Answer to Reviewer #1 Comments for “Structural changes in the shallow and transition branch of the Brewer-Dobson circulation induced by El Niño” by Mohamadou Diallo et al.

Dear Editor-in-Chief, Gabriele Stiller,

We are submitting our revised article titled “Structural changes in the shallow and transition branch of the Brewer-Dobson circulation induced by El Niño”. We thank the two Reviewers for their detailed and well thought-out comments, which helped to significantly improve the paper. We have made substantial changes to the manuscript in order to thoroughly address the Reviewers’ suggestions and comments. The main changes concern:

- an additional new figure 6 describing the lag-correlation of the ENSO-induced changes in the transition and shallow branches with the MEI in the manuscript as suggested by Reviewer #1 and the related discussion.
- an additional new figure 10 and new paragraph describing the ENSO-induced changes in the net wave forcings, planetary wave drag and gravity wave drag as suggested by Reviewer #1.
- we included Dr. Manfred Ern as as a new co-author, as he provided the wave decomposition data from ERA-I.
- adding two new paragraphs: one for the lag-correlation and another one in the discussion about the decomposition of wave drag as suggested by Reviewer #1.
- recalculation of the ENSO-induced effect on CLaMS O3, which is sampled CLaMS ozone exactly onto MLS locations and discussion of the possible factors that could contribute to the factor of 2 difference between CLaMS and MLS as suggested by Reviewer #2.
- an additional new panel in each of figures 1, 2 and 3 describing the ENSO-induced changes in the CLaMS O3 driven by the JRA-55 reanalysis as suggested by Reviewer #2
- rephrasing of certain paragraphs in order to clarify the manuscript.

With these changes, we are convinced that the paper is highly relevant for a wide-ranging journal like *Atmospheric Chemistry and Physics*. Please see below our answers point by point to all reviewers’ comments and suggestions.

Reviewers comments are in bold, followed by our respective replies. Changes in the manuscript are in blue, allowing them to be tracked easily.
Kind regards,
Mohamadou Diallo (on behalf of the co-authors)

Reviewer #1 (Comments to Author):

This paper investigates the influences of ENSO on lower stratospheric ozone distribution and BDC strength using a chemical transport model and satellite observations. The ENSO-induced variability in the BDC is thoroughly studied with detailed analysis of the mean age of air, age spectrum, residual circulation, and residual circulation transit time. The authors argue that ENSO causes a structural change of the lower stratospheric BDC, with an increase of the shallow branch and a decrease of the transition branch. Overall the paper is well written. There are some very interesting results. I recommend publication after the authors address my comments.

Specific comments:

1. ***The major conclusion of the paper is that ENSO induces structural changes in the BDC. This conclusion needs to be quantified. I suggest that the authors calculate changes in the strength of the transition and shallow branches using the definitions of Lin and Fu (2013).***

   We have calculated changes in the strength of the transition and shallow branches from the RCTT as follows. The El Niño induced changes in RCTT for the following regions have been considered: 20–60 degrees and 370-420K for the transition branch and 10–60 degrees and 420-500K for the shallow branch. The lag-correlation of the RCTT anomalies is then inferred with the MEI at each grid point and altitude by taking into account the lag from the regression. Finally, we averaged values over these regions in latitude and altitude bins. This analysis quantifies the ENSO-induced impact on both branches and the associated lag-correlation. These results are shown in the new figure 6 and discussed on Page 10, line 15-27.

We are suggesting here the Simpson et al, (2011) explanation i.e. the equatorward shift of the midlatitude jet induced by El Niño results in an enhanced source of waves with higher phase speeds in the midlatitudes and in changed propagation characteristics into the stratosphere. The positive EP flux divergence anomalies near the tropopause suggest an upward shift in the dissipation level. We have separated the discussion into two paragraphs: one for the jet shift and temperature gradient relationship (Page. 12, line 12-31) another one about the EP-flux and DF (Page 12, line 29-Page 13, line 8).

2. ***Page 8, line 27-32: These are very interesting results. However, the explanation is not complete. One can also argue that, from the Lagrangian view, an increased downwelling in the extratropics will lead to a decrease of the mean age there, because it takes less time for an air parcel to reach the extratropics. Indeed, many studies have shown that an enhanced downwelling due to global warming is associated with mean age decrease in the extratropics. I am very interested in why the mean age responses to ENSO differ from its responses to global warming.***

   We thank the Reviewer for pointing that out. The main difference in the response of the AoA to El Niño compared to its global warming response lies in the difference in the transition branch response and, the difference in time-scale of the El Niño perturbations compared to those induced by global warming, which is on the order of years. In a warming climate, climate models predict a globally decreasing AoA due to faster upwelling and downwelling of all branches (transition, shallow and deep) over a time-scale of decades, leading to a shorter stratospheric residence time of air parcel tropically ascending. In contrast, during El Niño, the shallow and transition branch evolve in different regime i.e. a weakening transition branch, strengthening shallow branch and not clear response for the deep branch. El Niño strengthening the downwelling of the shallow branch has a typical time-scale of a few months and maximizes in winter, transporting much older air downward to the lower extratropical stratosphere and hence increasing AoA. The El Niño effect is analogous to the effect of seasonality, where also stronger winter downwelling is related to increasing AoA in the extratropical lower stratosphere. Page 9, line 21-31.

3. ***Page 9, line 14-17: Quantify the changes in the transition and shallow branches. See my comment 1.***

   Please see my reply to comment (1).

4. ***Page 9, line 17-20: Please explain what do you mean by "the upward shift of the strengthening shallow branch".***

   We have removed the typo "the upward shift of". Page 10, line 30

5. ***Page 11, line 10-21: The authors appear to suggest that the positive EP flux divergence anomalies near the tropopause are due to the equatorward and upward shift of the jet. Please explain in more detail.***

   We are suggesting here the explanation by Simpson et al, (2011), i.e. the equatorward shift of the midlatitude jet induced by El Niño results in an enhanced source of waves with higher phase speeds in the midlatitudes and in changed propagation characteristics into the stratosphere. The positive EP flux divergence anomalies near the tropopause and negative changes above suggest an upward shift in the dissipation level. We have separated the discussion into two paragraphs: one for the jet shift and temperature gradient relationship (Page. 12, line 9-28) another one about the EP-flux and DF (Page 12, line 29-end). The modified explanation should be much clearer.

6. ***Page 11, last paragraph: Is it possible to examine ENSO induced changes in gravity wave drag?***

   Thanks for this very good suggestion. To address the El Niño impact on the wave drags we have decomposed the zonal mean wave drag of the resolved waves into gravity and large-scale wave drag for ERA-Interim (an analogous analysis for JRA-55 was not possible as we don't have all necessary data available). Figure 10(a-c) shows the zonal mean distribution of the ENSO impact on monthly-mean net wave forcings (PWD+GWD-du/dt) (a), planetary wave drag (PWD) (b) and gravity wave drag (GWD) (c). The net wave forcings (Fig. 10a) explain the changes in the branches and the hemispheric asymmetry to a remarkable degree. Clearly, the weakening of the transition branch is due to an upward shift in the wave dissipation height up to 425 K, while the strengthening of the shallow branch results from wave breaking above 425 K. The hemispheric asymmetry is a consequence of the asymmetry in both wave distributions (large-scale and gravity), with a larger contribution in the northern hemisphere than southern hemisphere. Most of the ENSO-induced variations in wave forcings are contained in the zonal wavenumbers up to 20 (large-scale waves) and are focused around the tropopause. In the northern hemisphere, there is a positive pattern of planetary wave changes above the tropopause and a negative pattern below the tropopause over a wide latitude range in the extratropics (Fig. 10b), consistent with results from the WACCM model [see Fig. 3 of Calvo et al. (2010)]. This pattern of changes indicates an altitude shift in the dissipation height of the large-scale waves. In the southern hemisphere, the pattern of planetary wave changes is somewhat different and indicates a general shift towards positive values. For the gravity wave response to El Niño, Fig. 10c shows a positive response in the subtropics around 380 K, which is however weaker than the planetary wave response. Interestingly, there is a negative response at higher altitudes in the northern hemisphere subtropics between 425 and 550 K that is even stronger than the response for the zonal wavenumbers up to 20 (Fig. 10b). In summary, the altitude shift in the dissipation height of the large-scale and gravity waves clearly induces the slowdown of the transition branch, while the gravity wave breaking in the tropics-subtropics combined with planetary wave breaking at high latitudes drive the acceleration of the shallow branch. Gravity wave breaking contributes the most to the strengthening of the shallow branch. As gravity wave drag changes occur in the subtropics close to the edge of the upwelling region, they are likely more effective in driving the structural circulation changes than planetary waves. We added a thorough discussion of these new results in Page 13, line 17-35, Page 14, line 1-12.