Supplementary Information for “The strength of the meridional overturning circulation of the stratosphere”

Marianna Linz, R. Alan Plumb, Edwin P. Gerber, Florian Haenel, Gabriele P. Stiller, Douglas E. Kinnison, Alison Ming, and Jessica L. Neu

Included in this supplementary information is a more thorough examination of age and age difference from the two satellite data products, GOZCARDS N$_2$O$^{30}$ and MIPAS SF$_6$.$^4$ It includes how we chose the upwelling and downwelling regions, use of a different empirical relationship to calculate age from N$_2$O, a comparison between N$_2$O-age and MIPAS SF$_6$-age, an extrapolated extension of the N$_2$O age difference, and plots of age of air from MIPAS SF$_6$ on surfaces above and below 500 K.

Choosing the upwelling region

Because satellite data do not reveal where air is upwelling and where it is downwelling, we must choose the latitudinal extent of the upwelling region in some other way. For this paper, we have chosen 35° N and S. Using 40° in a simple atmospheric GCM was very close to using the actual upwelling and downwelling regions at all heights (ref. 11 Figure 8). To determine whether these are characteristic turnaround latitudes for the real atmosphere, we have plotted the total diabatic vertical velocity climatology from MERRA at four different levels in Figure S1. The lower levels have less seasonal variability, while at upper levels, upwelling extends poleward of 50° in some seasons, and downwelling reaches nearly to the equator. We are satisfied with using 35° as an approximate average of this strong variability over the course of the year for all levels. The coarse meridional resolution of the GOZCARDS N$_2$O (10°) does not lend itself to more precision than this, and choosing 40° for the upper levels with MIPAS makes little difference as the meridional gradient of age in the midlatitudes is relatively weak.

These climatologies are also useful to visualize the difference between the diabatic vertical velocity on isentropes and the transformed Eulerian mean vertical velocity on pressure surfaces, which has a narrower extent in the lower stratosphere and a wider extent in the upper stratosphere. The upwelling associated with the motion of the isentropes during the final warming is evident at all levels, and is not seen in the transformed Eulerian mean vertical velocity in pressure coordinates. This polar upwelling does not strongly bias the area-weighted age differences as compared to the mass-flux-weighted age differences because it occurs for such a short period of time and at the pole, where there is much less area. Note that the climatology at 1200 K is somewhat suspect because of sparseness of observations that are assimilated at that level. (See Ref. 9, Figure 1.)
Figure S1: Climatology of the zonal mean total diabatic vertical velocity, calculated as the total potential temperature tendency divided by the mean stratification ($\dot{\theta}/\Theta_z$), from MERRA monthly means from 1979–2013 on four different levels. At 1200 K, the vertical velocities at both poles in winter are larger than this color scale shows. Contours are spaced every $1\times10^{-4}$ m/s.
Calculating age from GOZCARDS $N_2O$

For this study, we used the cubic empirical relationship between $N_2O$ and age of air calculated from a large number of aircraft flights\textsuperscript{29}, and it has a relatively wide range of $N_2O$ values over which it is apparently valid. To explore the robustness of this result, we have used two different empirical relationships, both linear, based on the data from ref. 31 shown in Figure S2 (courtesy of S. Strahan, personal correspondence).

![Figure S2: Co-located age and $N_2O$ concentrations from balloons, ACE, and flights. Points above 50 hPa are in teal, tropical points below 50 hPa are in blue and extratropical points below 50 hPa are in red. Three different lines are shown. The black line is the overall fit to all points with $N_2O$ above 150 ppb. The red line is the fit to the extratropical points, and the blue line is the fit to the tropical points. The black dotted line shows the cubic relationship\textsuperscript{29}, which has been adjusted for the trend in tropospheric $N_2O$ as described in the Methods.

The $N_2O$ data Figure S2 are six year means of observations from the Atmospheric Chemistry Experiment (ACE) instrument onboard SCISAT-1, 68°S-68°N from 150 hPa. The age data are from balloon $CO_2$ profiles in the tropics and both $CO_2$ and $SF_6$ balloon measurements in the midlatitudes\textsuperscript{2} and from the same aircraft flights used by ref. 29 at 50 hPa. The points that overlap in altitude and latitude (regardless of timing) are shown in the scatter plot. This decision to look at colocated points without accounting for changes in timing neglects the considerable seasonal and interannual variability. The compact relationship appears to hold for values of $N_2O$ above 150 ppb and below 315 ppb. Although the same fit was calculated including the tropical points and the midlatitude points together, there
is reason to believe that the tropical and extratropical relationships should be different, and so we have calculated the slopes separately for the tropical points and the extratropical points beneath 50 hPa (shown in blue and red lines) for comparison to the original fit (shown in the black line). The original fit, which was calculated from data up to 10 hPa in the tropics and up to 30 hPa in the extratropics, is dominated by the extratropical points, with the same slope and nearly the same intercept. When the tropics are treated separately, the relationship appears different. Both tropical and extratropical fits are performed using reduced major axis regression with each variable scaled by its standard deviation and are significant at the 95% level. To create a smoother transition, the 35° points are the average of the age from the extratropical and the tropical fit \( \Gamma = -0.035 \times N_2O + 11.36 \). However, there are still artefacts of using this relationship evident in the meridional gradient of the age, and so we do not calculate age difference using this. The original fit was used in ref. 31. The cubic fit of does not agree as well with these more recent data except in the tropics. In particular, the newer data never have an age above 5 years, whereas the measurements that went into the cubic fit included values of nearly six years. This difference could reflect a difference in the methods or a change in the \( N_2O \) age relationship over the course of a decade.

Figure S3 shows the zonal mean 2007–2011 mean age of air calculated using these three different empirical relationships. In the upper row, the mean values of the existing data are shown, neglecting data gaps. The bottom row shows only the points for which continuous data is available between 2007–2011. Ages are oldest using the cubic relationship (left), with the extratropics and tropics older than the age using the linear fit by about 0.5 yr for lower levels. The linear fit that does not treat the tropics separately (middle column) has the youngest tropical air, while fitting the tropics separately results in older air, though not as old as the cubic. Because the linear fits for the separate regions were calculated with only data at or below 50 hPa, the relationship shown in the right column is only valid up to that level, and the transition between the two fits is very evident. The tropical data for the cubic relationship in the upper left panel is biased high because the only times the relationship holds at lower levels are when the tropical air has unusually low \( N_2O \).

We explore the data gaps and how they lead to biases by looking at the time series of the age determined using both the cubic and linear relationship. These are shown at five different pressure levels in Figure S4. The ages calculated using the cubic relationship are older than those from the linear relationship. Because of the different ranges of \( N_2O \) over which they are valid, the two relationships produce different data gaps. The cubic relationship does not hold above 300 ppb, making tropical coverage very limited at 100 hPa. At 68 hPa, there is only one gap in the data, and at 46 hPa, the data gaps are all now in the Southern Hemisphere winter pole, where the air is oldest. For the purposes of the paper, I have not used anything above 46 hPa, since the long data gaps in the Southern Hemisphere winter above that level will cause biases of unknown magnitude (there are no in situ measurements of South Pole SF6 at these levels). Looking at Figure S4, it is evident why this linear relationship was not appropriate for drawing conclusions about the strength of the circulation. The linear relationship holds only below 315 ppb, which adds some tropical coverage compared to the cubic relationship. However, already at 68 hPa, the polar air is getting below 150 ppb, the lower limit for this linear relationship, in Southern Hemisphere winter. By 46 hPa, the polar air is almost always out of the range.
Figure S3: The average age of air as a function of latitude and pressure based on GOZCARDS \( \text{N}_2\text{O} \) data from 2007–2011 that has been converted to age of air using three different relationships: In the left column, the cubic relationship\(^{29}\) is used. In the middle column, the linear relationship\(^{31}\) is used. In the right column, the linear relationships shown above in Figure S2 for the tropics and extratropics are used. The right column is shaded above 50 hPa because the linear fits for this column were calculated only for points beneath 50 hPa. The first row is the mean value neglecting any data gaps, and the second row is the mean value only where there are no data gaps for the five years. Contours are every half year.

of the empirical relationship. This relationship yields younger ages (about 0.5 yr) in the tropics and midlatitudes and similar ages at the poles. Because they are derived from the same data, the two different age relationships are highly correlated.
Figure S4: 2007–2011 zonal mean age on four different pressure levels, calculated using the cubic empirical relationship between age of air and N$_2$O (from GOZCARDS)$^{29}$ (left column) and using the linear empirical relationship between age of air and N$_2$O$^{31}$. Contours are every half year.
Comparison of GOZCARDS $N_2O$-age and MIPAS $SF_6$-age

This study benefits from having two completely independent global satellite data products that cover the same time period. This section presents a comparison of the age from these two different data products.

Figure S5: Vertical profiles of age of air from MIPAS $SF_6$ and using three different empirical relationships for the relationship between $N_2O$ and age of air. The left panel is January 2007 and the right panel is June 2011. The blue lines show tropical profiles (5°N) and the black lines are extratropical or subpolar (55°N). Solid lines are MIPAS $SF_6$-age, long dashed lines are derived from the cubic relationship between $N_2O^{29}$, bold dotted lines are derived from the linear relationship between $N_2O$ and age of air$^{31}$, and the thinner dotted lines are derived from the different tropical and extratropical linear fits between $N_2O$ and age shown in Figure S2. Where the profiles are based on extrapolation of the fit to levels for which there was no data informing the fit, they are shown in light blue and gray and are thin.

In Figure S5, we show monthly mean vertical profiles of age from MIPAS $SF_6$, and from the three different relationships between GOZCARDS $N_2O$ and age presented in Figure S2. On the left is January 2007 in both a tropical and an extratropical Northern Hemisphere location. On the right is June 2011 for the same locations. The MIPAS $SF_6$ age is consistently older than the $N_2O$ age in the tropics, except at the lowest level in January of 2007. This is consistent with the small high bias seen previously$^4$. In the subpolar region, the cubic $N_2O$-age is closer to the MIPAS $SF_6$-age, and in June the $SF_6$-age is actually younger than the cubic $N_2O$-age. Both linear relationships produce ages from $N_2O$ that are younger than the MIPAS $SF_6$-age. Higher in the stratosphere, the difference between the extratropical $SF_6$-age and the cubic $N_2O$-age becomes more pronounced, with the $SF_6$-age being higher.
by at least two years at 20 hPa. It is possible that this is the influence of the mesospheric sink, though that would be more prominent at high latitudes only. Because vortex air is mixed to low latitudes after the vortex breakdown, the influence of the mesospheric sink is not necessarily limited to these polar regions. The ages calculated using separate tropical and extratropical linear relationships agree more closely with the cubic relationship in the tropics and with the linear relationship in the extratropics. The seasonal difference is not large.

In order to calculate the age difference on an isentrope, both satellite data products are interpolated to isentropes on a finer grid than either are reported on. MIPAS SF₆-age is calculated at height levels, and both temperature and pressure are simultaneously retrieved. GOZCARDS N₂O is reported on pressure levels. The interpolation method makes only a small difference. Nevertheless, it is important to recognize that the multiple isentropic levels reported here are, for N₂O, based on about three levels in the original data. Because of the seasonal motions of the isentropes in pressure, the data gaps look different from the gaps on pressure levels. Figure S6 shows time series of the zonal mean age of air from GOZCARDS N₂O on isentropes using the cubic relationship and the linear relationship respectively. Figure S7 shows the same for the MIPAS SF₆-age. The color bar is the same for both figures and has a maximum at 5.5 years, which is saturated for the SF₆-age. For the N₂O-age, the final warming period is associated with the 420 K surface dipping down below the measurement range of GOZCARDS, so the data gaps are the same for both top panels of Figure S6. Other data gaps are different, based on where the two empirical relationships apply. Generally, again we can see that the cubic relationship results in older ages overall, except at the poles, where the linear relationship makes the air relatively older.

The MIPAS SF₆-age is noticeably older than either of the N₂O-ages. Age on the 420 K surface is older than 5.5 years for the Southern Hemisphere wintertime vortex. This is surprisingly old, but there is no in situ data to compare with at those latitudes. The upwelling in the tropics appears to be maximized towards the edges of the tropics and not directly at the equator. The age at the equator is 1.5 years old, which is unrealistically high. This could be due in part to the use of the tropospheric surface SF₆ time series to perform the age calculation, but that is not enough to account for these high ages. The structure of the age from MIPAS SF₆ is potentially useful here, but as this bias is not necessarily consistent between the equator and the pole. Because of these high ages at the equator, we suggest cautious interpretation of the age difference and resulting circulation calculations at this level. At 450 K, the timeseries look more similar, with all three age estimates showing the disturbed Northern Hemisphere winters of 2009 and 2010, as can be seen from the younger air around the turn of the year in each case. The linear relationship between N₂O and age produces the youngest tropical ages, the cubic somewhat older, and the MIPAS SF₆-age is clearly the oldest. This is consistent with the old bias shown in validation papers on this product¹.⁴.
Figure S6: 2007–2011 zonal mean age on four isentropic levels, calculated using the cubic empirical relationship between age of air and N$_2$O (from GOZCARDS)$^{29}$ (left column) and using the linear empirical relationship between age of air and N$_2$O$^{31}$. Contours are every half year.
Figure S7: 2007–2011 zonal mean age on four isentropic levels from MIPAS SF$_6$. Contours are every half year and the color bar is saturated at 5.5 years for comparison with Figure S6. The Southern Hemisphere vortex gets much older than this, as can be seen in Figure S10.
Calculating age difference and circulation strength from GOZCARDS

$N_2O$

Figure S8 shows the 2007–2011 average zonal mean age calculated from $N_2O$ in two different ways interpolated to isentropes. At no level does the linear relationship have no gaps, and as these gaps are consistently of old polar air, this will create a systematic bias. Nevertheless, recognizing that the result can only be qualitative, we have extended the age difference calculation using the available data. We have ignored the missing data and calculated the average upwelling age as the average age for the available data in the upwelling region, and the average downwelling age as the average age for the available data in the downwelling region. This will tend to lead to a low bias in age difference where the tropics are missing and a high bias in age difference where the poles are missing. The polar bias will be smaller because the poles represent such a small total area. We have extrapolated between 450 K and 550 K although the only level for which the $N_2O$-age has no gaps is the 460 K surface, which is around 60 hPa in the tropics and close to the 68 hPa surface overall. This is for the cubic relationship only—the linear relationship still has gaps in the Southern Hemisphere vortex.

We have reported the value of the total overturning at 460 K in Table S1. The three data products are all within 5% of the mean value (where $N_2O$-age has been given equal weight as SF$_6$-age). WACCM is very close to the total overturning strength. The three reanalysis products, however, are a bit further away. The average value of the total overturning circulation $7.3 \times 10^9$ kg/s is derived from two completely independent satellite data products and is insensitive to the treatment of the $N_2O$-age. The only bias left then is that the age difference calculated using area-weighting rather than mass-flux-weighting is biased 10% or less low at that level. This means that our calculation is at most a 11% overestimate of the total overturning strength. Therefore, we can surmise that JRA 55 is too strong and MERRA is dramatically too weak at this level. ERA-Interim is barely within the tolerable error, assuming that the bias is indeed 10% high and accounting for the $\pm 0.3 \times 10^9$ kg/s error bar for variability.

We note, also, that MIPAS SF$_6$-age is evidently too old at the poles above 500 K due to the influence of the mesosphere. However, based on the modeled SF$_6$-age in WACCM, this effect is not felt below 500 K. Furthermore, this level is considerably above the level where, based on Figure S6, the equatorial region is biased more than the poles. Both data products are reliable at this same level, and they agree.

Figure S9 shows the extended age difference calculated using the cubic and the linear relationship. Where there is not continuous data, we have little confidence in this result. The slopes of these two are distinctly different, with the cubic relationship aligning much more closely with the model, and the linear relationship aligning with the MIPAS SF$_6$-age circulation strength. A more careful characterization of the compact relationship between age of air and $N_2O$ (or methane, which is closely related) could yield much more certainty for the overturning circulation strength at these low levels.
Figure S8: The average age of air as a function of latitude and potential temperature based on GOZCARDS N\textsubscript{2}O data from 2007–2011 that has been converted to age of air using three different relationships: In the left column, the cubic relationship\textsuperscript{29} is used. In the right column, the linear relationship\textsuperscript{31} is used. The first row is the mean value neglecting any data gaps, and the second row is the mean value only where there are no data gaps for the five years. Contours are every half year.
Table S1: Total overturning circulation strength at the level for which both satellite data sets exist.

| Data set              | 460 K overturning (×10^9 kg/s) |
|-----------------------|----------------------------------|
| MIPAS SF\textsubscript{6}-age | 7.43                             |
| GOZCARDS N\textsubscript{2}O cubic | 7.17                             |
| GOZCARDS N\textsubscript{2}O linear | 7.05                             |
| WACCM                  | 7.11                             |
| JRA 55                 | 7.90                             |
| MERRA                  | 5.52                             |
| ERA-Interim            | 6.48                             |

Figure S9: Like Figure 3, the average total meridional overturning circulation strength for 2007–2011 as a function of potential temperature. The strength from MIPAS SF\textsubscript{6}-age and the simultaneously retrieved temperature and pressure is shown in the navy solid line. The dotted blue line shows the total meridional overturning strength from the WACCM model. The bold red line is an extension of the cubic relationship between age of air and N\textsubscript{2}O, ignoring data gaps. The bold magenta line is based on the linear relationship between age of air and N\textsubscript{2}O, ignoring data gaps. The black line is from the cubic relationship, and spans the levels for which the data gaps are minimal, including 460 K where there are no gaps at all.
MIPAS age on isentropic surfaces

Here we show the MIPAS SF$_6$-age data on isentropic surfaces throughout the depth of the stratosphere. The discontinuity before and after the large data gap of April - December 2004 is due to a change in the operation mode of MIPAS. For any temporal analysis of the data set this discontinuity needs to be accounted for. In this study, we considered only data after this gap.

Figure S10: Age of air from MIPAS SF$_6$ data on the 400 K, 600 K, 800 K and 1200 K surfaces. Note that the color scale is not the same for these four plots.