Ozone Hole and Southern Hemisphere Climate Change

Seok-Woo Son
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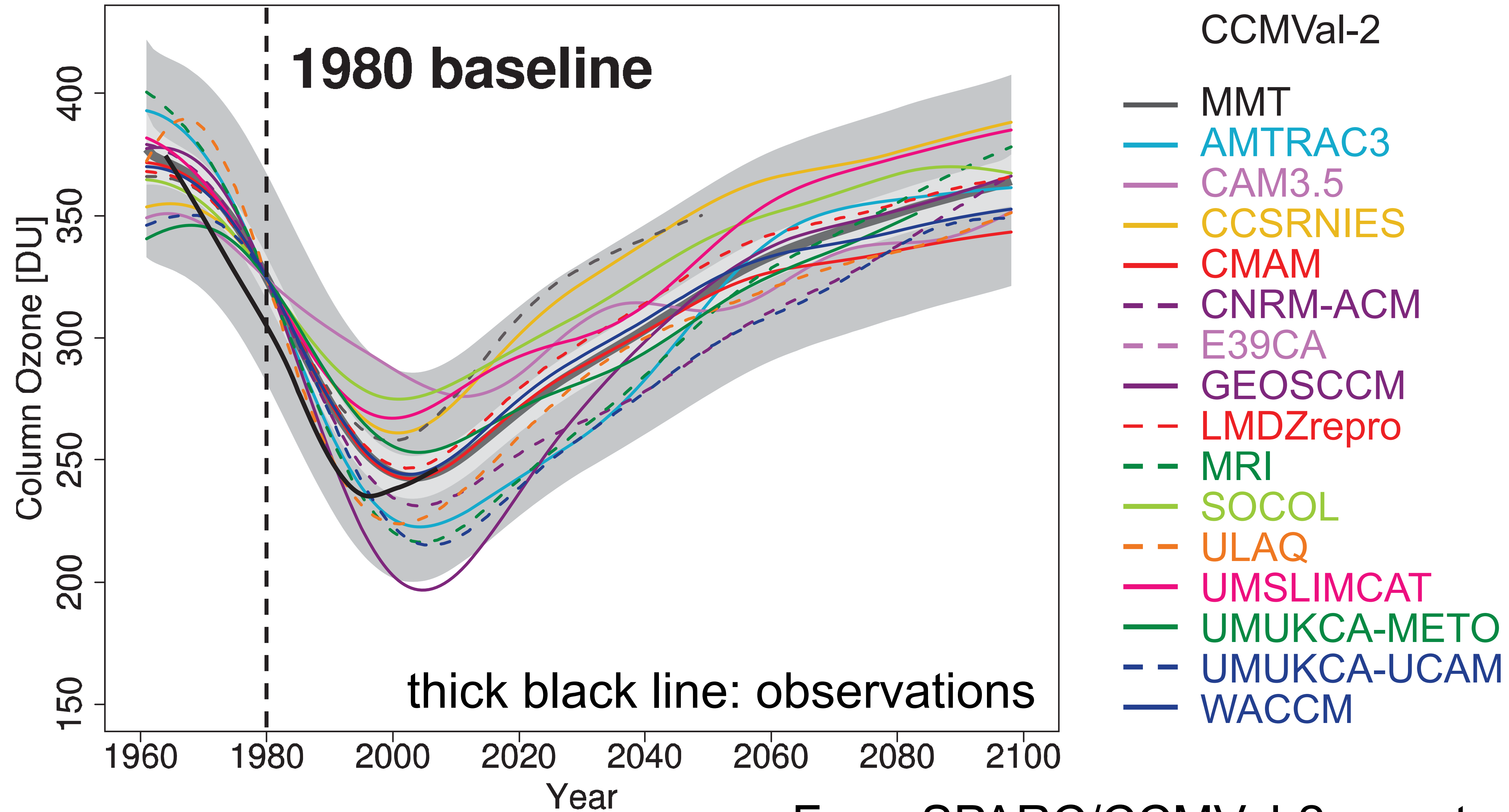
and many collaborators including the SPARC/CCMVal-2 coauthors

Ozone Hole & Montreal Protocol



From SPARC/CCMVal-2 report

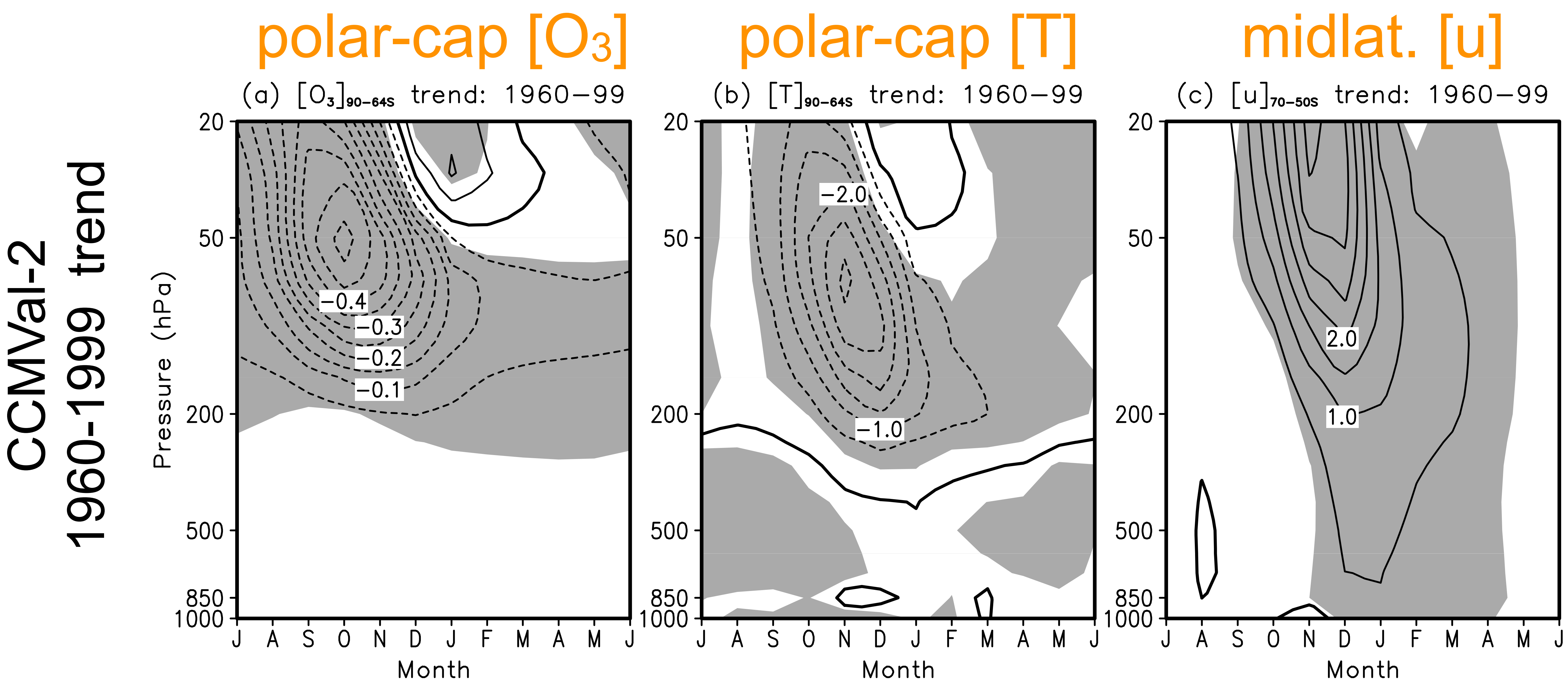
- Although Antarctic stratospheric ozone has decreased in the past, it is anticipated to increase in the future due to the implementation of the Montreal Protocol.

Fundamental Question

What is the impact of the Antarctic ozone depletion and recovery on the Southern Hemisphere (SH) climate change?

As Antarctic ozone hole has occurred at high altitudes (15 km above the ground) and very high latitudes (poleward of 60S), far away from the extratropical troposphere and surface, its impact on climate systems is not trivial.

Does the Ozone Hole Really Matter?



- Shown is multi-model mean trends of polar-cap ozone, temperature and mid-latitude zonal wind as a function of pressure and month. All plots are based on SPARC/CCMVal-2 model output.

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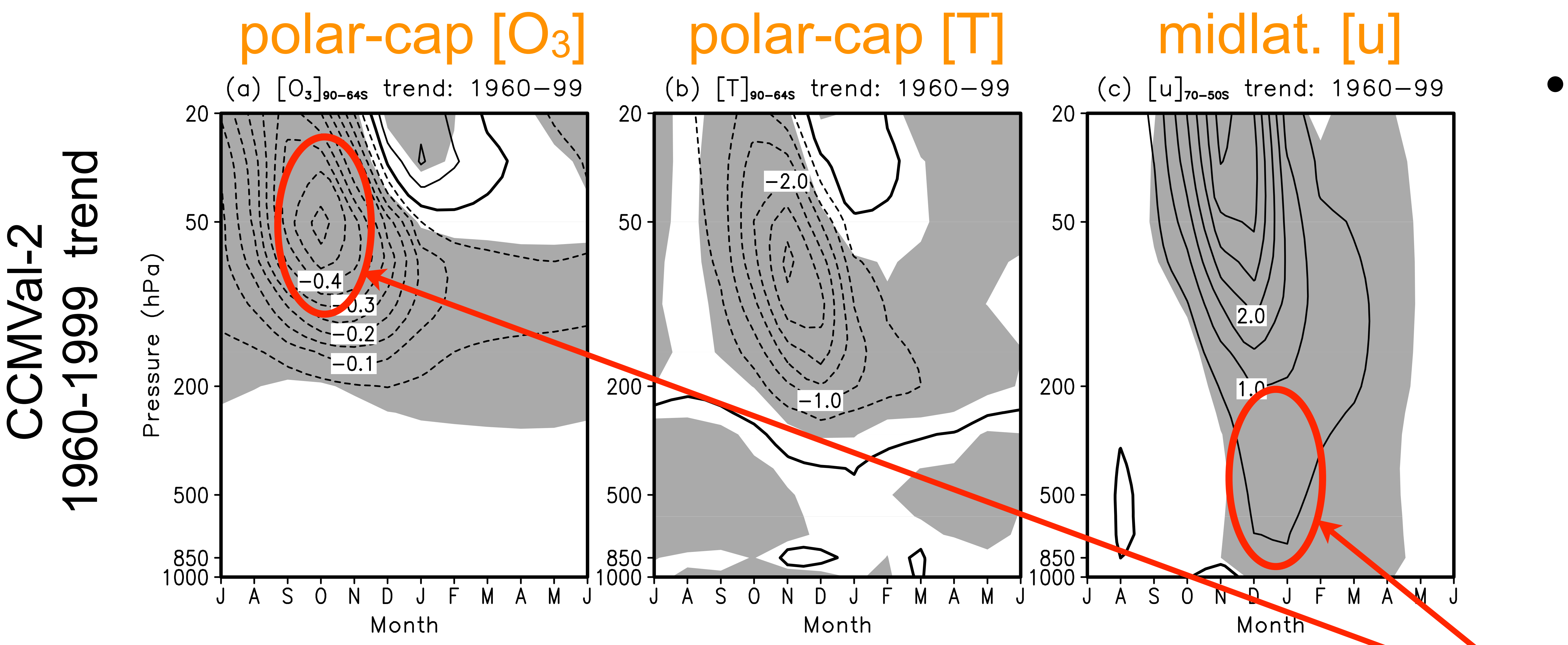

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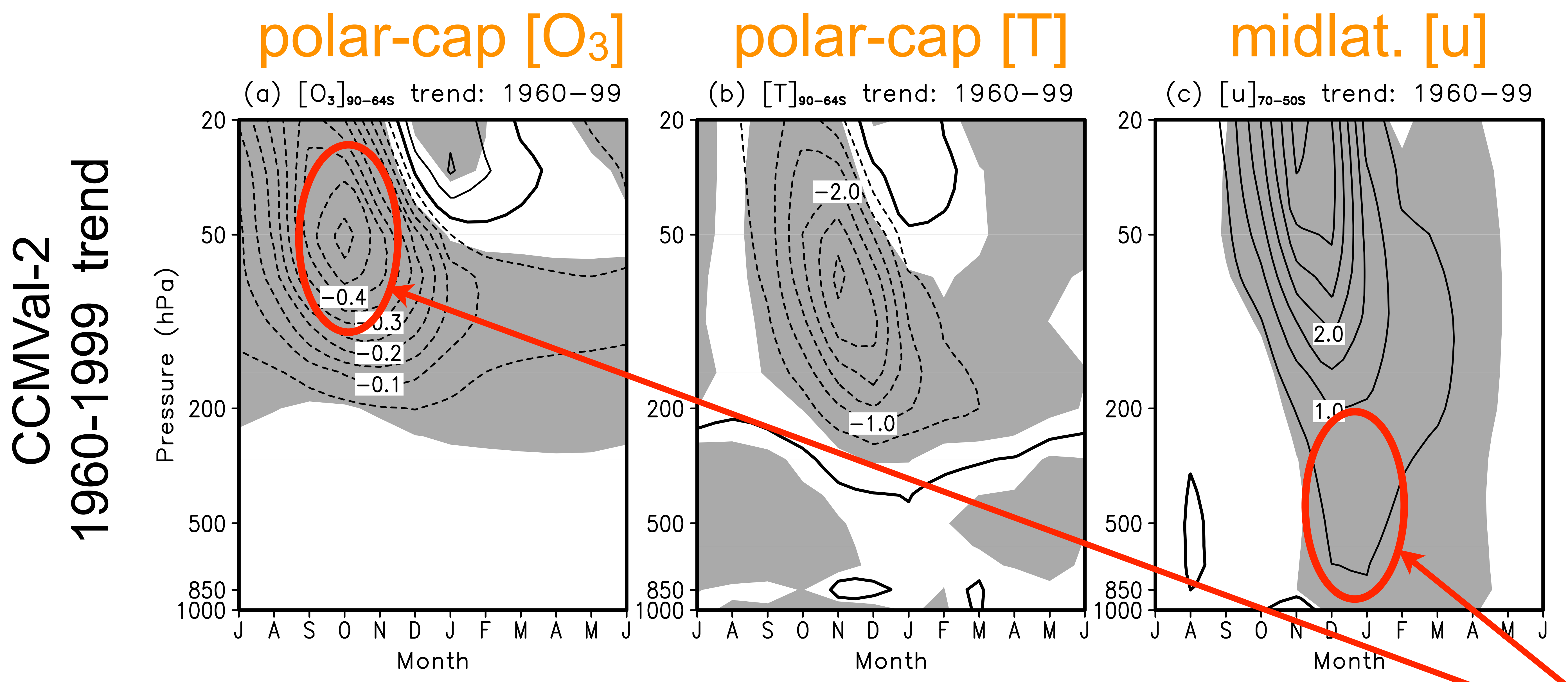

- Shown is multi-model mean trends of polar-cap ozone, temperature and mid-latitude zonal wind as a function of pressure and month. All plots are based on SPARC/CCMVal-2 model output.
- The ozone hole in the stratosphere significantly influences tropospheric circulation.
- The ozone hole is one of the most important anthropogenic forcings in the SH-summer climate change (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Shindell and Schmidt, 2004; Arblaster and Meehl, 2006; Miller et al. 2006; Cai and Cowan, 2007; Perlwitz et al. 2008; Son et al. 2008,2009,2010; Polvani et al. 2011; McLandress et al. 2011).

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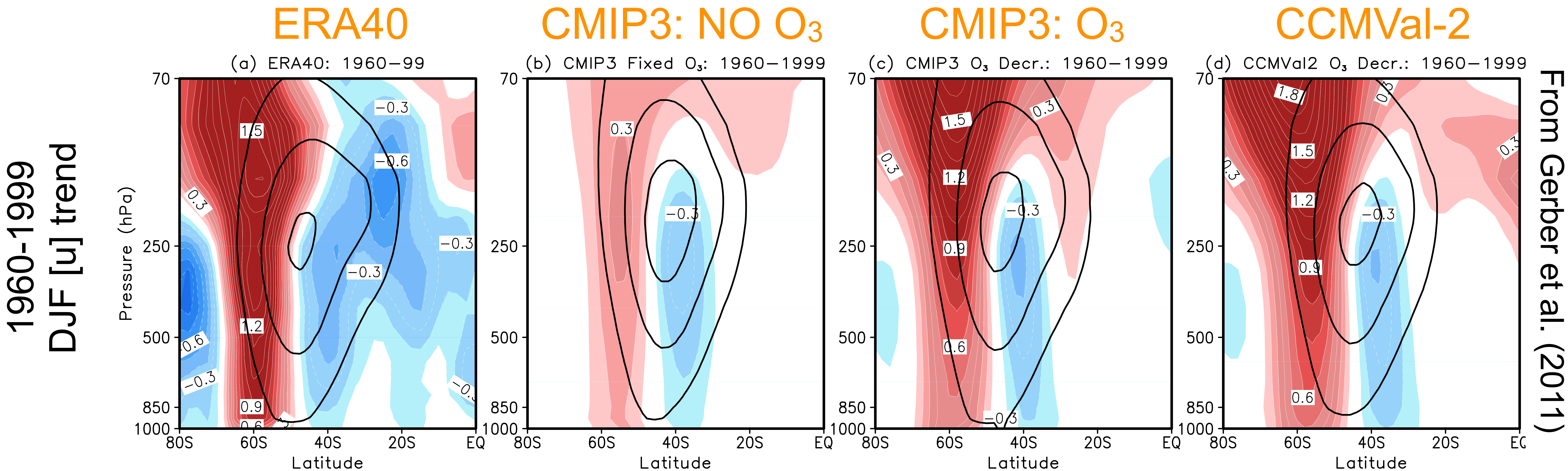

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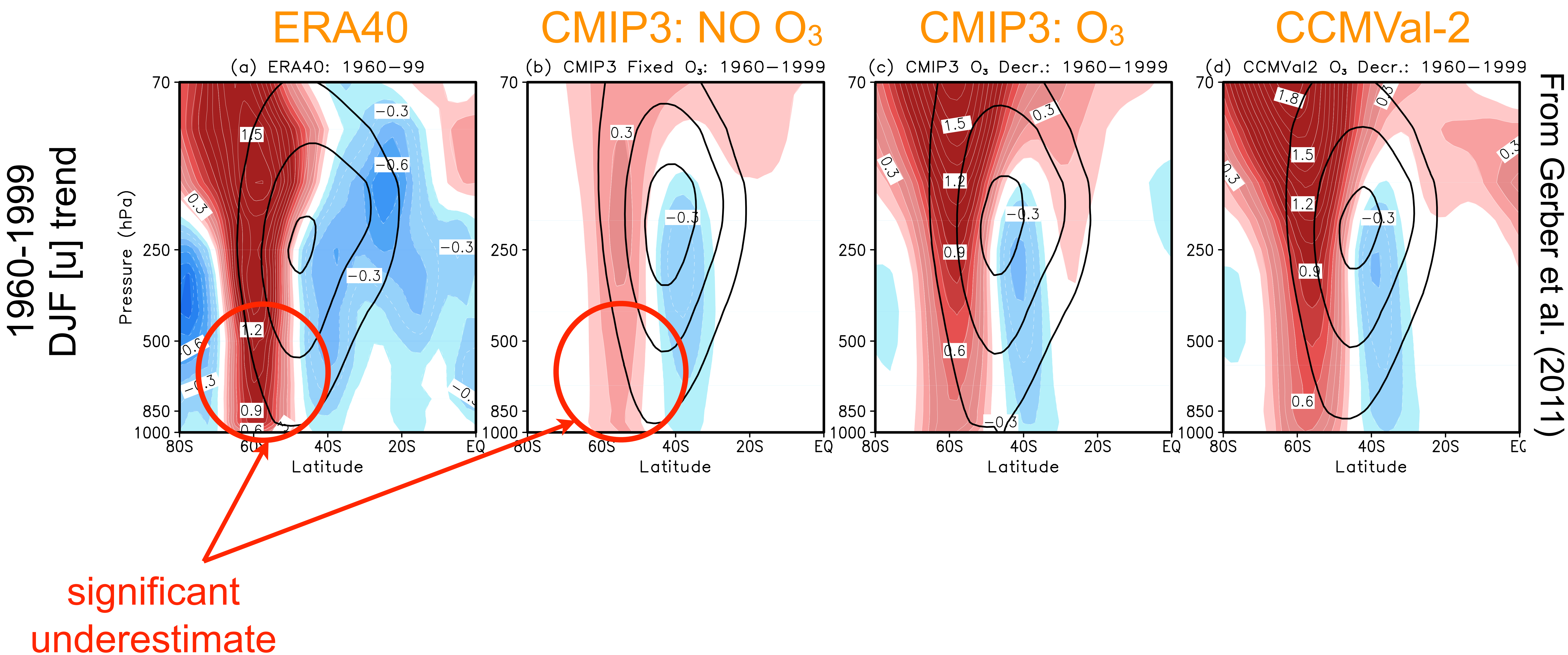

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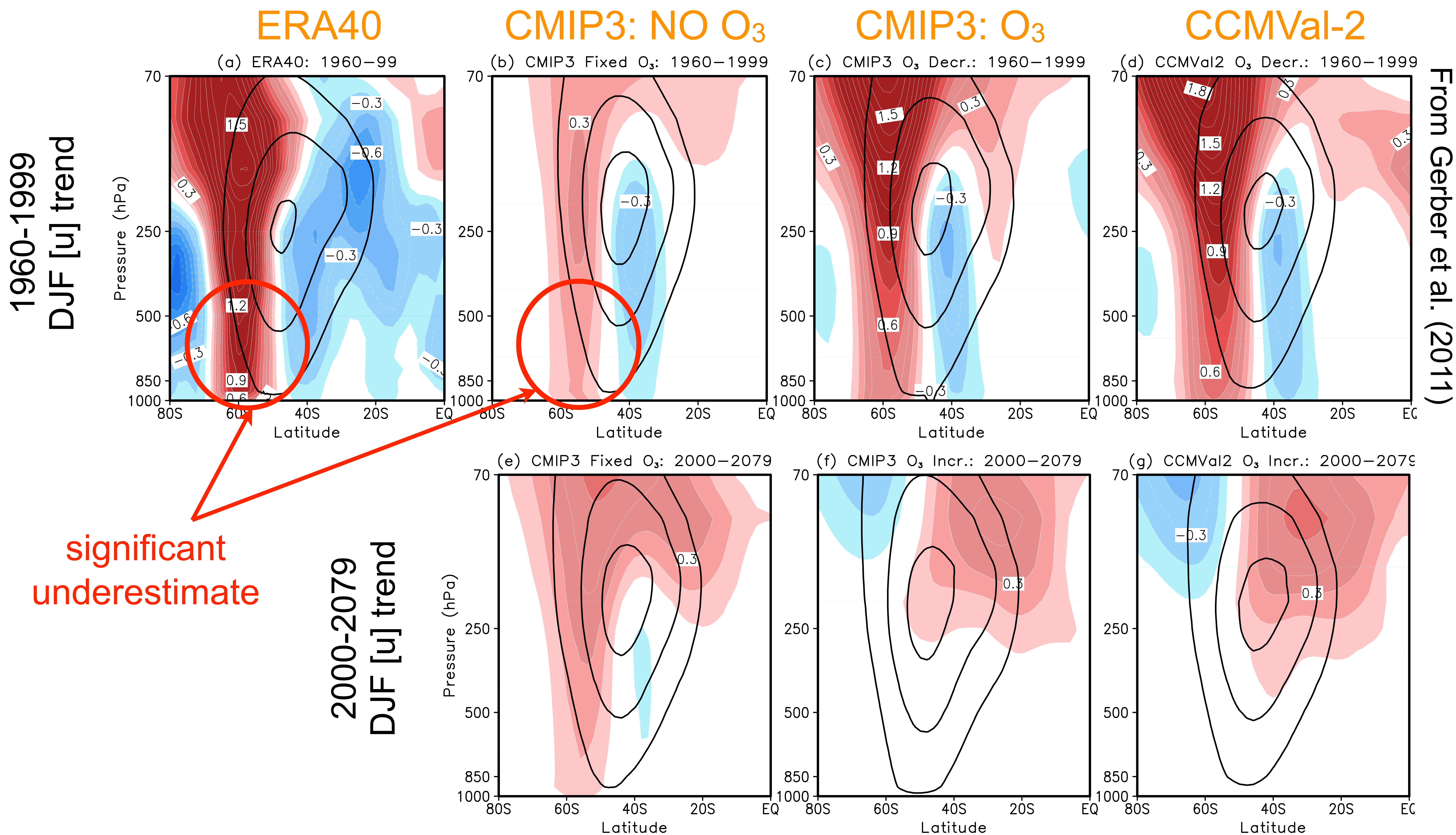

Questions to be Addressed

How does the SH climate systems, from the stratosphere to the surface (and to the Ocean), respond to the ozone hole?

How much important is the ozone hole? Is it comparable to the anthropogenic GHG forcing?

What is the possible mechanism?

Data

a) CMIP3 (IPCC/AR4) data

Model Name	20C3M (1960-1999)	A1B (2000-2079)
CSIRO Mk3.0	2 (Y)	1 (Y)
GFDL CM2.0	3 (Y)	1 (Y)
GFDL CM2.1	3 (Y)	1 (Y)
INGV SXG$^+$	1 (Y)	1 (Y)
MIROC3.2(medres)$^+$	3 (Y)	3 (Y)
MPI ECHAM5/MPI-OM$^+$	4 (Y)	4 (Y)
NCAR CCSM3.0$^+$	8 (Y)	7 (Y)
NCAR PCM1$^+$	4 (Y)	4 (Y)
UKMO HadCM3$^+$	2 (Y)	1 (Y)
UKMO HadGEM1$^+$	2 (Y)	1 (Y)
GISS EH$^+$	5 (Y)	3 (N)
GISS ER$^+$	9 (Y)	5 (N)
BCCR BCM2.0	1 (N)	1 (N)
CCCma CGCM3.1(T63)	1 (N)	1 (N)
CNRM CM3*	1 (N)	1 (N)
GISS AOM	2 (N)	2 (N)
IAP FGOALS-g1.0	3 (N)	3 (N)
INM CM3.0	1 (N)	1 (N)
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- Others simply used **climatological ozone** for the past and future climate integrations.
- Spatio-temporal distribution of stratospheric **ozone is NOT archived and NOT even documented** well.

Data (Cont.)

b) SPARC/CCMVal-2 data

Model Name	REF-B1 (1960-1999)	REF-B2 (2000-2079)	References
AMTRAC3	1		*Austin and Wilson* [2010]
CAM3.5	1	1	*Lamarque et al.* [2008]
CCSRNIES	1	1	*Akiyoshi et al.* [2009]
CMAM	3	3	*Scinocca et al.* [2008], *de Grandpré et al.* [2000]
CNRM-ACM	2	1	*Déqué* [2007], *Teyssédre et al.* [2007]
E39CA	1		*Stenke et al.* [2009], *Garny et al.* [2009]
EMAC	1		*Jöckel et al.* [2006]
GEOSCCM	1	1	*Pawson et al.* [2008]
LMDZrepro	3		*Jourdain et al.* [2008]
MRI	4	2	*Shibata and Deushi* [2008a, b]
Niwa-SOCOL	1		*Schraner et al.* [2008], *Egorova et al.* [2005]
SOCOL	3	3	*Schraner et al.* [2008]
UMETRAC	1		*Austin and Butchart* [2003]
UMSLIMCAT	1	1	*Tian and Chipperfield* [2005], *Tian et al.* [2006]
UMUKCA-METO	1	1	*Morgenstern et al.* [2008, 2009]
UMUKCA-UCAM	1		*Morgenstern et al.* [2008, 2009]
WACCM	4	3	*Garcia et al.* [2007]

- Stratospheric **ozone chemistry is fully interactive** with circulations.

Methods

CMIP3

20C3M runs with ozone depletion (1960-1999): 12 models
20C3M runs with no ozone depletion (1960-1999): 8 models
A1B scenario runs with no ozone recovery (2000-2079): 10 models
A1B scenario runs with ozone recovery (2000-2079): 10 models

CCMVal-2

REF-B1 runs with ozone depletion (1960-1999): 17 models
REF-B2 runs with ozone recovery (2000-2079): 10 models

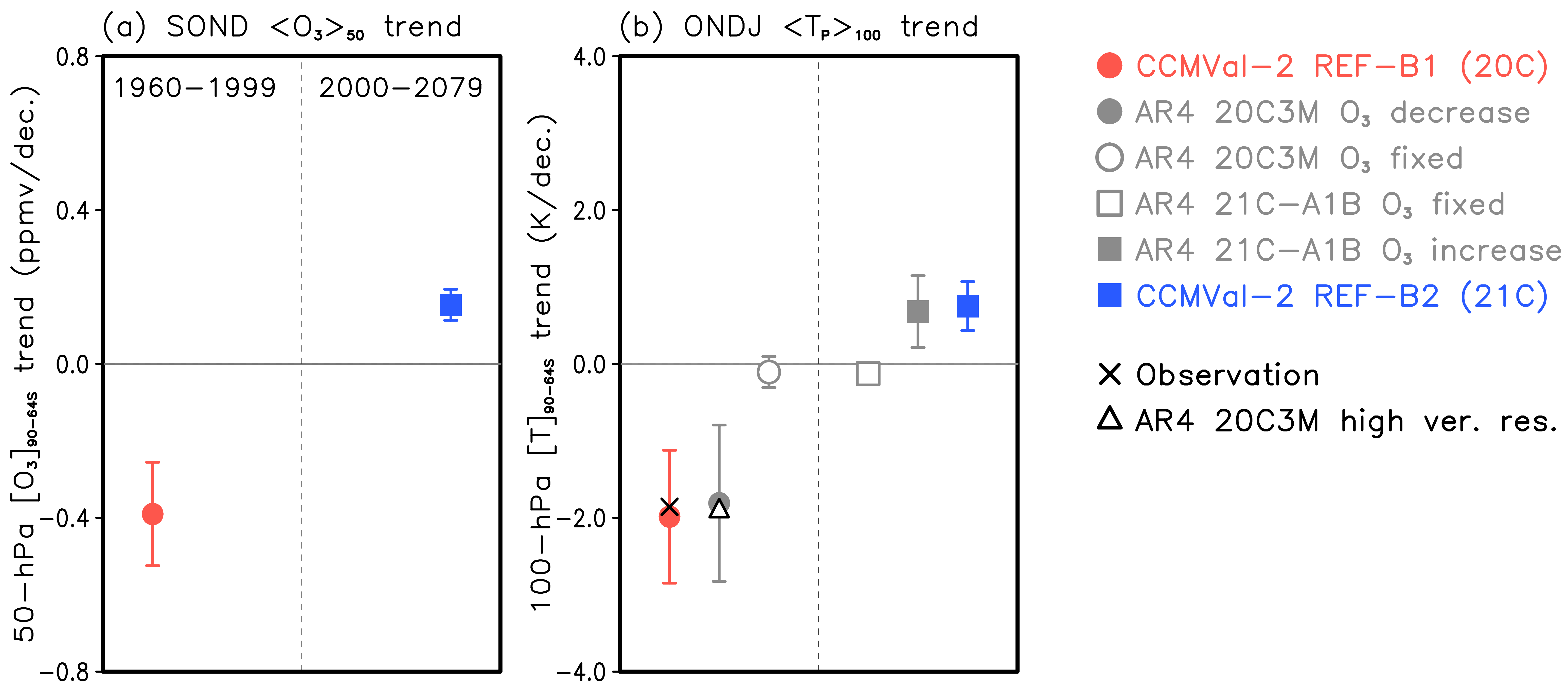
Multi-model Averaging and Intercomparison

Methods (Cont.)

- For all variables of interest, ***linear trends*** are computed using least square fit for the time periods of ***1960-1999*** and ***2000-2079*** *(or 2000-2049)*.
- Results are primarily shown for ***December-February*** when ozone impact is maximum.

Acronym	Content
$\langle O_3 \rangle_{50}$	Polar-cap $[O_3]$ at 50 hPa integrated south of 64°S
$\langle T_P \rangle_{100}$	Polar-cap [T] at 100 hPa integrated south of 64°S
$\langle p_{trp} \rangle$	Extratropical zonal-mean tropopause pressure integrated south of 50°S
$[u]_{max}$	Jet strength defined by maximum [u] at 850 hPa
$[u]_{lat}$	Jet location defined by location of maximum [u] at 850 hPa
$[H]_{lat}$	Location of the Hadley-cell boundary defined by zero $[\Psi]$ at 500 hPa

Strato. Trend: ONDJ [T]100hPa (<64°S)



- Both **CMIP3 and CCMVal-2 models show similar temperature trends** at 100 hPa over Antarctica: i.e., **significant cooling (warming) in response to ozone depletion (recovery).**
- Simulated cooling is **quantitatively similar to the observations**.

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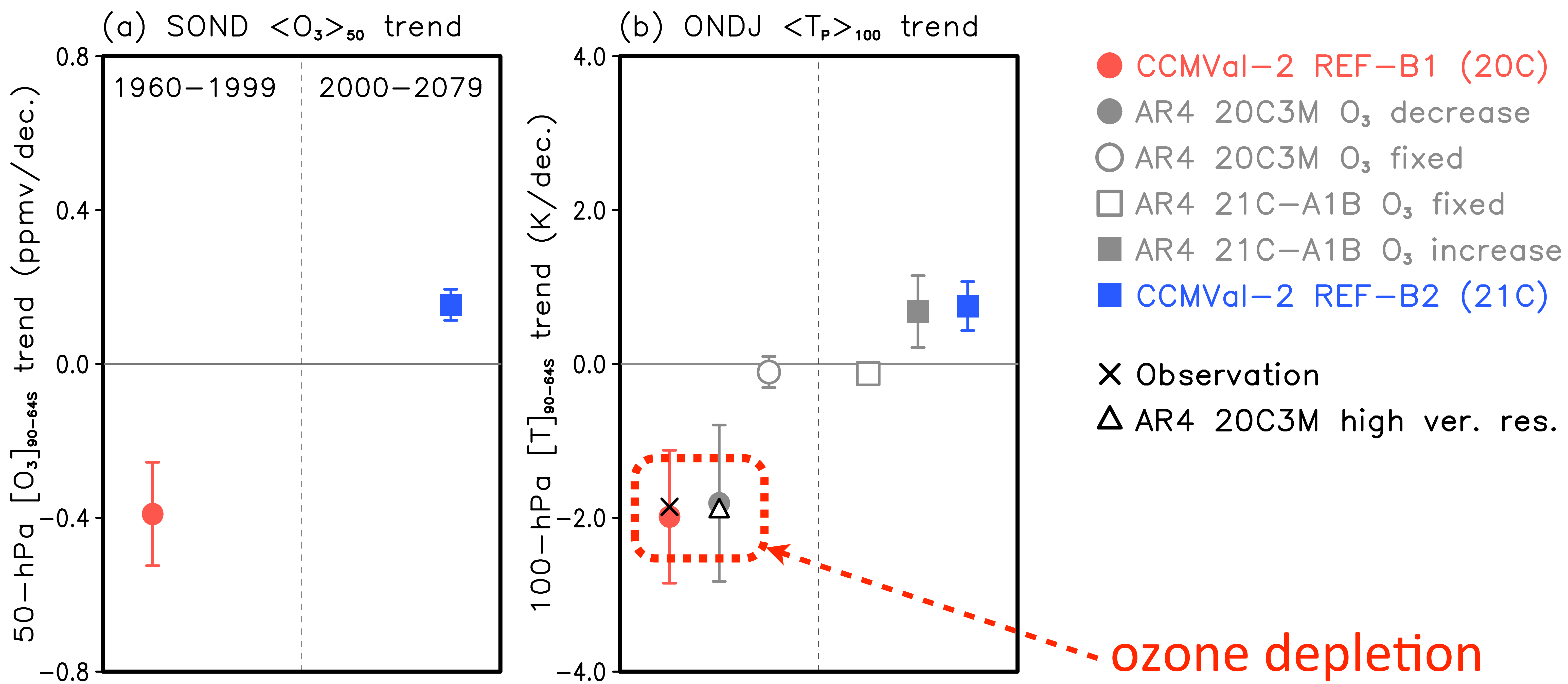

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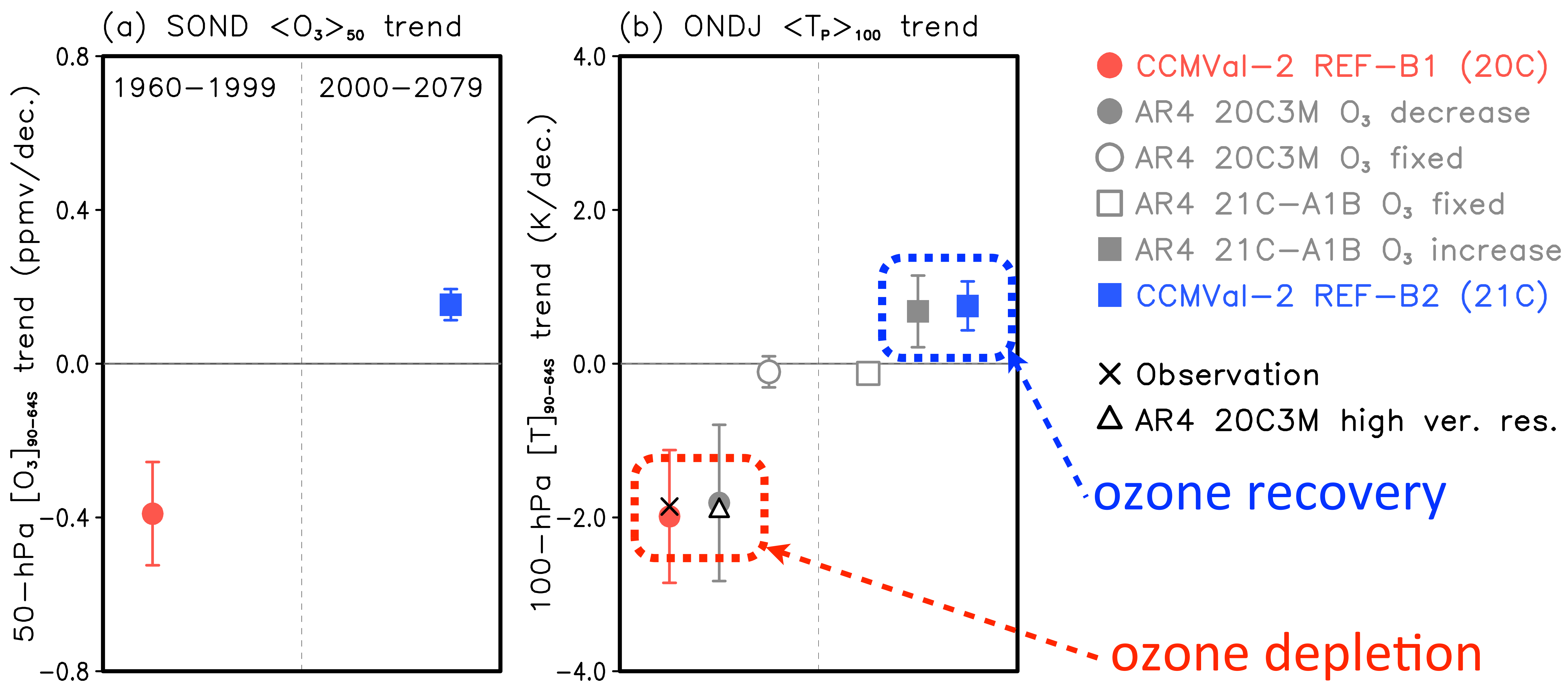

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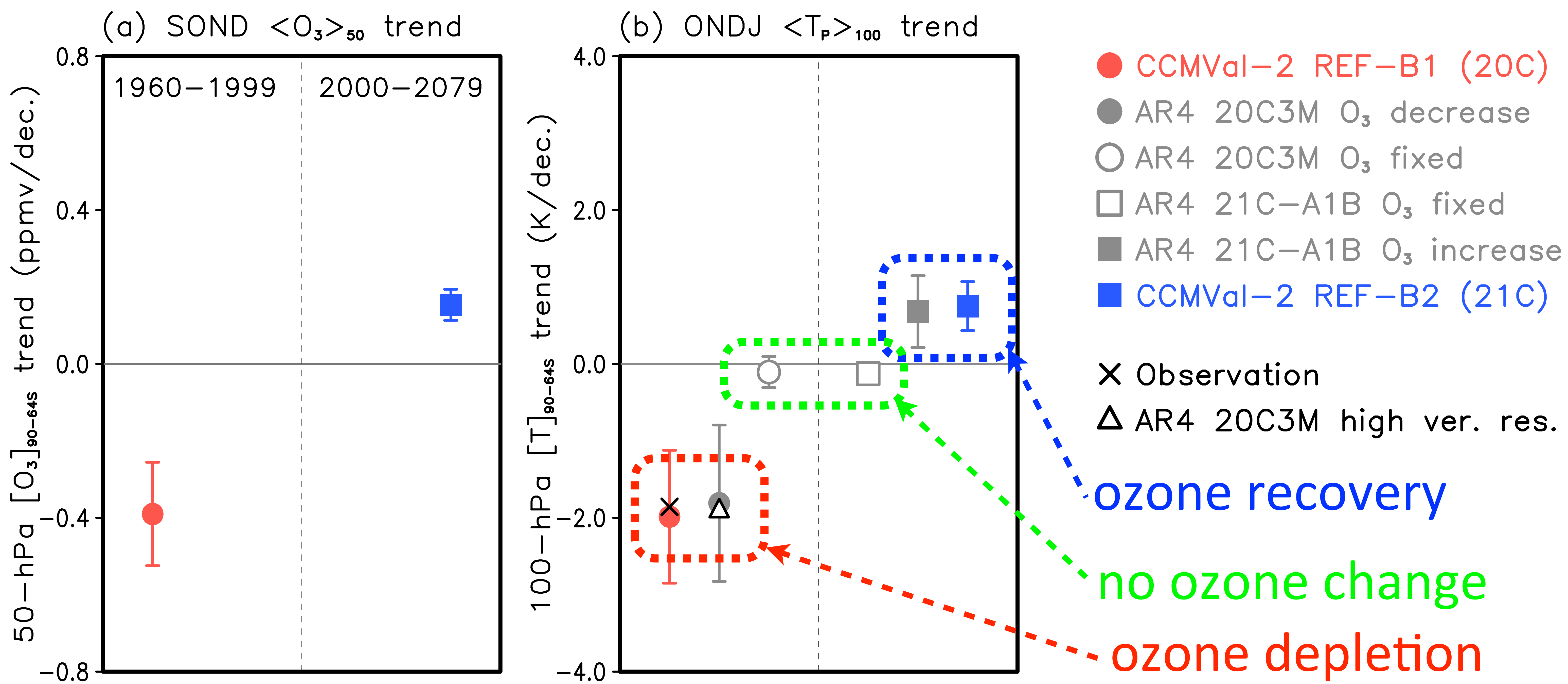

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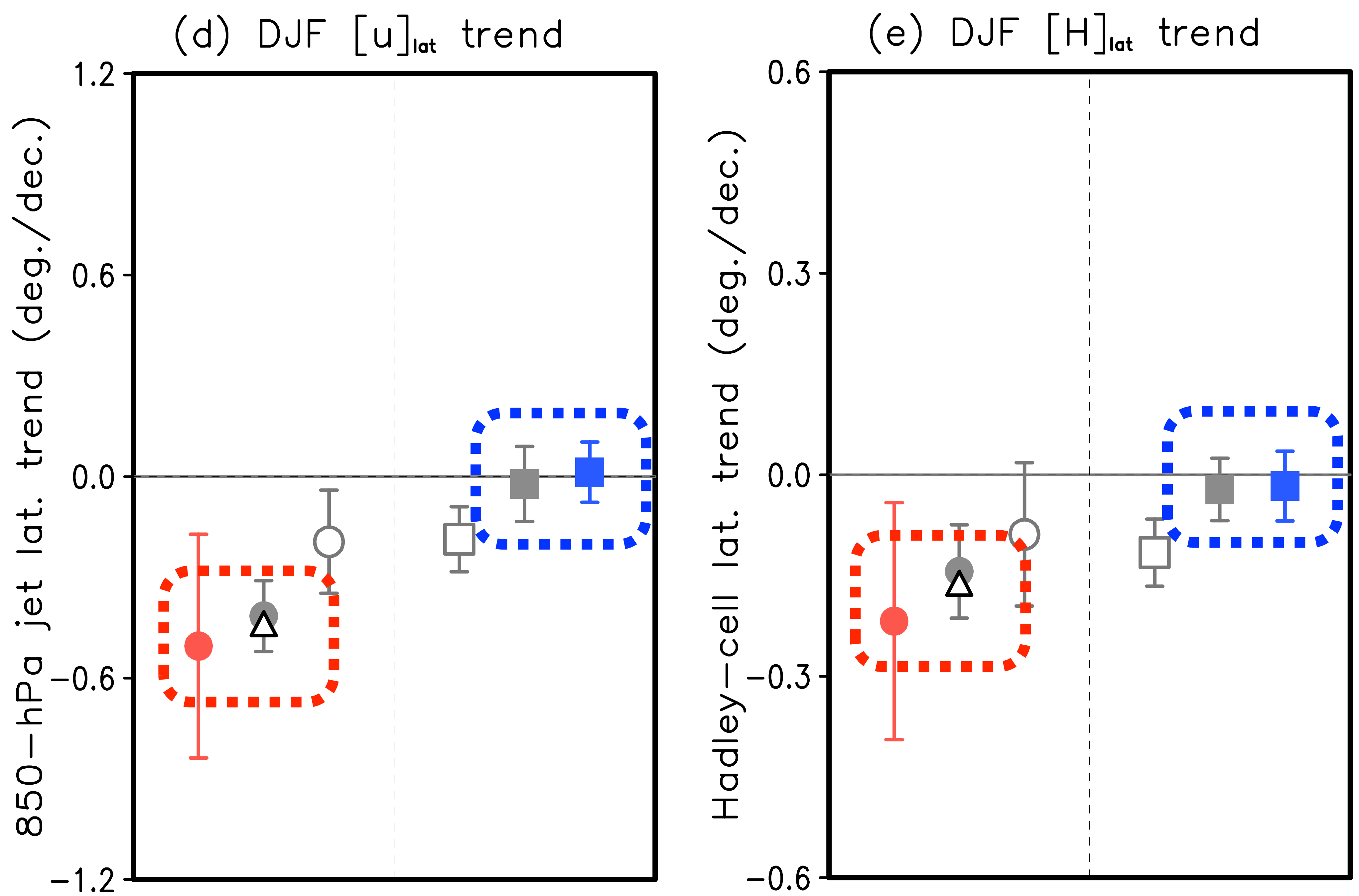
Tropo. Trend: DJF SH Jet & Hadley Cell

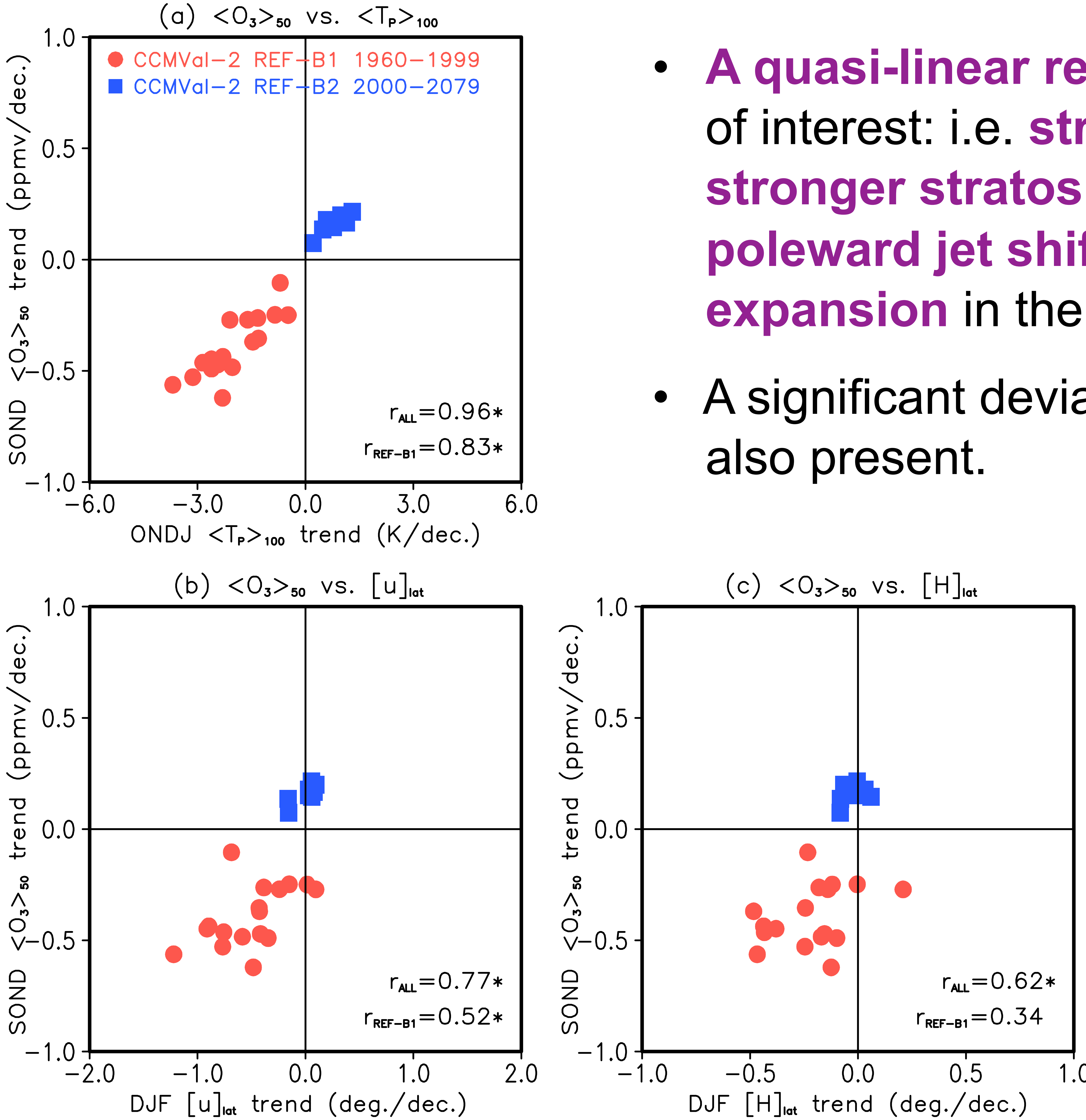


Negative trend: poleward displacement of the SH-summer jet or poleward expansion of the SH-summer Hadley cell boundary

- The extratropical jet and subtropical Hadley-cell boundary have **shifted poleward in response to ozone depletion**. This change is **comparable to the one associated with anthropogenic warming**.
- Both jet location and Hadley-cell boundary are predicted **not to change in the future** due to large cancellation between anthropogenic warming and ozone recovery effects.

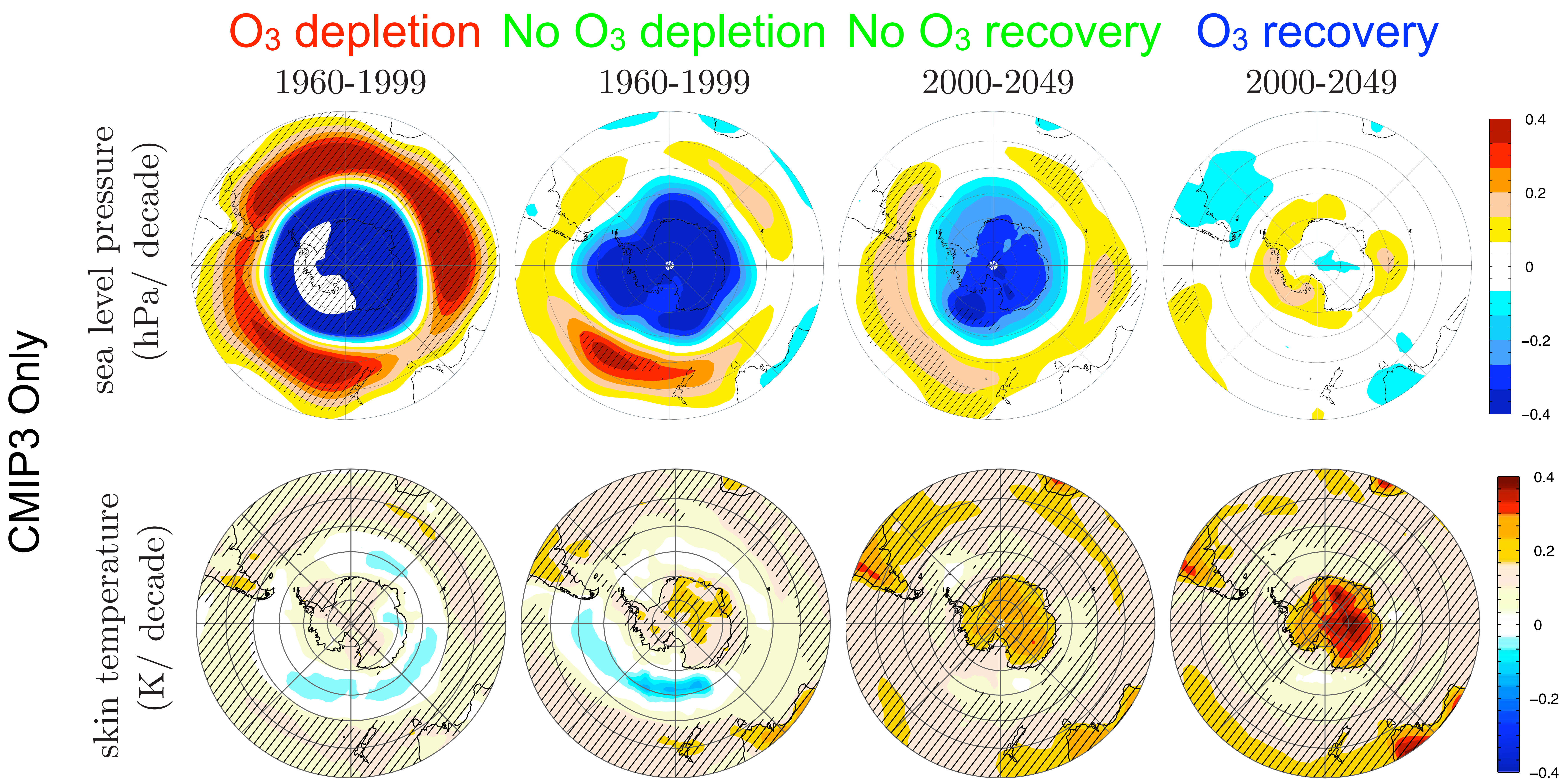
Tropo. Trend: DJF Trend Relationship

CCMVal-2 Only



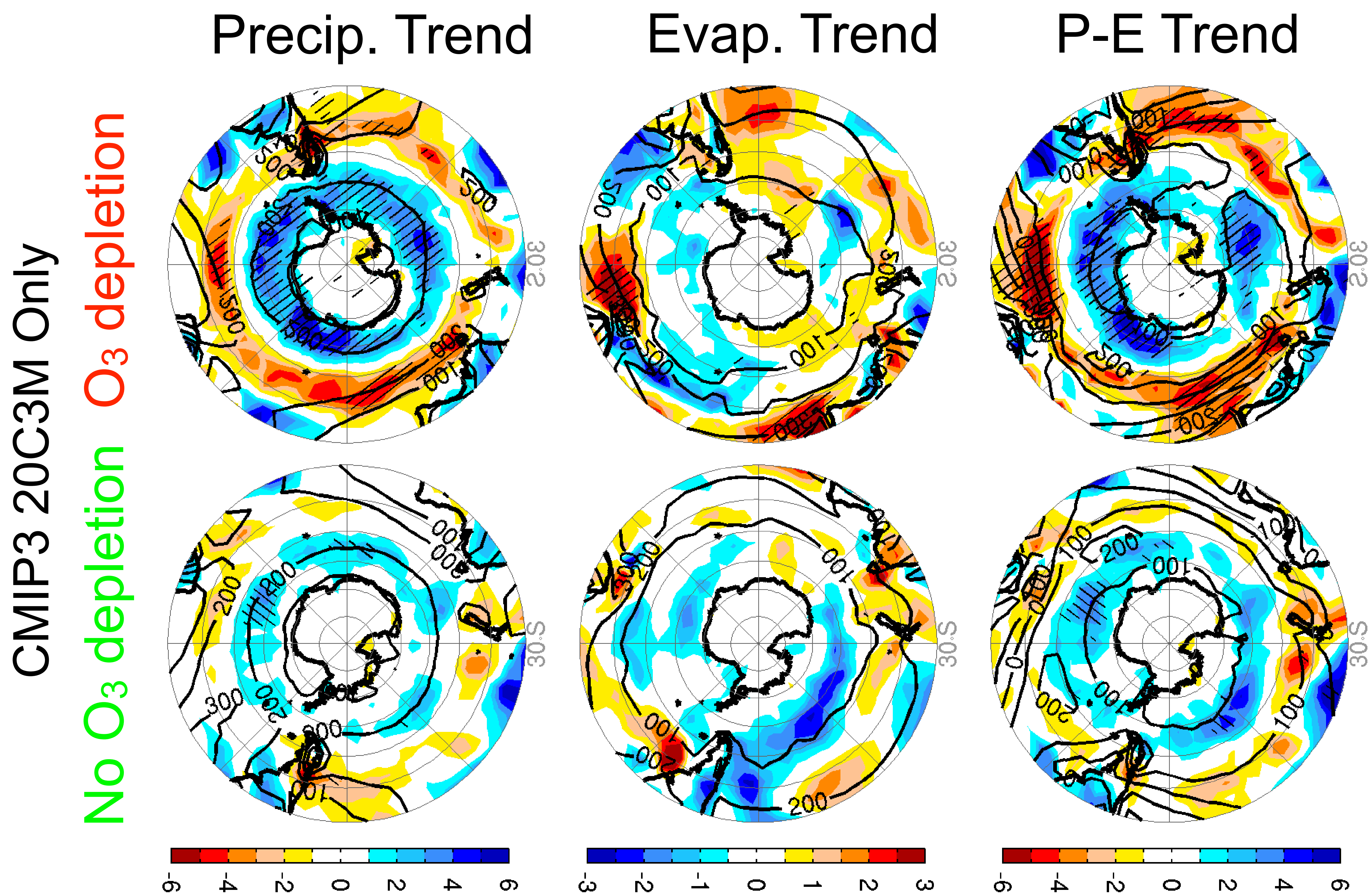
- **A quasi-linear relationship** is found in all variables of interest: i.e. **stronger ozone depletion** results in **stronger stratospheric cooling, stronger poleward jet shift** and **stronger Hadley-cell expansion** in the SH summer.
- A significant deviation from the linearity, however, is also present.

Surface Trend: DJF SLP & Temp



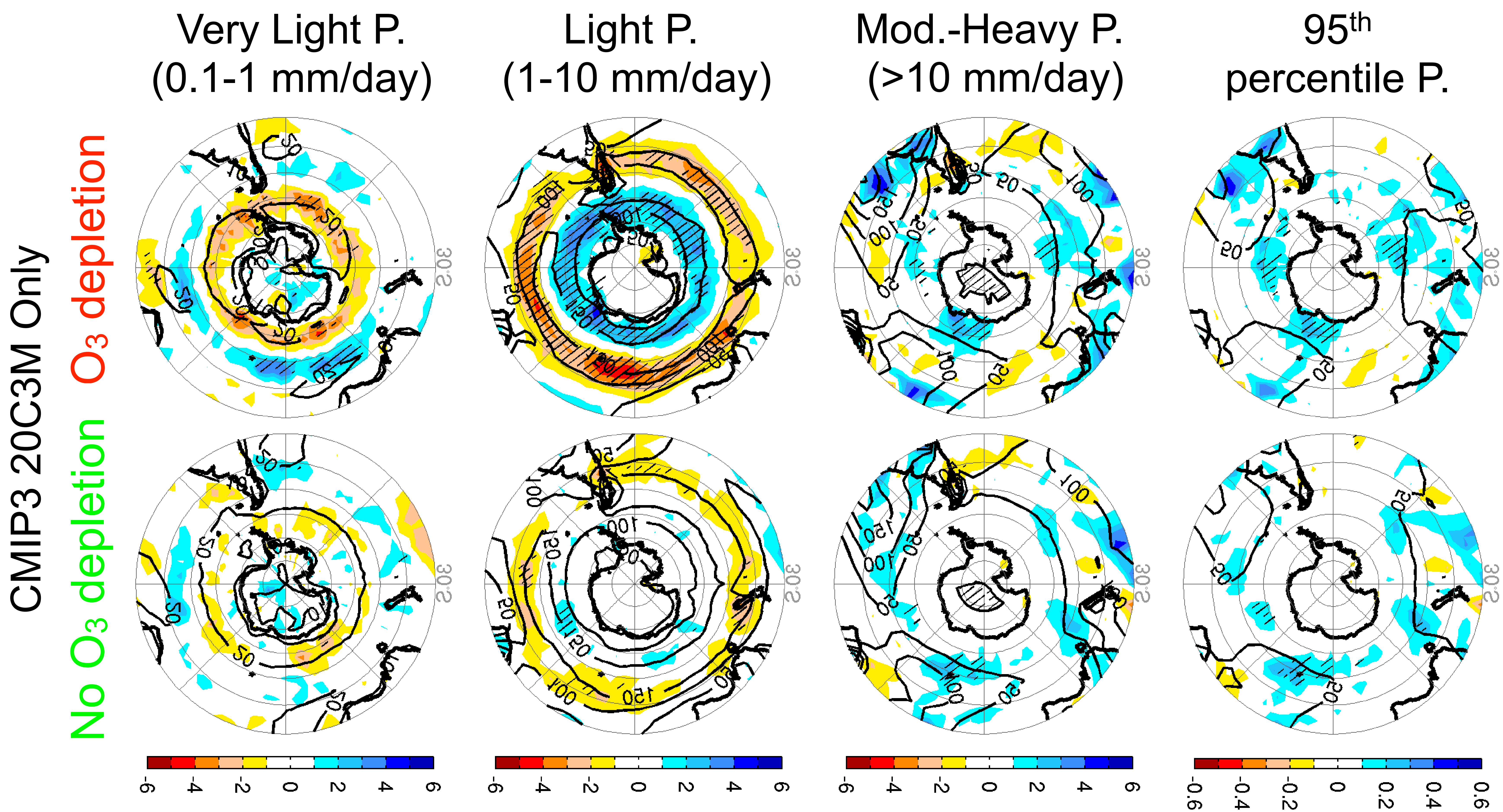
- In general **Ozone depletion strengthens SAM-like SLP trend but weakens Antarctic surface warming**. The opposite is largely true for ozone recovery.

Surface Trend: DJF Precip. (P) & Evap. (E)



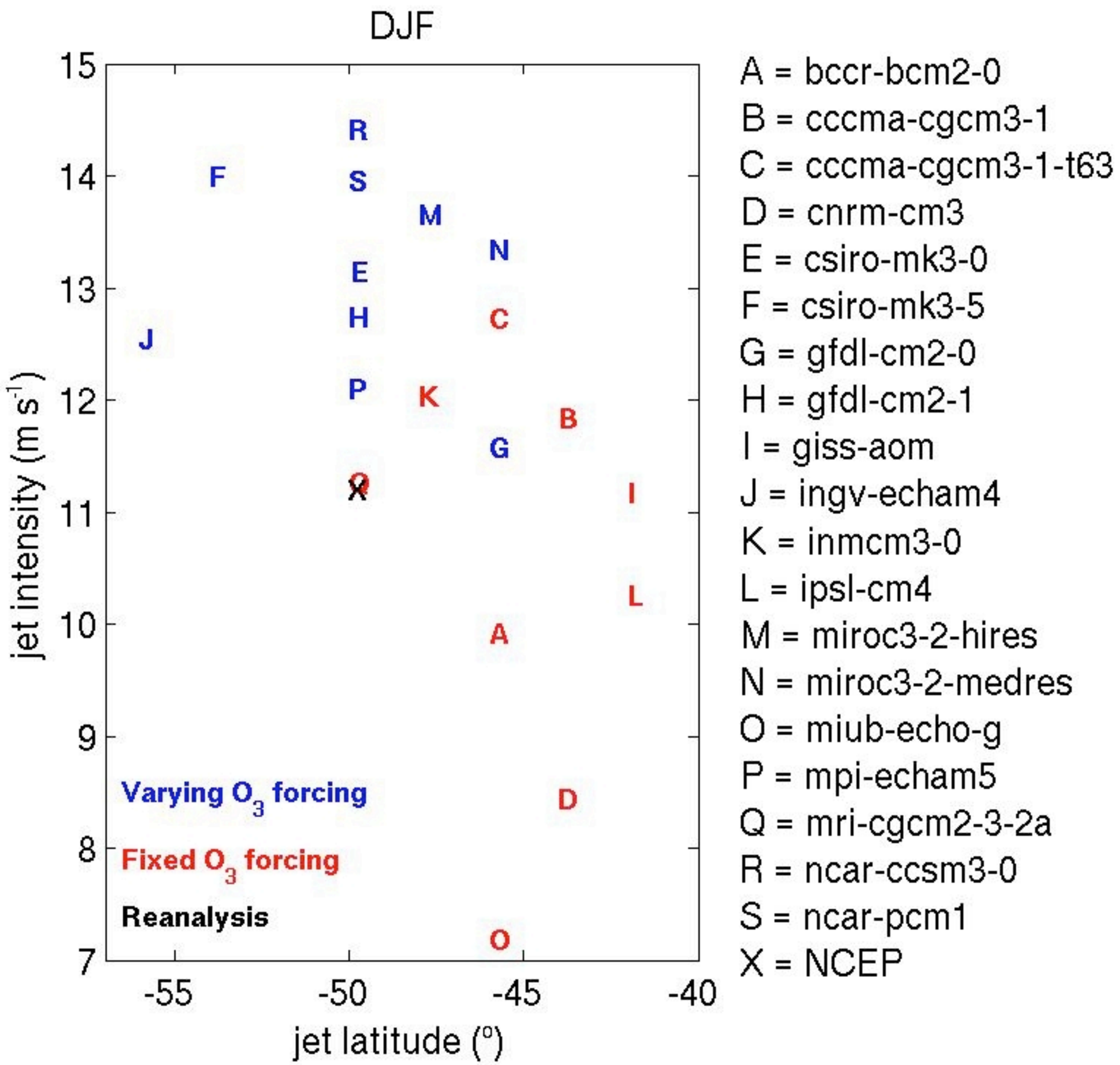
- Trends are estimated with decadal difference: 1990's-1960's. Unit is mm/ season/ decade.
- **P-E trends are dominated by precipitation trends.** This result suggests that **Antarctic ozone hole has likely helped freshening of the Southern Ocean** in the recent past.

Surface Trend: DJF Extreme Precip.



- Precipitation trends are **dominated by light precipitation**; **no noticeable change in extreme precipitation**. Unit is mm/ season/ decade.

Surface Trend: Revised Analysis

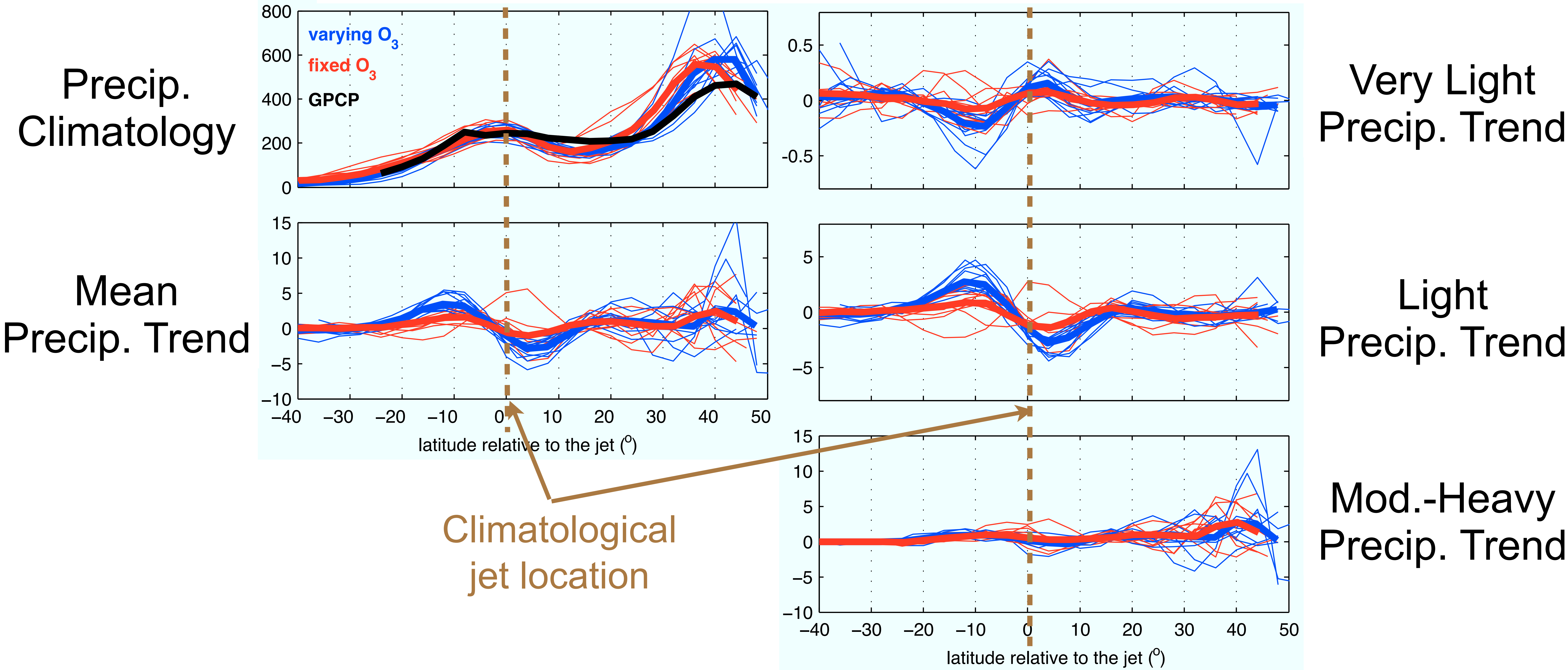


- Individual models show significant difference in climatology.

- **Multi-model average should take this difference into account**. Simple average could result in average of wet (poleward side of the jet) and dry regions (equatorward side of the jet), misleading ozone-related precipitation change.

Surface Trend: DJF Zonal-Mean Precip.

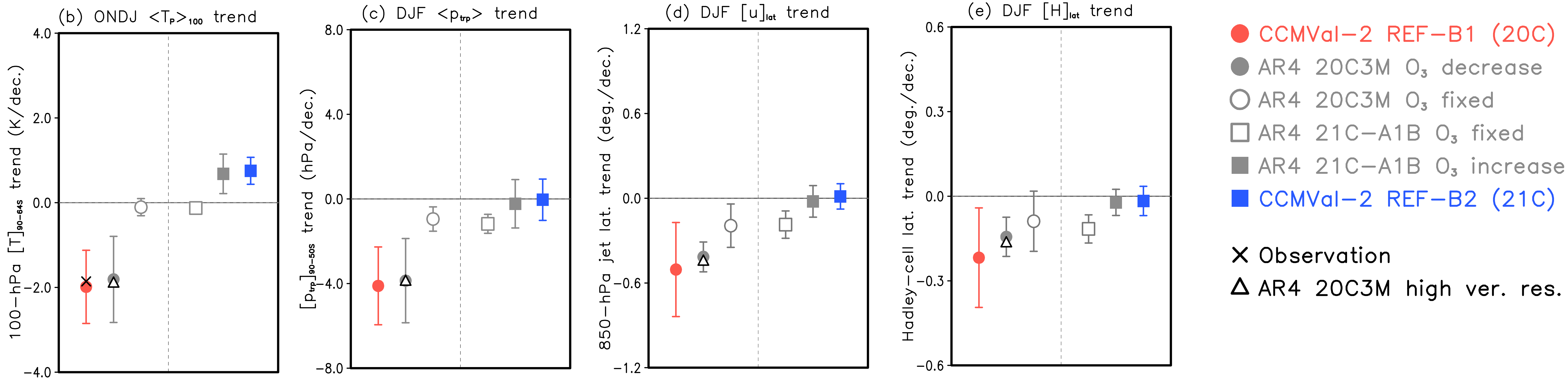
Multi-Model Average w.r.t. Climatological Jet



- Multi-model average with respect to climatological jet confirms that **ozone hole affects mean precipitation trend by modifying light precipitation trend**. No significant impact on extreme precipitation is found.

Summary: DJF vs. JJA Trends

DJF



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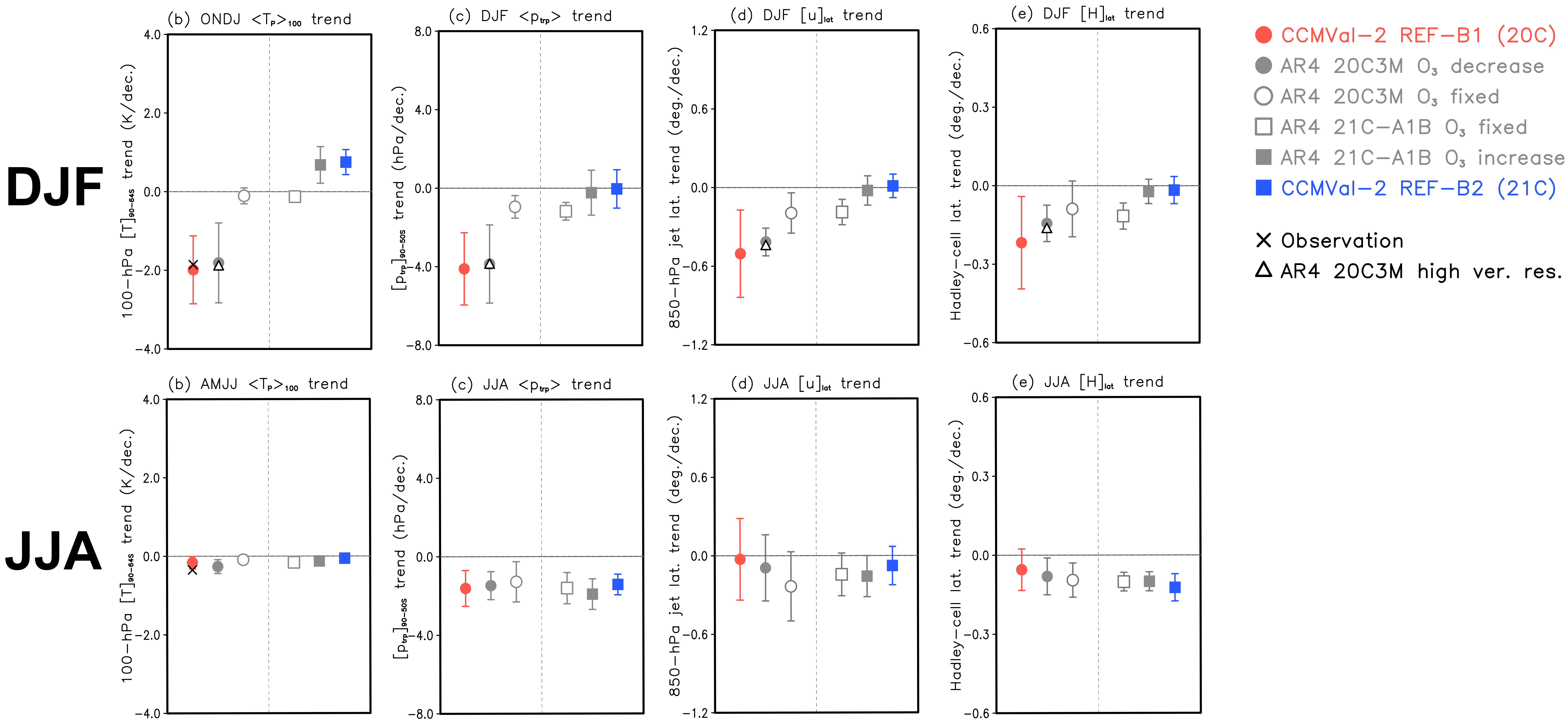


- **No systematic variation in JJA when stratospheric ozone is inactive**. This indicates that systematic difference in DJF climate change by Antarctic ozone forcing is indeed caused by ozone forcing rather than model bias or other forcings.

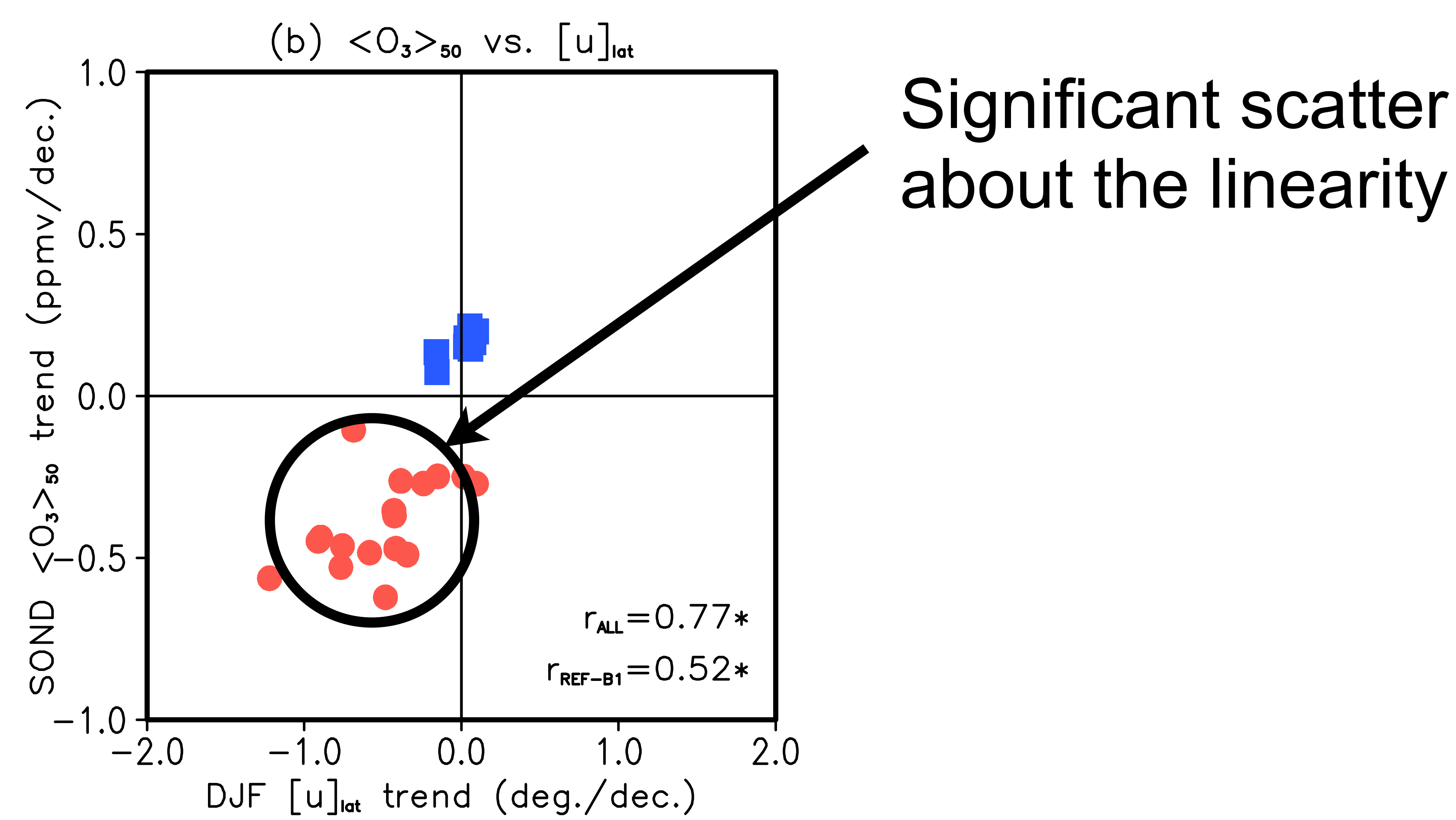
Mechanism(s)

How does the ozone hole influence tropospheric circulation and surface climate?

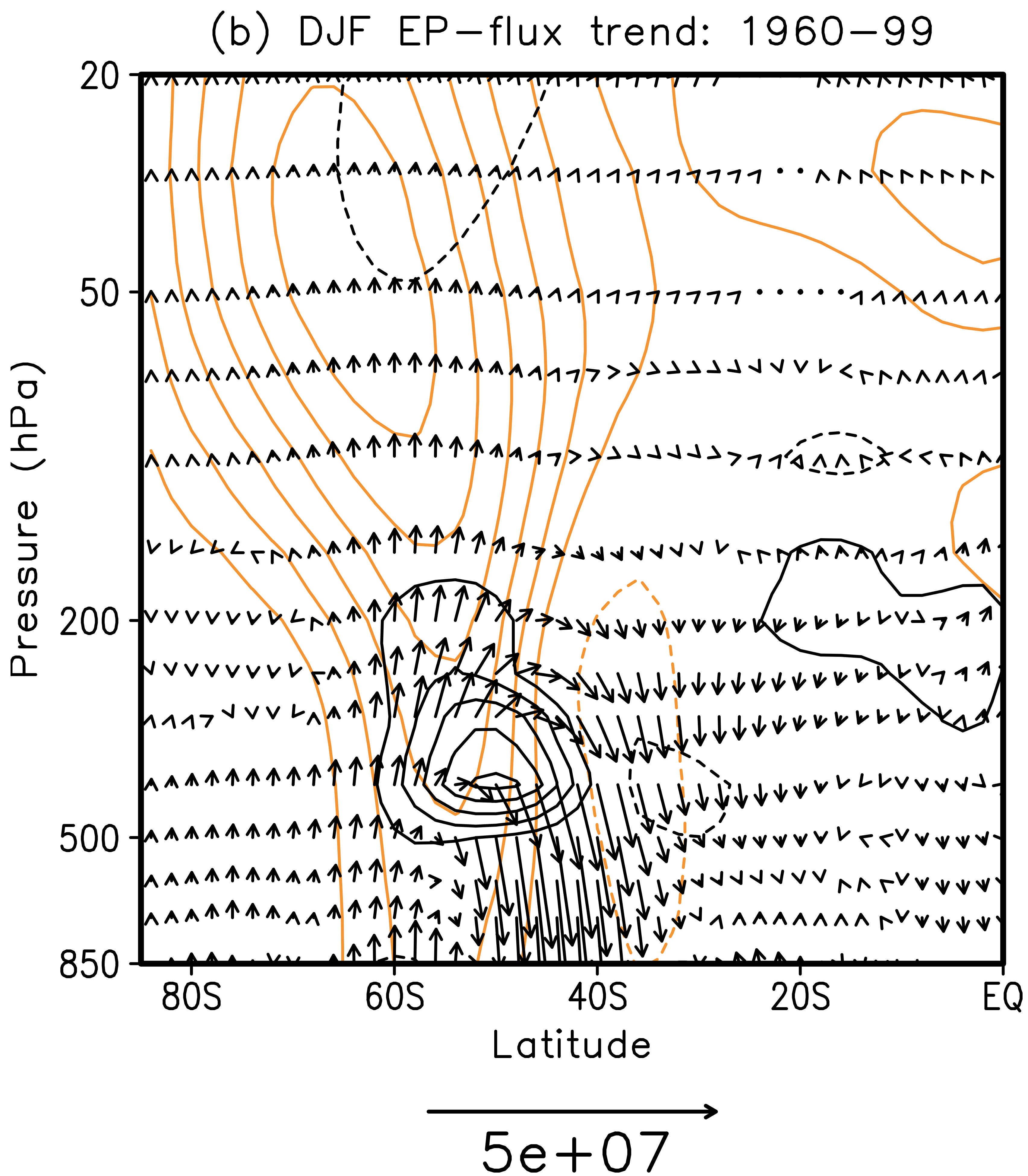
Mechanism(s)

How does the ozone hole influence tropospheric circulation and surface climate?

Why does tropospheric response to a given ozone forcing "quantitatively" differ among the models?



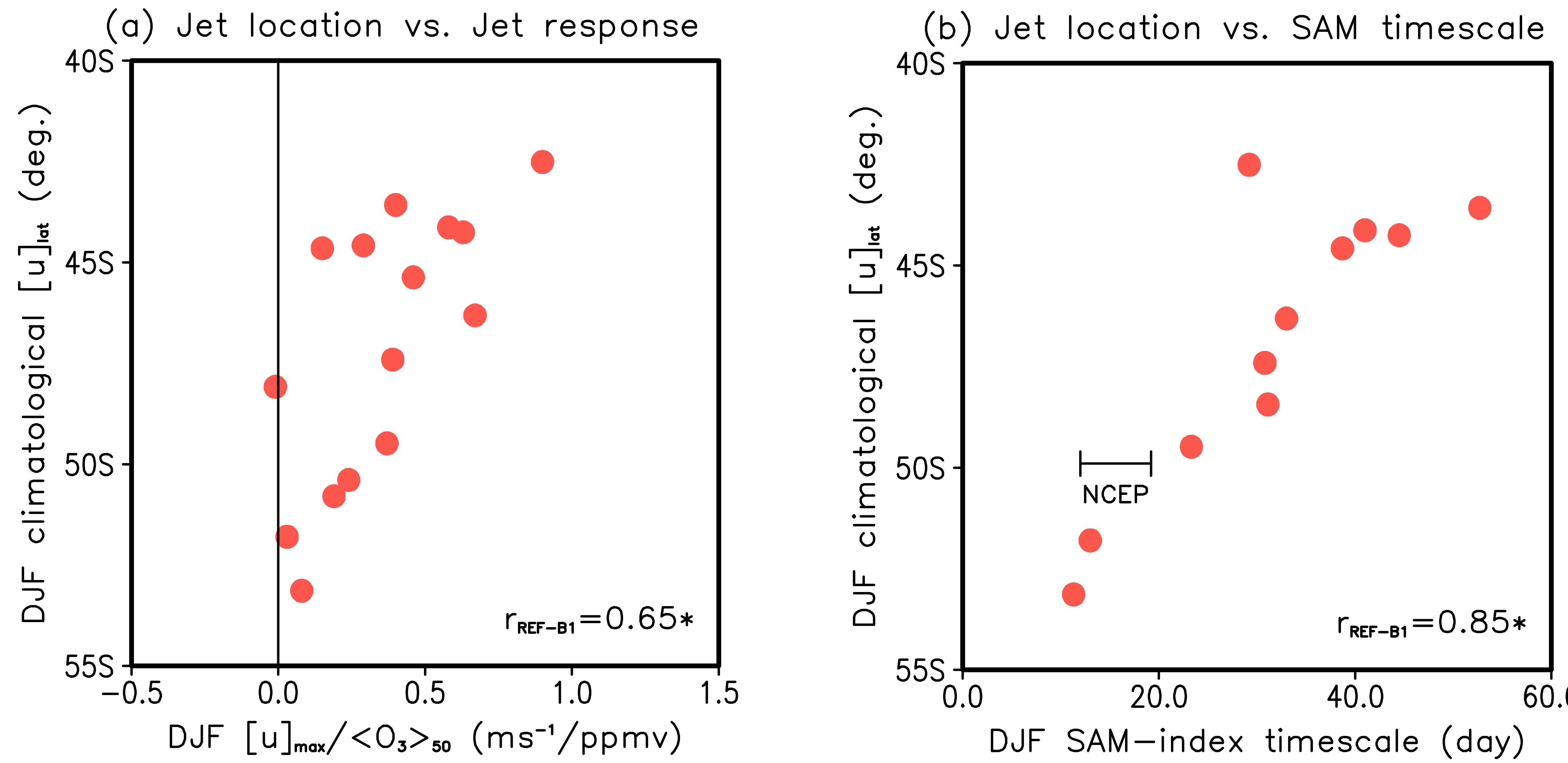
Ozone-related Climate Change



Orange: [u] trend
Black: EP flux div trend

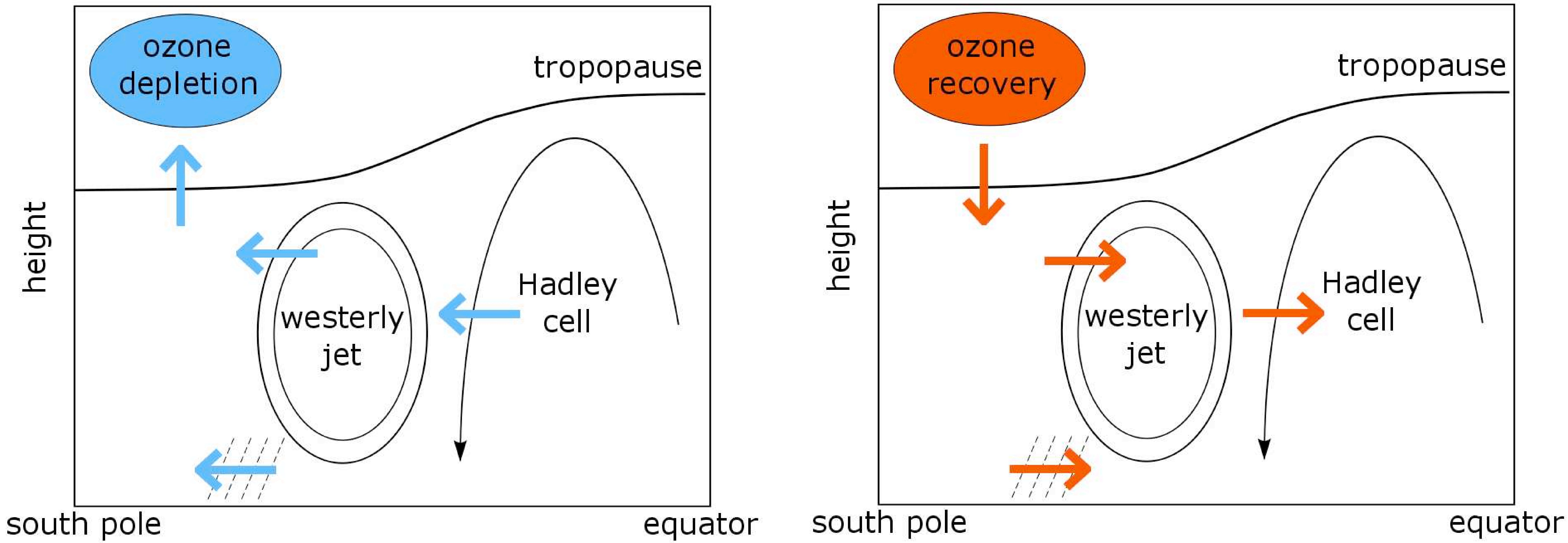
- **Radiative forcing - ozone-induced long wave cooling** (Grise et al. 2009): Unlikely, as polar-cap cooling in the troposphere is negligible in CCMVal-2 past climate simulations.
- **Downward control** (and its amplification in the troposphere via eddy feedback): Unlikely, as wave drag in the stratosphere would result in surface easterly instead of westerly in CCMVal-2 past climate simulations.
- **Eddy-mean flow interaction - changes in phase speed** (Chen and Held, 2007) or **propagating direction of baroclinic waves** (Simpson et al., 2009): Questionable.
- **Need further studies**

Different Response Among the Models



- **Scatter is partly associated with model climatology which differs among the models.**
- **Tropospheric response is weaker if climatological jet is located in higher latitudes.** This is associated with time scale of internal variability (e.g., SAM index).
- Climatological jet in a higher latitude ⇒ More chances for waves to see the turning latitude ⇒ Weaker wave breaking ⇒ Weaker wave-mean flow interaction ⇒ Shorter time scale of internal variability (Barnes and Hartmann, 2010)

Summary and Discussion



- Stratospheric ozone affects the entire climate systems in the SH summer, from the polar regions to the subtropics, and from the stratosphere to the surface and possibly to the ocean. This result is confirmed by attribution studies for individual components of the SH climate system (e.g., Arblaster and Meehl, 2006; Perlwitz et al. 2008; Polvani et al. 2011; McLandress et al. 2011).

Summary and Discussion

- Stratospheric ozone depletion (recovery) generally strengthens (weakens) SH-summer climate change driven by anthropogenic GHGs increase. Exceptions are Antarctic surface temperature trends (opposite impact) and extreme precipitation trends (no impact). Quantitatively the impact of stratospheric ozone forcing is at least comparable to that of GHGs in the SH summer. As such, recent climate changes in the SH will likely be substantially weakened in the future due to the anticipated recovery of stratospheric ozone.

- Similar results between CMIP3 and CCMVal-2 models suggest that interactive ozone chemistry may not be crucial for predicting ozone-related climate change. Stratospheric ozone forcing can be prescribed in the model (e.g., CMIP5).

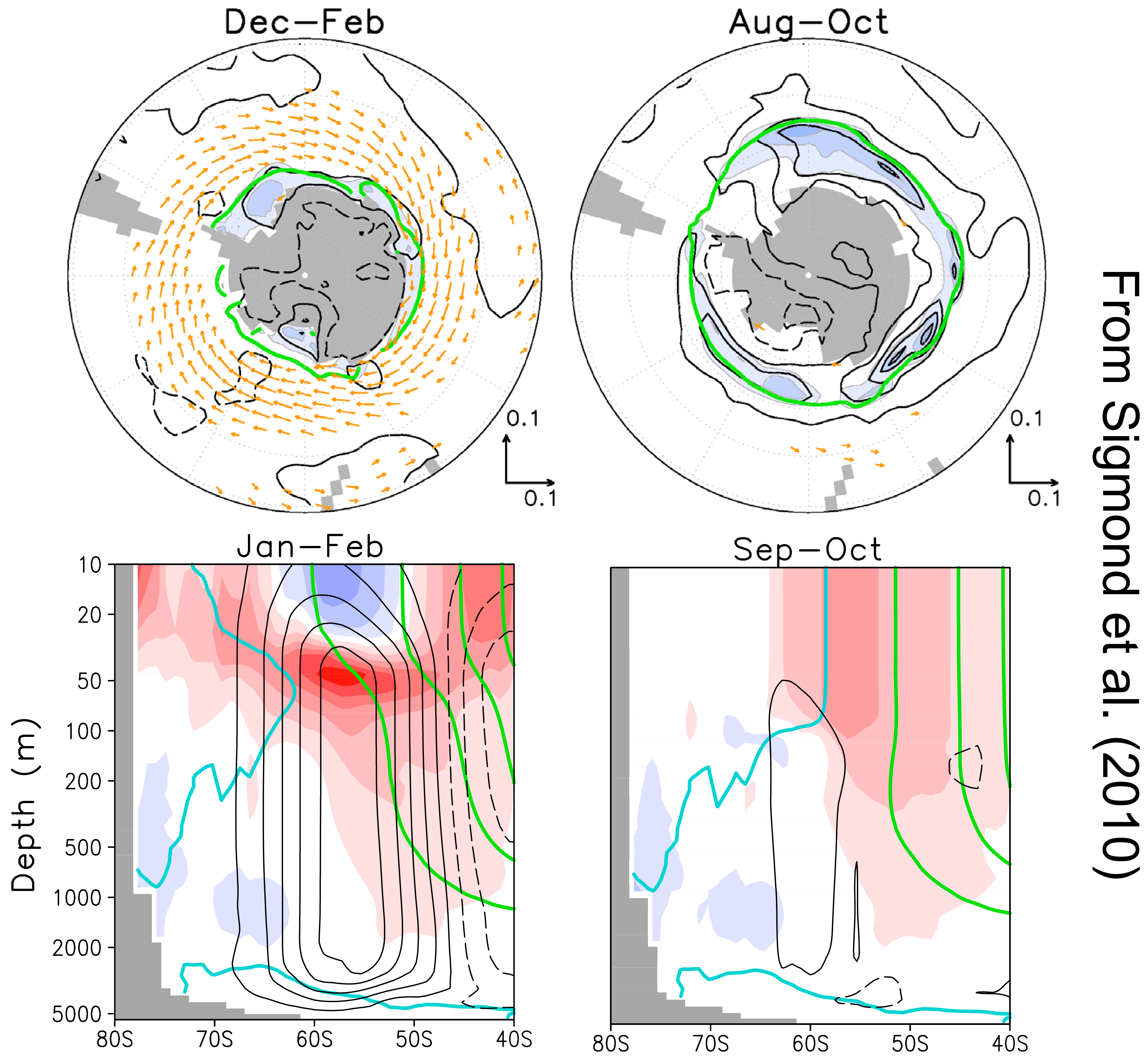
- Extreme precipitation events are insensitive to stratospheric ozone change. Further attribution studies are needed.

- Dynamical mechanism(s) on how stratospheric ozone communicates with tropospheric circulations is still not clear. Further studies are needed.

Summary and Discussion

Any impact on the Southern Ocean and Antarctic Sea Ice?

- Enhanced surface westerly by ozone depletion may strengthen the overturning circulation in the Southern Ocean and modify the upper-ocean temperature and sea ice distribution. While evidences are emerging, further studies are needed.



- Top: green line for climatological sea ice edge, blue shading for sea ice extent decrease, vectors for surface wind acceleration.
- Bottom: black contour for overturning circulation change, shading for ocean warming or cooling, cyan line for zero temperature.

Thanks! Any suggestions or comments are welcome.

Key references

- Son, S.-W., and co-authors, 2009: Stratospheric ozone and Southern Hemisphere climate change, Geophysical Research Letters, 36, L15705.
- Son, S.-W., and co-authors, 2010: The impact of stratospheric ozone on the Southern Hemisphere circulation change: A multimodel assessment, Journal of Geophysical Research - Atmosphere,115, D00M07, doi:10.1029/2010JD014271.
- Purich A., and S.-W. Son, 2011: Impact of Antarctic ozone depletion and recovery on Southern Hemisphere precipitation, evaporation and extreme changes, Journal of Climate, in press.

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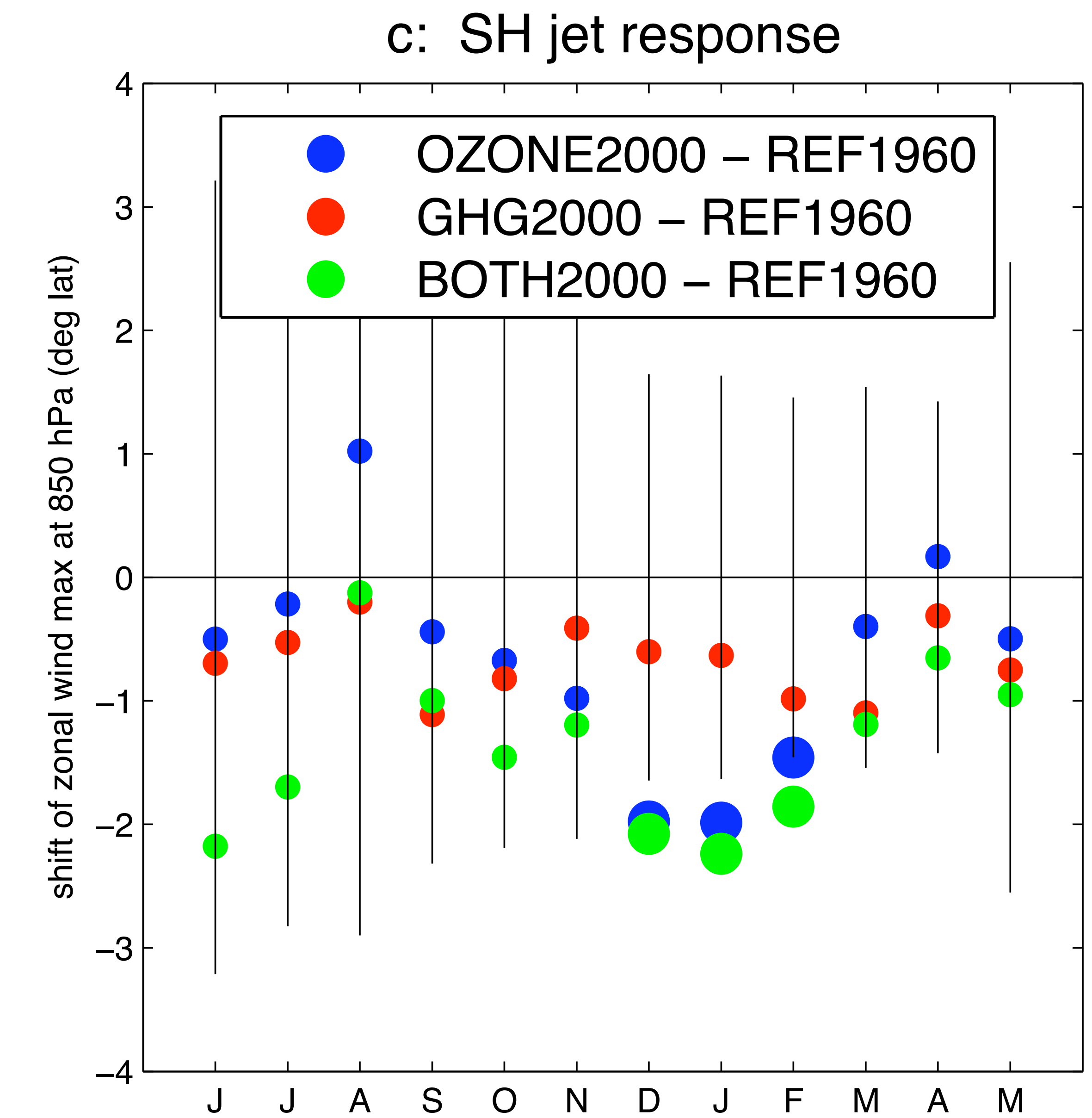
Attribution study: Polvani et al. (2011)

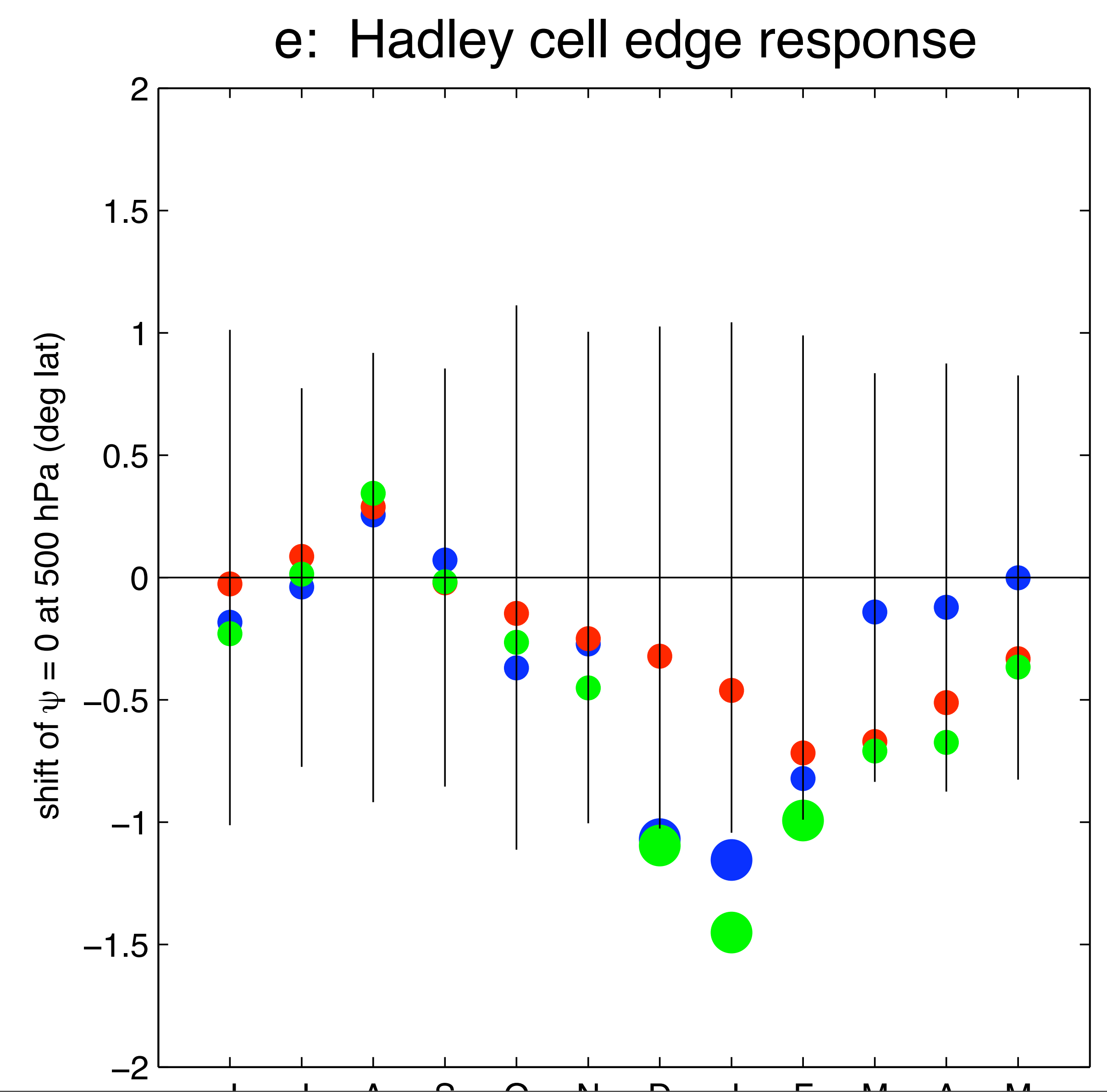
Time-sliced CAM3 runs

40-year change (1960-1999)

model integration	polar cap cooling (K)	tropopause raising (hPa)	midlatitude jet shift (° lat)	Hadley cell edge shift (° lat)
OZONE2000	−8.3	−17.4	−1.9	−1.0
GHG2000	−0.35	−2.3	−0.74	−0.50
BOTH2000	−7.5	−17.3	−2.1	−1.2
CCMVal2	−7.9	−16.4	−2.0	−0.87
CMIP3	−7.2	−15.5	−1.7	−0.58

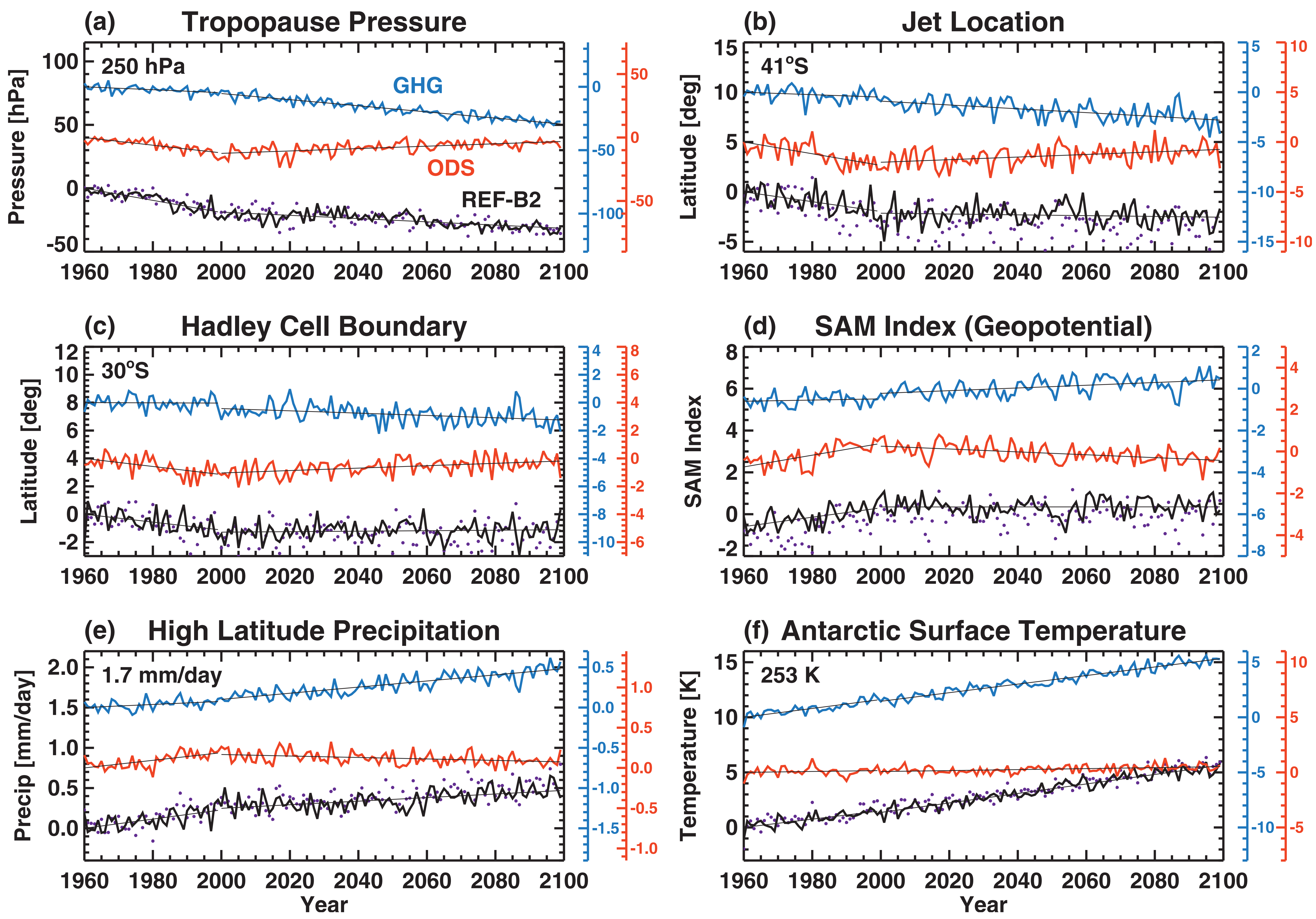
- The AGCM experiments show the consistent results to the CMIP3 and CCMVal-2 models. It confirms the importance of ozone hole in the 20th climate change in the SH summer.





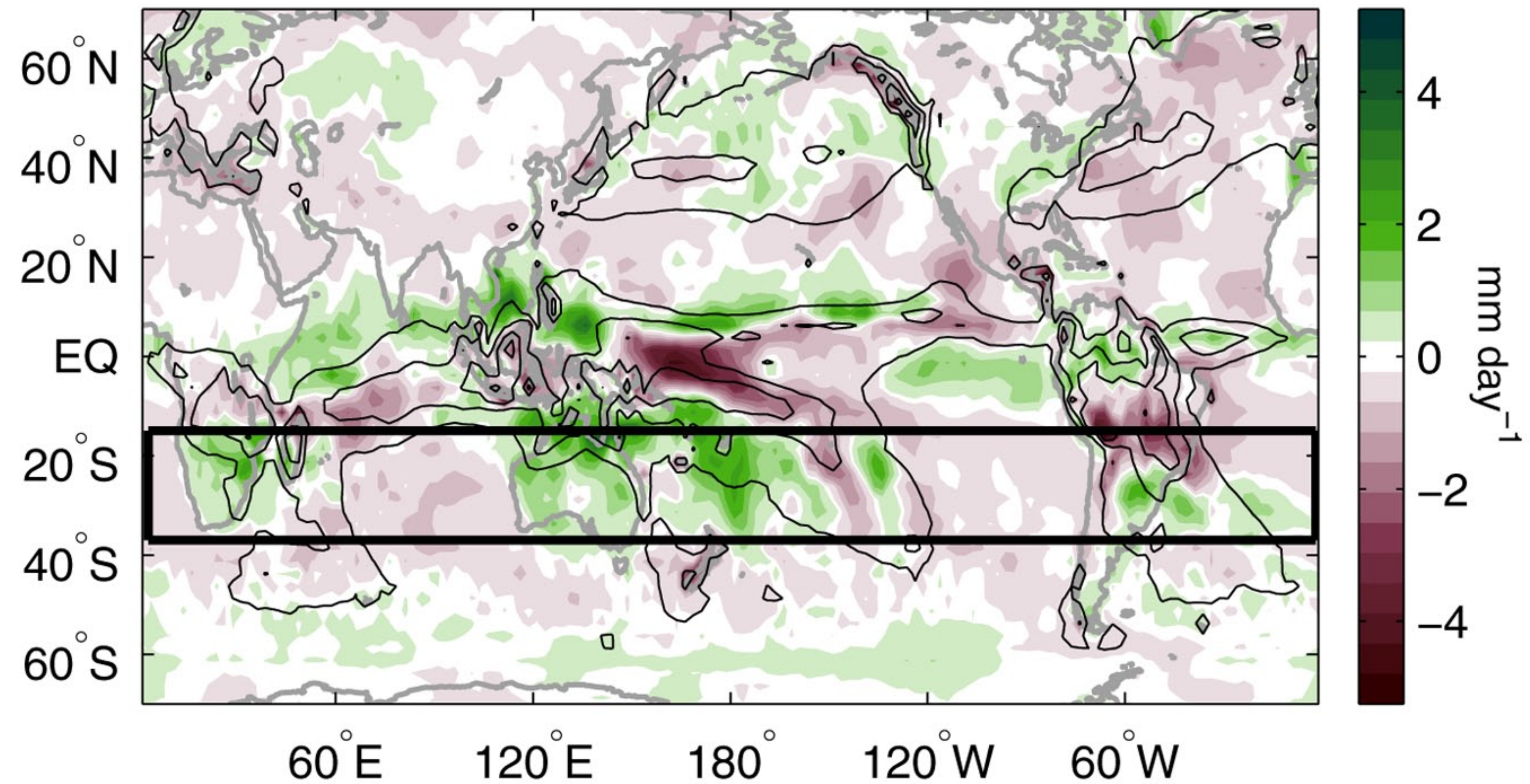
Attribution study: McLandress et al. (2011)

Transient CMAM runs



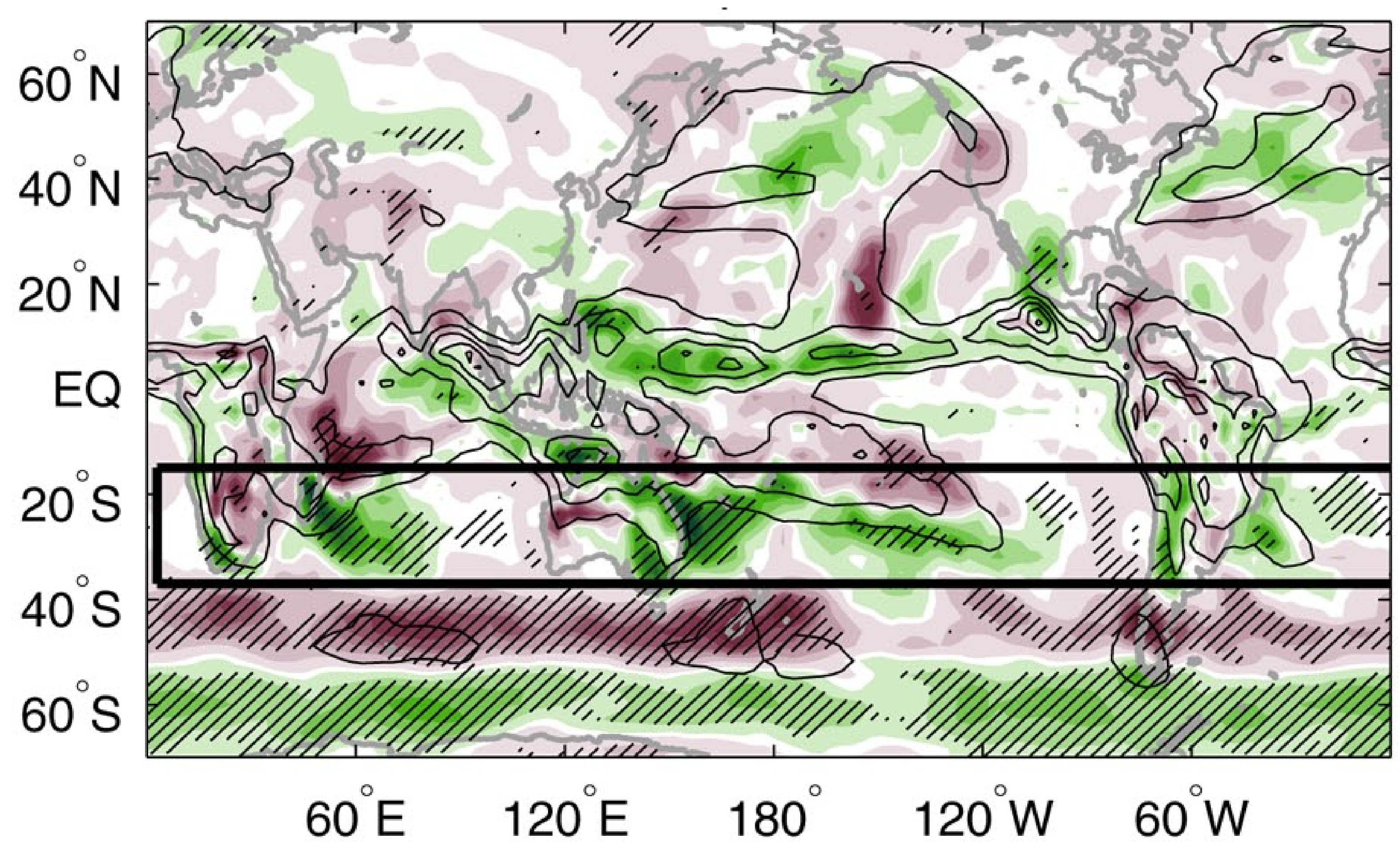
Surface Trend: Precip. (Kang et al. 2011)

GPCP: DJF Precip. trend (1979-2000)

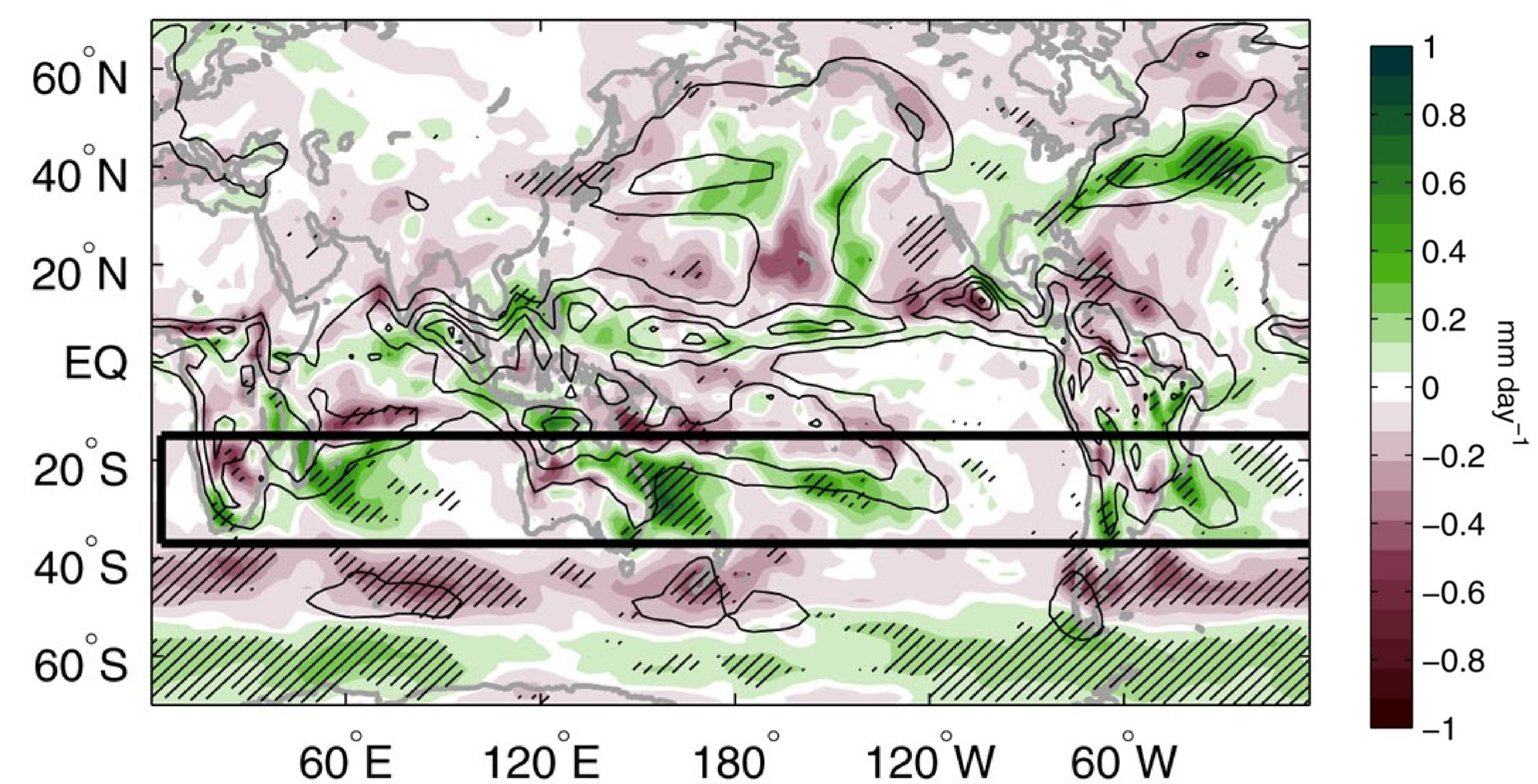


- Ozone hole has likely also **driven subtropical moistening.**

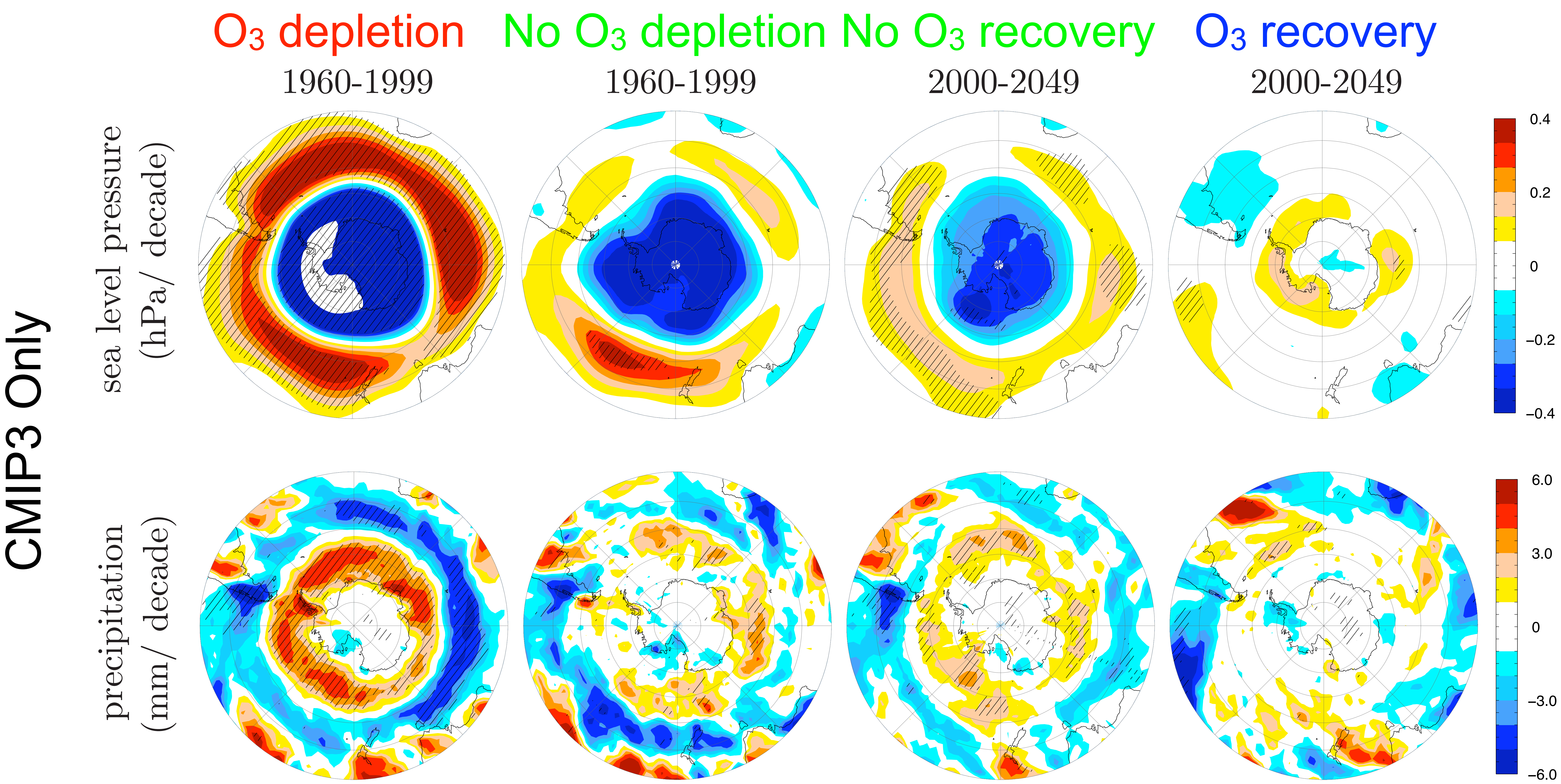
CAM3 control run



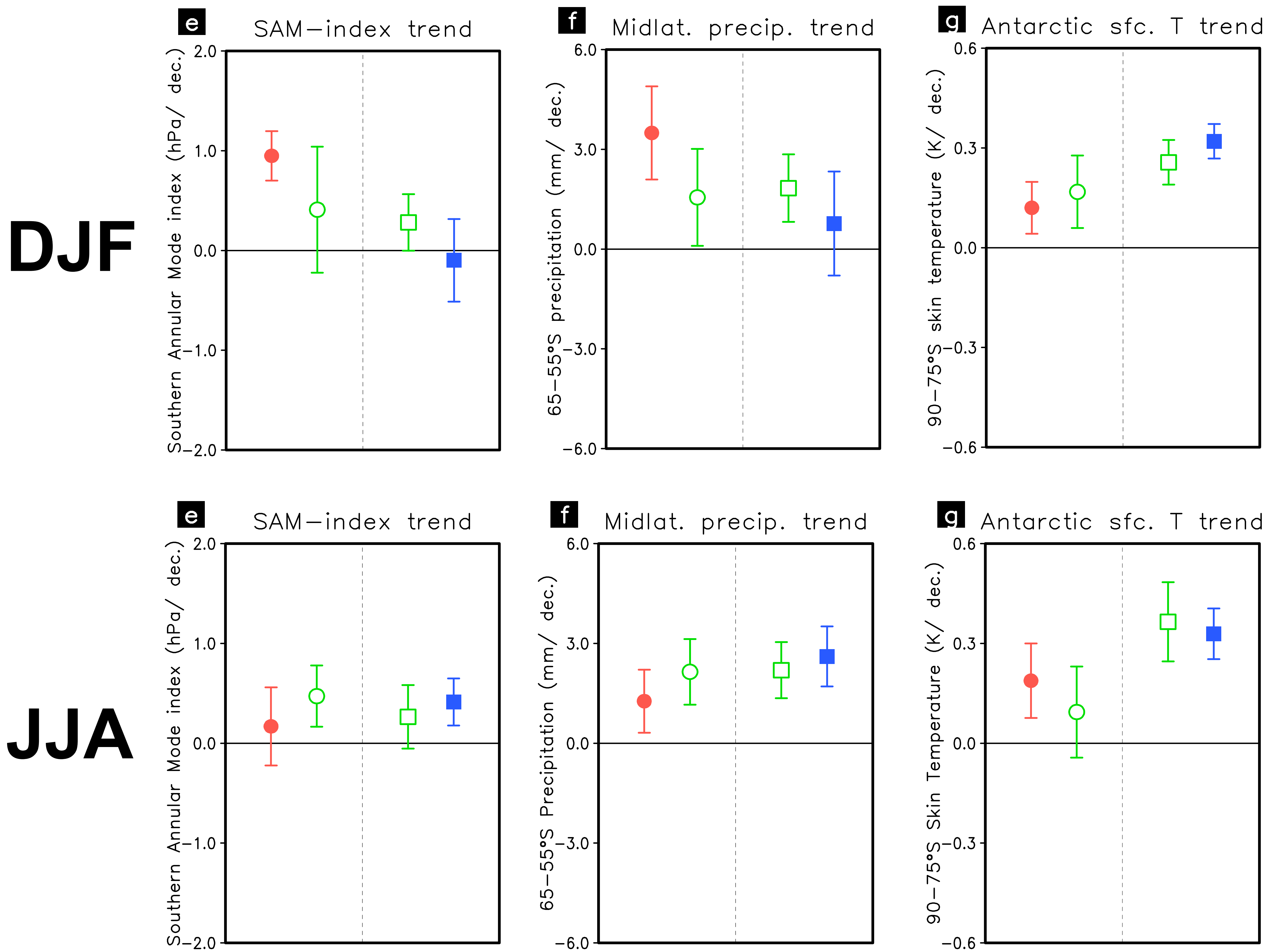
CAM3 with only O_3 forcing



Surface Trend: SLP & Precip.



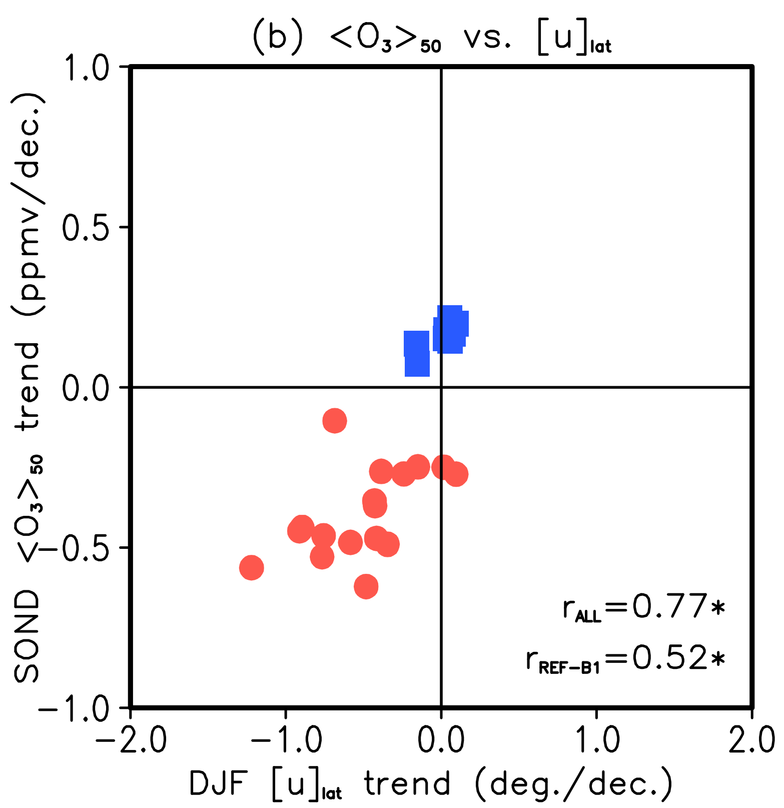
Summary: DJF vs. JJA Trends

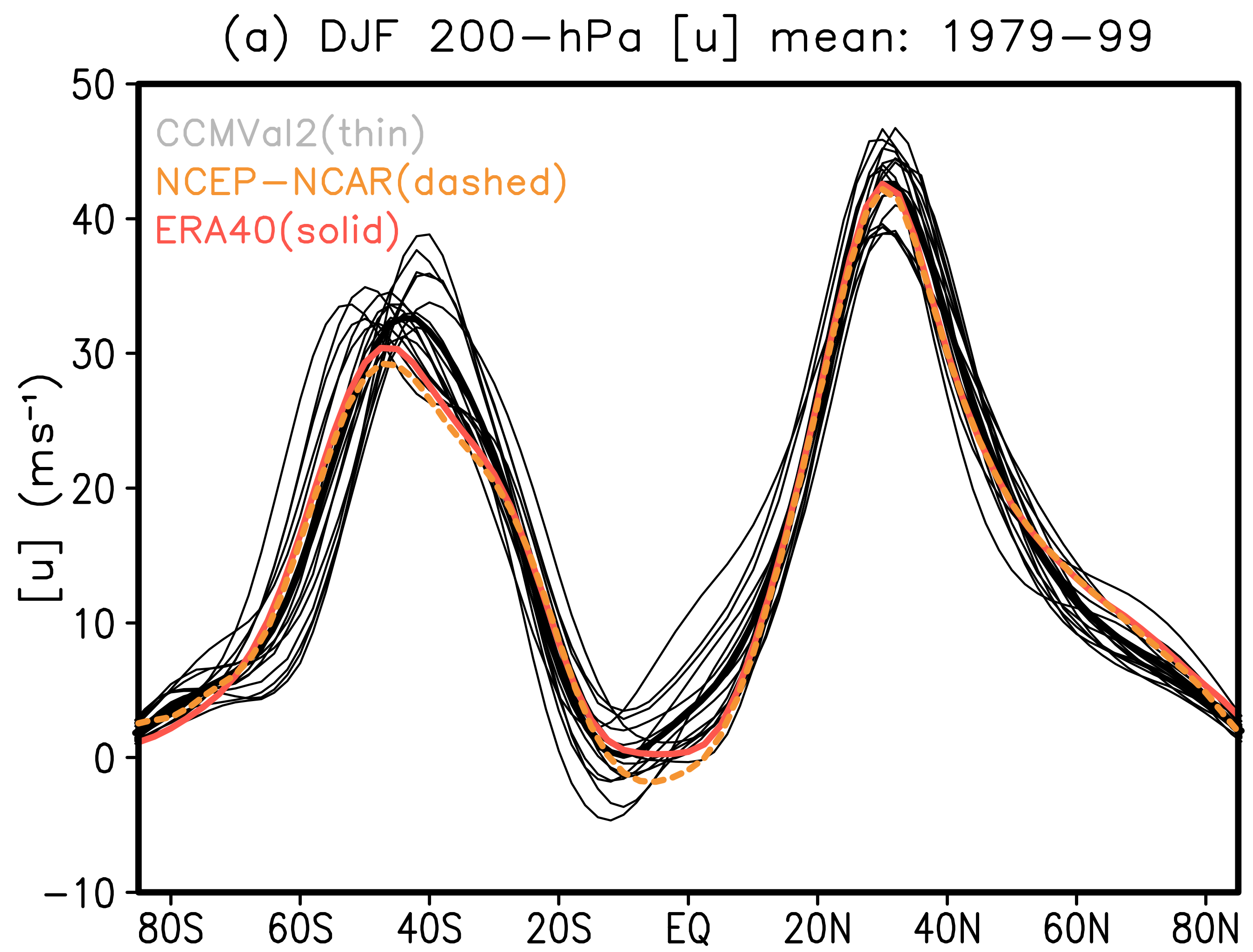


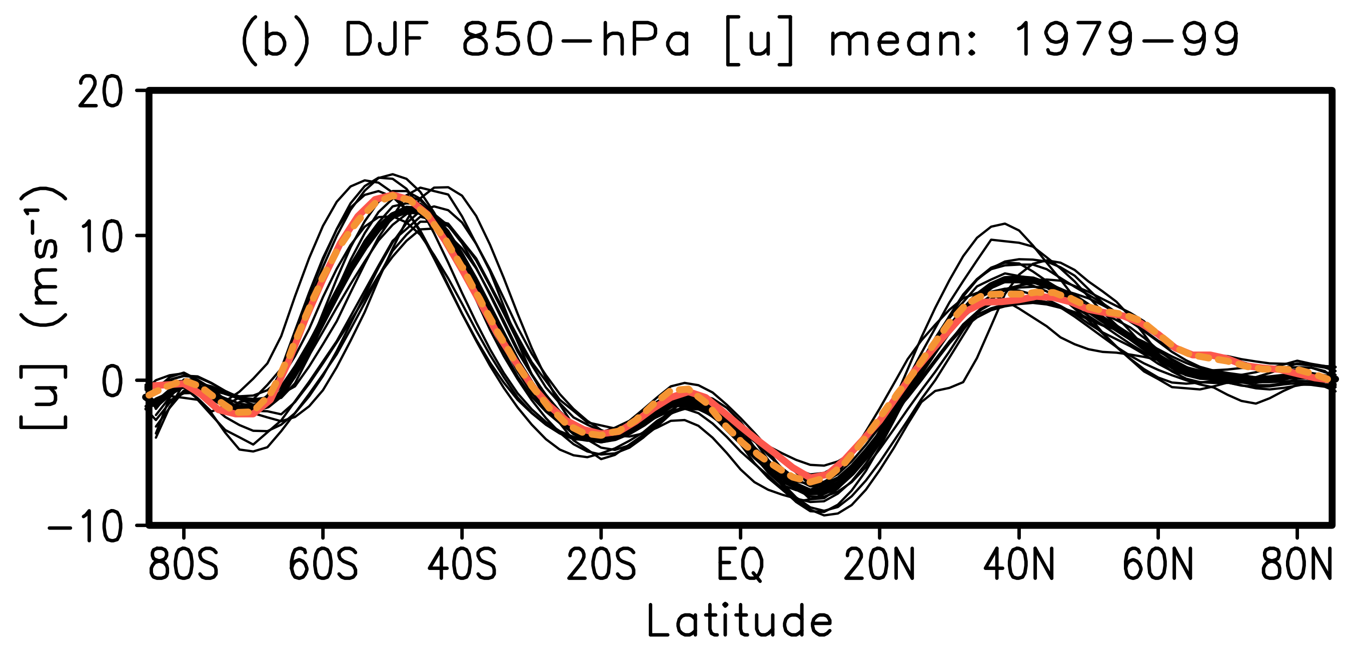
Surface climate changes in the CMIP3 models only

- Again, **no systematic difference is found in the SH winter**. No systematic difference is also found in the NH circulations.
- This suggests that difference in the SH-summer climate change between 6 groups of models is primarily caused by stratospheric ozone.

Different Responses among the Models







- Time-mean [u] of the CCMVal-2 models shows **bimodal distribution**, and is **located in somewhat lower latitudes** than the one in the reanalysis data.