S.W. Lubis[1], V. Silverman[3], K. Matthes[1, 2], N. Harnik[3], N. Omrani[1, 2], S. Wahl[1]

[1] GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
[2] Christian-Albrechts Universität zu Kiel, Kiel, Germany
[3] Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
[4] Department of Geophysical, Atmospheric and Planetary Sciences, Tel Aviv University, Israel

Correspondence to: S.W. Lubis (slubis@geomar.de)

3. Reviewer #4

The manuscript analysis the instantaneous and cumulative impact of (Downward Wave Coupling) DWC events on Arctic ozone. While it is well known that planetary waves impact polar ozone through modulations of the residual circulation and stratospheric temperatures, the study adds new aspects by explicitly investigating the impact of DWC events on ozone via vertical advection and eddy transport. The analysis is convincing and highlights the role of wave reflection for high latitude ozone field. I recommend publication after addressing the following comments.

We thank the reviewer for reading the manuscript and providing their helpful comments and suggestions. We address their specific comments in turn below.

3.1 Specific Comments:

1) Directly comparing the impact of DWC events on ozone with the impact of upward wave events somehow implies that positive wave activity (as seen before the DWC) without the occurrence of wave reflection would turn into such strong upward wave events. The line of argumentation (and in particular the wording '. . . prevents ...') reinforces this impression (e.g., line 265). Please clarify if DWC events indeed prevent large positive ozone anomalies as shown in Figure 4 and 8. If this cannot be clearly concluded revise the text accordingly.

It is expected that increased wave absorption in the stratosphere (without an occurrence of wave reflection) result in stronger wave convergence (**Figs. S1b, S3b**) and thus, leads to a stronger transport of ozone to the polar region (i.e., increased ozone concentration). Our results (**Fig. 4 and Fig. 8**) confirmed this by showing that in the absence of DWC event (**red lines**), the ozone tendency in the polar stratosphere increases. This means that winters dominated by DWC events are characterized by lower ozone levels compared to those during absorptive winters. Nevertheless, we agree with the reviewer (as with reviewer #3), that the impact of DWC on ozone is actually to 'minimize/ weaken' the typical increase in ozone, but not to 'prevent' ozone increase due to upward wave events. We have changed our text thoroughly.

2) Some aspects of Figures 2 and 6 are not discussed in the text. Why does the vertical advection imply negative ozone tendencies in the upper stratosphere in case of upward wave events? This can be discussed by using the shape of the ozone VMR profile. What about the instantaneous chemical response in the upper stratosphere? Why does the upper stratospheric signal of the eddy transport from upward wave events last much longer in the model simulation?

As stated in the title, the paper is focused on the impact of DWC on polar stratospheric ozone. Therefore, the analysis of the upward wave event in this paper can be seen as a complementary to DWC. Nevertheless, we appreciate the reviewer's suggestions and we have modified the text accordingly. Our specific responses are given below:

- ***Why does the vertical advection imply negative ozone tendencies in the upper stratosphere in case of upward wave events?*** By decomposing the vertical advection term into -w* and dO3/dz using a TEM continuity equation, we found that this negative anomaly is associated with negative vertical gradient of ozone (dO3/dz) at the upper stratosphere. This negative vertical gradient is expected, more ozone transported downward to the mid-lower stratosphere, leading to less ozone concentration at the upper stratosphere. The opposite behavior occurs during DWC events.

- ***What about the instantaneous chemical response in the upper stratosphere?*** The negative ozone tendency due to chemistry in the upper stratosphere prior to DWC is likely associated with increased chemical ozone loss due to increased temperature prior to DWC event. This is consistent with the ozone sink reaction in the upper stratosphere, which is more strongly dependent on temperature, where the increase (decrease) in temperature leads to more (less) ozone destruction (Brasseur and Solomon 2005). We have discussed this in the text (**see P7, L16**).

- ***Why does the upper stratospheric signal of the eddy transport from upward wave events last much longer in the model simulation?*** This associated with biases in the model in reproducing the evaluation of upward wave pulses prior to DWC. In the model, the upward heat flux is more persistent and lasts longer compared to the MERRA2. Since the eddy transport term (**M**) is dependent on the divergence of eddy heat flux term, the longer evolution of the eddy heat flux prior to DWC can lead to more persistent ozone tendency due to eddy transport. We have now discussed this discrepancy in association with a persistent heat flux signals in the model prior to DWC events (**see P9. L17 and P9. L32**).

3) It is not at all clear why at the end of the winter the dynamical composite gives positive ozone anomalies for reflective winters (Figure 12e). This needs to be clearly explained and related to the weaker or reversed ozone transport. The argument from line 413 is confusing since sharpened meridional gradients should even more so result in negative anomalies in case of less transport.

We have revised this particular part. Our results showed that the contribution of dynamics on ozone tendency in REF during early spring (late winter) is higher compared to ABS (see **Figs. S8k,l and Figs. S9k,l**).

The increase ozone tendency due to dynamic in REF is likely associated with an early spring final warming events (**Fig. R4 above**), allowing more waves to break in the stratosphere in late winter and thus, enhances the dynamical ozone transport to the pole during this period. However, since contribution from CHM is dominant during REF, the total net effect is still negative (i.e., less ozone concentration), which is expected during reflective winters. In contrast, during ABS, the final warming is delayed resulting in less dynamical ozone transport to the pole during late winter (**Fig. R4 above**). This is consistent with previous observational studies (e.g., Hu et al., 2014), showing that early spring final warming events that on average occur in early March tend to be preceded by non-SSW winters (i.e., typical of REF winter), while late spring final warming that on average take place up until early May are mostly preceded by SSW events in midwinter (typical of ABS winter). We have modified the text accordingly (**see P13. L25**) and added **Fig. R4** into the supplemental material (**see Fig. S10**).

4) The positive chemical ozone anomaly in reflective year's midwinter (Figure 12c) is not mentioned or explained in the text. We have now discussed this in the text (see **P13. L6**).

5) Please explain if Figure 1 is based on a DWC composite or a single DWC event?

We have now clarified this. The Fig.1 is based on a DWC composite life cycle. We have also revised the text accordingly.

6) Line 190: Deceleration doesn't necessarily result in adiabatic cooling.

We have revised this sentence: "The negative residual circulation anomaly suggests a deceleration of poleward transport of air mass, resulting in negative potential temperature *tendency* over this region" (**see P6, L26**).

7) Line 211-212: The negative and positive values seemed to be almost at the same level (instead of in the 'upper' and 'lower' stratosphere.)

Yes, the negative and positive values seemed to be almost at the same level in the stratosphere. We have revised this sentence accordingly (**see P7, L14**).

8) Line 216: Or transport out of the polar vortex?
We have revised this sentence (**see P7. L5**).

9) How were the terms in Figure 2 calculated? Are the DYN and CHM+ANA composites MERRA-2 output? Are the composites in 2d-2f calculated with equation 2? Are the terms consistent (i.e. is the sum of 2d-2f the same as DYN)?

All the terms are consistent. The dynamical terms in Fig. 2 were calculated using Eq. 2 and Eq. 3. In particular, the sum of the first three right-hand side terms of Eq. 2 is equal to total ozone tendency from dynamics in Eq. 1, while the last term of Eq. 2 is equal to the total ozone tendency due to chemistry and analysis in Eq. 1. We have now clarified this in the text (**see P5. L5**).

10) Line 395: Is the direct effect mentioned here the effect over the DWC life cycle? This was shown to be nearly zero and not a 'weak increase'.

We have revised this in the text (**see P13. L5**).

<u>3.2 Minor comments:</u>

1) Line 95: AURA -> Aura
Corrected.

2) Line 169: Please explain the minimum ozone term in Table 1. Is this the ozone tendency related to the date of the DWC (and this not necessarily a temporal minimum)?
This is the minimum value of the total 5-day smoothed ozone tendency from 60-90N during the date of DWC event. We have clarified this in the text (**see P5. L27**).

3) Line 222: 2e -> 2d
Corrected.

4) Caption Figure 1: a-d -> a-b
Corrected.