On the relationship between the strength of the Brewer-Dobson circulation and the age of stratospheric air

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[1] The strength of the Brewer-Dobson circulation is computed for multi-decadal simulations of a coupled chemistry-climate model covering the period 1960 to 2100. The circulation strength, as computed from the tropical mass upwelling, generally increases throughout the simulations. The model also includes an age of air tracer which generally decreases during the simulations. The two different transport concepts of mass upwelling and reciprocal of the age of air are investigated empirically from the model simulations. The results indicate that the variables are linearly related in the model but with a change of gradient some time near 2005. Possible reasons for the change of gradient are discussed. **Citation:** Austin, J., and F. Li (2006), On the relationship between the strength of the Brewer-Dobson circulation and the age of stratospheric air, *Geophys. Res. Lett.*, *33*, L17807, doi:10.1029/2006GL026867.

1. Introduction

[2] The so-called Brewer-Dobson circulation [*Holton et al.*, 1995] is a global circulation which in the annual average consists of motion which is upward in the tropics and downwards in the middle and high latitudes. The tropical mass upwelling in the very low stratosphere is a measure of the strength of the Brewer-Dobson circulation [*Butchart and Scaife*, 2001] and in multi-decadal simulations of a climate model was shown to increase mainly due to an enhancement of the planetary wave driving in the lower stratosphere. The year to year fluctuations in the circulation were found to be large, but over long time scales an overall increase in tropical upwelling was found to occur. This is supported by recent results from a wide range of simulations of independent models [*Butchart et al.*, 2006].

[3] Model simulations suggest that the rate of increase of the mass upwelling varies from decade to decade. For an ensemble of simulations for the recent past, *Austin et al.* [2006] found that the tropical upwelling was approximately constant for the period 1960 to 1975, but then increased rapidly for the next 20 years. It is possible that the change in circulation trend from 1975 may have been related to the loss of ozone from that time. The coupling of the system is thus suggested by the likelihood that changes in circulation will change ozone transport and that the ozone itself will also affect the circulation.

[4] An alternative measure of circulation strength is the age of stratospheric air [e.g., *Hall and Plumb*, 1994; *Waugh and Hall*, 2002], which is essentially the mean time since the air parcel previously resided in the troposphere. It might be expected that mean age of air and the strength of the Brewer-Dobson circulation are closely connected, but despite the established trend in simulations of the latter, there has so far been no clear indication in the published literature that age of air might change systematically either in the atmosphere or in models. The relationship with atmospheric transport is also not yet clearly established. Although several works have recognized the relationship between heat fluxes and ozone transport [*Salby and Callaghan*, 2002; *Weber et al.*, 2003] these have referred primarily to interannual and not to secular variations.

[5] In this work, we use multi-decadal simulations of the GFDL coupled chemistry climate model (AMTRAC — Atmospheric Model with TRansport And Chemistry) to relate the strength of the Brewer-Dobson circulation with the stratospheric age of air.

2. Model Description and Simulations Completed

[6] The model simulations are described by *Austin and Wilson* [2006] and include an ensemble of three members covering the periods January 1960 to January 2005 and January 1990 to January 2100. The past simulations used observed sea surface temperatures (SSTs) as forcing data. The future simulations used SSTs from the GFDL coupled atmosphere ocean model. Apart from the usual photochemical and dynamical fields, the model simulates the age of stratospheric air, treated as a ‘clock tracer’ [*Schoeberl et al.*, 2005].

3. Strength of the Brewer-Dobson Circulation

[7] Following *Butchart and Scaife* [2001] the tropical upward mass flux was determined in the model simulations by integrating the residual meridional circulation between the latitudes near the tropics where the circulation is upwards. In the formulation presented by *Austin et al.* [2003], the upward mass flux was calculated for the model level at 77 hPa as the difference in the mass stream function F_m between the ‘turnaround latitudes’, where the circulation changes from upward to downward.

[8] The turnaround latitudes and upward mass flux are shown in Figure 1 for the period 1960 to 2100. All the values have been computed from daily data and annually averaged. The turnaround latitudes decreased slightly between about 1975 and 2000, but otherwise remained constant, consistent with the results of *Butchart and Scaife* [2001]. The corresponding upward mass flux (Figure 1, bottom) increased overall but there were several periods when the mass flux changed little (1960 to 1975) or even

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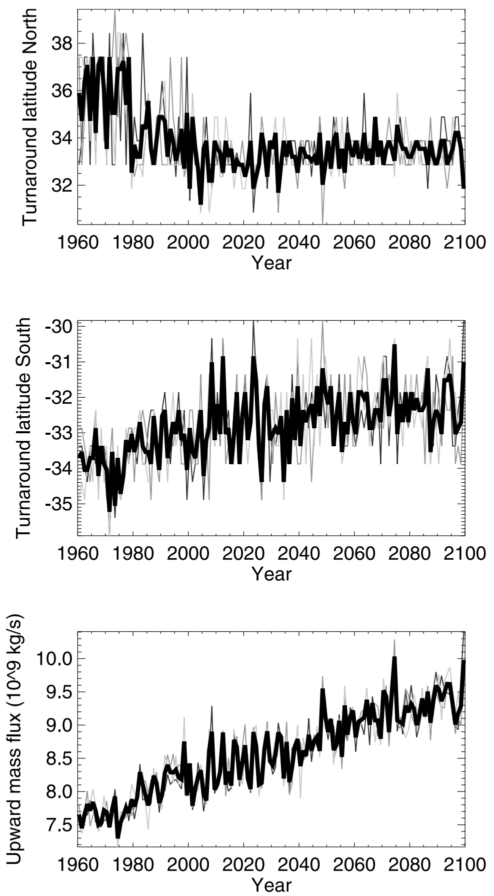

Figure 1. (top and middle) 'Turnaround' latitudes corresponding to the change in annually averaged circulation from upwards to downwards for the three ensemble simulations. The thin lines are the results for the individual model experiments (gray scaling) and the thick black line is the average for all three ensemble members. (bottom) Annually averaged upward mass flux at 77 hPa between the turnaround altitudes.

decreased (1995 to 2005). During 1975 to 1995 the upward mass flux increased at a more rapid rate, as demonstrated by *Austin et al.* [2006].

4. Stratospheric Age of Air

[9] The annual mean stratospheric age of air, averaged for all three ensemble members is shown in Figure 2 as a function of latitude and pressure. Values for representative years at 40–50 year intervals are shown. The position of the tropopause is indicated approximately by the 0.1 year contour in each of the figure panels. The values increase towards the model upper boundary (0.002 hPa) and towards the polar regions. These results are generally consistent with previous calculations [e.g., *Hall et al.*, 1999] and also indicate for the year 2000 atmosphere a significant underprediction of order 20% compared with measurements [e.g., *Andrews et al.*, 2001; *Schoeberl et al.*, 2005]. Despite the wide separation in model time for the results in each panel of the figure, the structure of the age of air is almost identical. However the most important aspect of the results is that the age of air decreased substantially over the course of the simulations. This is most clearly seen in Figure 3. For example, in the polar lower stratosphere the age of air decreased from 4.8 years in 1960 to 3.6 years by 2099, but with the change occurring more rapidly at some times than at others. There were also several periods, 1960–1975, 2020–2040 and possibly 2080–2099 when the age of air had no appreciable trend. These features occurred in the results of all the ensemble members.

5. Comparison of Time Averaged Tropical Upwelling With Age of Air

[10] Age of air represents the atmospheric transport over a duration of the mean age of air itself. To compare tropical upwelling with the age of air, we have therefore averaged the former over the previous four years (the results do not depend critically on the averaging period in the range 3–5 years). In Figure 4 is plotted the reciprocal of the age of air in the lower stratospheric northern polar region (60–90°N) versus the tropical upwelling. Similar results are obtained using the stratospheric age at other locations, as implied from Figure 3. The least squares linear curve fits through the points are shown as a solid line and a dotted line for the past and future respectively. There is a ten year period of overlap between the results of the past and the future experiments, but the data are not easily distinguishable in the figure. The figure shows that the functional relationship between age of air and tropical mass flux is different for the past run than for the future run.

[11] The direct variables in Figure 4 have correlation coefficients of about 0.94 and 0.93 for the past and future respectively, but this is dominated by the long term trends in both variables. Table 1 shows the correlation coefficients between the reciprocal of the age of air at 46 hPa and the

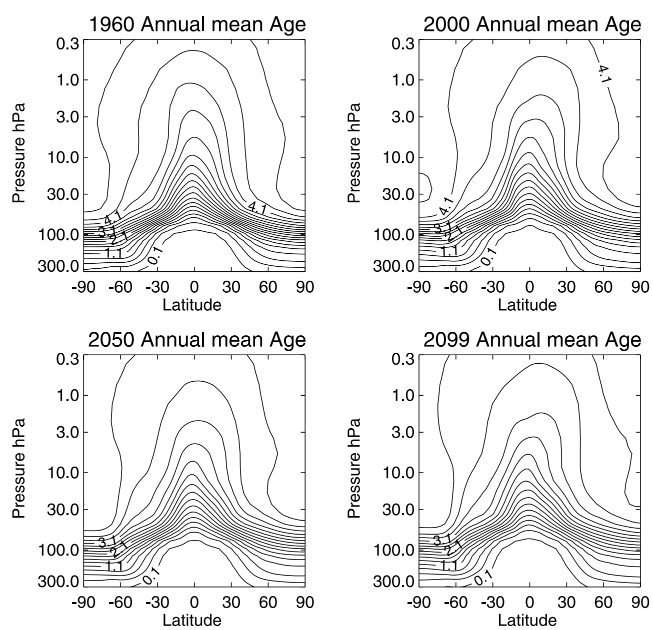

Figure 2. Annual mean stratospheric age (years) as a function of pressure and latitude, averaged over the three simulations for the years 1960, 2000, 2050 and 2099. The contour interval is 0.25 in all four plots starting at 0.1, indicating the approximate position of the tropopause.

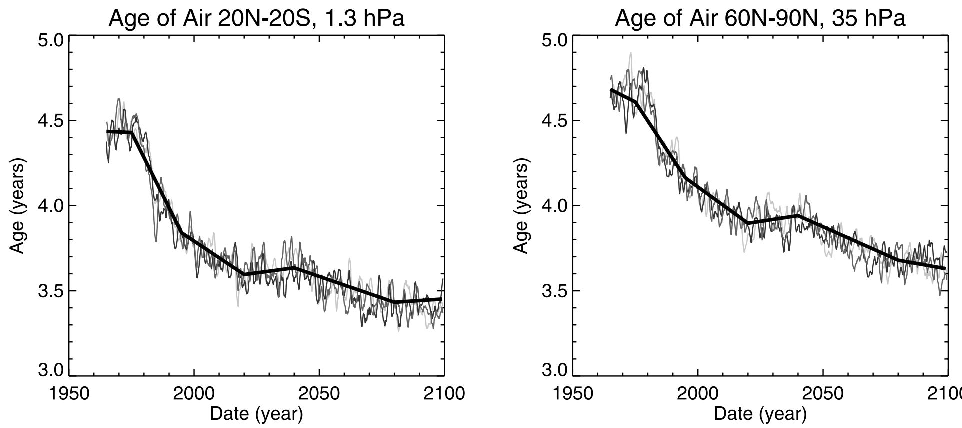

Figure 3. Simulated annual mean stratospheric age (years) as a function of time, (left) in the upper tropical stratosphere and (right) in the Arctic lower stratosphere. The thin lines (gray scaling) are the individual model simulations. The thick black line is a piecewise linear functions through the results.

tropical upwelling for the past and future, after removing the long-term trends. For the individual simulations, the correlation coefficients are in the range 0.55 to 0.81 for the hemispheric average of the age of air. The impact of spatial variability is reduced further in the global average values and in the ensemble mean. These correlations are all statistically significant.

6. Conclusion and Discussion

[12] We have demonstrated that the upward mass flux (averaged over the previous four years) in long coupled chemistry-climate model simulations, is a linear function of the reciprocal of the stratospheric mean age. Hence, the previously demonstrated increase in upward mass flux [*Butchart and Scaife*, 2001; *Butchart et al.*, 2006] is entirely equivalent to an overall decrease in stratospheric age. Moreover, the rate of change of age of air was not constant during the simulations. As we have demonstrated previously [*Austin et al.*, 2006] variations in the rate of change of the circulation had important implications for the water vapor concentrations simulated by the model.

[13] The relationship between reciprocal age of air and tropical upwelling is either a piecewise linear function with change in gradient near the current time, or there are model differences between the past and future simulations. The reasons for any change in gradient are unclear. By averaging over the ensemble members and obtaining a clearer signal, we can be confident that this is not due in some way to model internal variability. Therefore, the changes must be due to external forcing parameters of the system, which are the sea surface temperatures (SSTs), and the concentrations of the greenhouse gases (GHGs) and chlorofluorocarbons (CFCs). It is unlikely that the GHGs are responsible, since their variability is smooth and there is no characteristic change near the year 2000–2005. One possibility is that in changing from observed to model SSTs for the future simulations, tropospheric planetary waves have been

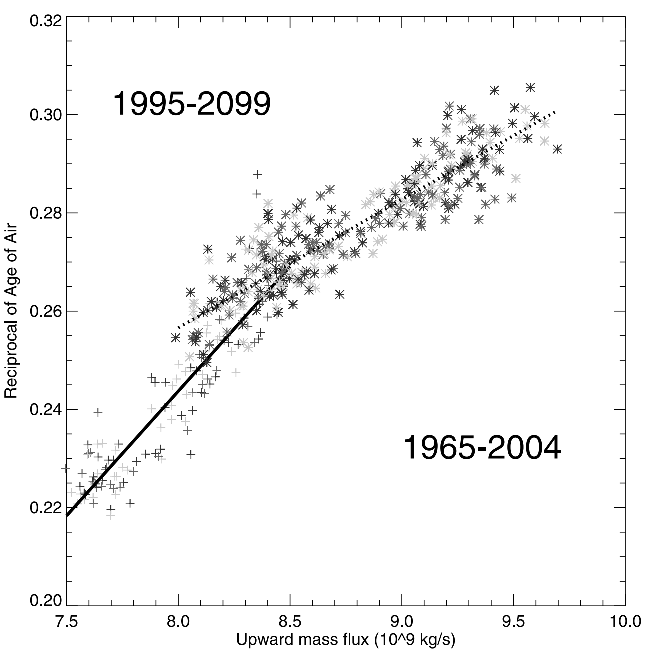

Figure 4. Stratospheric age of air, averaged polewards of 60°N at 47 hPa plotted as a function of tropical upwelling in the model simulations. The plus symbols denote results from the past simulation, with a gray scale denoting the ensemble member (of three). The asterisks denote similar results from the future simulations, with dates indicated in bold. The solid and dotted lines are linear regressions through the past and future results respectively.

Table 1. Correlation Coefficient Between the Reciprocal of the Hemispheric and Globally Averaged Age of Air and the Tropical Mass Upwelling After Removal of the Overall Trends[a]

Expt.	Period	SH	NH	GA
A	1965–2004	0.666	0.738	0.759
B	1965–2004	0.756	0.809	0.830
C	1965–2004	0.706	0.641	0.748
Mean	1965–2004	0.728	0.769	0.797
A	2005–2099	0.562	0.612	0.646
B	2005–2099	0.686	0.673	0.733
C	2005–2099	0.559	0.677	0.710
Mean	2005–2099	0.691	0.689	0.744

[a]Results are given for two periods, for the three ensemble members, denoted A, B, C and for the ensemble mean. The results for the northern and southern hemispheres and the global average are denoted NH, SH and GA respectively.

affected, leading to a changed relationship between GHGs and tropical upwelling.

[14] Other evidence, such as the absence of a significant trend in age of air for 1960 to 1975 when ozone in the model was increasing, together with the large reduction in age of air when major ozone destruction occurred, would suggest that the CFCs were largely responsible for the circulation change. If this were confirmed, by further model simulations, the results would provide a clear demonstration of the coupled nature of the atmospheric climate system.

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