Communicating Lower Stratospheric Ozone Losses to the Arctic Polar Vortex: Role of Zonally Asymmetric Ozone

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Introduction

The World Meteorological Organization Assessment of Stratospheric Ozone Loss (WMO 2007) states that in the last 27-years, the northern high latitudes (50°-90°N) have steadily cooled due to human-caused reductions in stratospheric ozone abundance. Despite this trend, the observed decrease in temperature was only half of what was expected from the earlier WMO (2003) assessment; the WMO (2007) report attributed the large discrepancy between the projected and observed ozone reductions to unknown dynamical feedbacks and natural variability. Thus it is clear that our current knowledge of ozone-dynamics interactions is incomplete.

In addition to changes in the long-term trends in ozone abundance, severe ozone loss episodes have been observed in the Northern Hemisphere lower stratosphere during the winters of 1999/2000 and 2004/2005. In light of these significant ozone losses, we investigate how perturbations to the zonal-mean ozone distribution of the lower stratosphere are communicated to the entire stratosphere and lower mesosphere via zonal asymmetries in ozone. Important questions that will be addressed include: i) Do changes in the horizontal and vertical gradients in zonal-mean ozone due to arctic ozone losses impact the vertical flux of planetary wave energy via ZAO; ii) Can ZAO provide a pathway to communicate and amplify stratospheric ozone losses local to the lower stratosphere to the entire stratosphere and lower mesosphere?

Are results indicate that zonal asymmetries in ozone amplify and communicate lower stratospheric ozone losses to the entire stratosphere and lower mesosphere.

Pathways

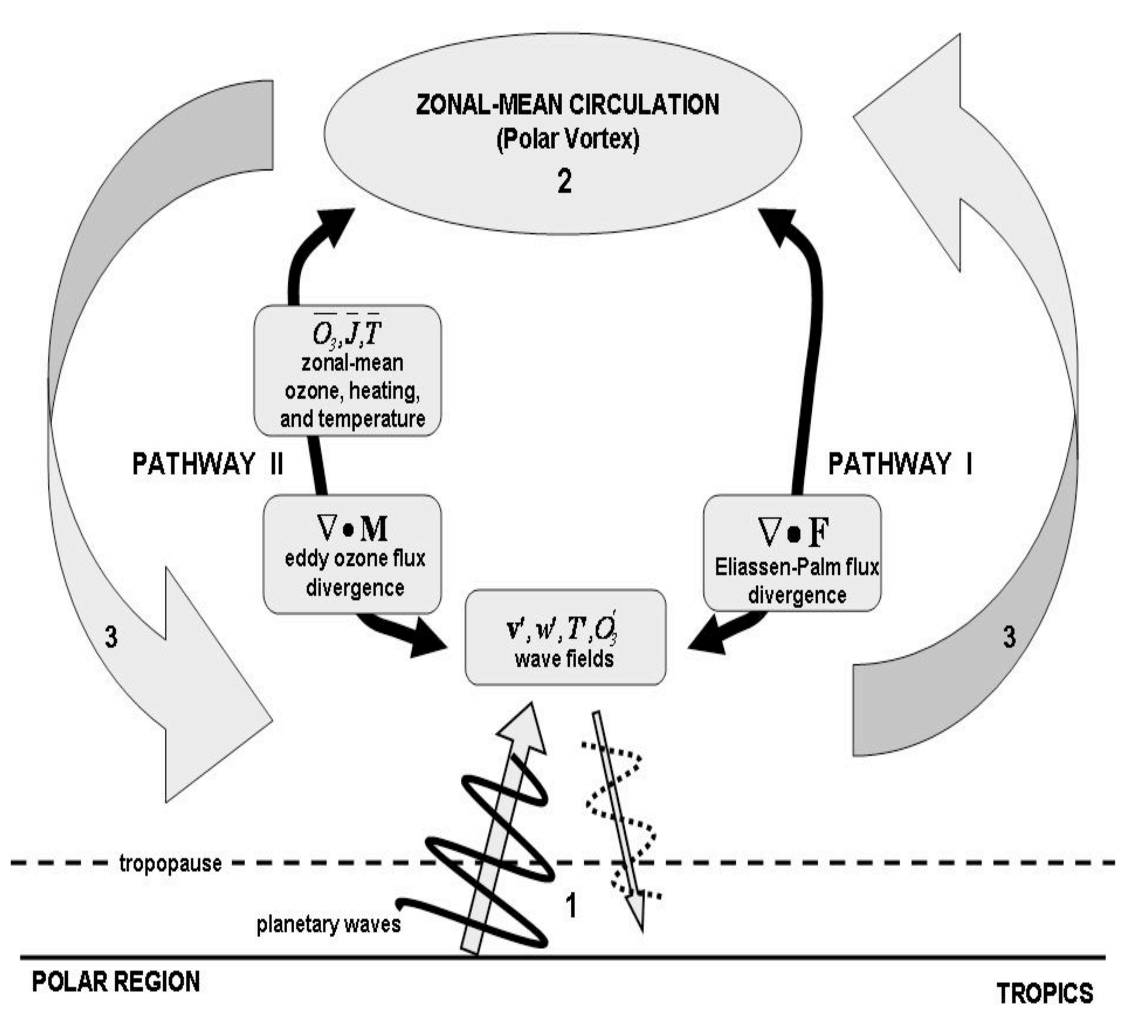

Figure 1. Schematic of ozone-modified pathways that affect wave-mean flow interaction. A planetary wave propagates vertically into the stratosphere where it is partially reflected (**1**). The phasing between the wind, temperature and ozone wave fields affects the planetary wave drag (**pathway P1**) and eddy ozone flux convergence (**pathway P2**). Along P2, the wave ozone flux convergence, wave-driven residual circulation (**3**), and zonal-mean ozone production/destruction combine to change the zonal-mean ozone heating rate and temperature. Changes in temperature produce, via thermal wind, changes in the zonal-mean wind. Pathways I and II combine to produce a net change in the zonal mean circulation, which manifests in the polar vortex (**2**) and the Brewer-Dobson circulation (**3**). Changes in the zonal-mean circulation, in turn, cause changes in the attenuation and propagation of the wave fields (Albers and Nathan, submitted to *J. Atmos. Sci.*)

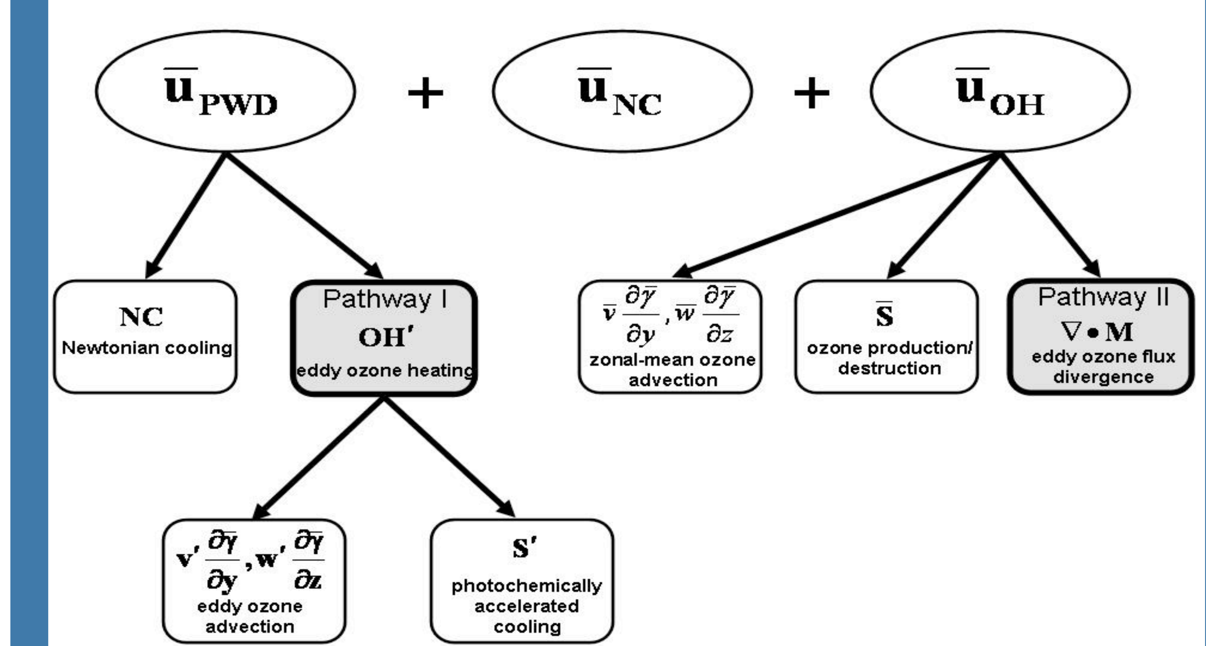

Figure 2. Schematic showing contributions to the steady state zonal-mean wind. The net driving of the zonal-mean wind is due to the combined effects of planetary wave drag ($\bar{u}_{PWD}$), Newtonian cooling ($\bar{u}_{NC}$), and ozone heating ($\bar{u}_{OH}$).

Model

We extend the Holton and Mass (1976) model to include zonally asymmetric ozone (ZAO) and zonal-mean ozone (ZMO). The quasigeostrophic model dynamics are governed by perturbation and zonal-mean equations for potential vorticity, wind, temperature, ozone, and the meridional circulation.

Experiments

We consider the relative importance of ZMO and ZAO in communicating the effects of lower stratospheric ozone loss to the entire stratosphere and lower mesosphere. Ozone losses are imposed as initial condition perturbations taken from NH observational data (Jin et al. 2006), where ozone losses are confined to the region below 30 km in height.

The three experiments considered are: a climatological control run with ZMO and ZAO (Full-O_3; O_3 CTL); ozone loss with ZMO only (Mean-O_3; ΔO_3); and ozone loss with ZMO and ZAO (Full-O_3; ΔO_3).

Results

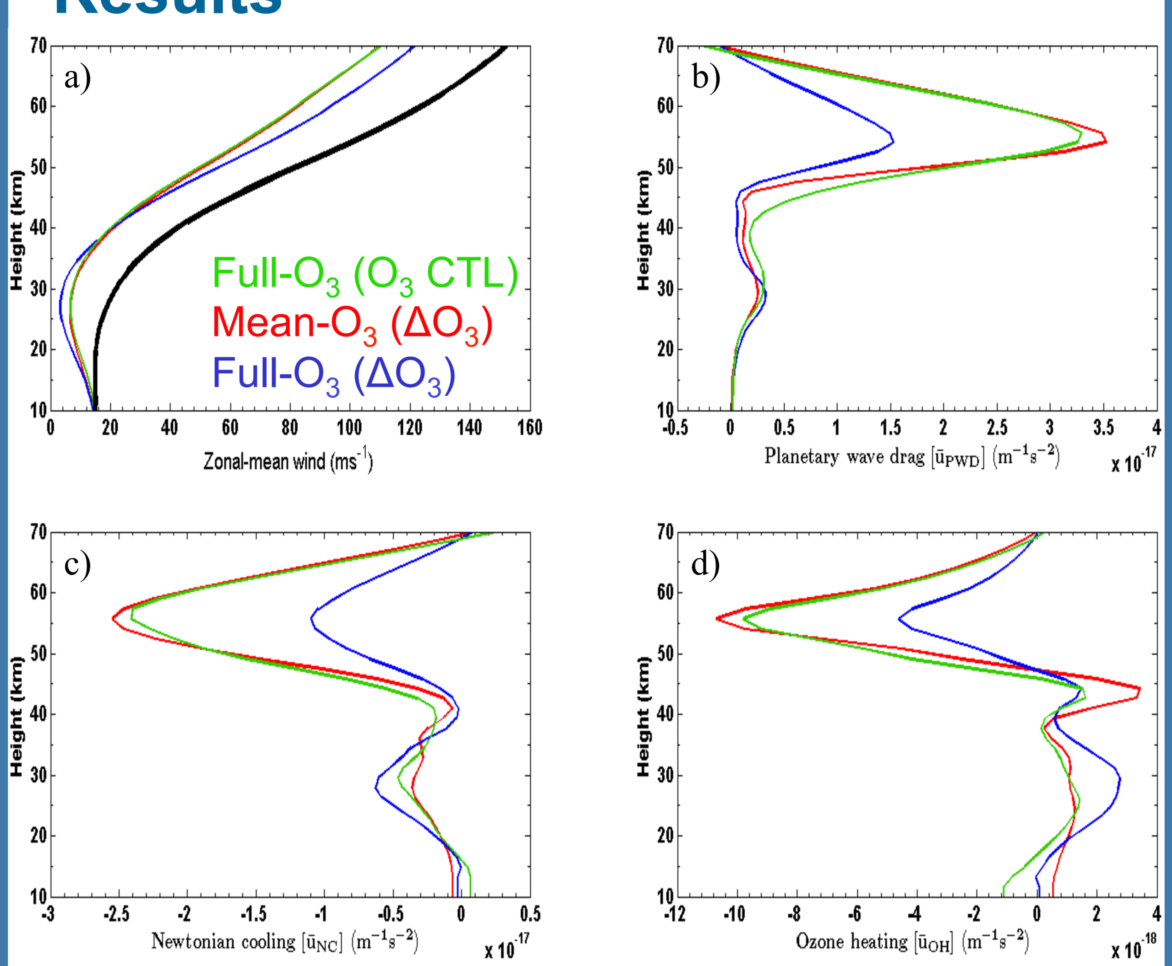

Figure 3. Response of (a) zonal-mean wind; (b) planetary wave drag($\bar{u}_{PWD}$); (c) Newtonian cooling($\bar{u}_{NC}$); and (d) ozone heating ($\bar{u}_{OH}$) to steady wave forcing. Radiative equilibrium is shown as the thick, solid, black line in Figure (a).

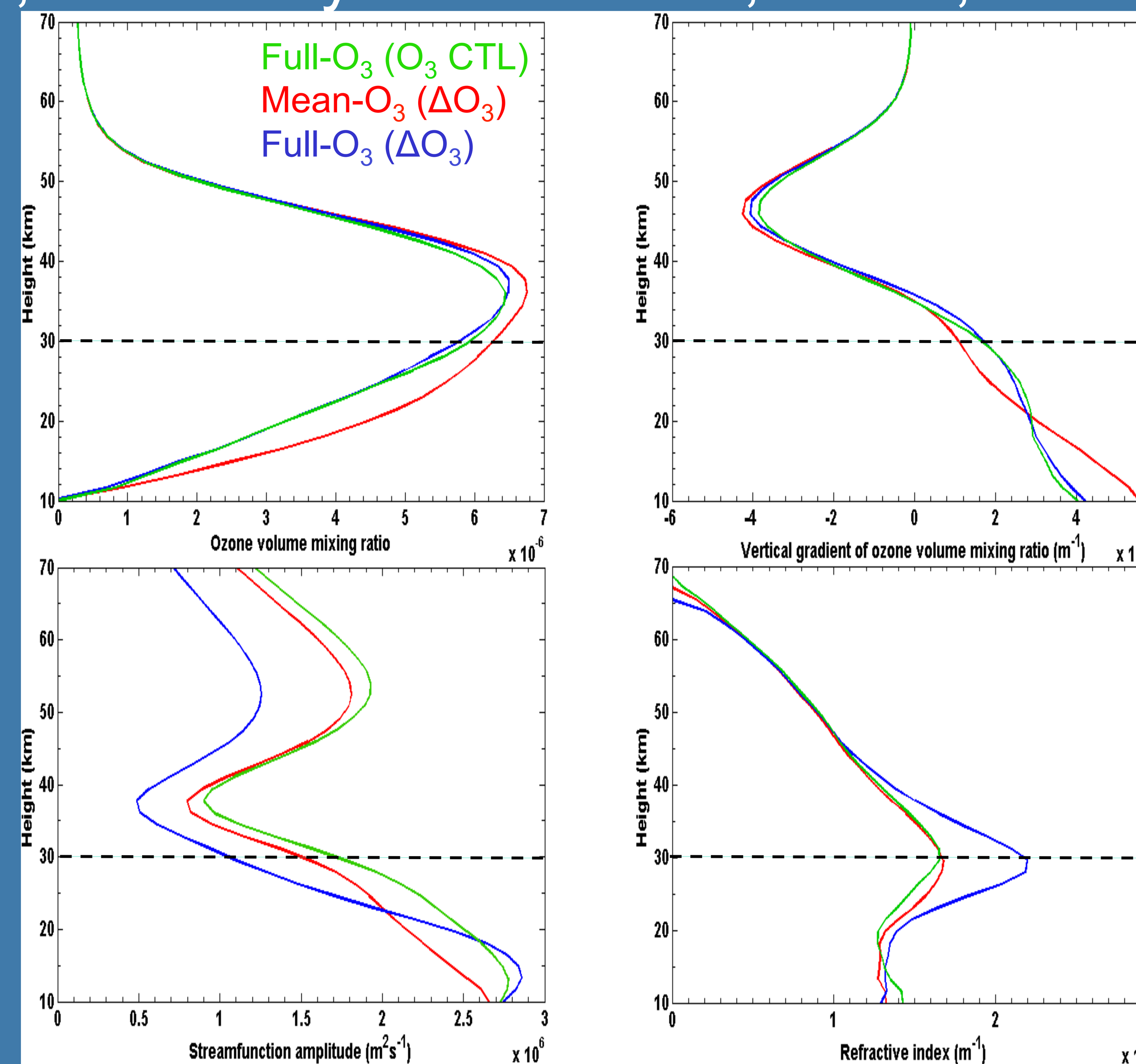

Figure 4. Response of (a) zonal-mean ozone volume mixing ratio; (b) vertical gradient of zonal-mean ozone volume mixing ratio; (c) streamfunction amplitude; and (d) refractive index. The initial condition ozone loss perturbation is confined to the region below the dashed, black, horizontal line at 30 km in height.

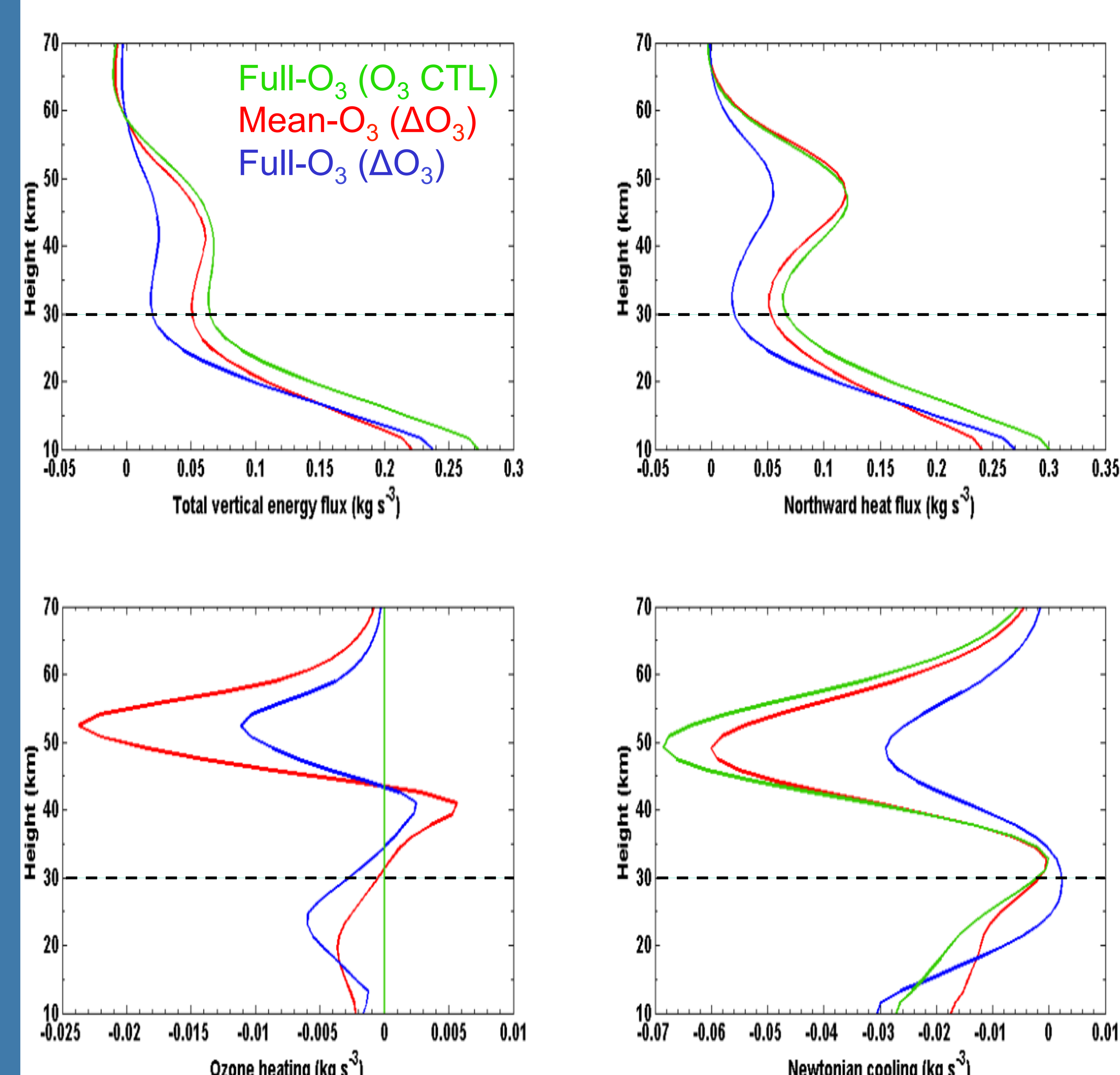

Figure 5. Response of the (a) total vertical energy flux and the three contributions to the total vertical energy flux: (b) northward heat flux; (c) ozone heating; and (d) Newtonian cooling. The initial condition ozone loss perturbation is confined to the region below the dashed, black, horizontal line at 30 km in height.

Conclusions

Lower stratospheric ozone losses observed below 30 km in height during the winter of 2004/2005 were imposed as an initial condition in a model that couples quasigeostrophic dynamics, zonal-mean ozone (ZMO), and zonally asymmetric ozone (ZAO).

- When only ZMO is included in the model, the effect of the ozone perturbation on the zonal-mean circulation is largely confined to the region local to the ozone loss (i.e. below 30 km in height)
- When ZAO is included in the model, the effect of the ozone perturbation is increased in magnitude and communicated far above the region of ozone loss (i.e. upwards to 70 km in height)
- The far field effects of the ozone perturbation are communicated primarily via ZAO along pathway P1. The changes in the zonal-mean circulation imparted by ZAO along pathway P1 are communicated by the following mechanism:
  1) A planetary wave propagates into the region of ozone loss
  2) If the ozone loss perturbation increases (decreases) the vertical gradient of zonal-mean ozone, ZAO decreases (increases) the planetary wave amplitude
  3) The decrease (increase) in planetary wave amplitude decreases (increases) the vertical energy flux leaving the lower stratosphere
  4) The decrease (increase) in the vertical energy flux leaving the lower stratosphere is associated with a decrease (increase) in planetary wave drag within the middle stratosphere and lower mesosphere
  5) The decrease (increase) in planetary wave drag results in a stronger and colder (weaker and warmer) polar vortex

Implications for climate variability

As the circulation of the middle atmosphere continues to evolve due to natural and human-induced changes to the stratospheric ozone distribution, it is important to gain an understanding of the full scope of ozone-dynamics interactions. For example, because the effect of ZAO on planetary wave drag is dependent on the gradients of zonal-mean ozone, knowledge of the precise spatial structure of changes in stratospheric ozone must be known in order to predict how Earth's future climate will change due to natural and human-induced changes in stratospheric ozone.

References

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