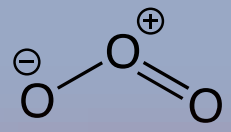
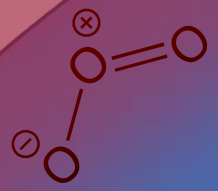
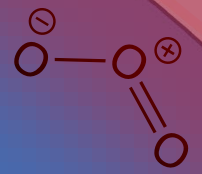


Record-high Ozone in the Southern Mid-latitude UTLS driven by the 2019 Sudden Stratospheric Warming





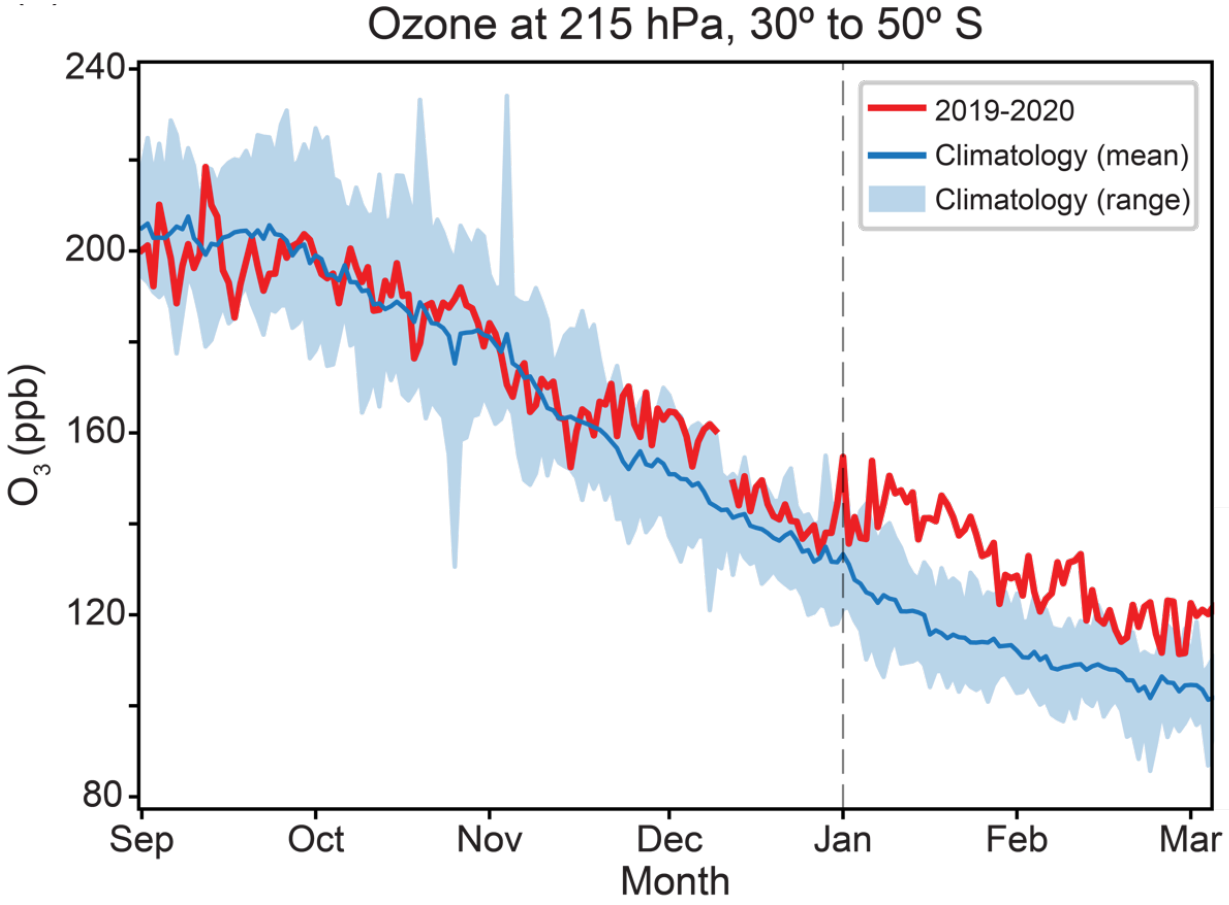
Selena Zhang

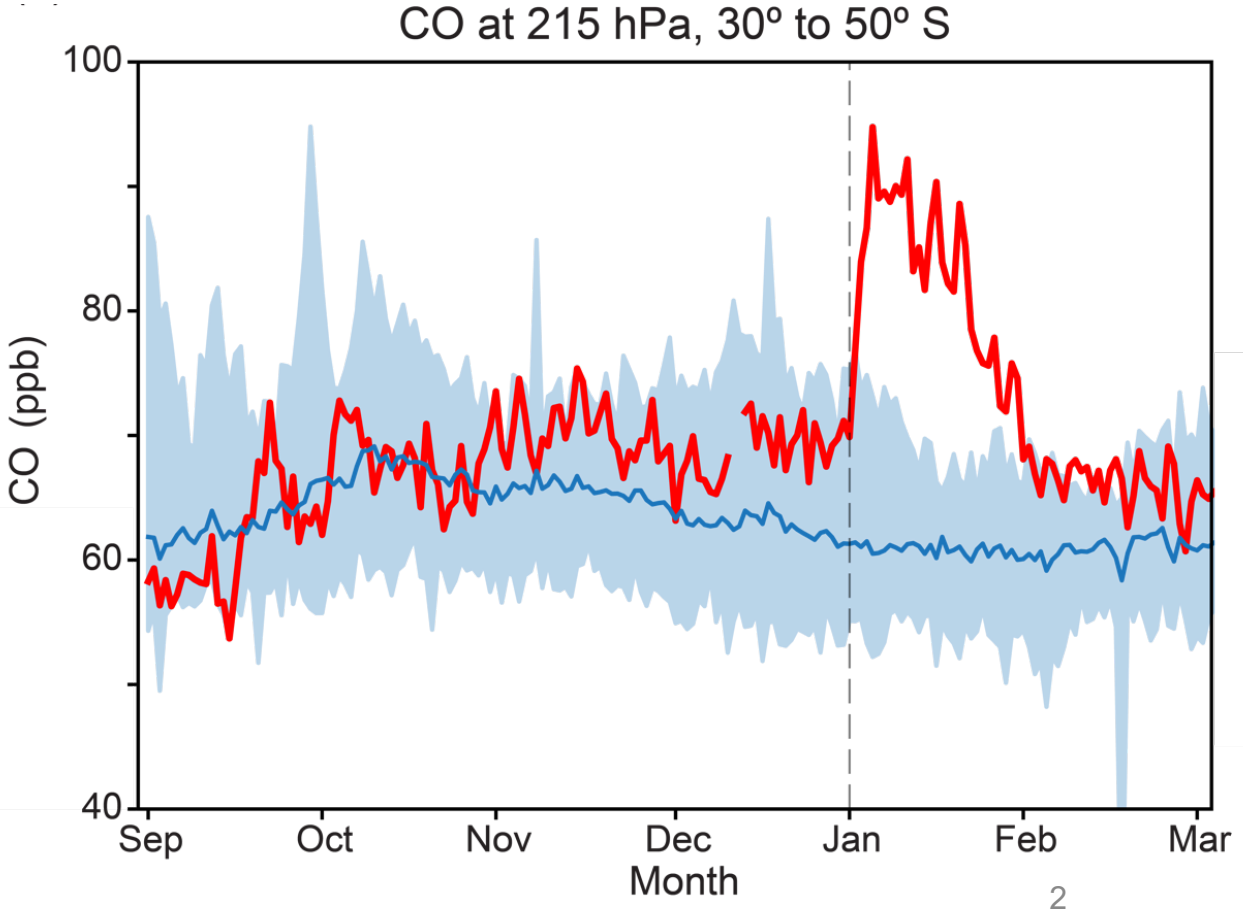
CESM Workshop WAWG, June 11, 2025

Co-authors: Susan Solomon, Jun Zhang, Doug Kinnison

Large UTLS chemical perturbations were observed in 2020

O_3 and CO in the austral midlatitude UTLS were record-high in early 2020 relative to the previous MLS data record (2004 to 2018)

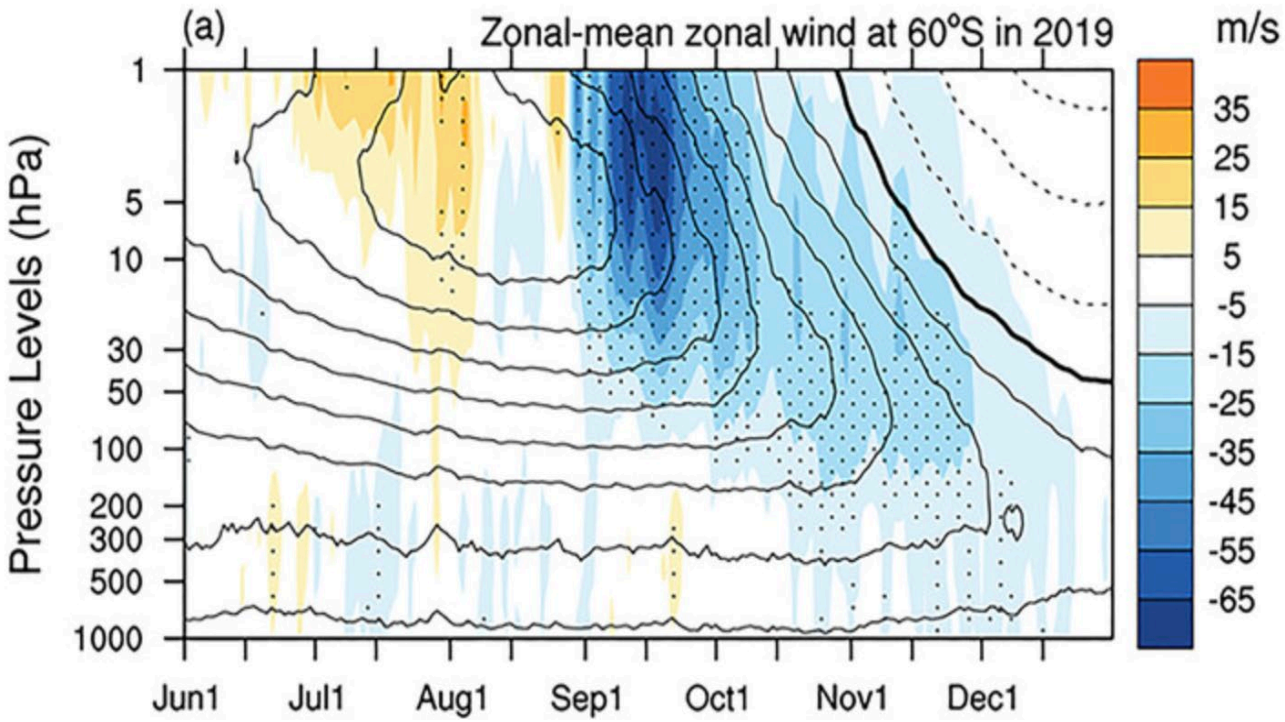


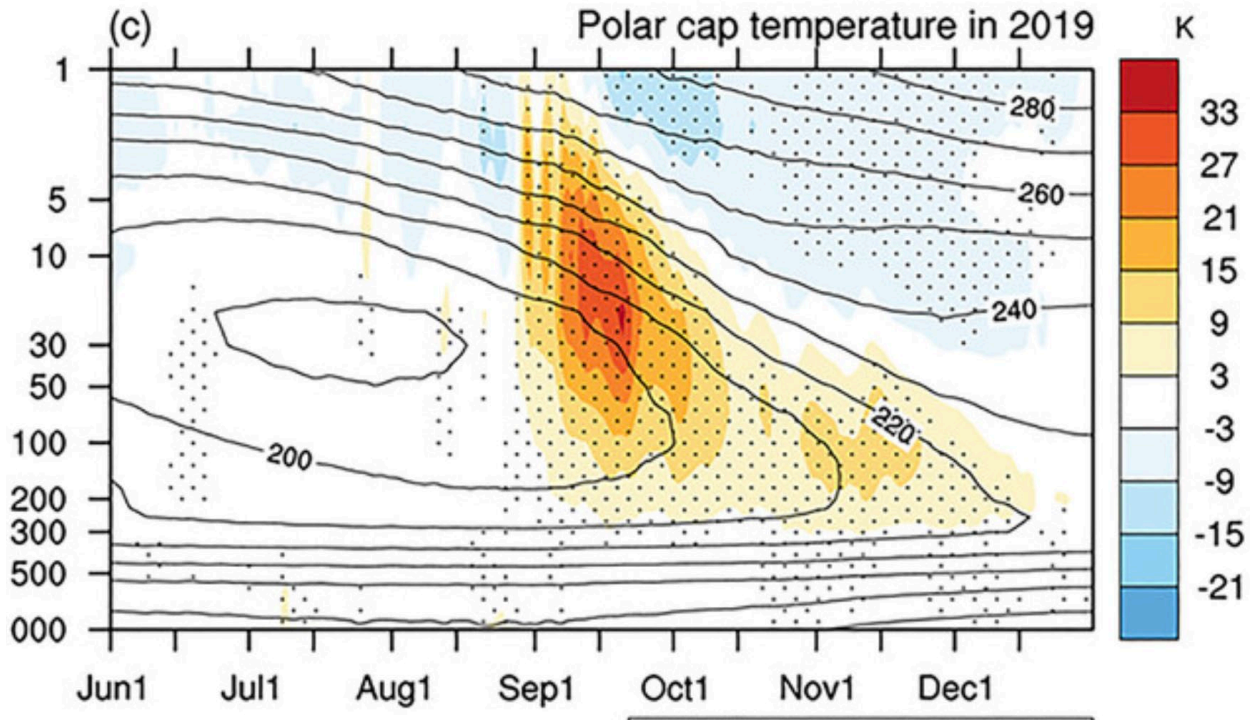


Zhang et al., 2025

2019 was an anomalous year in the Southern Hemisphere

A rare sudden stratospheric warming (SSW) in September

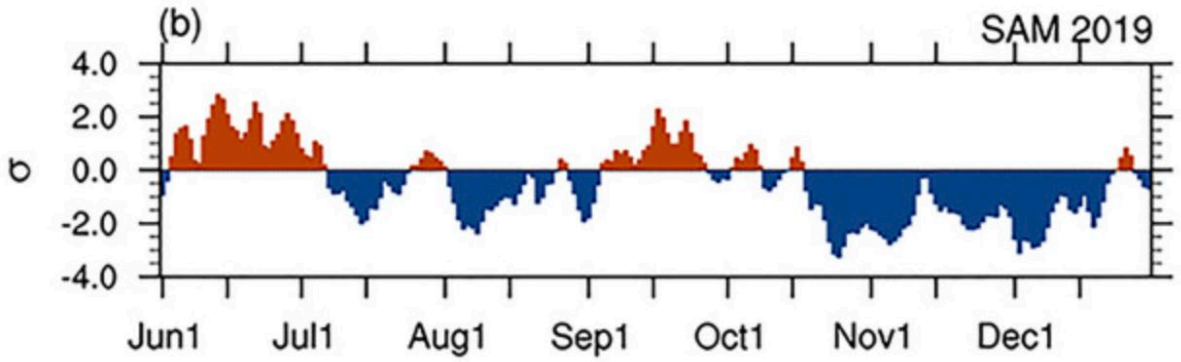




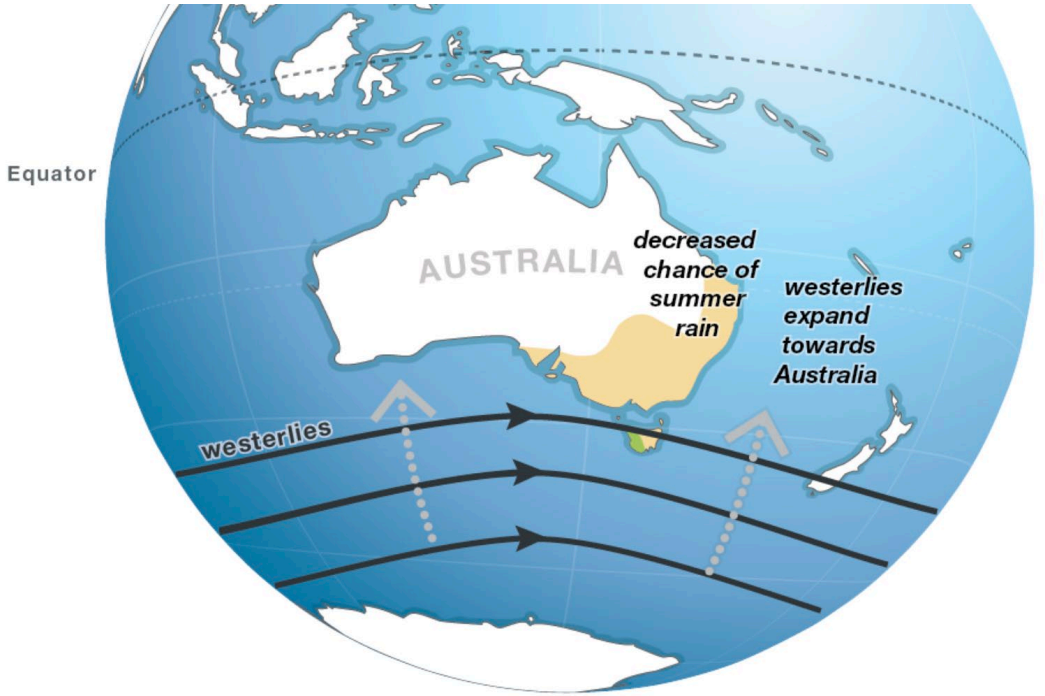
Lim et al., 2021

2019 was an anomalous year in the Southern Hemisphere

A rare sudden stratospheric warming (SSW) in September
promoted a swing to a record-negative Southern Annular Mode…



Australian Bureau of Meteorology

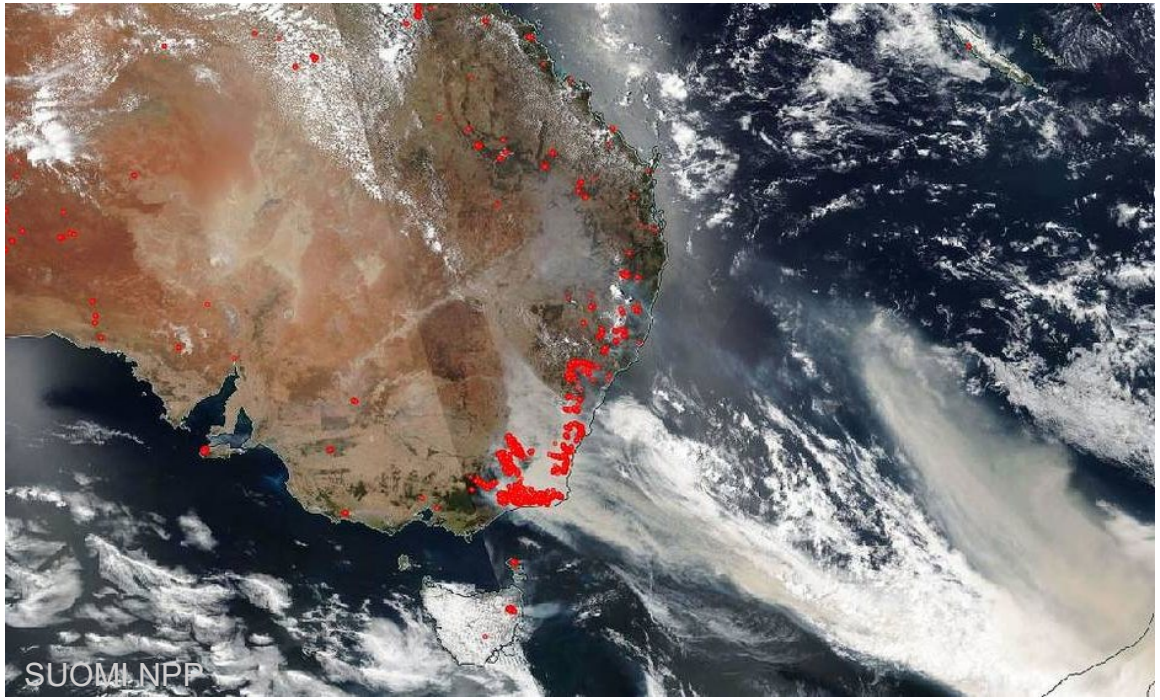


Southern Annular Mode (SAM): **Negative phase (summer)**

Lim et al., 2021

2019 was an anomalous year in the Southern Hemisphere

A rare sudden stratospheric warming (SSW) in September promoted a swing to a record-negative Southern Annular Mode…



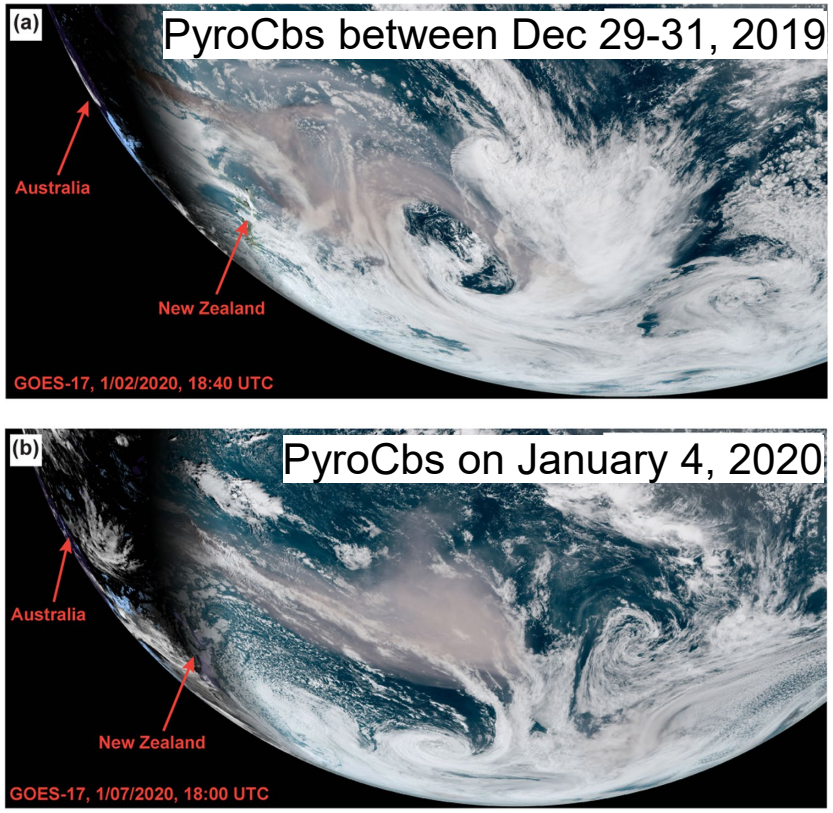
which drove a severe 2019-2020 Australian bushfire season

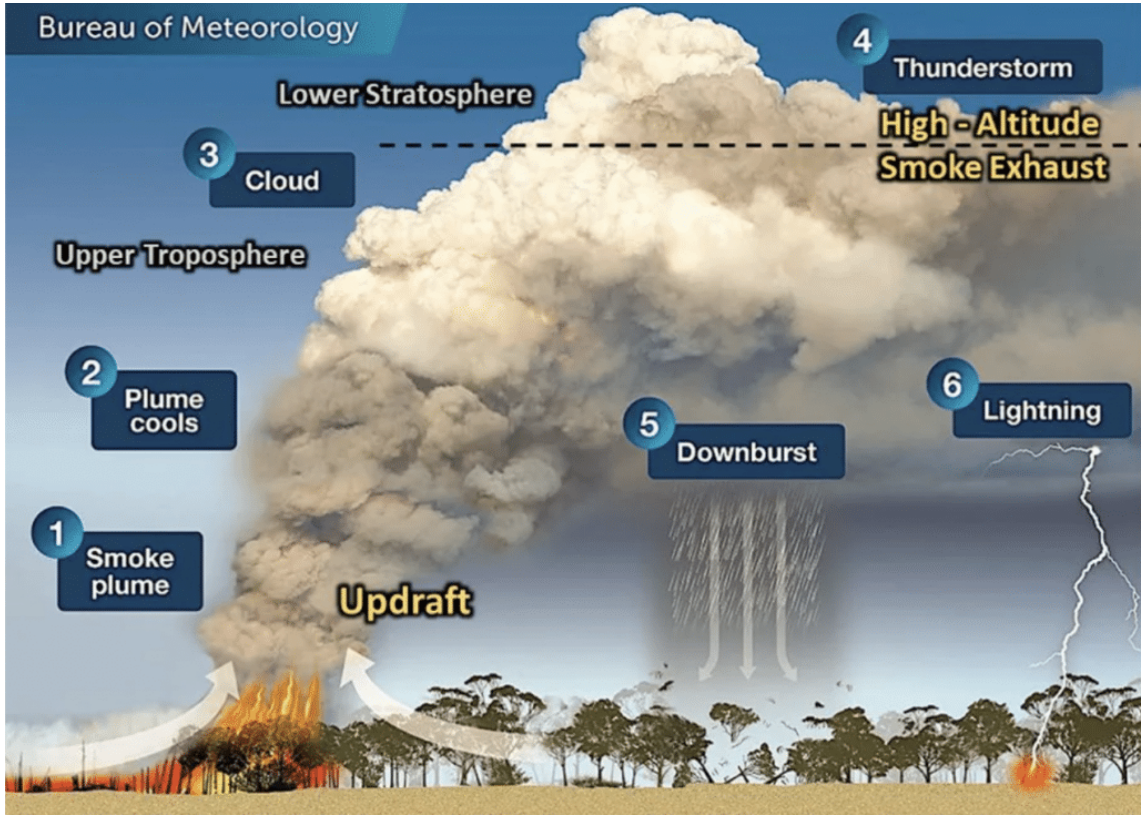
via extreme hot and dry conditions over subtropical eastern Australia

Lim et al., 2021

2019 was an anomalous year in the Southern Hemisphere

A rare sudden stratospheric warming (SSW) in September promoted a swing to a record-negative Southern Annular Mode…





Peterson et al., 2021

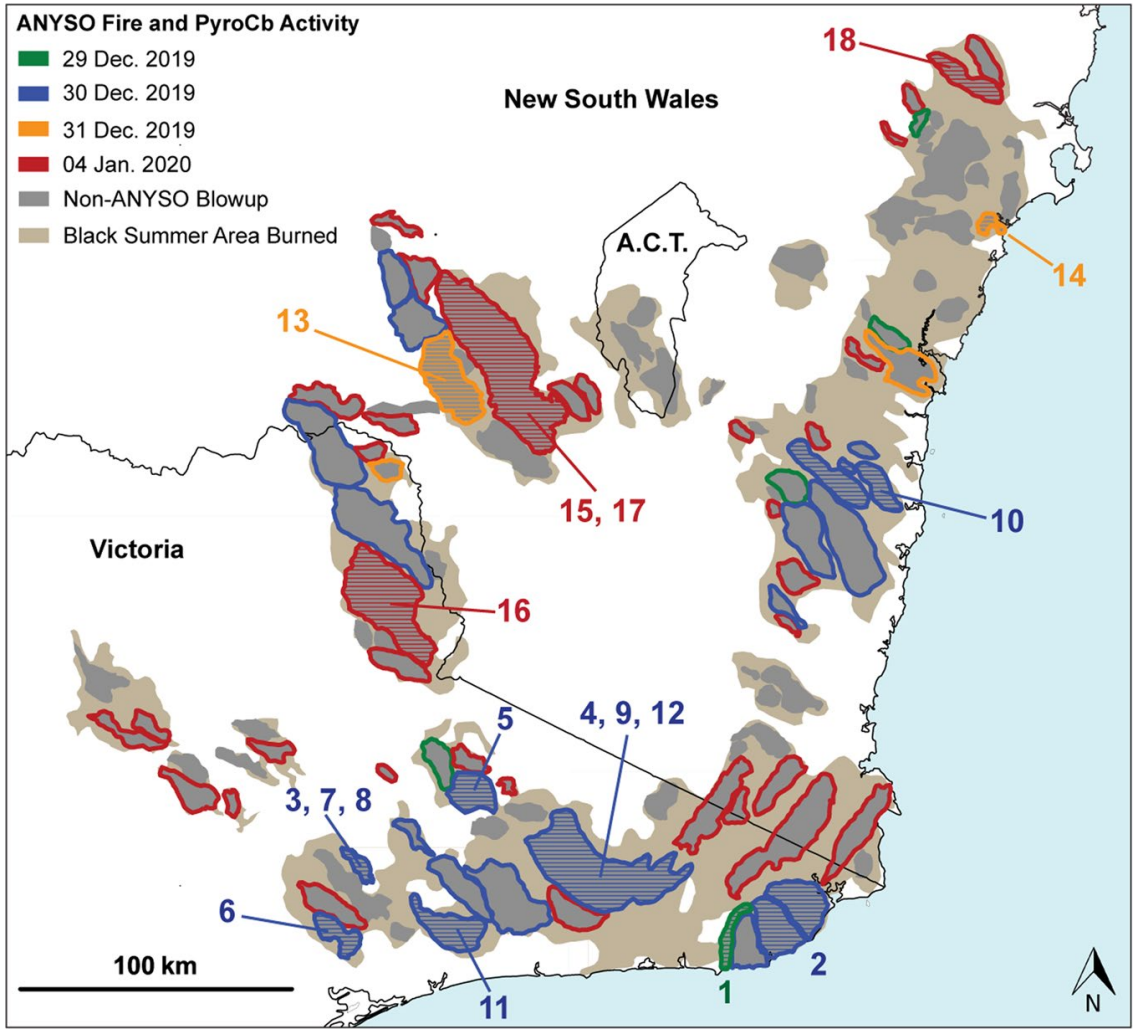
which drove a severe 2019-2020 Australian bushfire season

including pyrocumulonimbus clouds (pyroCbs) that injected smoke at 10+ km

Peterson et al., 2021

The Australian New Year Super Outbreak

ANYSO injected ~1.1 Tg of smoke from 18 events into the stratosphere over the course of a week in early January 2020



Peterson et al., 2021

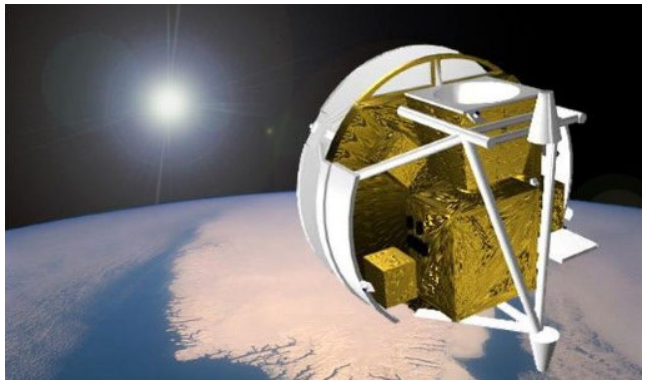
Our guiding questions:

- **How did the ANYSO pyroCbs affect UTLS composition and chemistry?**
- **Did the dynamical effects of the SSW also influence midlatitude UTLS ozone?**

The tools

Satellite data

Microwave Limb Sounder



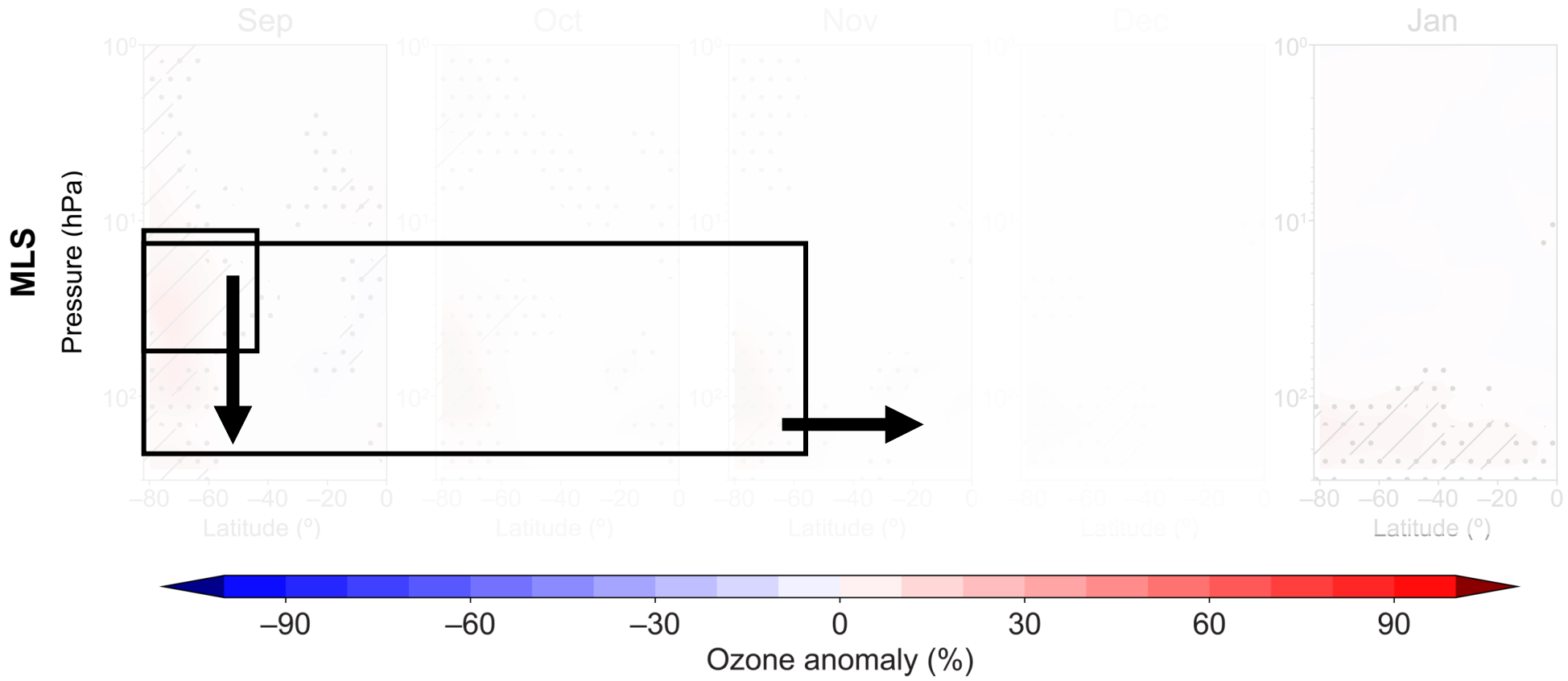
Atmospheric Chemistry Experiment

Model simulations

Specified dynamics configuration (SD-WACCM6) nudged to MERRA-2 reanalysis
0.9º × 1.25º 70 vertical levels

Mixing is more efficient near the tropopause than in the mid-to-upper stratosphere

// is ≥ 3 σ + mean
:: is ≥ 2 σ + mean



Downward transport advects tracers equatorward into the midlatitudes in December and January

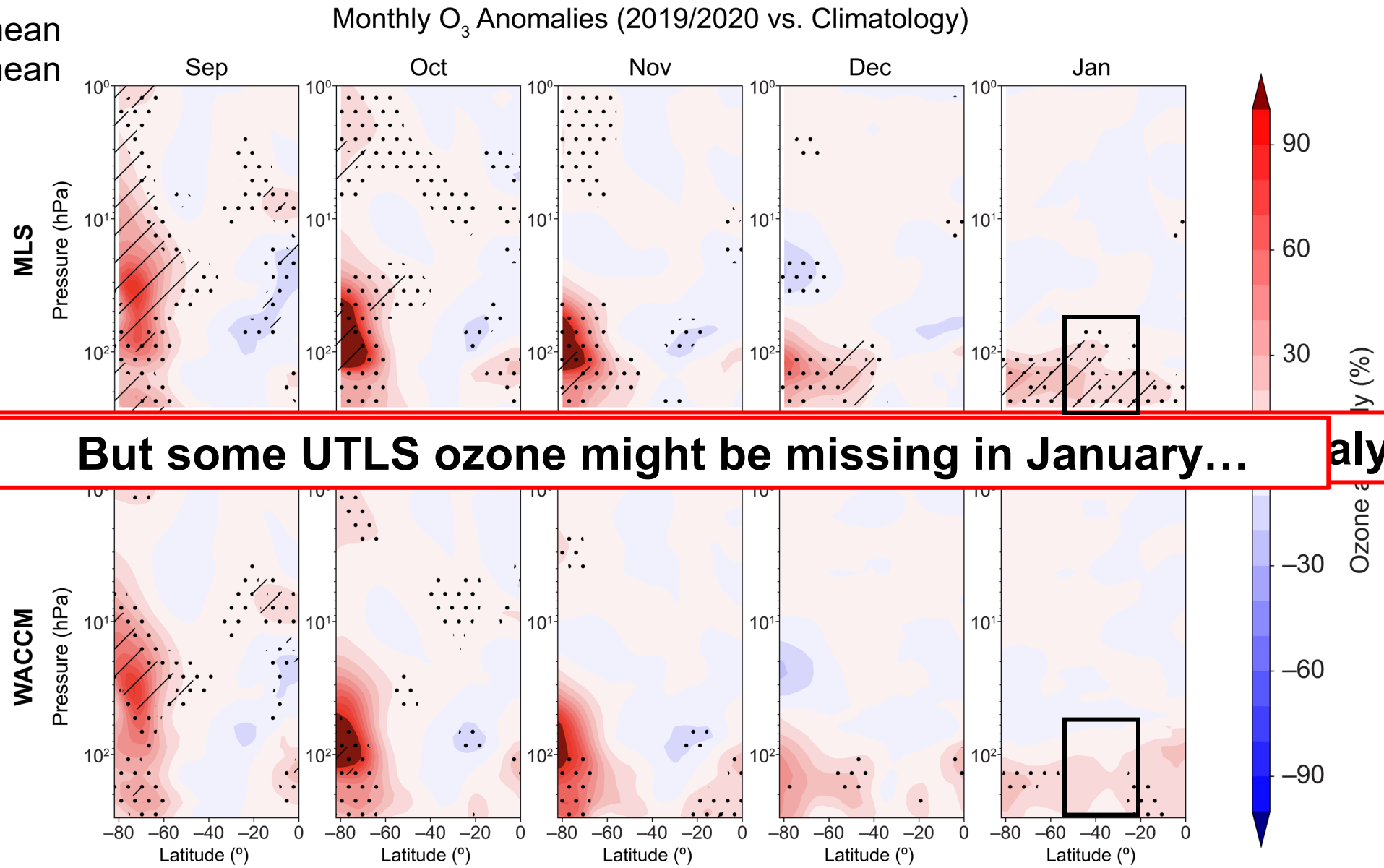
High polar ozone near the tropopause mixes equatorward

suppressed ozone destruction

→ reduced heterogeneous ozone depletion

SD-WACCM simulates the 2019/20 ozone anomaly well

// is ≥ 3 σ + mean
:: is ≥ 2 σ + mean



But some UTLS ozone might be missing in January…

Simulations in SD-WACCM

"**Climatology**": Run from 2004 to 2018 initialized from a long historical simulation

"**Control**": Six month run from 9/2019 to 3/2020, no added emissions

"**Wildfire**": Six month run from 9/2019 to 3/2020, wildfire emissions added at pyroCb injection altitude

Observed 2019/2020 dynamics, no added chemistry

Quantifies how anomalous the dynamics in 2019/2020 were

Control – Climatology = Dynamical effects

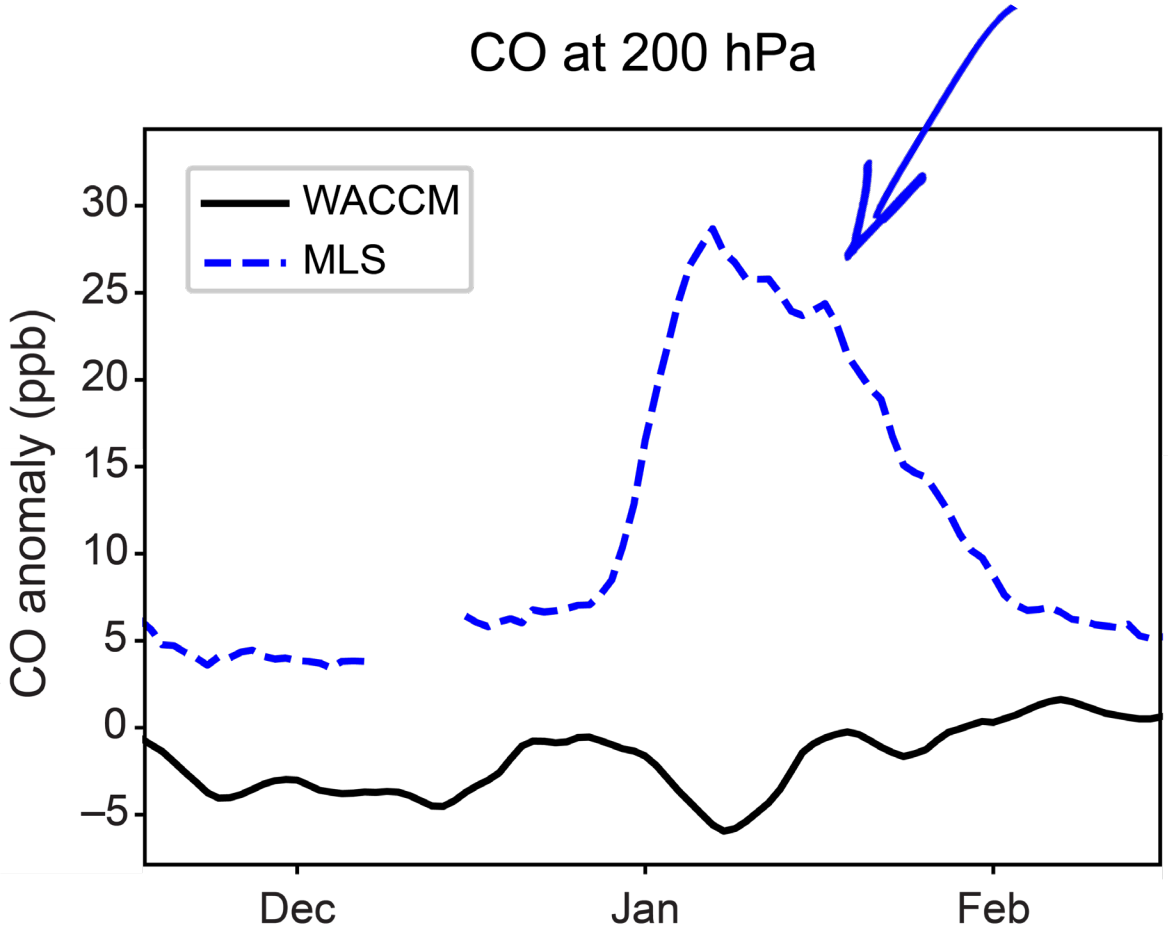
(what we've been looking at so far)

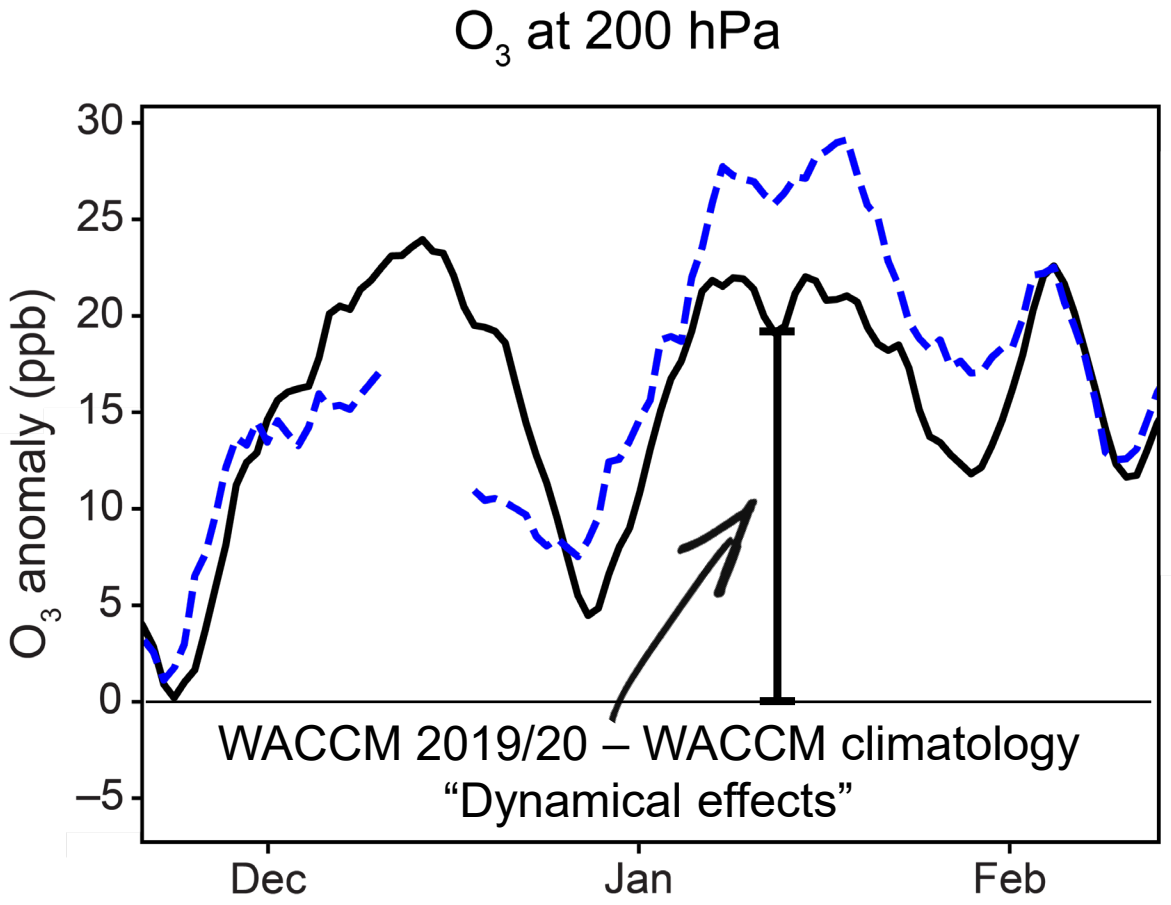
Monthly average from 2004-2018, representative of "typical" climatological dynamics

SD-WACCM is missing some chemistry in January!

Averaged between 30 and 50 ºS

MLS 2019/20 – MLS climatology





Simulations in SD-WACCM

"**Climatology**": Run from 2004 to 2018 initialized from a long historical simulation

"**Control**": Six month run from 9/2019 to 3/2020, no added emissions

"**Wildfire**": Six month run from 9/2019 to 3/2020, wildfire emissions added at pyroCb injection altitude

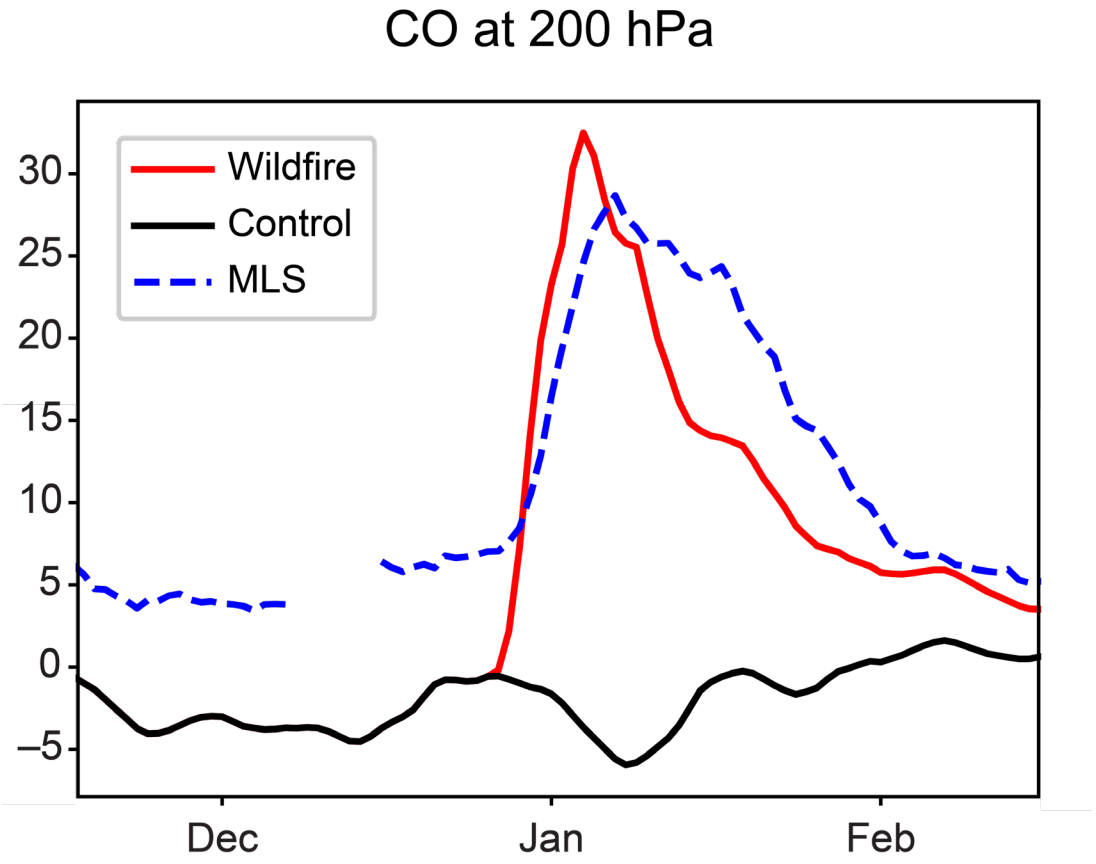
Observed 2019/2020 dynamics + wildfire emissions

Wildfire – Control = Chemical effects

Observed 2019/2020 dynamics, no added chemistry

Adding emissions in the “wildfire” simulation

1. Inject CO on the dates of ANYSO pyroCbs at different amounts and altitudes until the model anomaly reproduces the satellite anomaly
2. Add emissions of VOCs, NOx, and smoke based on literature-based emissions ratios to CO



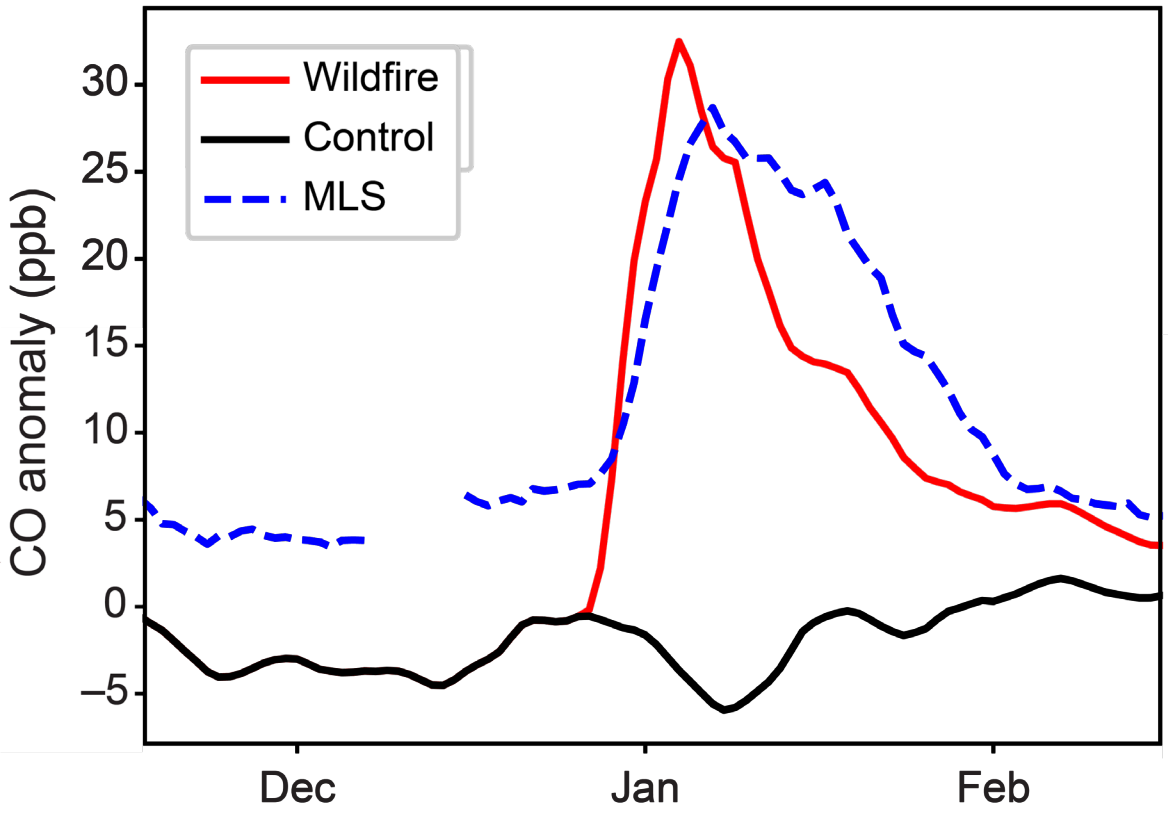
Species	Emission ratio to CO
CO	1
CH_4	3.0×10^{-2}
C_2H_4	1.1×10^{-2}
C_2H_6	4.1×10^{-3}
CH_3OH	1.7×10^{-2}
CH_3COCH_3	6.6×10^{-3}
HCOOH	3.3×10^{-3}
NO_2	2.1×10^{-3}
NO	2.6×10^{-4}

Guérette et al., 2018

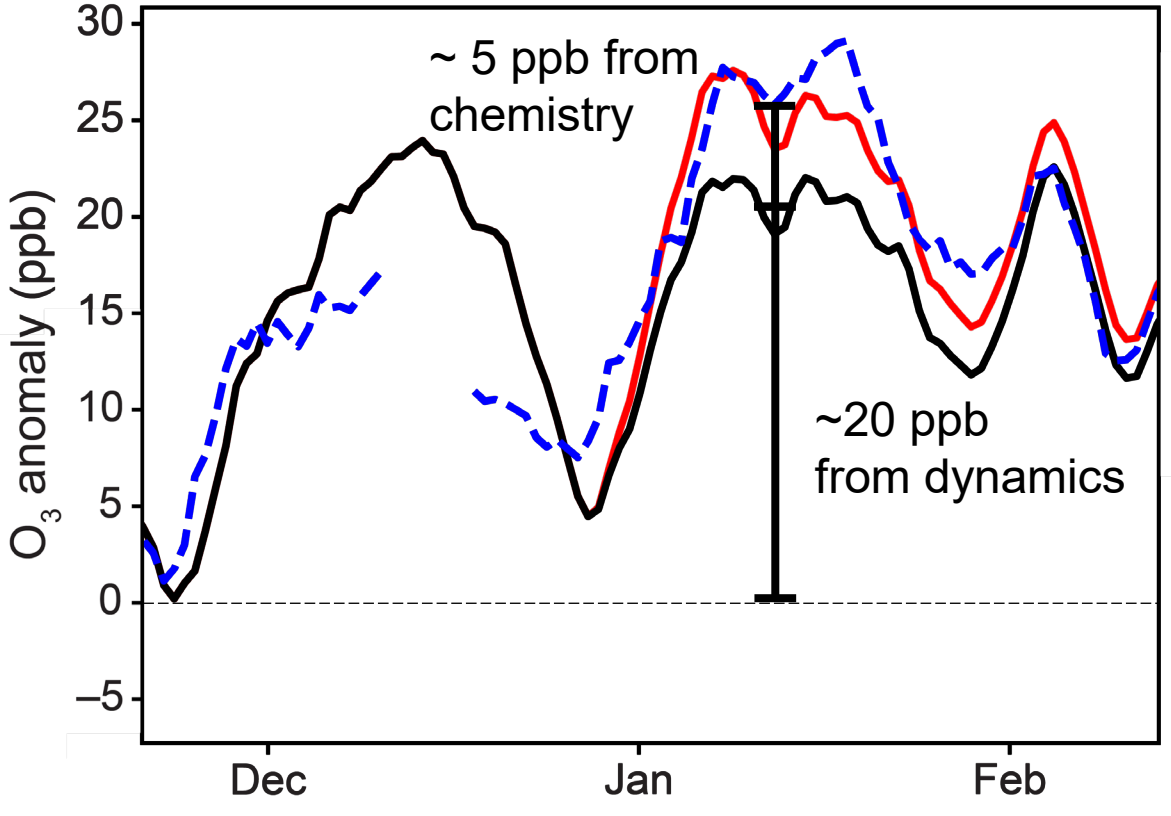
Dynamics is the dominant (80%) contributor to high ozone

Injected species react to form up to ~10 ppb of ozone in January

CO at 200 hPa



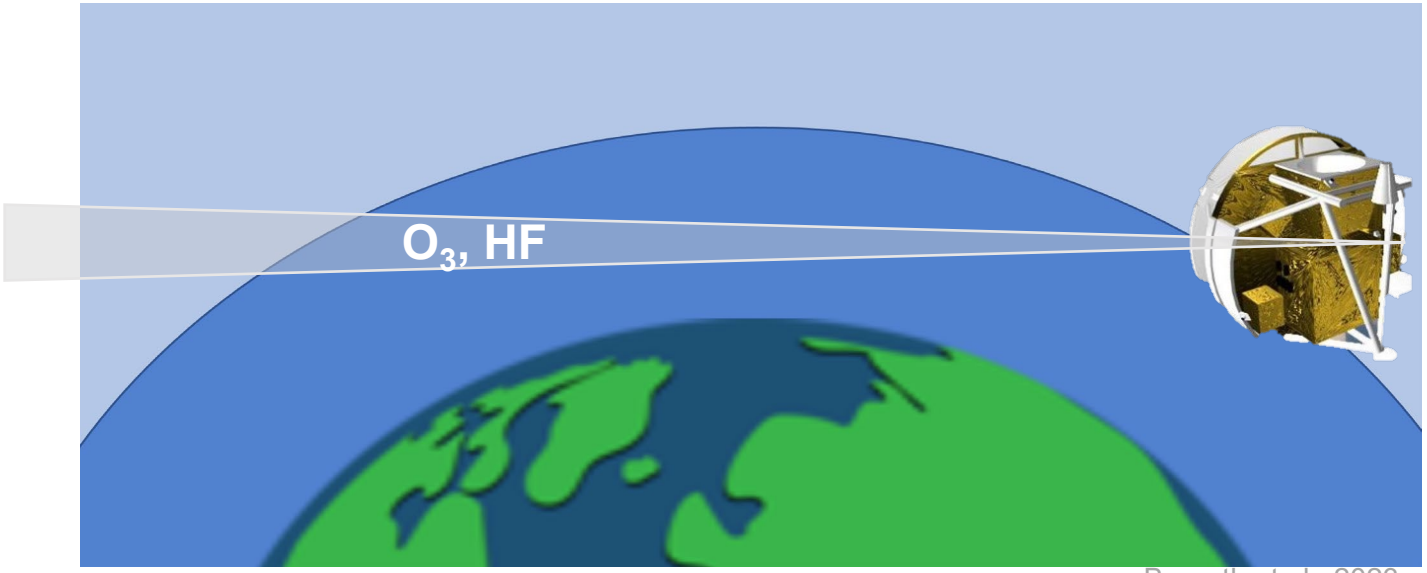
O_3 at 200 hPa



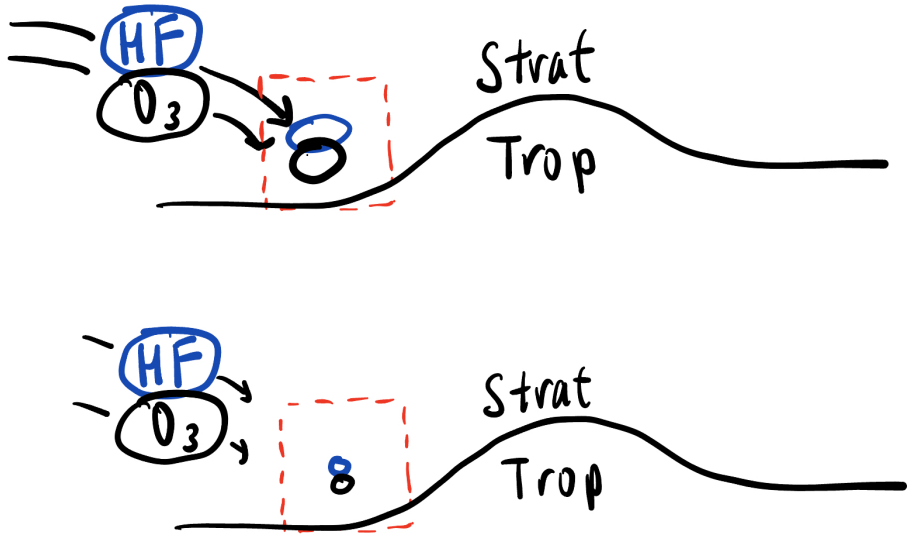
But uncertainty in model transport cannot be ruled out

Can we separate chemical and dynamical effects from satellite data alone?

Tracer-tracer correlation analysis



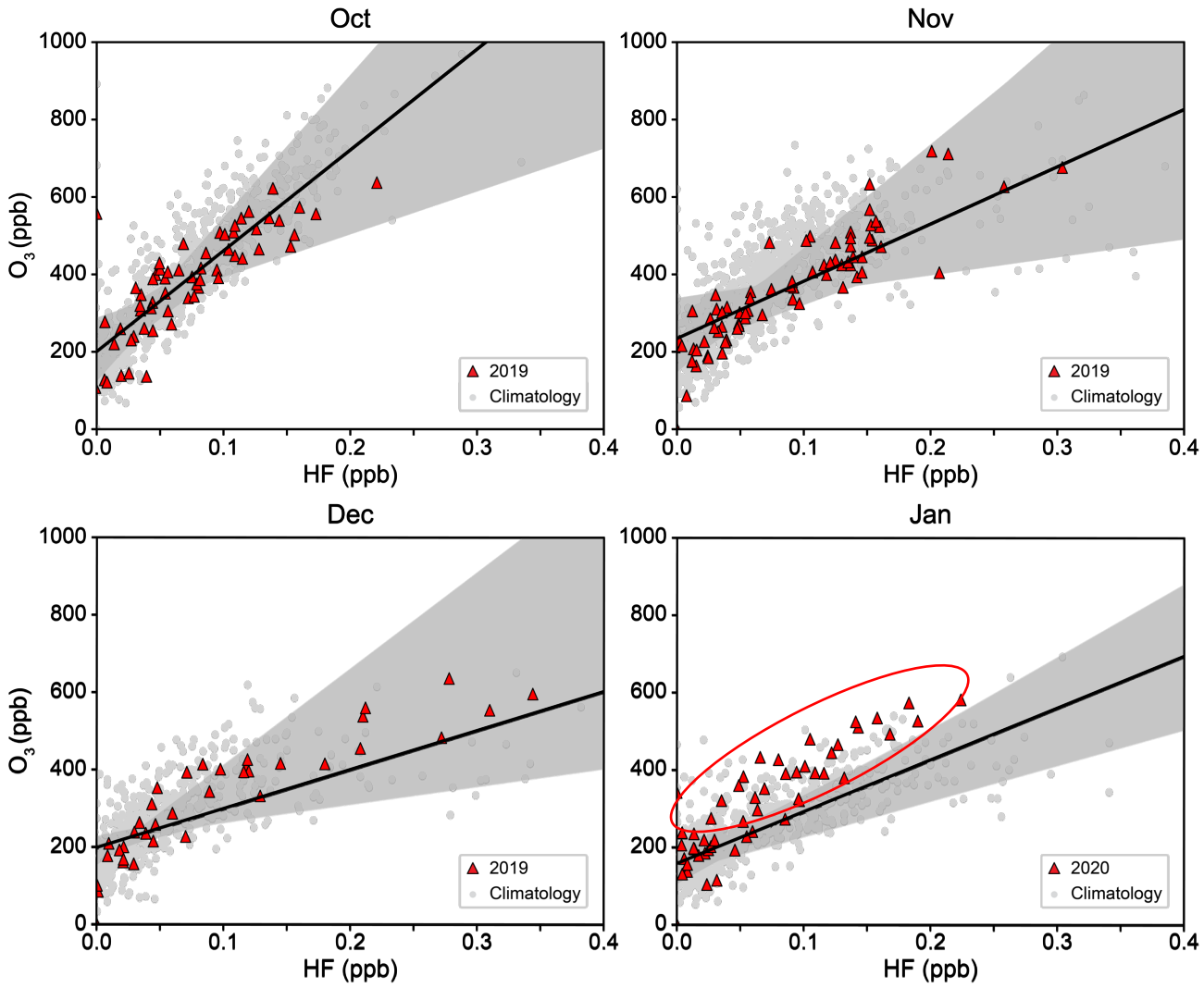
Bernath et al., 2023



- ACE–FTS measures inert and chemically active species in the same occultation
- HF is an inert stratospheric tracer; dynamics should influence O_3 and HF abundances in a similar manner

In January 2020, ozone is high and outside the range of interannual variability

30 to 50 ºS, 14 km



This indicates chemical production!

Conclusions

- Anomalous 2020 southern midlatitude UTLS ozone was caused by both dynamical and chemical (exacerbated wildfire) effects of the 2019 SSW

- The dynamical effect—downward and equatorward transport of ozone-enhanced air from the polar stratosphere to the mid-latitude UTLS— is the dominant contributor (around 80%)

- Chemical production of ozone plays an important role in January following the injection of wildfire species into the UTLS

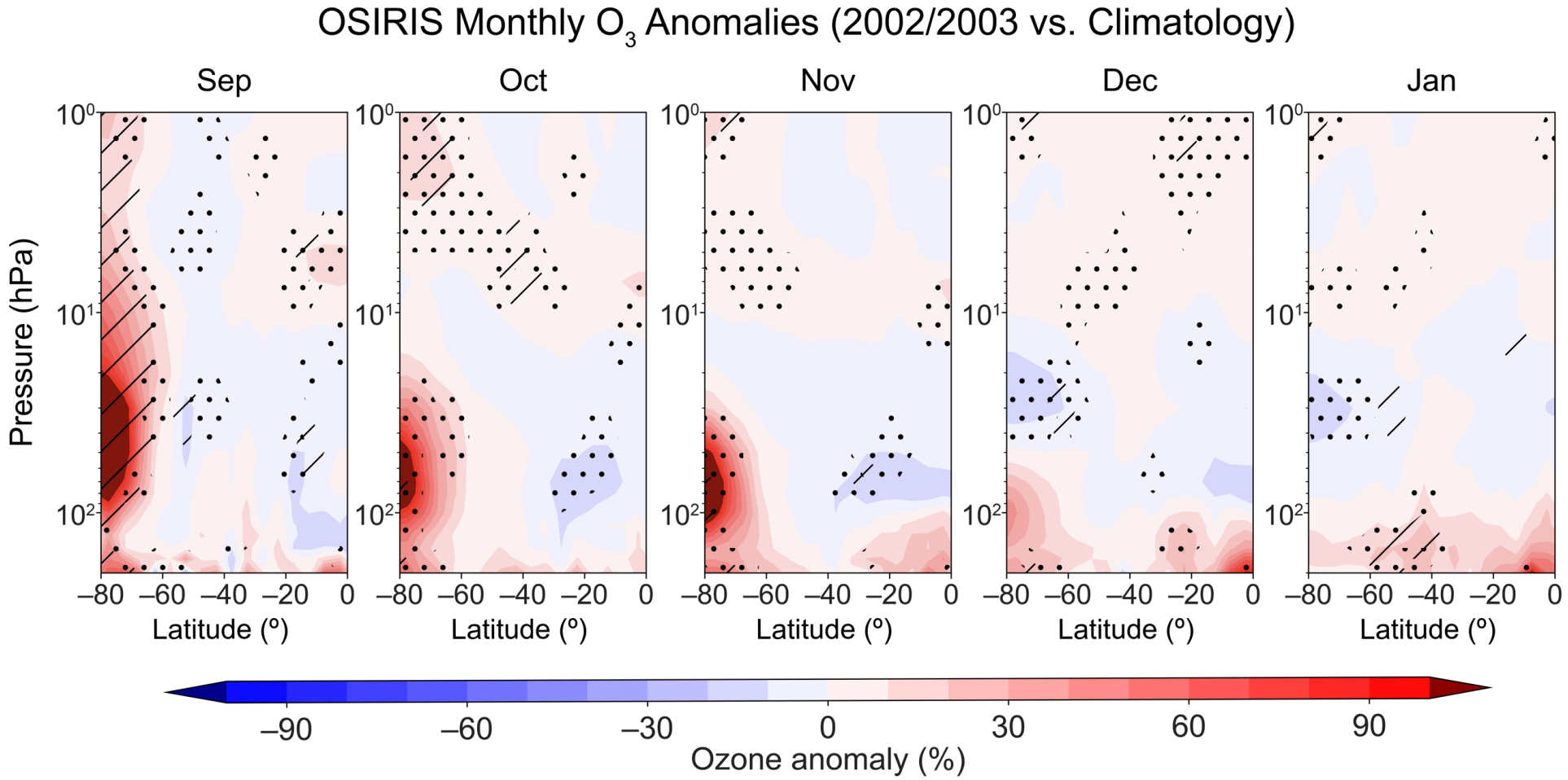
Thank you! Questions?

Zhang, S., S. Solomon, J. Zhang, and D. Kinnison (2025), *GRL*, *52*(9).

Supplemental slides

2002 major southern SSW featured a similar anomaly

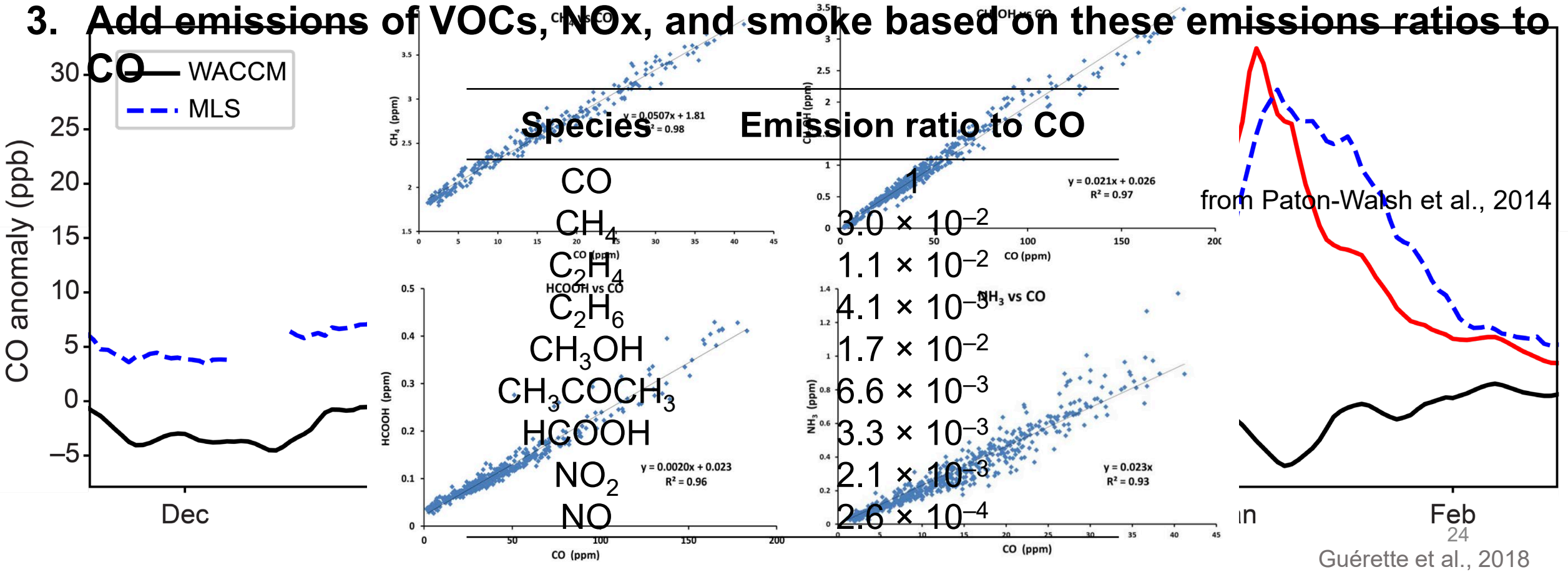
// is ≥ 3 σ + mean
:: is ≥ 2 σ + mean



O_3 data from Odin-OSIRIS features a similar anomaly pattern to the 2019 SSW

Adding emissions in the “wildfire” simulation

1. Inject CO on the dates of ANYSO pyrocbs at different amounts and altitudes until the model anomaly reproduces the satellite anomaly
2. Find literature-based emission ratios from in-situ and satellite measurements
3. **Add emissions of VOCs, NOx, and smoke based on these emissions ratios to CO**

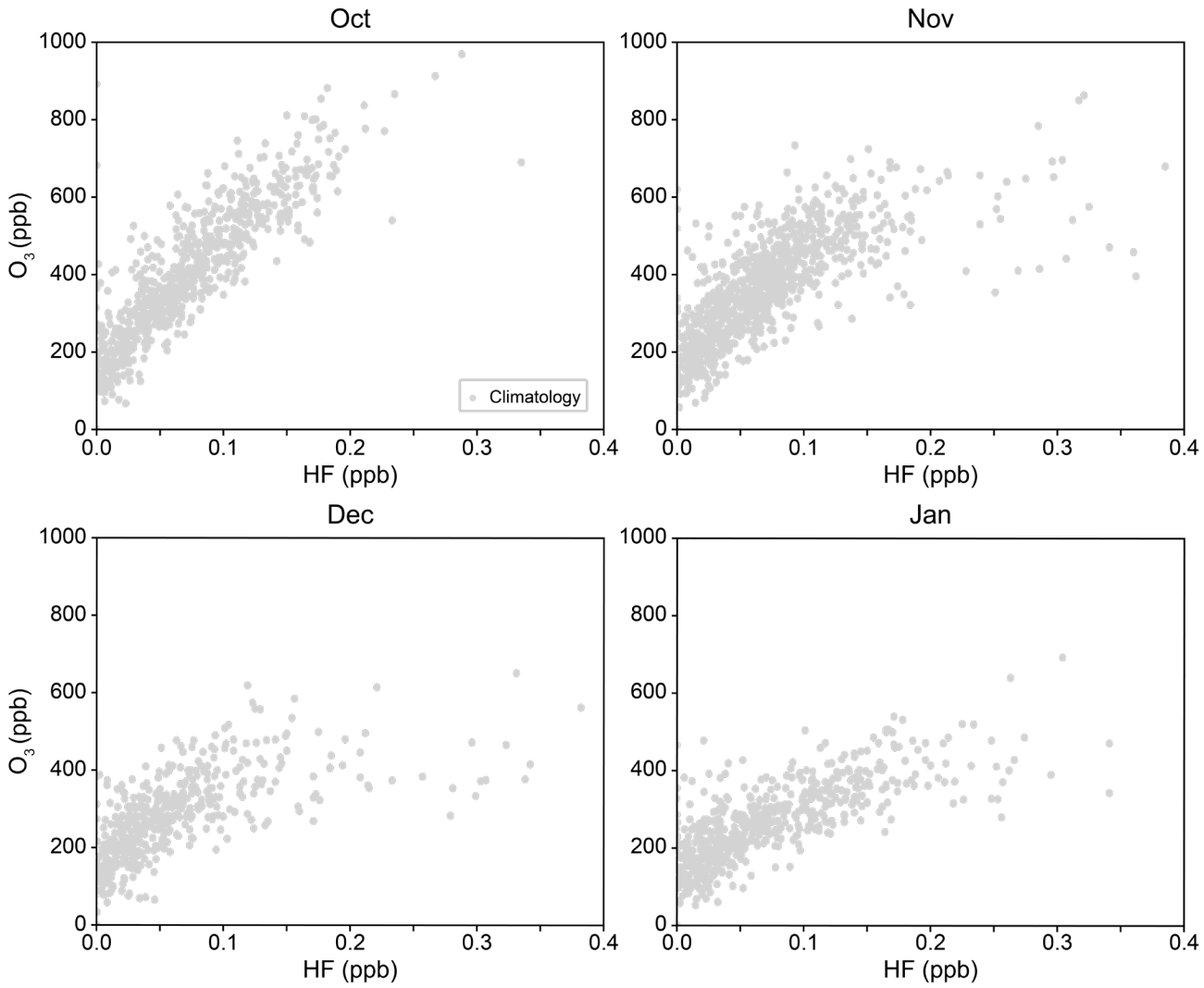


Species	Emission ratio to CO
CO	1
CH_4	3.0×10^{-2}
C_2H_4	1.1×10^{-2}
C_2H_6	4.1×10^{-3}
CH_3OH	1.7×10^{-2}
CH_3COCH_3	6.6×10^{-3}
HCOOH	3.3×10^{-3}
NO_2	2.1×10^{-3}
NO	2.6×10^{-4}

Guérette et al., 2018

HF to O_3 correlation over the data record forms a climatological baseline

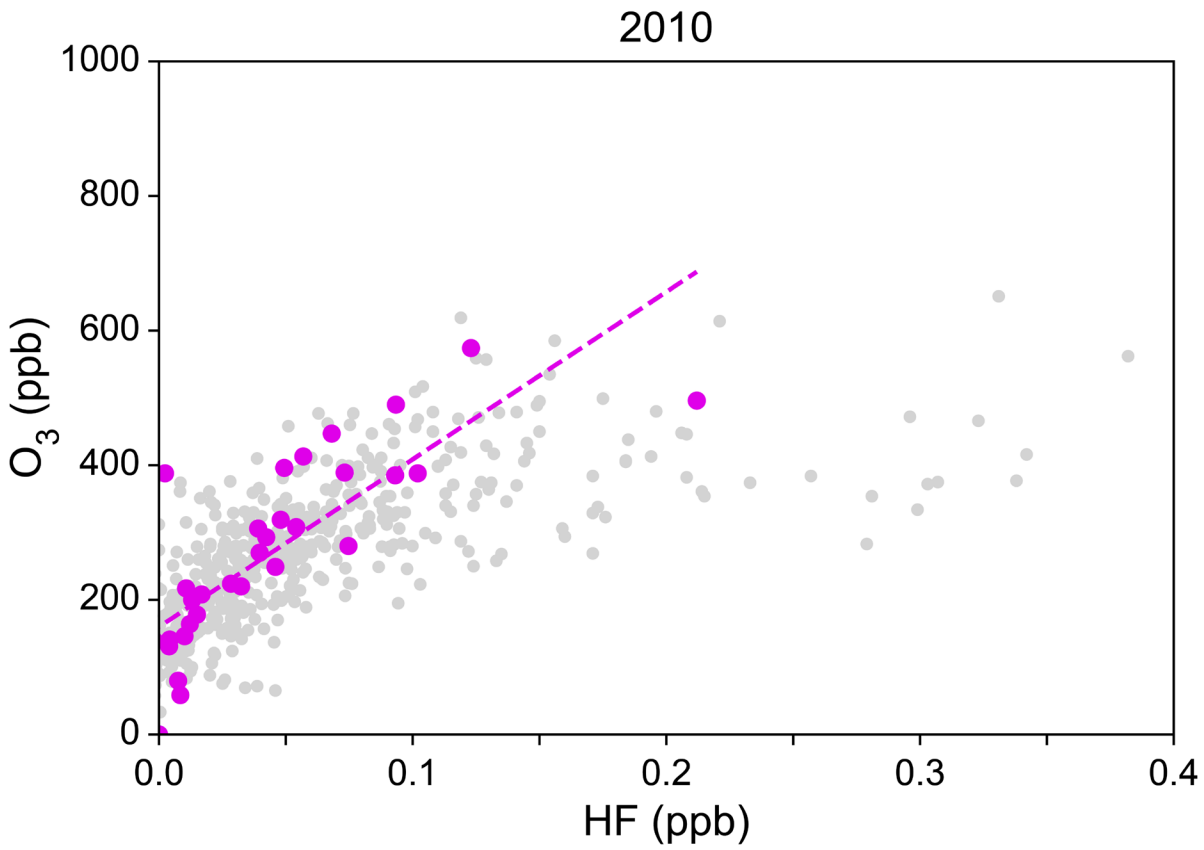
30 to 50 ºS, 14 km

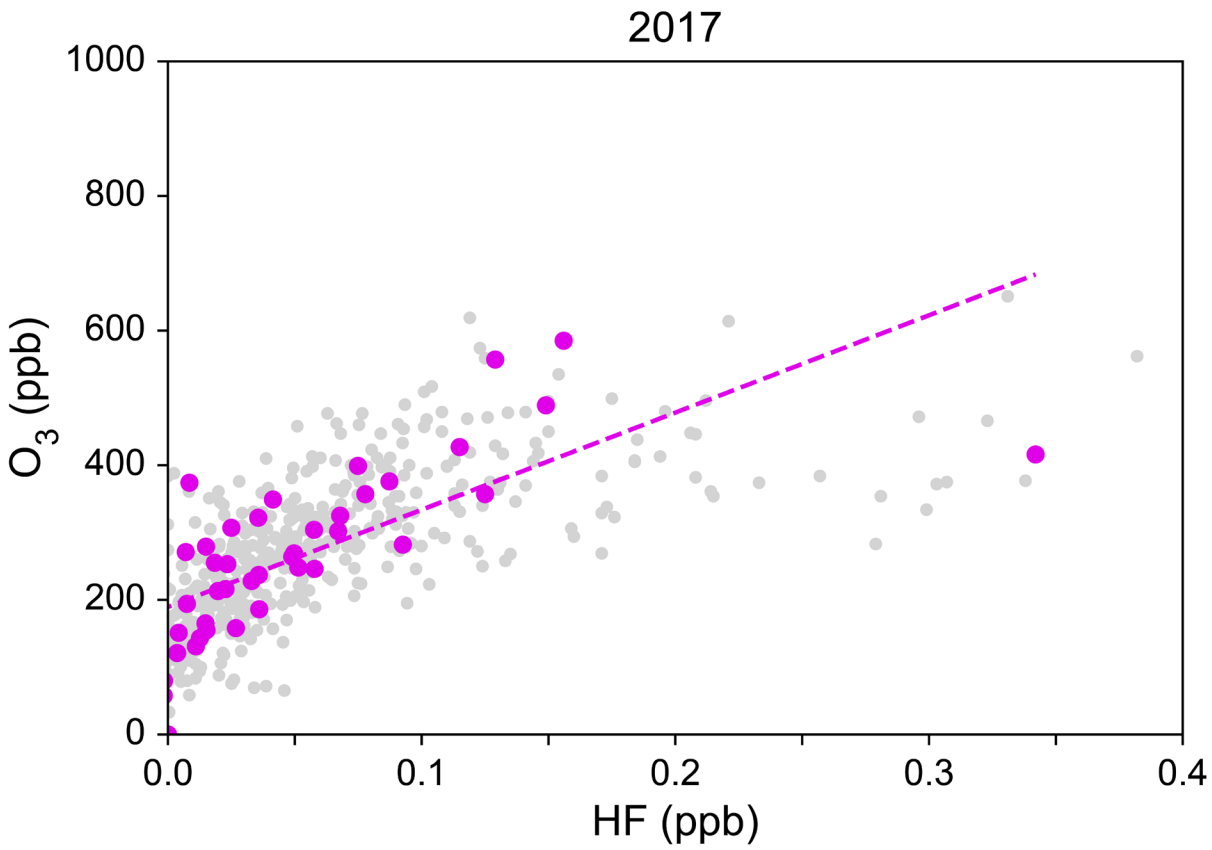


There is interannual variability in annual linear fits

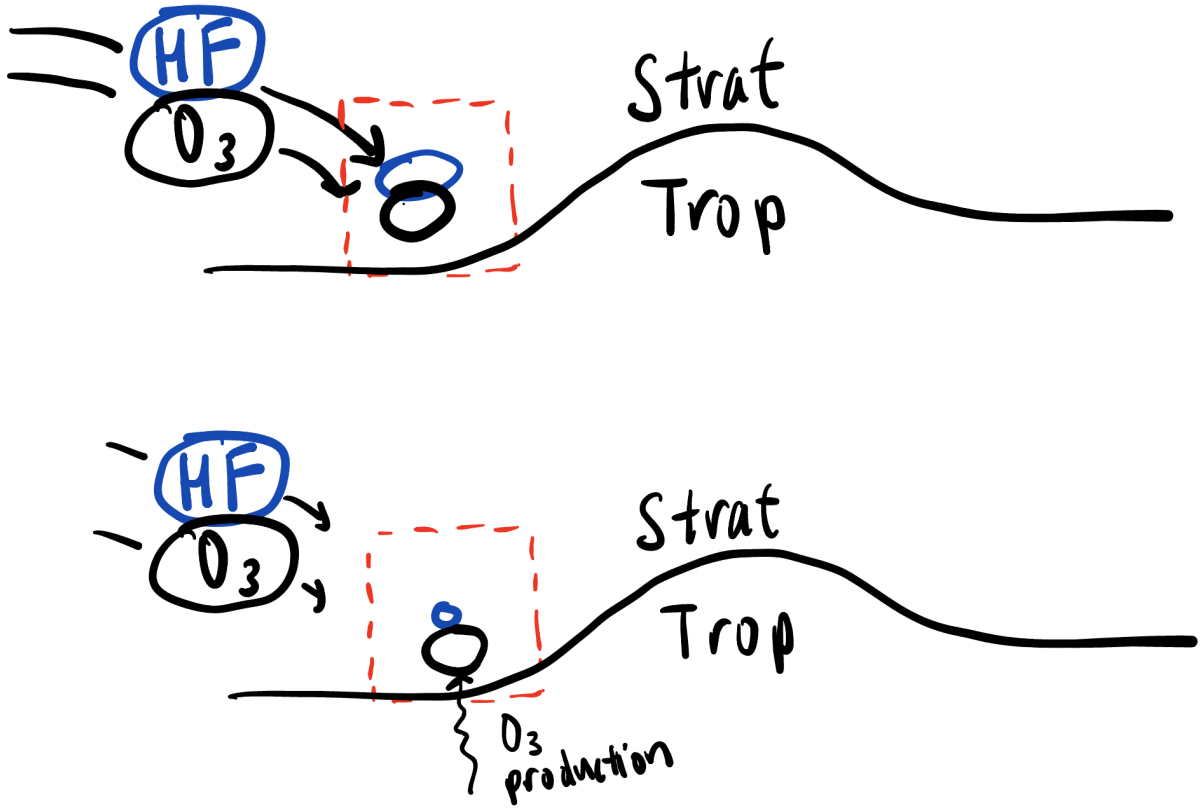
30 to 50 ºS, 14 km

Example: December in two different years

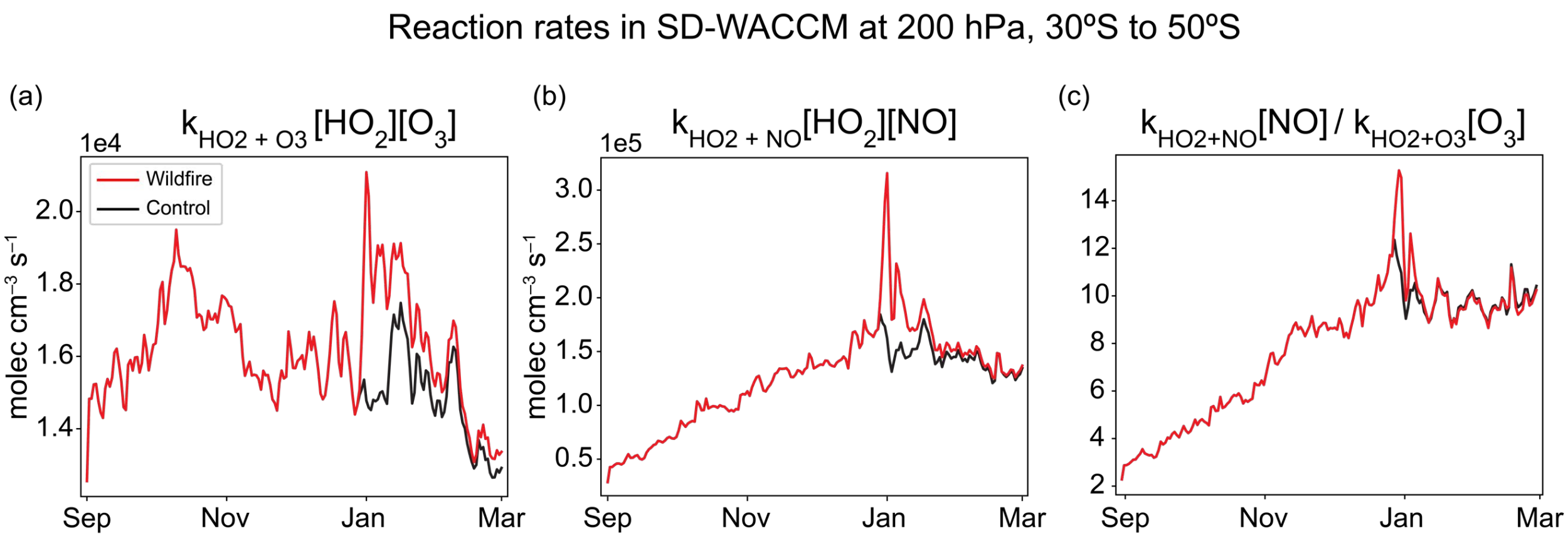




Separating dynamical and chemical effects



What limits ozone production in the UTLS?



HF as a tracer in WACCM