A pause in Southern Hemisphere circulation trends due to the Montreal Protocol

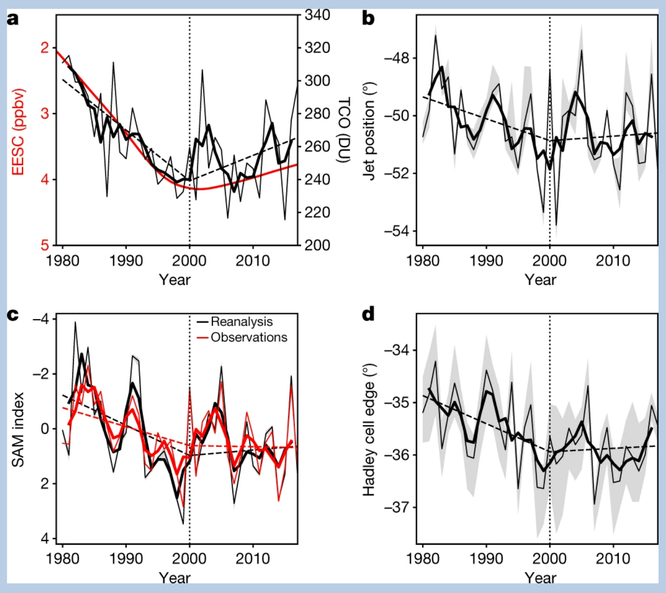
Antara Banerjee[1,2], John C. Fyfe[3], Lorenzo M. Polvani[4], Darryn Waugh[5,6], Kai-Lan Chang[1,2]

[1]CIRES, [2]NOAA ESRL CSD, [3]CCCMa, [4]Columbia University, [5]John Hopkins University, [6]University of New South Wales

1. Trends in near-surface circulation

EESC
Ozone

SAM index



Jet position

Hadley cell edge

Figure 1: *(a) EESC (winter) and total column ozone (SON; SBUV). (b)-(d): circulation metrics (DJF). Black lines and shading in (b)-(d) are averaged values across four reanalyses (ERA-I, JRA-55, MERRA2-asm, MERRA2-ana) and their full range. Unsmoothed (thin lines) and 3-yr smoothed (bold lines) values are shown. The red line in (c) is the SAM index based on observations. Two piecewise linear trend lines are drawn for the ozone* ***depletion (1980-2000)*** *and ozone* ***recovery (2000-2017)*** *periods.*

Observations and reanalyses show a robust poleward expansion of the Southern Hemisphere (SH) summertime tropospheric circulation towards the end of the 20th century[1]. However, Fig. 1b-d suggests that these trends have now **paused** since around 2000. We posit that this pause is a result of declining ozone-depleting substances and the recently detected recovery of the Antarctic ozone hole[2] (Fig. 1a) due to the Montreal Protocol.

2. Models and experiments

CCMs (CCMVal2 + CCMI)	**ALL** (all forcing) 50	**fGHG** (fixed GHGs) 22	**fODS** (fixed ODSs) 21	
CanESM2	**ALL** (all forcing) 50	**OZ** (ozone) 50	**AA** (aerosols) 50	**NAT** (natural) 50

Table 1: *Models, experiments and ensemble members.*

These ensembles allow a separation of the effects of ozone (OZ) and greenhouse gases (GHG) as follows:
OZ: ALL-fODS *[CCMs]* and OZ *[CanESM2]*
GHG: ALL-fGHG *[CCMs]* and ALL-(OZ+AA+NAT) *[CanESM2]*

3. Trends in atmospheric zonal wind

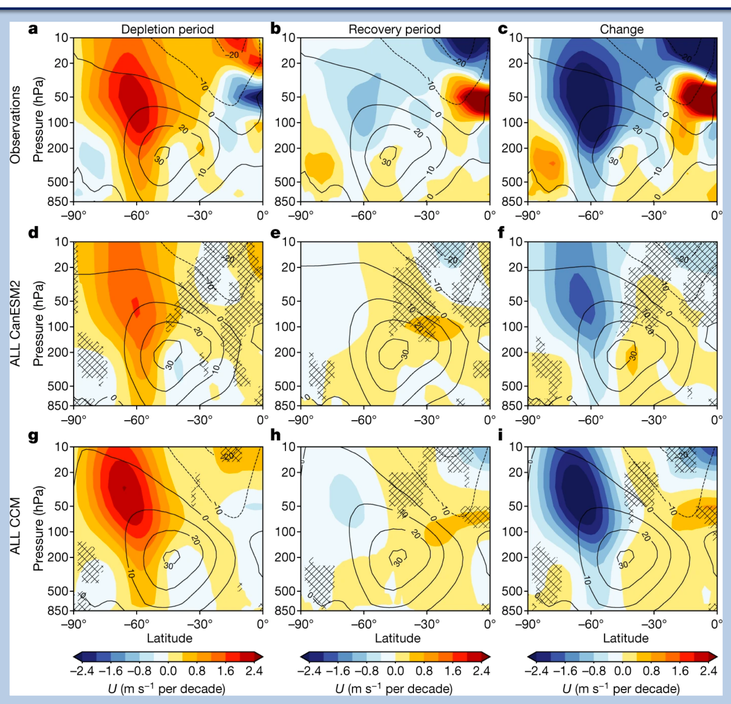


Figure 2: *Trends in DJF zonal mean zonal winds in observations (reanalysis average) and model ALL ensemble means. Hatched areas are where the observations lie outside the 5-95% range of simulated trends.*

In the depletion period, springtime ozone losses in the Antarctic lower stratosphere result in local cooling trends that are associated with a strengthened vortex. By summer, strengthened winds extend down to the surface (Fig. 2a). In contrast, the recovery period shows no such responses (Fig. 2b). The pause is illustrated by the change between the two periods (Fig. 2c). The models reproduce observed trends, including the pause (Fig. 2d-i).

4. Trends due to ozone and GHGs

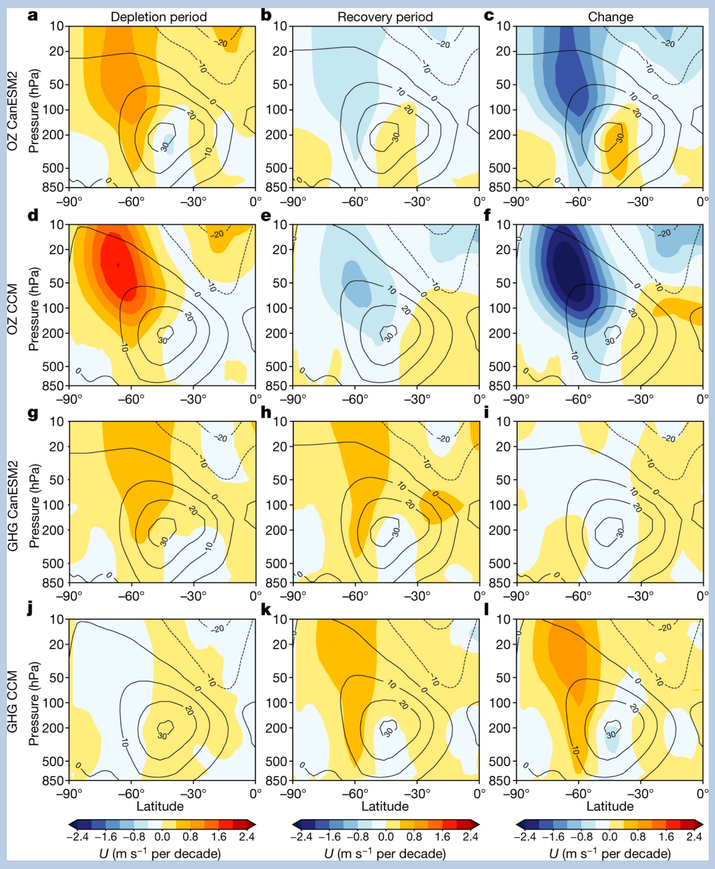


Figure 3: *Trends in DJF zonal mean zonal winds for model simulated effects of ozone and GHGs (ensemble means).*

The effect of ozone alone is a striking reversal of trends between the depletion and recovery periods (Fig. 3a-f). GHGs may have reinforced the effects of ozone in the depletion period (Fig. 3g) and cancelled their effects in the recovery period (Fig. 3h,k).

5. Detection and attribution

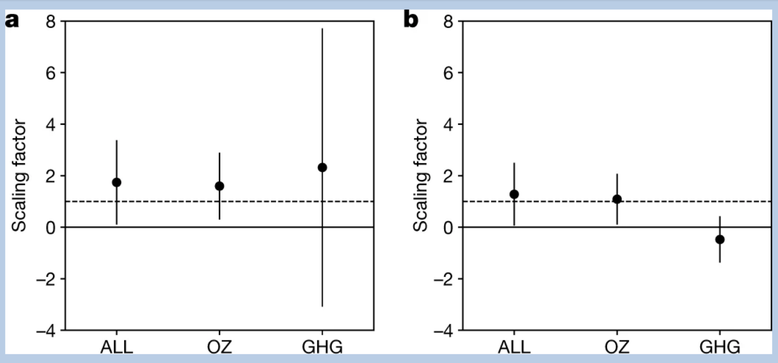


Figure 4: *Detection and attribution scaling factors.*

We perform a pattern-based fingerprinting approach on the change in zonal wind trends (the pause) in two stages:
(1) The observation is linearly regressed against the model ALL fingerprints (ensemble means). The scaling factor is the regression coefficient and uncertainties show the 5-95% range, estimated from the ensemble spread (CanESM2) or a long piControl run (CCMs). The ALL scaling factors encompass 1 and are distinct from 0. The observed pause is thus detected over internal variability.
(2) The observed pause is regressed against the OZ and GHG fingerprints (multiple linear regression). The scaling factors are consistent with 1 for OZ and 0 for GHG. The pause is therefore formally attributed to ozone forcing and not to GHGs.

6. Conclusions and Outlook

We have provided evidence that the observed poleward shift in summertime SH tropospheric circulation towards the end of the 20th century, which has been widely documented, paused around year 2000, due to Antarctic stratospheric ozone recovery resulting from the Montreal Protocol. Given the wide-ranging impacts of the pre-2000 atmospheric circulation trends - for example, on precipitation[3], and ocean circulation and salinity[4] - we propose that the pause in these trends will have important consequences for the Earth System generally.

7. References

[1]Thompson, D. W. J. & Solomon, S. Interpretation of Recent Southern Hemisphere Climate Change. *Science* **296**, 895–899 (2002).
[2]Solomon, S. *et al.* Emergence of healing in the Antarctic ozone layer. *Science* **353**, 269 (2016).
[3]Scheff, J. & Frierson, D. M. W. Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones. *Geophys. Res. Lett.* **39**, L18704 (2012).
[4]Waugh, D. W., Primeau, F., Devries, T. & Holzer, M. Recent changes in the ventilation of the southern oceans. *Science* **339**, 568–570 (2013).
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