Project 850: Past and future evolution of the 3D Brewer-Dobson circulation

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Introduction

● The Brewer-Dobson circulation (BDC) denotes the time-mean mass circulation of the middle atmosphere (10-100km). The BDC is driven by planetary waves, synoptic-scale waves and gravity waves, and transports important trace gases (stratospheric ozone: O_3, water vapour: H_2O) from the tropics to polar latitudes.

● The interaction of the BDC, stratospheric O_3 and climate change is an important issue of current research. In this context the BDC is usually examined by using the zonal mean (2D) residual circulation[1], whereas examinations of the three-dimensional (3D) BDC are very sparse. The identified changes of the 2D BDC are very uncertain because of strong discrepancies between model results and observations[2].

● The aim of the project is to investigate the past and future changes of the 3D BDC based on a recent formulation of the 3D residual circulation[3]. In particular, the effects of local changes in tropospheric wave activity on the 3D BDC, the effects of the 3D BDC on the stationary waves and local trends in the stratosphere (10-50km), and the feedbacks of the 3D BDC to the local changes in the troposphere will be examined.

[1] The residual circulation describes the net mass transport due to both the time-mean Eulerian winds and "eddy fluxes", and provides an in-depth analysis of the wave driving decomposed in planetary waves, synoptic-scale waves and gravity waves
[2] For example: Butchart et al. (2010, *J. Climate*); Seviour et al. (2011, *Q. J. R. M. S.*); Weber et al. (2011, *Atm. Chem. Phys.*)
[3] Kinoshita et al. (2010, *J. Meteor. Soc. Japan*); Kinoshita and Sato (2013a,b, *J. Atm. Sci.*)

Project 850: Overview

● The past and future changes of the 3D BDC will be investigated based on the consortia simulations with the Earth-System Model MPI-ESM MR (CMIP5 simulations; resolution: T63L95/TP04L40; model top ≈80km) for the time period 1960-2005 and the projections up to 2100 (scenarios RCP2.6, RCP4.5, RCP8.5).

● For validation and aspects of climate-chemistry interaction, the 3D BDC will also be analyzed based on simulations with the general circulation and chemistry model HAMMONIA[1], reanalysis data (ERA-Interim[2], MERRA[3]), and a new data set of global wind fields for the middle atmosphere which will be derived from Aura/MLS satellite data[3] via balanced equations and inversion of tracer transport. Sensitivity simulations with the MPI-ESM[4] will be performed to analyse the involved stratosphere-troposphere coupling processes.

● These simulations will include specific forcing terms derived from observations (surface temperatures, corrections of tropospheric and/or stratospheric wave driving; details see below); the aim is to understand the interactions between the long-term changes in the 3D BDC, tropospheric wave activity, wind-driven ocean currents and regional climate conditions.

[1] HAMMONIA data 1960-2006 provided by H. Schmidt, MPI-Met, Hamburg
[2] ERA-Interim data 1979-2012 provided by ECMWF, Reading, UK
[3] MERRA data 1979-2012, and Aura/MLS data (temperature,O_3,H_2O) 2004-2012, provided by NASA, USA
[4] The model code of the MPI-ESM is provided by the MPI-Met, Hamburg

Sensitivity simulations with the MPI-ESM (project period: 1.1.2013 – 31.12.2015)

The sensitivity simulations will include prescribed forcing terms deduced from observations, which smoothly push the monthly means of the tropospheric wave activity and/or the stratospheric 3D BDC towards observations, under the same conditions of the CMIP5 simulations otherwise. These "corrections" are specified by:

(1) local surface temperatures (surface temperatures of the Pacific and the Atlantic oceans, and of the cold anti-cyclone over Asia during northern winter), in order to quantify their effects on the longitudinal variations of the 3D BDC and the polar vortex;

(2) local tropospheric eddy fluxes deduced from observations and implemented into the model via a 3D diffusivity approach[1]; the aim is to identify the sensitivity of the 3D BDC and stratospheric stationary waves to the variability in local tropospheric wave activity;

(3) local stratospheric eddy fluxes implemented into the model via the 3D diffusivity approach; the aim is to quantify the effects of the local upwelling and downwelling of the 3D BDC on the polar vortex structure, the westerly jet and regional circulation patterns (e.g., the NAO);

[1] In detail: via a 3D eddy diffusion term $D=\nabla \underline{\mathbf{K}}_{corr}\nabla q$ for quasi-geostrophic potential vorticity q, where the time-mean diffusion tensor $\underline{\mathbf{K}}_{corr}$ is the difference between $\underline{\mathbf{K}}_{model}$ of the ongoing simulation and $\underline{\mathbf{K}}_{obs}$ derived from observations; this approach is a meaningful extension of previous works investigating the effects of observed changes in planetary and synoptic-scale waves on the tropopause height and on the interannual and decadal variability of stratospheric ozone in a 2D version of the ECHAM model with interactively coupled chemistry (Gabriel and Schmitz, 1999, *J. Atm. Sci.*; 2002, *GRL*.; 2003, *J. Climate*).

(4) stationary waves in stratospheric temperature, which might also modulate the longitudinal variations in the 3D BDC and subsequent changes in the troposphere[2];

(5) stationary waves in stratospheric O_3, H_2O and aerosol, which might affect the 3D BDC via modulating the radiation budget[3];

(6) both the tropospheric and stratospheric "corrections", to analyse how the "one-way"-effects of (1)-(5) are modulated by the interaction between the 3D BDC and tropospheric wave activity (based on a new linear feedback analysis which quantifies the amplification or damping processes operating either internal or external of the stratosphere and troposphere);

(7) long-term means of the SST derived from the CMIP5 projections (RCP2.6, RCP4.5, RCP8.5), to examine the 3D BDC with and without its feedback to the wind-driven ocean currents (i.e., the Kuroshio, the Gulfstream, the Antarctic Circumpolar Current)[4].

[2] Stationary wave patterns are usually not captured accurately by current state-of-the-art models in comparison to observations (Boer and Lambert, 2008; SPARC CCMVal report, 2011), but they largely control various aspects of regional climate change (e.g., IPCC AR4, 2007, Chapter 3).
[3] The effects of stationary waves in stratospheric O_3 have been discussed, e.g., by Gabriel et al. (2007, *GRL*; 2011, *JGR*), Crook et al. (2008, *GRL*), Gillett et al. (2009, *GRL*) and Waugh et al. (2009, *GRL*); in the project the effects of the 3D BDC on the stationary waves in the tracer distributions will be examined based on transport budgets, similar to Gabriel et al. (2011, *ACP*).
[4] The effect of stationary waves in stratospheric O_3 on wind-driven ocean currents via modulating the surface drag has recently been discussed by Gabriel et al. (2012, "CAWSES" priority program, Springer Press, The Netherlands, pp. 443-466).

Preliminary results – 3D residual circulation and QBO-signatures in Aura/MLS satellite data and HAMMONIA simulations

(I) Figure 1 illustrates the structure of the 3D residual circulation at 60°N during northern winter. The downwelling of the 3D BDC is directed towards the centre of the polar vortex over Siberia (60°E). The Eulerian and the eddy time-mean flow are largely counteracting. In the HAMMONIA simulations the large-scale quasi-geostrophically balanced waves are weaker, the synoptic-scale transient waves stronger than in observations.[1)]

Aura/MLS (quasi-geostrophic)

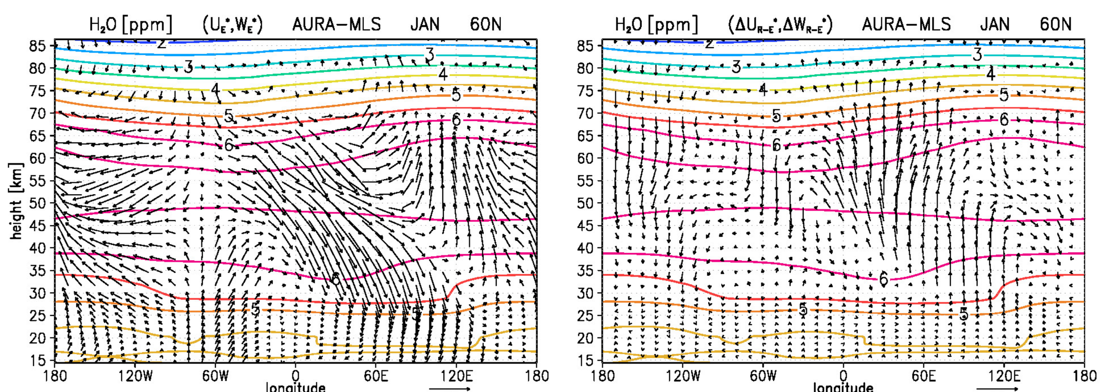


Figure 1a, left: Zonally asymmetric Eulerian wind vector (u_e*, w_e*) (u_e* in ms^{-1}, w_e* in mms^{-1}, scaling at the bottom); right: difference between residual and Eulerian winds (Δu_{r-e}*, Δw_{r-e}*); isolines: H_2O [in ppm]; mean January 2005-2010; the underlying quasi-geostrophically balanced daily-mean winds are derived from Aura/MLS temperature profiles sampled on a 10°x10° grid (longitude x latitude)[2)] .

HAMMONIA

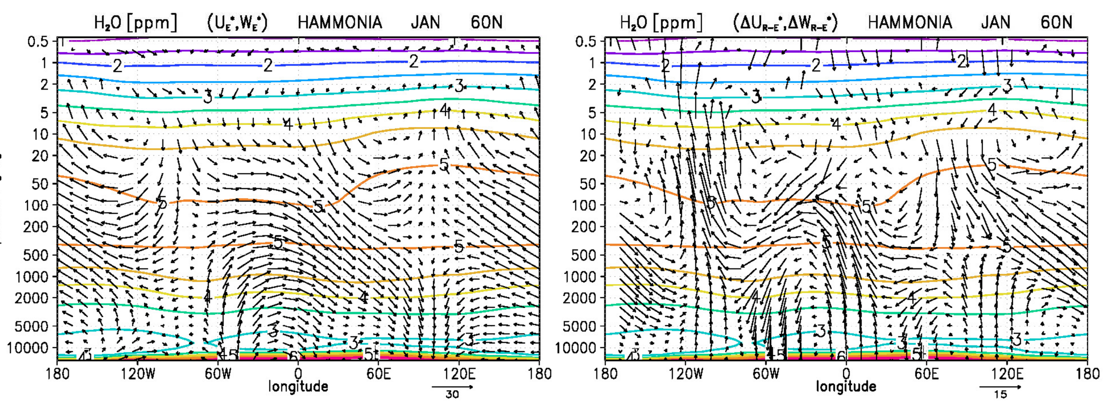


Figure 1b: as Figure 1a, but for HAMMONIA simulations (T31, 119 layers up to ≈250km) with prescribed monthly mean AMIP-SST , January 2001-2006 .

HAMMONIA (quasi-geostrophic)

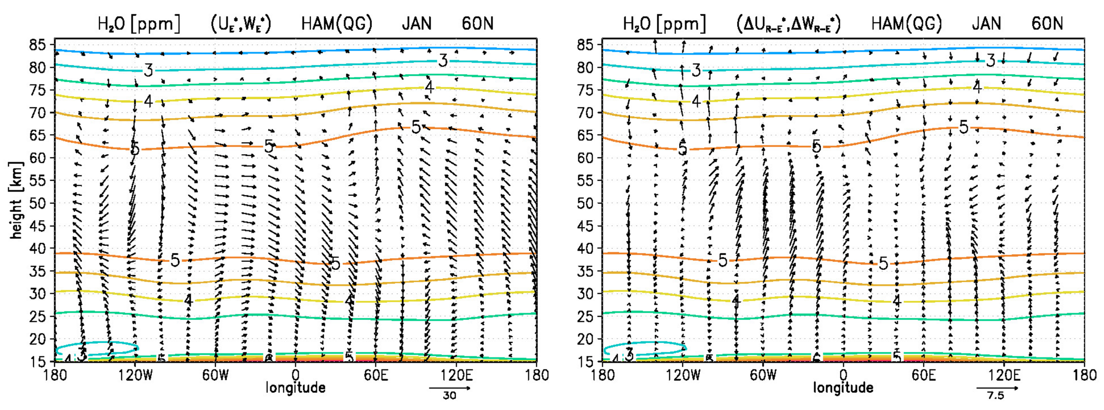
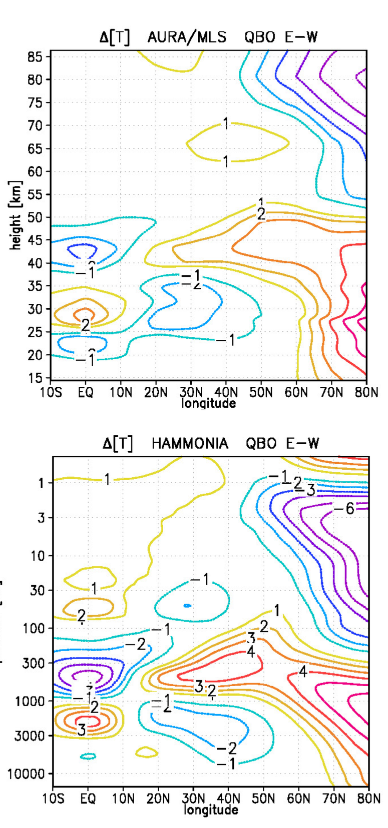


Figure 1c: as Figure 1b, but for quasi-geostrophically balanced winds on a 10°x10° grid derived from HAMMONIA temperature profiles in exactly the same way as the winds from Aura/MLS temperature profiles shown in Figure 1a.

[1)] Further comparison including validation in the lower and middle stratosphere with ERA-Interim data is given in Demirhan-Bari et al., 2013; *J.Geophys.Res.*, in press)
[2)] Analogously to Gabriel et al. (2011, *Atmos. Chem. Phys.*)

(II) Long-term changes in the stratospheric stationary wave-1 pattern can significantly alter the stratospheric and tropospheric circulation, and wind-driven ocean currents[3)]. It is also known that the Quasibiennal Oscillation (QBO) of zonal winds in the tropical stratosphere can alter the polar vortex and the wave-1 pattern (wave-1 is stronger during QBO-East, wave-2 is stronger during QBO-West) via modulating the poleward wave propagation[4)]. The QBO is therefore a suitable test-bed for analysing the associated modulations in the 3D residual circulation and in the troposphere.



← **Figure 2a**: Difference in zonal mean temperature between QBO-East and QBO-West; upper panel: Aura/MLS lower panel: HAMMONIA

→ **Figure 2b**: Zonally asymmetric component of the vertical residual wind w_{res} for QBO-East (left, pronounced wave-1) and QBO-West (right, pronounced wave-2); upper panel: Aura/MLS, lower panel: HAMMONIA

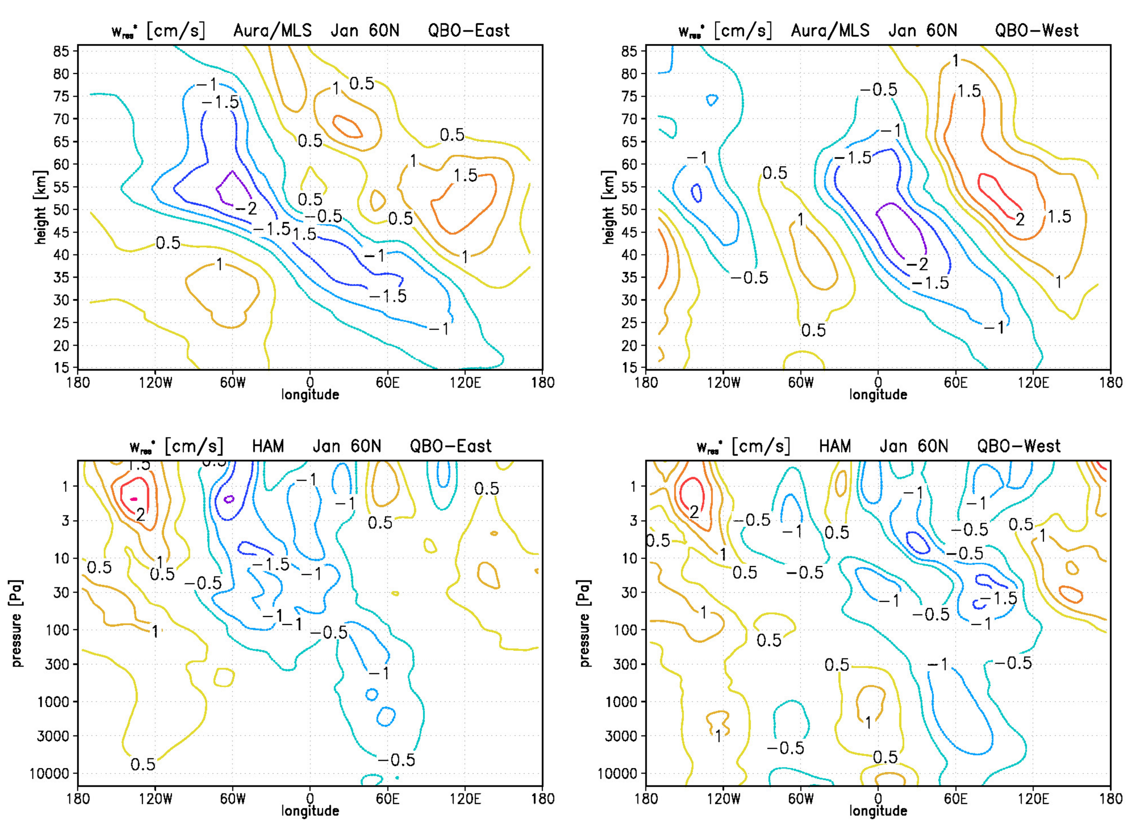


Figure 2 illustrates that HAMMONIA captures quite well the QBO-signatures in the zonal mean temperature (warmer stratospheric polar vortex during QBO-East) and in the vertical residual wind (wave-1 during QBO-East, wave-2 during QBO-West), although the signal looks much more disturbed than in Aura/MLS because of strong transient wave activity.

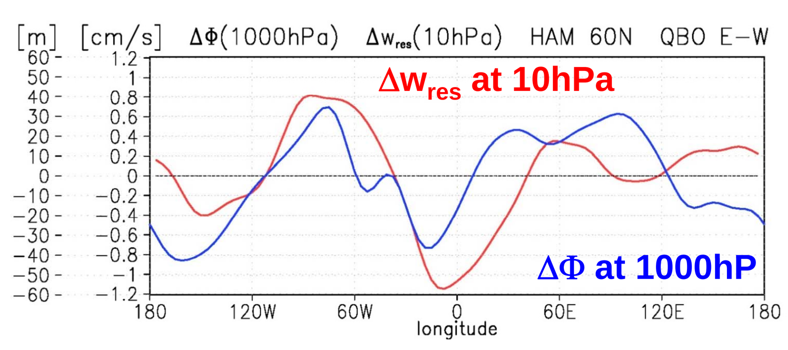


Figure 3: Differences in the vertical residual wind w_{res} at 10hPa (red line), and in geopotential height Φ at 1000hPa (blue line), between QBO-East and QBO-West; HAMMONIA, January 2001-2006

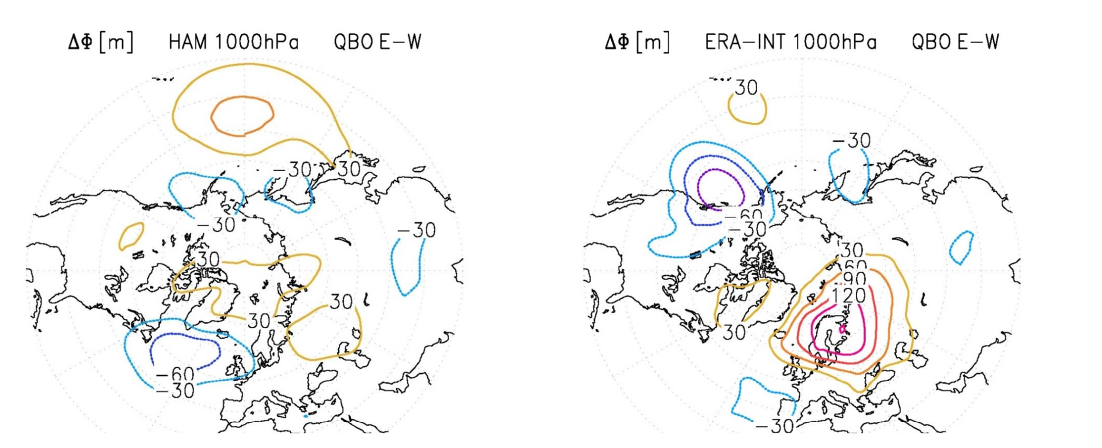


Figure 4: Difference in geopotential height at 1000hPa between QBO-East and QBO-West, left HAMMONIA, right: ERA-Interim 2005-2010

Figure 3 indicates a correlation between the QBO-signals in the stratospheric vertical residual wind (i.e., the local up- and downwelling of the 3D BDC) and in geopotential height at the 1000hPa pressure level , i.e., the induced change in the stratospheric mass circulation might lead to a change in the distribution of high and low anomalies at the surface.
Figure 4 shows the related anti-cyclonic perturbations over Northern Europe/Scandinavia and cyclonic perturbations over the Atlantic ocean in both HAMMONIA and ERA-Interim, i.e., a change towards negative phase of the North-Atlantic Oscillation (NAO) similar to other results investigating the effects of stratospheric stationary waves on the troposphere[3)].

[3)] Gabriel et al. (2007, *GRL*; 2011, *JGR*; 2012, "CAWSES", Springer Press, 443-466), Crook et al. (2008, *GRL*); Gillett et al. (2009, *GRL*); Waugh et al. (2009, *GRL*).
[4)] Holton and Tan (1980, *J. Atmos. Sci.*)