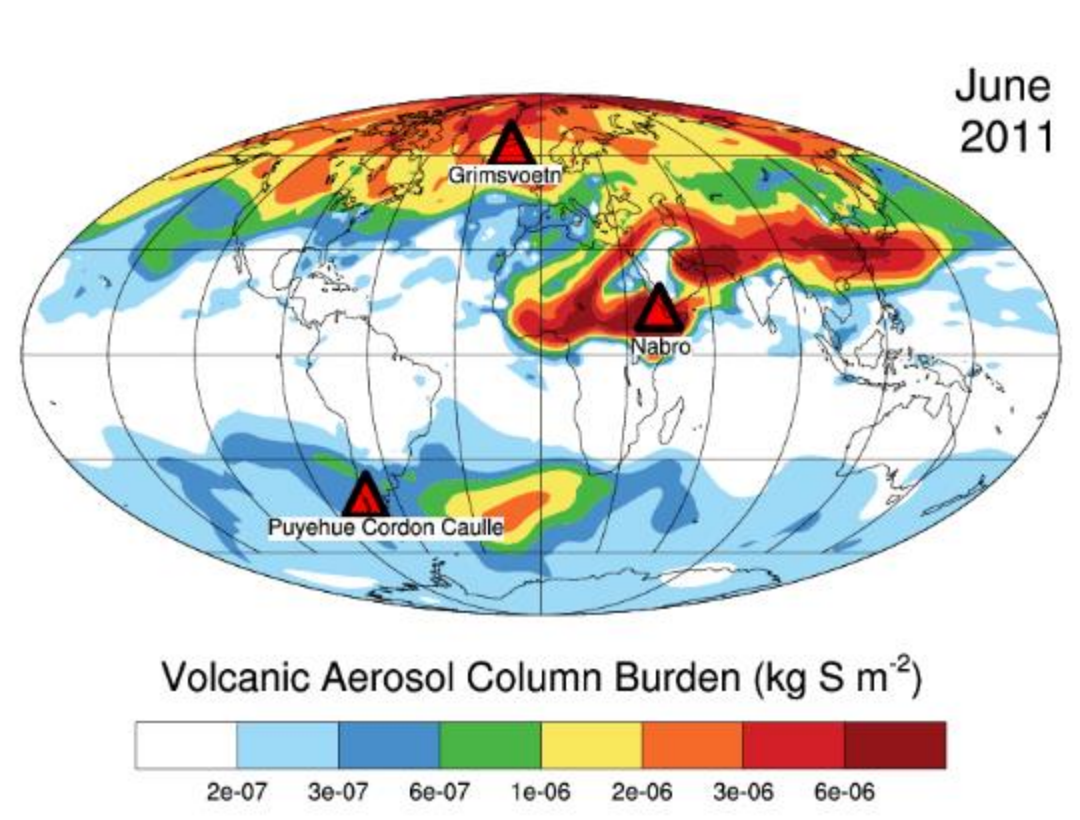
Status quo

Focus on large-magnitude eruptions (obs + models)

- 1991 Mt. Pinatubo (VEI 6)
  → 1 eruption every 50 years on average
- ~850 publications

Recently more recognition of role of ‘smaller’ explosive + effusive eruptions

- 2011 Nabro (VEI 4) → 1 eruption per year on average
- ~80 papers



Based on Mills, Schmidt et al. (2016)

Ocean heat uptake

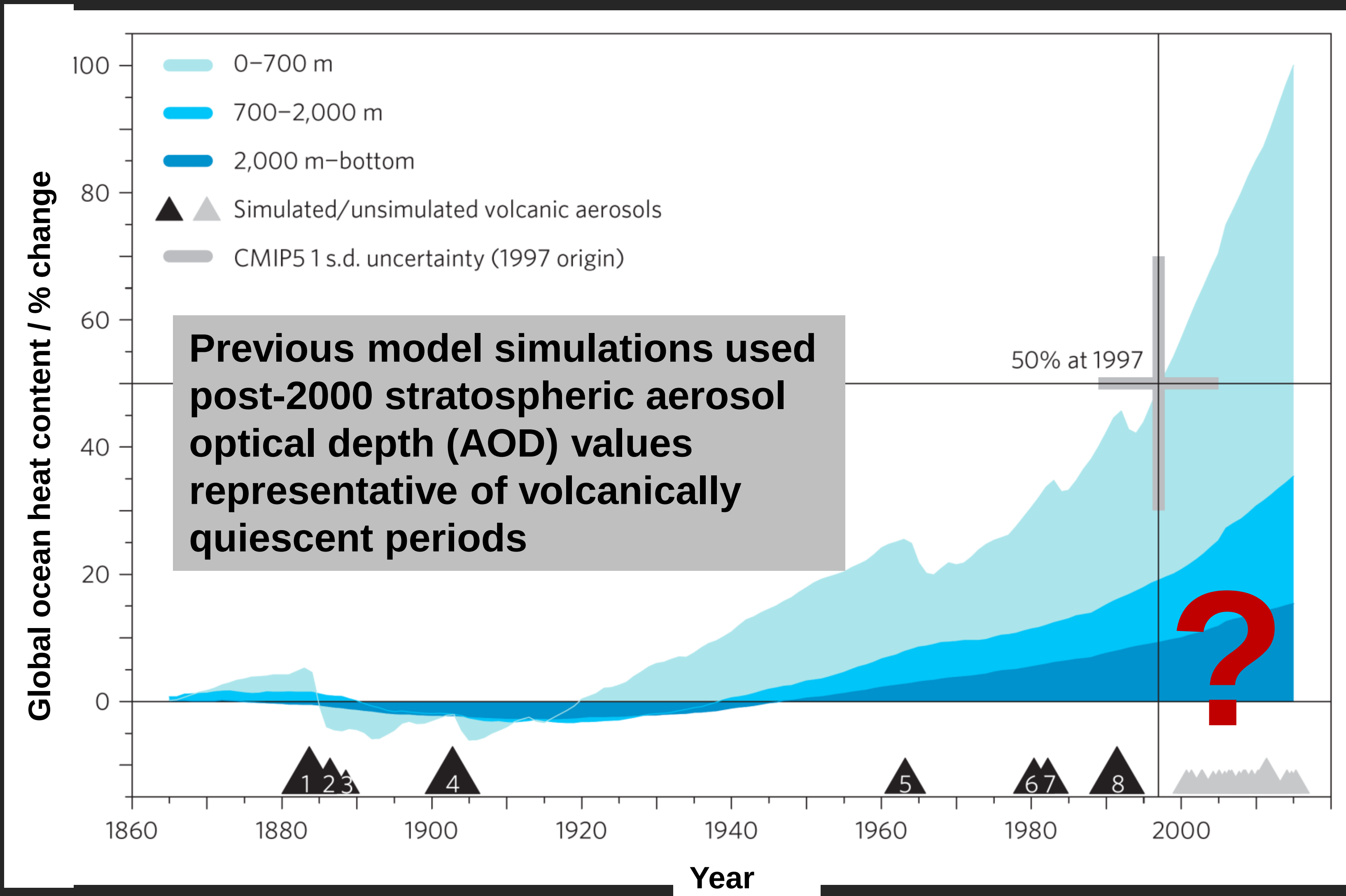
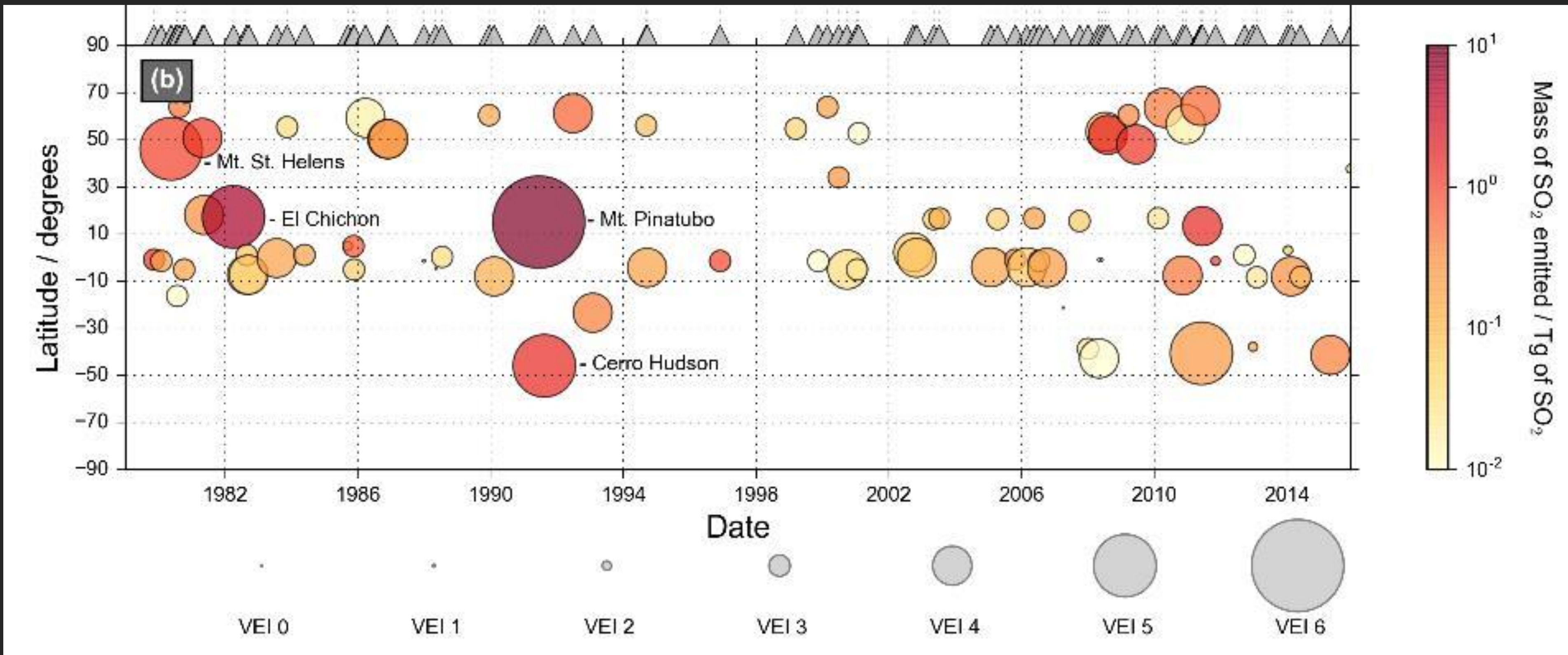


Figure from Gleckler et al. (2016), Nature CC

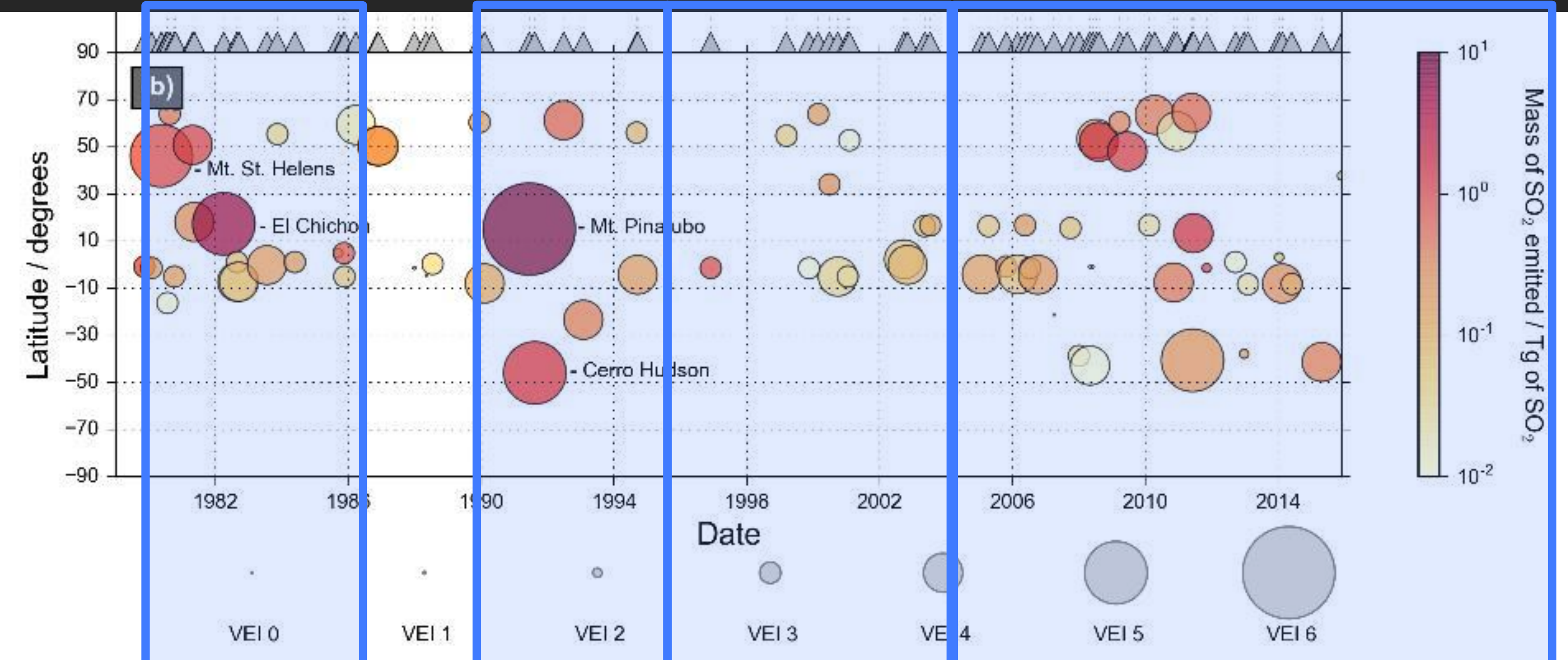
Volcanic eruptions since 1980

- Volcanic eruptions increasingly well characterized
  → Satellite retrievals, in-situ measurements, geochem. & geophys. Monitoring

- Several databases available (Bingen et al., 2017; Neely and Schmidt, 2016; Carn et al., 2016; Diehl et al., 2012)



Volcanic eruptions since 1980



VEI 5
1982 El Chichón
~6 Tg of SO_2

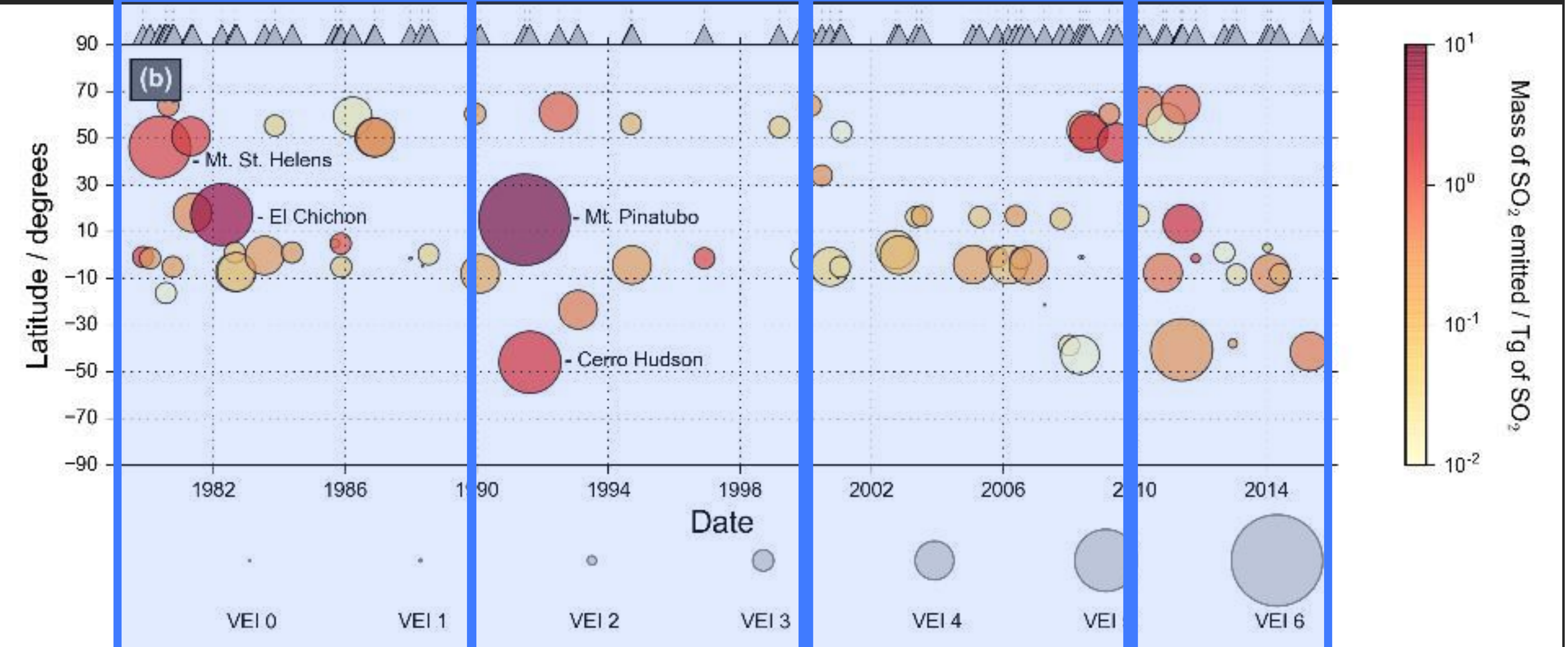
VEI 6
1991 Mt. Pinatubo
~10 Tg of SO_2

1996-2005 volcanically quiescent period

Post-2005 high frequency of small-to-moderate magnitude eruptions (VEI 3 & 4)

Emissions predominantly in upper troposphere / lower stratosphere

Small-to-moderate volcanic eruptions (VEI 3,4,5)



1980s:
18 eruptions
6.3 Tg of SO_2

1990s:
6 eruptions
1.4 Tg SO_2

2000s:
22 eruptions
5.3 Tg SO_2

2010-2015:
10 eruptions
3.7 Tg SO_2

Research questions

What is the impact of post-2005 small-to-moderate magnitude eruptions on stratospheric aerosol properties and global climate change?

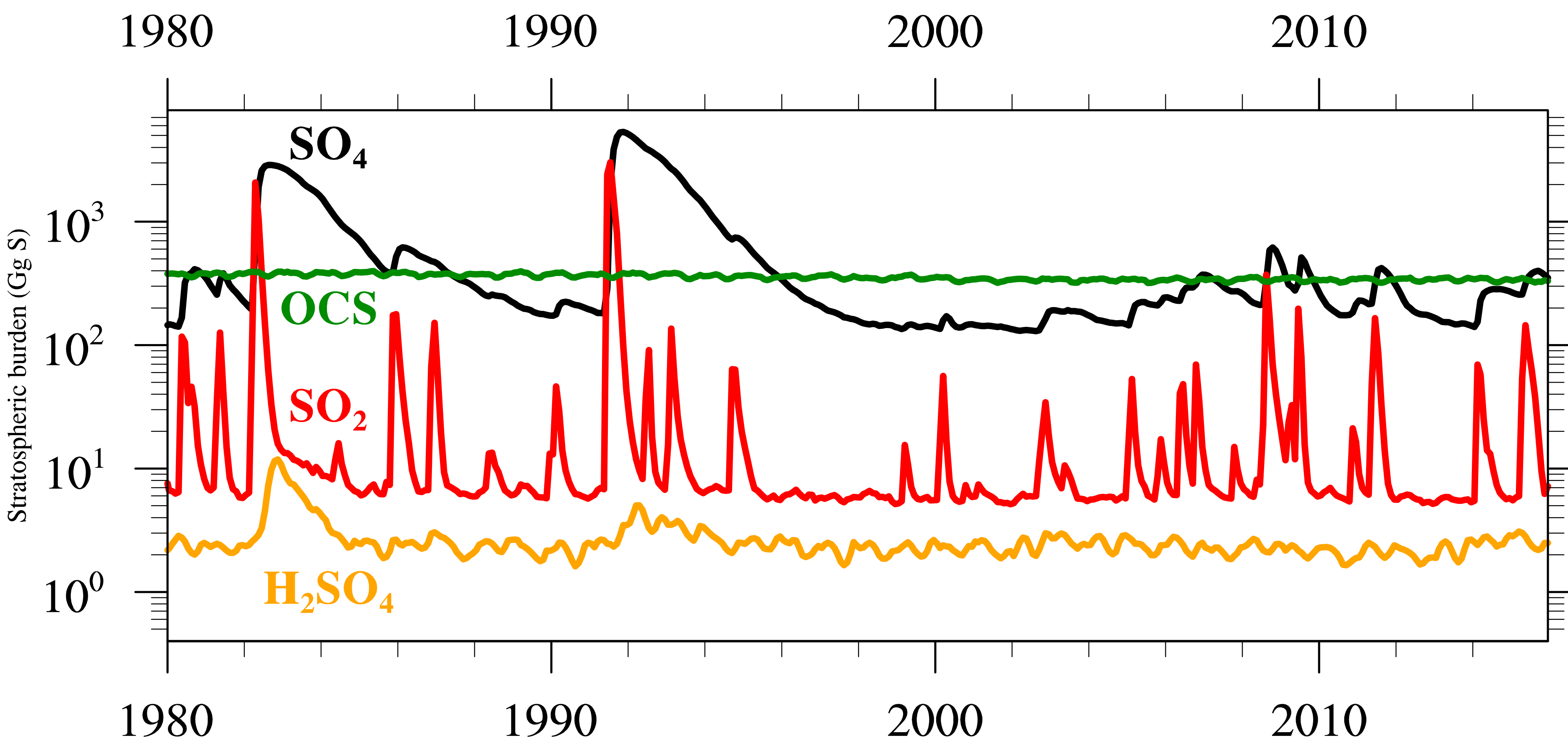
How frequent are small-to-moderate magnitude eruptions? Is the period 2005-2015 unusual?

A recent paper by Ge et al. (2016) suggested that “IPCC’s volcanic sulfate radiative forcing efficiency (with respect to AOD) has a factor of 2-4 low bias”. Is this true?

Methods

CESM-WACCM with interactive chemistry and prognostic modal stratospheric aerosols

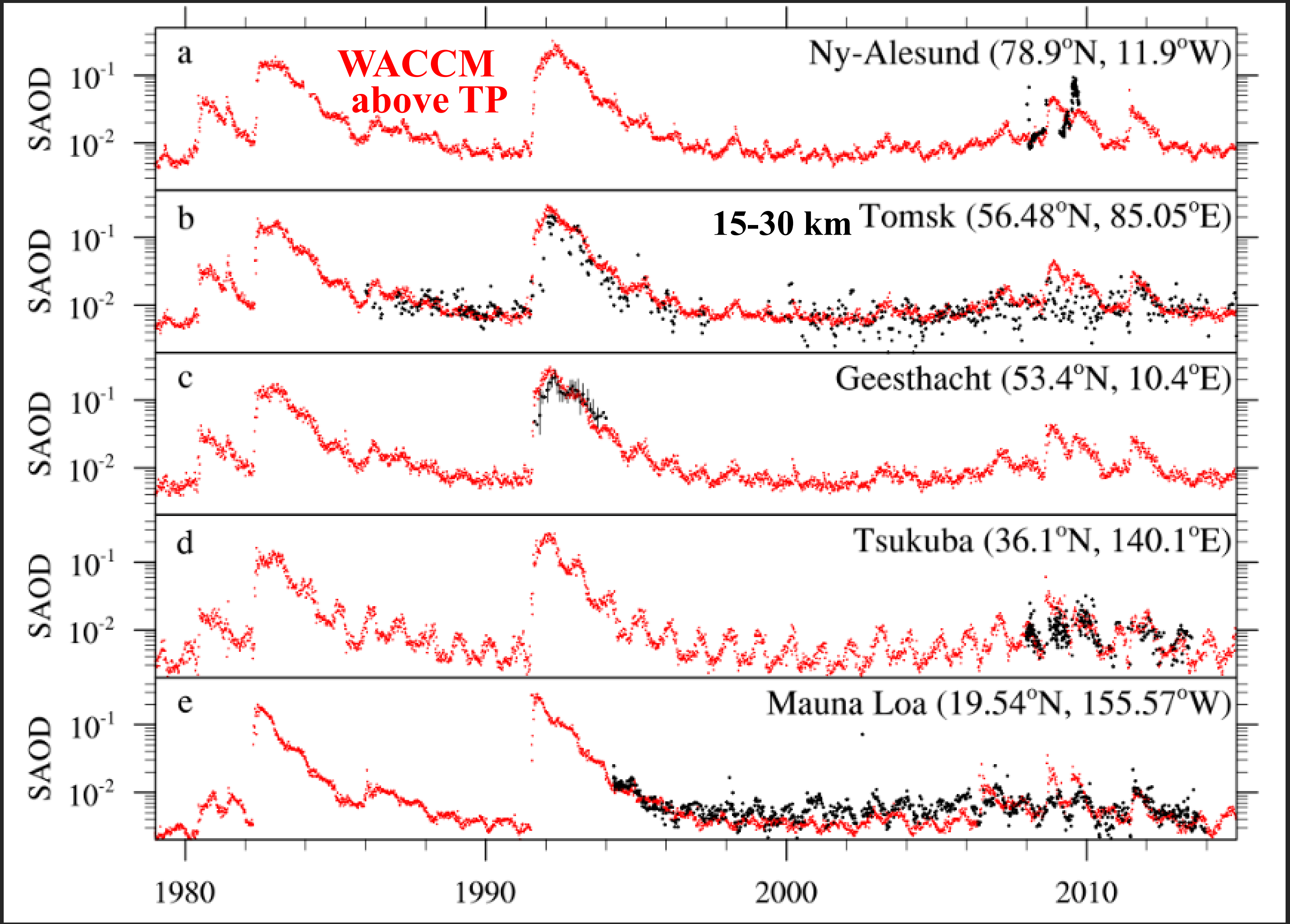
WACCM 1980-2015: stratospheric sulfur burdens



OCS: 360 Gg S, close to MIPAS (M. Höpfner)
Background sulfate close to CMIP6's 164 Gg S

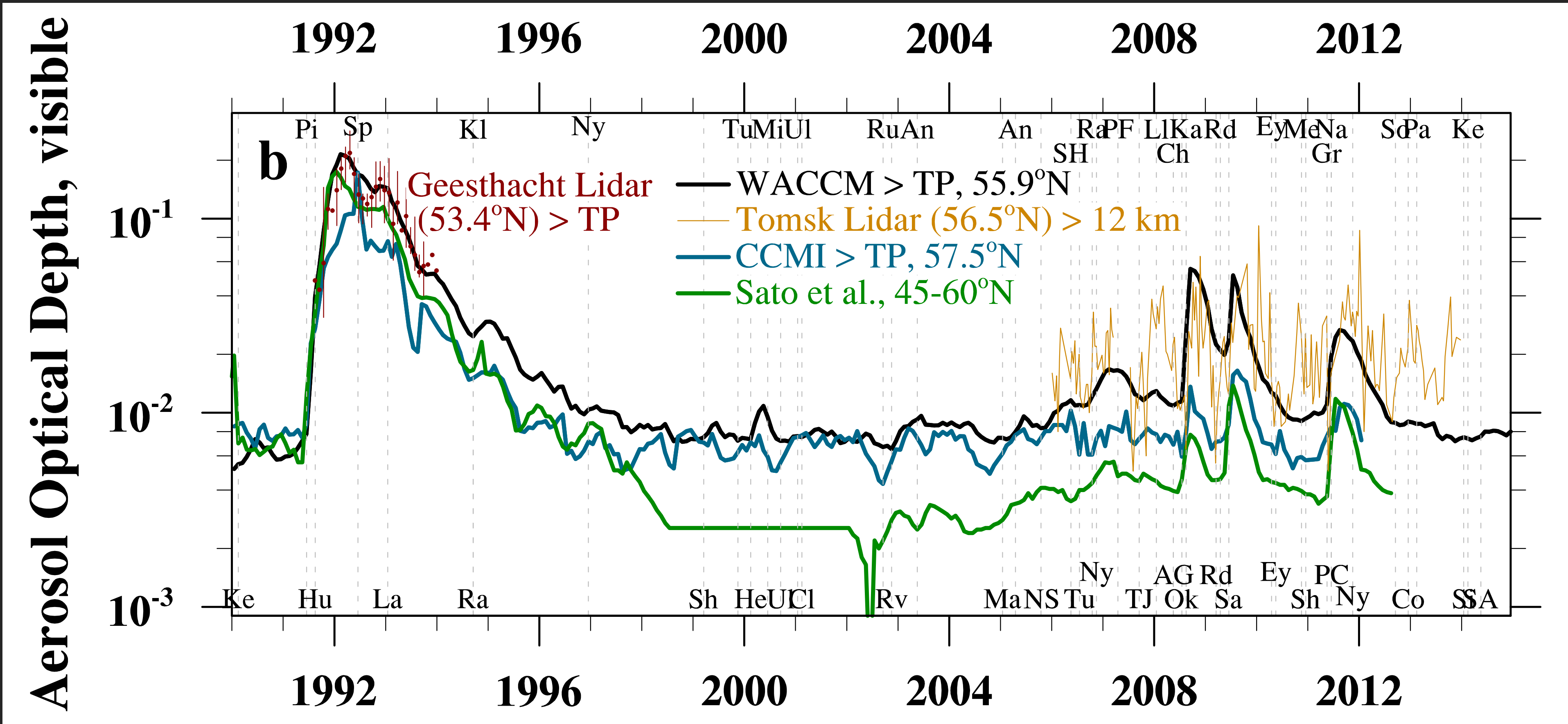
Corrected and extended version of figure from Mills, Schmidt et al., 2016, JGR

1979-2015 WACCM simulations compared to lidars



1990-2015 CESM1(WACCM) simulations

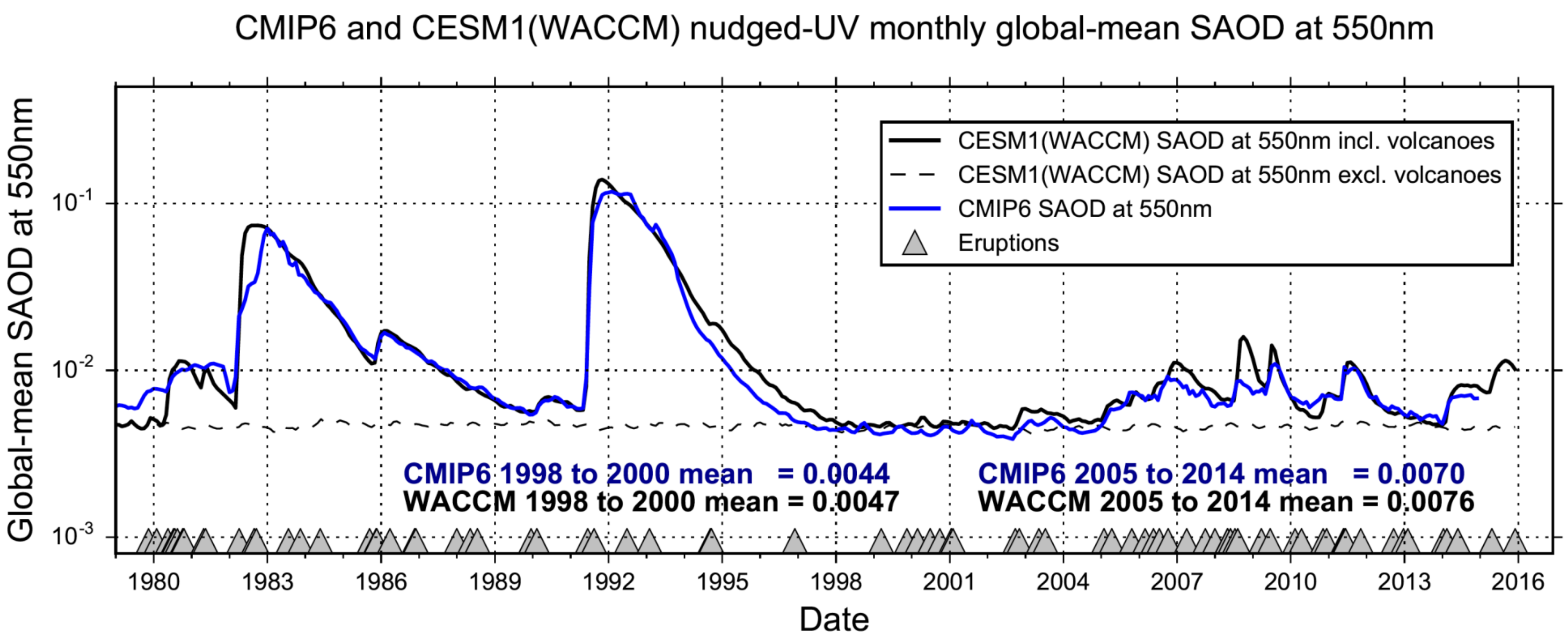
- Comparison to lidar data shows good agreement & reveals limitations of previously used satellite datasets (i.e. neglect of volcanic aerosol between tropopause and 380 K potential temperature level)



Mills, Schmidt et al., 2016, JGR

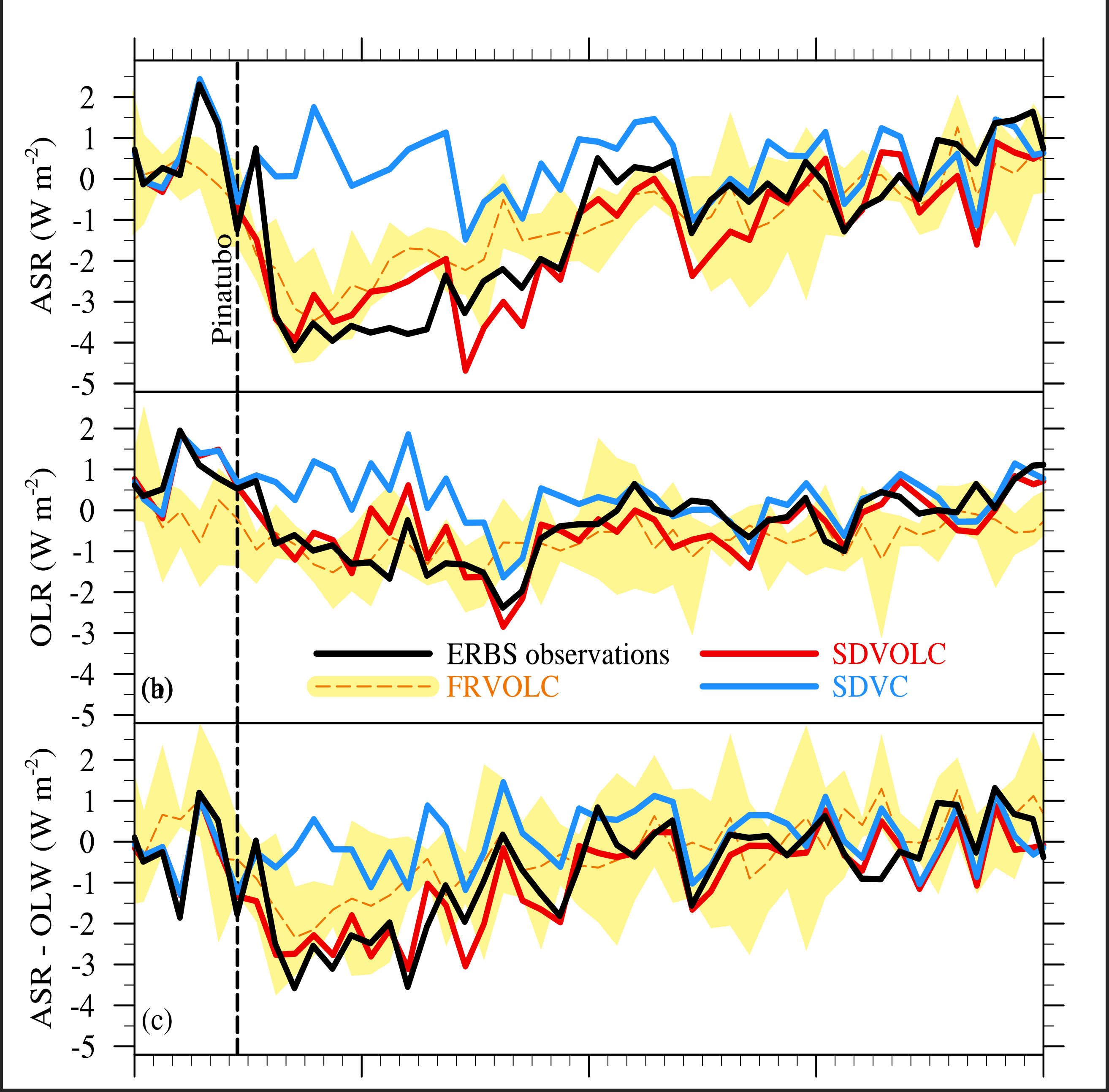
1980-2015 CESM1(WACCM) simulations

- Comparison to CMIP6 SAOD
- Very good agreement in quiescent and volcanically-perturbed periods



Schmidt et al., in prep

Radiative response validation



Absorbed shortwave (ASR)

Outgoing longwave (OLR)

ASR - OLR

Mills et al., JGR, 2017

Small-magnitude eruptions are frequent

(b) VEI=3, 4, 5 N=36 dt=1yr λ=1.81

x	p(x)	Np(x)	Obs
0	0.164	5.918	5
1	0.297	10.685	12
2	0.268	9.646	10
3	0.161	5.806	4
4	0.073	2.621	4
5	0.026	0.946	1
6	0.008	0.285	0
7	0.002	0.073	0

$$p(x) = \lambda^x e^{-\lambda} / x!$$

x = number of occurrences (or absence) of eruptions in given VEI cat
λ = mean number of eruptions per dt
p(x) = Poisson probability
Np(x) = calculated expected number of eruptions
Obs = number of eruptions based on database
N = number of years of data
dt = time interval of data

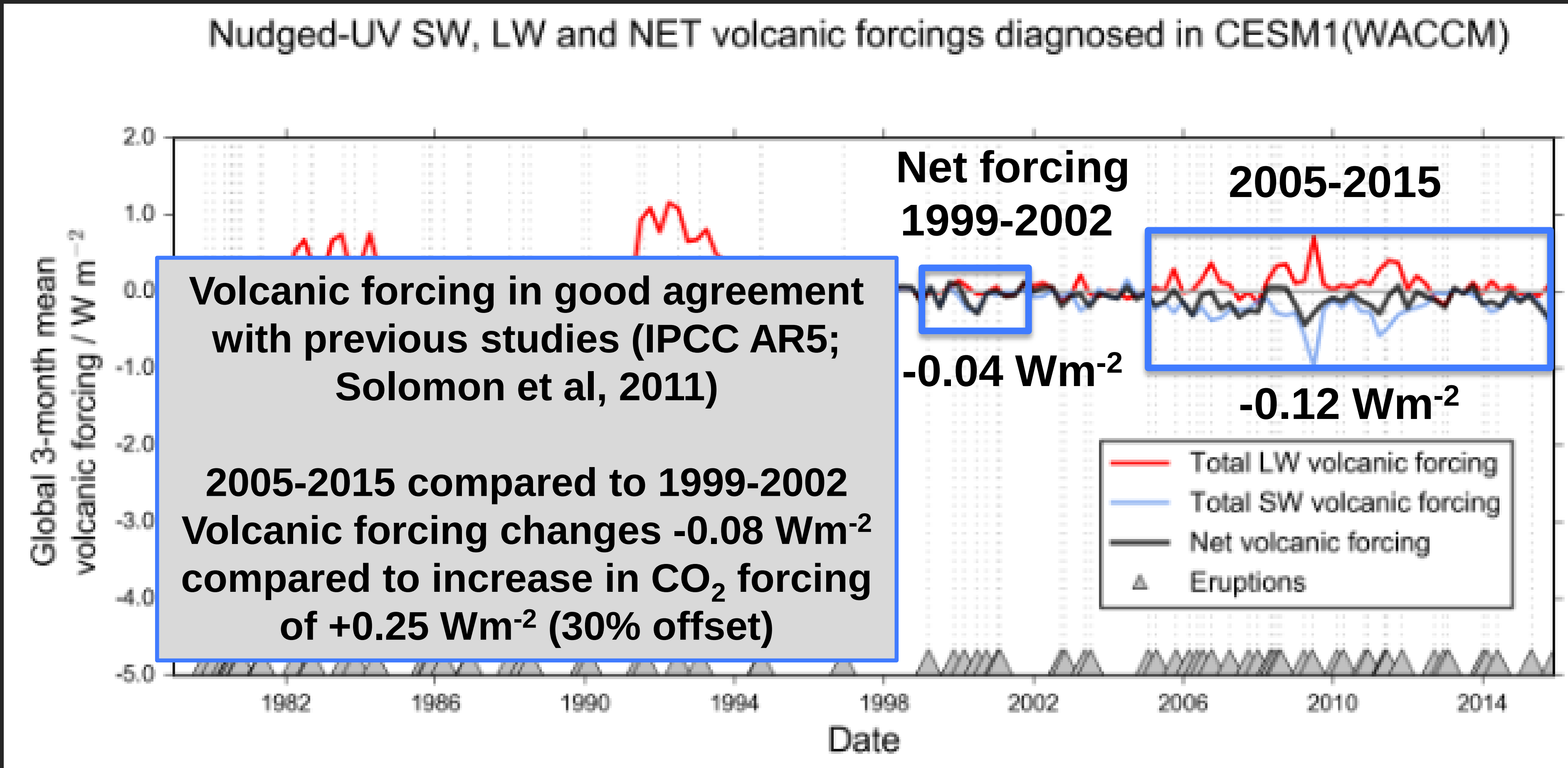
- Chance of no VEI 3, 4 or 5 eruption in any given year = 16%
- Chance of one or two VEI 3, 4, or 5 eruptions per year = 57%
- Chance of three or more VEI 3, 4, or 5 eruptions per year = 27%
- Frequency Pinatubo-magnitude eruptions (VEI 6) = 1 every 50 years

Volcanically quiescent periods are statistically rarer than periods of frequent small-to-moderate magnitude eruptions (VEI 3, 4 or 5)

Climate model studies ought to represent occurrence of these eruptions

Schmidt et al., in prep

Up-to-date volcanic radiative forcing estimates



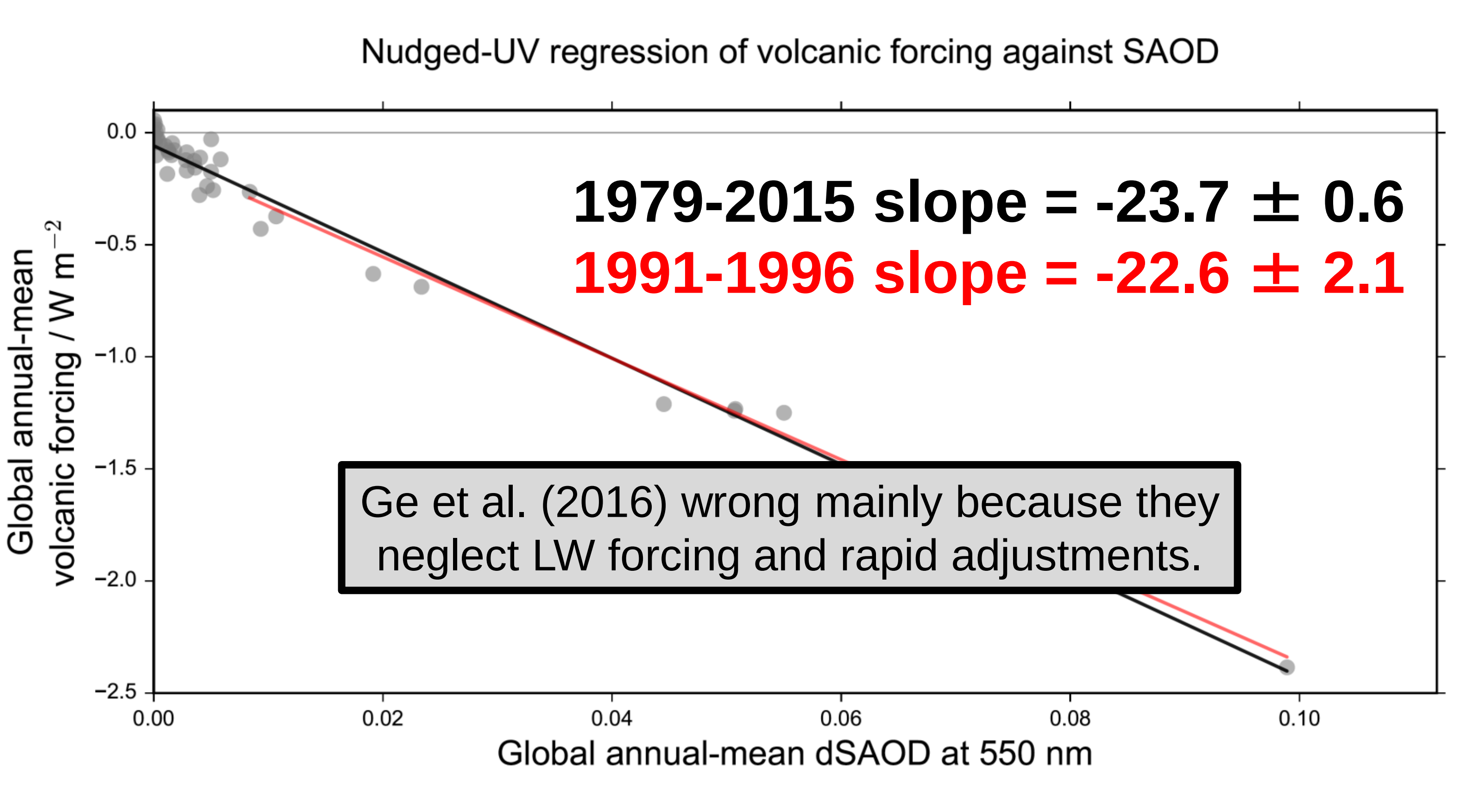
Volcanic forcing in good agreement with previous studies (IPCC AR5; Solomon et al, 2011)

2005-2015 compared to 1999-2002 Volcanic forcing changes -0.08 Wm^{-2} compared to increase in CO_2 forcing of +0.25 Wm^{-2} (30% offset)

Small-magnitude eruptions matter!
And they are <u>frequent</u> …

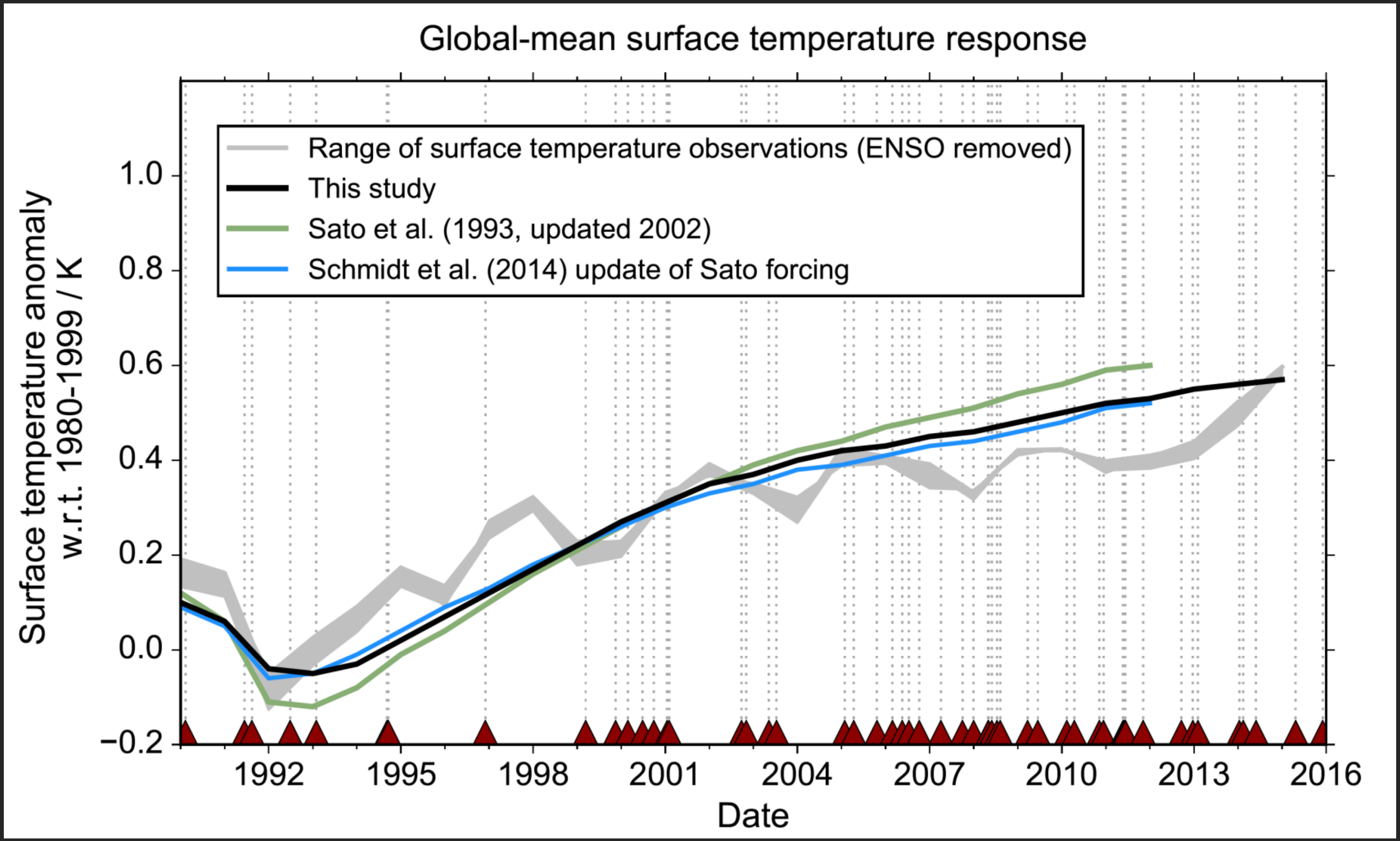
Regression of volcanic forcing against SAOD

Key metric used by IPCC: ΔF = -26 W m^{-2} per unit volcanic SAOD change
Ge et al. (2016): -40 to -80 W m^{-2} per unit volcanic SAOD change



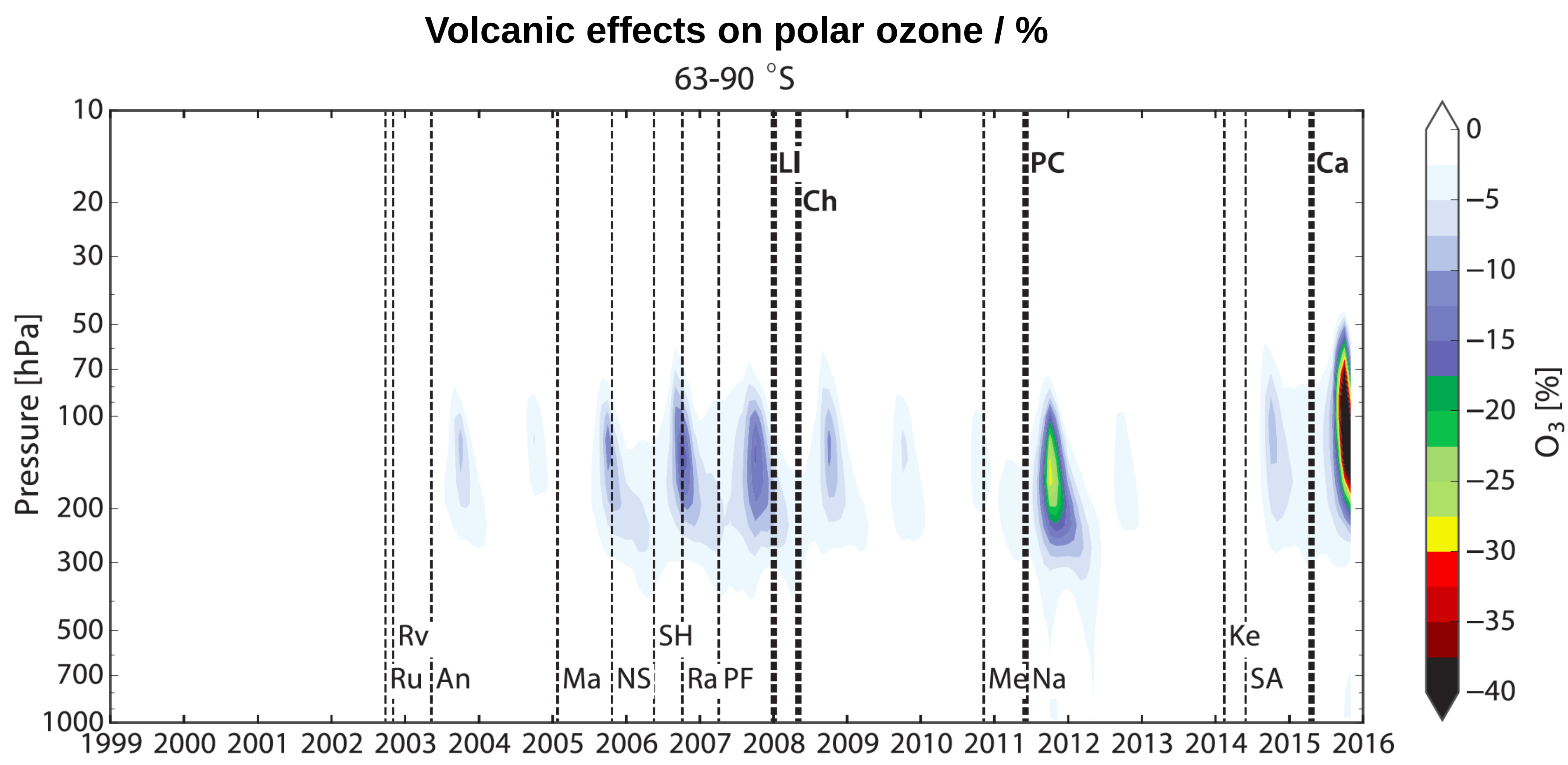
Forcing for large-magnitude eruptions (VEI≥6) per unit SAOD change is up to 30% smaller when rapid adjustments are considered compared to IPCC AR5 (in line w/ Gregory et al., 2015; Larson and Portmann, 2016)

Impact on global mean temperatures



Energy budget model calculations illustrate that post-2005 volcanic forcing results in small (about -0.07℃), but discernible in (model-simulated) global-mean decadal surface temperature changes.

Effects on polar ozone



2015 Calbuco eruption (Chile, VEI=4) caused additional ozone loss over Antarctica, resulting in an ozone hole ~4 million km^2 larger than without the eruption

Solomon et al. (incl. Schmidt), 2016, Science

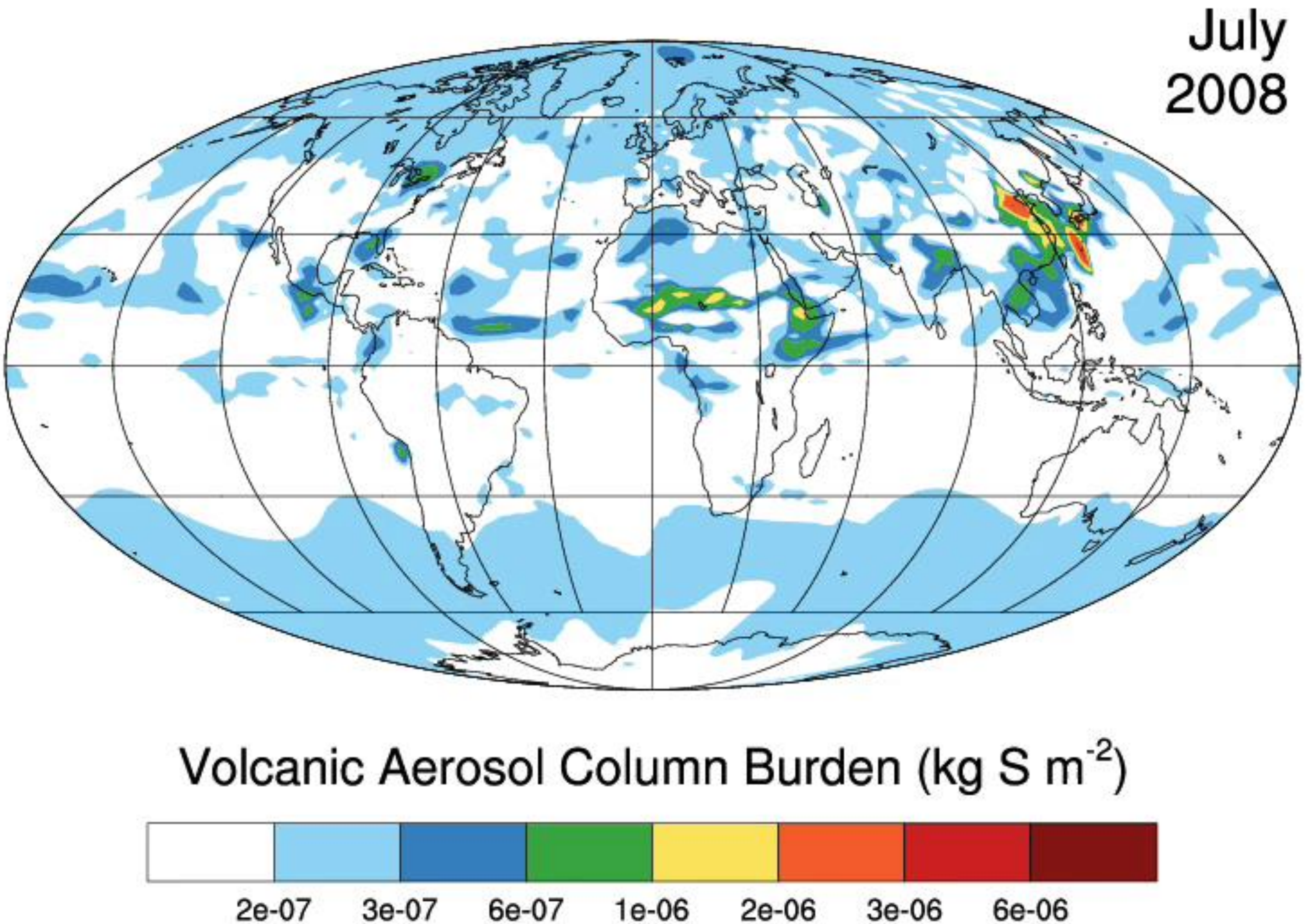
Summary

Mills, Schmidt et al. (2016), JGR
Solomon et al. (2016), Science
Mills et al. (2017), JGR
Schmidt et al., in prep

- Aerosol-climate models now rely on volcanic sulfur dioxide emissions estimates and other source term parameters
- CESM-WACCM stratospheric sulfur budgets and stratospheric aerosol properties and radiative responses are well validated in the satellite era (1979-2015)
- Small-to-moderate magnitude eruptions matter
    - Volcanically quiescent periods are statistically rarer than periods of frequent small-to-moderate magnitude eruptions
    - Change in time-mean global-mean volcanic forcing of -0.08 W m^{-2} during 2005-2015 relative to 1999-2002
    - Eruptions can affect recovery of polar ozone
- We are happy to share output, and eager to compare to observations!

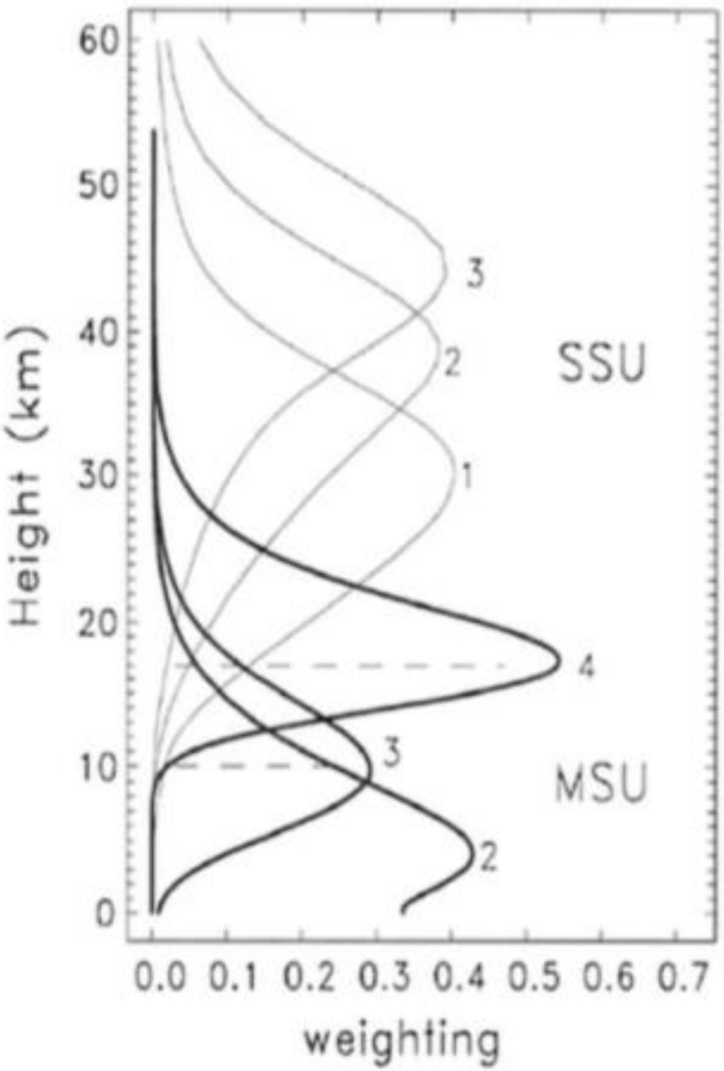
THANK YOU! @volcanofile

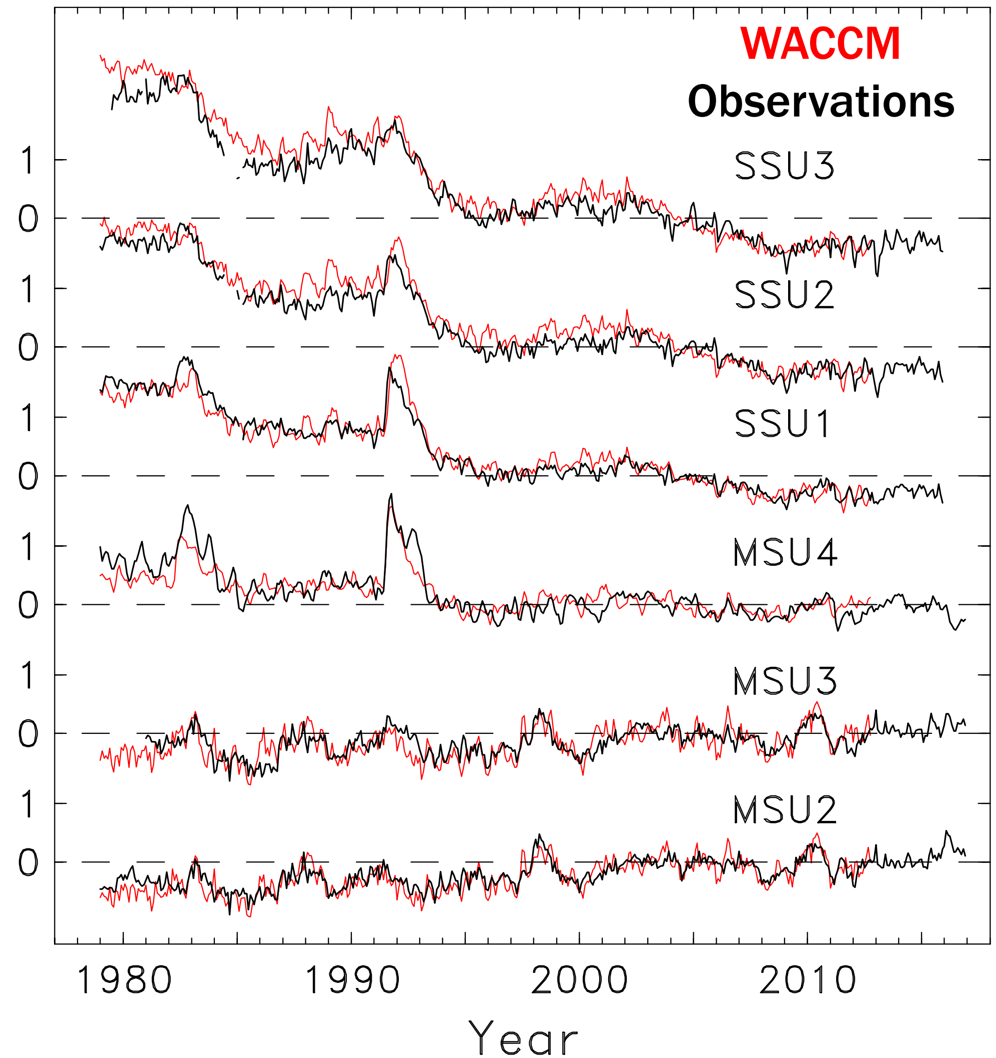
as2737@cam.ac.uk


July
2008
Volcanic Aerosol Column Burden (kg S m^{-2})
2e-07
3e-07
6e-07
1e-06
2e-06
3e-06
6e-06

Additional slides

Radiative response validation

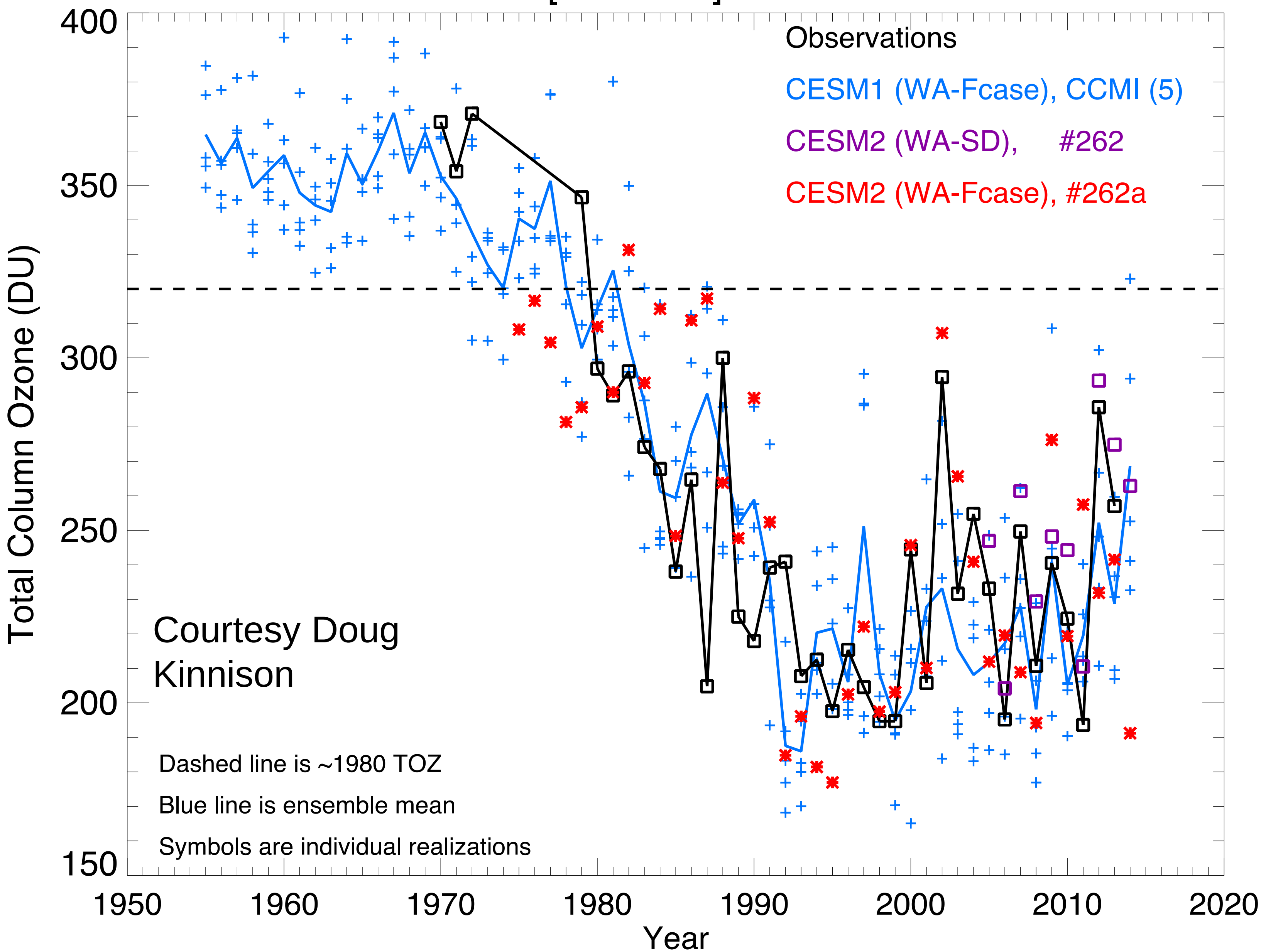




WACCM6 run (1 realization) global stratospheric temperatures compare very well to observations, including volcanic heating.
Figure courtesy of Doug Kinnison, Fei Wu and Bill Randel, NCAR.

NCAR WACCM Whole Atmosphere Community Climate Model

TCO [63S-90S] - October

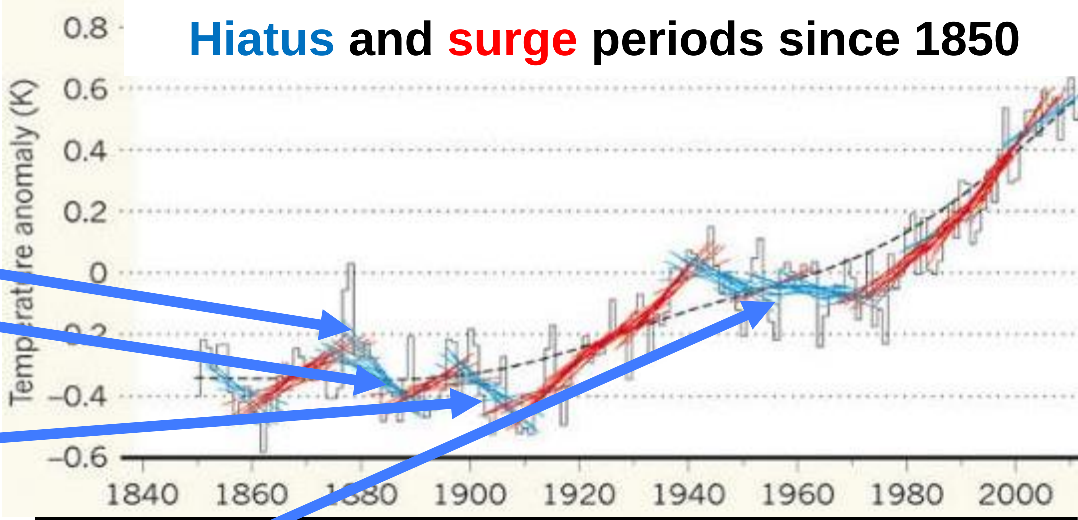


Eruption frequencies vs hiatus & surge periods

No. of eruptions per decade since 1850

	VEI=4	VEI=5	VEI=6	VEI>=4
1850s	3	1	0	4
1860s	2	0	0	2
1870s	6	1	0	7
1880s	7	1	1	9
1890s	3	0	0	3
1900s	4	1	1	6
1910s	7	2	1	10
1920s	4	0	0	4
1930s	6	1	0	7
1940s	4	0	0	4
1950s	6	1	0	7
1960s	5	1	0	6
1970s	4	0	0	4
1980s	7	2	0	9
1990s	5	1	1	7
2000s	10	0	0	10
2010-2015	7	1	0	8

Hiatus and surge periods since 1850

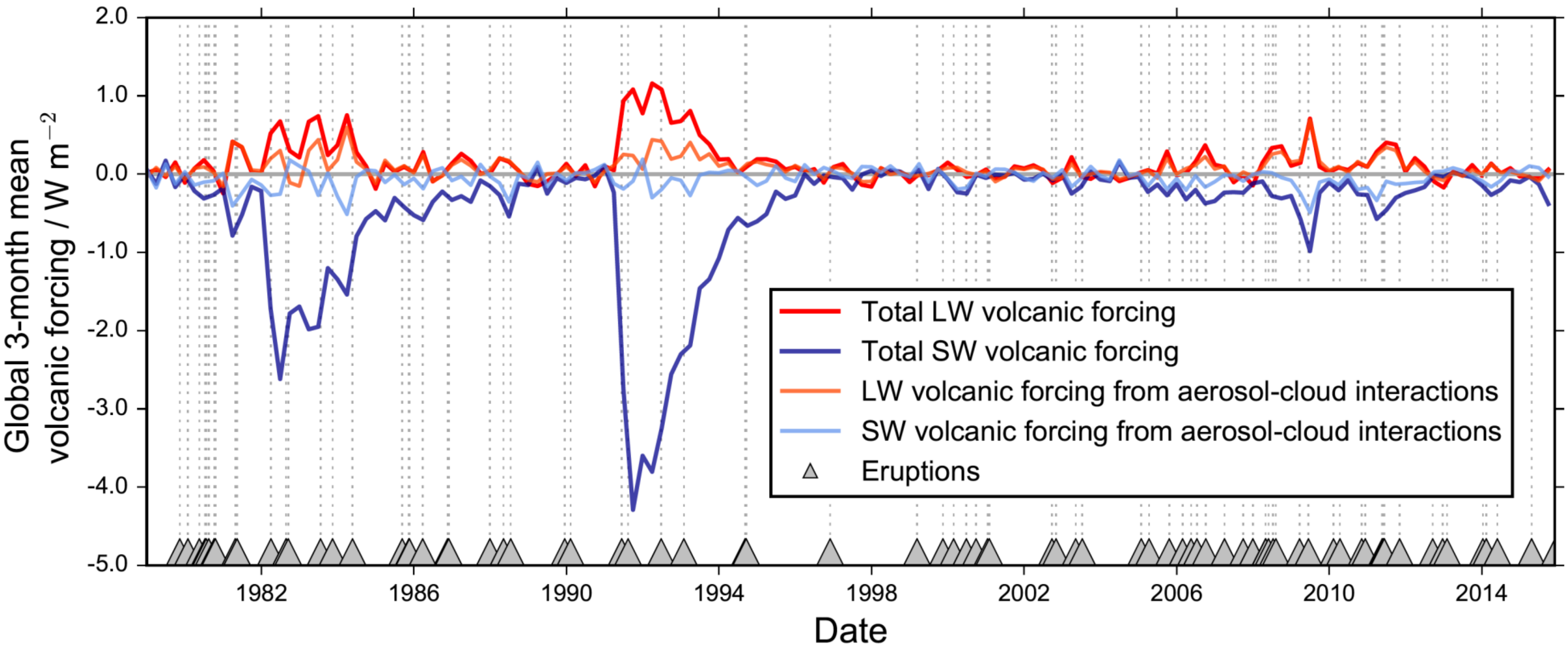


Rate of global warming not constant over time (hiatus and surge periods)

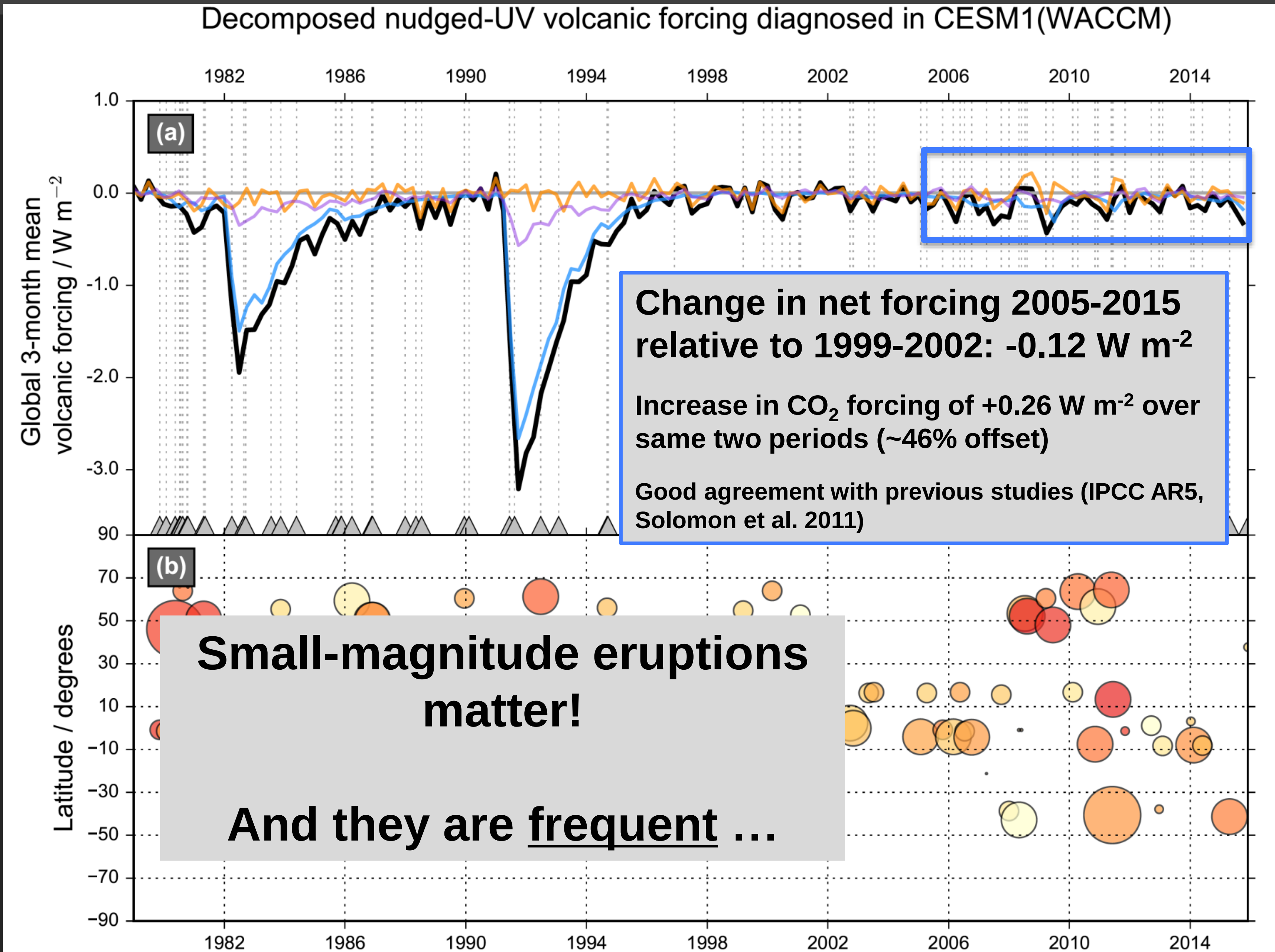
Role of volcanic eruptions in contributing to these hiatus and surge periods

Based on data from Smithsonian Global Volcanism Program

Nudged-UV SW and LW volcanic forcings diagnosed in CESM1(WACCM)



Up-to-date volcanic radiative forcing estimates



Change in net forcing 2005-2015 relative to 1999-2002: -0.12 W m^{-2}

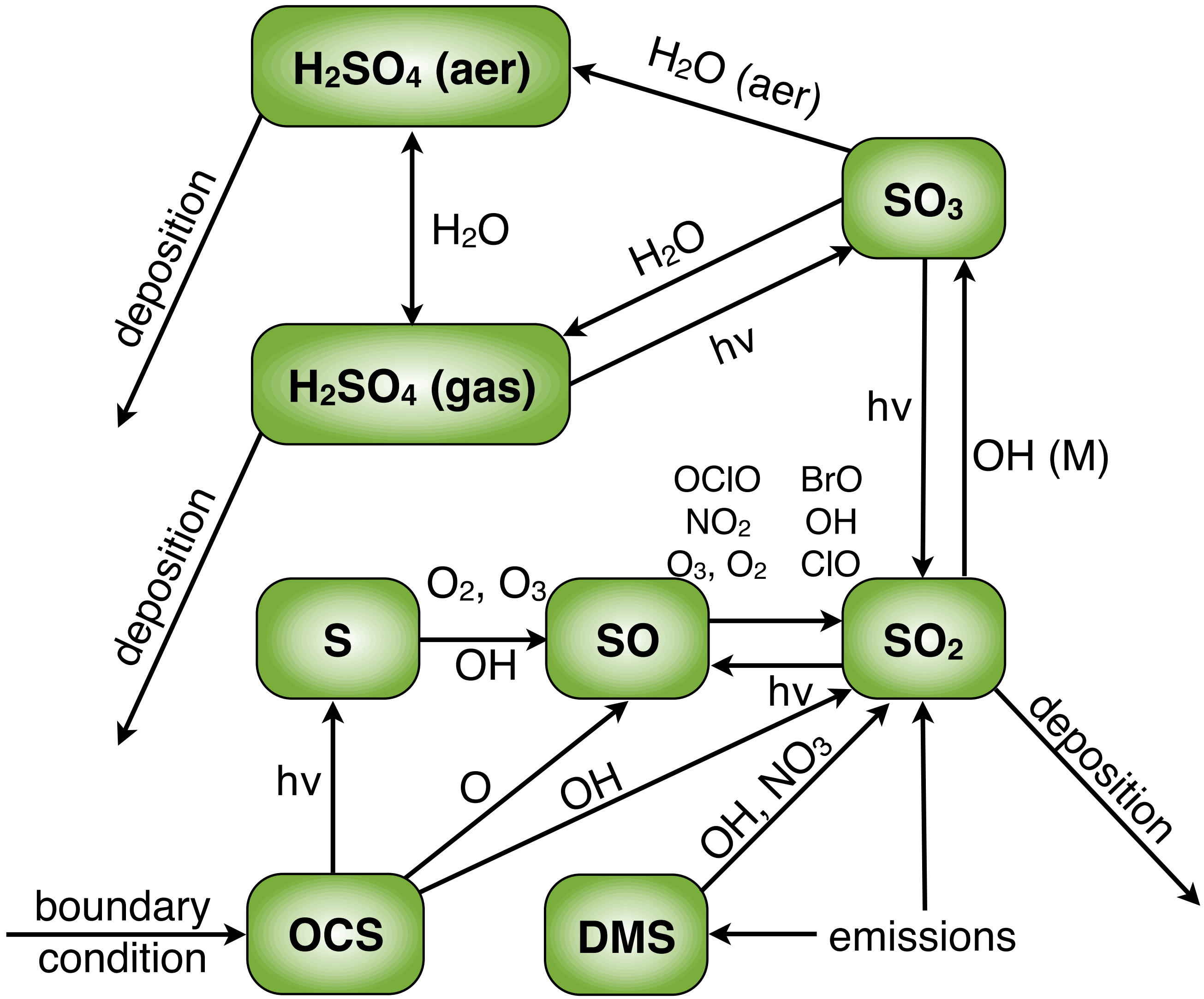
Increase in CO_2 forcing of +0.26 W m^{-2} over same two periods (~46% offset)

Good agreement with previous studies (IPCC AR5, Solomon et al. 2011)

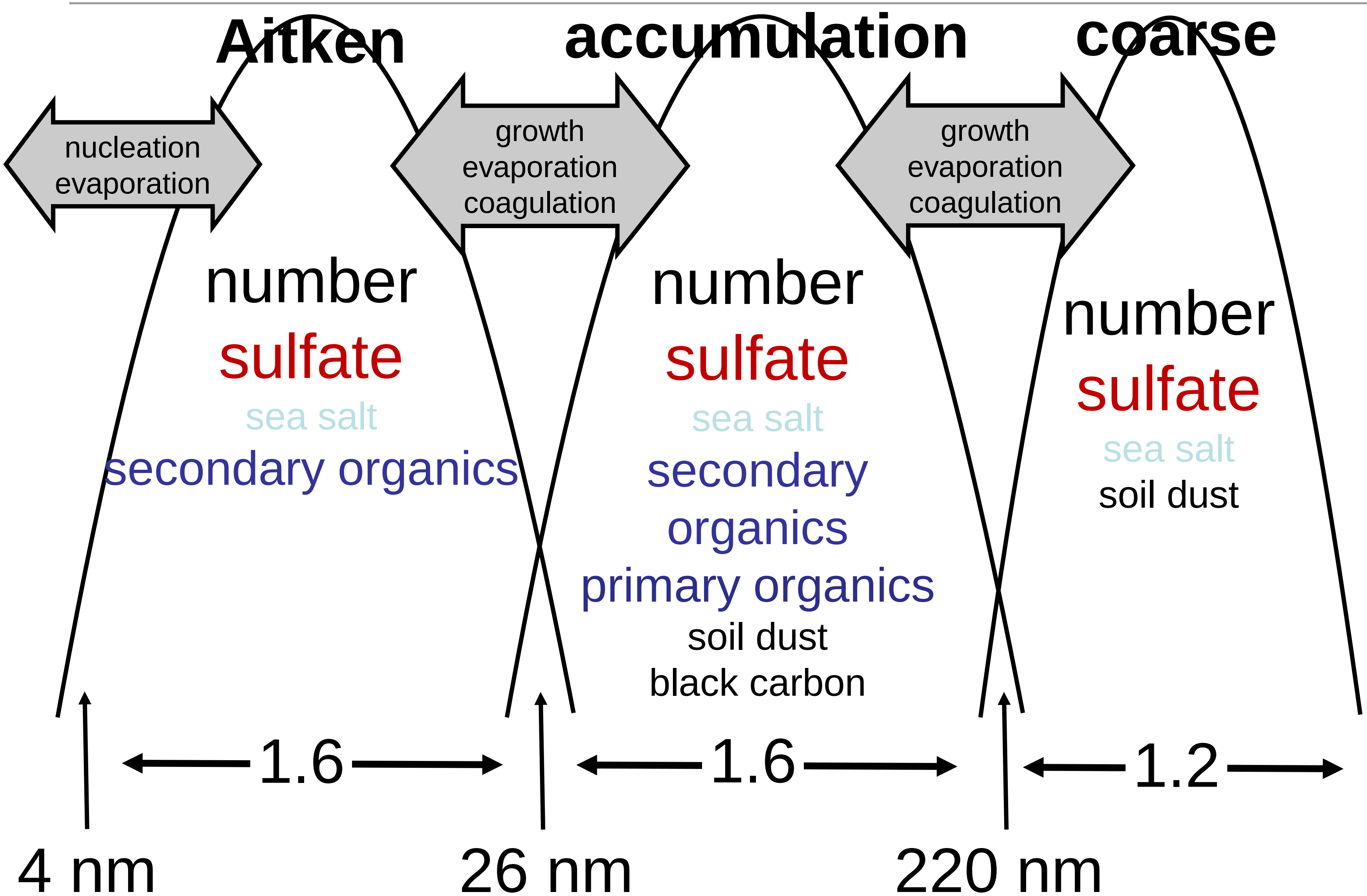
Small-magnitude eruptions matter!

And they are <u>frequent</u> …

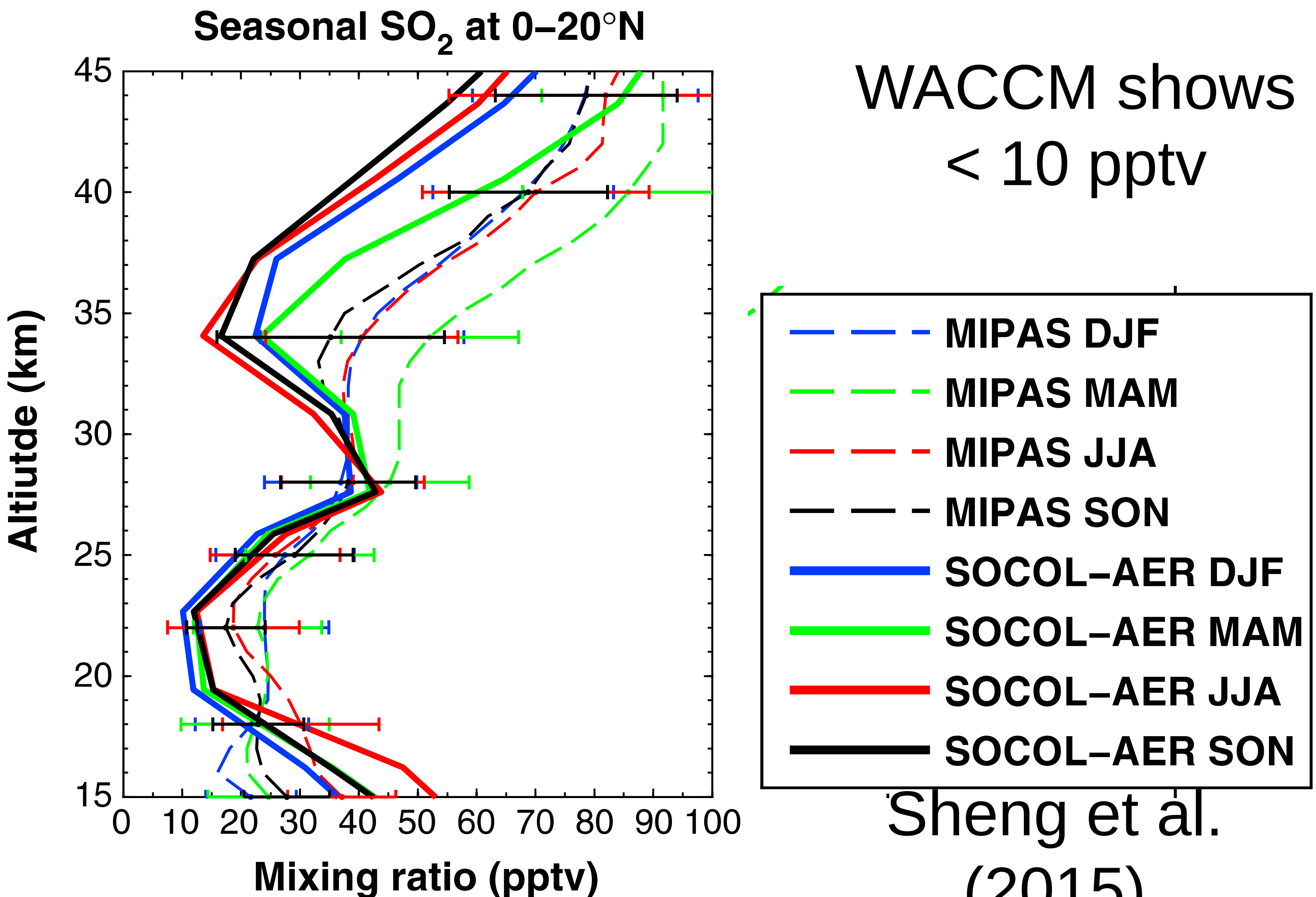
Gas-phase and aerosol sulfur chemistry



Modal aerosols in WACCM6: stratosphere



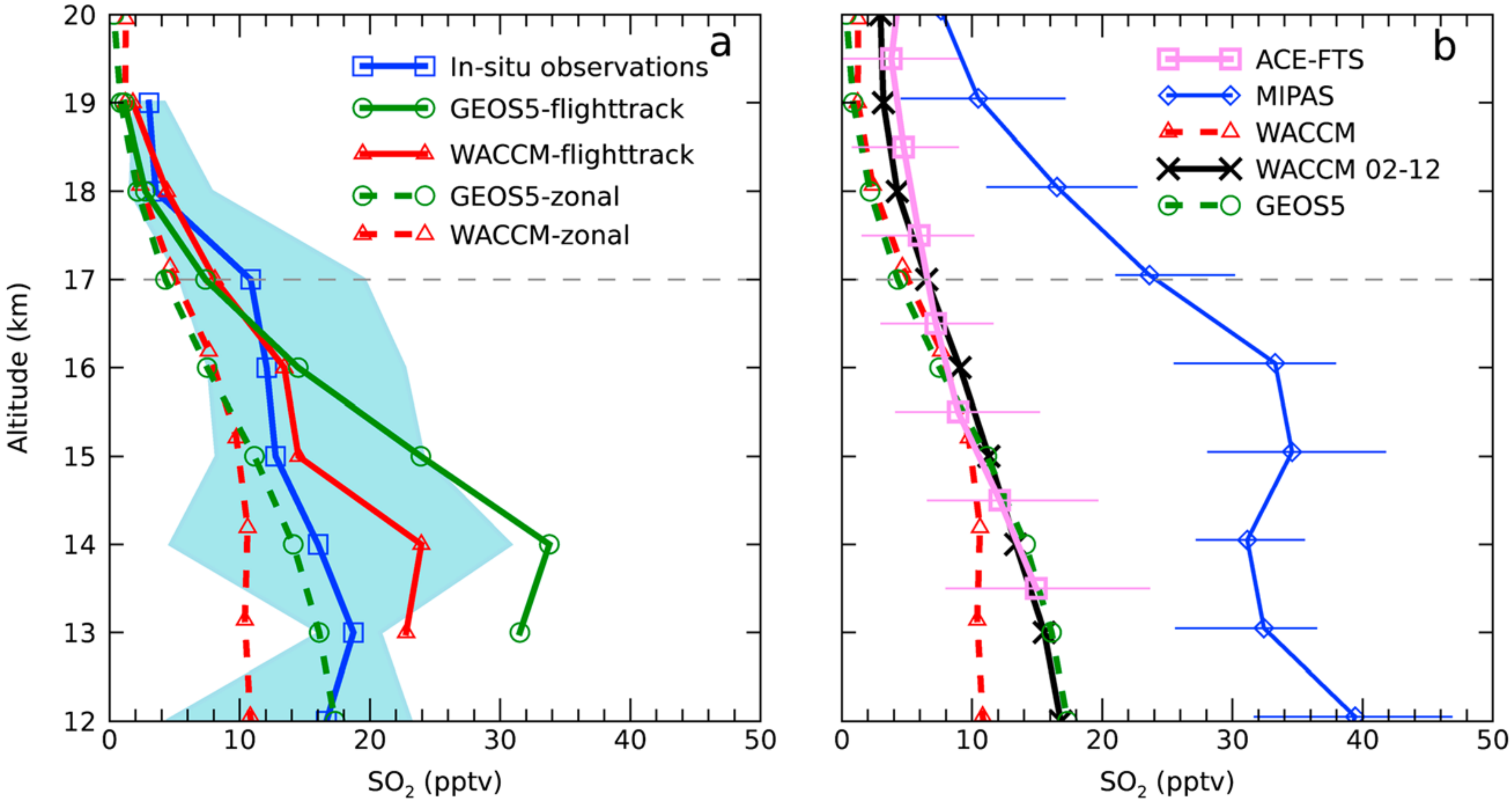
SOCOL-AER compares well to **MIPAS SO_2 observations** showing 20-30 pptv at TTL



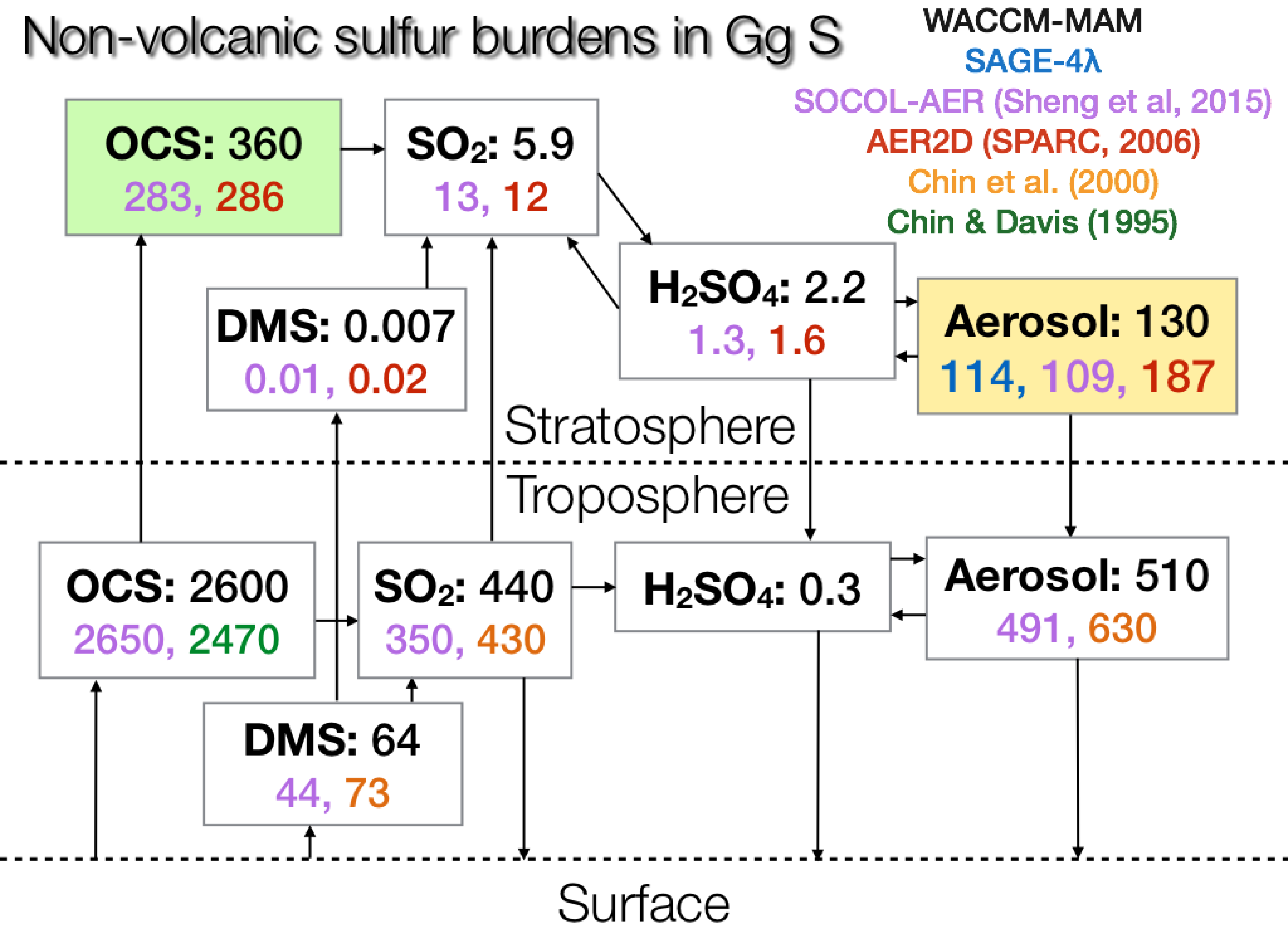
WACCM shows < 10 pptv

Sheng et al. (2015)

WACCM SO_2 compares well to in situ observations



Observations from VIRGAS experiment, October 2015.
Figure from Rollins et al. (2017).


Non-volcanic sulfur burdens in Gg S
WACCM-MAM
SAGE-4λ
SOCOL-AER (Sheng et al, 2015)
AER2D (SPARC, 2006)
Chin et al. (2000)
Chin & Davis (1995)
OCS: 360
283, 286
SO2: 5.9
13, 12
H2SO4: 2.2
1.3, 1.6
DMS: 0.007
0.01, 0.02
Aerosol: 130
114, 109, 187
Stratosphere
Troposphere
OCS: 2600
2650, 2470
SO2: 440
350, 430
H2SO4: 0.3
Aerosol: 510
491, 630
DMS: 64
44, 73
Surface

Volcanism and climate

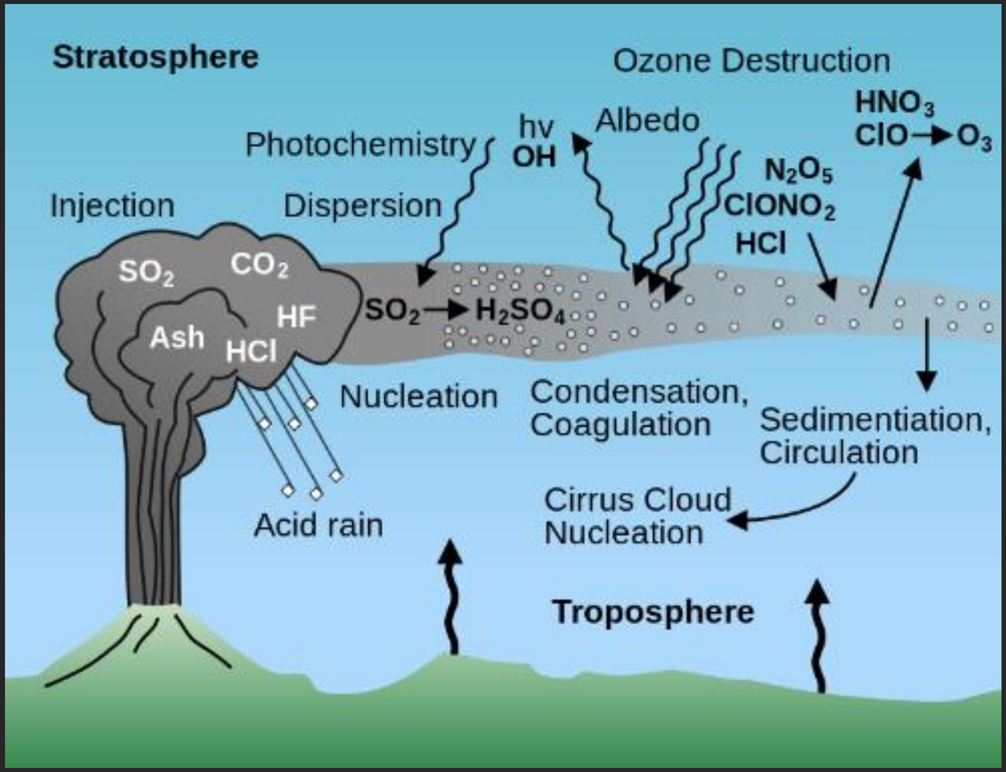


Figure from Timmreck (2012)

- Ash, H_2O, CO_2, SO_2, HCl, HF, …
- SO_2 → aerosol particles
- Aerosol lifetime in stratosphere = 1-3 years
- Aerosol lifetime in troposphere = days to weeks
- Surface cooling
- Heating of stratosphere

CMIP5-type climate models

Most models would:

- Prescribe aerosol optical properties & particle size (based on few observations)
  → **neglect of aerosol microphysics**
- Consider only large-magnitude explosive eruptions (such as 1991 Mt. Pinatubo)
  → **neglect of smaller-magnitude eruptions**
- Not consider any future volcanic forcing

Sulphur dioxide → Aerosol particles

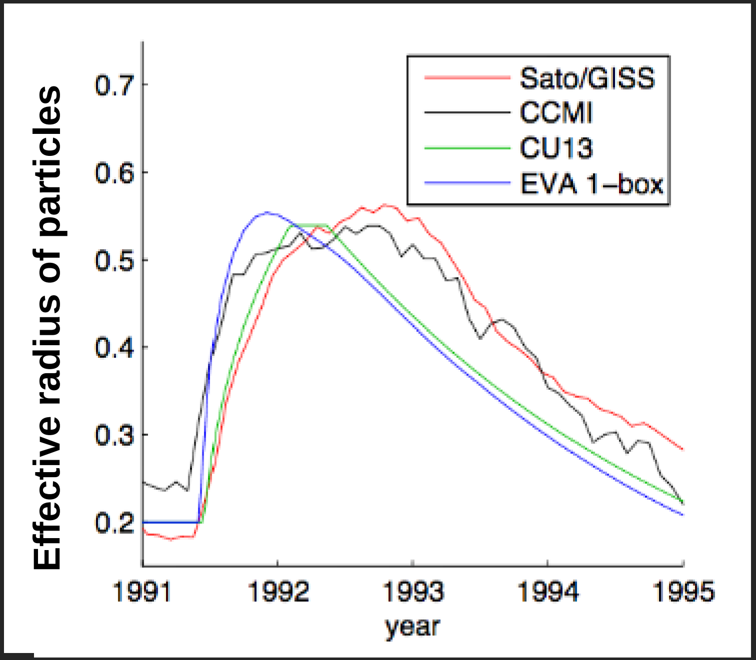
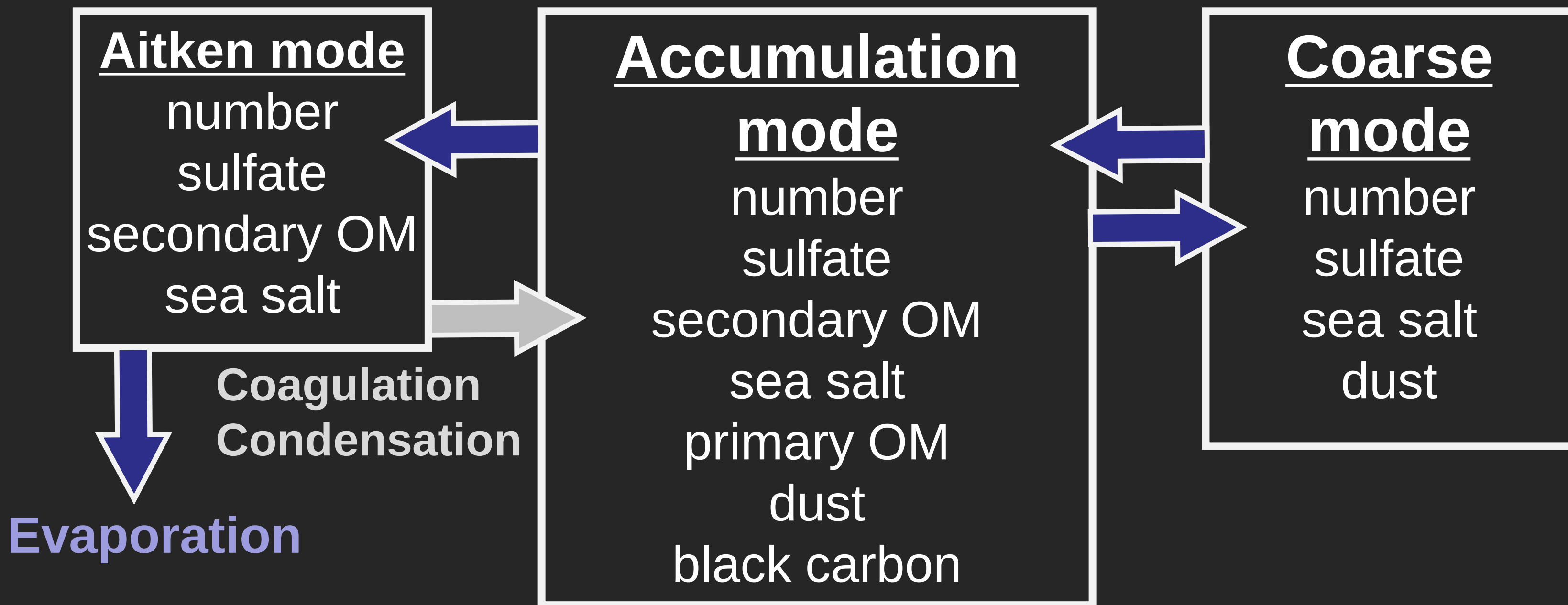


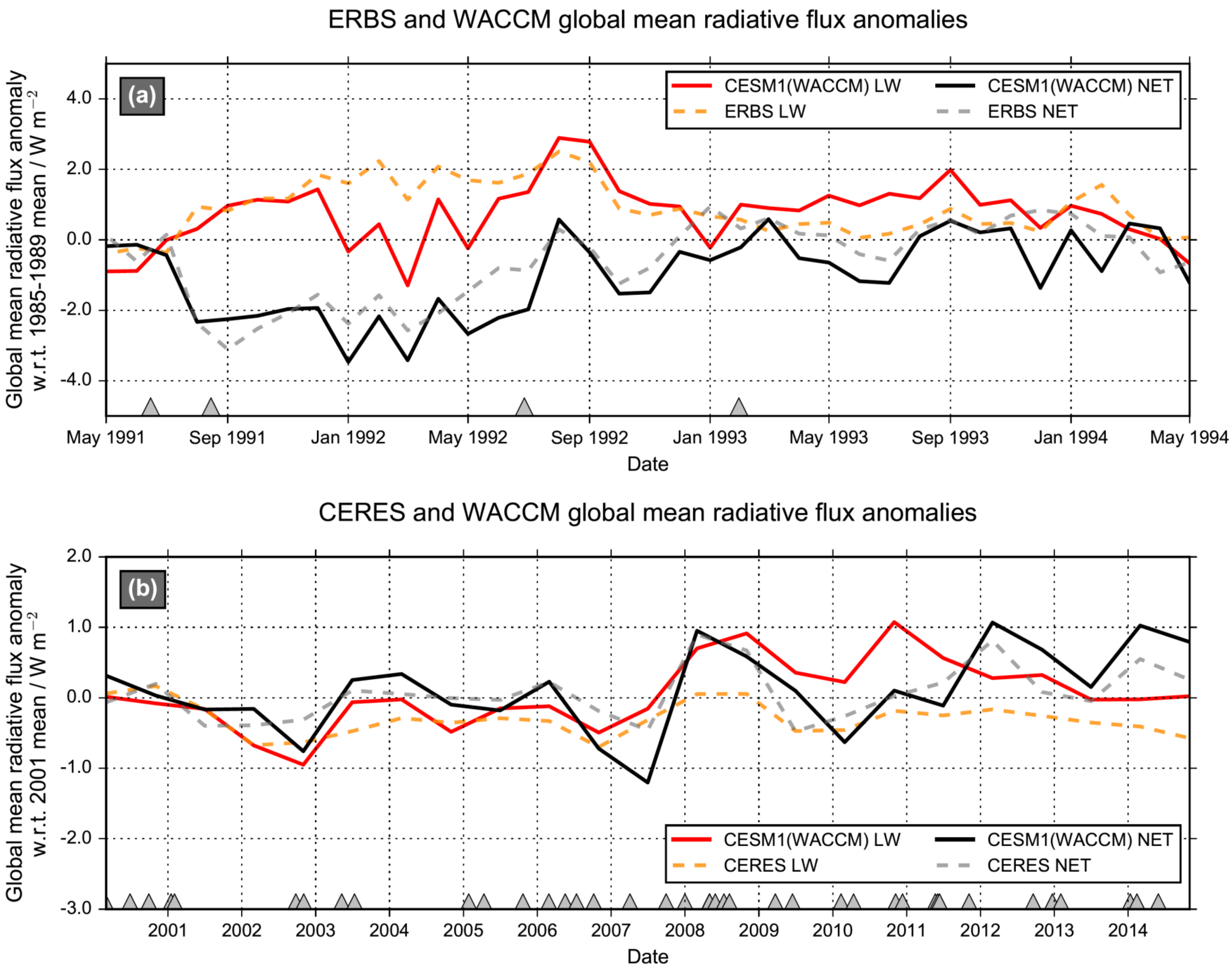
Figure from Toohey et al. (2016)

Exploiting new modelling capabilities

Prognostic stratospheric aerosol in CESM(WACCM) using modal aerosol scheme (MAM) + detailed S chemistry scheme



Mills et al., 2016, JGR


ERBS and WACCM global mean radiative flux anomalies
(a)
CESM1(WACCM) LW
CESM1(WACCM) NET
ERBS LW
ERBS NET
Global mean radiative flux anomaly
w.r.t. 1985-1989 mean / W m^{-2}
4.0
2.0
0.0
-2.0
-4.0
May 1991
Sep 1991
Jan 1992
May 1992
Sep 1992
Jan 1993
May 1993
Sep 1993
Jan 1994
May 1994
Date
CERES and WACCM global mean radiative flux anomalies
(b)
CESM1(WACCM) LW
CESM1(WACCM) NET
CERES LW
CERES NET
Global mean radiative flux anomaly
w.r.t. 2001 mean / W m^{-2}
2.0
1.0
0.0
-1.0
-2.0
-3.0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Date