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Mean age of air and transport in a CTM: Comparison of different ECMWF analyses

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[1] A comparison of the stratospheric circulation achieved by various data assimilation winds has been performed using multiannual simulations of the TOMCAT/SLIMCAT off-line 3-D chemical transport model (CTM). Data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.K. Met Office (UKMO) have been used to drive the CTM. We find that important improvements have been made in the ECMWF stratospheric winds during recent years. Therefore, a more realistic Brewer-Dobson (B-D) circulation, and subtropical mixing are achieved when ECMWF operational or new interim reanalyses are used instead of ERA-40 analyses. Age-of-air and trajectory calculations show that more realistic vertical and horizontal transport is achieved with the new ECMWF assimilated winds. The modelled tape recorder signal further shows the improvement in the tropical transport with the new winds. Overall, these results show that with the recent ECMWF reanalyses, off-line CTMs can produce stratospheric tracer transport over multiannual timescales more realistically than with other previous (re)analyses. Reasons for the improvements in the new reanalysis are discussed. **Citation:** Monge-Sanz, B. M., M. P. Chipperfield, A. J. Simmons, and S. M. Uppala (2007), Mean age of air and transport in a CTM: Comparison of different ECMWF analyses, *Geophys. Res. Lett.*, *34*, L04801, doi:10.1029/2006GL028515.

1. Introduction

[2] Chemical transport model (CTM) simulations rely on the accuracy of the forcing wind and temperature fields to obtain realistic tracer distributions. Meteorological fields used by CTMs may come from analyses or from general circulation models (GCMs). The use of analysed (or assimilated) fields has the advantage of making CTM results directly comparable with observations, since the model run will have been constrained by a realistic representation of the real atmosphere. However, the data assimilation process itself introduces discontinuities in the physical state of the numerical weather prediction (NWP) model that can affect the assimilated winds and therefore the modelled tracer transport.

[3] To achieve realistic tracer distributions in long-term stratospheric studies, it is essential to use winds that accurately represent the stratospheric circulation, i.e. the combined effects of the Brewer-Dobson (B-D) circulation and the mixing processes. So far, several studies based on long-term CTM simulations have shown that winds from analyses can produce too strong a stratospheric circulation. ERA-40 [*Uppala et al.*, 2005], ECMWF operational winds and UKMO winds [*Swinbank and O'Neill*, 1994] have been reported to produce a much too young age of air [e.g., *van Noije et al.*, 2004; *Meijer et al.*, 2004; *Scheele et al.*, 2005; *Chipperfield*, 2006]. The persistent underestimation of the age of air for a wide range of altitudes and latitudes implies that the models overestimate the B-D circulation, which is clearly affecting their ability to reproduce observed tracer distributions. To correct for this overestimation of transport, the use of forecasts rather than analyses [e.g., *Scheele et al.*, 2005], and the use of 3-hourly instead of 6-hourly winds [e.g., *Berthet et al.*, 2006; *Bregman et al.*, 2006], have already been investigated in CTMs. However, we focus here on the effect of improvements in the data assimilation system itself.

[4] *Schoeberl et al.* [2003] (hereinafter referred to as S2003) compared winds from two data assimilation systems (DAS), UKMO and FVDAS, with winds from the Finite Volume General Circulation Model (FVGCM). Their comparison highlighted the limitations of the DAS winds, and showed that FVDAS winds produced too strong vertical and horizontal tropical ventilation compared to the FVGCM winds. S2003 concluded that DAS winds are probably unsuitable for long-term stratospheric transport studies. Recently, some authors have even suggested that perhaps a point has been reached where the intrinsic elements of data assimilation prevent certain transport applications from further improvement [*Stohl et al.*, 2004; *Rood*, 2005].

[5] In this work, we use an off-line CTM to investigate further the accuracy of analysed winds for stratospheric transport. In particular, we assess a new one-year reanalysis recently produced by the ECMWF in order to test new assimilation procedures, and investigate its improvement over ERA-40. We also perform trajectory calculations similar to those in S2003, and calculate the tape recorder signal [*Mote et al.*, 1996, 1998] using a variety of ECMWF and UKMO wind fields to examine if the new analyses produce a better simulation of tropical transport.

2. Model Experiments

[6] The stratospheric B-D circulation can be assessed through the calculation of the mean age of air, a transport diagnostic independent of tracer chemistry which has become a standard test for stratospheric models [e.g., *Hall et al.*, 1999; *Meijer et al.*, 2004]. The mean age of air is defined as the average over the age spectrum, which is the statistical distribution of transit times for air parcels to travel from a source region (tropical tropopause) to a certain

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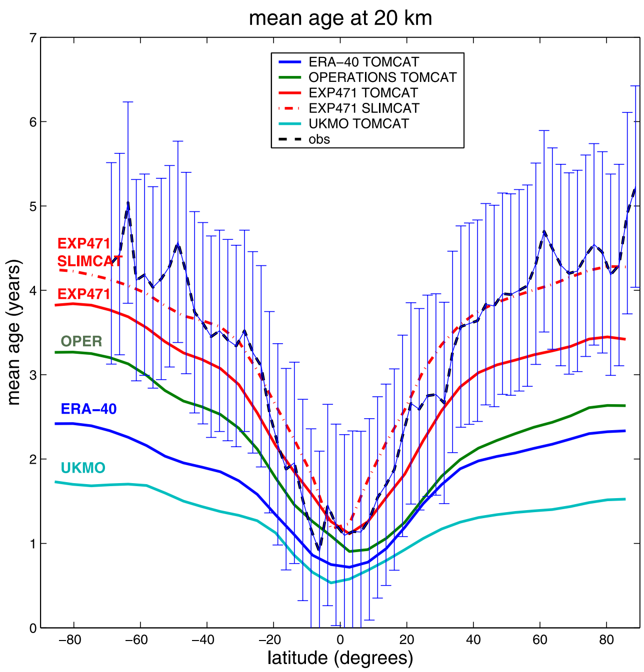

Figure 1. Mean age of air at 20 km altitude from TOMCAT/SLIMCAT simulations (coloured lines) using different ECMWF and UKMO analyses for year 2000, compared with the mean age of air derived from in-situ ER-2 aircraft observations of CO_2 [*Andrews et al.*, 2001] and SF_6 [*Ray et al.*, 1999] (black dashed line). 2σ error bars have been included for the observations. Results correspond to ERA-40 (dark blue), ECMWF operational (green), EXP471 (red), and UKMO (light blue) winds.

stratospheric location [see *Waugh and Hall*, 2002]. In this study, mean age distributions have been obtained by running the TOMCAT/SLIMCAT CTM [*Chipperfield*, 2006] with 3 different ECMWF analyses and with UKMO assimilated winds. The ECMWF products are: (1) the 3D-Var ERA-40 reanalyses, (2) the operational 4D-Var analyses, and (3) a recent test assimilation experiment with an updated 4D-Var assimilation system (hereinafter referred to as EXP471). EXP471 is one of a set of short experimental reanalyses carried out in preparation for a more extensive new reanalysis (ERA-Interim) that will succeed ERA-40 for the period from 1989 onwards. It is typical of other recent ECMWF experiments (not used here) with regard to its representation of the stratospheric circulation.

[7] A series of 20-year CTM runs were performed with a horizontal resolution of 5.6° latitude × 7.5° longitude. The CTM uses 24 vertical levels between the surface and ~60 km. All runs used repeating meteorological fields for 2000, as this is the only complete year for the interim reanalysis EXP471. For each set of winds a TOMCAT simulation was performed, i.e., with σ-p levels, and vertical motion calculated from the divergence of the horizontal winds. For EXP471 winds a SLIMCAT simulation was also run, i.e., using isentropic vertical levels in the stratosphere (a σ-θ hybrid system) and vertical transport in the stratosphere calculated from heating rates diagnosed by the CCMRAD radiation scheme embedded in SLIMCAT [*Chipperfield*, 2006; *Briegleb*, 1992]. An ideal inert tracer with a linearly increasing tropospheric mixing ratio (overwritten at the surface and then uniformly mixed through the troposphere) was used to diagnose the age of air. The auxiliary material shows age spectrum results from an alternative 'pulse' tracer.[1]

[8] To investigate the different analyses in the tropical lower stratosphere (LS), we also carried out backward kinematic trajectory calculations within TOMCAT for the 4 different analyses. These experiments released 36,000 particles, uniformly distributed along a 2° latitudinal band centered at the equator at 40 hPa (with a vertical range of 10K). For the trajectory studies the model was run backwards for 50 days from January 1, 2001 (December 30, 2000 for EXP471).

3. Results

3.1. Mean Age of Air

[9] Figure 1 shows the annual mean of the zonal-mean age-of-air obtained with TOMCAT/SLIMCAT at 20 km altitude, together with the mean age values derived from ER-2 aircraft observations. In the tropics all the simulations lie within the 2σ error range. However, in mid and high latitudes there are large differences between model runs. ERA-40 winds give age values 2–3 years younger than observed and clearly produce a too weak latitudinal gradient. This is even more evident for UKMO winds, indicating excessive transport between tropics and subtropics. As already observed with other CTMs [*Meijer et al.*, 2004; *van Noije et al.*, 2004], ECMWF operational winds show older ages and improved latitudinal gradients, but values are still about 2 years too young for latitudes poleward of 40°. The new ECMWF reanalysis winds (EXP471) produce the oldest and most realistic ages compared to observations; for these winds both TOMCAT (σ-p) and SLIMCAT (σ-θ) simulations differ from the observations by less than one year. With the new winds, the σ-θ model produces only slightly older ages than the σ-p model, while with ERA-40 the differences between the two models were between 2–3 years [*Chipperfield*, 2006]. This indicates that the noise in the vertical advection (which is lowered by the use of isentropic levels) has been very much reduced in EXP471 with respect to ERA-40; the remaining noise is still responsible for the younger ages TOMCAT obtains with EXP471 with respect to SLIMCAT.

[10] There are also large differences between the zonal mean ages obtained with the different σ-p simulations throughout the latitude/height plane (Figure 2). ERA-40 produces unrealistic contours both in shape and magnitude; note the depression in the contours between 25–35 km over the tropics. Our run with UKMO winds results in abnormally young ages at all altitudes, even younger than ERA-40 based values. This is due to the model recalculating the vertical motion from the divergence of the archived u and v fields on interpolated pressure levels rather than using any directly archived vertical velocities. This method is also used for ECMWF analyses but here we have the divergence field saved directly on the original model levels. Figures 2b and 2c show contour distributions in reasonable agreement

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL028515.

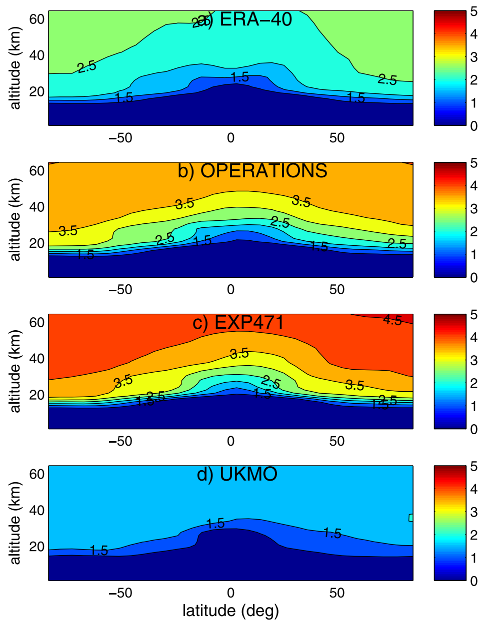

Figure 2. Cross sections of the annual mean age of air (years) from TOMCAT simulations with different data assimilation winds for year 2000.

with those expected from the stratospheric circulation pattern. However, as for Figure 1, the interim reanalysis EXP471 produces ages that are older than operational analyses, and also more realistic compared to balloon profile measurements extending up to 30 km [see *Chipperfield*, 2006, Figure 5]. These results are confirmed by age spectra presented in the auxiliary material which show that the improved mean age results from a more realistic combination of vertical advection and horizontal mixing. The auxiliary material also contains calculations of the eddy modified potential vorticity (MPV) flux [*Lait*, 1994; *Schoeberl et al.*, 2003] as a further comparison with the results in S2003. These MPV results show that differences in horizontal advection are probably not having such a large effect on mean age of air as differences in the vertical motion in our study. The mixing in the LS region is, however, an important difference between the DAS winds tested (as shown in section 3.2).

3.2. Trajectories

[11] The lack of wind observations in the tropics makes this region more sensitive to the effects of data assimilation. *Tan et al.* [2004] found that the forcing by the analysis increments was one of the causes for the excessive subtropical transport in the FVDAS. In our case, to examine in more detail how the different assimilation methods compared in this study affect the exchange of air between the tropics and higher latitudes, we have performed several trajectories experiments with our CTM.

[12] To intercompare the different winds in the tropical LS, we have performed backward kinematic trajectory calculations using the scheme embedded in TOMCAT/SLIMCAT [see *Chipperfield*, 2006]. Figure 3 shows that the transport of particles in TOMCAT simulations is significantly stronger for UKMO and ERA-40 winds than it is for ECMWF operational or EXP471 winds. The percentage of particles that remain in the stratosphere after 50 days is indicated for each panel in Figure 3; the anomalously low number of particles for UKMO winds is due to the method in which vertical motion is calculated for these winds in our CTM (see section 3.1).

[13] Differences in the distribution of particles in Figure 3 are consistent with the differences observed in the mean age. Figure 3 shows that the winds that produce the younger mean age (ERA-40 and UKMO) are also the winds that show a larger vertical mean transport and vertical dispersion of particles. This explains the excessively young mean age found over the tropics for the simulations using these winds. For ERA-40 versus EXP471 the differences in Figure 3 are mainly due to vertical dispersion of the particles, including unrealistic ascent, rather than differences in the mean vertical velocity. The reduction of latitudinal dispersion in the new winds can be seen from the stronger confinement of particles in Figure 3 and is confirmed by longitude/latitude plots (not shown). This reduction in dispersion contributes to the improvement of the latitudinal gradient when operational, and more significantly when EXP471, winds are used.

3.3. Tape Recorder Signal

[14] The seasonally varying signal of the water vapour in the tropical stratosphere, the so-called 'tape recorder' signal [*Mote et al.*, 1996, 1998], can be modelled by simply including a tracer with a sinusoidally varying mixing ratio at the tropical tropopause (period 1 year) within a CTM. The same TOMCAT simulations used in the rest of our study contain also such a tracer and have been therefore used for the tape recorder analysis.

[15] We compare TOMCAT results against those calculated from H_2O and CH_4 observations taken by the HALOE satellite and in situ measurements of CO_2 and $H_2O + 2CH_4$ from the Observation of the Middle Stratosphere (OMS)

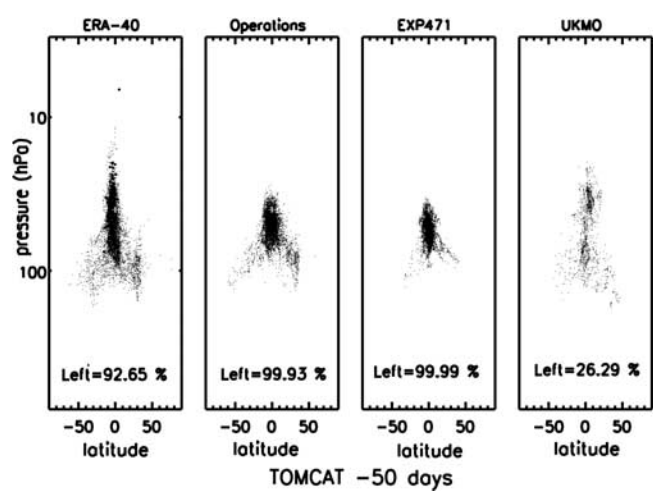

Figure 3. Distribution of particles (black dots) after 50 days of backward kinematic trajectories with σ-p CTM forced by 4 different analyses. The percentage of particles left in the stratosphere after 50 days is indicated. Initial position of particles is 40 hPa over the equator (indicated by a cross).

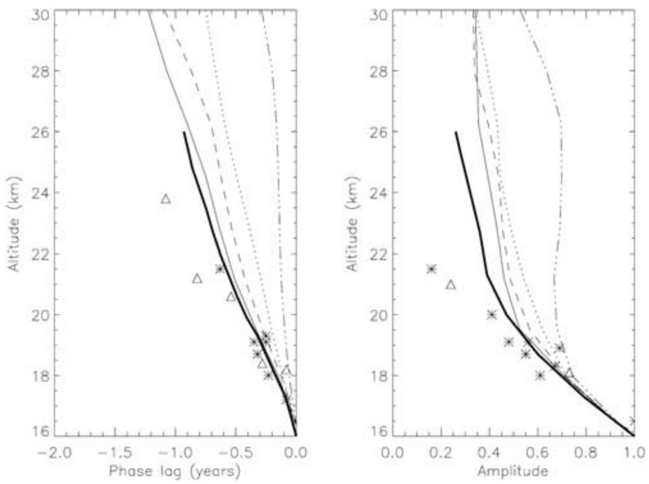

Figure 4. Vertical tropical profiles of (left) the phase and (right) the amplitude of the tape recorder obtained by TOMCAT with ERA-40 (dotted line), OPER (dashed line), EXP471 (solid thin line), and UKMO (dash-dotted line) winds. The thick solid line is for the estimations made from HALOE observations [*Mote et al.*, 1998] and the symbols for estimations from OMS in situ measurements of CO_2 (stars) and H_2O + $2CH_4$ (triangles). Data from *Hall et al.* [1999].

balloons and aircraft. These observations have already been used in published work, e.g. in *Mote et al.* [1998] or the NASA Models and Measurements II (MM2) study [*Hall et al.*, 1999], to evaluate the tape recorder signal reproduced by different models.

[16] Figure 4 shows the vertical profiles over the tropics (11.1°S–11.1°N) for the amplitude and phase of the tape recorder obtained with the four sets of winds used in our study, along with values derived from observations. EXP471 results are the closest to the observations; in particular, we find that the phase is very well reproduced with these winds. ECMWF operational and ERA-40 winds produce less realistic tape recorder, while the UKMO winds used here appear particularly poor. These differences in the tape recorder are consistent with the improvements that EXP471 exhibits in the trajectory calculations in terms of both vertical and horizontal mixing. Information on the temporal evolution of the tropical tape recorder can be found in the auxiliary material.

[17] Part of the differences in transport between the four sets of winds can be attributed to the different assimilation method used. However, as discussed in section 4, the differences are not only in the assimilation method but also in the forecast model and in the observations assimilated; determining how each of these differences influence the final product is not straightforward.

4. Discussion and Summary

[18] The results shown here demonstrate that progress is being made in the ECMWF forecast and assimilation systems that allows a more realistic representation of the stratosphere. The mean age-of-air distribution obtained with operational and new reanalysis winds is more accurate than with ERA-40 winds, indicating that the recent ECMWF products solve to a large extent the overestimation of the B-D circulation when used for multiannual simulations with TOMCAT/SLIMCAT. Also, trajectory experiments and tape recorder simulations have shown that the tropical isolation is much better represented by the ECMWF operational and interim reanalysis than by UKMO, ERA-40 winds, or the GEOS-4 winds used in S2003.

[19] The production of the different ECMWF data sets used in this work vary in the assimilation scheme (3D- or 4D-Var, 6- or 12-hourly cycling), the horizontal resolution and the version of the forecasting system employed. Forecasting system changes since ERA-40 have included changes in the amount, type, bias-correction and quality control of the data assimilated, changes in the parametrization of radiation and convection, and changes in the analysis of humidity and the dynamical background-error constraint, among others. It is not straightforward to identify which of the many changes are mainly responsible for improving the stratosphere, especially as the changes were implemented gradually over time and were not tested individually over periods of assimilation long enough to identify significant changes in the stratospheric circulation. However, some of the changes are more likely to have had a significant influence than others.

[20] One important factor in the improvement over ERA-40 and UKMO winds comes from the use of the more sophisticated 4D-Var assimilation method [*Rabier et al.*, 2000], with its more consistent treatment of data with observation times that vary within the time window of each assimilation cycle. Both the operational and the new reanalysis winds come from 4D-Var, but operations used 6-hourly cycling for much of the year 2000 rather than the 12-hourly cycling used throughout in EXP471. The new reanalysis alone benefits from using an ω-equation balance operator in the background constraint [*Fisher*, 2003]. This operator is likely to have reduced spurious propagation of eddy motion associated with analysis increments, which was linked by *Tan et al.* [2004] to an excessive subtropical horizontal transport in the Goddard FVDAS, especially in the LS.

[21] A further important factor is the reduced stratospheric temperature biases in the assimilating model, and improved correction of biases in satellite radiance data, as a too-strong B-D circulation in the ERA-40 data assimilation is believed to have been driven in part by systematic analysis increments in temperature that resulted from perceived biases in the background stratospheric forecasts [*Uppala et al.*, 2005]. Determining the relative contribution that different system developments have made in the improvement of the stratospheric circulation is beyond the scope of this work. NWP agencies themselves do not generally have the resources, both human and computational, to produce (re)analysis data sets suitable for the assessment of each system change separately. However, these issues are being investigated in ongoing research by groups associated with NWP centres.

[22] Our results show that all the recent advances made in the ECMWF assimilation system have significantly improved the quality of the stratospheric re-analysis, and that these improvements can be directly translated into an enhanced representation of the stratospheric circulation, which will positively influence the accuracy of distribu-

tions of chemical constituents achieved by long CTM simulations.

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References

Andrews, A., et al. (2001), Mean ages of stratospheric air derived from stratospheric observations of CO_2, CH_4, and N_2O, *J. Geophys. Res.*, *106*, 32,295–32,314.

Berthet, G., et al. (2006), On the ability of chemical transport models to simulate the vertical structure of the N_2O, NO_2, and HNO_3 species in the mid-latitude stratosphere, *Atmos. Chem. Phys.*, *6*, 1599–1609.

Bregman, B., E. Meijer, and R. Scheele (2006), Key aspects of stratospheric tracer modeling using assimilated winds, *Atmos. Chem. Phys.*, *6*, 4529–4543.

Briegleb, B. P. (1992), Delta-Eddington approximation for solar radiation in the NCAR community climate model, *J. Geophys. Res.*, *97*, 7603–7612.

Chipperfield, M. P. (2006), New version of the TOMCAT/SLIMCAT off-line chemical transport model, *Q. J. R. Meteorol. Soc.*, *132*, 1179–1203.

Fisher, M. (2003), Background error covariance modelling, paper presented at Seminar on Recent Developments in Data Assimilation for Atmosphere and Ocean, Eur. Cent. for Medium-Range Weather Forecasts, Reading, UK, 8–12 Sept. (Available at www.ecmwf.int/publications)

Hall, T. M., D. W. Waugh, K. A. Boering, and R. A. Plumb (1999), Evaluation of transport in stratospheric models, *J. Geophys. Res.*, *104*, 18,815–18,839.

Lait, L. R. (1994), An alternative form for potential vorticity, *J. Atmos. Sci.*, *51*, 1754–1759.

Meijer, E. W., B. Bregman, A. Segers, and P. F. J. van Velthoven (2004), The influence of data assimilation on the age of air calculated with a global chemistry-transport model using ECMWF wind fields, *Geophys. Res. Lett.*, *31*, L23114, doi:10.1029/2004GL021158.

Mote, P. W., et al. (1996), An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapour, *J. Geophys. Res.*, *101*, 3989–4006.

Mote, P. W., et al. (1998), Vertical velocity, vertical diffusion, and dilution by midlatitude air in the tropical lower stratosphere, *J. Geophys. Res.*, *103*, 8651–8666.

Rabier, F., et al. (2000), The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results with simplified physics, *Q. J. R. Meteorol. Soc.*, *126*, 1143–1170.

Ray, E. A., et al. (1999), Transport into the Northern Hemisphere lowermost stratosphere revealed by in situ tracer measurements, *J. Geophys. Res.*, *104*, 26,565–26,580.

Rood, R. B. (2005), Assimilation of stratospheric meteorological and constituent observations: A review, *SPARC Newsletter*, *25*, 31–37.

Scheele, M. P., P. C. Siegmund, and P. F. J. van Velthoven (2005), Stratospheric age of air computed with trajectories based on various 3D-Var and 4D-Var data sets, *Atmos. Chem. Phys.*, *5*, 1–7.

Schoeberl, M. R., A. R. Douglass, Z. Zhu, and S. Pawson (2003), A comparison of the lower stratospheric age spectra derived from a general circulation model and two data assimilation systems, *J. Geophys. Res.*, *108*(D3), 4113, doi:10.1029/2002JD002652.

Stohl, A., O. R. Cooper, and P. James (2004), A cautionary note on the use of meteorological analysis fields for quantifying atmospheric mixing, *J. Atmos. Sci.*, *61*, 1446–1453.

Swinbank, R., and A. O'Neill (1994), A stratosphere-troposphere data assimilation system, *Mon. Weather Rev.*, *119*, 2206–2223.

Tan, W. W., M. A. Geller, S. Pawson, and A. da Silva (2004), A case of study of excessive subtropical transport in the stratosphere of a data assimilation system, *J. Geophys. Res.*, *109*, D11102, doi:10.1029/2003JD004057.

Uppala, S. M., et al. (2005), The ERA-40 Re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

van Noije, T. P. C., H. J. Eskes, M. van Weele, and P. F. J. van Velthoven (2004), Implications of the enhanced Brewer-Dobson circulation in ECMWF reanalysis ERA-40 for the stratosphere-troposphere exchange of ozone in global chemistry transport models, *J. Geophys. Res.*, *109*, D19308, doi:10.1029/2004JD004586.

Waugh, D. W., and T. M. Hall (2002), Age of stratospheric air: Theory, observations and models, *Rev. Geophys.*, *40*(4), 1010, doi:10.1029/2000RG000101.

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