Past and future changes of the three-dimensional Brewer-Dobson circulation

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The aim of the project is to investigate the past and future changes of the three-dimensional (3D) Brewer-Dobson circulation based on the consortia simulations with the Earth-System Model MPI-ESM (CMIP5 simulations) and additional sensitivity simulations. The Brewer-Dobson circulation (BDC) denotes the time-mean mass circulation of the middle atmosphere (10-100km) and plays a key role in middle atmospheric dynamics and chemistry. The BDC is driven by planetary, synoptic-scale and gravity waves and characterized by upwelling in the tropical stratosphere and downwelling at mid- and polar latitudes during winter, transporting ozone (O_3), water vapour (H_2O) and other important trace gases from the tropics to mid- and polar latitudes. Usually the BDC and the wave driving are examined based on the zonal mean (2D) residual circulation approach which includes both the 2D Eulerian and eddy time-mean flow (the latter is a function of the time-mean eddy heat fluxes).

The interaction of climate change, the 2D BDC and stratospheric O_3 is an important issue of current research (e.g., Butchart et al., 2006, 2010; Garcia and Randel, 2008; McLandress & Shephard, 2009; Seviour et al., 2011; Weber et al., 2011). Most of the used models suggest a past and future increase of the upwelling (~2% per decade), but the trends of the extra-tropical downwelling and the 2D wave driving processes are very different. Further, in contrast to the models, reanalysis data and satellite data suggest a decrease in the strength of the 2D BDC during the last decades. Conclusively the resulting picture of the 2D BDC in a changing climate is very uncertain. Examinations of the 3D BDC might lead to a more detailed picture of the BDC and an improved understanding of the wave driving hidden by the 2D approach, but they are very sparsely up to now (Callaghan and Salby, 2002; Kinoshita et al., 2010). The 3D BDC might play a key role in configuring the observed stationary wave patterns in the middle atmosphere but also in the troposphere via stratosphere-troposphere coupling processes. For example, the radiative forcing due to stationary waves in stratospheric O_3 can significantly affect the stratospheric circulation but also tropospheric circulation patterns and wind-driven ocean currents (Gabriel et al., 2011b, 2012). On the other side, stationary wave patterns in the troposphere are an important factor controlling various aspects of regional climate change (IPCC, 2007, Chapter 3) but their amplitudes are usually too weak in current state-of-the-art models (Boer and Lambert, 2008; SPARC, 2010). Stationary waves in stratospheric O_3 are largely due to time-mean transport characteristics (e.g., Gabriel et al., 2011a). Therefore longitudinal variations of the 3D BDC might largely contribute to the differences between the observed local and zonal mean ozone trends, which are not fully understood (Terao and Logan, 2007). Overall an examination of the 3D BDC might significantly contribute to the understanding of local changes in both the middle atmosphere and the troposphere and to an improvement of current models used for climate change studies.

In the framework of the project the past and future changes of the 3D BDC, the wave driving and the eddy mixing processes will be investigated based on the 3D residual circulation approach of Kinoshita et al. (2010). The diagnosis will use the CMIP5 simulations with the MPI-ESM MR (T63L95/TP04L40, model top at ~80km) for the time period 1960-2005 and the projections up to 2100 (scenarios RCP2.6, RCP4.5 and RCP8.5). For validation and aspects which cannot be achieved by the CMIP5 simulations alone, the 3D BDC will also be analyzed based on long-term simulations with the general circulation and chemistry model HAMMONIA 1960-2006 (data provided by H. Schmidt, MPI-Met, Hamburg), reanalysis data (ERA-Interim, MERRA) and satellite data (Aura/MLS), where the latter will provide a new global wind data set suitable for validating the 3D BDC calculated by the models at altitudes where only very sparse local wind observations are available (ca. 30-80km). The examinations will include a quantification of the sources driving the 3D BDC (variability in surface temperatures and tropospheric wave activity, increasing concentrations of greenhouse gases, 11-year cycle in solar irradiation, Quasiennial Oscillation of the stratospheric winds over the tropics) and an analysis of the impacts of the 3D BDC on the local changes in the middle atmosphere, in the troposphere and in wind-driven ocean currents via stratosphere-troposphere coupling processes.

In this context sensitivity simulations with the MPI-ESM (the model code is provided by the MPI-Met Hamburg) will be performed because an accurate understanding of the involved processes cannot be achieved based on the used data alone. The specific goal is to quantify the sensitivity of the 3D BDC to the tropospheric wave forcing, the sensitivity of the tropospheric wave activity and circulation patterns to the stratospheric 3D BDC, and the effects of the feedback loops configuring the interaction between the 3D BDC and tropospheric wave activity. These sensitivity simulations will include specific forcing terms derived from the observations and assimilations but under the same conditions otherwise, and will be analysed based on the same diagnostics applied for the data described above. The forcing terms are specified by:
1) local time-mean surface temperatures deduced from observations (SST of the Pacific and Atlantic oceans, surface temperatures of the cold anti-cyclone of the Asian continent during winter) to quantify their influence on the longitudinal variations of the 3D BDC and the stationary waves,
2) local time-mean eddy flux terms deduced from observations and implemented via a 3D diffusivity approach, particularly to identify the sensitivity of the 3D BDC and associated stationary waves to the observed Pacific-Atlantic/European bimodality in tropospheric wave activity,
3) observed stratospheric stationary wave one patterns and polar vortex structure, in order to quantify the induced modulations in the local upwelling and downwelling of the 3D BDC and subsequent changes in the westerly jet and the associated local distribution of tropospheric wave activity,
4) observed local monthly mean stratospheric eddy flux terms which also modulate the local upwelling and downwelling of the 3D BDC, the westerly jet and the tropospheric wave activity,
5) observed stationary waves in O$_3$, H$_2$O and stratospheric aerosol modulating the 3D BDC by radiative forcing,
6) both observed local surface temperatures and monthly mean eddy flux terms to quantify how the “one-way”-effects identified by (1)-(5) affect the interrelationship between the 3D BDC and the Pacific-Atlantic/European bimodality in tropospheric wave activity,
7) prescribed time-mean SST derived from the CMIP5 simulations (RCP2.6, RCP4.5 and RCP8.5) in order to quantify the feedback of the 3D BDC to the surface drag and wind-driven ocean currents (i.e. the Kuroshio, the Gulfstream and the Antarctic Circumpolar Current).

The sensitivity simulations with the MPI-ESM will be performed for time periods of 30 years. Issues (1)-(6) will include time periods where observations or assimilations are available (1975-2005) and issue (7) representative time periods for quantifying the interaction between the 3D BDC and wind-driven ocean currents (2000-2030 and 2070-2100). Overall the simulations at the HRLE at the DKRZ will sum up to about 12x30years. In summary we expect important insights into the bottom-up- and top-down processes modulating the local upwelling and downwelling of the 3D BDC and its effects on the structure of the westerly jet, the local distribution of Rossby and gravity wave activity, regional circulation patterns like the North-Atlantic Oscillation (NAO), wind-driven ocean currents and regional climate conditions. We also expect important information how to improve the strength and structure of the 3D BDC and of the stationary and transient wave patterns in the climate model.

References