Author response to referee comments on Chrysanthou et al. (2020) "Decomposing the response of the stratospheric Brewer-Dobson circulation to an abrupt quadrupling in CO₂" submitted to Weather and Climate Dynamics Discussions

Reply to Anonymous Referee #2

This study is on the changes in the stratospheric Brewer-Dobson circulation in response to a quadrupling of CO2 concentration. Utilizing the HadGEM3-A model, the authors separate out the fast response to CO2 increase from the effect of uniform SST warming as well as the SST warming pattern. It is found that the uniform warming dominates the circulation changes in the lower stratosphere, but the rapid adjustment makes comparable contribution to the uniform warming at the 10 hPa. This is a useful study in understanding the climate changes in the stratosphere. The manuscript is generally well written and logically organized. I have some relatively minor comments on some of the results and discussion and would recommend publication after the authors address these comments.

We appreciate your constructive comments in order to improve the results and discussion of the study. We reply to the specific points raised below in red.

Main comments:

1. The mechanism for the rapid adjustment of the BDC. Can the authors elaborate a little more on how the rapid adjustment affect the BDC? The authors briefly mentioned the radiative cooling in the stratosphere. One possibility is that the radiative cooling then affects the strength of the polar night jet via thermal wind balance, which then affect wave dissipation and the BDC. However, the rapid adjustment of the zonal wind shows weak decrease in the NH upper stratosphere and moderate increase in the SH upper stratosphere (Fig. 3b). Such wind changes seem to be inconsistent with the changes in w* (Fig. 4b), which shows large strengthening of the downwelling over the Arctic and small strengthening over the Antarctic.

Thanks for this interesting comment. The thermal wind response due to the direct cooling is fairly small because the CO₂ radiative cooling is quite homogeneous in latitude (Fels et al., 1980). One hypothesis that we think is plausible is that the radiative cooling alters the refractive index in the stratosphere, which changes the propagation and breaking of Rossby waves. The refractive index, nr, is dependent on the Brunt-Väisälä frequency (e.g., Matsuno, 1970), N₂, which is in turn related to the vertical gradient of potential temperature:

$$N^2 = \frac{g}{\theta} \frac{d\theta}{dz}$$

Hence the stratospheric cooling, which increases with height, alters N₂ and in turn nr. Unfortunately, we do not have the model variables to calculate nr directly for the simulations. We have added a section discussing this possible mechanism (revised manuscript lines 350 - 359 / tracked changes manuscript lines 383-391):

"Previous studies have demonstrated mechanisms for tropospheric warming to influence the stratospheric EPFD and residual circulation (e.g., Shepherd and McLandress, 2011), but the mechanism through which the rapid adjustment acts on EPFD in the upper stratosphere is less well understood. The radiative cooling in the stratosphere due to increased CO₂ is relatively uniform in latitude (Fels et al., 1980), so we do not expect large direct changes in zonal wind through thermal wind balance. However, the temperature response to CO₂ represents a weakening of the vertical temperature gradient, particularly in the upper stratosphere where the cooling is larger. The characteristics for wave propagation and refraction can be

quantified using a measure of refractive index (e.g., Matsuno, 1970) that is dependent on the Brunt-Väisälä frequency ($N_2 = g/\theta(d\theta/dz)$). Hence, we hypothesise that the changes in background temperature structure due to the CO₂ radiative effects alter the propagation of Rossby waves, particularly in the upper stratosphere, and this leads to the changes in EPFD shown in Figures 7 and 8."

2. The EP flux divergence plots seem to be inconsistent with the changes in stream function. The downward control principle indicates that the latitudinal distribution of Psi* anomalies should be roughly consistent with those of EP flux divergence anomalies. However, the EP flux divergence anomalies seems to locate much poleward than Psi* anomalies, especially in DJF over the Southern Hemisphere (Fig. 6 vs. Fig. S1, Fig. 7 vs. Fig. S2). Based on the argument that stronger subtropical jets following warming allow more waves penetrate into the stratosphere, one would expect the anomalous wave dissipation to occur at the subtropics. This also seems to disagree with the pattern shown in Fig. 6 and 7, where maximum wave dissipation occurs around 50-60 degrees.

The torque exerted on the zonal flow and the associated w* anomalies is proportional to EPFD \times cos(lat) (Haynes et al., 1991); this explains the apparent difference in pattern of EPFD and psi*. When the EPFD is multiplied by cos(lat) the patterns more strongly resemble one another (see Figure R1 below), as expected. Furthermore, this weighted pattern of EPFD anomalies compares closely with the distribution of wave forcing found by Shepherd and McLandress, (2011) who showed in detail the role of changing Rossby wave critical lines in the subtropical lower stratosphere. We have replaced Figures 6 and 7 of the main text with the below figures which show the cosine(latitude) weighted EPFD anomalies. We have also replotted the parametrized wave forcing supplementary figures using the same scaling.



Figure R1: (left) As in Figure 6 of the main text, showing DJF EPFD anomalies for the four experiments, but multiplied by cosine of latitude. (right) As in Figure 7 of main text, showing JJA EPFD anomalies.

3. Model bias in climatology. The model simulated turn-around latitude in piControl climatology seems to be too poleward compared to reanalysis or other models (e.g., Fig. 1 in Hardiman et al. (2014)). At around 20 hPa, there are multiple turn-around latitude in the Northern Hemisphere, indicating more than one cell of the circulation, which seems unreasonable. Such bias in the mean circulation structure reflects bias in the waves forcing and/or other background condition. Would such model bias affect the model's ability to simulate the circulation changes in response to CO2 increase?

To further investigate this feature in the turnaround latitudes, Figure R2 below shows the w* anomalies and turnaround latitudes by season. This shows the feature in the NH midlatitude middle stratosphere is a feature of the DJF season. There is a similar but less pronounced feature in the SH in JJA. We agree that, like any model, HadGEM3 contains biases which may affect the specific results of the study. However, we emphasise that the overall simulated changes in residual circulation correspond very well with other studies analysing large forced changes in the BDC in a range of climate models (e.g., Shepherd and McLandress, 2011; Hardiman et al., 2014; Lin et al., 2015). We have added a sentence at the end of the conclusions caveating that the results are from one model and that climatological biases might affect its simulation of the forced response to CO₂: "The model contains mean biases that could affect some of the details of the responses described here."



Figure R2: As in Figure 4 of the main text, showing w* anomalies in the experiments and the turnaround latitudes, but for (left) DJF and (right) JJA seasons.

Other minor comments and typos:

Line 152-155: experiment "A, C, B, D" should be "B, D, C, E".

Thanks for spotting these typos. We have now corrected the experiment labels mentioned in this part.

Line 281-282: It is hard to compare the three components over NH extratropical middle and upper stratosphere in Fig. 5, as they all seem to be less than the contour interval. On the other hand, the w* changes shown in Fig. 4 seem to suggest that the SST pattern effect is much weaker than the uniform warming or the rapid adjustment.

We have added additional contour intervals to resolve the upper stratospheric anomalies.

Line 330: Fig. 7b should be Fig. 7c.

Thanks for pointing this out, we have now corrected it.

References

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