

Externally forced changes to Southern Hemisphere stratosphere-troposphere coupling variability

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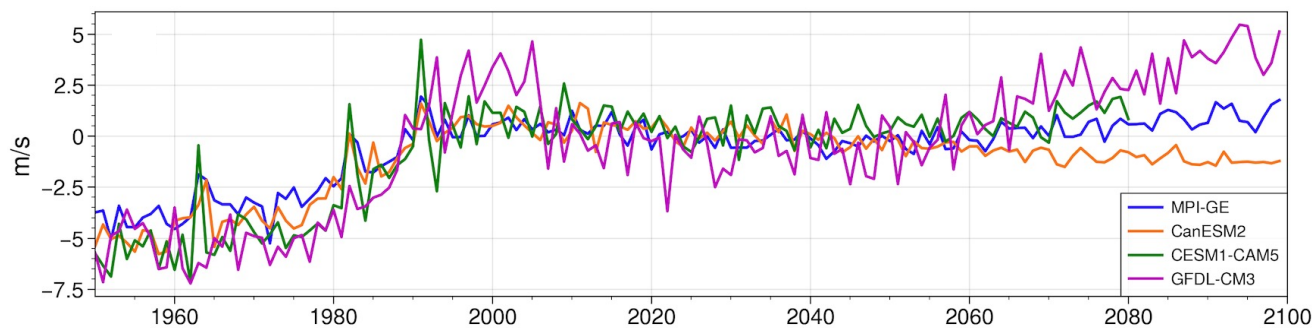
³ National Center for Atmospheric Research



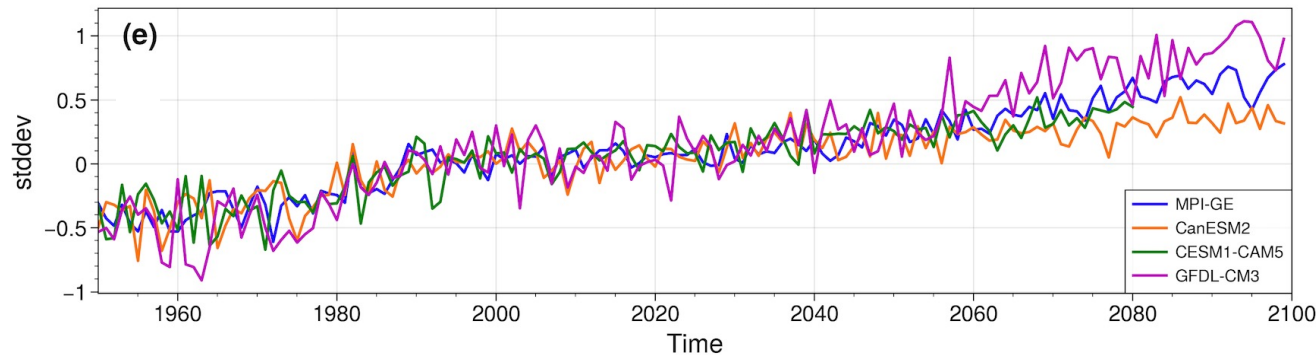
APARC GA 2026

Ozone depletion, recovery, and increasing greenhouse gases affect mean circulation

Ensemble-mean 50 hPa 55-65S SON Zonal Wind Anomalies

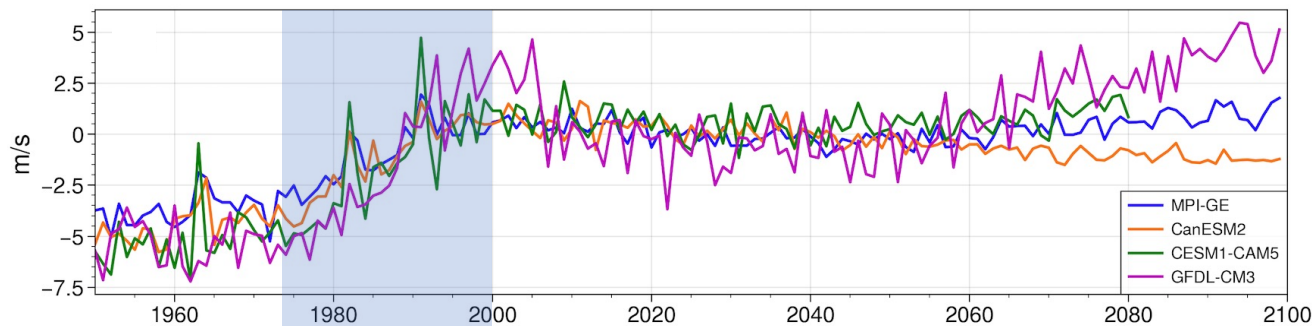


Ensemble-mean OND Southern Annular Mode (SAM)



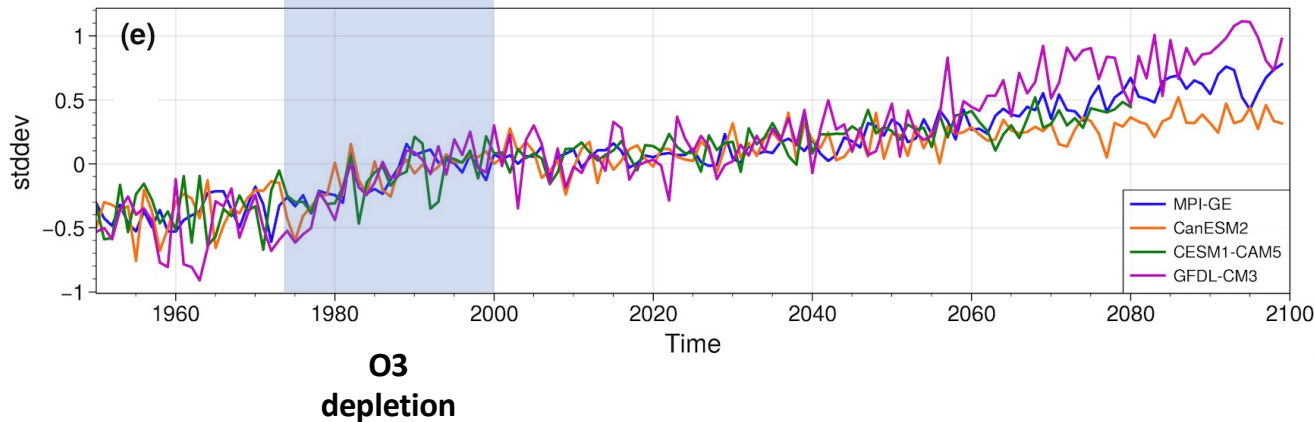
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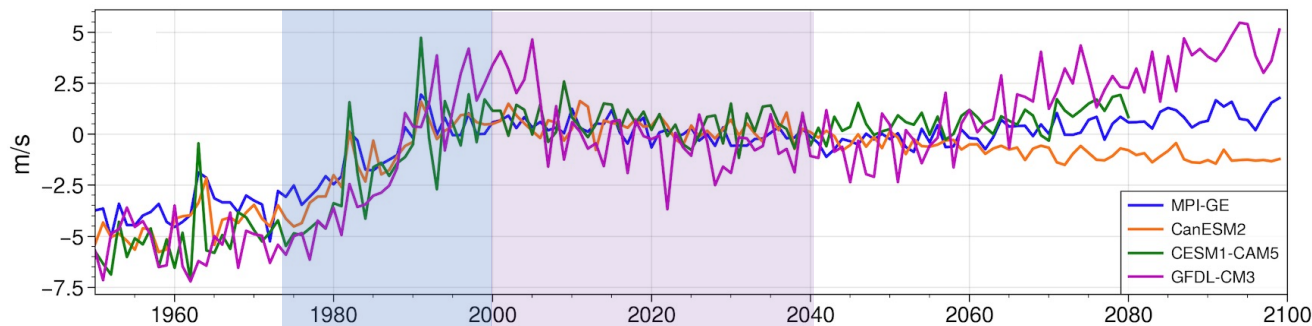
Ozone depletion: stronger spring polar vortex winds -> trend towards positive phase of SAM (e.g., Son et al. 2018)

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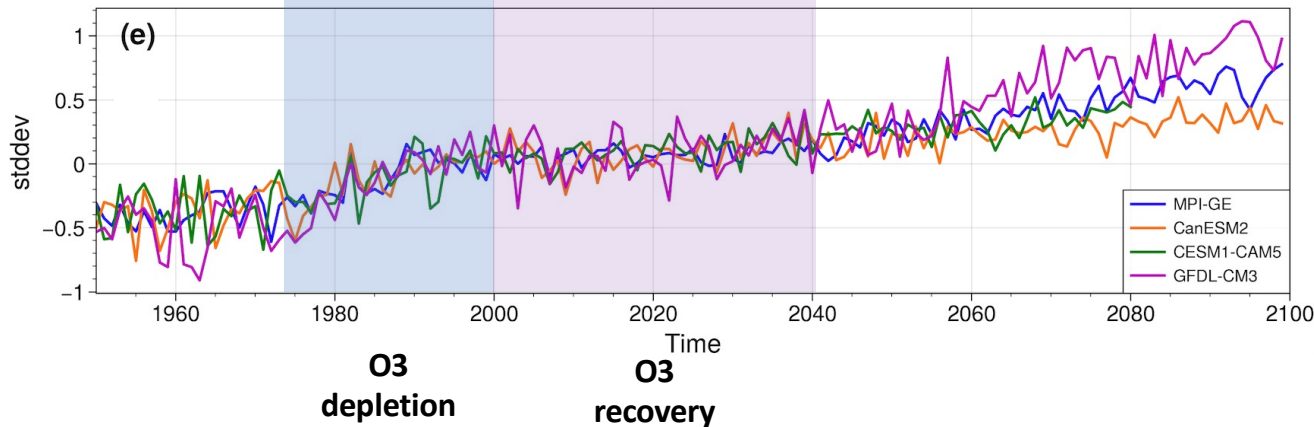
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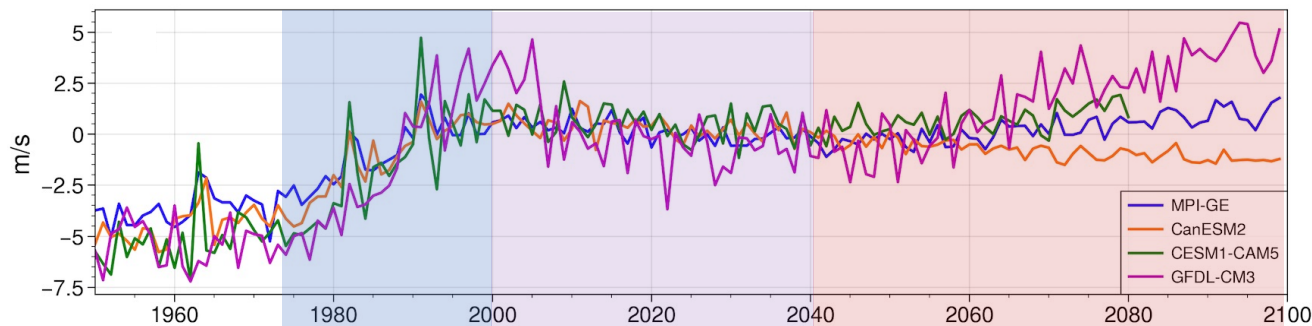
Ensemble-mean OND Southern Annular Mode (SAM)



Ozone recovery: polar vortex/SAM trends slow or reverse (e.g., Banerjee et al. 2020)

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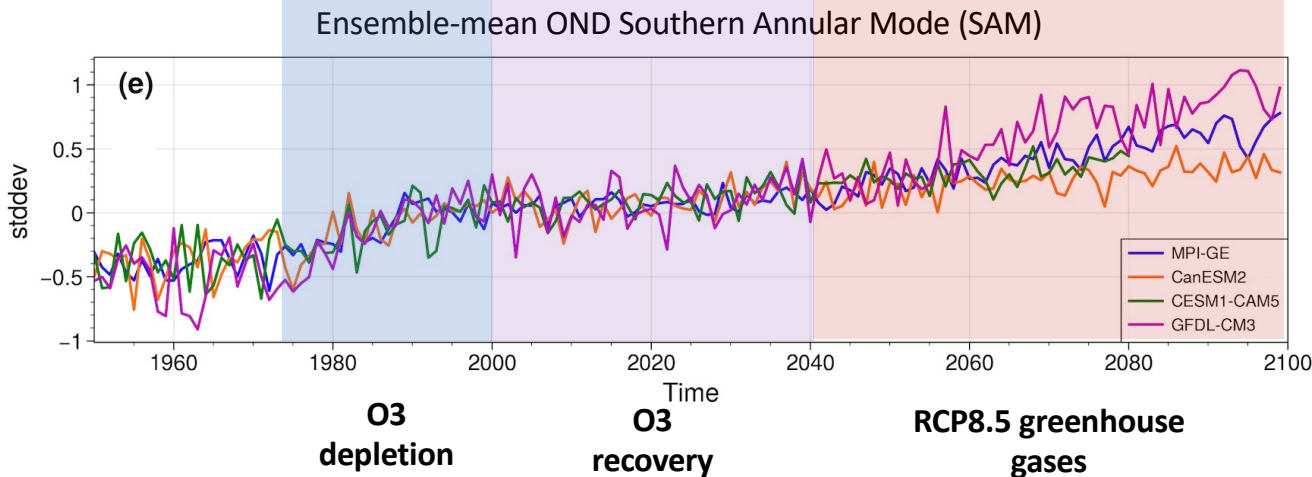
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Ozone recovery: polar vortex/SAM trends slow or reverse (e.g., Banerjee et al. 2020)

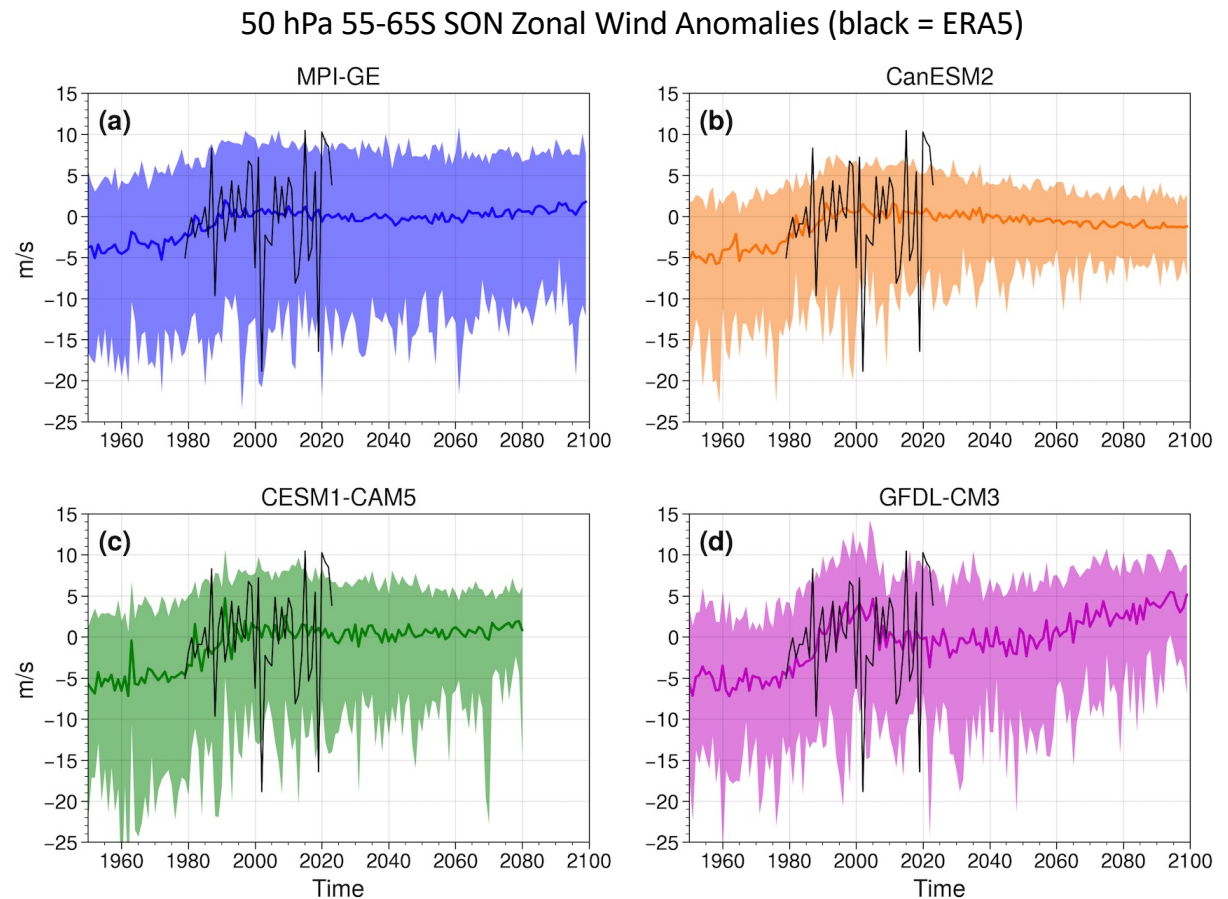
GHGs: positive trends in polar vortex winds and SAM continue in most models (e.g., Ivanciu et al. 2022)



... but how does variability change in response to external forcings?

When we plot the full ensemble spread for each model, we can see that some of the models show clear changes in the spread over time.

Why do we care if the variability changes? The variability changes the risk of extremes; larger variability is generally more predictable; and modes of variability (like the SAM) can change spatial structure, altering where impacts are felt.



Large Ensembles are an essential tool for quantifying changes in variability

Model Name	Ensemble members	Ozone
MPI-GE	100	Prescribed
CanESM2	50	Prescribed
CESM1-CAM5	40	Semi-offline
GFDL-CM3	20	Interactive

Ozone information from Eyring et al. (2013)
Data from MMLEA, Deser et al. 2020

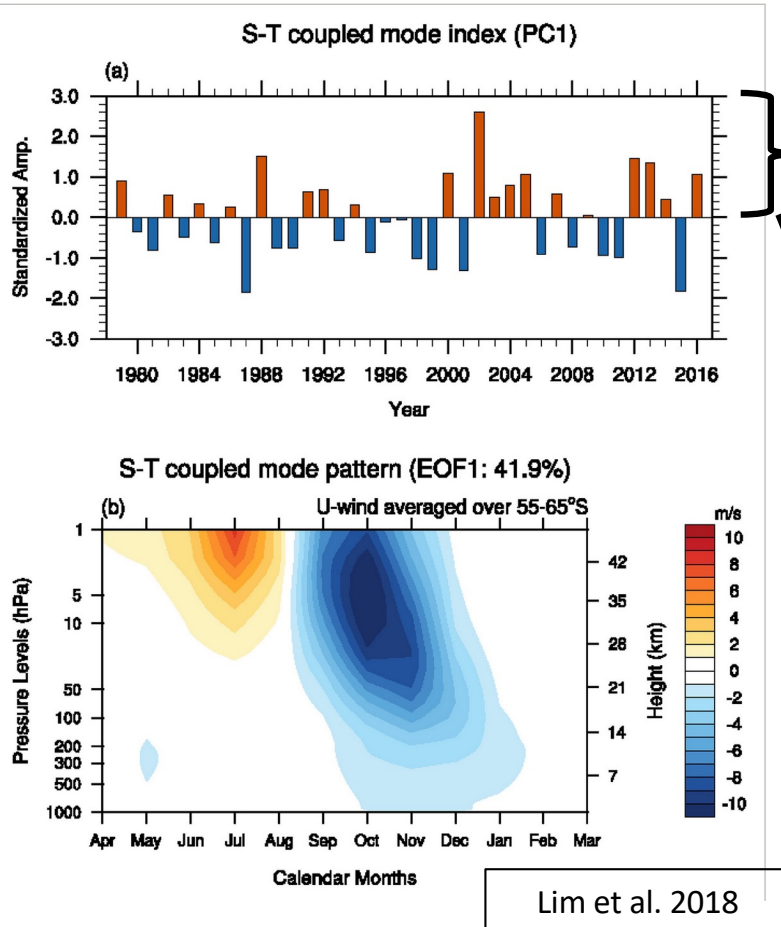


- All forced with historical + RCP8.5 climate
- Limitations: Mostly prescribed or semi-offline stratospheric ozone

Prescribed: tropospheric ozone follows matching RCP8.5 but stratospheric ozone follows IGAC/SPARC ozone database that use A1B scenario (Cionni et al (2011))

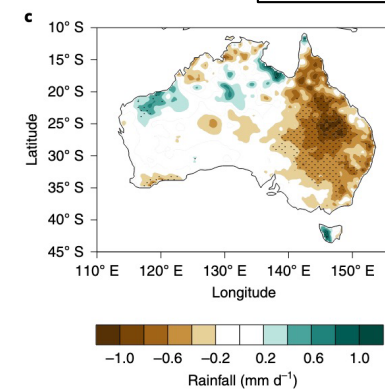
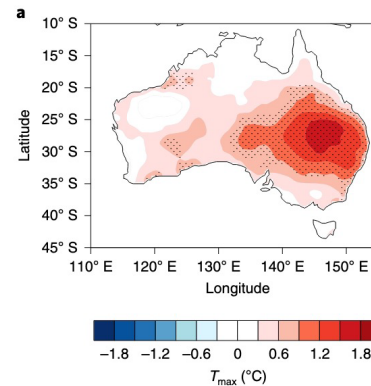
Semi-offline: prescribed using two-member RCP8.5 simulation in CESM1-WACCM that includes interactive chemistry.

The stratosphere-troposphere coupling mode



The pattern that explains the most variability in the height-time domain of SH zonal winds shows stratospheric variations in winter-spring that are linked to surface climate in early summer.

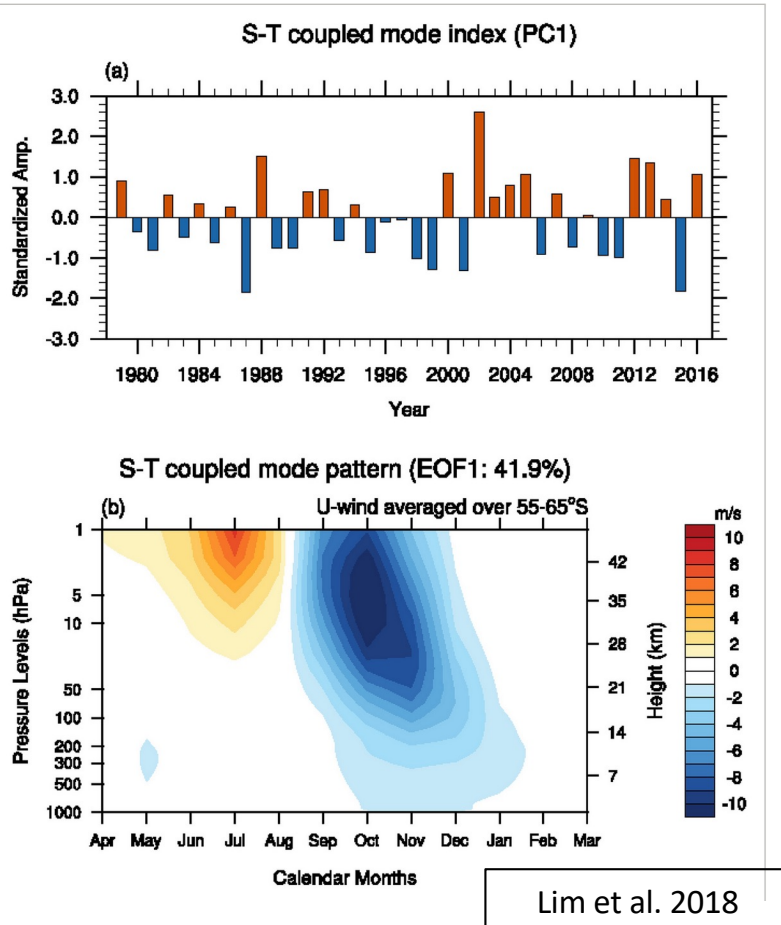
- PC1 is significantly correlated to spring total column ozone and spring-summer Southern Annular Mode (SAM)



Lim et al. 2019

Oct-Jan
Tmax
and
Precip

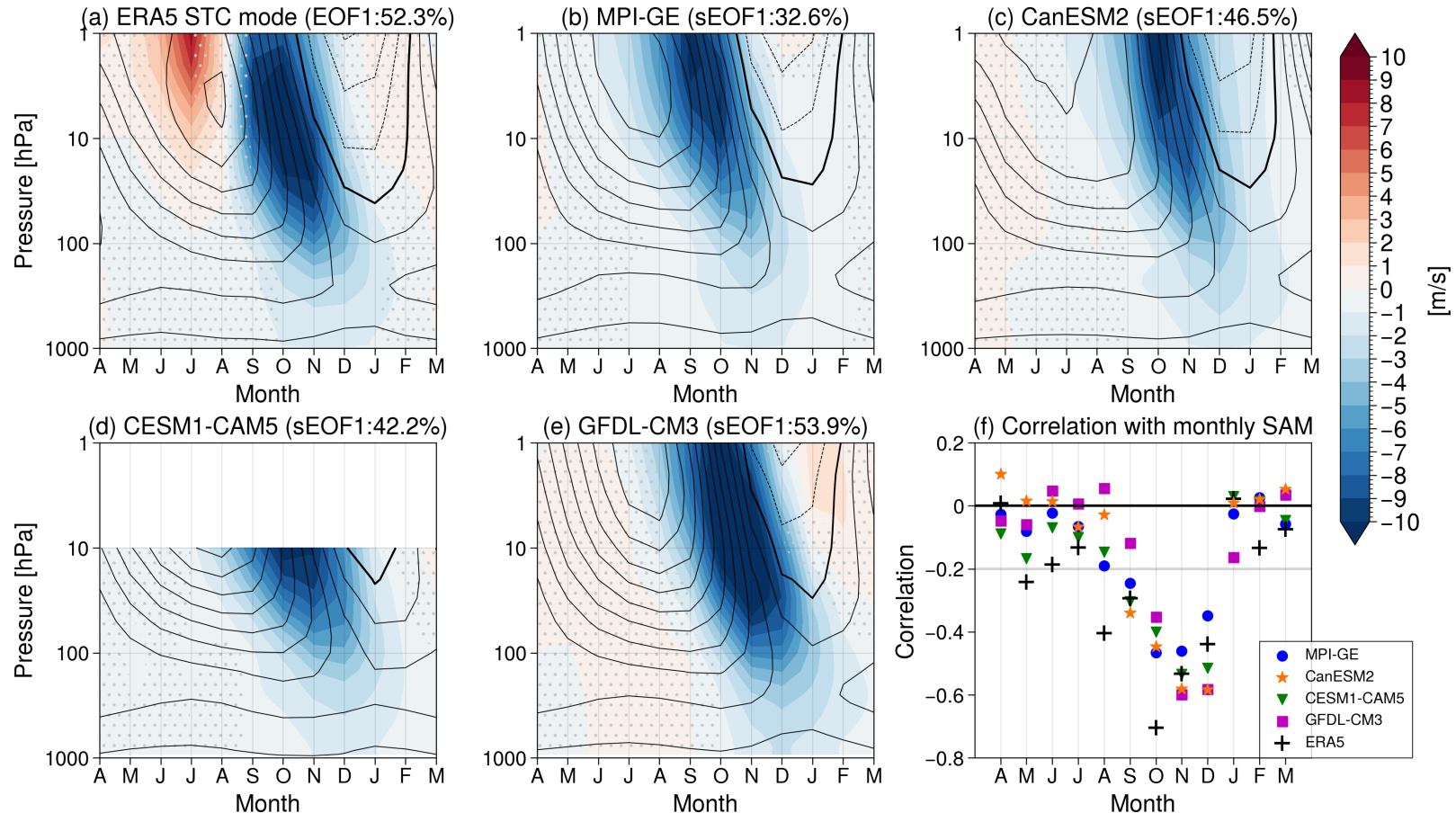
The stratosphere-troposphere coupling mode



- This pattern is calculated as the first EOF about the time dimension (the only way to calculate modes of variability in the one “realization” of the observational record)
- To quantify whether a mode of variability changes in response to external forcings, we need to instead calculate the EOF *across ensemble members*, rather than time- can get an EOF for each year (“**snapshot**” EOFs; e.g., Maher et al. 2018; Haszpra et al. 2020; O’Brien and Deser 2023)

Applying the snapshot EOF method to the STC mode

for the 5-year period centered on 2008

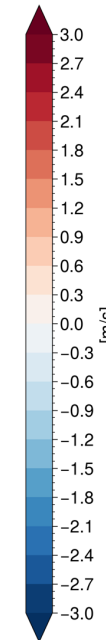
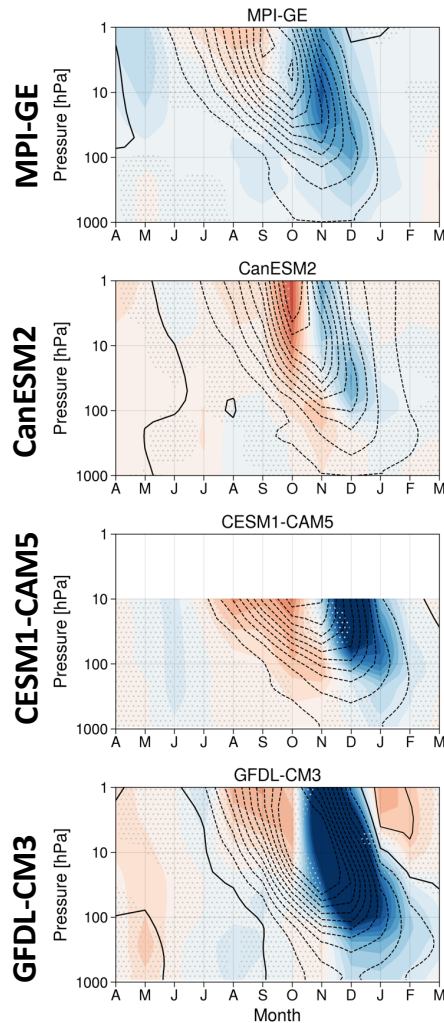


For reference, black contours are 1979-2023 55-65°S zonal wind climatology. Shading is EOF1 of S-T coupling.

O3 depletion (1955 to 2000)

O3 recovery (2000 to 2030)

RCP8.5 (2075 minus 2030)



Most of the models show a shift of ST coupling variability to later months during the period dominated by **ozone depletion**. This shift is related to the shift towards later final warmings during this period.

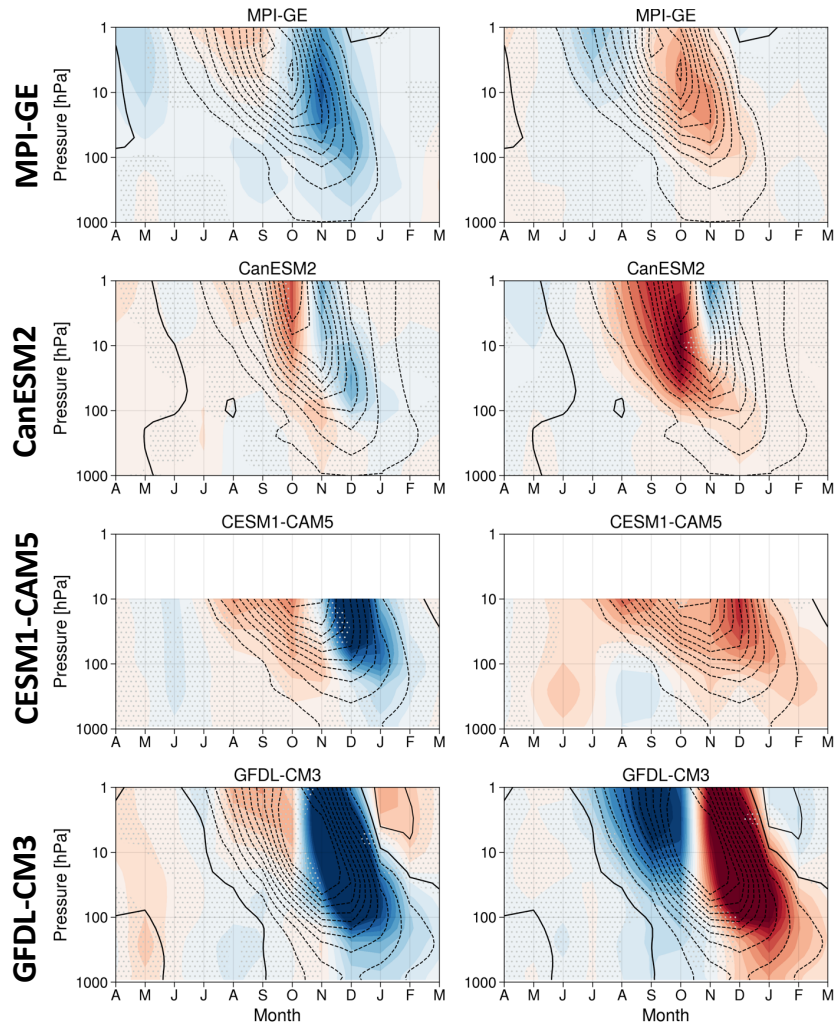
The only model with interactive chemistry (GFDL-CM3) shows the largest change in this period.

For reference, black contours are the 2008-centered EOF patterns from previous slide. Shading is linear trend in EOF pattern.

O3 depletion (1955 to 2000)

O3 recovery (2000 to 2030)

RCP8.5 (2075 minus 2030)



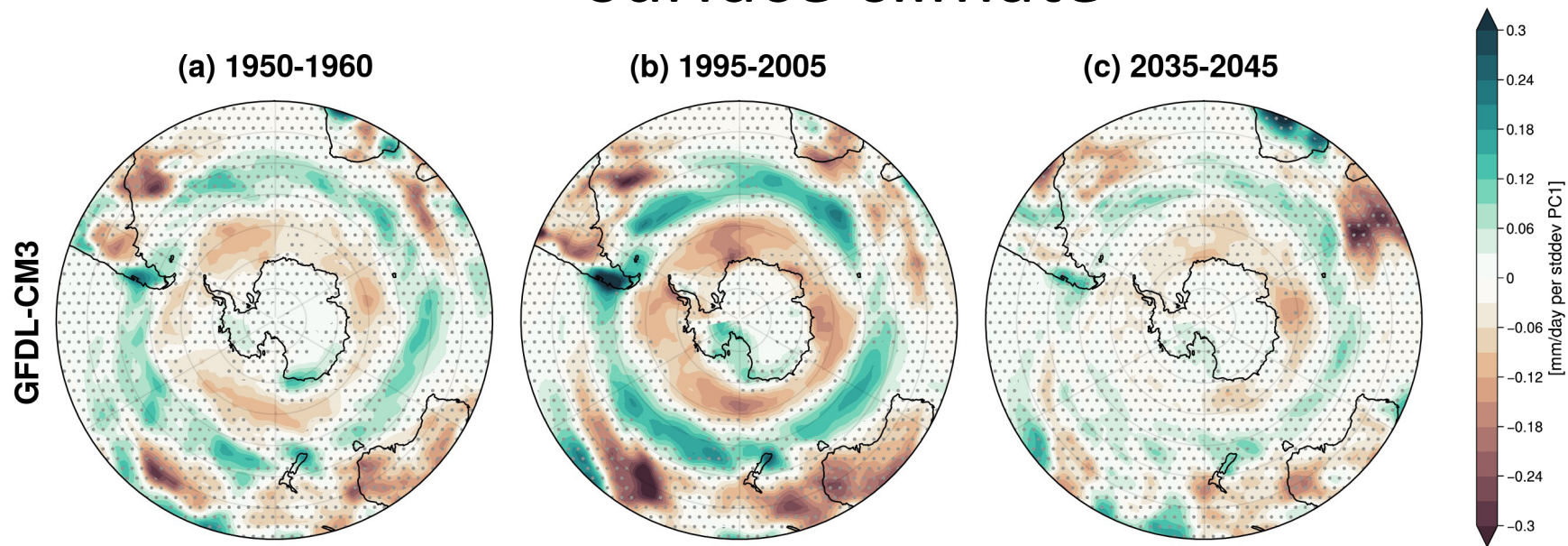
The response of the STC mode from 2000 to 2030 is less clear.

MPI-GE and GFDL-CM3 show a clear reversal of trends compared to the 1955-2000 period, suggesting a dominant role of **ozone recovery**.

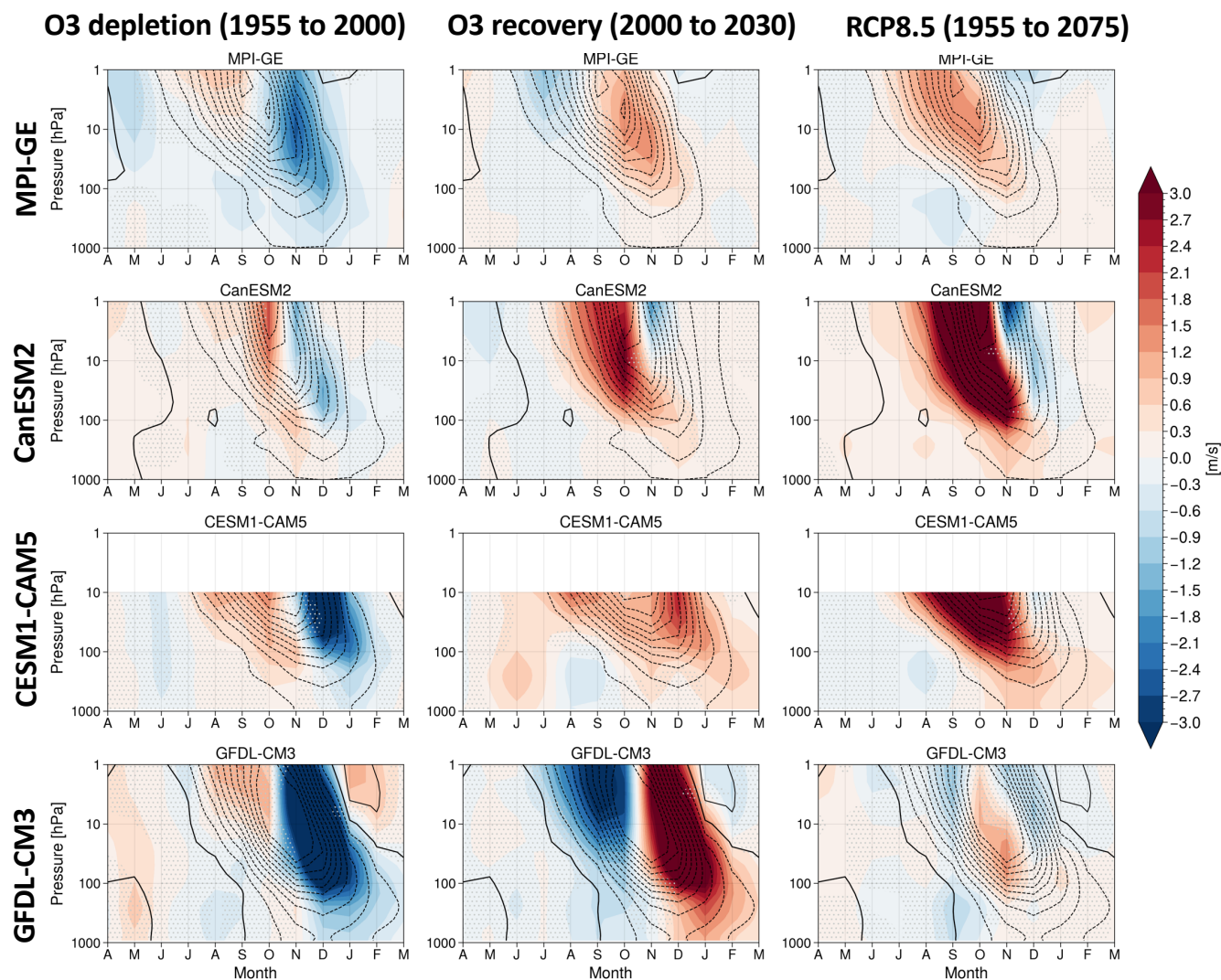
CanESM2 and CESM1-CAM5 instead show a general weakening of the mode.

For reference, black contours are the 2008-centered EOF patterns from previous slide. Shading is linear trend in EOF pattern.

Impacts of changing STC mode variability on surface climate



- The positive STC mode is associated with negative SAM-related impacts in DJF precipitation for all periods
- But, the amplitude and spatial pattern changes over time- with the greatest amplitude during the period of peak ozone depletion (panel b) and less zonal, much weaker amplitude during the period of ozone recovery (panel c)

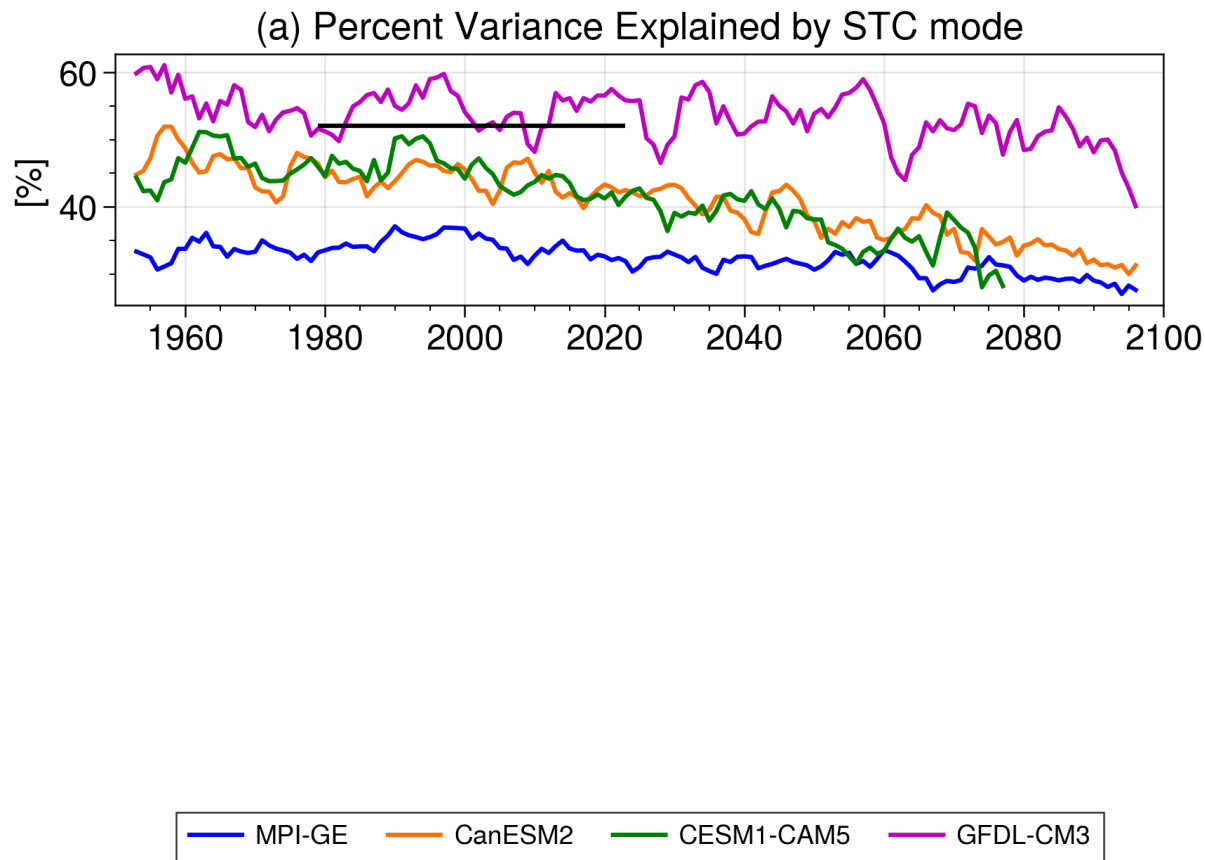


In the period dominated by greenhouse gas forcing (1955-2075), all models show a weakening of the STC mode, but with differences in magnitude and peak months.

The largest weakening is for CanESM2 and CESM1-CAM5, where the weakening of the mode extends down to the surface.

For reference, black contours are the 2008-centered EOF patterns from previous slide. Shading is linear trend in EOF pattern.

Decreasing SH strat-trop coupling variability and connection to the SAM

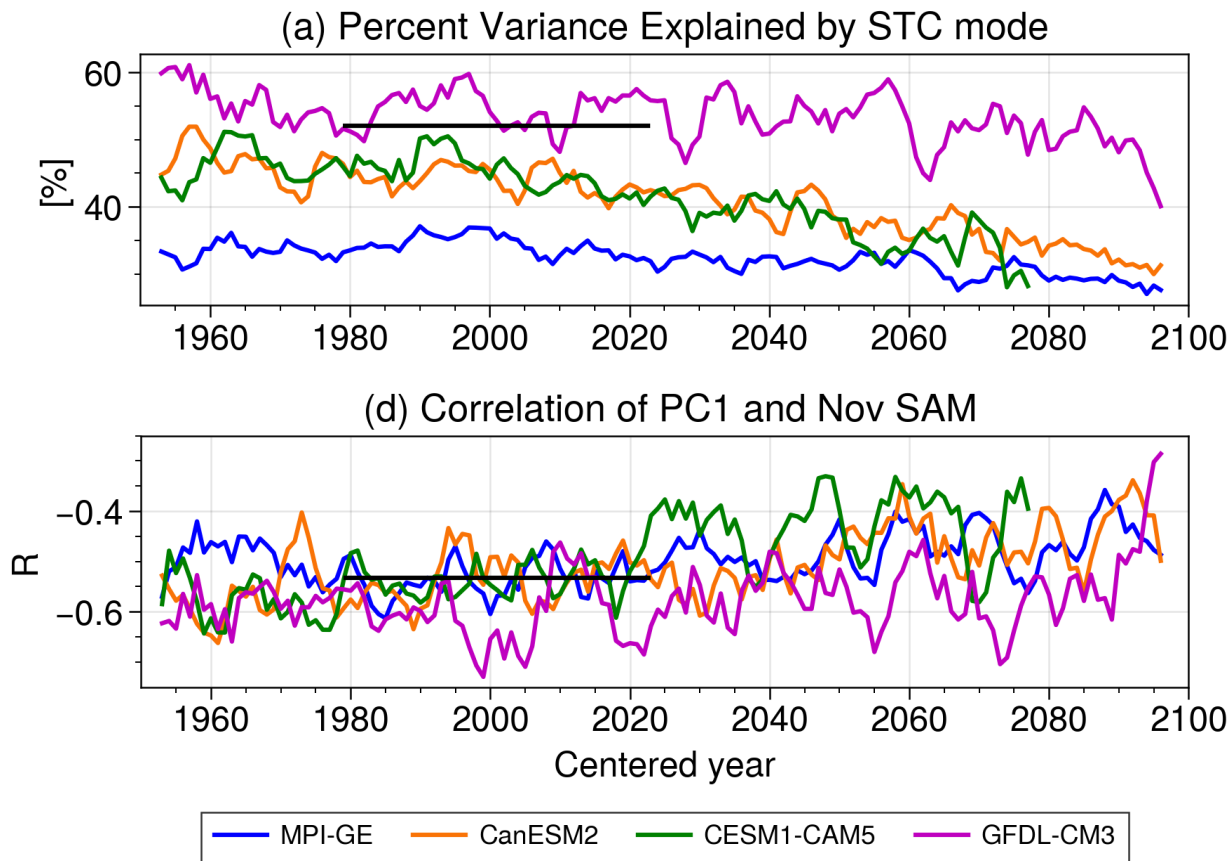


All models show the percent variance explained by the STC mode decreasing by the latter half of the 21st century:

- 2.7% (MPI-GE)
- 11.4% (CanESM2)
- 12.2% (CESM1-CAM5)
- 4.6% (GFDL-CM3)

Black horizontal line shows ERA5 value using STC mode calculated over the 1979-2023 period

Decreasing SH strat-trop coupling variability and connection to the SAM



All models show gradual decreases in the magnitude of the (negative) correlation with the SAM over time. This suggests the STC mode may become less useful as a seasonal predictor of the SAM in the future.

Black horizontal line shows ERA5 value using STC mode calculated over the 1979-2023 period

Conclusions

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Ozone depletion, recovery, and increasing greenhouse gases may drive changes not only in the mean circulation, but in patterns of variability.

The SH stratosphere-troposphere coupling mode is a useful seasonal predictor of spring-summer climate, but our results show that:

- (1) Ozone depletion shifted the variability explained by the mode to early summer
- (2) Ozone recovery may shift this variability back to spring, but only the model with interactive chemistry robustly shows this effect
- (3) Stratosphere-troposphere coupling variability decreases as greenhouse gases increase, diminishing related predictability of surface climate.

Butler, A.H., E.-P. Lim, I.R. Simpson, Externally-forced changes to Southern Hemisphere stratosphere-troposphere coupling variability, *Earth's Future*, 14, e2025EF007334.

<https://doi.org/10.1029/2025EF007334>