Fingerprinting the Recovery of Antarctic Ozone

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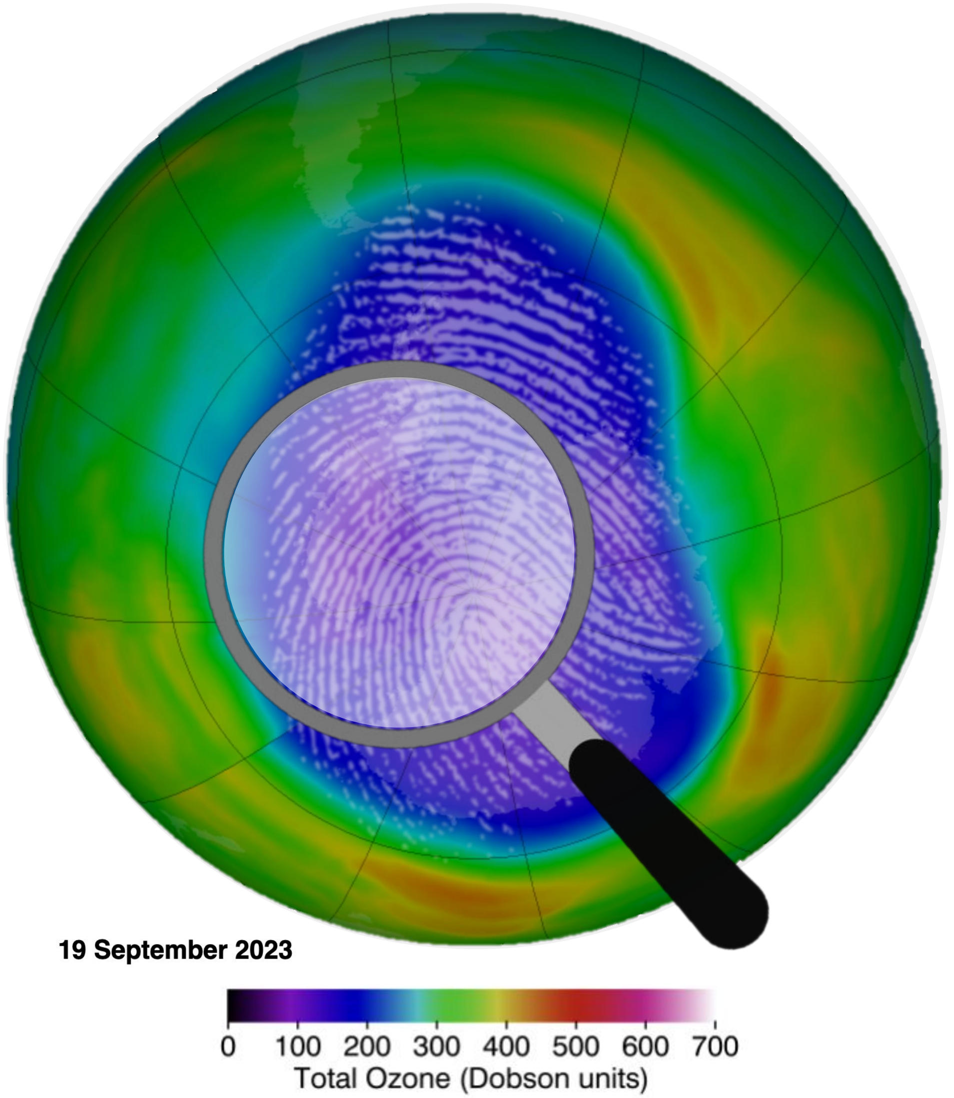

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Fingerprinting the Robust Recovery of Antarctic Ozone

Peidong Wang, Susan Solomon, Benjamin Santer, Douglas Kinnison, and 5 more

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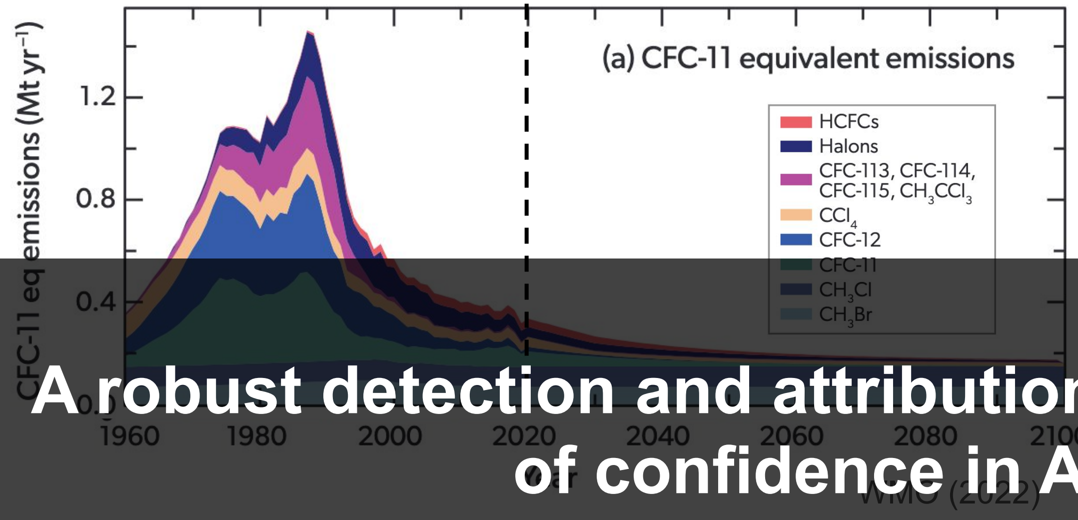
Abstract

The Antarctic ozone "hole" was discovered in 1985[1], and its primary cause is man-made ozone-depleting substances (ODS)[2]. Following reductions of ODSs under the Montreal Protocol[3], signs of ozone recovery have been reported, based largely on observations and broad yet compelling model-data comparisons[4]. While such approaches are highly valuable, they do not establish levels of overall confidence that account for the temporal and spatial structure of Antarctic ozone trends as well as uncertainties in internal climate variability. Here, we rely on trend pattern information as a function of month and height to separate anthropogenically forced ozone responses from internal variability, using pattern-based detection and attribution (D&A) methods as employed in climate change studies[5–11]. The analysis uses satellite observations together with both single-model and multi-model ensemble simulations to identify and quantify the month-height Antarctic ozone recovery "fingerprint"[12]. We demonstrate that the data and simulations show remarkable agreement in the fingerprint pattern of the ozone response to decreasing ODS forcing since 2005. We also show that ODS forcing has enhanced ozone internal variability during the austral spring, influencing detection of forced responses and their time of emergence. Our results provide robust statistical and physical evidence that actions taken under the Montreal Protocol to reduce ODSs are indeed resulting in Antarctic ozone recovery.

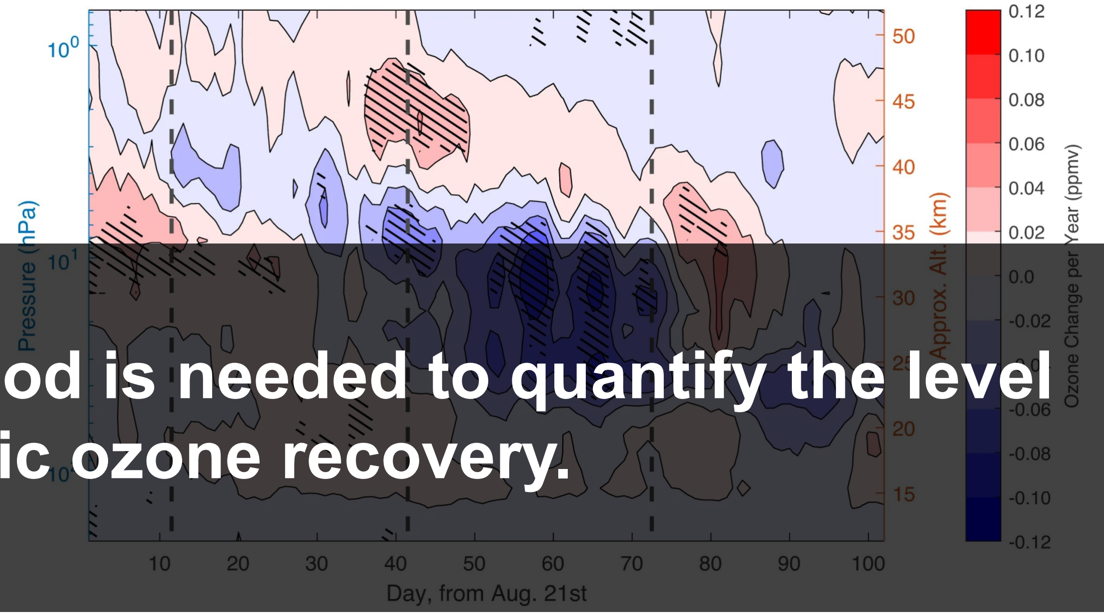
Earth and environmental sciences/Environmental sciences/Environmental chemistry/Atmospheric chemistry

This work is in press in *Nature*, the older version of the preprint is available on Research Square.

Ozone-depleting substance (ODS) emissions are decreasing, is ozone recovering?

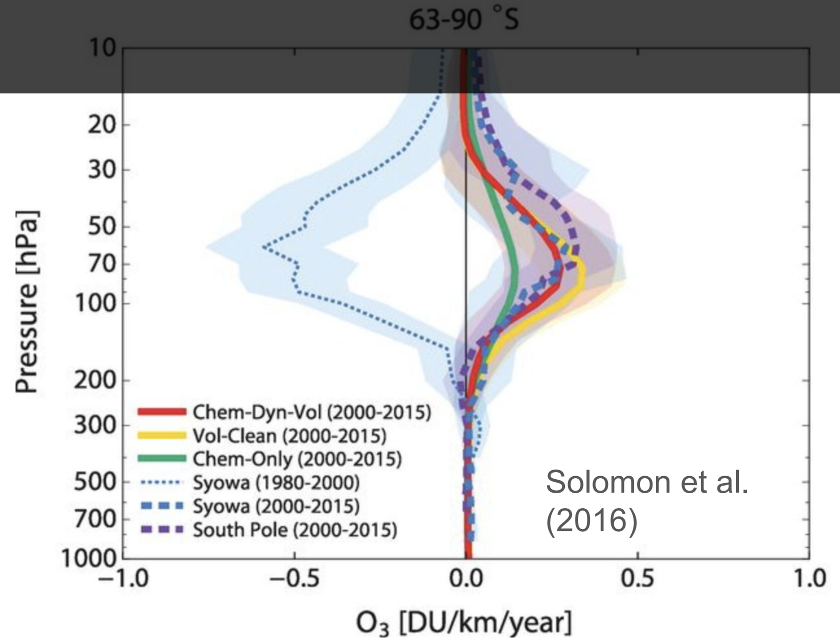


WMO (2022)



Kessnich et al. (2023)

A robust detection and attribution method is needed to quantify the level of confidence in Antarctic ozone recovery.

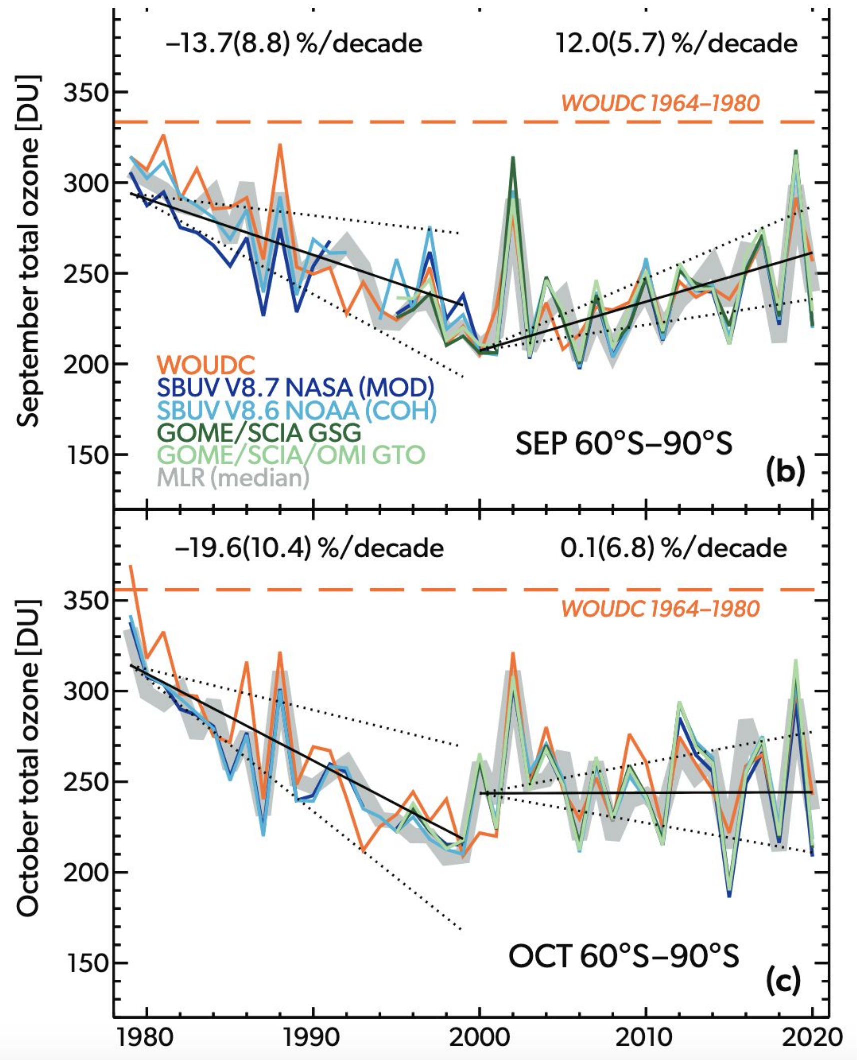


Solomon et al. (2016)

September as a key month to search for ozone recovery. Model and sounding data show consistent ozone increases.

Satellite data also shows increase in ozone during September, **but** a significant decrease in October in the middle stratosphere. Part of this decrease is due to the inclusion of 2020 Australian wildfire and 2022 Hunga volcanic eruptions.

Large variability makes it challenging to detect and attribute trends



WMO (2022)

<u>Multiple linear regression (MLR)</u>

$$y(t) = A \cdot QBO_1(t) + B \cdot QBO_2(t) + C \cdot ENSO(t) + D \cdot AOD(t) + E \cdot Solar(t) + F \cdot Linear_{pre}(t) + G \cdot Linear_{post}(t) + H \cdot C_1(t) + I \cdot C_2(t) + J \cdot C_3(t) + \varepsilon(t)$$

SPARC report on LOTUS (2018)

MLR synthesis available observations to fit sources of uncertainties in ozone variability. They provide valuable information on the uncertainty in trends. However, MLR assumes that:
1) Ozone has a linearly response to all the predictor variables
2) Different predictor variables are independent
3) Only based on limited observations
Cannot avoid **overfitting**.

<u>Alternative approach:</u> taking the advantage of large ensembles of fully coupled models with interactive chemistry

Borrowing the “Fingerprinting” technique from the climate community

Observed pattern

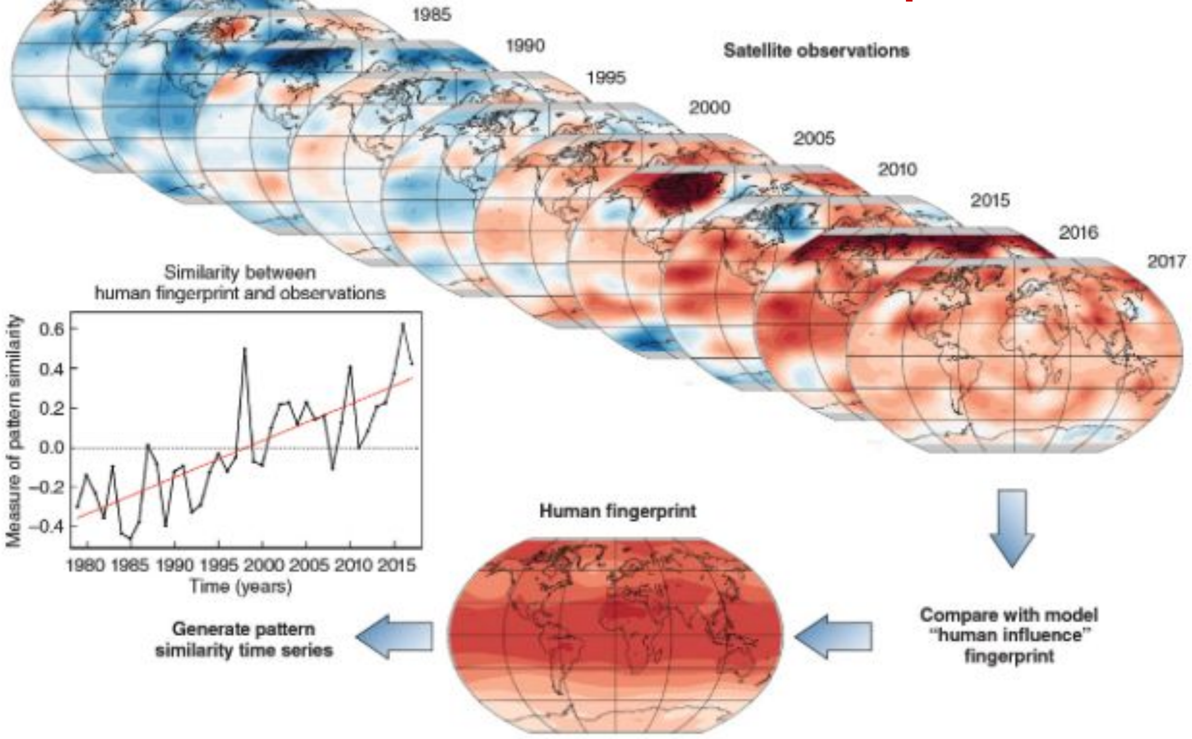
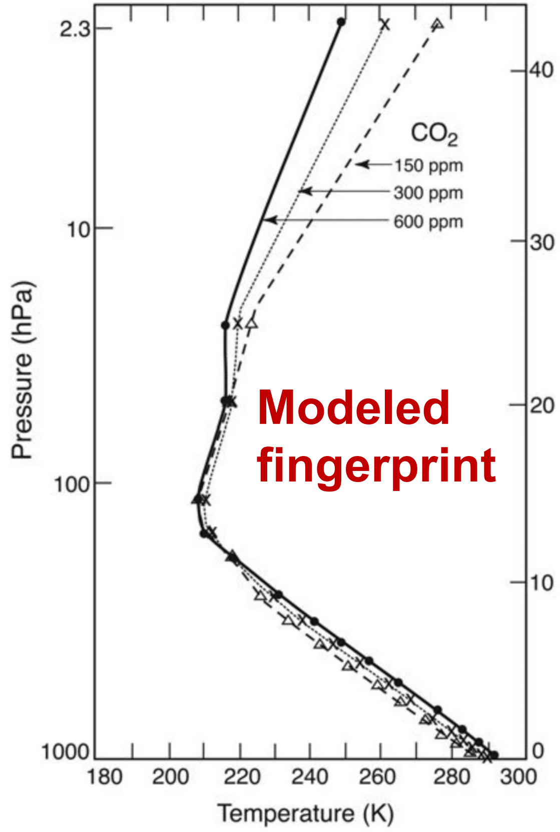


Image from Ben Santer

Modeled fingerprint



Manabe and Wetherald (1967)

Observed pattern

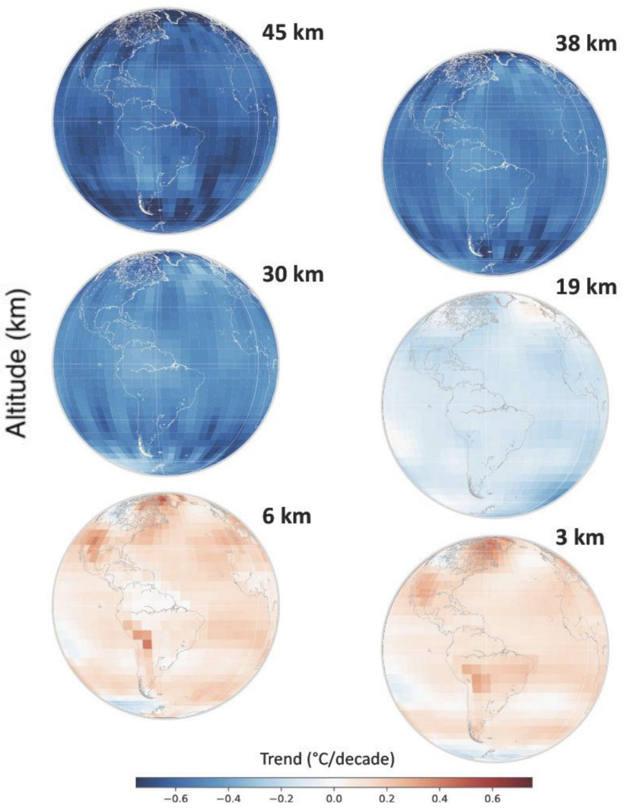


Image from Ben Santer

- Like human fingerprints, different forcings have **different characteristic signatures** in space and time.
- An increase in the pattern similarity between observations and the human fingerprint (based on model simulations) suggests the observed warming pattern is due to human activities and unlikely explained by the internal variability.

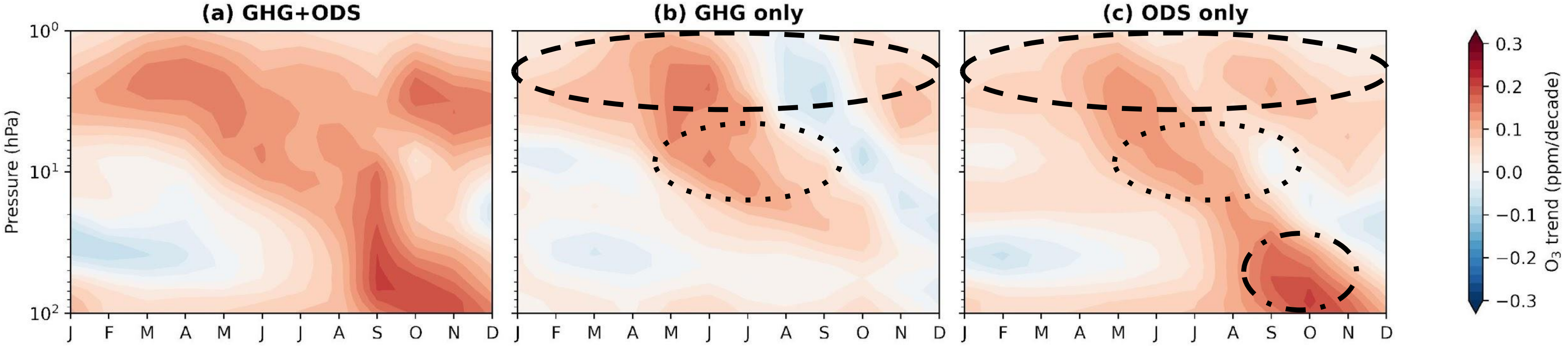
Models and observational data

Models:
- CESM1-WACCM4
    - Fully coupled atmosphere-ocean model with interactive chemistry runs from 1995 to 2024.
    - 10 realizations each for GHG+ODS, GHG only, and ODS only.
    - And another 10 realizations in a pre-ozone-depletion time from 1955 to 1979.
- CCMI-1
    - 19 different models runs from 1960 to 2100.
- Model ensemble mean indicates forced response, and subtracting this ensemble mean from each realization indicates internal variability.

Observations: MLS monthly mean pressure-resolved ozone from 2005 to 2023. It contains the real-world forced responses and the internal variability influence.

Region of interest:
- Latitude averaged from 66S to 82S (same as MLS latitude bounds).
- Pressure from 100 hPa to 1 hPa, model outputs are vertically interpolated to MLS pressure coordinates.

Searching for month-height fingerprints



Both GHG and ODS forcing can lead to ozone increase, but the timing, location and mechanisms can be different.

Upper stratosphere

- (GHG only) increasing GHG resulted in a decrease in temperature, slower down ozone loss rates with NOx.
- (ODS only) reducing ODS resulted in less reactive Cl.

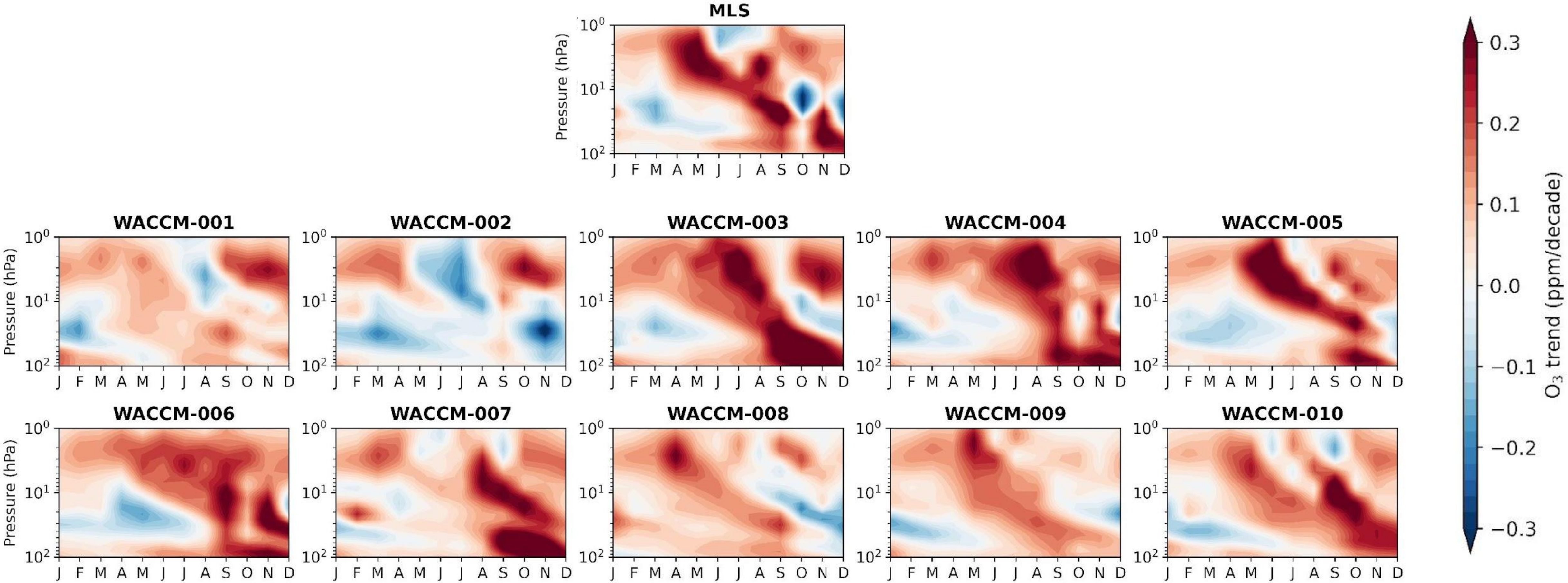
Middle stratosphere

- Strong polar winter mesospheric descend propagates down the ozone recovery signal from the upper stratosphere to the middle stratosphere.

Lower stratosphere

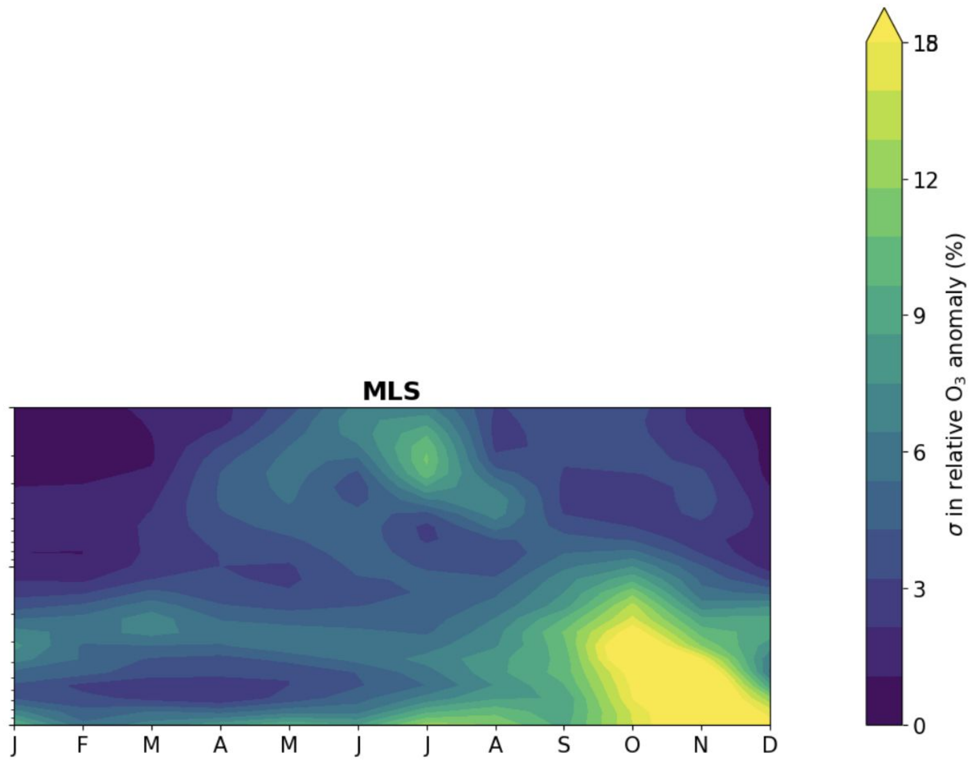
- Reducing ODS resulted in less heterogeneous Cl activation.

Modelled and observed Antarctic ozone trends



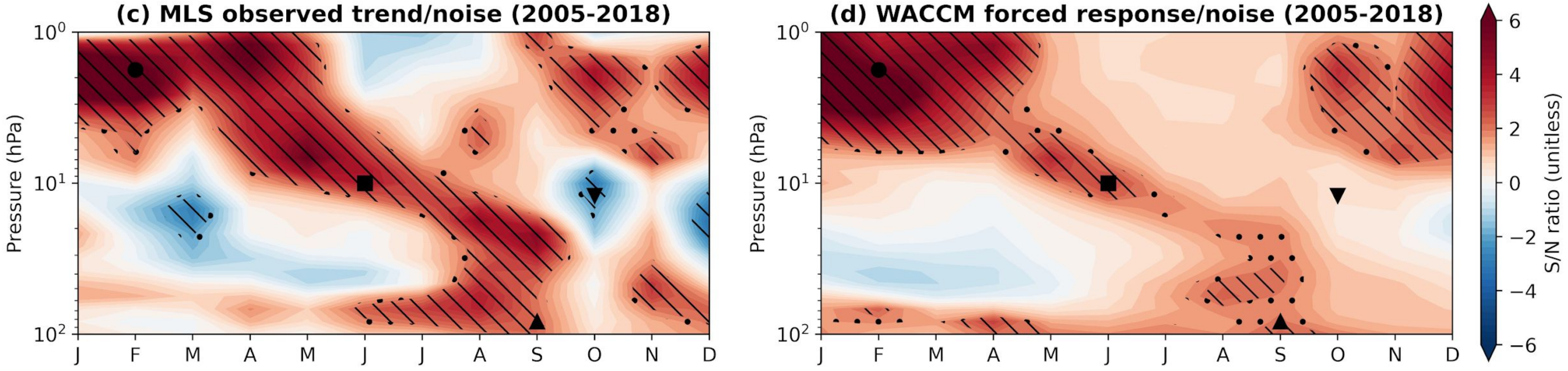
- The observed ozone trend and individual model realizations contain both the forced response (**signal**) and the internal variability (**noise**).
- The difference between individual realizations gives a spread of internal variability influence on top of the forced response to GHG+ODS forcing.

Ozone internal variability "noise"



- In the climate community, internal variability is commonly estimated from pre-industrial control runs (similar to "hist" scenario here).
- But ozone internal variability is significantly enhanced under present-day forcing, mainly due to elevated ODS.
- This enhanced internal variability can impact the statistical significance of the observed trends.
- Also highlight a potential pathway for external forcing to modulate internal climate variability.

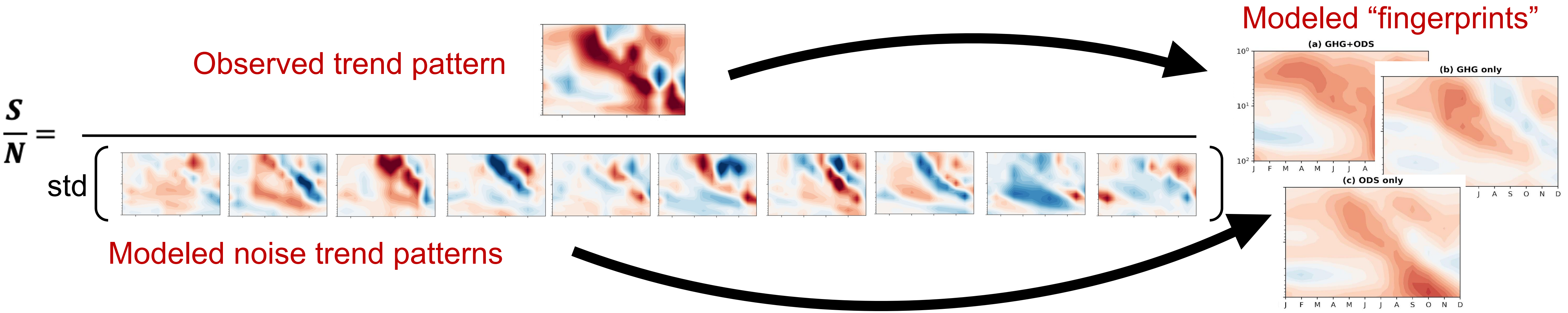
Signal-to-noise ratio at local month/height

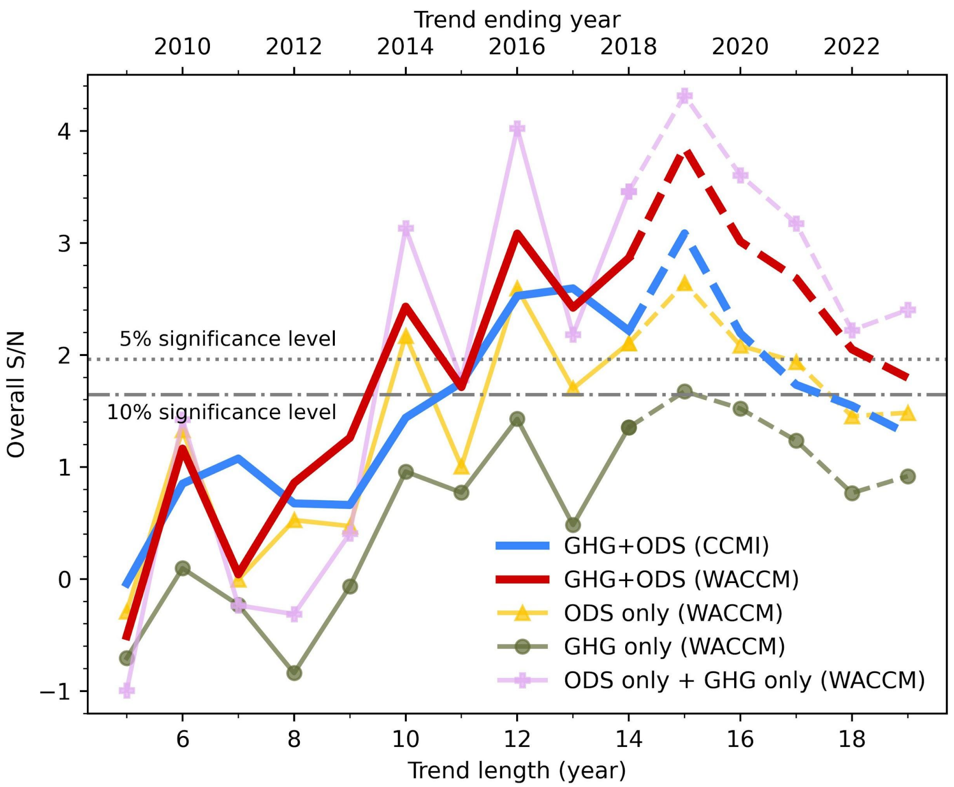


Hatches indicate 95% confidence, dots indicate 90% confidence.

Based on WACCM, we are expected to see significant ozone recovery in certain months/heights, and indeed we can see them in the observations.

Overall pattern similarity between observation and model





- By projecting the observed and noise patterns onto the modeled fingerprints, we can quantitatively estimate the pattern similarity in observation that reflect different external forcings.

- The observed ozone trend pattern is getting more similar to the forced GHG+ODS pattern over time, and this observed pattern is unlikely explained by internal variability.

- The higher S/N for MLS projected onto the ODS-only fingerprint compared to the GHG-only fingerprint suggest that the observed pattern is dominated by the forced response to decreasing ODS concentrations.

Conclusion

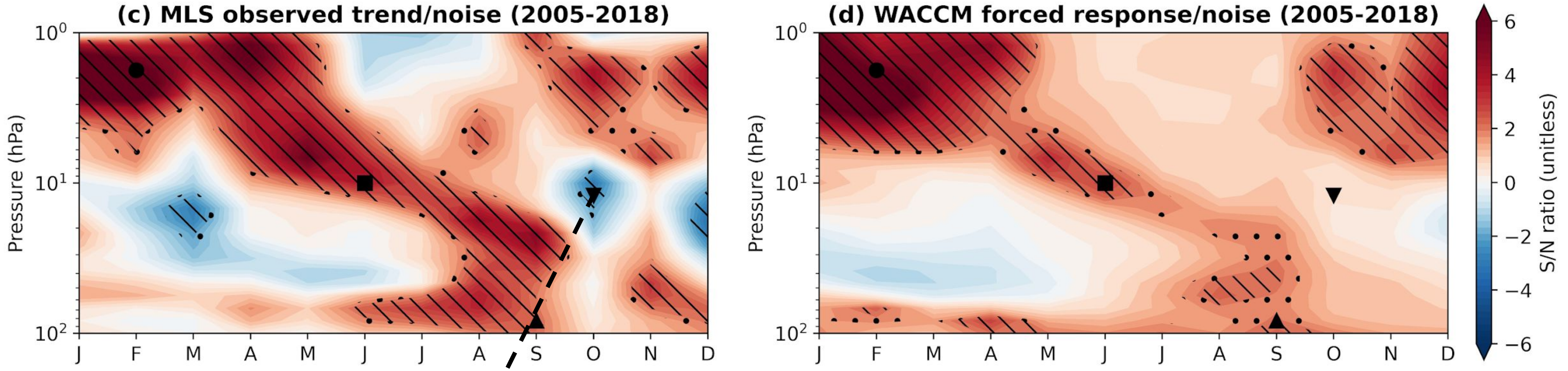
- The month-height trend patterns of Antarctic ozone are getting more similar to the fingerprint pattern of GHG+ODS in 10-member CESM-WACCM ensembles and in 19 multi-model CCMI ensembles.

- This pattern similarity is dominated by ODS forcing, suggesting that the Montreal Protocol in regulating ODS emissions is indeed leading to a significant recovery in Antarctic ozone that is unlikely explained by internal variability.

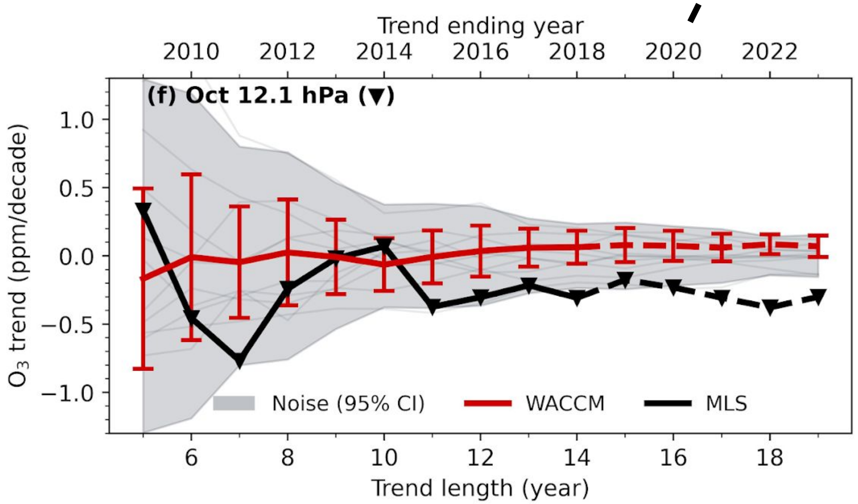
- These initial-condition large ensemble simulations with interactive chemistry provide valuable information to quantitatively estimate the uncertainty in chemical constituents due to internal climate variability (which may involve non-linear feedbacks).

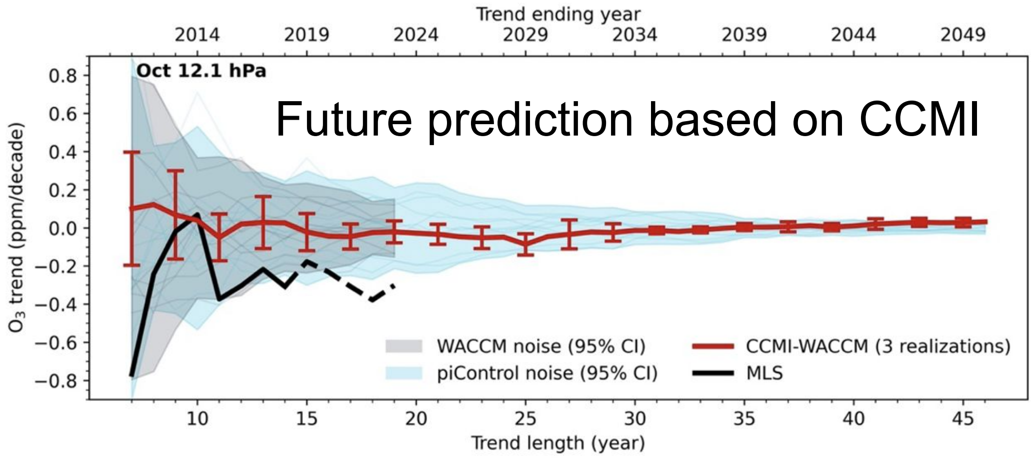
- Changes in stratospheric ozone variability due to elevated ODS forcing also highlight potential coupled chemistry-climate interactions for external forcing to modulate specific modes of climate internal variability, such as the Southern Annular Mode.

Ozone not recovering in October?



Hatches indicate 95% confidence, dots indicate 90% confidence.

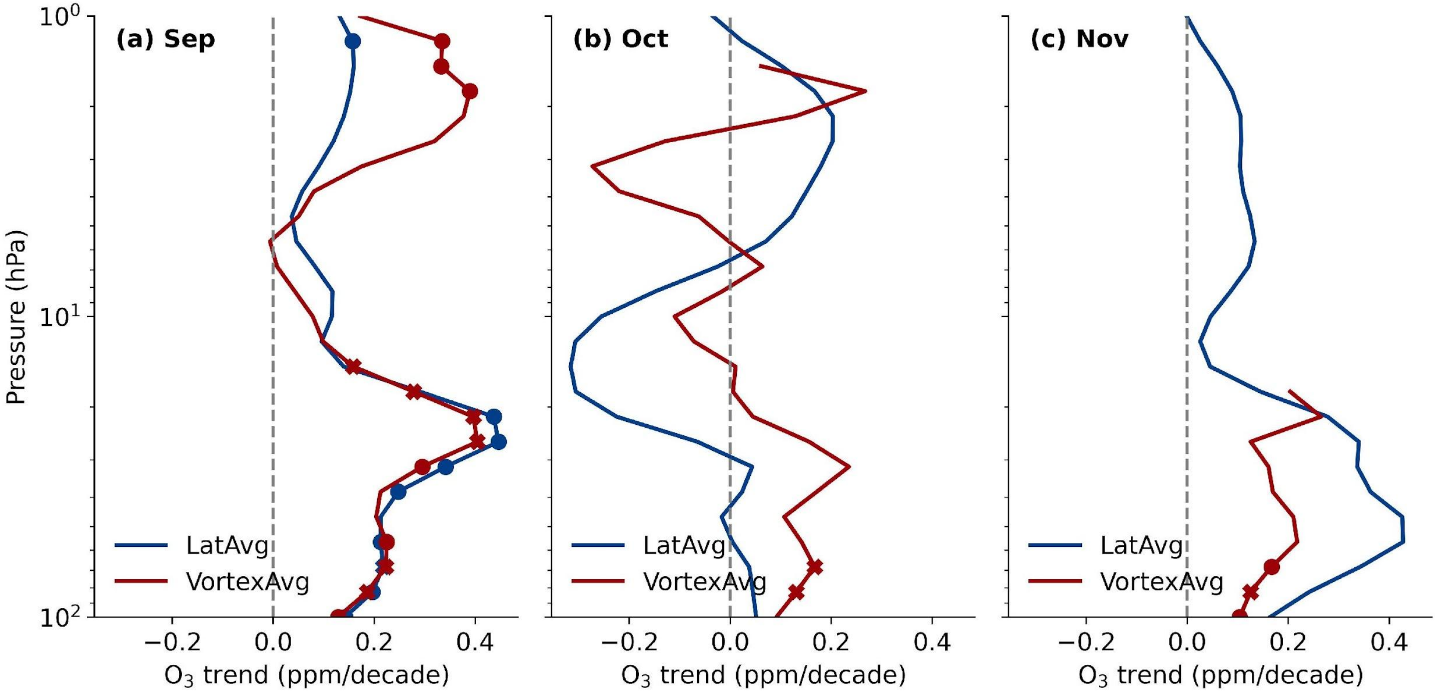




October ozone (especially at mid-stratosphere) exhibits large noise but small signal, it is not an ideal place to search for signs of recovery. Trends can be biased by exceptional events like volcanic eruptions and wildfires in recent years.

Ozone internal variability from polar vortex variations

Ozone anomaly (color shading) and vortex location (dots) in October at 850 K (~12 hPa).



- Averaging ozone in a fixed latitude range ignores the asymmetric vortex variations (especially important for October when the vortex is unstable).

- More area encompassed in 66-82S has moved into the vortex in later years, leading to a strong negative ozone trend.