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1. Reviewer #1

In this manuscript the authors show that Downward Wave Coupling (DWC) events impact high-latitude stratospheric ozone in two ways: 1) reduced dynamical transport of ozone from low to high latitudes during individual events and 2) enhanced springtime chemical destruction of ozone via the cumulative impact of DWC events on polar stratospheric temperatures. The authors motivate the study by highlighting the focus of previous work on the role of upward propagating waves. The results presented here broaden the scope of the impact of wave-mean flow interaction on stratospheric ozone by highlighting the key role of wave reflection. The authors make a convincing case supporting and extending previous published work. My recommendation is that this manuscript should be published with minor revisions, which are outlined in greater detail below.

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

1.1 General comments

1. I strongly recommend a reorganization of the figures in the main manuscript and the supplementary material. While it will not change the results of the paper I feel it would greatly improve the readability of the manuscript and highlight the key points in a simpler way. This would also reduce the total number of figures by 2. My recommendation is the following:

- Figure 1: Show pressure-time plots of VT, EPFD, Psi, dtheta/dt for the DWC events where VT and EPFD panels are taken from the old fig. S1. This would remove the duplication of figures in fig. S1 and focus the reader on the dynamics of DWC events with a consistent set of axes.
- Repeat the new fig.1 in fig. S1 for positive heat flux events.
- Figure 2: combine the 2 line plots in the current fig. 1 with the line plot in the current fig. 4. Again this would aid the reader with a consistent panel format in the figure.
- Figure 3: Move the current fig. 2 to new fig. 3.
- Figures 4: Don't change
- Figures 5-8: Repeat the new organization from figs. 1-4 for the model.

We agree with the reviewer's suggestion. We have now modified Fig.1 by adding the evolution of V'T' and EPFD from the old Fig. S1 to this figure (see Fig. 1). We have also now combined the 2 line plots in the old Fig.1 with the line plot in the old Fig. 4 (see Fig. 4). We repeated the new organization from Fig.1-4 for the model (see Fig. 5-8). In addition, we have now included the evolution of V'T', EPFD, Psi, and dtheta/dt, ozone time-tendency terms for upward wave events from both MERRA2 and CESM1 (WACCM) in the supplemental material (see Fig. S1 to Fig. S4). Correspondingly, we changed the order of the

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presentation to better fit the order of appearance in the figures (combined the discussion of reversibility of the overturning circulation, temperature and ozone to after figures 1-3). Furthermore, as suggested by reviewer #3, for a better comparison between the reanalysis and model, we have now combined the old Fig. 11 into old Fig. 10 (see new Fig. 10), and the old Fig. 13 into old Fig. 12 (see new Fig. 11). After doing these changes, the total number of figures is reduced by 2, as expected by reviewer #1.

2. While the authors focus on wave-1 heat flux events, there is no mention of wave-2. How do the results in the first part of the paper compare to a similar analysis using wave-2 for both positive and negative heat flux events? Do reflective winters exhibit more extreme negative wave-2 events and vice versa for absorptive winters? Shaw and Perlwitz 2014 use the total eddy heat flux in their analysis of the role of DWC on stratospheric temperatures suggesting that wave-2 might also be important.

We focus on wave-1 because it dominates the total eddy (deviation from zonal-mean) heat flux in the stratosphere and it represents the dominant source of downward wave coupling between the stratosphere and troposphere (e.g., Perlwitz and Harnik 2003, Shaw et al, 2010, Lubis et al., 2016a). Nevertheless, we also examined the impact of downward wave-2 coupling on Arctic ozone (see Fig S5 and Fig. S6 in supplement). The results showed that the stratospheric impacts associated with downward wave-2 events on ozone are not as robust as the corresponding downward wave-1 events (see Fig. S6). A possible reason for this is the evolution of the wave-2 events involves weaker heat flux values and weaker EPFD (Fig. S5, consistent with Dunn-Sigouin and Shaw, 2015), which results in a weaker connection to the total ozone time tendency, due to weaker changes in the associated residual circulation and temperature tendency.

We have included the discussion regarding the relation of wave-2 and ozone in the text (see **P8 L32**) and provided the supporting figures in supplemental material (see Figs. S5 and S6).

1.2 Specific comments

1. In terms of the definition of reflective winters, why not simply use the previously published definition from Perlwitz and Harnik 2003 based on the zonal-mean zonal wind shear? This index likely encapsulates both U and m2 criteria used here in a simple way. How does the PH03 shear index look when plotted next to the time series in figure 9?

We actually checked both reflective index definitions in the original version of the manuscript. We agree that zonal wind shear index (based on U2-10) can be used to determine the reflecting surface (similar as m^2), but that alone cannot directly determine the strength of the polar vortex.

REF is defined as winters characterized by (1) a formation of reflecting surface above the mid-stratospheric jet (i.e., polar vortex is strong, see Fig. 11a of Perlwitz and Harnik 2003, hereafter refer to PH03) and (2) dominated by downward wave activity (i.e., less wave absorption). To encapsulate these two criteria, the m2 is used to track the location of turning (reflecting) surface, while the mid-stratospheric U30 is used to measure the strength of the polar vortex. This method is similar as that used by Harnik (2009) to defined REF, where they included additional criteria to the U2-10 index in order to ensure that the vortex in REF remains strong.

The problem of using the U2-10 index alone is that negative U2-10 values sometimes occur during or after sudden warming events (see also our discussion in the comments below).

Thus, in defining a reflection index based on U2-10 (PH03), care should be taken to only look at negative U2-10 events for which winds in the lower stratosphere remain **strong** (Harnik 2009). As in Harnik's 2009 study, the winters dominated by SSW events are categorized as absorptive winters (ABS), due to the fact that the polar vortex is weaker (i.e., indicated by weaker U30 values) and is dominated by strong wave absorption in the stratosphere. We also note that the number of wave reflection events during/after SSW events is less compared to the amount of wave absorption in the stratosphere. Therefore, it is worth to use both m2 as an indicator for vertical reflecting surface and U30 as an indicator for vortex strength, in order to define the REF in our study.

To support our argument, these two types of definition are compared here. **Figure R1** (below) shows the comparison between REF/ABS based on our definition, and those based on PH03. In general, most of ABS and REF years defined in our study are consistent with PH03. However, some discrepancies exist, in particular for the REF winters: (1) 1997 and 2011 are grouped as REF in our study, but are not captured by PH03 because the reflecting surface is slightly higher (i.e., it is not well captured by U2-10 index). However, when using the U2-10 index, these winters can be grouped as REF, and (2) 1992, 2000, and 2003 are not categorized as REF in our study, because major warmings occur during this winter, as indicated by a weaker polar vortex (i.e., dominant wave absorption).



Fig. R1. Comparison of REF and ABS definitions based on our definition (top) and based on PH03 (bottom). The dark green horizontal lines indicate the region of the long-term average +/-0.25 std deviation.

2. Are reflective winters dominated by DWC events? Similarly do "absorptive" winters contain a large amount of extreme positive heat flux events? Quantifying whether the individual events defined in section 1 occur in the seasons defined in section 2 would add additional support to the cumulative argument.

Yes, the reflective (absorptive) winters are dominated by DWC (upward wave) events characterized by a large amount of extreme negative (positive) heat flux events during this period (see Fig. S7 in supplement). We have now included this figure in the supplementary material (see Fig. S7) and explained this in the text (see P11, L30).

3. I'm not sure I completely agree with the argument in the footnote of page 11 motivating the authors' removal of SSW's during "reflective" winters. It would be good if the authors could address the following points:

- SSW's are effectively a continuum that depends on the definition threshold (e.g. Butler et al. 2015 BAMS fig. 4), and so the current definition includes years that contain events that are very close to satisfying the SSW criteria, which would contribute to the season being "absorptive" when it is defined as "reflective".
- Doesn't the fact that seasons with SSW's can have increased wave reflection call into question the definition of "reflective" and "absorptive" winters based on the seasonal mean wind and wave geometry?

We agree with the reviewer that there is a continuum of events, in the sense that wave reflection events start with a deceleration in the upper stratosphere, whereas in sudden warmings the deceleration extends lower down, and that the level to which such deceleration reaches can occupy a continuum. A very relevant recent study by Kodera et al. (2016) showed that a subset of SSW events end with downward wave reflection. Comparing reflective and non-reflective SSWs they showed that while reflective SSWs are characterized by a quick termination of the warming episode due to the reflection of planetary waves, the SSWs events for which waves are not reflected have a longer timescale. The reflective SSW events can be viewed as a mixture between SSW and reflection events, as pointed out by the reviewer. We think however that these events may involve over-reflection rather than reflection, because a critical surface forms embedded by two opposite signs of PV gradient, thus they should be studied separately. In particular, it remains to be seen if the effect of the SSW event on ozone levels is reversible as it is in REF events or not (we expect it to be only partially reversible). This however is beyond the scope of this study, and to isolate the indirect effect of shorter/weaker wave reflection events on ozone via an influence on spring PSC concentration, we chose to exclude these reflective SSW events because of their different effect on polar temperatures. We have now removed the footnote and clarify the definition of REF winter with/without the inclusion of SSWs events (see P11 L26).

4. If you include SSW years but keep the rest of the definition the same, do you get similar results? Perlwitz and Harnik 2003 did not exclude SSW years.

There are no large differences *in the patterns* of wave geometry and temperature between the composites of reflective years which include and do not include SSW (see Fig. R2 bellow). In particular, it is shown that the structures of wave geometry and temperature in REF and ABS based on PH03 are in agreement with those composited using our criteria, characterized by elongated vertical reflecting surface during REF and termination of reflecting surface in ABS (the reflecting surface shifts poleward away from the meridional waveguide, Fig. R2). However, the strength of the temperature response in the polar lower to mid stratosphere based on PH03 index is somewhat weaker and not as robust, due to the inclusion of SSWs. Therefore, it is important to define REF winter where the vertical wind shear is negative, BUT the winds in the mid-lower stratosphere remain **strong**. As we discussed above, we used an extended definition of PH03 as in Harnik (2009), by separating the reflective events from the absorptive events associated with SSWs. We have now clarified and emphasized this in our manuscript (see P11, L25-32).



Fig. R2. (top) Composites of wave geometry (color shading) superimposed with zonal-mean zonal wind (contour lines) and temperature differences during REF and ABS winters based on PH03 index definition and our definition. The $m^2=0$ is denoted by solid blue line, and the $l^2>0$ is indicated by color shading. The zero wind line is denoted by solid pink line.

5. L198-200: Is there a difference when time averaging from day -10 to +5 from figure 1b (i.e. all days not only significant days)?

There are no large differences when the time averaging is done for the whole time series (see Fig. R3 below). However, we prefer to focus the discussion on the significant values only, since it represents the robustness of the result.



Fig. R3. The time evolution of residual mass-streamfunction anomaly and temperature tendency averaged from 100 to 1 hPa and 60 to 90N. The horizontal red (blue) lines indicate the time-integrated significant values of each quantity over the life cycle of upward (downward) wave events. On the other hand, the horizontal orange (green) lines indicate the time-integrated values of over the whole life cycle of upward (downward) wave events. Statistical significance at the 95% level is denoted with thick solid lines based on a 1000-trial Monte Carlo test.

6. L343-344: How do you calculate m2 and l2? everyday and then average or from the average U and T? Does it make a difference? Are the results sensitive to the meridional/vertical averages and thresholds used in the definition?

In this study, we calculated l and m for a given basic state based on monthly-mean zonalmean zonal wind and temperature data using a spherical QG model of Harnik and Lindzen (2001), except that the lower boundary is at the surface rather than at the tropopause. We found that it makes little difference for the results presented here, whether we calculate l and m from daily data and then average them or calculate them from the averaged basic state. We have clarified this in the manuscript (see **P17. L4**). We also note that the results are insensitive to the threshold used in the definition.

7. L364-365: Why is a wider meridional wave guide favorable for upward wave events? Presumably a narrower waveguide would focus wave activity polewards rather than equatorwards enhancing the positive heat fluxes. This seems to run counter to previous literature which argues that a strong poleward shifted vortex is conducive to upward wave activity (McIntyre 1982 and others).

We apologize for this oversight. We agree with the reviewer that the meridional wave guiding is important for focusing upward planetary wave propagation (i.e., wave energy) in the vertical direction. During REF a reflecting surface forms below 1 hPa poleward of 50N, along with a very clear meridional waveguide below 10 hPa between 50 and 80N. During the ABS, on the other hand, waves can propagate all the way up through the stratosphere, because the reflecting surface vanishes, and thus, the vortex tends to be weaker due to more wave deceleration. In addition, the meridional waveguide during ABS forms in the middle and lower stratosphere (i.e., below 30 hPa between 50 and 80N) allowing more upward planetary wave propagation from the troposphere to penetrate into the stratosphere. We have revised the text accordingly (see P12, L5 and P12, L15).

8. L412-413: What is meant by "sharpened gradients of ozone" and their relationship to dynamical terms? In addition, it seems that in the reflective winters during MA there are anomalous positive heat fluxes enhancing the climatological transport of ozone. This runs counter to the expectation during "reflective" winters.

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 increased ozone tendency due to dynamics in REF is likely associated with early spring final warming events (**Fig. R4 below**), 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 below**). 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).



Fig. R4. (top) Time series of the final vortex breakup day in the NH from MERRA2, defined as the first day when the zonal-mean zonal wind at 60N and 10 hPa is negative, and never recovers. (bottom) Composites of the final vortex breakup day for REF (blue) and ABS (red) winters. Dark green contour lines denote the time series of zonal mean wind from all years.

9. Figures 3 and 7: Why not simply plot all the data in the scatter plot instead of contours? The contours seem unnecessarily complicated and plotting the entire time series would allow the reader to see the large correlations from the full time series quoted in the text.

Plotting the full time series correlations as probability distribution (contour lines) allows the reader to clearly see the relation between extremes events (red and blue) and the whole time series. As stated in the text, the slope of the contour lines indicates the linear correlation from the full time series, so in principle it's the same as plotting the full time series as a scatter plot. This diagnostic was also used before by Abalos et al, (2014, Fig 11) to examine the relation between of wave forcing between high and low latitudes.

10. Figure 14: I'm not sure the current schematic is helping to succinctly convey the dynamical mechanisms detailed in the text. I suggest either streamlining it or completely removing it since it is not very helpful in its current iteration.

We have modified the schematic diagram. The current version describes the dynamical mechanism of DWC influence on ozone over the wave lifecycle, which includes the absorptive and reflective stages as well its corresponding impact on ozone, temperature and circulation tendencies (see Fig. 12).

1.3 <u>Technical Corrections:</u>

L34: Suggest changing "it represents" to "proportional to". Corrected (see P2-L7)

L49: "increases" should be "increased". Corrected (see P2-L19)

L137: "transform" should be "transformed". Corrected (see P4-L29)

L138: Suggest putting the equation number from Andrews et al. 1987. The equation number has been added into the text (see P4-L30 and P5-L6)

L140: I suggest adding a sentence linking Equation 1 and 2, i.e. the first 3 RHS terms in equation 2 sum to the 2nd RHS term in equation 1. Same for chemistry and analysis terms. It has been added into the text (see P5-L4)

L155: Suggest also citing Dunn-Sigouin and Shaw 2015 for the event definition. This citation has been included in the text (see P5-L15)

L159: Suggest citing Shaw et al. 2010 for period of maximum vertical wave coupling. This citation has been included in the text (see P5-L18)

L22: Fig. "2e" should be "2f". Corrected

L237: "circular" should be "oval". Corrected

L270: You could also add the point that the historical time series is short and so you can get a more robust sample of events in the model to support the reanalysis dynamics. Corrected (see P9-L9)

L307-309: Perhaps mention that the detailed analysis of why the model terms are biased is beyond the scope of the article. It has been added in the text (see P10-L11)

L321-322: Suggest mentioning the correlation for the entire data set in the model as was done for reanalysis data. Corrected

L341: "ozones" should be "ozone" Corrected

L361-362: "due to enhanced DWC events": could also be due to enhanced equatorward refraction and a lack of upward propagation. This sentence has been revised (see P12-L14)

L398-399 and L409: Why "not shown"? The plot has now been included in the supplemental material (see Figs. S8-9).