Final Report for Project **850**

Project title: **Past and future changes of the three-dimensional Brewer-Dobson circulation**

Principal investigator: **Axel Gabriel**

Report period: **Jan. 1, 2013 - Dec. 31, 2019**

(1) Introduction

The aim of the project was to investigate the past and future changes of the three-dimensional (3D) Brewer-Dobson circulation (BDC), i.e., the time-mean mass circulation and tracer transport of the middle atmosphere (10-100km). Before and since the beginning of the project, a large number of research works suggested that the increase in greenhouse gases (GHGs) can lead to significant changes in the zonal mean (2D) BDC, where the 2D BDC and its wave driving are usually examined based on the 2D residual circulation, which combines the Eulerian and eddy time-mean flow (Andrews et al., 1987). However, there are still strong uncertainties particularly in the changes of the extra-tropical 2D BDC. By using a new approach of the 3D residual circulation (following Sato et al., 2013), the results of the project contribute to a better understanding of the local long-term changes in the middle atmosphere and the associated coupling with the troposphere and surface climate.

The examinations were primarily based on the CMIP5 simulations with the Earth System Model MPI-ESM-MR with forcing by AMIP-SST 1979-2008 and by weak, moderate and strong scenarios of increasing GHGs during the 21st century, RCP2.6, RCP4.5 and RCP8.5 (data provided by M. Giorgetta, MPI-Met, Hamburg; for details see also Giorgetta et al., 2013, and Schmidt et al., 2013). The 3D BDC and wave driving processes were validated against reanalysis and residual winds derived from satellite data. Additional sensitivity simulations were planned with specific forcing terms derived from observations to understand the troposphere-stratosphere coupling processes. The project was funded by the Deutsche Forschungsgemeinschaft (DFG).

The results of previous years have been reported in previous reports; therefore these results are summarized only briefly (Section 2). Section 3 focuses on the last project period, which includes extended statistical analysis of the data as required during the publication process, and specific results on local stratosphere-troposphere coupling processes. Section 4 gives some conclusions

(2) Results of previous project periods

The MPI-ESM-MR (T63/L95) includes the middle atmosphere up to ~80km, and produces the equatorial Quasibiennial Oscillation between easterly (QBO-East) and westerly (QBO-West) stratospheric winds internally. Because of the well-known gap in direct wind measurements between 30km and 80km altitude, the time-mean circulation, interannual variability and linear changes had to be validated not only against reanalysis (ERA-Interim) and high-altitude model simulations (data of the chemistry-climate model HAMMONIA provided by H. Schmidt, MPI, Hamburg) but also against 3D wind fields and 3D BDC patterns derived from Aura-MLS satellite data (where balanced and unbalanced winds were derived by a new method from the Aura-MLS temperature and water vapour profiles provided by NASA). In summary, the quality of the interannual variability due to the QBO and the linear long-term changes in the middle atmosphere over the past decades produced by the model simulations provide strong confidence in the projections for the time period 2006-2100. Some selected results are given in the following.

(2.1) Time-mean 3D BDC and interannual variability under current climate conditions

For current climate conditions, the morphology and interannual variability of the northern winter 3D BDC derived from the MPI-ESM-MR simulations are well described in comparison to ERA-Interim, HAMMONIA and the wind fields derived from Aura-MLS data. The spatial structure of the 3D BDC is generally related to the stationary wave one and wave two components in geopotential height, temperature and balanced winds usually developing during northern winter. The 3D BDC includes one pronounced branch of downwelling in the region of the stratospheric polar low anomaly over Northern Europe/West-Siberia, and a second, less pronounced branch over North America. This structure is largely due to the effect of the equatorial QBO on the extra-tropical circulation, which forces a modulation between stationary wave one (QBO-East) and wave two (QBO-West) in the zonal westerly flow (as first described by Holton and Tan, 1980). This modulation includes an increase in transient wave fluxes and a decrease in stationary westerlies during QBO-East over a region around North America, which is consistent with the picture of the QBO-induced modulations in the zonal mean fields described by Garfinkel et al. (2012), but localized over North America (see discussion in Gabriel, 2019).

(2.2) Long-term changes in the 2D and 3D residual circulation

Generally, increasing GHGs force a warmer troposphere but a cooler stratosphere and mesosphere. For the zonal means at high latitudes, we also find a warming of the stratosphere due to an increase of the 2D BDC in the stratosphere (because of enhanced wave driving due to increasing GHGs) but a stronger cooling of the mesosphere due to the change in the parameterized gravity waves (as a function of the decrease in the thermally-balanced zonal mean zonal wind), which is consistent with a large number of other model simulations (see discussion in Gabriel, 2019). However, there are still strong uncertainties concerning the zonal mean changes in the northern extra-tropics (e.g., Haenel et al., 2015; Ossó et al., 2015; Fu et al., 2015).

In the northern mid-winter extra-tropics, the long-term changes of the 3D BDC derived from the MPI-ESM-MR simulations are generally embedded in the change of the stationary wave patterns, which are averaged out when looking at zonal means. In particular, we find an increase in the downwelling branch over Northern Europe/West-Siberia but a decrease of the second branch over North America, accompanied by an increase in transient waves and a decrease in the stationary westerly flow over North America. These patterns show strong similarity when deriving from the simulation with AMIP-SST 1978-2008 and ERA-Interim 1978-2008, and from the RCP4.5 and RCP8.5 simulations, where the amplitudes of the linear trends of the 21st century become stronger by a factor of ~2 when changing from the moderate RCP4.5 to the strong RCP8.5 scenario (Gabriel et al., 2019). Changes of the RCP2.6 simulation are not significant.

It is worthwhile to note that the local change in the downwelling at high latitudes is consistent with the relative increase of about 2% per decade in the tropical upwelling suggested by observations and a large number of model simulations, which is a new aspect resulting from the project works. For example, the RCP4.5 simulation shows an increase in the downwelling over Northern Europe/West-Siberia of ~5% per decade; assuming continuity equation for the stratospheric planetary-scale mass flux, and roughly estimated areas of ~32 million km^2 covered by the polar low anomaly and ~80 million km^2 covered by the tropical upwelling between 10°S and 10°N (i.e. an area-weighted factor of 2:5), the increase in the extra-tropical downwelling of ~5% per decade is consistent with the increase in the tropical upwelling of ~2% per decade (Gabriel, 2019).

(2.3) Long-term changes in relation to the QBO

A remarkable and surprising result of the project is that the analyzed long-term changes in the northern winter middle atmosphere are generally much stronger during the westerly than the easterly phase of QBO (Gabriel, 2019). Here, the striking similarity between the patterns of linear long-term changes and composite differences QBO-East minus QBO-East for current climate conditions indicates that much of the identified linear change in the stratosphere is due to a long-term change of the extra-tropical QBO-West towards QBO-East signature (note here that the equatorial QBO itself remains nearly unchanged in both the used simulations and ERA-Interim).

In particular, during QBO-West, we found a strong and significant increase and eastward shift of the stationary wave one at the cost of wave two (which is very similar to the transition from QBO-West to QBO-East signature) and an embedded increase in the local downwelling over Northern Europe/West-Siberia, whereas the second branch of the downwelling over North America nearly disappears. This change includes an increase in transient wave fluxes and a decrease in stationary westerlies over a region around North America. On the other side, during QBO-East, we find only a weak increase in the downwelling over West-Siberia and a weak change in the amplitude of the stationary wave one. In other words, the modulating effect of the equatorial QBO on the extra-tropical circulation first described by Holton and Tan (1980) will disappear during the 21st century. This change occurs much earlier (during the first half of the 21st century) in case of the stronger RCP8.5 scenario because the same degree of stratospheric cooling (about −2K at levels between 20hPa and 10hPa) is reached.

One important process controlling this trend behavior is located at lower mid-latitudes. Following Garfinkel et al. (2012), the QBO-induced modulation of the extra-tropical circulation is largely due to a cooler upper stratosphere at lower mid-latitudes during QBO-East, which restricts the propagation of transient Rossby waves into the subtropics enhancing transient wave activity and the meridional mass circulation at high latitudes. Analogously, the GHG-induced cooling of the mid-latitude upper stratosphere imposes a change towards QBO-East signature, independent from the state of the equatorial stratosphere. Conclusively, like the transition from QBO-West to QBO-East signature, the trend behavior is consistent with the processes controlling the QBO-induced change described by Garfinkel et al. (2012), but localized over North America.

The other important process controlling the trend behavior is the GHG-induced cooling of the stratospheric polar low anomaly over Northern Europe/West-Siberia, imposing an increase in the amplitude of the stationary wave one (which consists of the polar low and Aleutian high anomalies). As discussed in detail by Gabriel (2019), the GHG-induced increase in the amplitude of the wave one during QBO-West implies a change in meridional transport of planetary vorticity and a subsequent eastward shift in phase of the wave one and related zonal winds over East Pacific/North America. The associated decrease in the zonal westerlies over North America leads to a decrease in the excitation and vertical propagation of planetary-scale Rossby waves forced by the Rocky Mountains, which contributes to the change from stationary wave two towards wave one, until the wave one signature of QBO-East is reached.

Further analysis suggests that changes in the occurrence rate of sudden stratospheric warming events do not contribute to the identified long-term changes significantly, i.e., including or excluding extreme values in the time series of monthly means lead to changes in the amplitudes of the linear trends in the order of only 20% (Gabriel, 2019). However, we find evidence that the GHG-induced increase of the wave one at the cost of the wave two might induce a long-term change in the occurrence of the type of SSWs from vortex split to vortex displacement events, which would be consistent with recent findings on the occurrence of SSWs in relation to the background flow (e.g., Seviour et al., 2016). However, a more detailed analysis of this issue was beyond the scope of the project and needs some more model sensitivity experiments.

In the middle atmosphere, the interannual variability and long-term changes in important trace gases like H_2O are related to the changes in the stationary waves and 3D residual circulation. For current climate conditions, the H_2O distributions indicate a change from a stationary wave two pattern during QBO-West to a stationary wave one pattern during QBO-East. For the RCP4.5 simulation, we also find a change from a stationary wave two towards wave one pattern during the 21st century. Here, the separation of the transport terms into rotational and divergent components of the residual budget was helpful to quantify the changes related to the stationary balanced flow circling around the polar low and Aleutian high anomalies (~60% of the total change below ~60km) and to the divergent component of the 3D BDC (where the stationary wave patterns above ~60km are related to the local gravity wave fluxes, which are parameterized in the model as a function of the stationary balanced flow below). Overall, these results contribute to an extended understanding of the local trends in the trace gases of the middle atmosphere, which is an important issue of current research. A related publication is in preparation.

(3) Results of the last project period

As mentioned in previous project reports, publication of the results has led to an unexpected large number of critical comments concerning the general quality of the MPI-ESM-MR simulations, in particular concerning the equatorial QBO and extra-tropical QBO signatures, and on the significance of the identified linear changes against internal decadal variations. This has led to a strong delay of the project works beyond the original scope of the project. As far as possible, all the relevant results have been verified successfully. In particular, an extended Monte-Carlo boot strapping test was carried out in order to verify the linear trend behaviour. Examining the role of the 3D BDC in stratosphere-troposphere coupling is still an ongoing work and not finished finally.

(3.1) Extended statistical analysis

During the publication process the question arose whether the significance of the identified linear change due to increasing GHGs is affected by internal decadal variations, which can produce similar dipolar patterns at high latitudes (e.g., Ineson et al., 2011; Kuroda and Kodera, 2001; Manzini et al., 2006). In order to verify the statistical significance of the linear trends and their differences by a different method than linear regression, a Monte Carlo bootstrap test was performed, following the procedure described by Krueger and She (2011) and Mudelsee (2018). First a time series of monthly means was randomly resampled by a set of independent random integer numbers ranging between 1 and N (N is the number of months), where some months are not selected (typically 1/e of N) but replaced by duplicated original months. This was done for the whole time series, and for the QBO-West and QBO-East time series. Then the linear trend of a new time series was calculated by linear regression, which also gives a new difference between the trends for QBO-W and QBO-E. Repeating this procedure R times leads to a range of trends and trend differences, where the standard deviation over the replications R provides the bootstrap standard error as a measure of the uncertainty of the mean trend or mean trend difference. Trends and trend differences were calculated for different number of replacement sets R (50, 100, 500, 1000, 5000) to evaluate the dependence of the uncertainty on the used value R (for more details see Gabriel et al., 2019). Overall, the results of the Monte Carlo test clearly confirm the significance of the identified trends and trend differences calculated by linear regression. We may also conclude that the MPI-ESM-MR simulations generally provide an excellent tool for investigating the long-term changes in the troposphere-stratosphere circulation system.

(3.2) Implications for Stratosphere-Troposphere coupling processes

The identified changes in the stratosphere have a strong effect on the long-term changes in the upper tropospheric/lower stratospheric jet and related surface climate conditions. For example, for the RCP4.5 simulation, the changes in surface pressure, with increase in the southern and decrease in the northern European regions, are particularly strong during QBO-West (Figure 1, left panels). Similarly, the changes in the zonal wind at 200hPa (Figure 1, right panels), with decrease over North America and increase over Europe/West-Asia, are much stronger during QBO-West compared to the total changes. Overall, these changes indicate a change towards intensification and eastward extension of the positive North Atlantic Oscillation (NAO) pattern.

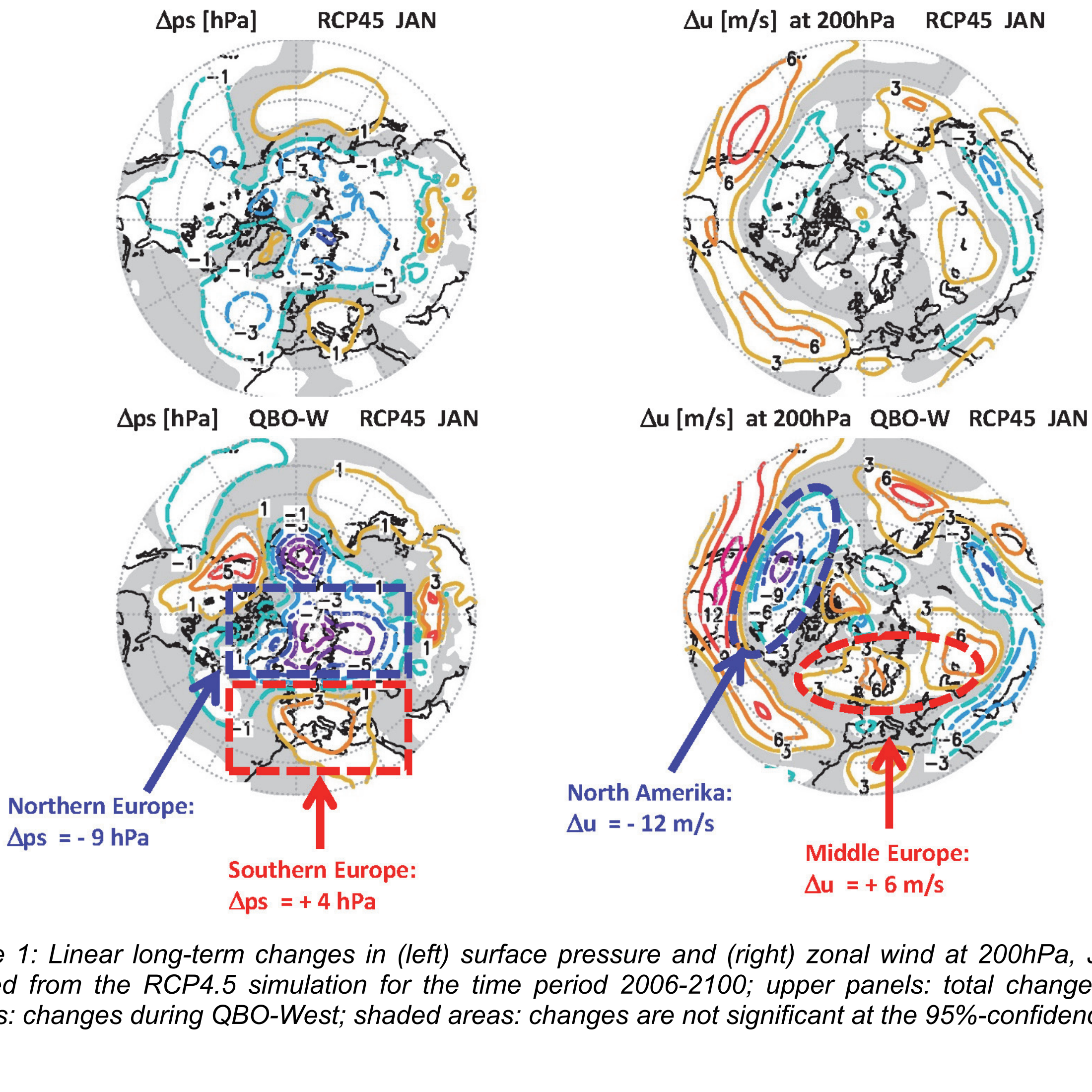

Figure 1: Linear long-term changes in (left) surface pressure and (right) zonal wind at 200hPa, January, derived from the RCP4.5 simulation for the time period 2006-2100; upper panels: total changes, lower panels: changes during QBO-West; shaded areas: changes are not significant at the 95%-confidence level.

Primarily this change might be due to the local decrease in the westerlies over North America and the subsequent decrease in Rossby waves forced by the Rocky Mountains, which might lead to a less disturbed stratospheric polar vortex and a subsequent increase in the westerlies over Northeast-Atlantic/Northern Europe. In addition, the eastward shift in the downwelling towards Eastern Asia might impose a corresponding eastward shift in a related top-down effect of the downwelling on the strength and spatial extension of the cold surface high anomalies usually developing during winter, forcing a decrease in anticyclonic blocking events over North-Eastern Europe but an increase over Asia. For current climate conditions, such a top-down forcing of blocking surface high anomalies is indicated by the good correlation between the surface pressure p_S averaged over a middle-east European region (20-50°E,40-60°N) and the downwelling w_{res} in the centre of the polar low anomaly at 60°E (here not shown). For months during QBO-West, this correlation pattern follows the eastward shift in the downwelling in case of increasing GHGs, as indicated by the change in the correlation between p_S and w_{res} at 10hPa during the 21st century (Figure 2, upper panels).

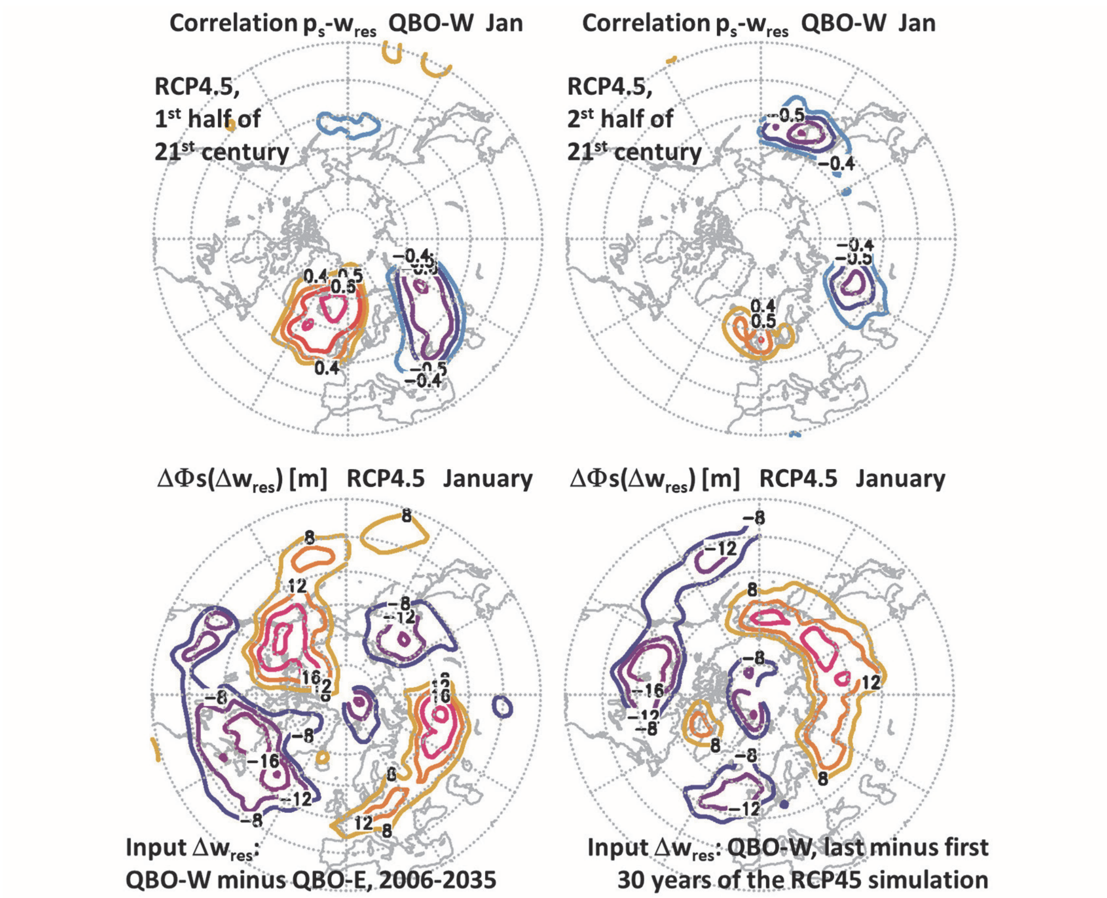

Figure 2, upper panels: Correlation between January means of surface pressure p_S averaged over a middle-east European region (20-50°E,40-60°N) and the downwelling w_{res} at 10hPa for (left) the first and (right) the last half of the 21st century, for months during QBO-West, derived from the RCP4.5 simulation; lower panels: approximated one-way effect of a change in the downwelling on near-surface geopotential height, for (left) the difference QBO-West minus QBO-East of the first 30 years of the RCP4.5 simulation, and (right) the difference between the last and first 30 years for months during QBO-West.

The related change in the top-down forcing of anti-cyclonic perturbations is indicated by Figure 2 (lower panels) which shows the imposed change in geopotential height Φs at the 1000hPa level, derived from the vertical advection term $\Delta w_{res}\cdot\partial\theta_0/\partial z\approx-\tau^{-1}\Delta\theta_{wres}$ (τ=10 days) and subsequent vertical integration of the resulting temperature change $\Delta\theta_{wres}$ or ΔT_{wres} via $\partial\Delta\Phi/\partial z=R\Delta T_{wres}/H$ (τ=10 days), for the difference QBO-West minus QBO-East of the first 30 years of the RCP4.5 simulation (Figure 2, bottom, left) and for the difference between the last and the first 30 years for the months during QBO-West (Figure 2, bottom, right). Accordingly, compared to QBO-East, the downwelling w_{res} of QBO-West imposes positive surface high anomalies over Northern Europe under current climate conditions, and the eastward shift in w_{res} (here indicated by the eastward shift of the correlation patterns in Figure 2, upper panels) leads to an eastward shift of this top-down effect. A related publication is in preparation.

(4) Conclusions

Because the equatorial QBO and the effect on the extra-tropics is initially a purely stratospheric phenomenon, the identified strong changes in the troposphere during the westerly phase of QBO underline the importance of stratosphere-/troposphere coupling in climate change simulations. In the MPI-ESM-MR simulations, the equatorial QBO remains nearly unchanged during the 21st century, which might be due to the restrictions in the used gravity wave drag parameterizations (and which is unavoidable in current general circulation models because of the limited resolution); therefore the identified long-term changes are related to a change in the extra-tropical QBO signature in case of a realistic equatorial QBO as boundary condition for the extra-tropics. Possible changes of the equatorial QBO itself are an important issue of current research (e.g., Anstey et al. 2015) and beyond the scope of the project.

It is evident that a number of issues addressed by the original project proposal are still in progress, particularly because of the strong delay during the publication process. The host institute of the project leader (IAP, Kühlungsborn) provides the possibility to continue the work and to finish the outstanding issues. However, because some of the reviewers of the WLA had some doubt on the necessity of additional model sensitivity experiments, and also recommended to finish the project works at DKRZ during 2019, further computer resources for the project 850 at the HLRE have not been applied. Many thanks to the DKRZ service for the support.

(5) References

Andrews, D. G., J. R. Holton and C. B. Leovy (1987), *Middle Atmosphere Dynamics*. 489 pp., Academic Press, San Diego, Californien.

Anstey, J. A., K. Hamilton, S. Osprey, N. Butchart, and L. Gray (2015), Report on the 1st QBO Modelling and Reanalyses Workshop, SPARC Newsletter No. 45, July 2015, 19-25, http://www.sparc-climate.org/newsletter.

Fu, Q., P. Lin, S. Solomon, and D. L. Hartmann (2015), Observational evidence of strengthening of the Brewer-Dobson circulation since 1980, J. Geophys. Res. Atmos., 120,10,214–10,228, doi:10.1002/2015JD023657.

Gabriel, A. (2019). Long-term changes in the northern midwinter middle atmosphere in relation to the Quasi-Biennial Oscillation. *J. Geoph. Res. Atmos.*, 124. https://doi.org/10.1029/ 2019JD030679.

Garfinkel, Chaim I., Tiffany A. Shaw, Dennis L. Hartmann, Darryn W. Waugh (2012), Does the Holton–Tan Mechanism Explain How the Quasi-Biennial Oscillation Modulates the Arctic Polar Vortex?. *J. Atmos. Sci.*, 69, 1713–1733.

Haenel, F. J., Stiller, G. P., von Clarmann, T., Funke, B., Eckert, E., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., and Reddmann, T. (2015), Reassessment of MIPAS age of air trends and variability, *Atmos. Chem. Phys.*, 15, 13161-13176.

Holton, J. R., and H.-C. Tan (1980), The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. J. Atmos. Sci., 37, 2200–2208.

Ineson, S., Scaife, A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray L., and Haigh, J. D. (2011), Solar forcing of winter climate variability in the Northern Hemisphere. *Nat. Geosci.* **4**, 753–757.

Kuroda, Y., and K. Kodera (2001), Variability of the polar night jet in the northern and southern hemispheres, *J. Geophys. Res*., 106(D18), 20703–20713, doi:10.1029/2001JD900226.

Manzini, E., M. A. Giorgetta, M. Esch, L. Kornblueh, and E. Roeckner (2006), The influence of sea surface temperatures on the northern winter stratosphere: Ensemble simulations with the MAECHAM5 model, *J. Clim., 19(16)*, 3863–3881.

Ossó, A., Y. Sola, K. Rosenlof, B. Hassler, J. Bech, and J. Lorente, (2015), How robust are trends in the Brewer–Dobson circulation derived from observed stratospheric temperatures? *J. Climate*, 28, 3024–3040, doi:10.1175/JCLI-D-14-00295.1

Sato, K., T. Kinoshita, and K. Okamoto (2013), A new method to estimate three-dimensional residual-mean circulation in the middle atmosphere and its application to gravity wave – resolving general circulation model data, J. Atmos. Sci., 70, 3756–3779, doi:10.1175/JAS-D-12-0352.1.

Schmidt, H., S. Rast, F. Bunzel, M. Esch, M. Giorgetta, S. Kinne, T. Krismer, G. Stenchikov, C. Timmreck, L. Tomassini, and M. Walz (2013), Response of the middle atmosphere to anthropogenic and natural forcings in the CMIP5 simulations with the Max Planck Institute Earth system model, J. Adv. Model. Earth Syst., 5, 98–116, doi:10.1002/jame.20014.

Seviour,W. J. M., L. J. Gray, and D. M. Mitchell (2016), Stratospheric polar vortex splits and displacements in the high-top CMIP5 climate models, *J. Geophys. Res. Atmos.*, *121*, 1400–1413, doi:10.1002/2015JD024178.