WACCM: The High-Top Model

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NCAR

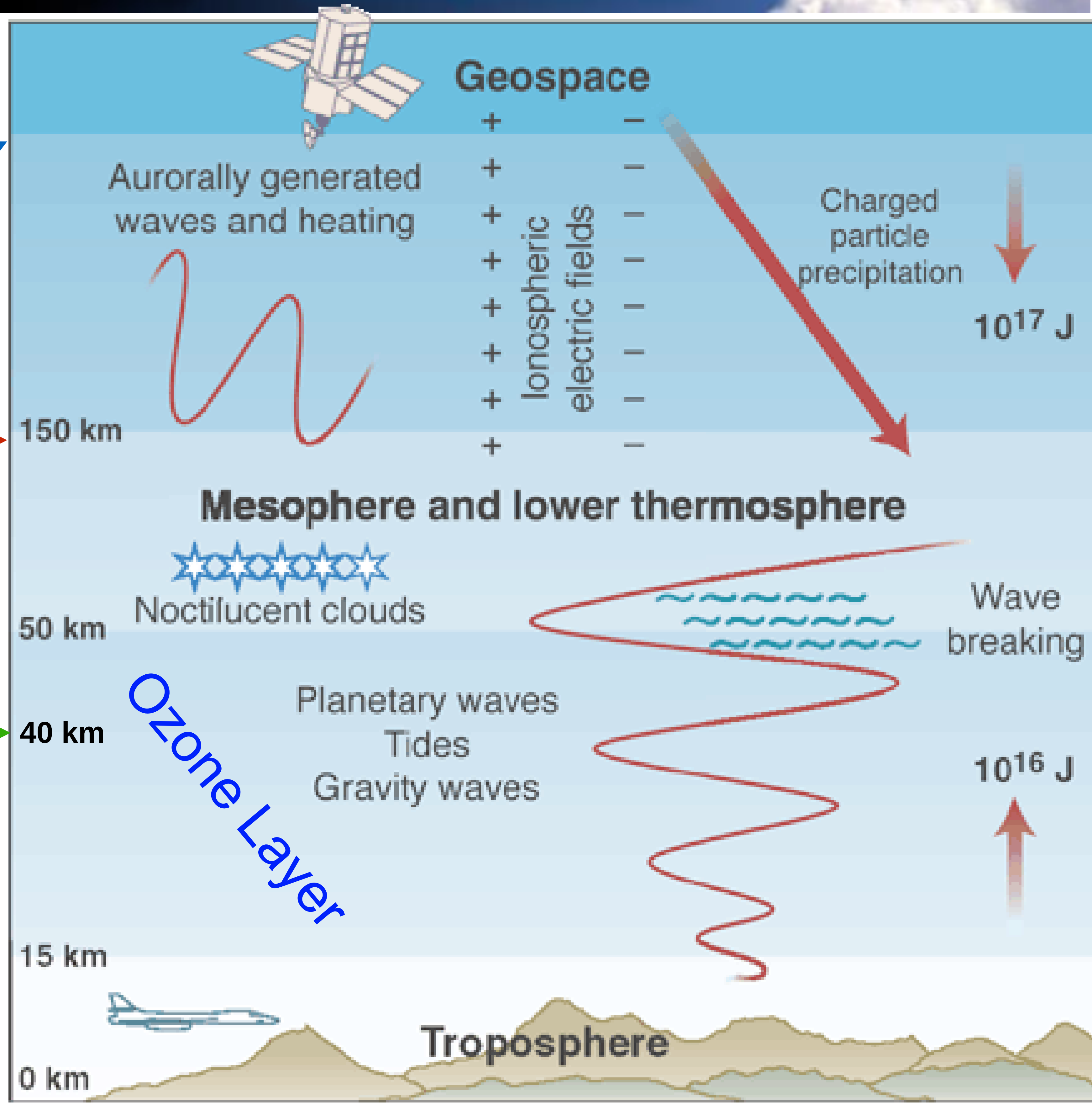
WACCM

Whole Atmosphere Community Climate Model

Whole Atmosphere Community Climate Model - eXtended (WACCM-X): surface to 500-700 km

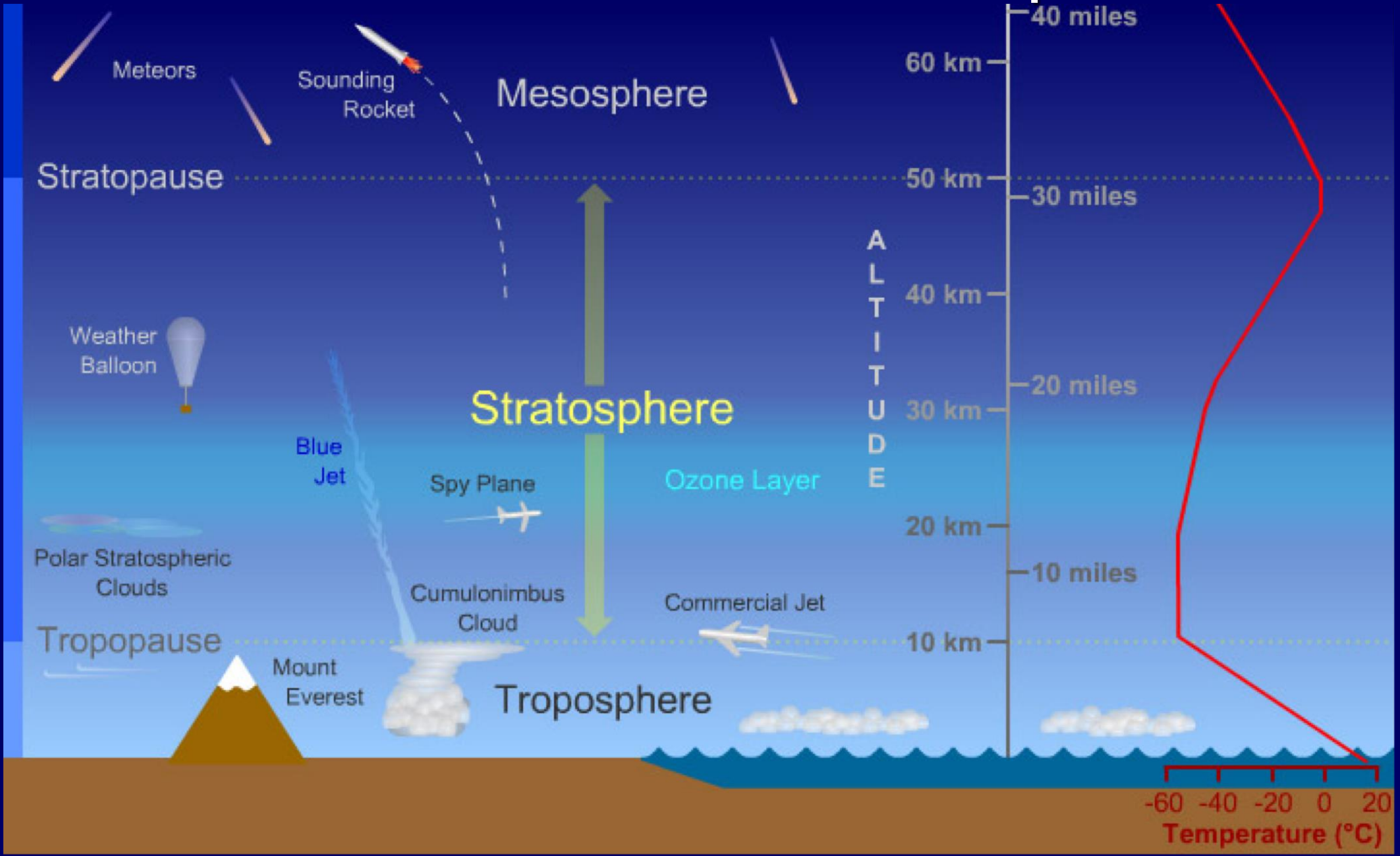
Whole Atmosphere Community Climate Model (WACCM): surface to 145 km

Community Atmosphere Model (CAM): surface to 45 km



Jarvis, “Bridging the Atmospheric Divide”, *Science*, **293**, 2218, 2001

Ozone defines the stratosphere



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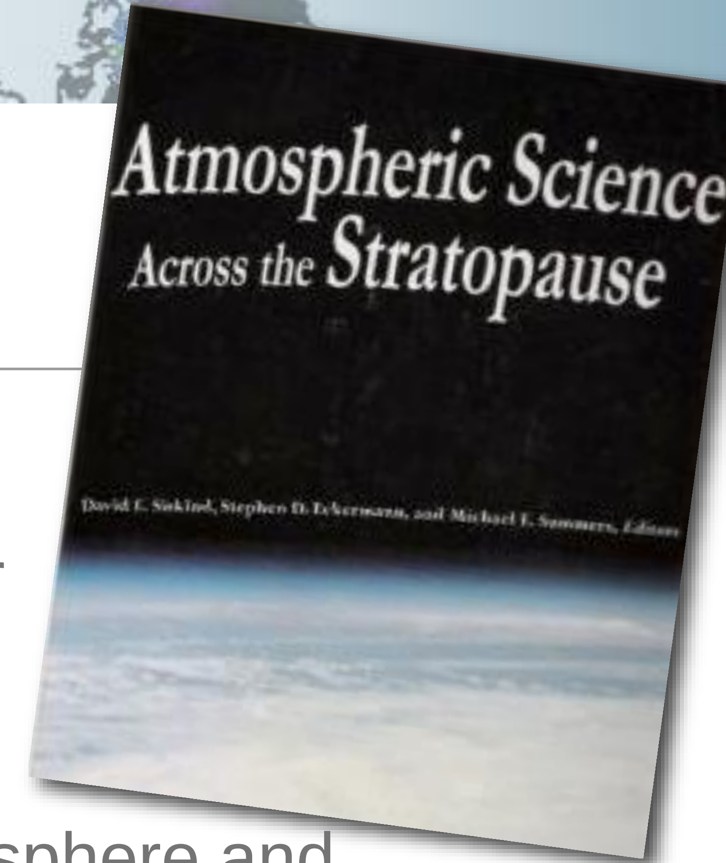
WACCM Additions to CAM

- Extends from surface to 5.1×10^{-6} hPa (~150 km), with 70 vertical levels
- Detailed neutral chemistry models
  - middle atmosphere (MA): catalytic cycles affecting ozone, heterogeneous chemistry on PSCs and sulfate aerosol, heating due to chemical reactions
  - troposphere, stratosphere, mesosphere, and lower thermosphere (TSMLT): adds chemistry affecting tropospheric air quality
- Prognostic stratospheric aerosols derived from sulfur emissions
- Model of ion chemistry in the mesosphere/lower thermosphere (MLT), ion drag, auroral processes, and solar proton events
- EUV and non-LTE longwave radiation parameterizations
- Gravity wave drag deposition from vertically propagating GWs generated by orography, fronts, and convection
- Interactive QBO derived from wave forcing
- Molecular diffusion and constituent separation
- Thermosphere extension (WACCM-X) to ~500-700 km

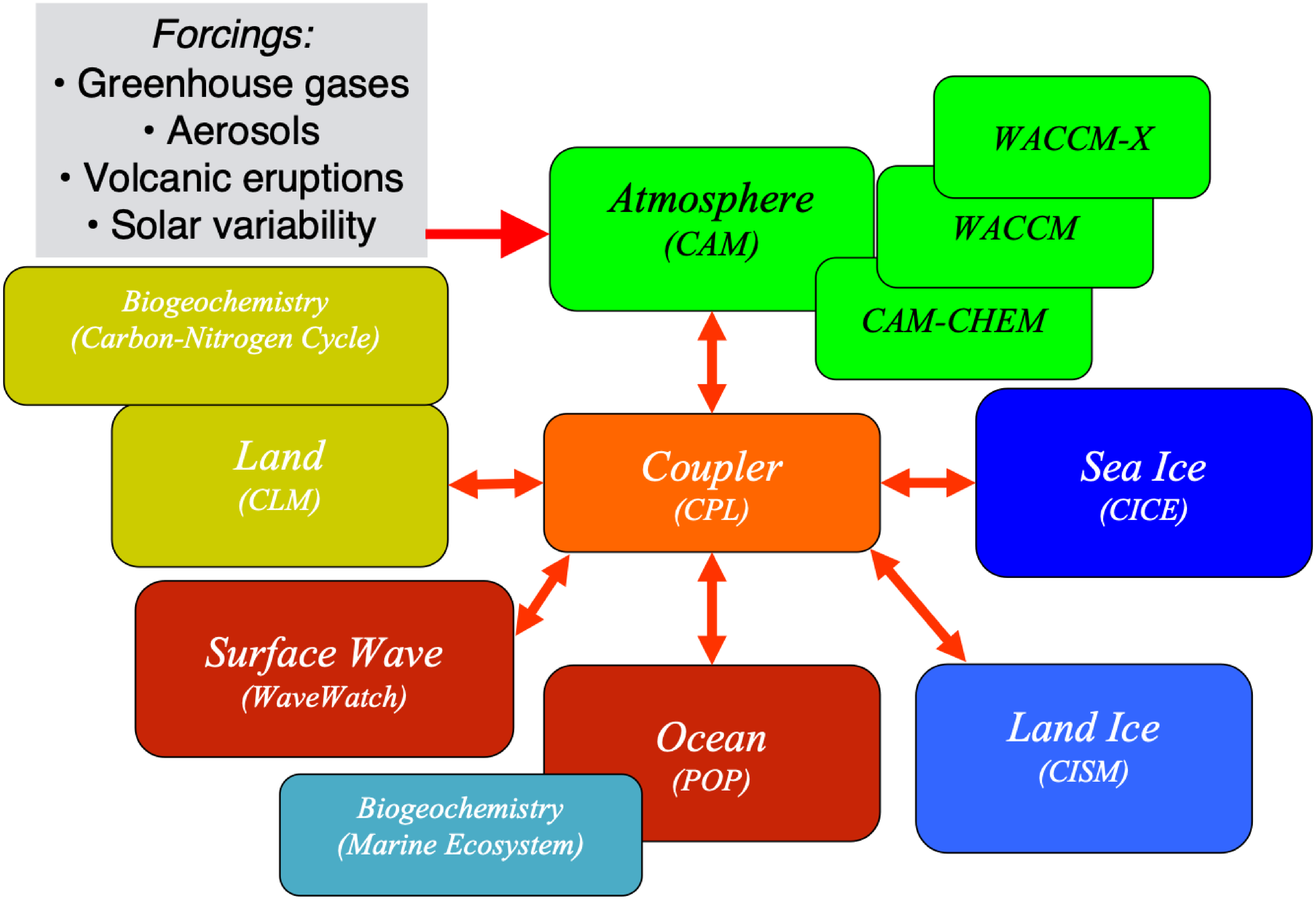
WACCM Motivation

Roble, Geophysical Monograph, **v. 123**, p. 53, 2000



- Coupling between atmospheric layers:
  - Waves transport energy and momentum from the lower atmosphere to drive the QBO, SAO, sudden warmings, mean meridional circulation
  - Solar inputs, e.g. auroral production of NO in the mesosphere and downward transport to the stratosphere
  - Stratosphere-troposphere exchange
- Climate Variability and Climate Change:
  - What is the impact of the stratosphere on tropospheric variability?
  - How important is coupling among radiation, chemistry, and circulation? (e.g., in the response to O_3 depletion or CO_2 increase)
  - Response to solar variability: impacts mediated by chemistry?
- Interpretation of Satellite Observations

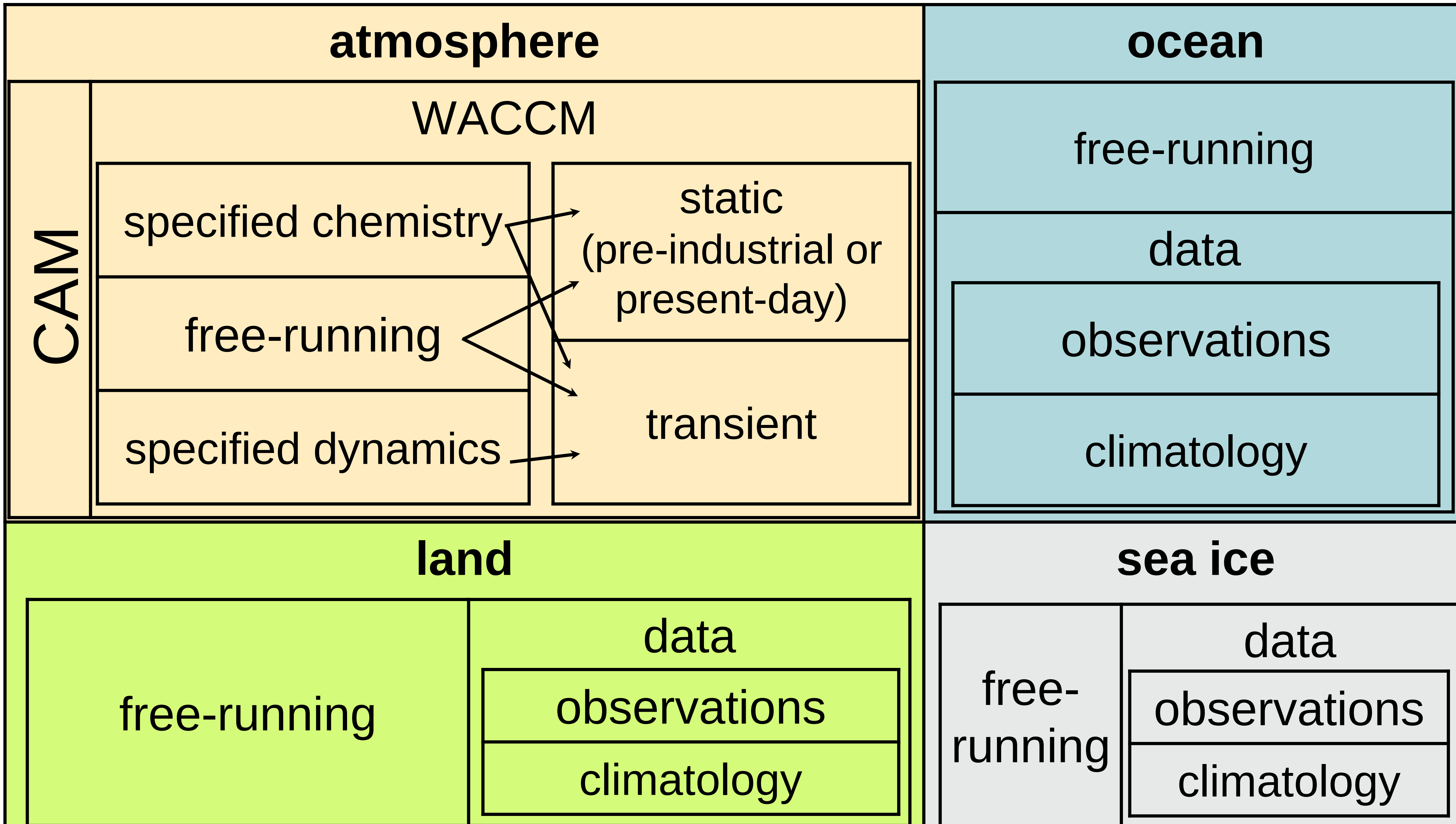
CESM2 components



CESM2: WACCM6 & WACCM-X v2

	WACCM6	WACCM-X v2
Vertical Levels	70, 88(SD)	126, 145(SD)
Model Top	6×10^{-6} hPa (~140 km)	4×10^{-10} hPa (500-700 km)
Horizontal Resolution	$0.95^\circ\times1.25^\circ$, $1.9^\circ\times2.5^\circ$	$1.9^\circ\times2.5^\circ$
Time step	30 minutes	5 minutes
Specified Dynamics	SD-WACCM6 option	SD-WACCM-X option
Chemistry	TSMLT (233), MA (99), SC (37)	MA (76)
QBO	Interactive at $0.95^\circ\times1.25^\circ$, Nudged at $1.9^\circ\times2.5^\circ$	Nudged
Tropospheric Physics	CAM6	CAM4
Radiation	RRTMG	CAM-RT
Tropospheric Aerosol	Interactive MAM4	Prescribed Bulk
Stratospheric Aerosol	Interactive MAM4	Prescribed
Non-orographic GW	Yes	Yes
Molecular Diffusion	minor	minor and major
Auroral Physics	Yes	Yes
Ions	E-region or E&D-region	E-region
Ion transport	No	Yes
E Dynamo	No	Yes

WACCM component configurations



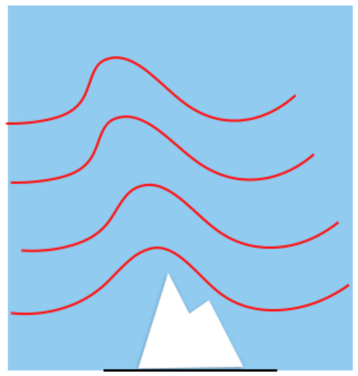
Specified Dynamics: SD-WACCM and SD-CAM-Chem

- Reproduce winds and temperatures from specific periods in analyses from GEOS5 (2004-present) or MERRA (1979-present).
- **FSDW** compset starts on 1 Jan 2005, uses GEOS5, out of the box.
- Increased vertical resolution
  - CAM-Chem: 32 levels → SD-CAM-Chem: 56 levels
  - WACCM: 70 levels → SD-WACCM: 88 levels
- Nudge T, U, V, PS towards analyses at every dynamics timestep. Nudging strength (i.e. 1%, 10% each timestep) and top altitude (50 km default for WACCM) can be adjusted.
- Chemistry interacts with radiation, atmosphere, land, ocean
- Data ocean and sea ice components

WACCM Gravity Wave Parameterization

1. Orographic GWs:

Uncertain: Efficiency

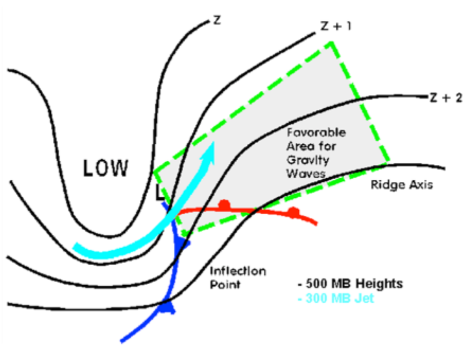


Orographic GWs:

- McFarlane (1987)
- 1 wave with c = 0
- Amplitude dependent on orography height and wean wind

2. Frontally generated GWs:

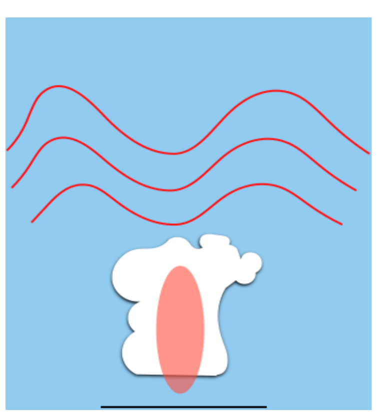
Uncertain: Efficiency, amplitude, phase speeds



- 40 waves with -100 < c < 100 m/s
- Gaussian distribution in phase speed centered at U 600 mb
- Constant wave amplitude

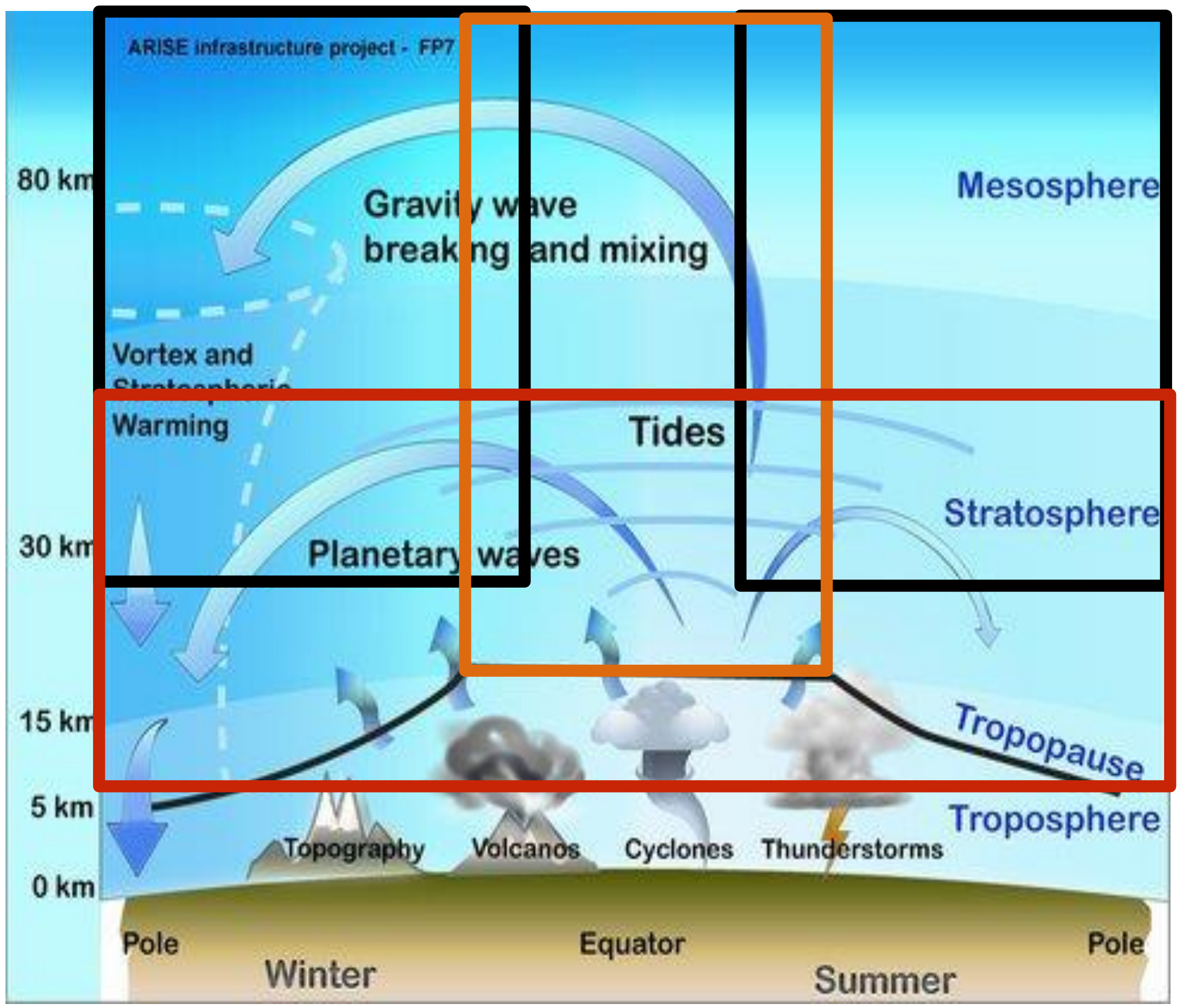
3. Convectively generated GWs:

Uncertain: Efficiency, amplitude conversion



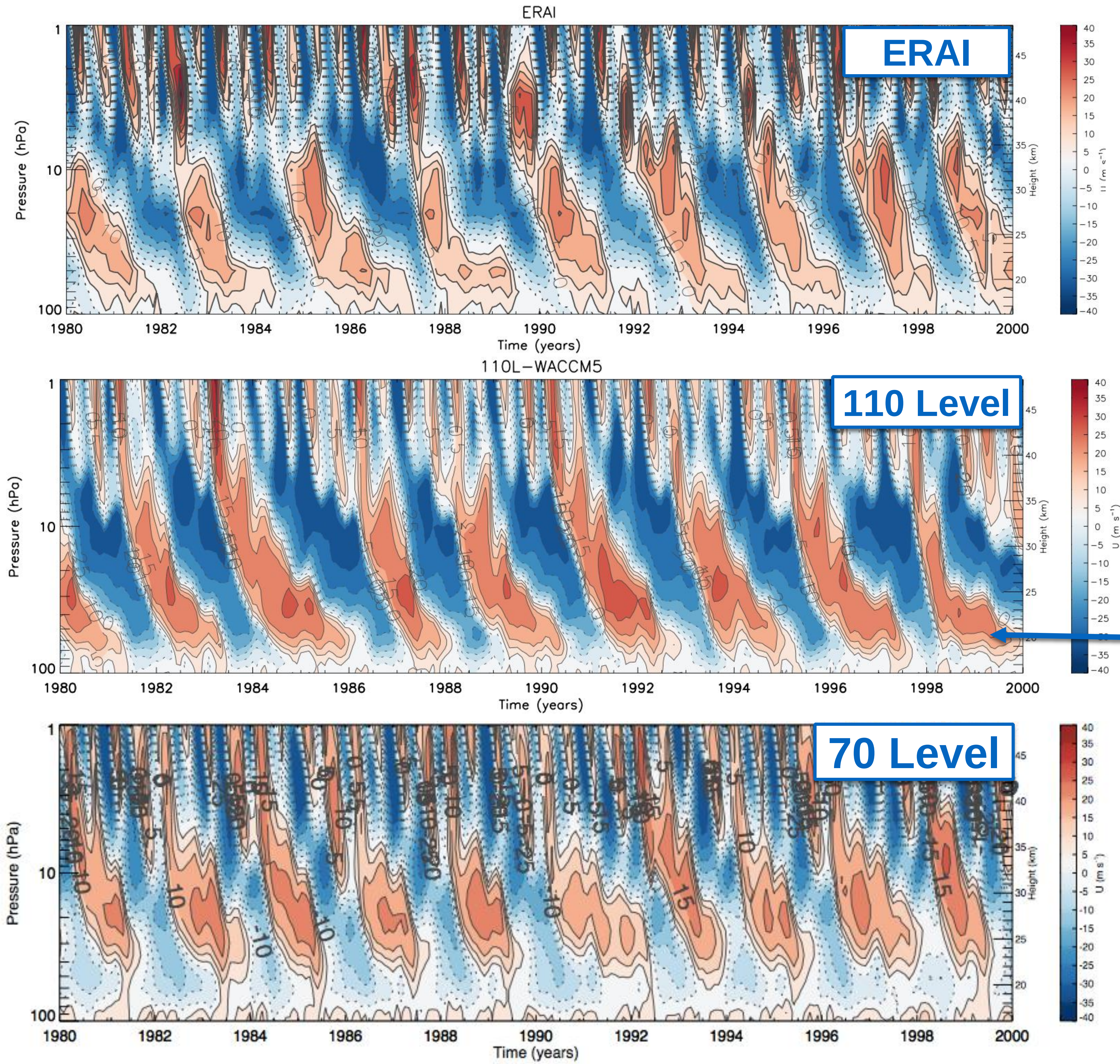
- 40 waves with -100 < c < 100 m/s
- Dominant c related to h (depth of heating)
- Wave Amplitude ∝ Q^2
- Wave spectrum impacted by wind in heating

Beres et al. 2004 (Beres = Richter)



Richter et al. 2010

QBO: 70 vs 110L WACCM



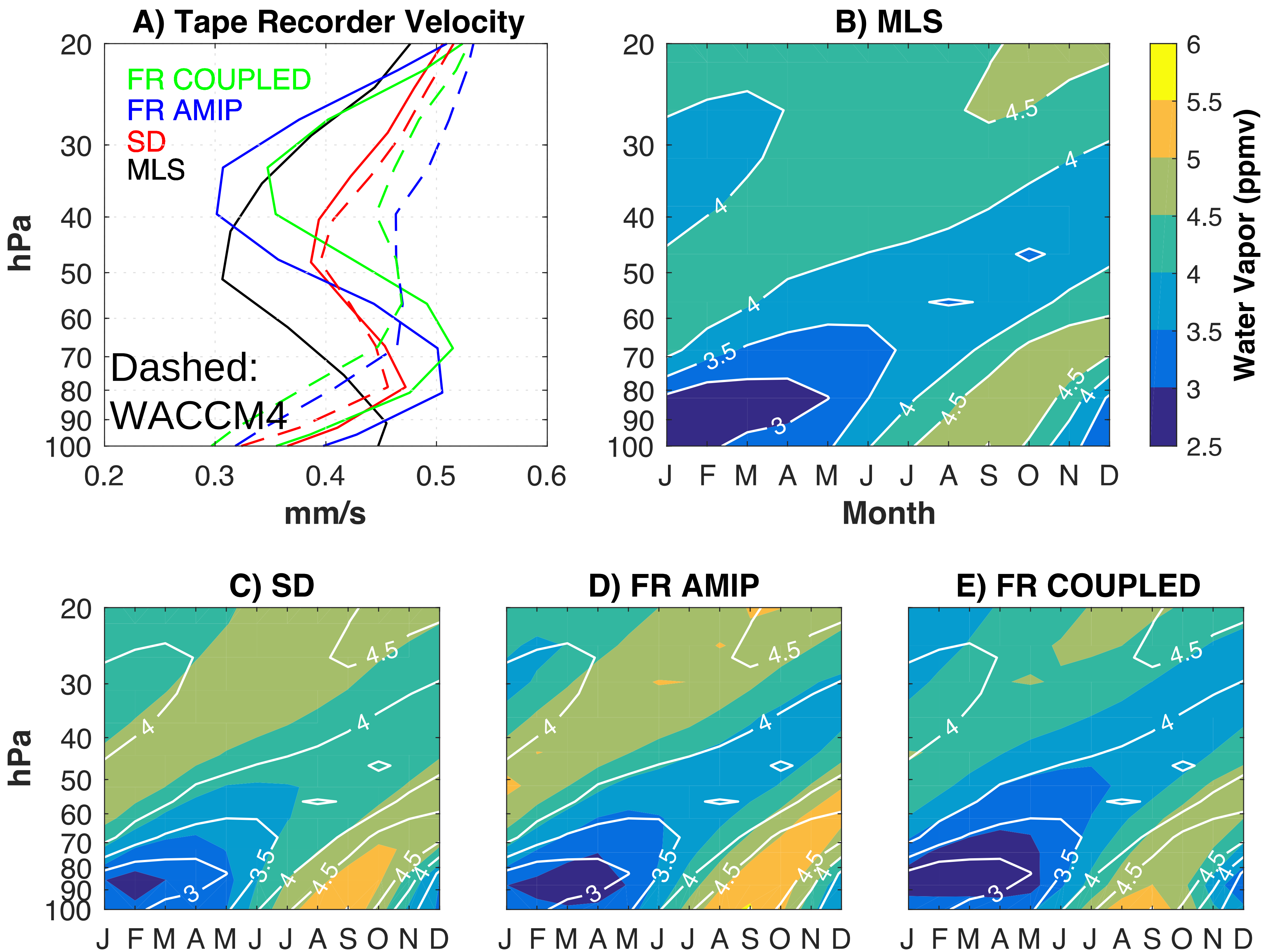
Higher vertical resolution

QBO descends to 100 hPa as observed (tropical Kelvin and RG waves are well resolved in the 110L model)

Standard WACCM6

Courtesy Yaga Richter

Water vapor "tape recorder"

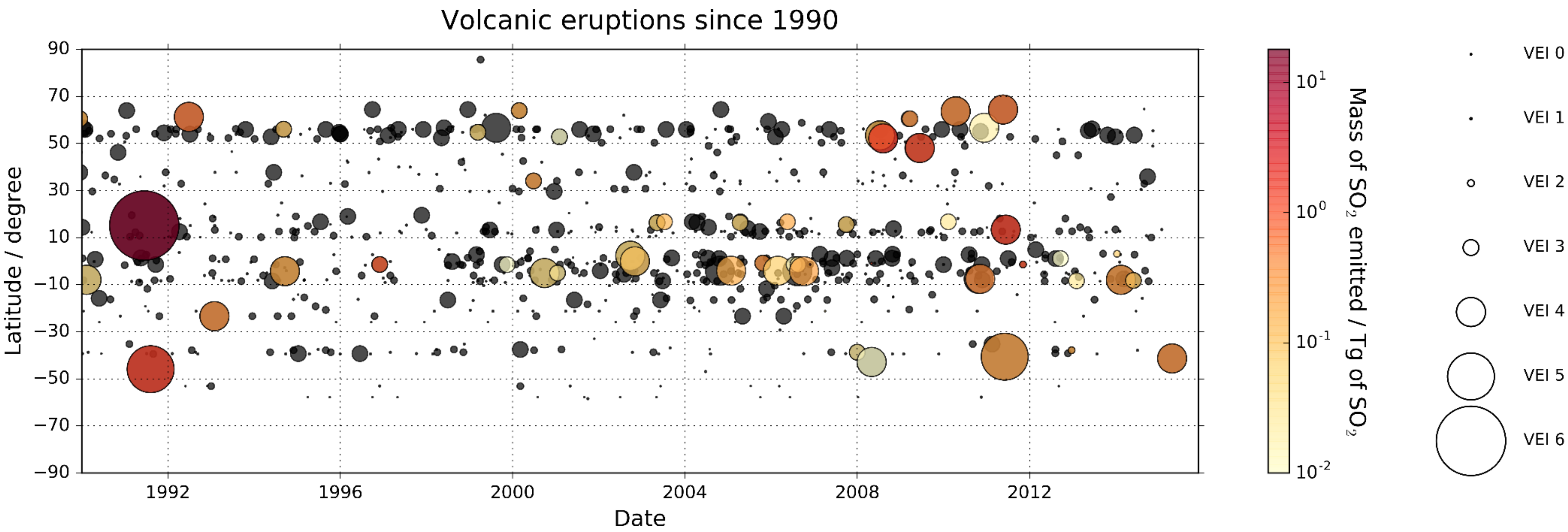


- Vertical propogation speed is shifted upward slightly
- Amplitude is well-represented
- Improves on WACCM4 speed in upper stratosphere
- ~0.5 ppmv positive bias in summer

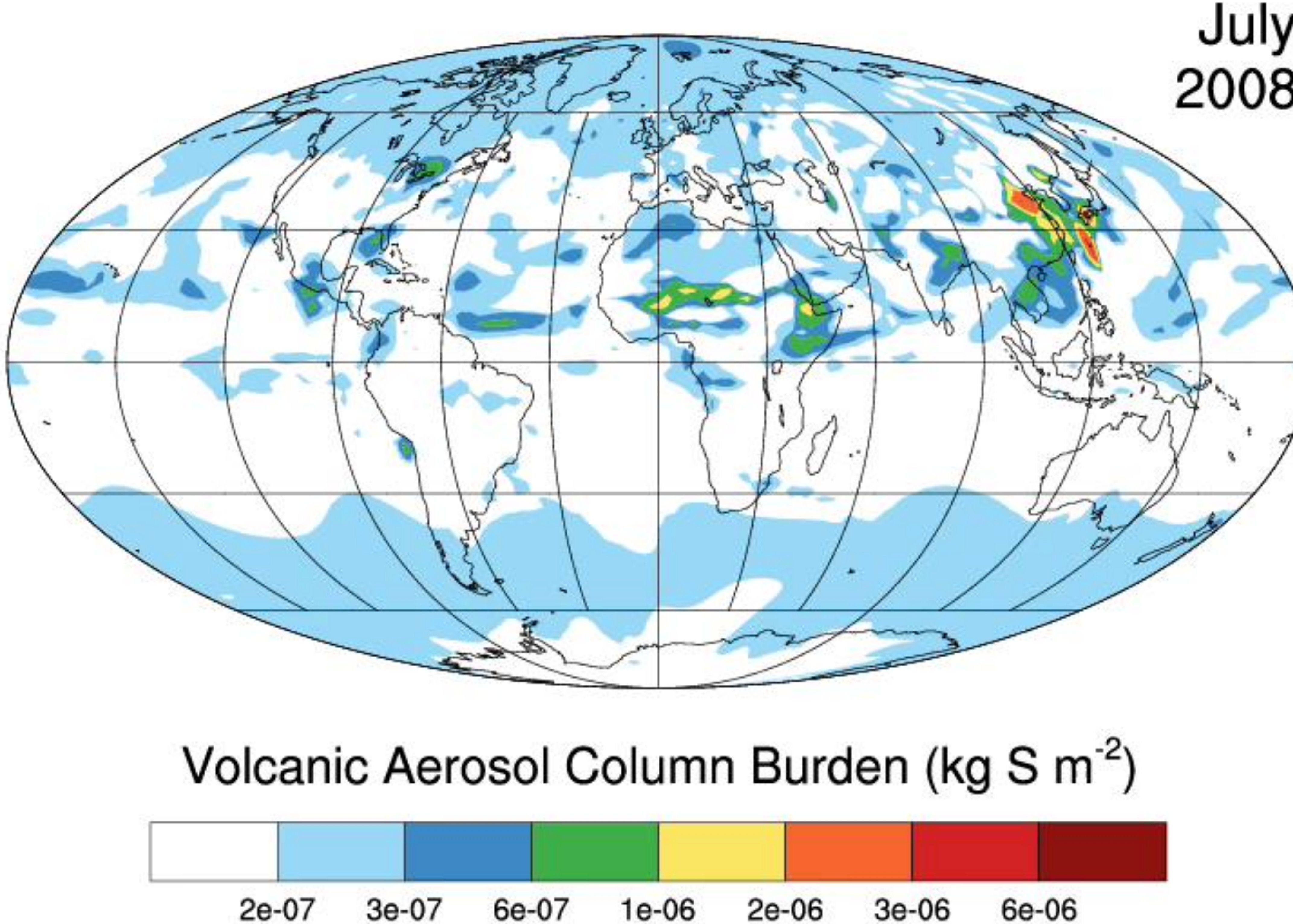
Figure from Gettelman et al., submitted to JGR, 2019

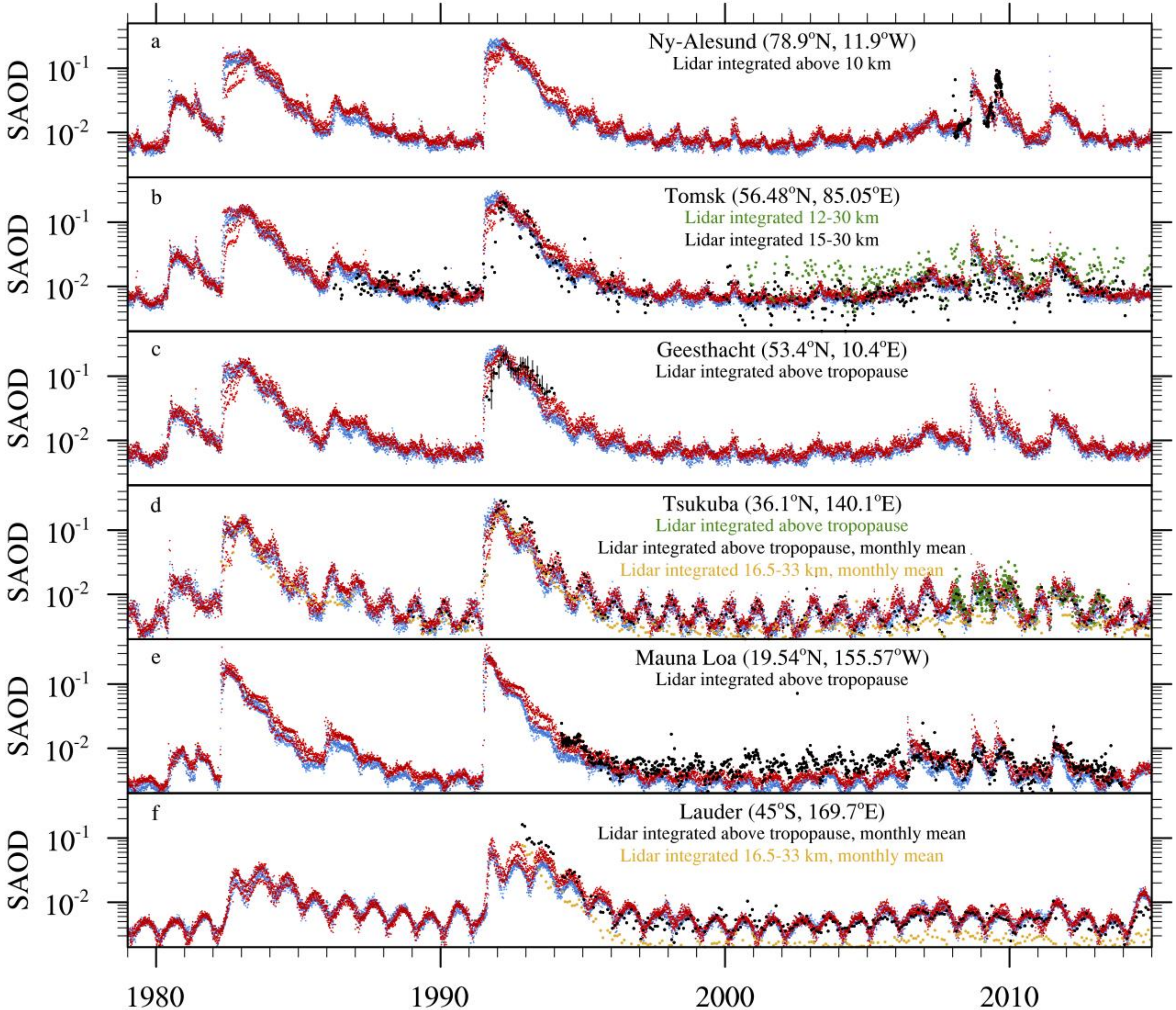
Volcanic eruptions SO_2 database (1850-2016)

- Volcanic eruptions increasingly well characterized
  (Satellite retrievals, in-situ measurements, geochem. & geophys. monitoring)
- 1979 first TOMS volcanic SO_2 retrievals
- Compiled volcanic emission dataset for use in climate models



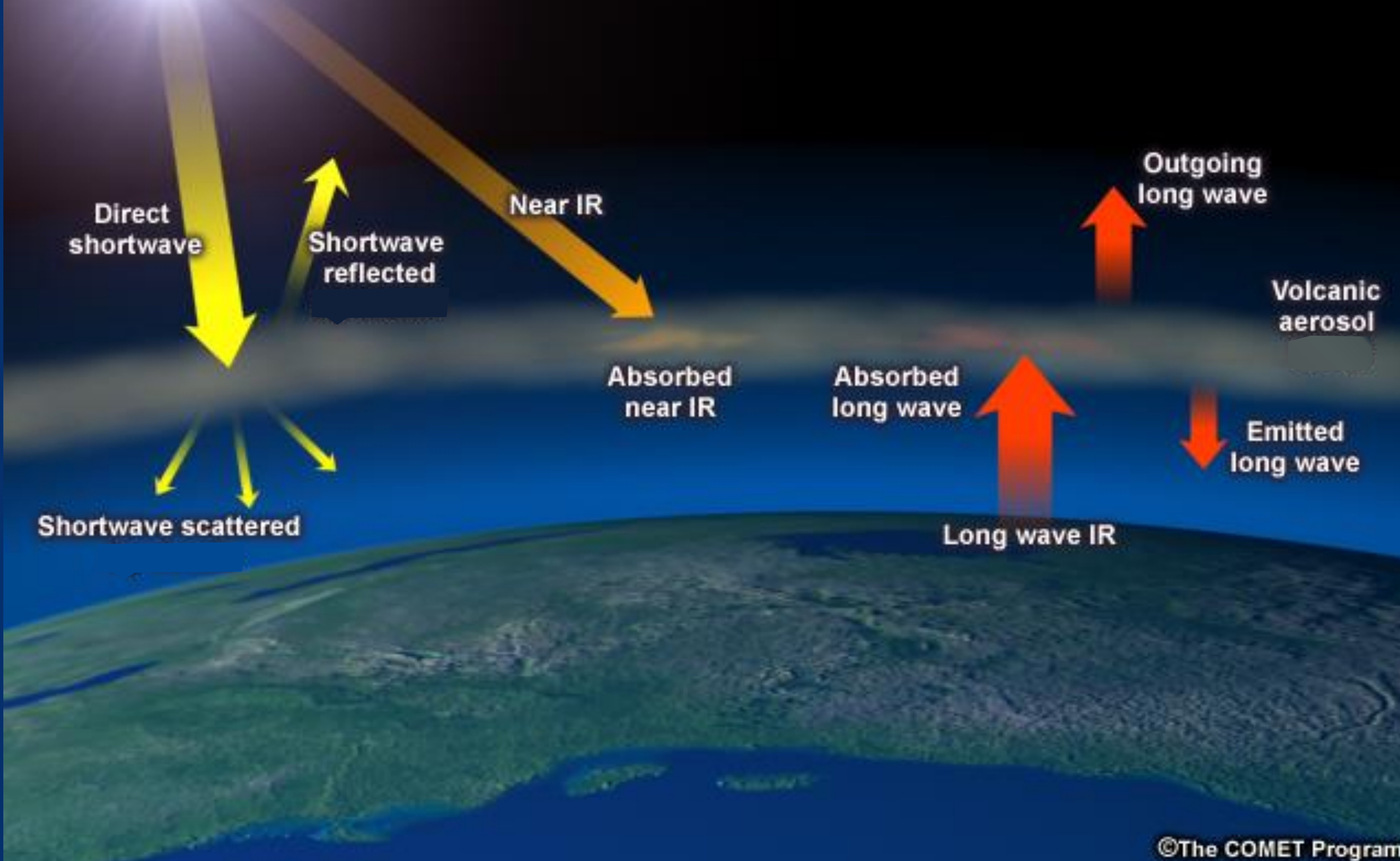
1990-1994	1995-1999	2000-2004	2005-2009	2010-2015
12.85 Tg of SO_2	0.93 Tg of SO_2	0.93 Tg of SO_2	7.56 Tg of SO_2	8.55 Tg of SO_2


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

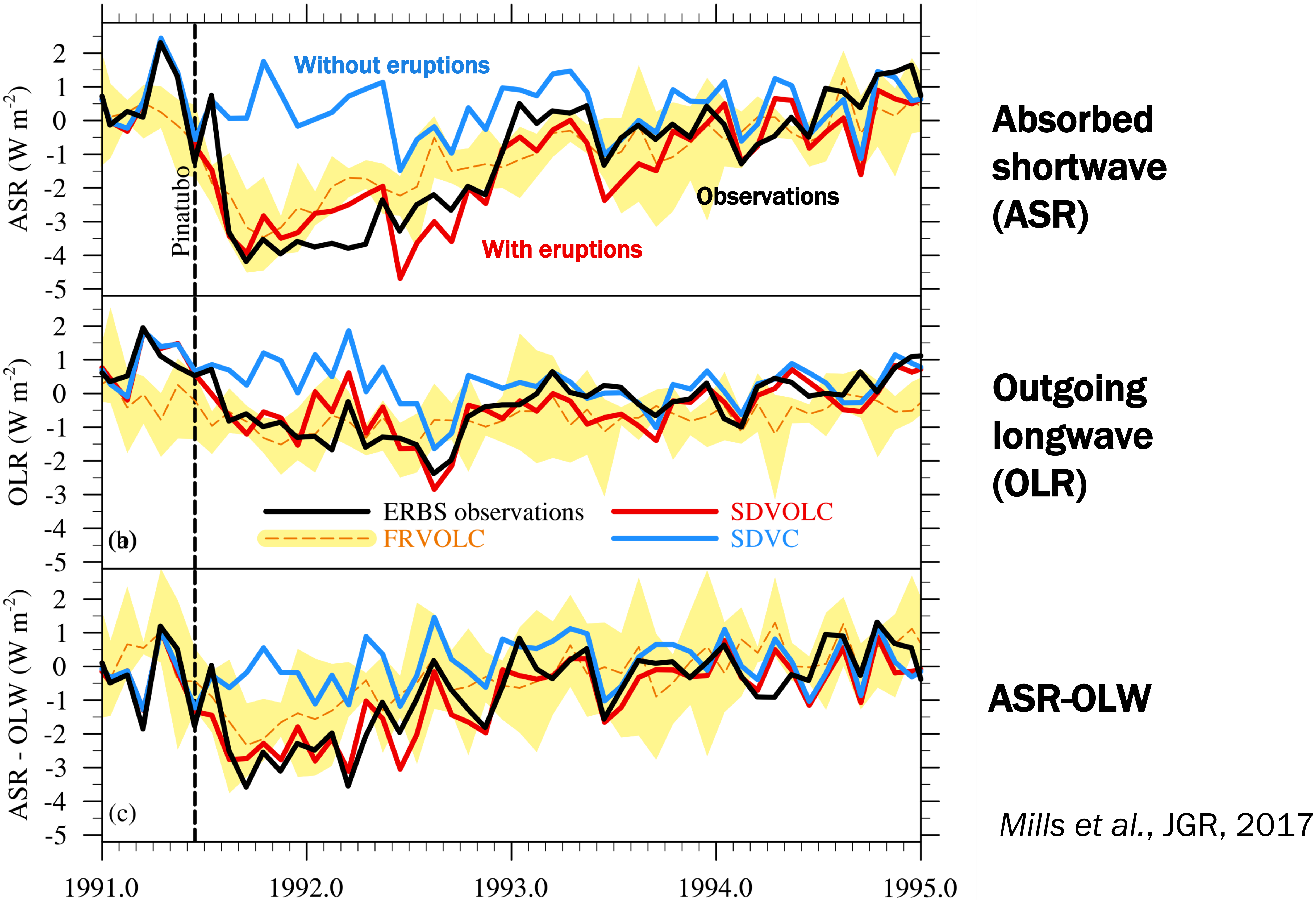


Volcanic aerosol optical depth agrees well with lidar observations at multiple latitudes. Figure from Gettelman et al., submitted to JGR, 2019.

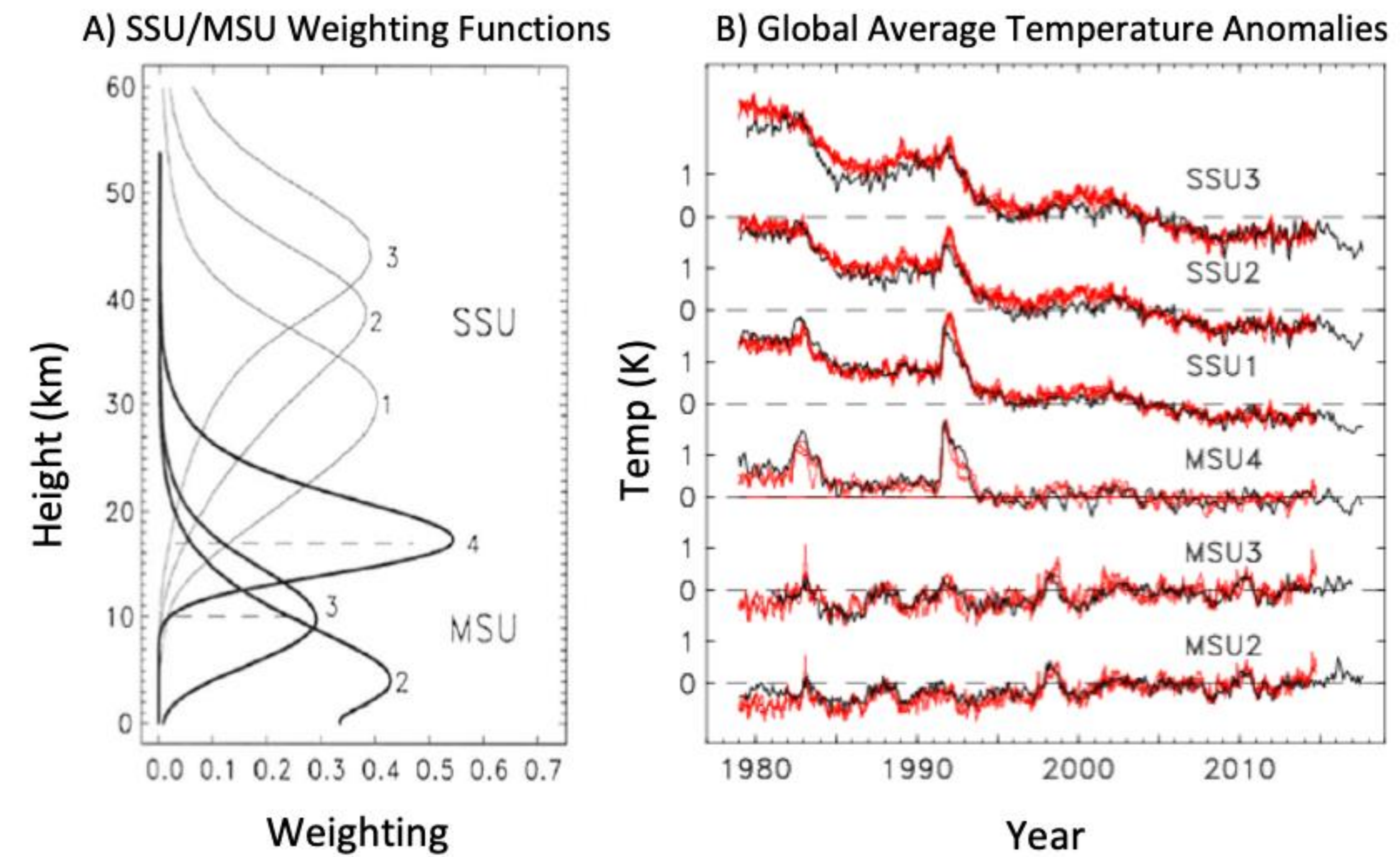
Direct radiative effects of stratospheric sulfate



http://www.comet.ucar.edu



Top-of-atmosphere radiative flux response to Pinatubo eruption agrees well with satellite observations.



al stratospheric temperatures compare very well to observations, including volc

Figure from Gettelman et al., submitted to JGR, 2019.

Warming in coupled historical simulations

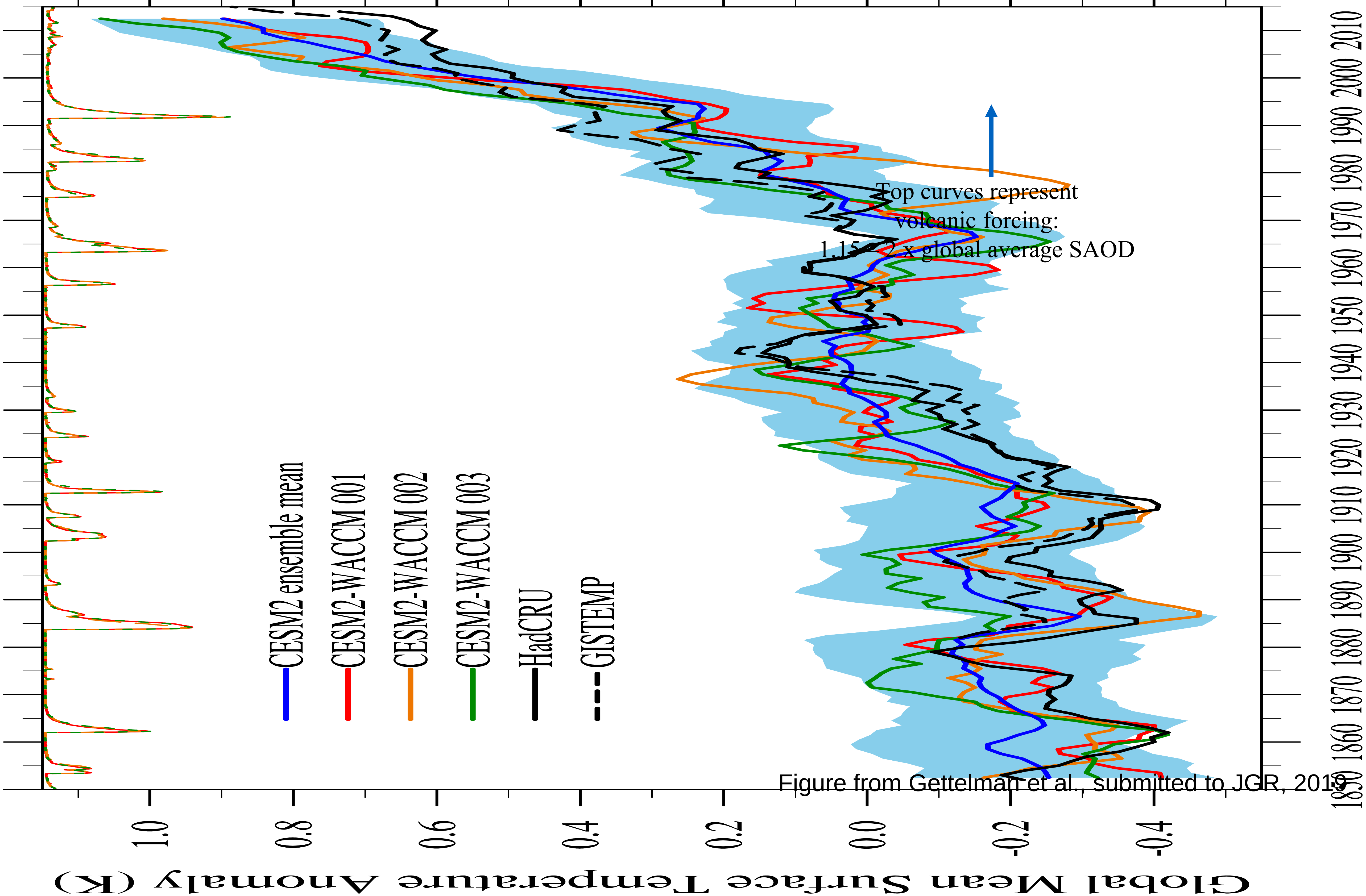
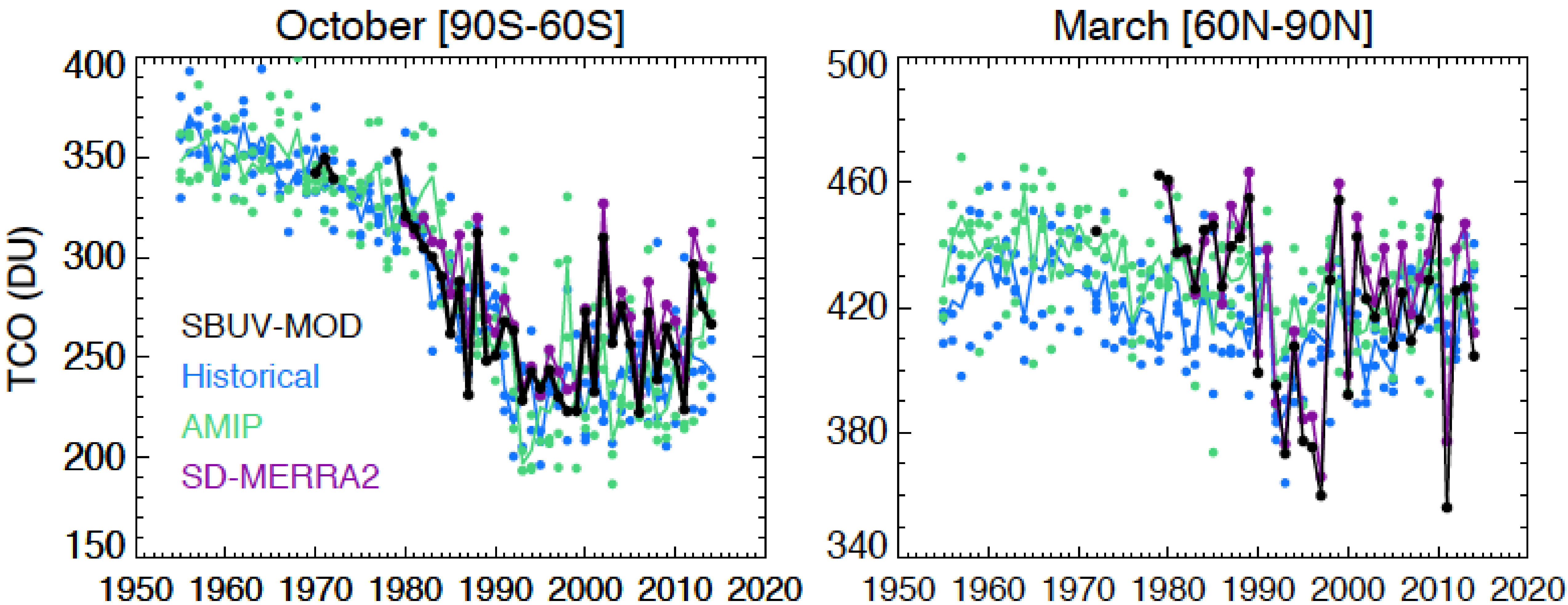


Figure from Gettelman et al., submitted to JGR, 2019

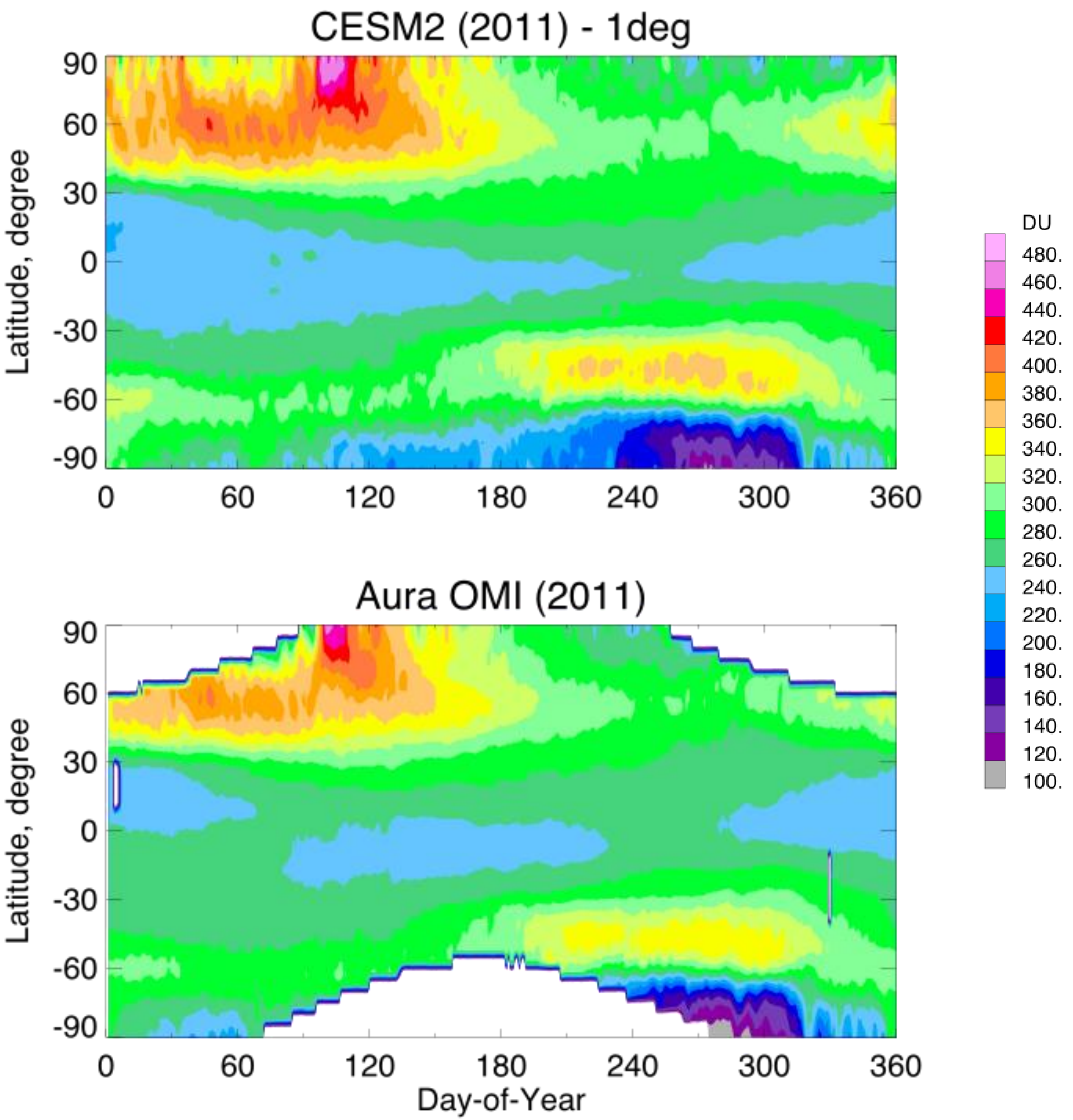
Polar ozone evolution



- WACCM6 reproduces well the observed evolution of the Antarctic ozone hole, and Arctic ozone loss.
- Nudged with specified dynamics, WACCM6 reproduces the observed interannual variability at both poles.

Figure from Gettelman et al., submitted to JGR, 2019

Total Column Ozone (TOZ), SD configuration



Slide courtesy of D. Kinnison.

WACCM and CAM-Chem Customer Support

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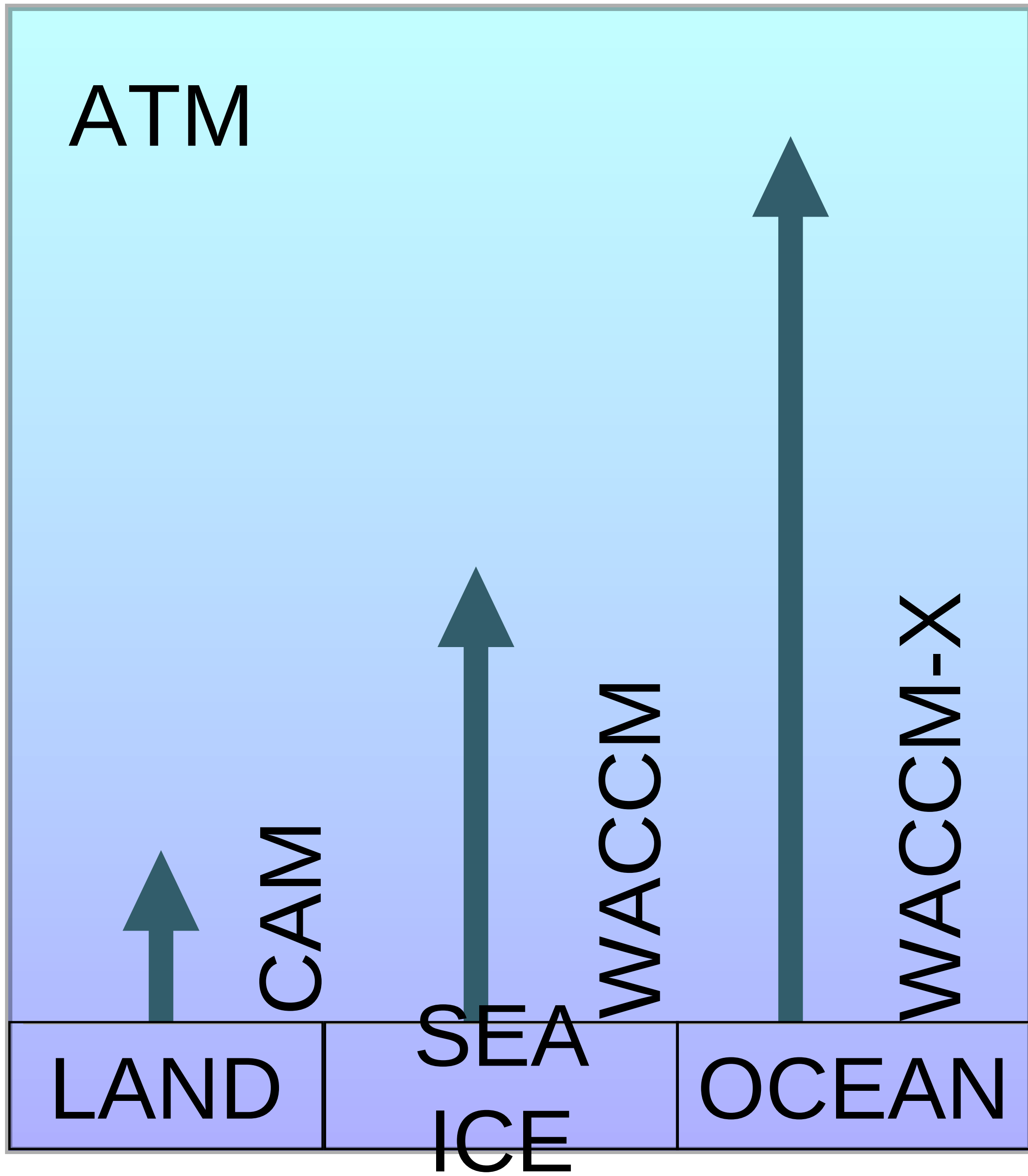
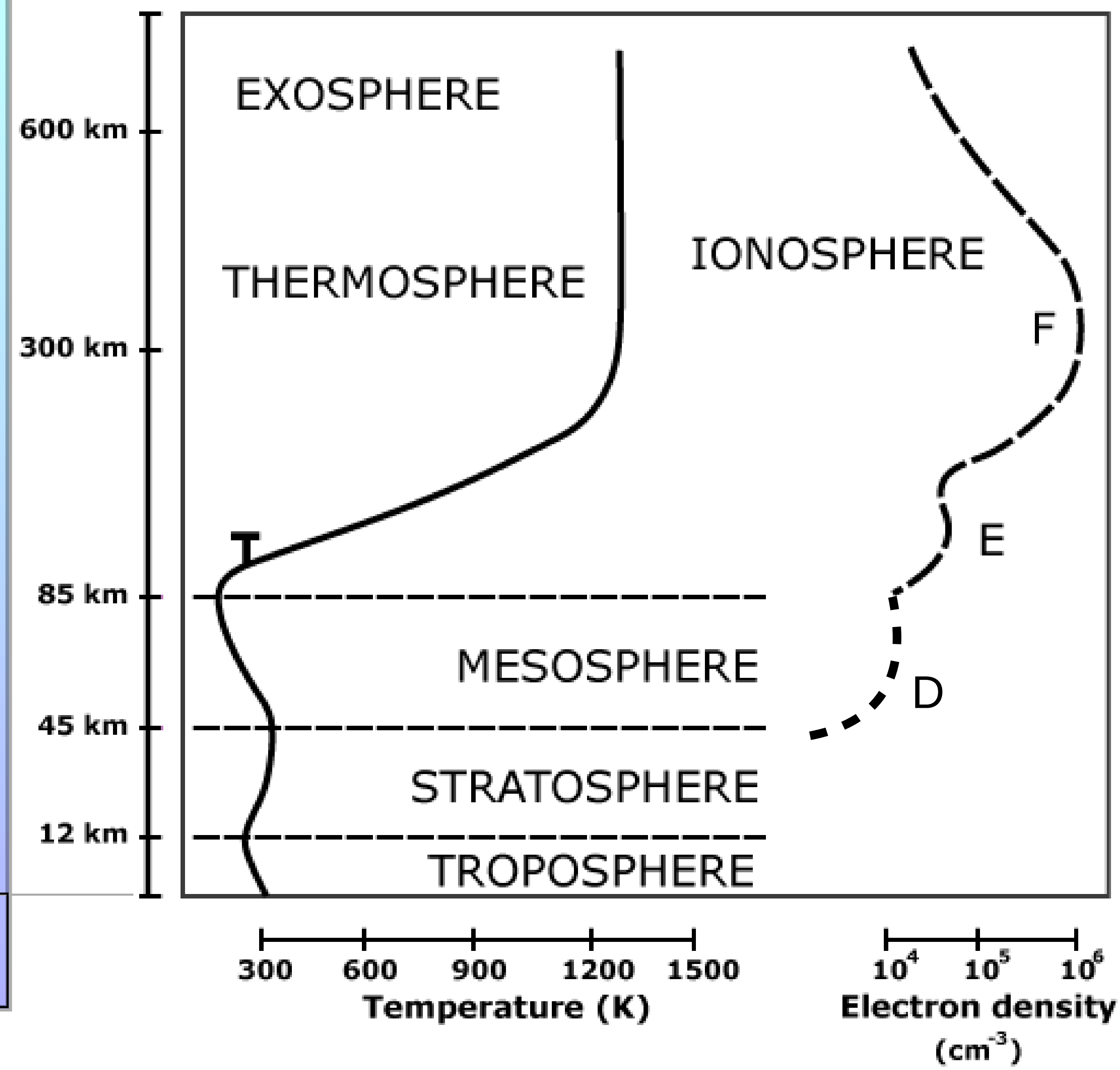
Extra slides

CESM2 atmosphere components





WACCM costs (approximate)

Configuration	Resolution	Chemistry	Core-hours / simulation year
CAM6	1°, 32L	CAM	3,700
WACCM6	2°, 70L	MA	5,400
WACCM6	1°, 70L	TSMLT	22,000
WACCM6-SC	1°, 70L	SC	6,000
WACCM6-SD	1°, 88L	TSMLT	23,000
WACCM5.4	1°, 110L	MA	20,000
WACCM5.4-SC	1°, 110L	SC	9,000

WACCM version evolution

Common Name	WACCM4	WACCM-CCMI	WACCM5	WACCM6
Horizontal Resolution	1.9°x2.5°	1.9°x2.5°	0.95°x1.25°	0.95°x1.25°
Vertical Levels	66	66	70	70
Deep Convection	ZM	ZM	ZM*	ZM*
Boundary Layer	HB	HB	UW	CLUBB
Shallow Convection	Hack	Hack	UW	CLUBB
Macrophysics	RK	RK	Park	CLUBB
Microphysics	RK	RK	MG2	MG2
Radiation	CAMRT	CAMRT	RRTMG	RRTMG
Aerosols	Bulk	Bulk	MAM3	MAM4
QBO	Nudged	Nudged	Interactive	Interactive
Chemical Mechanism	MA(59)	TSMLT (180)	MA(59)	TSMLT1 (228)
Chemical Rates	JPL-06	JPL-11	JPL-06	JPL-15
SOA	2-product	2-product	SOAG	VBS
Sulfate SAD	CCMVal2	CCMI	Interactive	Interactive
Ice SAD	Bulk	Bulk	Bulk	MG2
Solar Variability	CMIP5-Solar	CCMVal2-Solar	CMIP5-Solar	CMIP6-Solar
GHG Abundances	CMIP5 RCPs	CMIP5 RCPs	CMIP5 RCPs	CMIP6 SSPs
Halogens	CMIP5 RCPs	WMO 2010	CMIP5 RCPs	CMIP6 SSPs

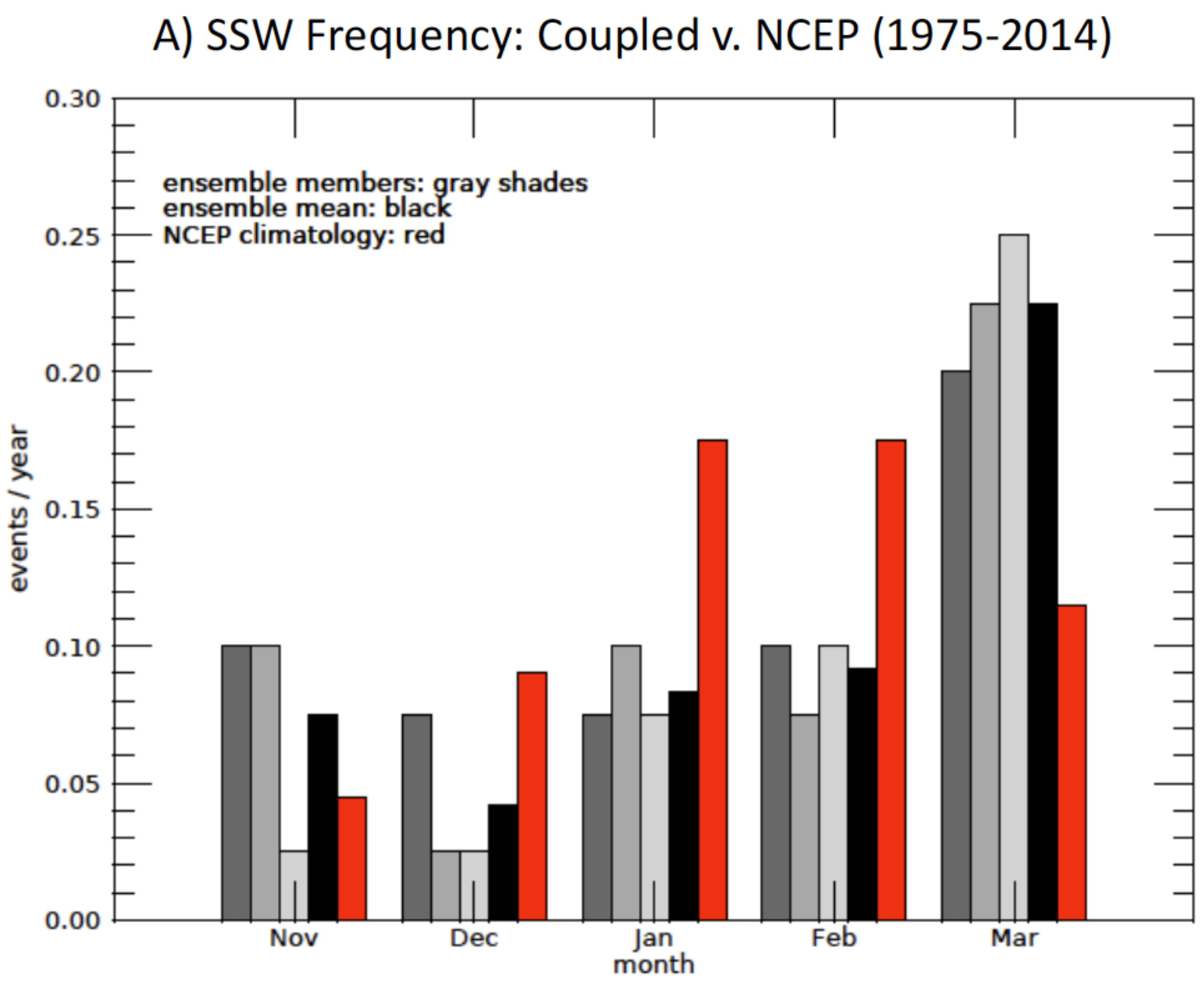
Gettelman et al., submitted to JGR, 2019

WACCM6 highlights

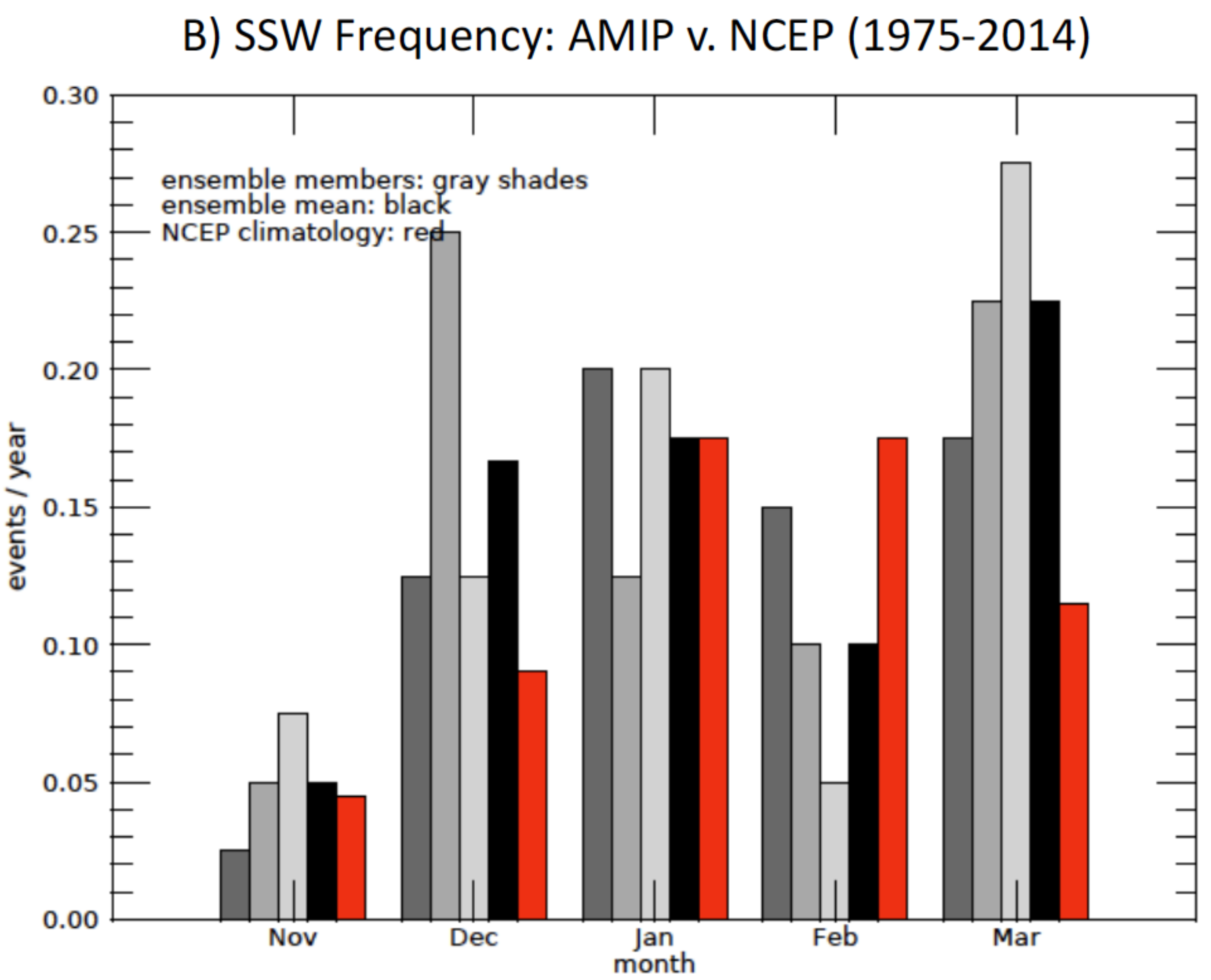
(from Gettelman et al., 2019)

SSW Climatology (Nov-Mar); 3 realizations

Coupled ocean

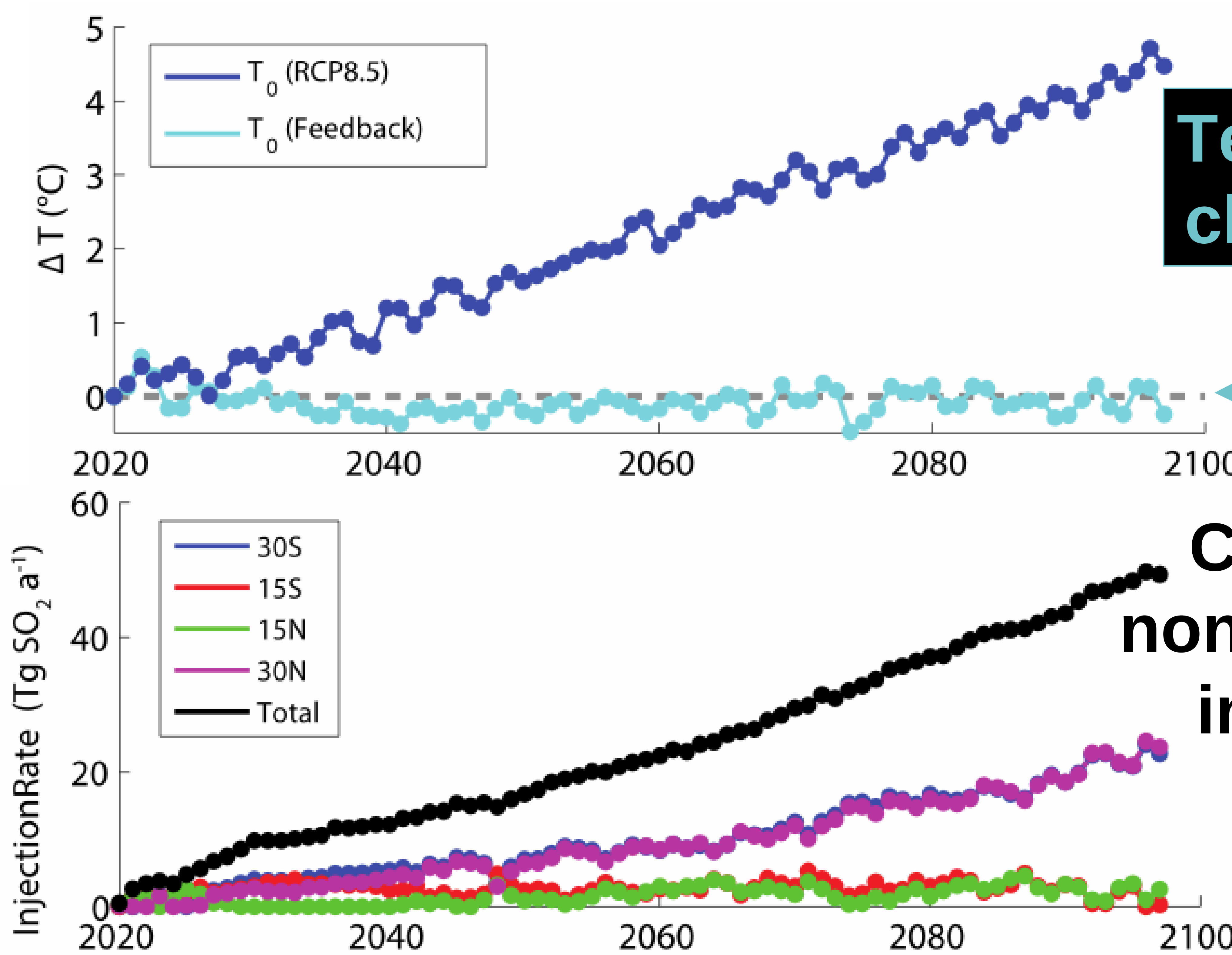


Specified SST



WACCM
Whole Atmosphere Community Climate Model

WACCM Sulfate Geoengineering Feedback Simulations



Temperature change goal

Combined non-equatorial injections

Kravitz et al. (2017)

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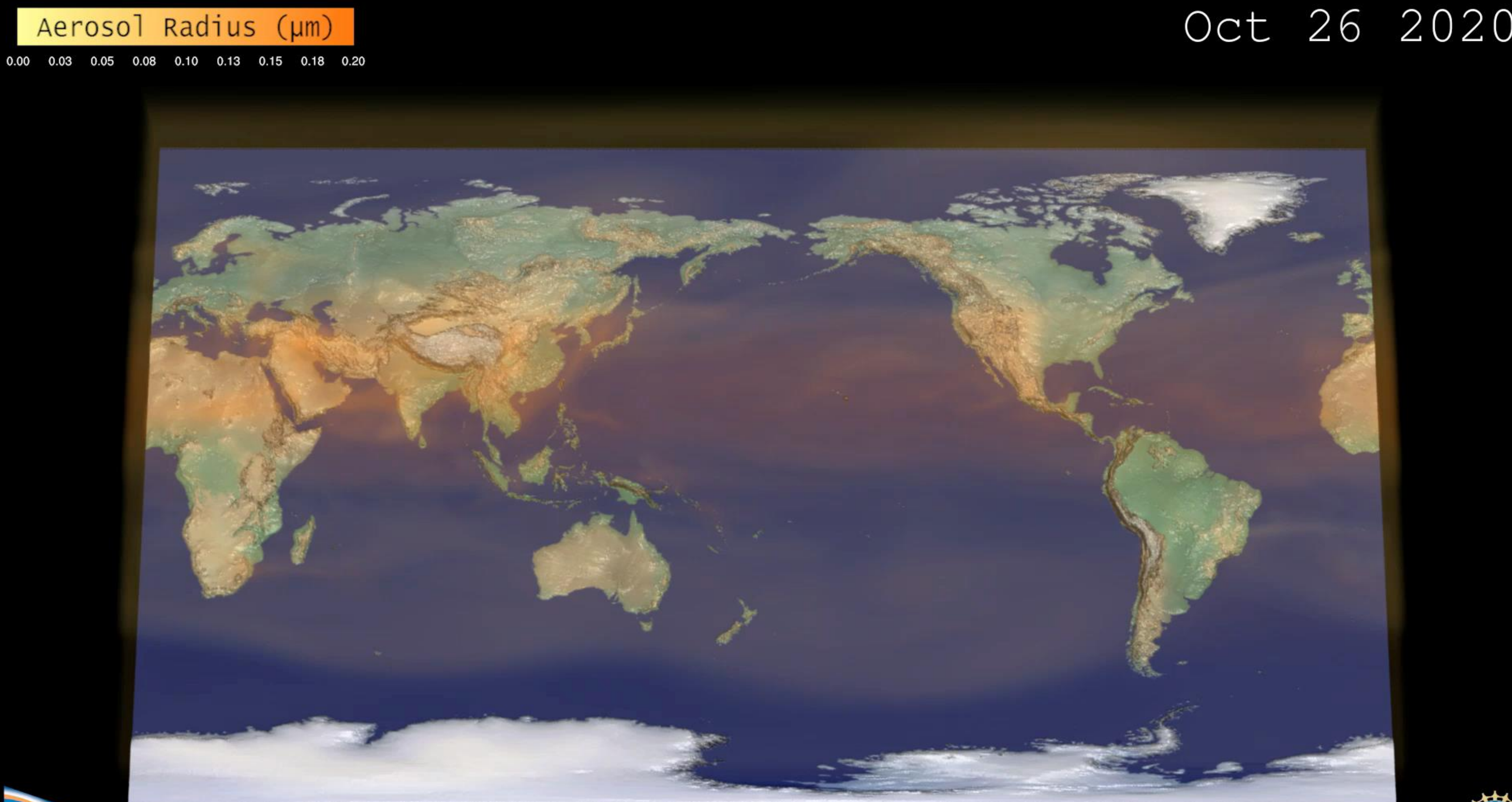
WACCM

Whole Atmosphere Community Climate Model



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Why WACCM-X?

Because the thermosphere- ionosphere system responds to variability from the Earth's lower atmosphere as well as solar-driven "space weather"

Including:

- Waves and tides
- Tropospheric weather
- Middle-atmosphere events
- Seasonal variations
- Anthropogenic trace gases

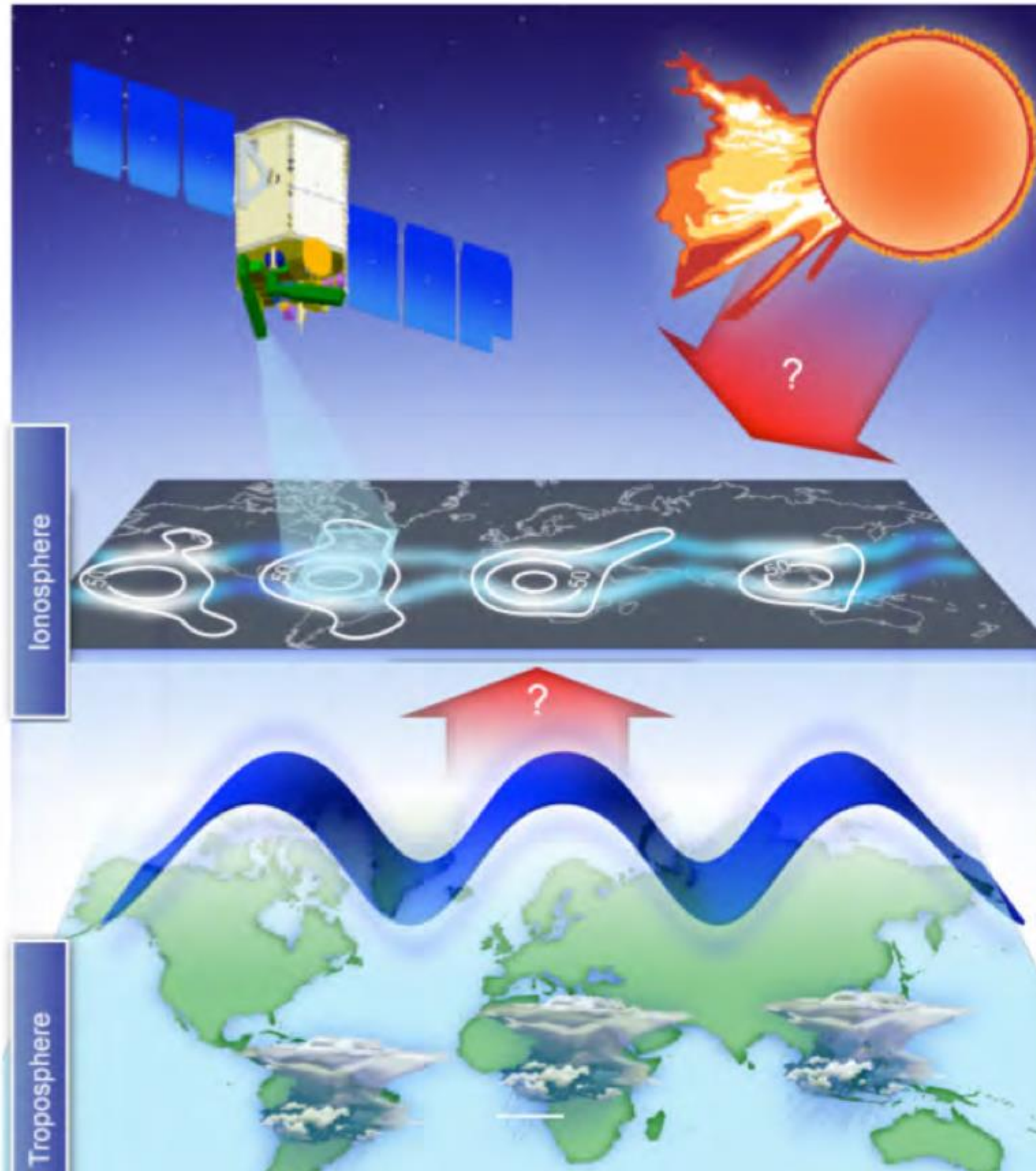
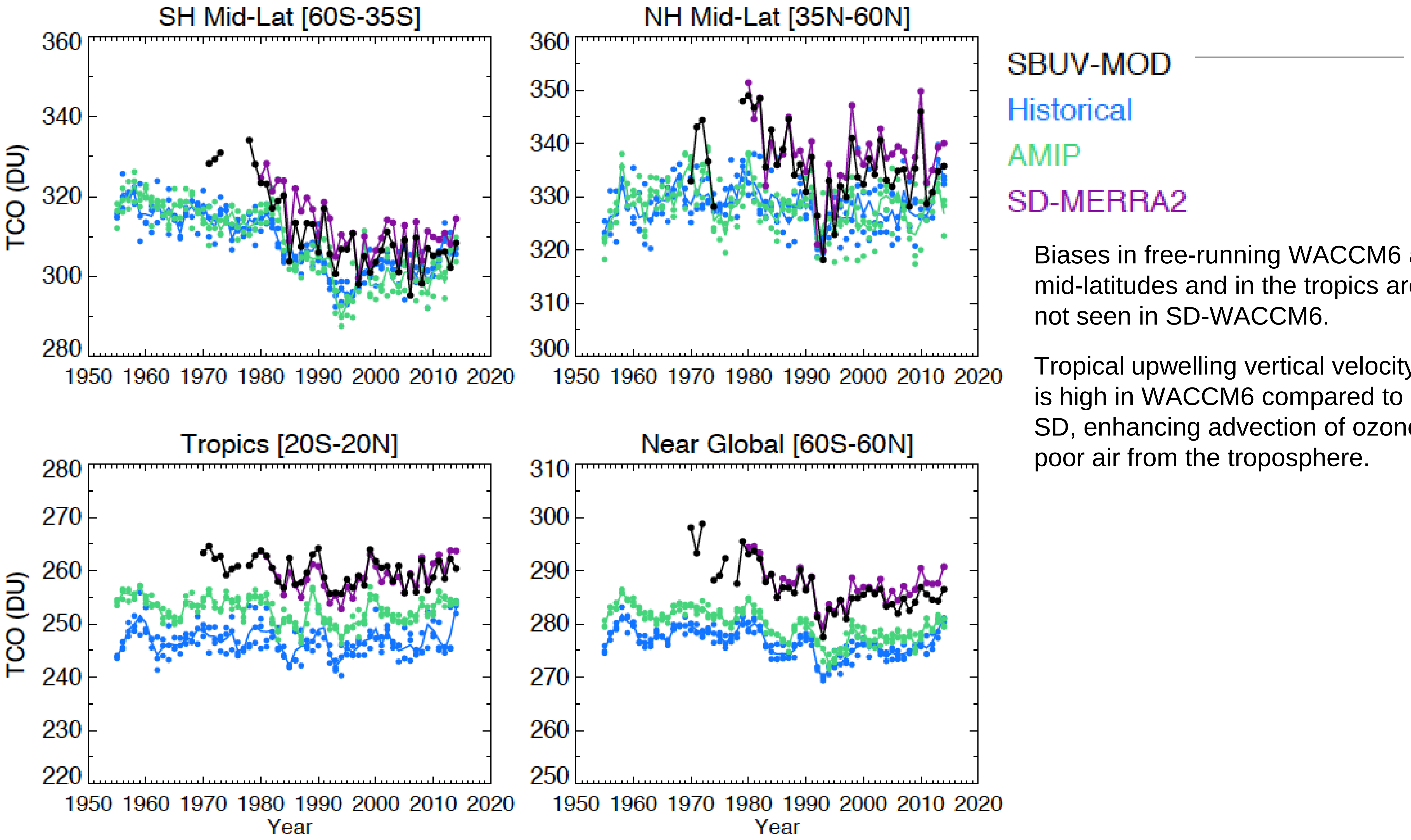


Illustration from the ICON mission, T. Immel et al.

Ozone layer evolution

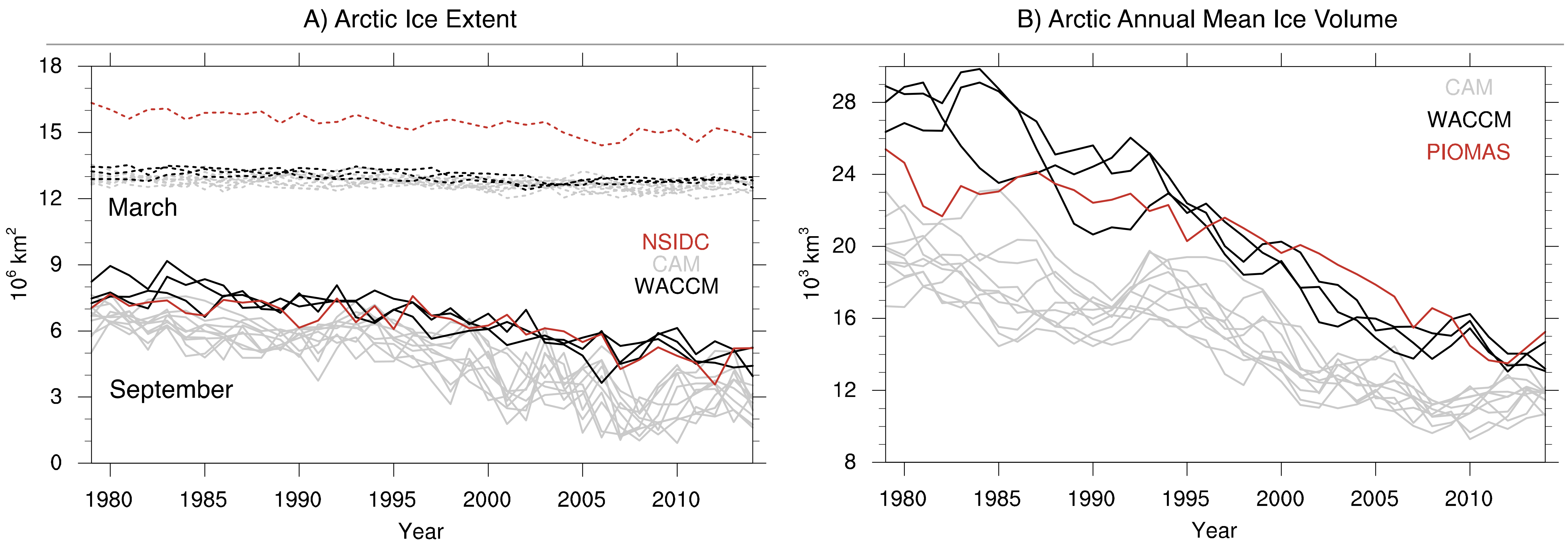


Biases in free-running WACCM6 at mid-latitudes and in the tropics are not seen in SD-WACCM6.

Tropical upwelling vertical velocity is high in WACCM6 compared to SD, enhancing advection of ozone-poor air from the troposphere.

Figure from Gettelman et al., submitted to JGR, 2019

Sea ice extent

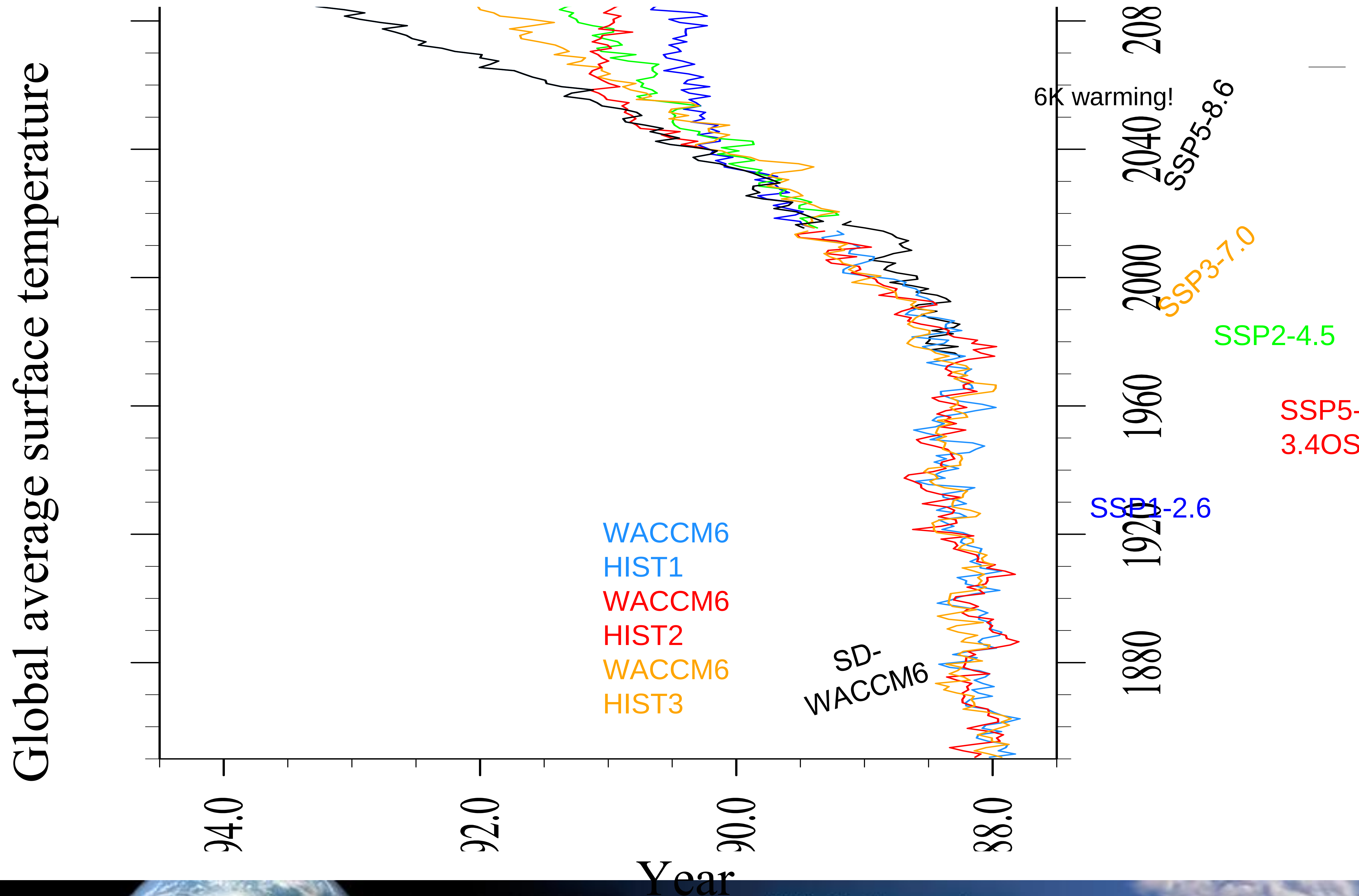


WACCM6 has higher September NH SIE than CAM6, in better agreement with observations.

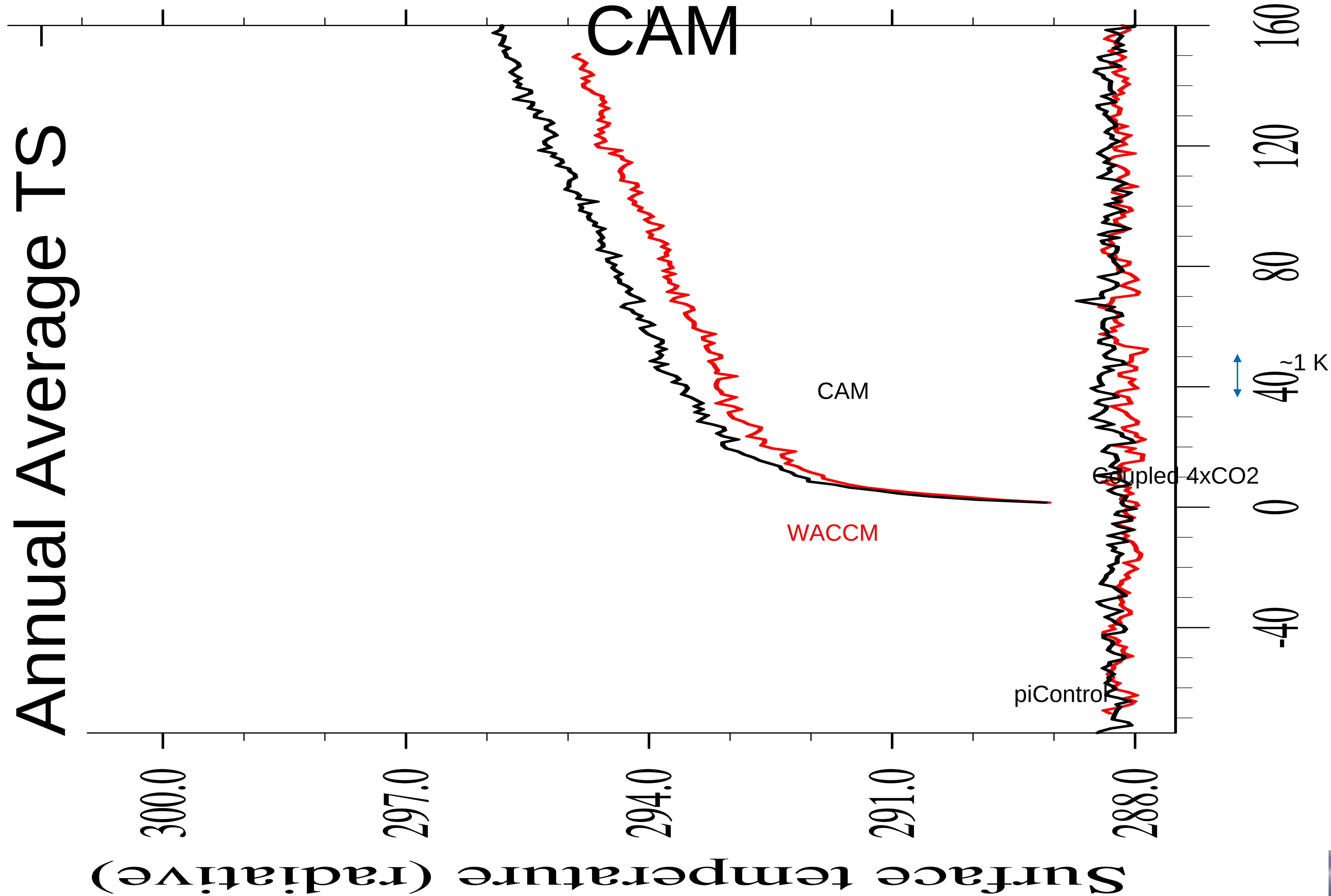
Analysis: Less downward surface SW and LW in WACCM6 due to higher LWP, which results from higher aerosol number. The higher aerosol number increases CCN and cloud drop number, resulting in smaller drops that do not precipitate as readily. Thus the tropospheric aerosol chemistry impacts Arctic sea ice.

Figure from Gettelman et al., submitted to JGR, 2019

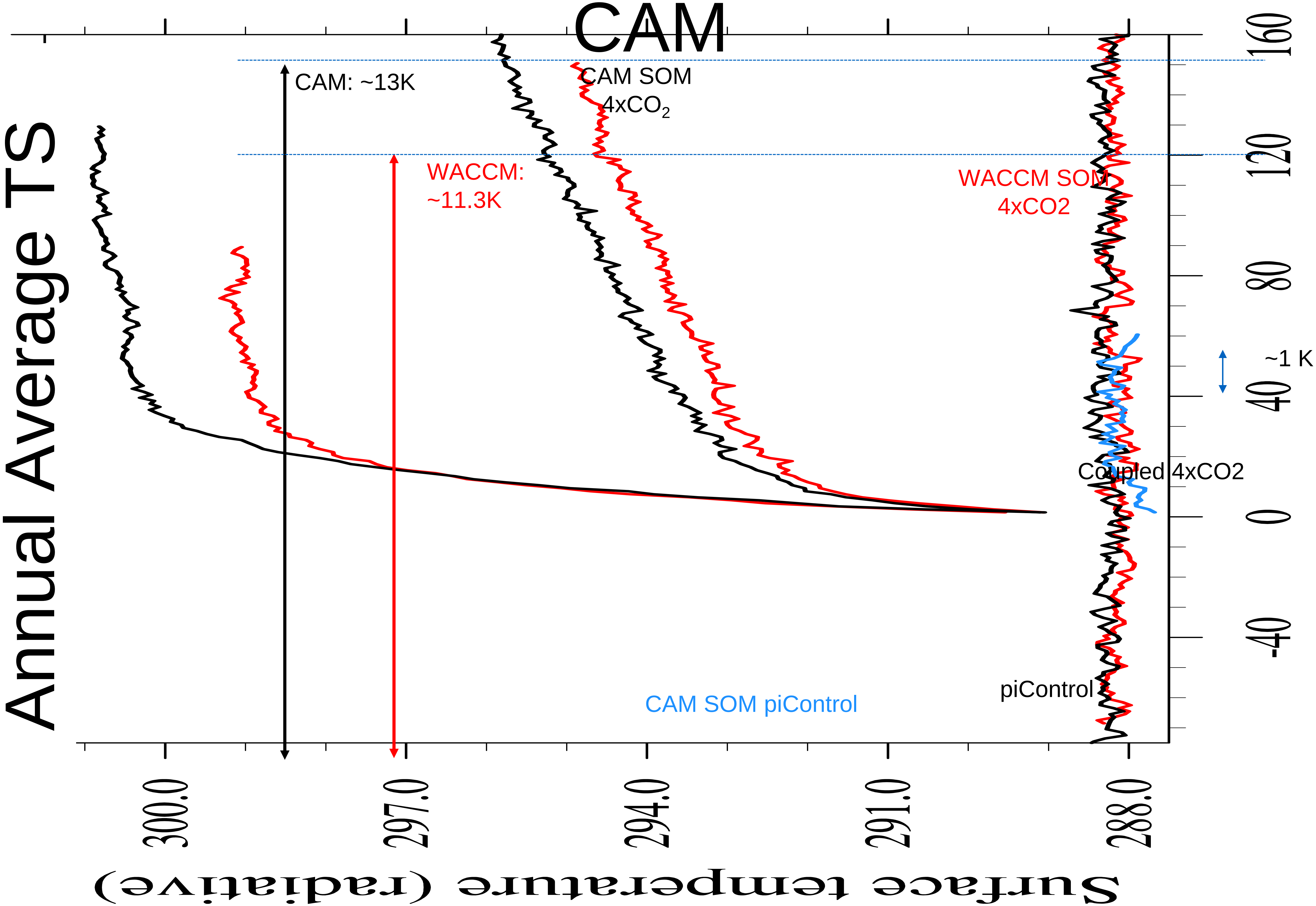
WACCM historical and future scenarios



Climate Sensitivity: WACCM vs CAM



Climate Sensitivity: WACCM vs CAM



Climate Sensitivity: WACCM vs CAM