Supporting Online Material for

Impact of Polar Ozone Depletion on Subtropical Precipitation

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Supporting Online Material

1 Climate model integrations

CMAM is a global climate model with T63 horizontal resolution and 71 vertical levels from the surface to around 100 km (*17*). The model is either 1) coupled to an ocean and sea ice component with a horizontal resolution of approximately 1.41° (longitude) and 0.94° (latitude) and 40 vertical levels, or 2) forced with prescribed sea surface temperatures, and sea ice concentrations obtained from the coupled reference integration.

CAM3 is a global climate model with T42 horizontal resolution and 26 vertical levels from the surface to around 2.2 hPa (*18*); the sea surface temperatures and sea ice concentrations are prescribed from observations (*19*), averaged from 1952 to 1968.

Both models are integrated in a time-slice manner (i.e. with seasonally varying forcing, but no year-to-year trend) with zonally symmetric latitude-height ozone fields representative of the change in ozone from pre-ozone-hole times to the period when the ozone hole reached a record physical size. Specifically, in CMAM, the climatological ozone fields in the reference integration is perturbed with the observed change between 1979 and 2005 in the ozone hole integration, whereas in CAM3 ozone concentrations are fixed to year 1960 in the reference integration and to year 2000 in the ozone hole integration.

2 Moisture budget

The moisture budget indicates that time and zonally averaged precipitation (P) and evaporation (E) are balanced by the moisture convergence.

$$\left[\overline{P}\right] - \left[\overline{E}\right] = -\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}F\cos\phi = -\nabla \cdot F,$$

where overbars denote time averages, brackets zonal averages, and F the vertically integrated moisture flux, which can be decomposed into the contributions from the mean, the transient eddies, and the stationary eddies, i.e.

$$F = \left\langle [\overline{v}]\,[\overline{q}] \right\rangle + \left\langle \left[\overline{v'q'}\right] \right\rangle + \left\langle [\overline{v}^*\,\overline{q}^*] \right\rangle,$$

where $\langle \cdot \rangle \equiv \int_{p_s}^{0} \cdot\, dp/g$ is the vertical integral from the surface to the top of the atmosphere, primes denote deviations from the time average, and asterisks deviations from the zonal average; v is meridional wind and q is specific humidity.

Denoting with δ the changes between the ozone hole and reference integrations, we show in Fig. S1 changes in the moisture budget associated with the mean, i.e. $-\delta \nabla \cdot \langle [\overline{v}] [\overline{q}] \rangle$, in red; those associated with the transient eddies, i.e. $-\delta \nabla \cdot \left\langle \left[\overline{v'q'} \right] \right\rangle$, in blue; and those associated with the stationary eddies, i.e. $-\delta \nabla \cdot \langle [\overline{v}^* \, \overline{q}^*] \rangle$, in green. It is clear from Fig. S1 that the precipitation changes $\delta \left[\overline{P} \right]$ (black with dots) are largely associated with changes in the mean (red).

Furthermore, we find that $\delta \left[\overline{P} \right]$ is almost completely associated with changes in the mass convergence, i.e. $\delta \left[\overline{P} \right] \approx - \left\langle [\overline{q}]_{ref} \, \delta \nabla \cdot [\overline{v}] \right\rangle$ (red dashed in Fig. S1) where the subscript ref denotes the reference integration. Hence, precipitation changes are associated with changes in the circulation.

3 Precipitation changes congruent with jet shift

Changes in precipitation that are congruent with a latitudinal shift in the extratropical westerly jet are computed as follows. First, the correlations between the time-series of zonal-mean precipitation and latitude of maximum zonal-mean zonal wind at 850 hPa are calculated in the reference integration. Fig. S2 shows that a very strong correlation exists between the jet latitude and the zonal-mean precipitation. In particular, in the highlighted 15-35°S region, a poleward shifted jet corresponds to a moistening. Second, the two time-series are regressed to obtain the amount of precipitation changes for each one degree shift of jet in the reference integration. Third, these regression coefficients are multiplied by the response in westerly jet latitude due to ozone depletion. The response in jet latitude in our model experiments – and in the observation between 1979 and 2000 – range from -1° to -3° latitude.

4 Momentum budget

The zonal momentum budget indicates that

$$-f [\overline{v}] \approx -\frac{\partial [\overline{uv}] \cos^2 \phi}{a \cos^2 \phi \, \partial \phi} - \frac{\partial [\overline{u\omega}]}{\partial p} = -\nabla \cdot [\overline{uv}] - \frac{\partial [\overline{u\omega}]}{\partial p}$$

where f is the Coriolis parameter, u the zonal wind, and ω the pressure velocity . We decompose the zonal momentum flux $[\overline{uv}] = [\overline{u}] [\overline{v}] + \left[\overline{u'v'} \right] + [\overline{u}^* \, \overline{v}^*]$ into contributions from the mean, the transient eddies and the stationary eddies.

First, Fig. S3 shows the vertical distribution of the changes in the transient eddy momentum divergence, i.e. $\delta \nabla \cdot \left[\overline{u'v'} \right]$ and changes in the zonal-mean zonal wind, to

demonstrate that a poleward jet shift is accompanied by changes in transient eddy momentum fluxes.

Second, it is shown in Fig. S1 that precipitation changes are mostly associated with changes in the mass divergence. In Fig. S4, we demonstrate that changes in the mass divergence (red shading) are largely associated with changes in transient eddy momentum fluxes (gray contours), i.e. $-f\delta\nabla \cdot [\overline{v}] \approx -\nabla \cdot \left(\delta\nabla \cdot \left[\overline{u'v'}\right]\right)$. The stationary eddy component of momentum flux is negligible in the Southern Hemisphere.
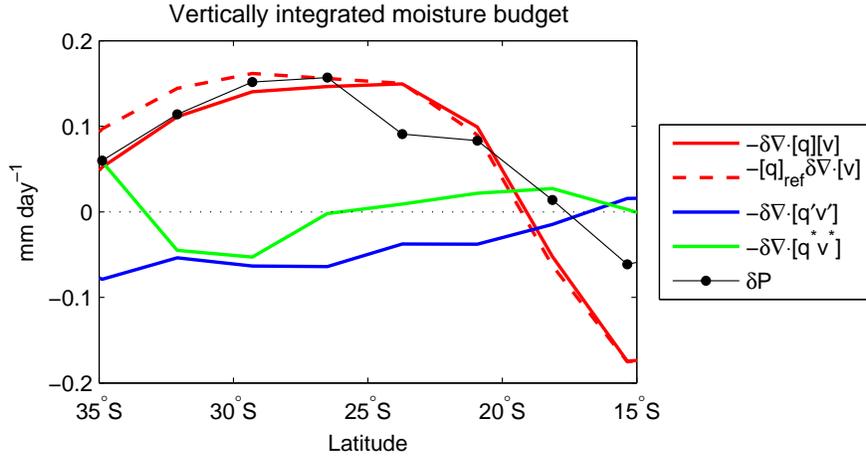
Figure S1: The austral summer zonal-mean change in: precipitation $\delta\left[\overline{P}\right]$ (black), vertically integrated convergence of time- and zonal-mean moisture flux $-\delta\nabla\cdot\langle[\overline{v}]\,[\overline{q}]\rangle$ (red), transient eddy moisture flux $-\delta\nabla\cdot\left\langle\left[\overline{v'q'}\right]\right\rangle$ (blue), and stationary eddy moisture flux $-\delta\nabla\cdot\langle[\overline{v}^*\,\overline{q}^*]\rangle$ (green). The red dashed line shows the mean change resulting from changes in mass convergence $-\left\langle[\overline{q}]_{ref}\,\delta\nabla\cdot[\overline{v}]\right\rangle$. All quantities are for experiment (iii). See Section 2 for details of the moisture budget.
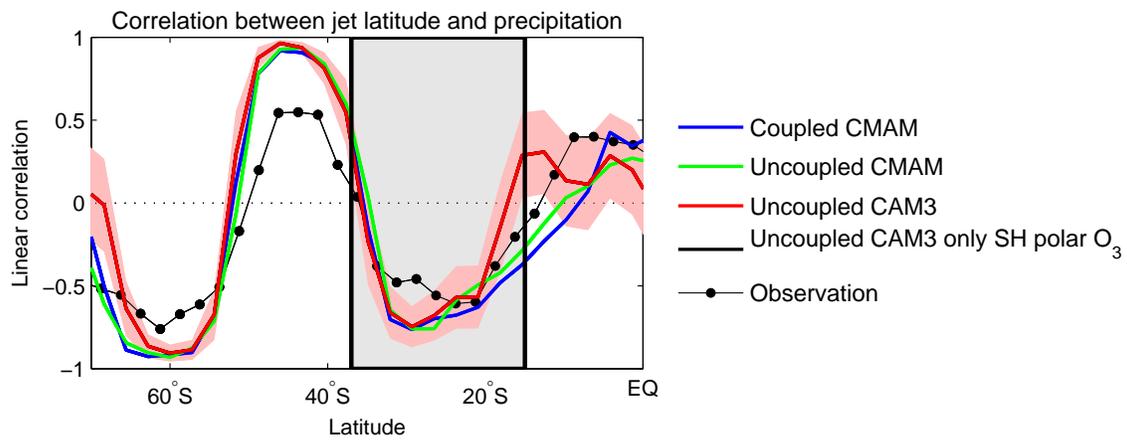
Figure S2: Linear correlation coefficient, between zonal-mean precipitation and the latitude of maximum zonal-mean zonal wind at 850 hPa, in austral summer, with 95% confidence interval shown with red shading for experiment (iii).
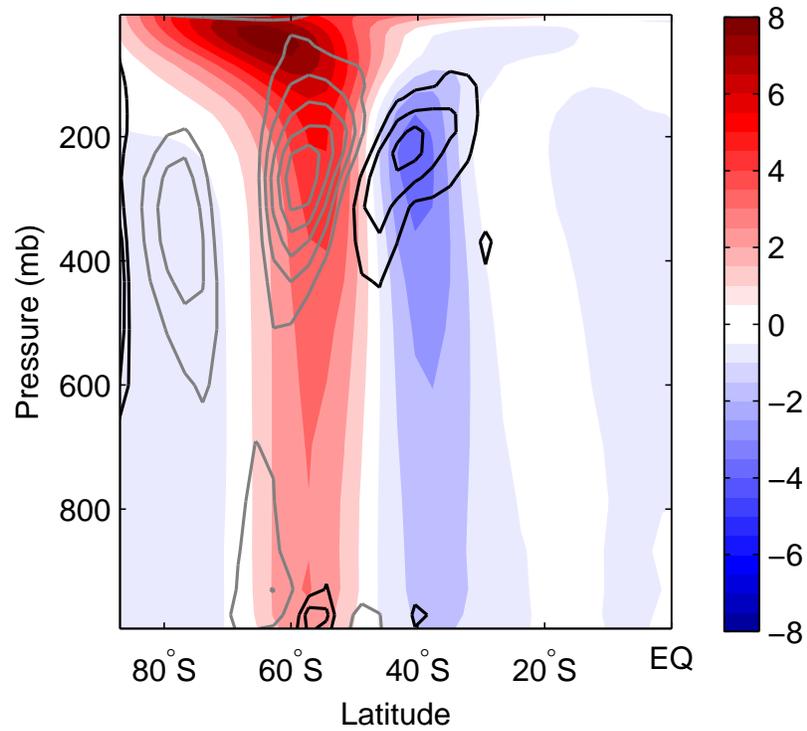
Figure S3: Shading: the zonal-mean zonal wind change in DJF (m s^{-1}). Contours: the changes in transient eddy momentum divergence in black, and the convergence in gray, with contour interval of 2×10^{-6} ms^{-2}. All quantities are for experiment (iii). See Section 4 for details of the momentum budget.
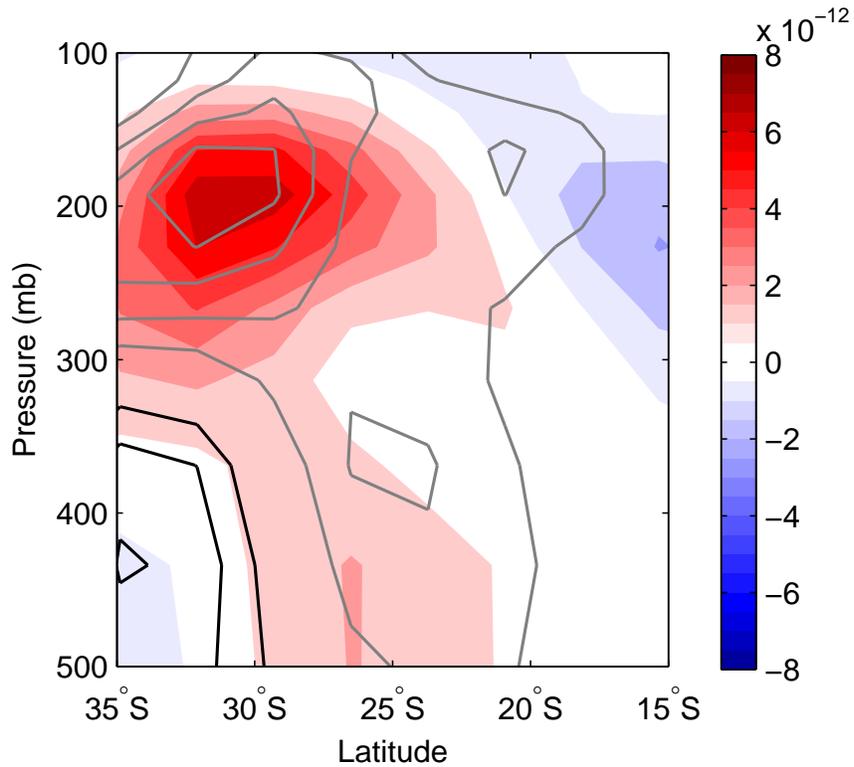
Figure S4: Shading: the zonal-mean change of upper-level mass divergence multiplied by negative of the Coriolis parameter, $-f\delta\nabla \cdot [\overline{v}]$. Positive values are indicative of anomalous upward motion, and negative values of downward motion. Contours: changes in divergence of transient eddy momentum convergence (gray) and divergence (black), $-\nabla \cdot \left(\delta\nabla \cdot \left[\overline{u'v'}\right]\right)$, with contour interval of 1×10^{-12} kg m^{-2} s^{-2}. All quantities are for experiment (iii) in austral summer, and a 1-2-1 filter is applied to latitude and height.

References and Notes

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16. Materials and methods are available as supporting material on *Science* Online.

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