Polar Ozone Depletion and Trends as Represented by the Whole Atmosphere Community Climate Model (WACCM)

Doug Kinnison[1], Susan Solomon[2], Diane Ivy[2], Mike Mills[1], Ryan Neely III[3], and Anja Schmidt[3]

[1]NCAR, USA; [2]MIT, USA; [3]U. Leeds, UK

FESD Meeting, MIT

June 7, 2016

ccmi
chemistry-climate model initiative

NCAR
WACCM
Whole Atmosphere Community Climate Model

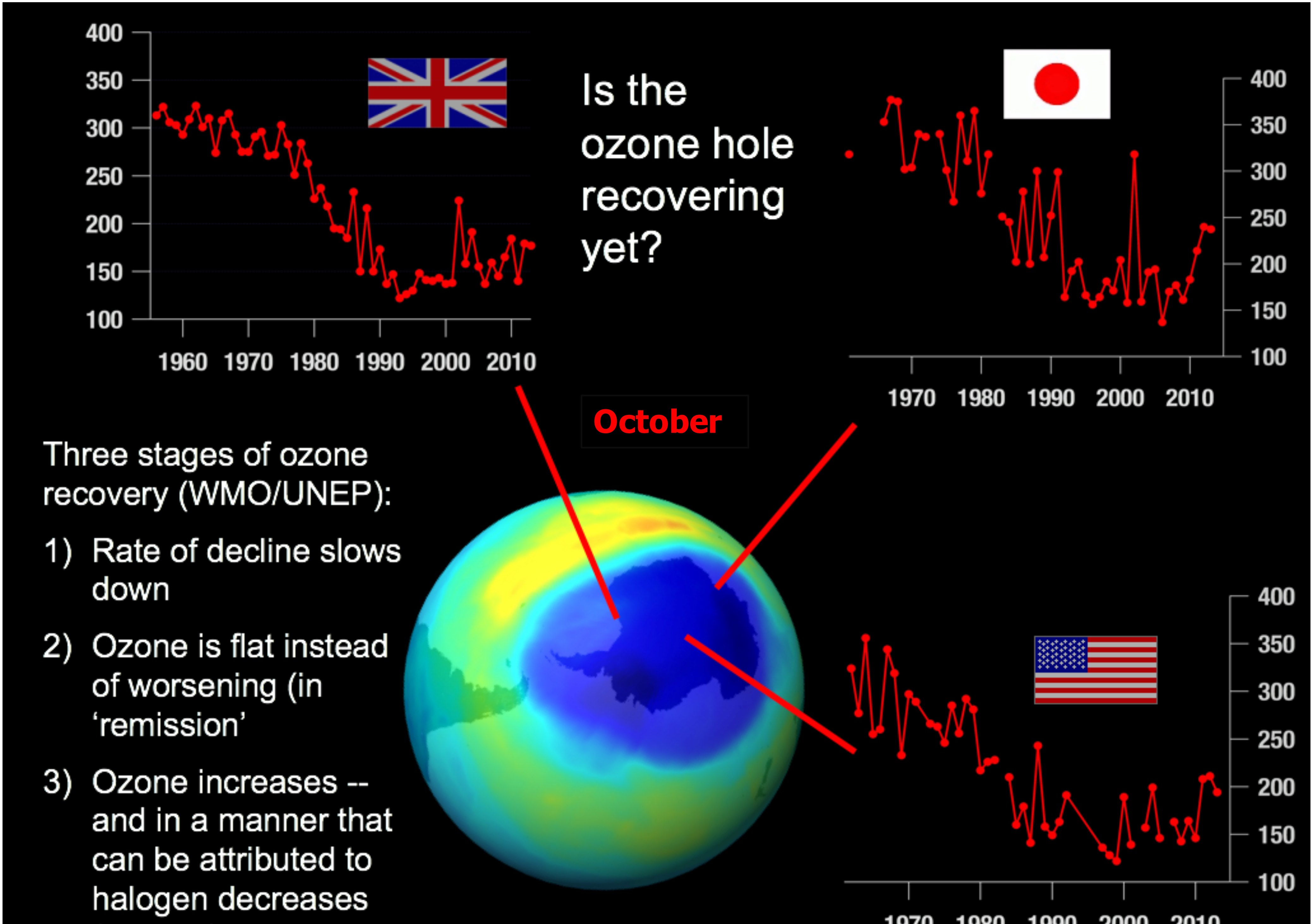


Figure courtesy of S Solomon.

Approach

- Model Description.
- Choice of input stratospheric sulfate surface area density (SAD).
- Impact of small volcanic eruptions on ozone (post year 2000).
- Total OZone (TOZ) trends (obs vs model).
- Ozone profile trends (obs vs model).
- Monthly breakdown of the dynamical/temperature, chemical, and volcanic SH polar cap trends in TOZ.

Solomon, et al., in review, Science, 2016

Model: Whole Atmosphere Community Climate Model

The CESM1 (WACCM) Version 4 is a fully interactive chemistry climate model, where the radiatively active gases affect heating and cooling rates, therefore dynamics (Marsh et al., *J. Climate*, 2013).

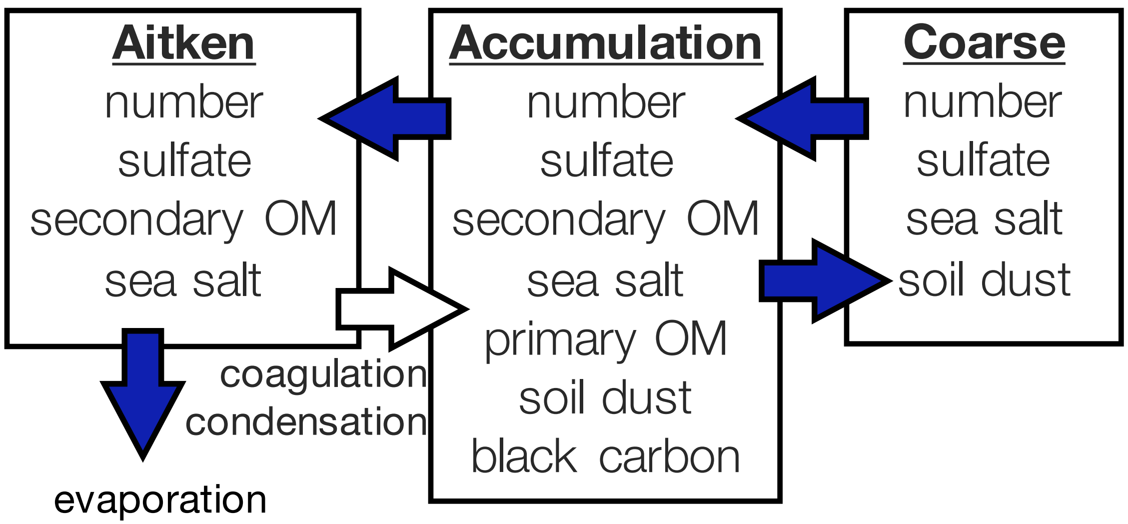
- CAM4 finite volume dynamics/transport and column physics.
- CCMI TSMLT Chemistry: ~180 species, >450 gas-phase rxns; 17 heterogeneous rxns on sulfate, NAT, and Water-Ice.
- Resolution: surface to ~140km (66-levels), 1.9 x 2.5° horizontal.

WACCM with Specified Dynamics (SD) option is used to drive the physical processes that control boundary layer exchange, advective and convective transport, and the hydrological cycle.

- NASA GMAO MERRA meteorological fields (i.e., T, U, V, PS) are used to "nudge" the interactive version, with a relaxation time constant of 50-hrs.
- Resolution: surface to ~140km (88-levels), 1.9 x 2.5° horizontal
- Nudge up to 50km, linearly transition to interactive version at 60km.

Stratospheric Sulfate Surface Area Density (SAD) Option

Derived from modal aerosol model (MAM): stratospheric sulfate



Added Gas-phase species:
H_2SO_4, SO_2, DMS, SOA (gas), OCS, S, SO, SO_3, HSO_3

Added: sulfate evaporation above tropopause

Added: growth between modes

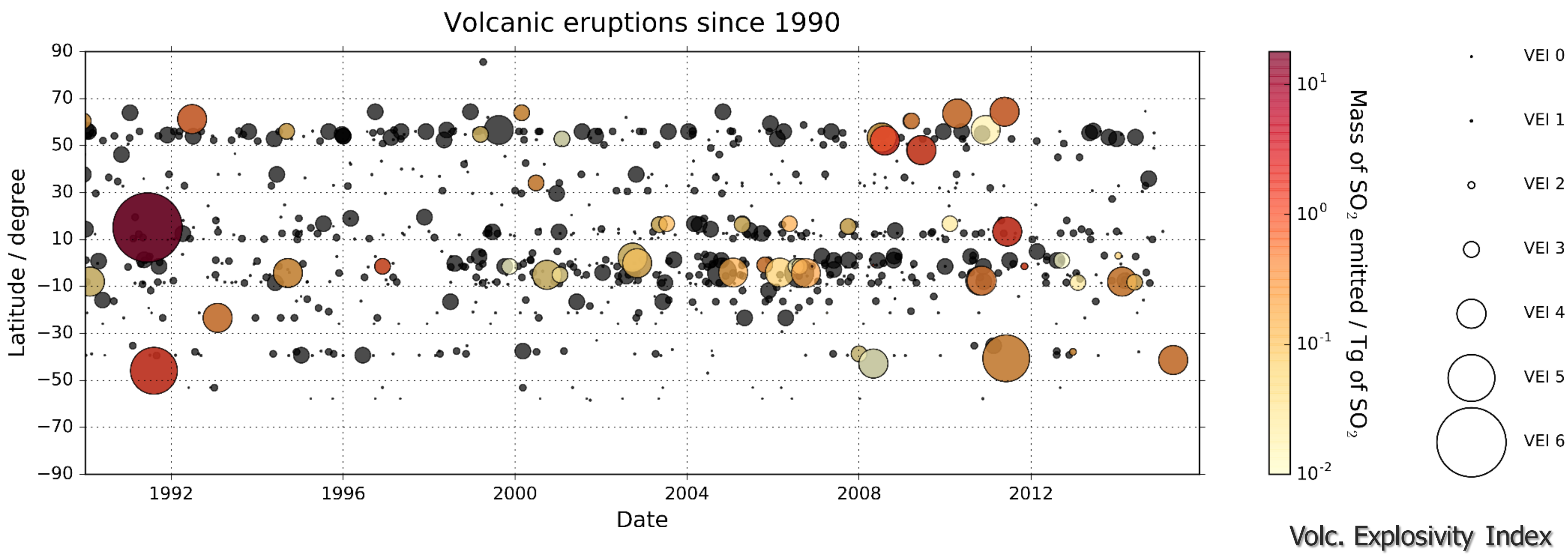
Added: Volcanic SO_2 emission (A. Schmidt, Leeds)

- Originally designed for CMIP6 simulation (1850-present).
- For this presentation we will call this the MAM SAD approach.

Mills, M., A. Schmidt, R. Easter, S. Solomon, D. Kinnison, S. Ghan, R. Neely, D. Marsh, A. Conley, C. Bardeen, A. Gettelman, Global volcanic aerosol properties derived from emissions, 1990-2014, using CESM1(WACCM), *J. Geophys., Res.,* 2015.

Volcanic Eruptions Since 1990

- 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



Database: 42 volcanoes, 52 eruptions, 171 days of eruption

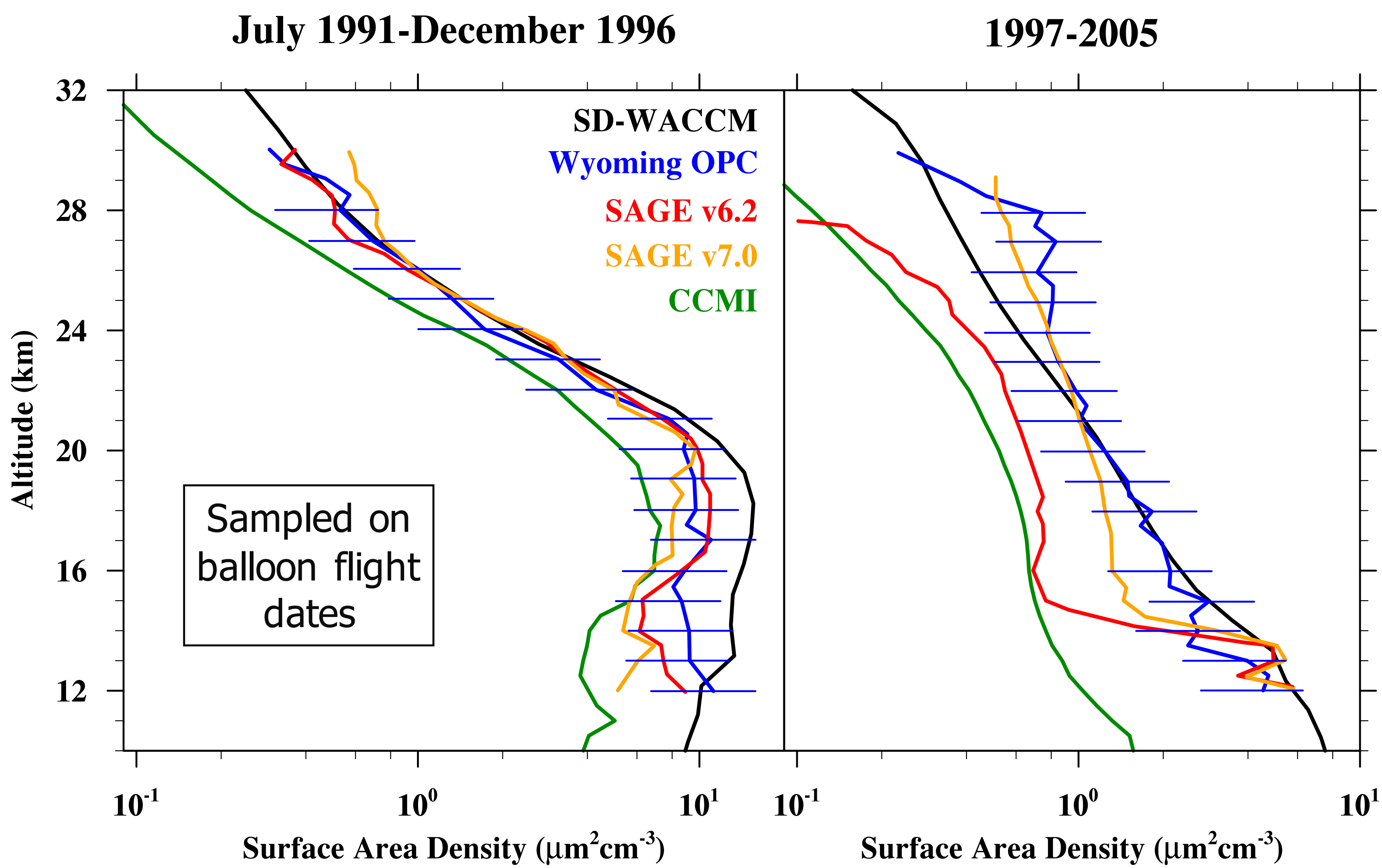
1990-1994	1995-1999	2000-2004	2005-2009	2010-2015
12.85 Tg of SO_2	0.93 Tg of SO_2	0.93 Tg of SO_2	7.56 Tg of SO_2	8.55 Tg of SO_2

Figure courtesy of Anja Schmidt, U. Leeds

Simulations for this Study

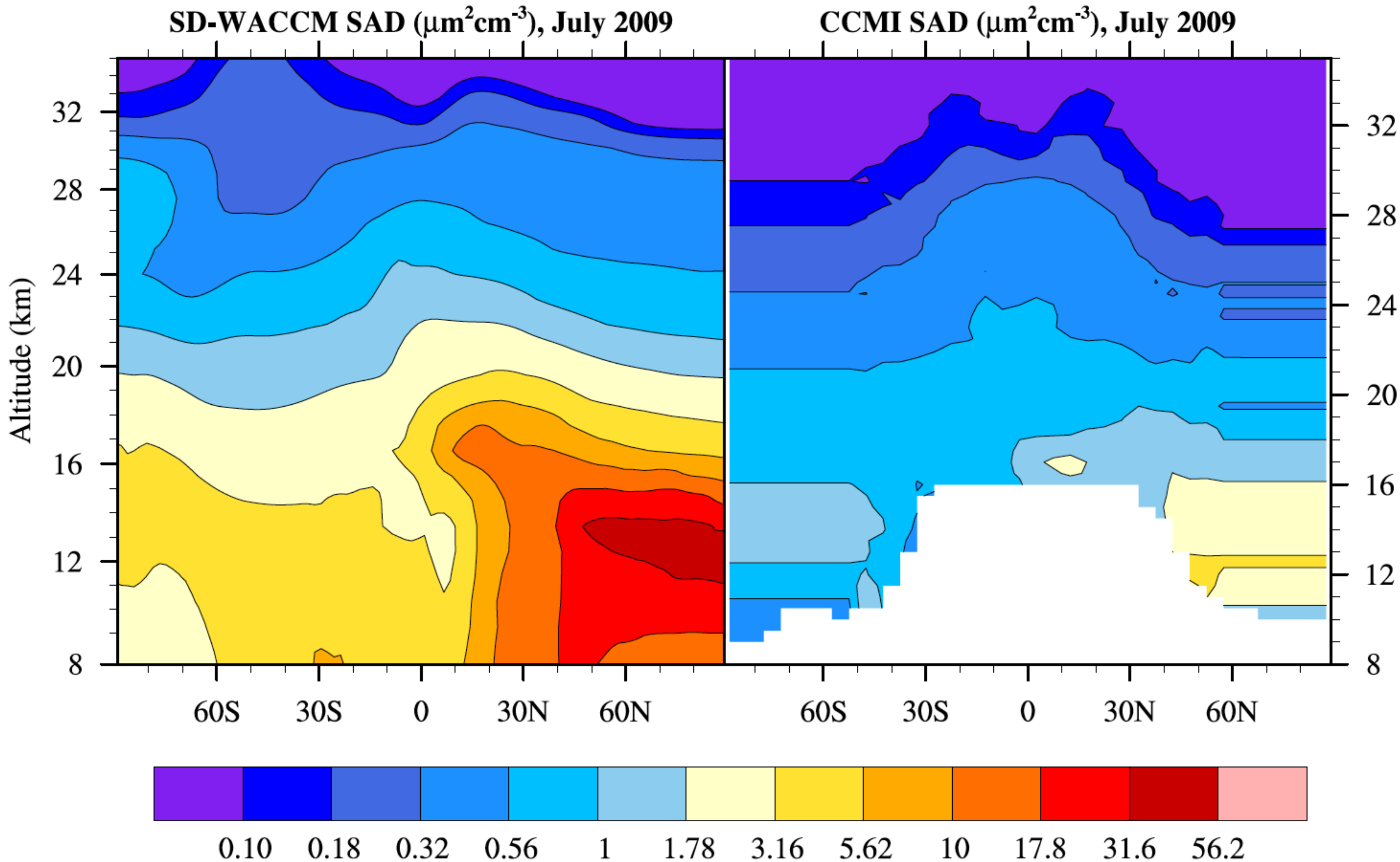
CCMI:	REFC1SD (MERRA), with volcanic SAD (CCMI).
Chem-Dyn-Volc:	Same as CCMI, except with volcanic SAD (MAM).
Volcanic Clean:	Same as Chem-Dyn-Vol, with no volcanic SAD (MAM).
Chem only:	Save as Volcanically Clean, with repeating year 1999 meteorological conditions, with no volcanic SAD (MAM).

Comparison of CCMI, MAM, OPC SAD *** 41N



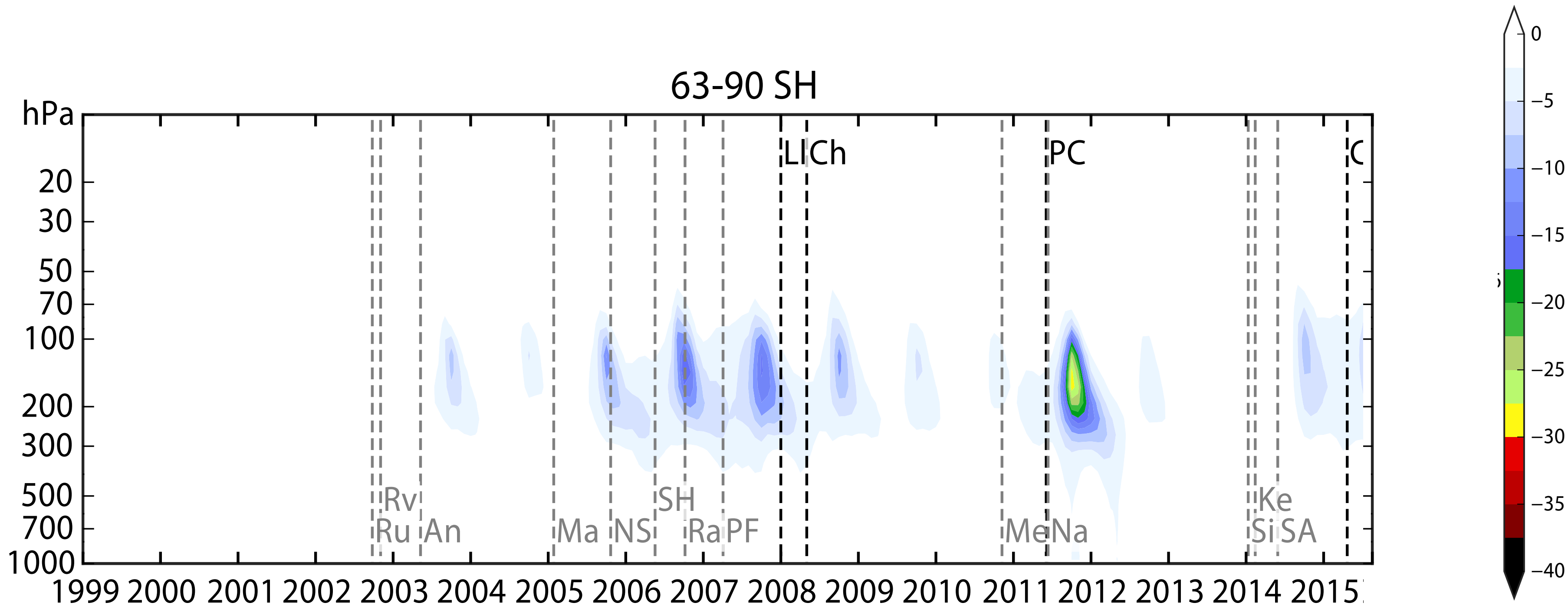
U. Wyoming, Balloon-borne optical particle counter, Kovilakam, and Deshler, JGR, 2015.

Comparison of CCMI vs MAM SAD.



Mills et al., JGR, 2015.

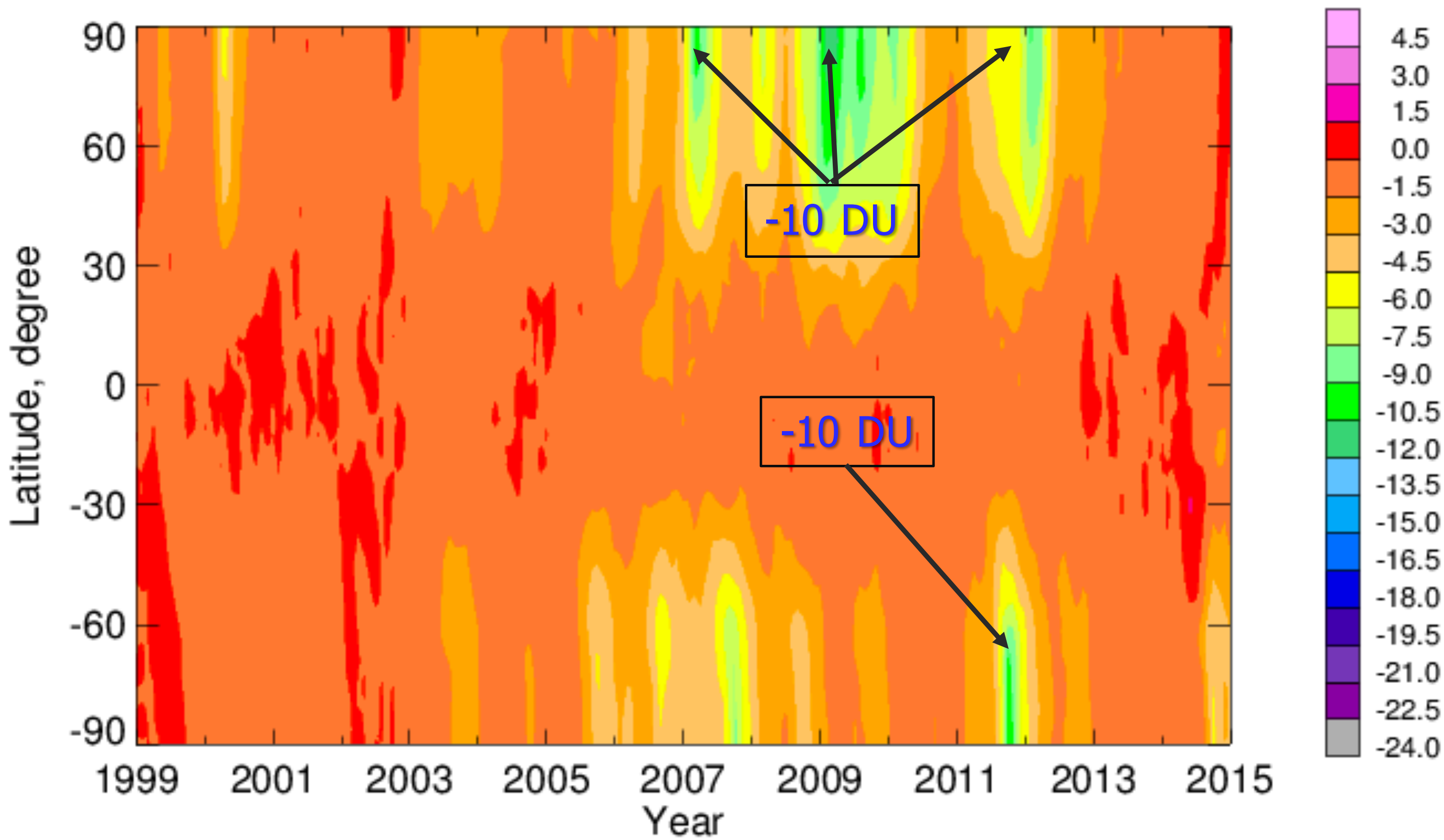
Volcanic Impacts on Polar Ozone (%) using MAM SAD.



Comment:

- Higher latitude eruptions can directly influence the polar stratosphere but tropical eruptions can enhance polar aerosols following transport.
- The 2011 Chilean eruption of Puyehue-Cordon Caulle (PC) strongly influenced SH ozone in the 100-300hPa region (-30%).
- At pressures >100hPa, temperatures are generally too warm for many PSCs to form, but there is sufficient water that effective heterogeneous chemistry can take place under cold polar conditions (Hanson et al., 1994).

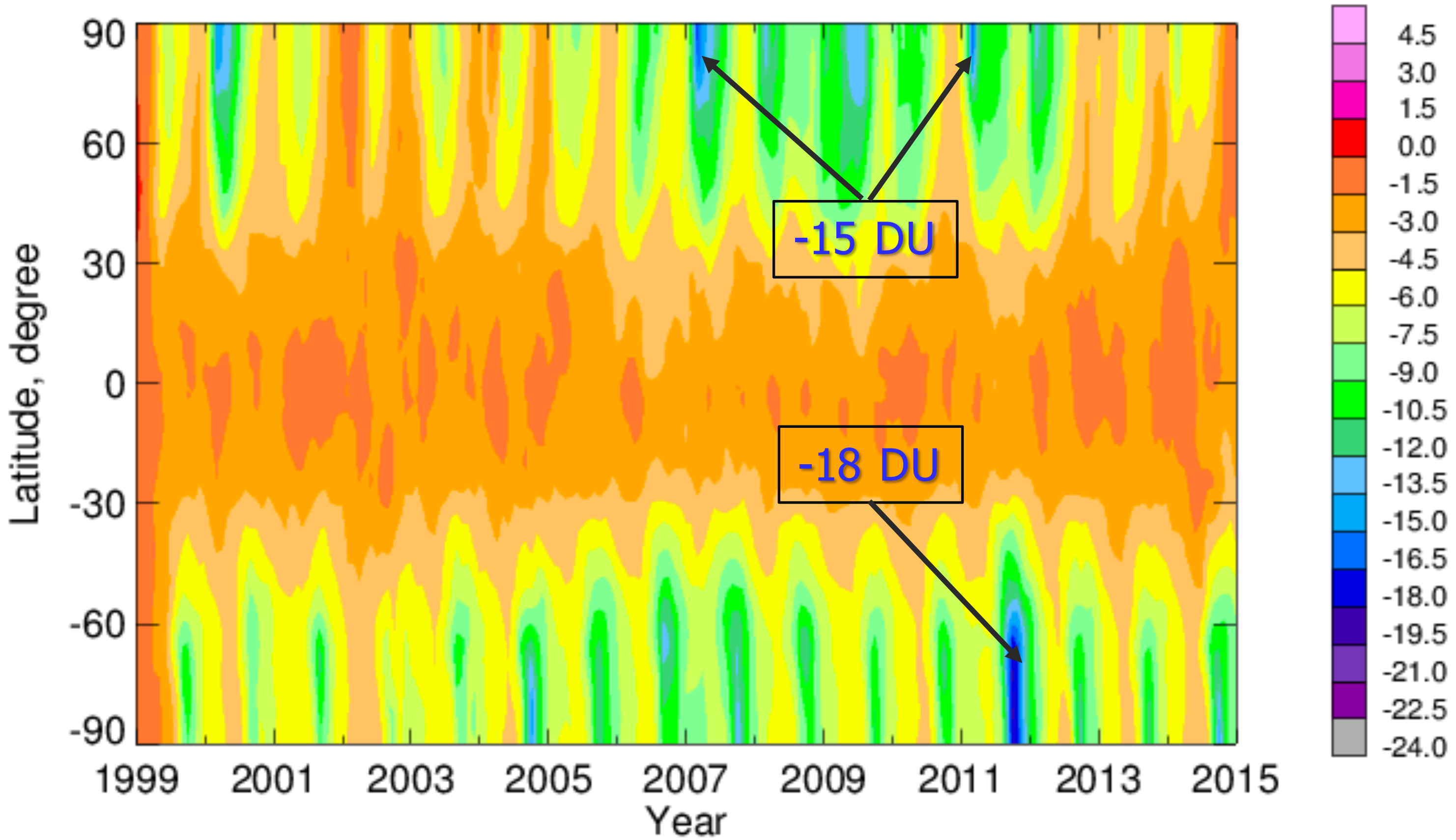
TOZ Change (DU) *** MAM - VCMAM



Comments:

- In SD-WACCM, Chem-Dyn-Vol (MAM) minus Volcanically Clean (VCMAM) shows differences in polar TOZ, with largest differences up to 10DU.

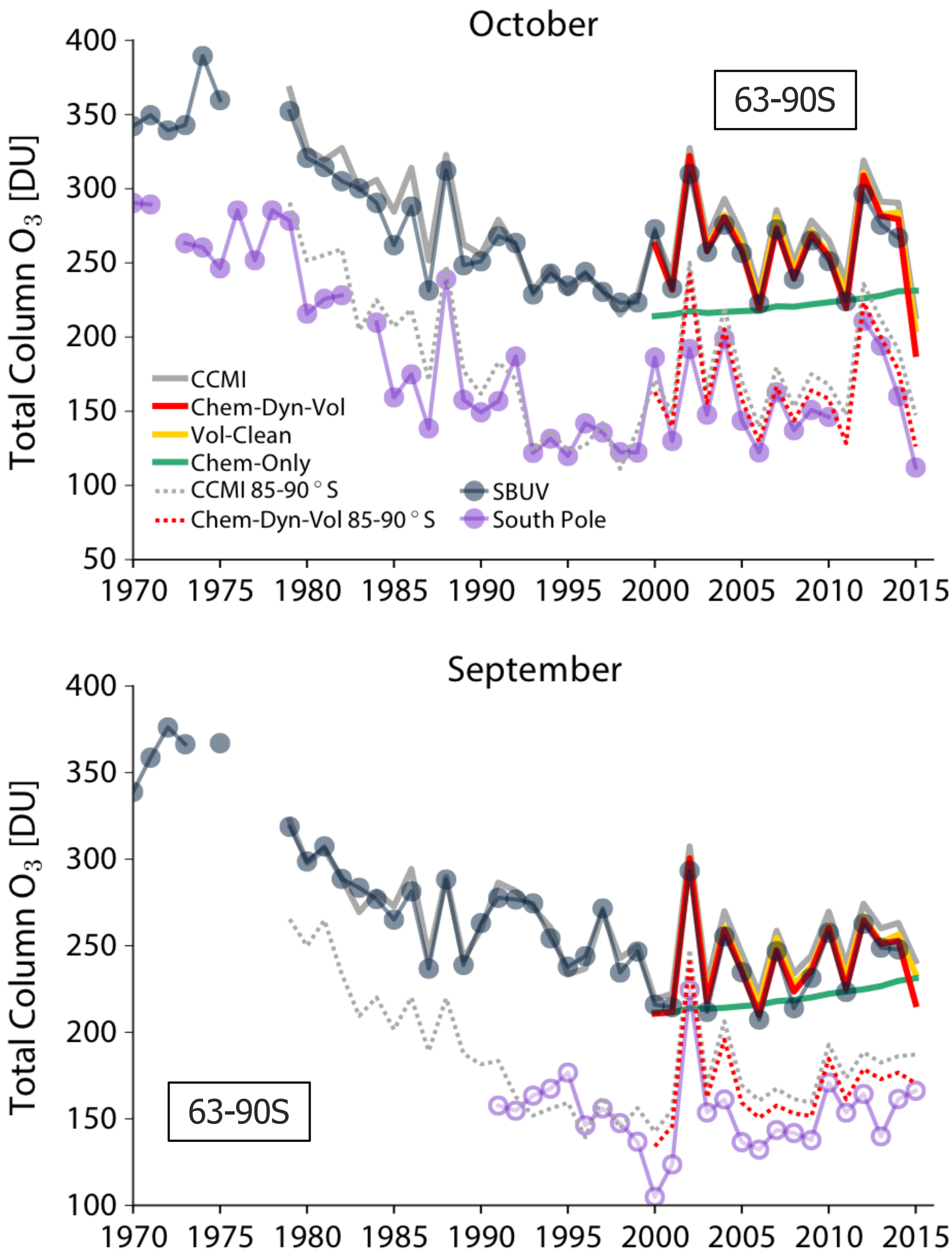
TOZ Change (DU) *** MAM - CCMI



Comments:

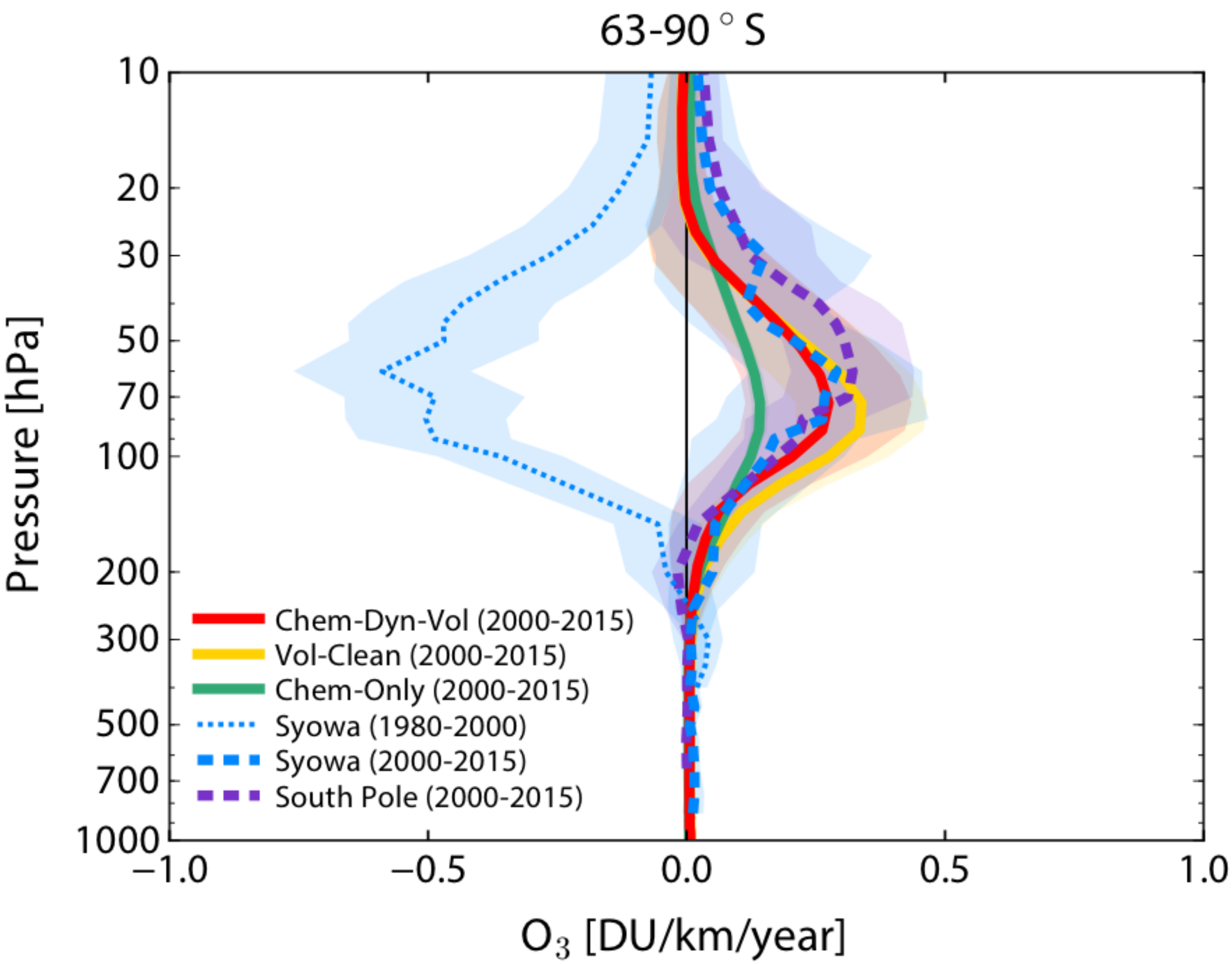
- In SD-WACCM, Chem-Dyn-Vol (MAM) minus CCMI shows differences in polar TOZ, with many years showing >10DU differences.
- It should be noted that after 2011, the CCMI input sulfate SAD is an average of years 1998/1999.
- There is less difference between MAM-VCMAM vs MAM-CCMI!

Polar SH Total Ozone



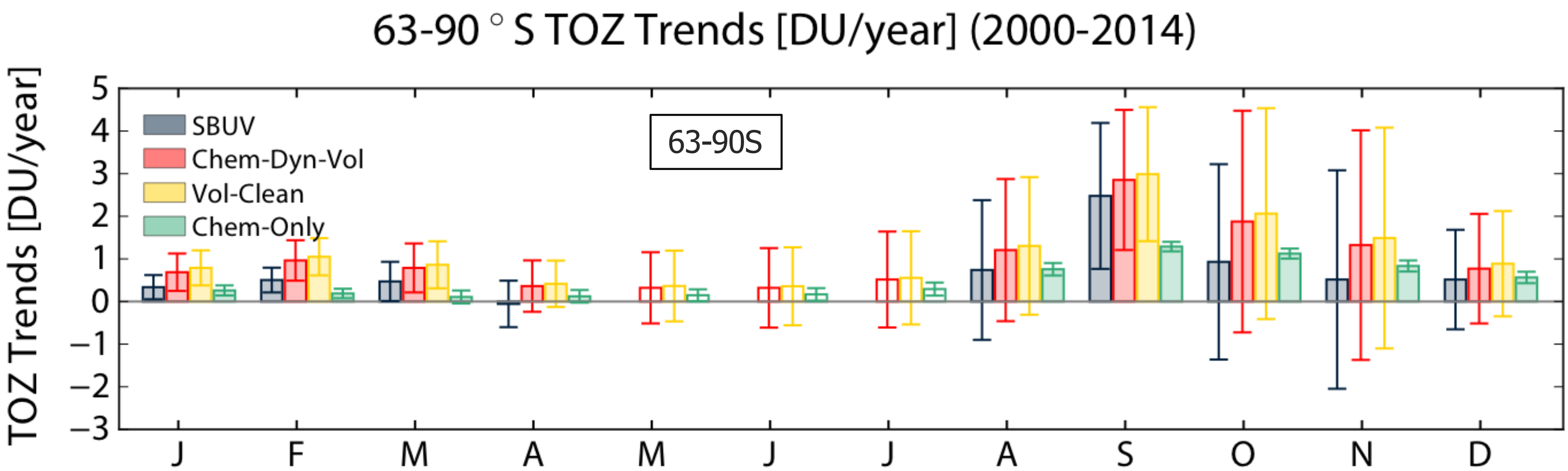
- Obs show significant variably post 2000. SBUV is averaged over the polar cap.
- The Chem-Dyn-Vol reproduced the observed October year-to-year variability.
- The October TOZ is significantly more variable than September.
- The Chem-Only sim, shows a gradual "healing" in the TOZ (i.e., due to reduction in EESC).
- In the following trend figures, year 2002 is not considered due to its anomalous occurrence.

Trends in September Ozone Profiles for 2000 – 2015.



- Observations (dashed lines) are from balloon data at Syowa (69S,40E) and South Pole.
- 1980-2000 trends show the formation of the ozone hole from obs.
- The Chem-Dyn-Vol trends compares well to the obs.
- There is a clear recovery (healing) of post 2000 ozone.
- The Chem-Only trend is approximately 50% of the observed healing.
- The model total September O_3 healing has been reduced locally by ~10% due to increased volcanic SAD.

Seasonal Cycle of TOZ Trends (2000-2014)



Comments:

- Chem-Dyn-Vol and SBUV are in good agreement for September. The trend is statistically significant (90% confidence interval).

- The October trend is poorly constrained due to large variability in that month.

- There is also statistically significant trends in January-March; however the absolute magnitude is small. These months are more dominated by dynamics and temperature (next slide).

TOZ Trends: Chemistry, Dyn/Temp, and Volc. (2000-2014)

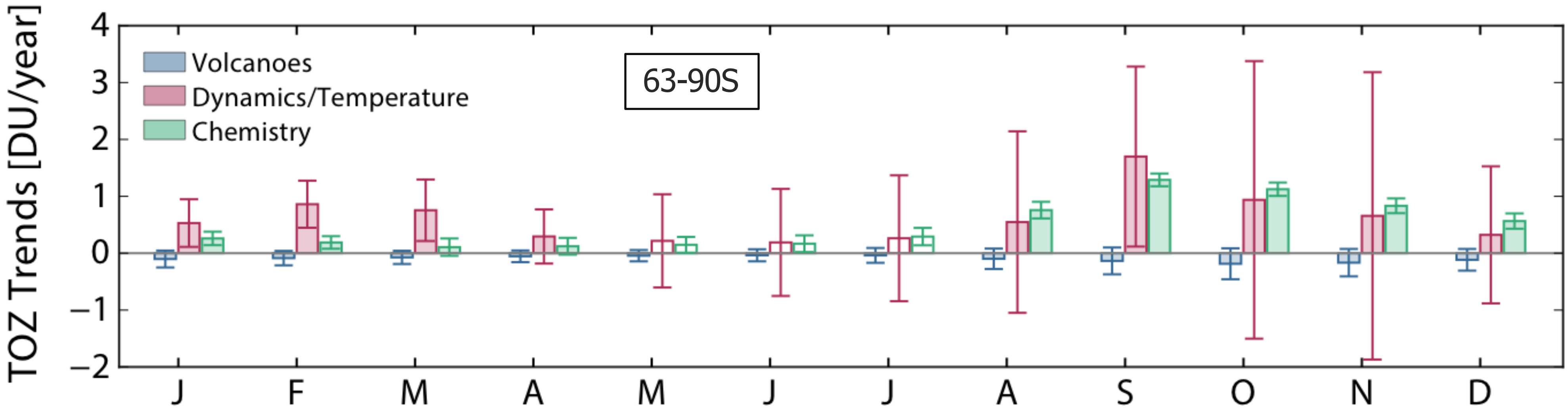
Definitions:

Volcanoes:	Chem-Dyn-Vol – Volc Clean
Dynamics/Temperature:	Volc Clean – Chem-Only
Chemistry:	Repeating 1999 conditions (Chem-Only)

TOZ Trends: Chemistry, Dyn/Temp, and Volc. (2000-2014)

Definitions:

Volcanoes:	Chem-Dyn-Vol – Volc Clean
Dynamics/Temperature:	Volc Clean – Chem-Only
Chemistry:	Repeating 1999 conditions (Chem-Only)



Comments:

- September Chemistry and Dynamics/Temperature trends are nearly equal.
- It should be noted that some of the Temperature trend impact on ozone are likely due to the influenced of chemical ozone increases.
- Volcanoes have reduced the apparent chemical recovery by ~10%.

Summary/Conclusion: Is the Ozone Hole Recovering Yet?

- After accounting for dynamics/temperature and volcanic factors, the fingerprints presented here indicate that healing of the Antarctic ozone hole is emerging.
- This is especially true for the September period where post 2000 chemical ozone loss is large and dynamic variability is moderate (relative to October).
- Our result underscore the combined value of balloon and satellite ozone data, as well as volcanic aerosol measurements together with a CCM to document the progress of the Montreal Protocol in recovery of the ozone layer.