Mechanisms for the Acceleration of the Brewer-Dobson Circulation in a Climate Change Scenario

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Outline

• Motivation
• Model and Simulations – trends in AOA
• Trends in wave driving
• Analysis via Downward Control Principle
• Discussion
• Conclusions
Motivation: GHG increases influence stratospheric circulation

Mass flux trends ~ 10 kton sec\(^{-1}\) yr\(^{-1}\): a robust result seen in many GCMs
Whole Atmosphere Community Climate Model, Version 3

**WACCM3**
- Extension of NCAR’s CAM3 to lower thermosphere (domain 0-140 km; 66 levels)
- Fully interactive chemistry-dynamics; Lin (2004) FV advection
- $\Delta z \sim 1$ km (troposphere, UTLS) ... $\sim 3$ km (MLT); $\Delta x, \Delta y \sim 2^\circ \times 2.5^\circ$ or $4^\circ \times 5^\circ$
- GW parameterization: orographic + spectrum
- UV, EUV heating and NLTE IR in MLT
  
  References: Garcia et al. (2007), Kinnison et al. (2007), Marsh et al. (2007)

**REF1 Simulation**
- Ensemble of 4 simulations, 1950-2003
- Observed SST, GHG, CFC
- Volcanic aerosol effects

**REF2 Simulation**
- Ensemble of 3 simulations, 1975-2050
- SSTs from CCSM3 IPCC A1b simulation
- Trends in trace gases from A1b scenario 1995-2050

**NCC Simulation**
- “No climate change”
- Ensemble of 3 simulations, 1995-2050
- Same as REF2, *except that CO$_2$, CH$_4$ and N$_2$O are held constant to 1995 values*
Age of Air: Tropical Average at 10 mb

AOA decreases systematically in REF1, REF2; does not change significantly in NCC
• Much of the change in AOA occurs in the lower stratosphere; much of the cumulative trend at 10 mb (red dots) shown earlier is due to changes below 50 mb (~20 km; red circles)
• The lower stratosphere trend is associated with an increase in the BDC in the Tropics and subtropics (arrows)
• In REF1 there is also significant change over the SH polar cap at most altitudes (blue oval)
Trends in (resolved) $\text{div}(\mathbf{F})$ (m s$^{-1}$ day$^{-1}$ decade$^{-1}$) and $\mathbf{F}$ (kg s$^{-2}$ decade$^{-1}$)

- Except for the SH polar cap in the period of rapid ozone loss (REF1; blue oval), statistically significant changes in $\text{div}(\mathbf{F})$ are confined mainly to the lower subtropical stratosphere (red ovals); it is shown next that these account for much of the change in the BD circulation.

- A robust result for REF1 and REF2, although the morphology of the trend in $\mathbf{F}$ varies somewhat.
Attribution: mass flux from Downward Control

The Downward Control (DC) Principle (Haynes et al., 1991) yields the following expression for the vertical mass flux, $M$, averaged between latitudes $\theta_1$ and $\theta_2$:

$$M = \int_{\theta_1}^{\theta_2} 2\pi a^2 \rho \cos \theta w^* d\theta = 2\pi a^2 \left[ \int_{z}^{\infty} \rho \cos^2 \theta \left( \frac{\rho a \cos \theta}{m_\theta} \right)^{-1} \nabla \cdot F + X \right] d\theta'$$

where:

- $\theta$ is latitude, $z$ is log-pressure altitude, and $a$ is the Earth’s radius
- $\rho = \rho_0 \exp(-z/H)$ is the density in log-pressure coordinates
- $m_\theta$ is the zonal-mean angular momentum
- $F$ is the Eliassen-Palm flux and $X$ is the zonal-mean force due to parameterized gravity waves

$M$ depends only on the vertical integral of the wave forcing at the edges of the region bounded by the latitudes ($\theta_1$, $\theta_2$). The expression may be applied over any latitude range where DC is expected to hold; it is used here to evaluate trends in tropical upwelling, as well as the compensating trends in downwelling in extratropical regions.
• Tropical-mean vertical mass flux profiles reveal clearly two distinct regimes: above and below ~20 km
• Most of the trend in mass flux trend occurs in the lowermost stratosphere (< 20 km) and is due to changes in del(F) due to resolved waves (tropical Rossby waves)
• In the middle/upper stratosphere (> 20 km) the trend is dominated by changes in parameterized GW forcing; however, in REF1 a significant fraction comes from resolved waves (extratropical planetary Rossby waves)
Applicability of the DC Principle

• The width of the tropical upwelling and extratropical downwelling regions varies with altitude (left panel).
• Choice of tropical region cannot be too broad in lower stratosphere or else tropical averages will include both upwelling and downwelling.
• Defining the Tropics to encompass ±22° is a good compromise: (a) coincides with the conventional definition; (b) includes mainly upwelling in the lower stratosphere; (c) includes the strongest upwelling in the middle and upper stratosphere.
• Angular momentum distribution (right panel) indicates that DC should be applicable at ±22°.
Tropical vs. Extratropical $M$ Trends (REF1)

- In the lower stratosphere (< 20 km) tropical trend in $M$ (blue arrow) is balanced by the trend in midlatitudes only (red arrows).
- In the middle and upper stratosphere (> 20 km), much of the extratropical trend in $M$ occurs over the SH polar cap.
- The SH polar trend is forced partly by the large trend in extratropical div($\mathbf{F}$) shown earlier (which is related to changes in SH winter westerlies associated with the development of the ozone hole), and partly by parameterized GW trends (not shown).
- REF2 results are similar, but the SH polar cap no longer dominates the extratropical trend, and trends are due mainly to changes in GW forcing.
Discussion:

• Changes in AOA are driven by changes in the BD circulation

• Most of the change in AOA occurs in the lower stratosphere and is driven by the acceleration of the BDC in the Tropics and subtropics

• Changes in the BDC below 20 km are explained largely by changes in div($\mathbf{F}$) in the subtropical lower stratosphere

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– *What causes the trend in div($\mathbf{F}$) in the lower stratosphere?*
Time-mean and Trend of $\text{div}(\mathbf{F})$ (REF1)

- Most wave activity generated in the troposphere [$\text{div}(\mathbf{F}) > 0$] is dissipated there [$\text{div}(\mathbf{F}) < 0$] (left panel)
- Trends in wave activity are mostly insignificant except in Tropics (right panel)
- BD circulation in lower stratosphere is driven by subtropical $\text{div}(\mathbf{F}) < 0$ between 15-20 km
- BD circulation trends result from intensification and upward extension of subtropical $\text{div}(\mathbf{F})$ centers (red circles)
- Results for REF2 case are similar, although details differ
Zonal-mean T, U and F Trends: focus on UTLS

- Tropospheric warming and stratospheric cooling driven by GHG sharpens zonal-mean T gradients in the lower stratosphere.
- Zonal-mean U changes accordingly.
- Trends in F (superimposed on U trends) coincide with regions of increasing westerlies in the lower stratosphere.
- Suggests trends in $\text{div}(F)$ in subtropical lower stratosphere may also be related to enhanced wave propagation into the region.
Changes in Q are not large compared to maximum time-average values.

But they are comparatively much larger in the upper troposphere above 10 km.

Therefore, changes in the excitation of tropical Rossby waves may play a role in the increased wave driving documented here.
Conclusions

• Increasing GHG lead to stronger stratospheric BD circulation
• Acceleration of BD circulation (and decrease in AOA) occurs *mainly in lower stratosphere*
• Trends are driven mainly by changes in $\text{div}(\mathbf{F})$ *in subtropical lower stratosphere* (15-20 km)
• Trends in $\text{div}(\mathbf{F})$ in the lower stratosphere related to:
  — increases in convective heating in the Tropics?
  — enhanced wave propagation into the lower stratosphere following from changes in the zonal wind distribution?
• There are also significant trends in the *SH high latitudes* associated with the development of the *ozone hole*
• Results are consistent in two simulations (REF1, 1950-2003) and (REF2, 1980-2050), although details differ