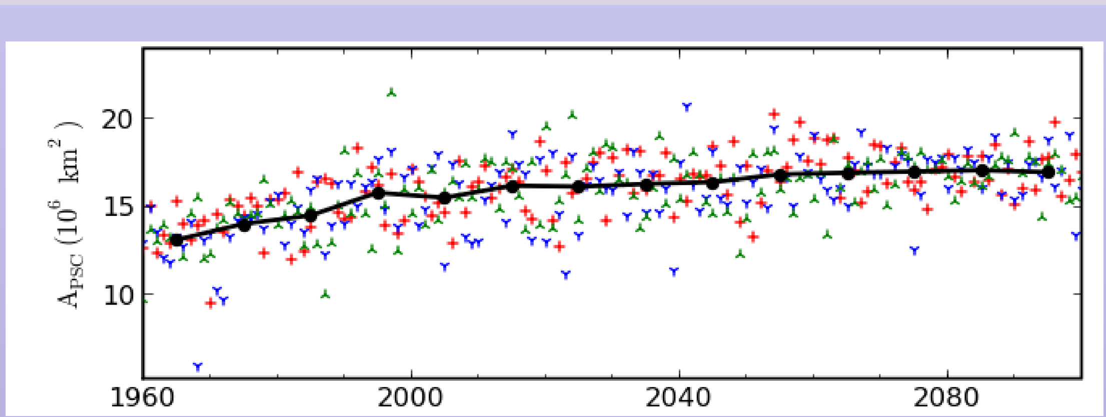
Conditions for Polar Stratospheric Cloud formation in the Canadian Middle Atmosphere Model

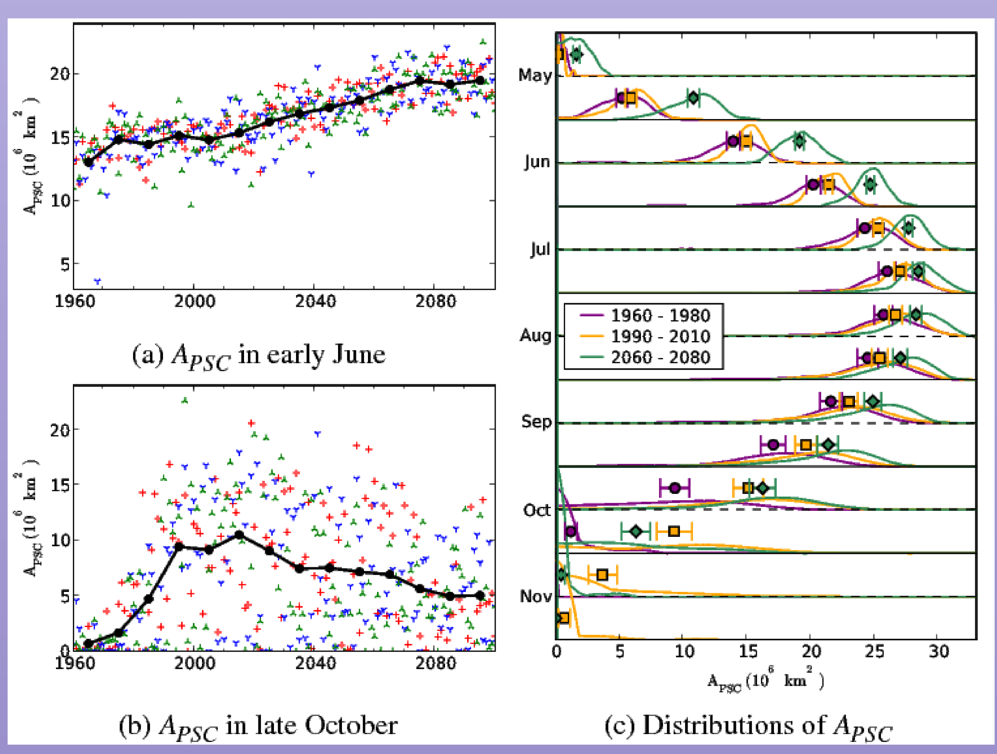
Peter Hitchcock†, Theodore Shepherd, and Charles McLandress

Dept. of Physics, University of Toronto, Toronto, Ontario, Canada. †peterh@atmosp.physics.utoronto.ca

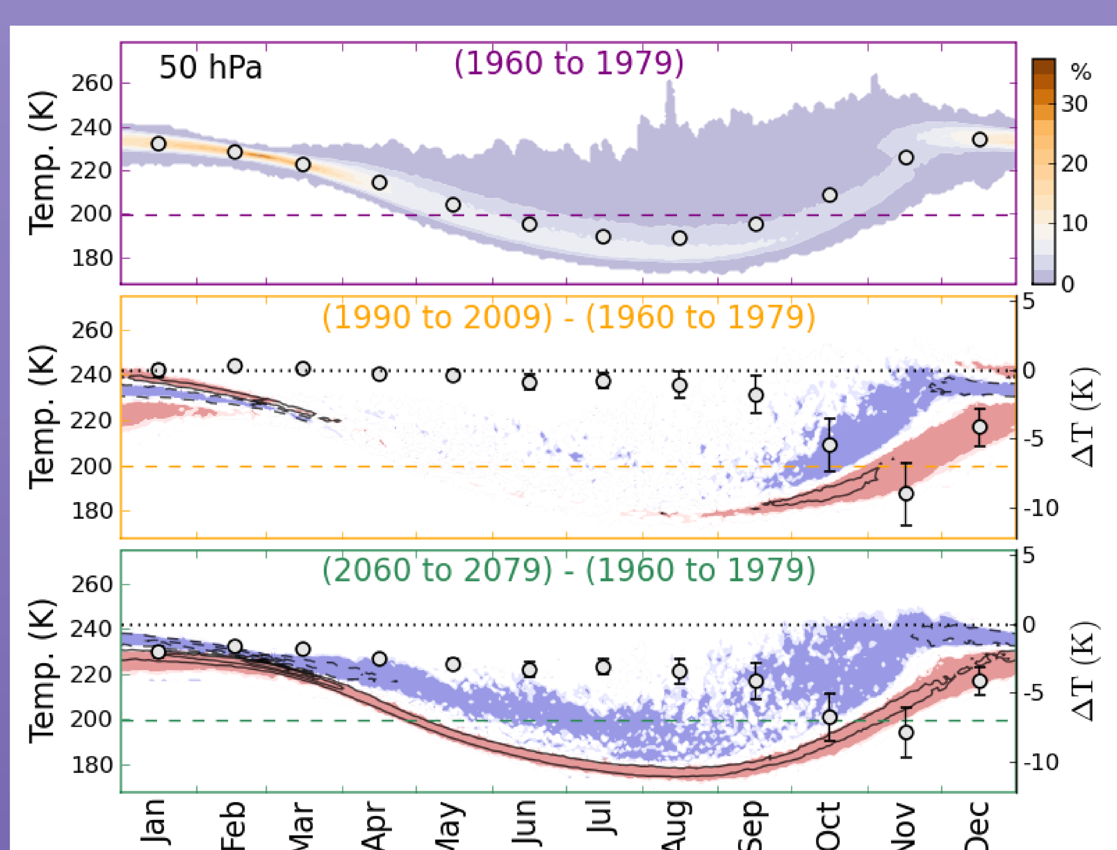
Southern Hemisphere



(S1) May-Dec averaged A_{PSC} at 50 hPa increases more rapidly through the latter half of the 20th century than throughout the 21st century, slowing near the peak of ozone depletion. Yearly values from each member are shown together with the ensemble, decadal averages.

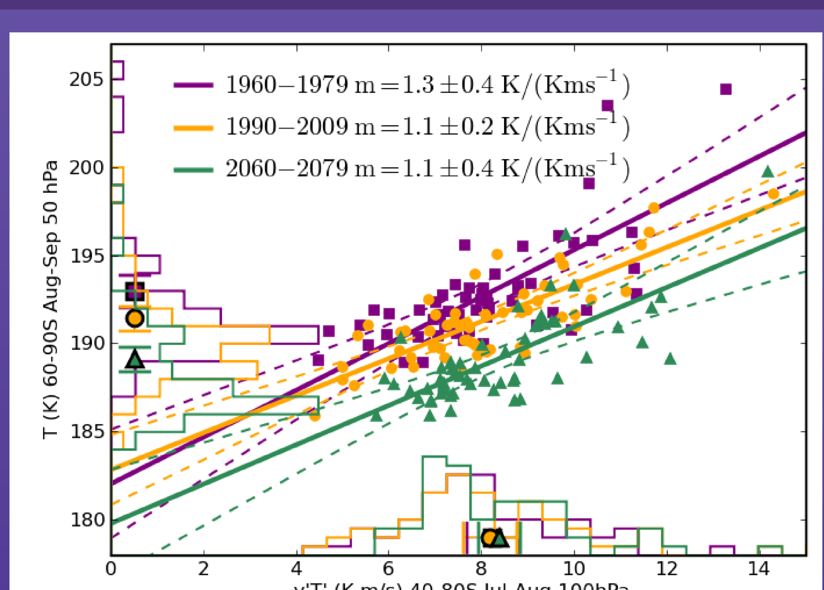


(S2) A_{PSC} in the fall and early winter increases steadily through the simulations (a,c). In spring time it peaks strongly near the turn of the century then declines, though at the end of the simulation it remains above 1960s levels (b,c). Error bars in (c) indicate twice the standard deviation about the mean. Distributions are estimated using a kernel method.



(S3) (a) Shading indicates climatological (1960-1979) area on the 50 hPa surface in each 1 K temperature bin expressed as a fraction of the area south of 60°. Circles show monthly mean temperatures. (b,c) Changes in the temperature distributions (left axis) and monthly mean temperatures (right axis) for (1990-2010) and (2060-2080). Dark/light shading indicates statistically significant changes (99% / 95%); the magnitude of the change is indicated by the black contours. The first contour indicates a change of 2.5% of the polar cap area per bin, subsequent contour intervals are 5%. Zero contour omitted. Error bars on the changes in monthly mean are 95% confidence intervals. Dashed lines indicate T_{NAT}.

Changes in climatological temperature distributions through the three periods of interest are consistent with the changes in A_{PSC}, indicating strong springtime cooling at the peak of ozone depletion (b), but cooling largely independent of the season after ozone recovers (c).



(S4) Regression of midlatitude meridional heat-flux against polar cap temperature lagged by one month. No indication is found that wintertime cooling of the polar region is related to a change in midlatitude waveactivity.

Motivation

Chemical ozone loss over both poles correlates strongly with the extent of air below the thermodynamic threshold for PSC formation (T_{NAT} ~ 195K) in the lower stratosphere (e.g. Rex et al. 2004). Observations suggest that the area of air below T_{NAT} on lower stratospheric surfaces (A_{PSC}) or their vertical integral (V_{PSC}) during the coldest Arctic winters has increased over the past few decades (Rex et al. 2004, 2006).

The mechanism for this trend remains unclear, but if it continues in the near future it could lead to severe ozone depletion in the Arctic. Thus we look for evidence of such a trend in Canadian Middle Atmosphere Model (CMAM) simulations, examining both hemispheres to better understand possible mechanisms.

Model description

We have analyzed (Hitchcock et al. 2008) lower stratospheric temperatures in the polar regions of an ensemble of three, 150-year integrations of the CMAM (Scinocca et al. 2008).

These 'REF2' runs participated in the CCMVal intercomparison project (Eyring et al. 2006, 2007) and were found to compare favourably with observations and other climate-chemistry models. Driven by observed and projected halogen and greenhouse gas concentrations from 1950 to 2100, the runs simulate ozone depletion/recovery and climate change.

Methods

Low temperature extremes poleward of 60° are examined in both hemispheres. Three, two-decade periods of interest are compared:

1960-1979: Before ozone depletion
1990-2009: Peak ozone depletion
2060-2079: After ozone recovery

We deduce the mechanisms of modelled changes based on their seasonal and decadal dependencies. We present climatologies of daily temperature distributions to connect changes in the low-temperature tails to changes in monthly mean temperatures. Finally, we present diagnostics of the impact of circulation changes on polar temperatures.

Discussion

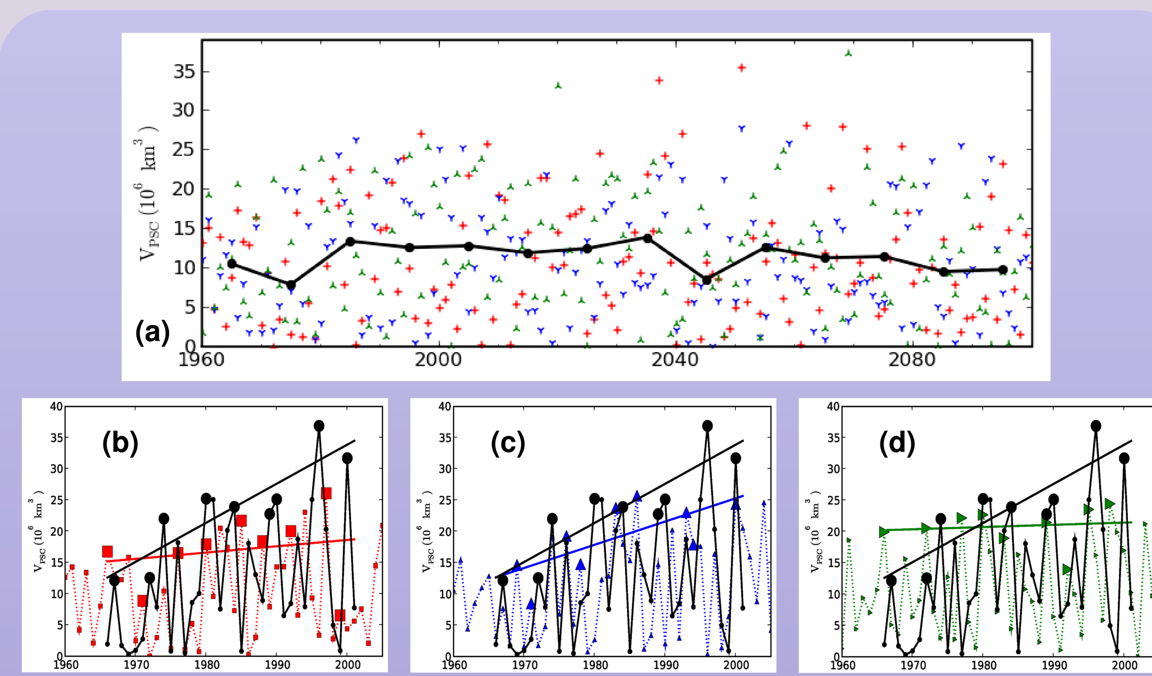
Antarctic conditions for PSC formation in this ensemble respond clearly to the radiative impacts of ozone depletion and recovery and climate change. Changes in dynamical heating do not play a significant role.

Changes in the simulated Arctic conditions are less easily interpreted. Though there are suggestions of a weak radiative response similar to the Antarctic, variability and dynamical changes overwhelm this signal. Only one of three ensemble members reproduces a trend in the coldest winters similar to the observations; this trend is not projected to continue as ozone recovers. Since Arctic ozone depletion is underestimated in this ensemble (Shepherd 2008), these points suggest that ozone loss itself is playing a role in the observed trend.

Climate change strengthens polar downwelling in the Arctic in theis ensemble, which compensates for the radiative cooling in the lower stratosphere. Although there is no present consensus on the response of the Brewer-Dobson circulation to climate change, this feature of the ensemble does not support the hypothesis that climate change is behind the observed trend.

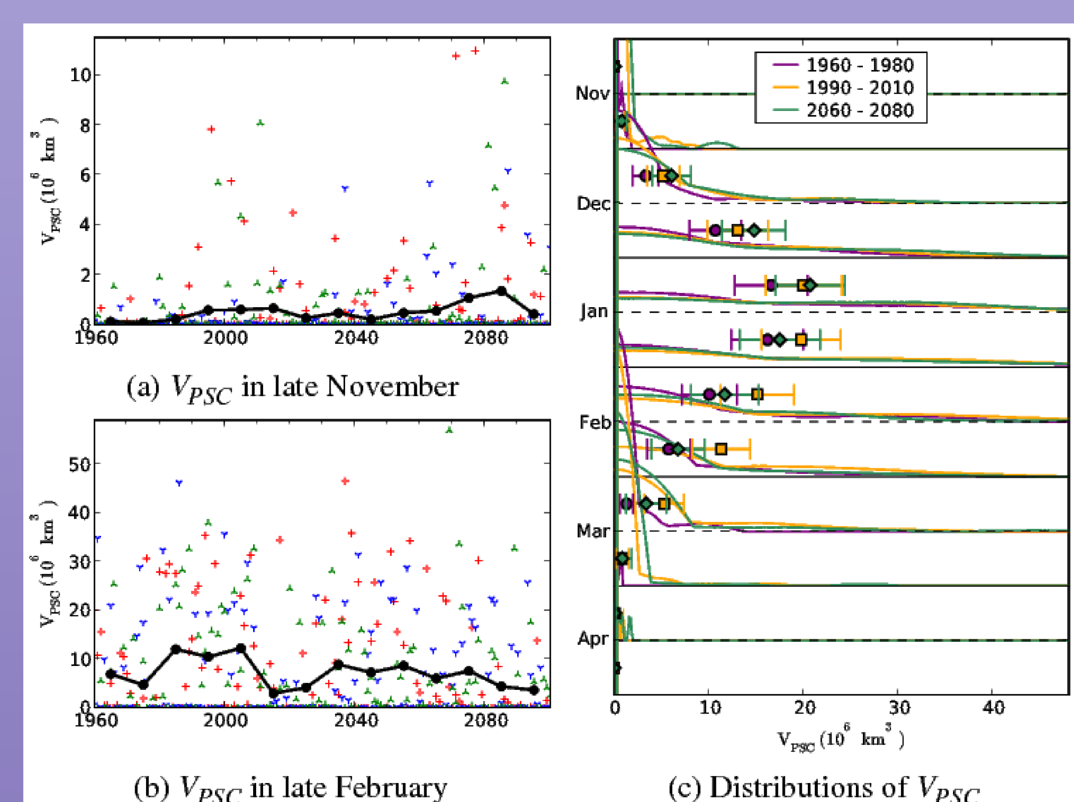
These simulations cannot provide much guidance on the role of natural variability in the observed trend. The observed trend is roughly reproduced in one of the three ensemble members and not the other two. Moreover, volcanic and solar forcings and the QBO—important sources of natural variability in the stratosphere—are not included in this simulation. Though this suggests the role of natural variability is a plausible cause of the observed trend, there are not enough members in this ensemble to quantify the statistics of the 'coldest' winters.

Northern Hemisphere

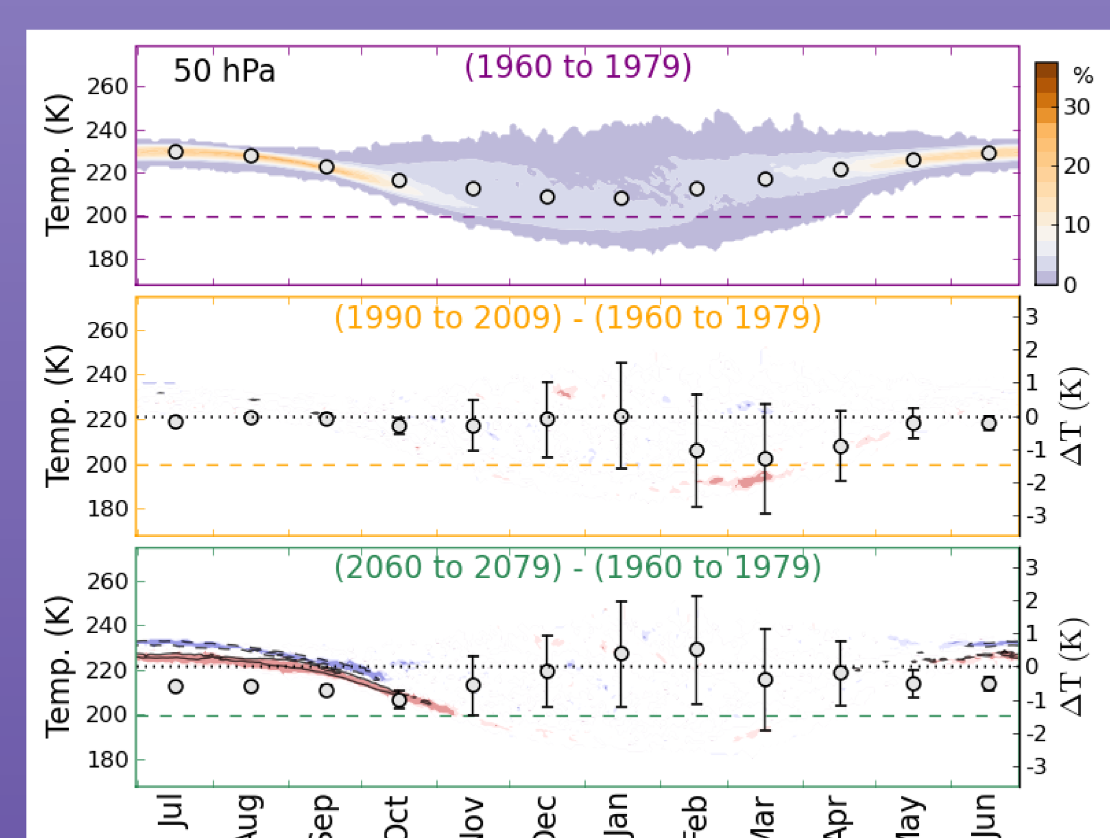


(N1) (a) Dec.-mid Mar. averaged V_{PSC} from 1960-2100. (b-d) Modelled V_{PSC} from each member (colours) plotted against observations (black). Trend lines drawn through 'coldest' year (largest V_{PSC}) in each four-year interval. V_{PSC} is estimated from A_{PSC} on the 50 hPa and 30 hPa surfaces after Rex et al. 2006, in order to compare directly to their results.

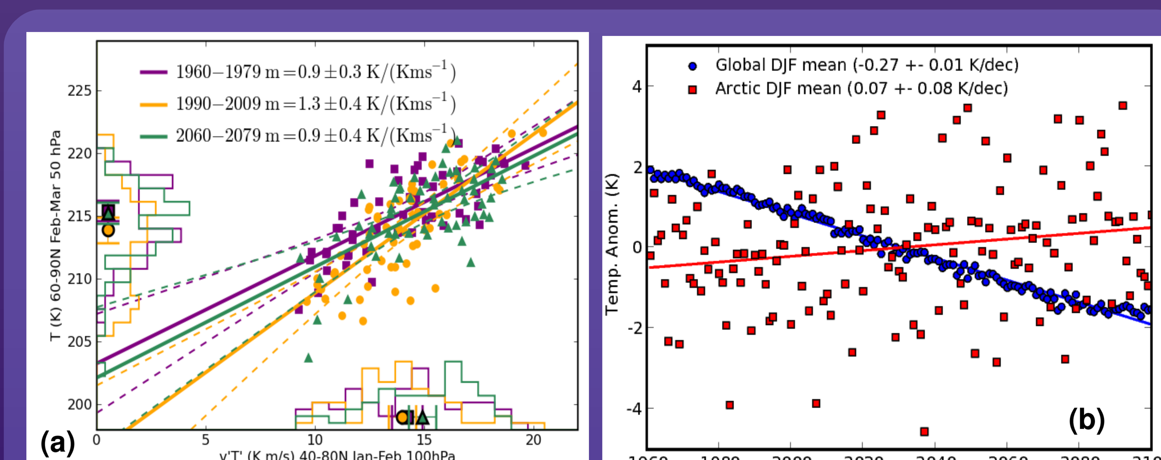
Decadal, ensemble means of V_{PSC} do not change appreciably during the simulations (a). One ensemble member reproduces a trend in the coldest years similar to the observations (c), but the other two do not (b,d).



(N2) V_{PSC} shows only weak indications of the spring-time cooling during ozone depletion (b,c) and winter-time cooling (a,c) seen in the Antarctic (S2).



(N3) As (S3) but for the Arctic. From 1990-2010, weak indications of spring-time cooling below T_{NAT} are seen in the Arctic temperature distributions and mean temperatures (b–shading below dashed line). No indication of winter-time cooling is seen in the temperature distributions or monthly mean temperatures even by the end of the simulations, though summer-time temperatures drop (c).



(N4) (a) As (S4) but for the Arctic. (b) Anomalies from the 1960-2100 mean. Standard diagnostics of dynamically induced heating (see, e.g., Austin et al. 2003 and Eyring et al. 2006) do not indicate significant changes (a), but direct inspection of downwelling and EP fluxes indicate a significant increase in the strength of the overturning circulation (McLandress and Shepherd, sbmt.) which results in a weak winter-time warming trend in the lower Arctic stratosphere (b).

This work was done under the auspices of the CSPARC project supported by funding from CFCAS and NSERC.

Austin, J. et al. (2003) *Atmos. Chem. Phys.*, 3, 1–27.
Eyring, V. et al. (2006) *J. Geophys. Res.*, 111, D22308.
Eyring, V. et al. (2007) *J. Geophys. Res.*, 112, D16303.
Hitchcock, P. et al. (2008) *Atmos. Chem. Phys. Discuss.*
McLandress, C. and Shepherd, T. G. *J. Clim.*, submitted.
Rex, M. et al. (2004) *Geophys. Res. Lett.*, 31, L04116.
Rex, M. et al. (2004) *Geophys. Res. Lett.*, 33, L23808.
Scinocca, J. et al. (2008) *Atmos. Chem. Phys. Discuss*, 8, 7388–7930.
Shepherd, T.G. (2008) *Atmos-Ocean*, 46, 117138.