Project: **850**

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

Principal investigator: **Axel Gabriel**

Report period: **2018-01-01 to 2018-12-31**

Report (24.10.2018)

The aim of the project is 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), in order to better understand the local long-term changes in the middle atmosphere and the associated vertical coupling with the troposphere and surface climate. The examinations are 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 greenhouse gases (GHGs) during the 21st century, RCP2.6, RCP4.5 and RCP8.5 (data provided by M. Giorgetta, MPI-Met, Hamburg). The 3D BDC is diagnosed based on the 3D residual circulation that combines the 3D Eulerian and eddy time-mean flow (Sato et al., *JAS*, 2013), and validated against reanalysis data (ERA-Interim) and Aura/MLS satellite data (where balanced and non-balanced daily-mean winds are derived from temperature and H_2O profiles provided by NASA). The latter provide verification of the model dynamics for altitudes where local wind measurements are sparse (30-80km). Additional sensitivity simulations with forcing terms derived from observations will help to understand the troposphere-stratosphere coupling via the 3D BDC. The project is funded by the Deutsche Forschungsgemeinschaft (DFG).

Unexpectedly, ongoing publishing of the results has led to a large number of critical comments concerning the general quality of the MPI-ESM-MR simulations, in particular concerning the extra-tropical effects of the tropical Quasibiennal Oscillation (QBO) and the use of a gravity wave parameterization. This has led to strong delay in carrying out the planned additional model experiments because of extended model validation beyond the original scope of the project. As far as possible, all relevant features have now been validated, e.g., the linear trend behaviour, the tropical and extra-tropical signatures of the QBO, and the long-term changes in stationary wave patterns. At the moment we expect that the project can be finished successfully during 2019.

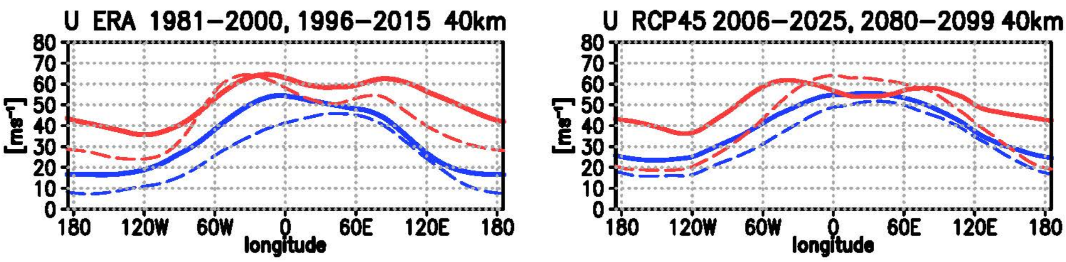

Figure 1. Time-mean zonal wind u at 60°N and ~40km altitude (3hPa), January, derived from early and late 20 years of (left) ERA-Interim (solid: 1981-2000, dashed: 1996-2015) and (right) the RCP4.5 simulation (solid: 2005-2025, dashed: 2080-2099); red: QBO-W, blue: QBO-E.

Focussing on the most significant trends during northern winter, one key result of the project is that the change in the 3D BDC is embedded in the change of the extra-tropical stationary waves of the balanced flow, but that it also contributes to the changes in the balanced flow. Under current climate conditions, we find a modulation in the extra-tropical stratosphere between zonal wave number one during easterly phase of QBO (QBO-E, one maximum) and wave number two during westerly phase of QBO (QBO-W, two maxima), as illustrated by Figure 1. In the RCP4.5 simulation, the QBO-W signature changes towards the obviously more stable QBO-E signature, including a decrease in the westerly flow over the Rocky Mountains (~120°W) and the associated contribution of orographically-forced Rossby waves to the wave two signature. This change is not completed within the ERA-Interim time period, but it is completed two times earlier in case of the RCP8.5 scenario, i.e., it depends on the rate of increasing GHGs. These changes are due to an increase in transient eddy fluxes over North America, and an increase and eastward shift of the stratospheric polar low anomaly (polar vortex) over Siberia and associated changes in cross-polar transport of planetary vorticity, while the tropical QBO itself remains nearly unchanged.

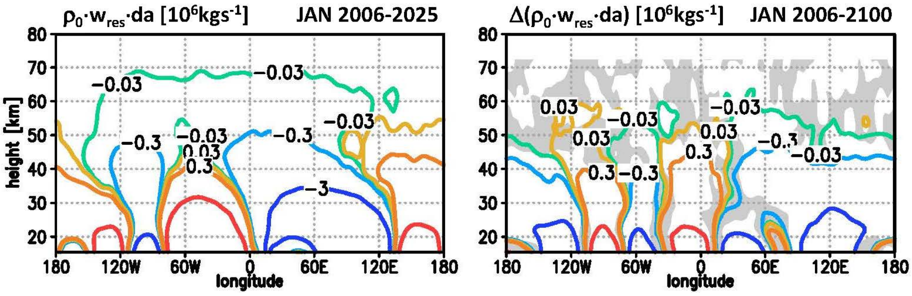

Figure 2. (Left) Time-mean vertical residual mass flux per grid box area $\rho_0 \cdot w_{res} \cdot da$ at 60°N, January 2006-2025, and (right) linear change $\Delta(\rho_0 \cdot w_{res} \cdot da)$ during 2006-2100 (shaded: not significant).

Accordingly, Figure 2 (left) indicates an inherent stationary wave two in the extra-tropical vertical residual mass flux of the first 20 years of the RCP4.5 simulation, with branches of downwelling over North America (90°W) and over Northern Europe/West-Siberia embedded in the stratospheric polar vortex (0°-120°E). Figure 2 (right) shows that the time-mean wave pattern over 180°W-30°W disappears during 2006-2100 (opposite signs of the trend compared to the wave pattern), but also an increase and eastward shift of the downwelling over 0°-120°E towards East-Siberia. Further we find that, in the area of the stratospheric polar vortex, the radiative cooling due to increasing GHGs is partly compensated by adiabatic warming due to the increase in the stratospheric downwelling. The latter also forces a significant long-term increase in the tropospheric high anomaly usually occurring over Northern Asia during winter, similar to the transition from QBO-W to QBO-E signature as has been reported in previous project reports.

The local trends of important tracers like H_2O are also embedded in the change of the stationary waves, i.e., during QBO-W, we find a change from stationary wave two towards wave one pattern (Figure 3, left; note here that the maximum of total H_2O is located in the upper stratosphere). The contribution of the 3D BDC to the local changes in H_2O is derived by separating the rotational and divergent components in the residual budget: $\partial H_2O/\partial t \approx -(\underline{v}_b+\underline{v}_{dres})\nabla H_2O + D_{H2O}$ ($\underline{v}_b$ is the horizontal balanced flow with $\underline{v}_b \approx \underline{v}_{rot}$, $\underline{v}_{dres}=\underline{v}_{res}-\underline{v}_b$ is the divergent residual flow, D_{H2O} is a mixing term). Then, Figure 3 (middle) shows an increase in the horizontal transport by $\underline{v}_b$ circling around the centre of the polar vortex, at the cost of the wave-like patterns over 180°W-60°W, and Figure 3 (right) a change from wave two towards wave one in the divergent horizontal transport at higher altitudes (the sign of the patterns depends on the horizontal and vertical gradients of both winds and H_2O). The different altitudes of most pronounced tendencies indicate that the balanced flow extends up to ~60km, whereas the stationary wave patterns at higher altitudes are related to local vertical gravity wave propagation which depends on the wave patterns of the balanced flow below.

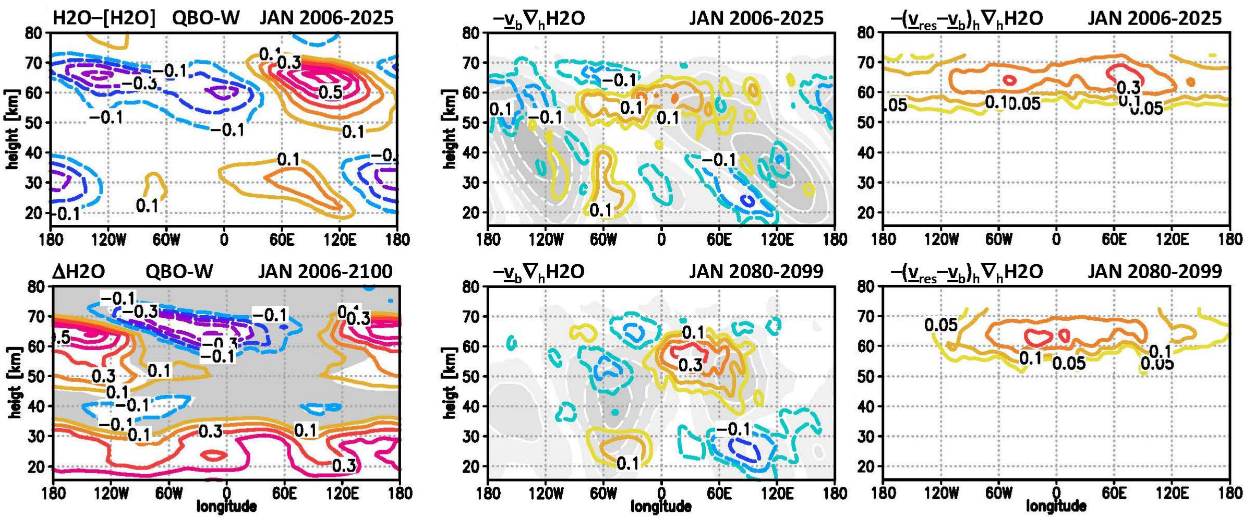

Figure 3. (Left, top) Deviation of H_2O from zonal mean during QBO-W, RCP4.5 simulation, 60°N, January 2006-2025, and (left, bottom) total change of H_2O during 2006-2100 (both in ppm), and local tendencies due to the advection of H_2O by (middle) rotational winds (shaded: meridional wind v_b) and (right) horizontal divergent residual winds, averaged over the first and last 20 years of the RCP4.5 simulation (in ppm day^{-1}).

Reference: Gabriel, A. (2018), Long-term changes in the northern mid-winter middle atmosphere in relation to the Quasibiennal Oscillation, *J. Geophys. Res.*, in revision.