Interactive comment on "Local and Remote Response of Ozone to Arctic Stratospheric Circulation Extremes" by Hao-Jhe Hong and Thomas Reichler

Anonymous Referee #2
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This study analyzes ozone anomalies associated with stratospheric sudden warming, vortex intensification and final warming events based on MERRA-2 reanalysis data. Long-lasting anomalies are found both in over the Arctic and in the tropics following these extreme events. In particular, the ozone anomalies only become apparent after the QBO-related signals are removed. It is a useful exercise to document the evolution and distribution of ozone anomalies following the stratospheric circulation extremes. The paper is logically organized and clearly written. I have a few comments regarding some of the methodology and results. I recommend publication of the paper after these comments are addressed.

1. Removal of the QBO signals. It is not surprising that the SSW-related ozone anomalies are masked by the QBO-related anomalies, but it is somewhat surprising that authors tried several methods to filter out QBO and only one worked. What about the linear regression with a QBO index such as in Randel and Wu (2015 JAS)? The description of the method the authors chose ("subtract the preexisting ozone anomalies of each event from its subsequent daily ozone fields") is not clear to me. The authors cited Gomez-Ecolar et al. (2014) for the method. But what described here does not seem to agree with any of the three methods described in Gomez-Ecolar et al. (2014). It sounds like calculating the difference of ozone between different periods. Then the resulting is actually ozone tendency rather than ozone anomalies itself.

We did not use linear regression in our analysis. Instead, we tested a similar method, taking into account the mean QBO ozone structure (Fig. 4a) and QBO phase during each event. However, we were not satisfied with the result and therefore used another filtering method.

Our filtering method defines a pre-existing QBO ozone signal from the mean ozone anomalies over day -60 to day -30 with respect to the SSW/VI central date. We subtract this QBO signal from the ozone anomalies associated with each circulation event before taking composites. This method assumes that the QBO time scale is much longer than the time scale of SSWs or VIs. Our method is similar to Gómez-Escolar et al. (2014) (Fig. 7 in their study) and Kodera (2006), however we defined a somewhat different time period for removing the QBO signal than the previous two studies.

To make this clearer, we reworded our manuscript as follows:

L291-299: *"…by Dunkerton et al. (1988). To filter out the QBO influences from the tropical ozone, we define the QBO ozone signal as the mean ozone anomalies over day -60 to day -30 with respect to the SSW/VI central date, which is then subtracted* *from the ozone associated with each Arctic circulation event. We use the resulting ozone anomalies for preparing Figs. 5c and 5d."*

2. Why there is a persistent minimum at about 20 hPa in the QBO-related ozone anomalies shown in Fig.4a? This feature seems unrealistic and is not seen in other studies (e.g. Fig. 1 of Tweedy et al. 2017 ACP).

Our result of the QBO ozone composite (Fig. 4a) is consistent with Tweedy et al. (2017) (Fig. R6), which only shows ozone anomalies between 10 and 70 hPa (right axis of their figure). The QBO ozone composite of Tweedy et al. (2017) (Fig. R6a) reveals a nodal point for ozone minimum between 10 and 20 hPa that is also seen in our result of Fig. 4a. As requested, we show below in Fig. R7 (black line) the evolution of ozone at 20 hPa, suggesting that the 20 hPa ozone undergoes a sign change within the QBO cycle. Another reason for the apparent discrepancies is that Tweedy et al. show the anomalies in percent, whereas we show them as absolute anomalies (in ppmv).

To clarify the similarity between Tweedy et al. (2017) and our result, we now reword our manuscript as follows:

L283: *"Our results (Fig. 4a) are in good agreement with their study, e.g., there is a nodal point of small ozone variations between 10 and 20 hPa, with much stronger variations above and below."*

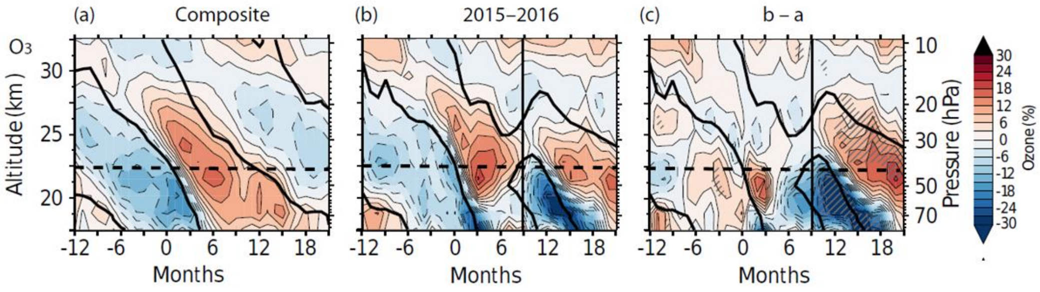

Figure R6. Time-height cross-sections for QBO ozone. Shown are ozone anomalies for (a) QBO composite, (b) 2015-2016 QBO event and (c) b-a. Adapted from Tweedy et al. (2017), Fig. 1.

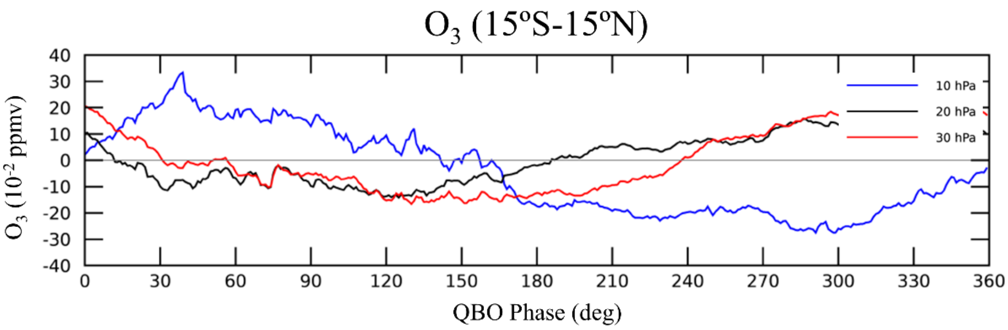

Figure R7. Composite tropical ozone anomalies for QBO events. Shown are anomalies at (blue) 10 hPa, (black) 20 hPa, and (red) 30 hPa.

3. The authors show the ozone tendency due to residual mean circulation and eddy flux convergence, and the eddy convergence term contribute significantly over the Arctic. Can the authors elaborate a bit more on the physical process associated with the eddy convergence, especially what determines the sign of this term?

To answer your question, we revised our manuscript and explained in more detail the meaning of the eddy flux convergence term in Sect. 2.3:

L132: *"The eddy flux convergence contains effects that are not explained by the advection of zonal mean ozone by the zonal mean circulation. The convergence is associated with transports of zonal disturbances in ozone by zonal disturbances in meridional or vertical velocity. In the stratosphere, these disturbances (or eddies) are primarily due to upward propagating planetary waves. The convergence term indicates that covariance between eddy velocities and ozone can transport ozone, and that where this eddy ozone flux converges a zonal mean ozone tendency can be induced. For example, a northward ozone flux is created if the signs of the meridional velocity and the ozone perturbations tend to be the same, and if this flux decreases in the northward direction (converges), it would create a positive ozone tendency in the zonal mean. Our result (not shown) suggests that the meridional component of the eddy flux convergence (the first term of the **M**-vector in equation (1) dominates the vertical component over most of the stratosphere."*

4. Line 118: "180-day smoothed" Do the authors mean a running mean with 180 day window?

Yes, we understand our wording is not clear. We now revise our manuscript as follows:

L118: *"We use a 180-day running mean window to smooth the zonal-mean equatorial (±5°) zonal wind at 30 hPa (UEQ30) and determine the phase of the QBO."*

5. Line 208-209: Why is the magnitude of the ozone anomalies associated with SSW differ so much between Hocke et al. (2015) and this study?

The differences are only apparent. While we show area-weighted latitudinal averages over 65°N-90°N (with a maximum of ~50 DU), Fig. 2 in Hocke et al. (2015) shows larger ozone anomalies (up to 90 DU) only close to the pole (which represents a small area). Therefore, we believe that our result is consistent with Hocke et al. (2015).

In the revised manuscript, we add a clarification at line 209 as follows:

L209: *"However, we note that the differences are only apparent, as we show area-weighted latitudinal averages of column ozone and as the extreme ozone increases in Hocke et al. (2015) occur only close to the pole."*

6. Line 225: From Fig. 2, the FW anomalies following a VI event is stronger and extends to the lower stratosphere.

Yes, actually there are some negative ozone anomalies in the lower stratosphere at the FW following the VIs. We revised our manuscript as follows:

L224-226: *"The structure of these anomalies is somewhat similar to that of SSWs, except that they are weakly negative in the lowermost stratosphere."*