Final Report for Project **1146**

Project title: **Long-term trends in relation to the QBO**

Principal investigator: **Axel Gabriel**

Report period: **Jan. 1, 2020 - Dec. 31, 2021**

Final Report (31.12.2021)

(1) Introduction

Understanding the interaction between long-term changes in the atmospheric circulation due to anthropogenic greenhouse gases (GHGs) and natural variability is a current problem of climate change research. The most prominent component of interannual variability in the stratosphere is the ~28-month Quasi-Biennial Oscillation between westerly (QBO-West) and easterly (QBO-East) winds in the equatorial stratosphere and its effect on the extratropical northern winter stratospheric circulation (e.g., Holton and Tan, 1980; Baldwin et al., 2001; Anstey et al., 2010; Garfinkel et al., 2012), where the change from extra-tropical QBO-West- to QBO-East signature includes a change from mid-winter stratospheric stationary wave two to wave one (Holton and Tan, 1980; Gabriel, 2019).

In the framework of a previous project work (Gabriel, 2019), CMIP5 simulations with the Earth-System model MPI-ESM-MR including GHG emission scenarios for 1978-2008 (AMIP-SST) and for the 21st century (RCP4.5 and RCP8.5) have been analysed to investigate the long-term changes in the atmospheric circulation in relation to the QBO, including – as far as possible – validation with ERA-Interim reanalysis (original model output data of the MPI-ESM-MR provided by M. Giorgetta, MPI-Met Hamburg; for more details of the simulations see Giorgetta et al., 2013, and Schmidt et al., 2013; ERA-Interim data provided by ECMWF, Reading). Gabriel (2019) found that long-term changes in the high-latitude northern mid-winter stratosphere and mesosphere are much stronger during QBO-West than QBO-East, locally by a factor of up to ~4. This unexpected trend behavior is related to a change in the response of the extra-tropical circulation to the QBO, i.e., a change of the extra-tropical QBO-West towards QBO-East signature, while the equatorial QBO itself remains nearly unchanged.

In particular, the results of Gabriel (2019) show a pronounced long-term change in the stratospheric three-dimensional (3D) residual circulation (calculated following Sato et al., 2013), including an increase in the regional downwelling w_{res} located in the centre of the polar low over Northern Europe/West-Siberia, which is embedded in a long-term change from stationary wave two towards wave one during QBO-West, whereas the changes during QBO-East include only a slight increase in the strength of the polar vortex and the downwelling. Although there is some evidence that the GHG-induced cooling of the stratospheric polar vortex over Northern Europe/Siberia and/or the GHG-induced changes in planetary-scale Rossby waves forced by the Rocky Mountains might play a key role in controlling this trend behavior, there is a strong need in understanding the causal relationships because of the non-linear interdependencies between the polar vortex and the planetary waves.

(2) Outline of the project

The aim of the project was to contribute to a better understanding of these processes, as well as on the related stratosphere-troposphere coupling processes and the feedback of imposed changes in the troposphere to the changes in the stratosphere. The items included additional data analysis, and additional model sensitivity simulations where the effect of the increasing GHGs are geographically restricted either to high-latitudes over the Northern European/Siberia region (i.e., to the radiative cooling of the polar vortex), or up to mid-latitudes over North-East-Pacific/North America (which affects the westerlies in this region similar to the QBO, and subsequently the development of mid-latitude planetary waves).

At the beginning, the project work was designed for a project period of approximately two years. Additional analysis of reanalysis data and existing model data have been carried out, providing new insights into the processes controlling the long-term circulation changes in both the stratosphere and troposphere. Some examples are given in the following and in an accompanying publication going to be submitted soon (Gabriel, 2022). Unfortunately, because of a strong delay of the research works during the last two years, the planned simulations were not carried out during the two-year project period. New computer resources for the year 2022 were not applied. However, the new results obtained so far and described below might stimulate further project works including the planned sensitivity simulations.

(3) Long-term changes in the stratosphere and troposphere relation to the QBO

Since Holton and Tan (1980) it is known that the zonal mean northern winter stratospheric polar vortex is warmer and the accompanying zonal mean westerly jet at high latitudes weaker during QBO-East than QBO-West (Holton-Tan relationship). However, important regional changes due to the QBO are averaged out when looking only at the zonally averaged picture of the extra-tropical QBO signatures as usually examined, particularly the change from sinusoidal stationary wave two during QBO-West to wave one during QBO-East. Subsequently, regional trends in monthly means describing the atmospheric circulation might be much stronger and more evident than expected up to now when separating in months during QBO-West and QBO-East.

For example, the detected long-term change from stratospheric stationary two to wave one during QBO-West found by Gabriel (2019) include an increase in amplitude and eastward shift in phase of the wave one with decreasing stratospheric westerlies over North America but increasing westerlies over Europe, i.e., a stronger and cooler stratospheric polar low anomaly over Northern Europe/Siberia – in contrast to the zonal mean picture usually examined – together with a stronger and warmer stratospheric Aleutian high anomaly. One idea of the project was that the change in the downwelling within the polar low over Northern Europe/Siberia might impose blocking surface high anomalies, as suggested by basic meteorology.

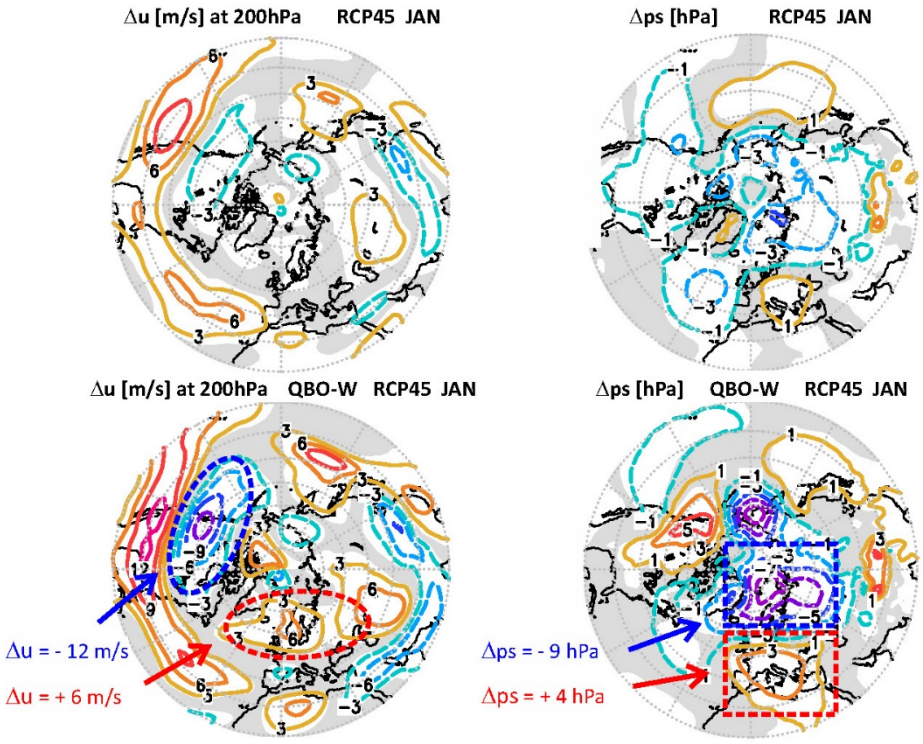

Figure 1: Linear long-term changes in (left) zonal wind at 200hPa and (right) surface pressure; upper panels: total changes, lower panels: linear changes during QBO-West; the linear changes are derived from January means 2006-2100 of the MPI-ESM-MR simulation including the RCP4.5 scenario; shaded areas: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

On the other side, the induced increase in amplitude and eastward shift of the easterlies at the southern branch of the Aleutian high anomaly might strongly affect the westerly flow across the Rocky Mountains, which could lead to a decrease in orographically-forced Rossby wave developments extending over the North-Atlantic, and therefore to less disturbances of the polar vortex over Northern Europe/Siberia. This could explain the long-term change from stationary wave two (forced by the Rocky Mountains) towards wave one signature independent on the equatorial QBO.

Figure 1 compares the total long-term changes in the zonal wind at 200 hPa (~12 km) and in surface pressure with the changes during QBO-West, as derived from the RCP4.5 simulation. The changes in the zonal wind at 200 hPa (Figure 1, left panels) show a pronounced decrease over North America and an increase over Europe/West-Asia, where the changes during QBO-West are much larger than the total changes. Consistently, the changes in surface pressure (Figure 1, right panels) show an increase in the southern and a decrease in the northern European regions, i.e., a change towards positive phase of the North Atlantic Oscillation (NAO), which is also much stronger during QBO-West compared to the total changes. The decrease in the westerlies over North America is consistent with the increase in amplitude and eastward shift of the Aleutian high anomaly, whereas the increase of the westerlies over Europe might be due to less disturbances by Rossby waves over the North-Atlantic but also by a change in the frequency of blocking anticyclones in this region.

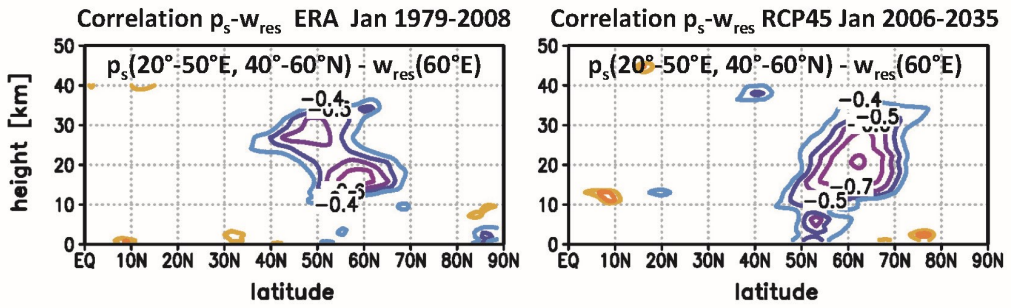

Figure 2: Temporal correlation between January means of a surface pressure p_s averaged over (20-50°E,40-60°N) and the vertical residual wind w_{res} at 60°E (isoline distance is 0.1), derived from (left) ERA-Interim 1979-2008 and (right) the first 30 years of the RCP45 simulation.

Figures 2 and 3 illustrate this relation by the temporal correlation between the January-mean patterns of w_{res} and a surface pressure p_s averaged over an eastern European region (20°-50°E, 40°-60°N), derived from ERA-Interim and the RCP45 simulation. For a cross-section of w_{res} at 60°E, Figure 2 shows that, during current climate conditions, the variability of p_s over Eastern Europe is well correlated with the variability of the downwelling in the centre of the polar low, indicating the assumed top-down forcing of blocking surface high anomalies in this region.

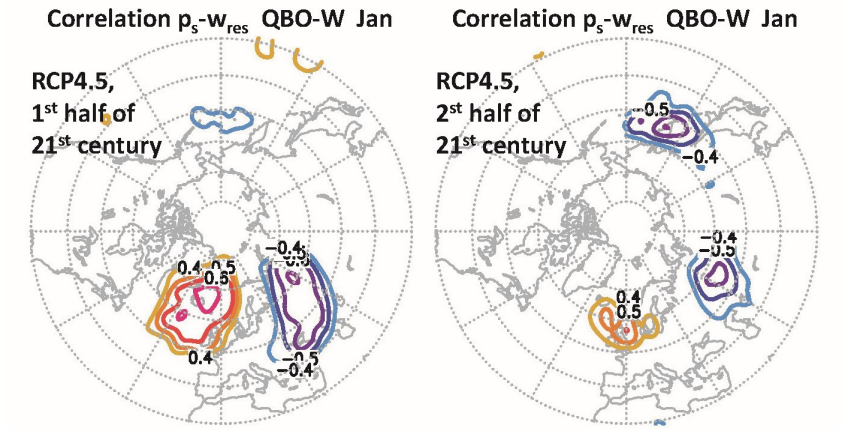

Figure 3: Temporal correlation between January means of a surface pressure p_s averaged over (20-50°E,40-60°N) and the vertical residual wind w_{res} at 10hPa during the westerly phase of the QBO (isoline distance is 0.1), derived from (left) the first and (right) the second half of the RCP45 simulation.

Figure 3 shows the correlation for w_{res} at 10 hPa for the first and second half of the 21st century for QBO-West, derived from the RCP45 simulation, indicating an eastward shift of the top-down forcing effect from Eastern Europe towards Eastern Asia, following the increase in amplitude and eastward shift of the polar low embedded in the stratospheric wave one. Note here that the correlation patterns under current climate conditions are consistent with the QBO-induced changes in the surface climate conditions of the Northern European region reported by Thompson et al. (2002). Conclusively, the probability of severe winter conditions over North-Eastern Europe might decrease during the 21st century.

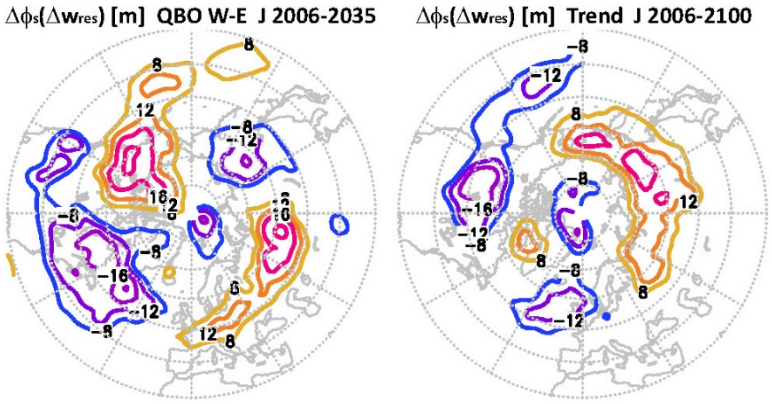

Figure 4: Imposed change in geopotential height Φs at the 1000 hPa-level (isolines in m) due to the change in the downwelling w_{res}; left: QBO-West minus QBO-East, 2006-2035; right: last minus first 30 years of RCP4.5, QBO-West.

For a first-guess quantification of the described effect, Figure 4 shows the imposed change in geopotential height Φs at the 1000 hPa-level due to the change in the downwelling w_{res}, where $\Delta\Phi s$ is derived via $\Delta w_{res} \cdot \partial\theta_0/\partial z \approx -\tau^{-1}\Delta\theta_{wres}$ (τ=10 days) and vertical integration of $\partial\Delta\Phi/\partial z = R\Delta T_{wres}/H$, (where $\Delta\theta_{wres}=\Delta T_{wres}\,(p_0/p)^{\kappa}$). In Figure 4 (left), the input field is the difference Δw_{res} between QBO-West and QBO-East under current climate conditions (2006-2035), and in Figure 4 (right) it is the difference Δw_{res} between the last and the first 30 years of RCP4.5 during QBO-West. Overall, Figure 4 illustrates that the top-down forcing of high anomalies over Europe during QBO-West under current climate conditions in the order of ~15 to ~20 m, and an eastward shift of this process towards Asia during the 21st century.

(4) Concluding remarks

The results obtained so far opens a new viewpoint in understanding the atmospheric circulation in a changing climate. Much of the stratospheric trend behavior is related to a change of the extra-tropical QBO-West signature towards QBO-East signature, including a change from stationary wave two towards wave one, whereas the change of the QBO-East signature is much weaker. Subsequently, the regional trends in the troposphere are different and much more significant than the total trends when separating between monthly means during QBO-West and during QBO-East, underlining the importance of stratosphere-troposphere coupling in the atmospheric circulation. Of course, the addressed processes cannot explain the whole tropospheric trend behavior, and the top-down forced changes in the troposphere might also feedback to the stratosphere. However, it is important to understand the different components in the atmospheric circulation and their interdependencies, and the results might stimulate further project works including the outstanding simulations.

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