Interactive comment on "The major stratospheric final warming in 2016: Dispersal of vortex air and termination of Arctic chemical ozone loss" by Gloria L. Manney and Zachary D. Lawrence

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This paper provides a thorough description of the evolution of the 2015/2016 Northern Hemisphere stratospheric winter until the breakup of the polar vortex and the dispersal of its fragments. This winter was unique: while it initially presented the characteristics for an unprecedented ozone loss (i.e. prolonged temperatures below ice polar stratospheric cloud thresholds), an anomalous early and strong major final warming interrupted the ozone depletion process. Dynamical and chemical processes are characterized using Microwave Limb Sounder satellite trace gas measurements, and advanced mixing and polar vortex diagnostics derived from meteorological reanalysis. This case study of the winter 2015/2016, and its comparison with the series of singular recent winters, very well illustrates the complexity of the dynamical and chemical interactions that drive Arctic ozone depletion. In my opinion, this paper is important as it further contributes to showing that each Arctic winter season is unique and that substantial research efforts are needed to better understand their extreme variability and the consequences of this variability (e.g. on ozone depletion, stratosphere/troposphere couplings). The methods and diagnostics used in this study are scientifically sound and relevant. The analysis is very carefully conducted. My main criticism rather concerns the form: the main text and its figures are extremely dense and contains a lot (too much?) of information so that it is sometime hard to differentiate what is important from what is more anecdotal. While in some places the degree of detail seems to me exaggerated (e.g. p10l32-p11l10 where tracer extrusions are discussed while not really obvious), in other places, including further details may help to make the paper easier to follow (see comments below).

Motivated both by this comment, and those of Referee #3, we have gone through the paper with a focus on assessing the clarity and necessity of the text and each figure/figure panel. As a result, we have eliminated several figure panels that were not as critical to our message, and clarified the text to indicate the motivation for showing the information that is included.

Regarding the particular example given above of the discussion of filamentation in relation to Figure 6, we have revised and reduced this discussion to eliminate details that are less critical to the paper.

Hence in my opinion, this paper is suitable for publication in Atmospheric Chemistry and Physics after consideration of the specific (minor) comments and suggestions provided below.

We thank Dr. Thiéblemont for his careful and thorough review, and very helpful comments on our paper.

Specific comments:
1) p3l32: Typo change "MERRRA" to "MERRA"

Done.

2) p4l20: Please provide further detail on the way the potential vorticity is scaled. The sPV is widely used throughout the paper so few precisions about it may be useful for the readers.

Changed to "... (sPV, scaled to have a similar range of values throughout the stratosphere using a standard atmosphere value of static stability, as in Dunkerton and Delisi, 1986; Manney, et al, 1994) ..."

3) Diagnostics (i.e. sections 2.3 & 2.4): This paper makes use of a very high number of diagnostics to describe mixing processes, transport, vortex size and so on. Although the different diagnostics are very well explained in the main text, non-expert reader may quickly be lost once the description of the (dense) analysis begins. The authors may consider adding a table which gives a summary describing (briefly) the different diagnostics and their usefulness.

We have added a list that summarizes the transport and mixing diagnostics we use at the end of section 2.4. While we did not do the same for the polar processing diagnostics in section 2.3, we did remove some of the diagnostics previously shown in Figures 1 and 3, and added more explicit text clarifying how each diagnostic is related to the evolution of trace gases in the polar vortex. We hope this helps reduce the complexity, and makes the motivation for including each diagnostic clear.

4) p7l25: "The 2010/2011 winter". Please mention the associated color line in bracket to help the reader.

A note with the line colors has been added the first time each year is mentioned.

5) p8l1: "In early January 2013". Same here, please mention the associated color.

A note with the line colors has been added the first time each year is mentioned.

6) p8l2: "strongest "vortex-split" SSWs on record" What does strong mean here? What defines the strength of a SSW (persistence, temperature, vertical extension?)? Please clarify.

We have revised the text to indicate that we mean among the largest abrupt temperature increases, deepest range of wind reversals, and most prolonged periods of easterlies.

7) p8l6: "2014/2015". Please mention the associated color.

A note with the line colors has been added the first time each year is mentioned.

8) p8l6: "brief minor SSW". Please give the date. (I guess early January)

The date has been added: "...very brief minor SSW (with a brief vortex split on 5~January~2015)..."

9) p8l13: Typo change "though" to "through"

Done.

10) p8l14: "unprecedented". On MERRA record? Please clarify.

We now specify that it is in the MERRA-2 record: "...unprecedented in the Arctic, where the MERRA-2 record rarely shows more…"

11) p8l31: "in 2015/1016, 2012/2013, and 2010/2011". Why not 2014/2015?
The green curve looks similar in early winter on Figure 2a.

This is indeed true if the period is limited to early winter, and we now simply state that it was similar in all the years highlighted.

12) p11l1-2: "This is consistent [...] anticyclone during this period". Does anticyclone

refer to the Aleutian High here? Please clarify.

We have modified this to note that we do, indeed, mean the Aleutian anticyclone.

13) Figure 8: Please replace y-axis "Effective diffusivity" by "Keff" to be consistent with the main text (p11l30).

We have labeled the y-axis in Figure 8b, as well as the color bars in Figures 5--7b, "Effective Diffusivity (K_{eff})".

14) p11l33: "Keff and M minima" Is it not rather M maximum? M maximum -> vortex edge -> transport barrier.

Thanks for catching this error. We have revised it to say "...sPV gradient and *M* maxima, K_{eff} minima, and strongest trace gas gradients…"

15) Figure 9-14: Please make the continents more visible on maps and provide at least on longitude coordinate. Otherwise it is quite hard to follow Figures together with the main text and the geographical location that are refereed (e.g. Alaska p13l7 but also at other places).

We have done our best to make the continents and latitude/longitude lines more visible in all cases. In addition, we have provided an orientation reference in the first figure caption for each type of map, noting that 0 degrees longitude is at the bottom of the maps and 90 degrees E to the right.

16) P13l12: "in the anticyclone.". Is it not "in the edge of the anticyclone" that the M values are the strongest?

It is both along the edge and along the persistent filaments that spiral into its interior; the text has been modified to reflect this.

17) At 550 K, a doubled vortex edge appears in the main vortex fragment (see Fig 11, 14) from beginning of April. Is this an artifact or a real structure? Please comment on this.

It is difficult to say whether the doubled-edge structure is real or an artifact since it represents the sPV dropping slightly below our vortex-edge threshold in the core of the fragment. However, we do not think it has any particular significance in relation to

transport/mixing in this case, since the M maps show that the highest M values are around the outer edge. We have added additional text stating this.

18) Figure 13-15 (and associated text). The green and blue offsprings seem actually switched between the 490 and 550 K levels. If indeed this is the case, it may be confusing. Therefore, it may be more relevant to keep the same color for the upward extension of the same offspring.

We have switched the colors of the vortices so those of the smaller offspring that persist longest (and are the extension of the same vortex in the vertical) are the same color. We now label the vortices as "parent," and "offspring-p" and "offspring-s" for the "persistent" and "short-lived" small vortex regions, respectively. (Offspring vortices that persisted about a day or less are labeled and described as "transient".)

19) p15l17-19: May this vortices coherence dependence with height be partly related to differences in diabatic processes with height?

We do believe this to be the case. There is a large body of literature showing that most final warmings proceed from the top down, and this is largely related to shorter radiative timescales in the middle to upper stratosphere. However, in removing material that, though interesting, seemed peripheral to our primary focus, we have deleted the statement that raised this question; therefore we have not modified the text in this regard.

20) p16l7: "begins dropping earlier,": earlier than when? Please clarify.

We meant "begins dropping earlier than the vortex area…" and have added this to the text.

21) p16l7: "period between the beginning of the MFW and the split": is it the period between the two dashed lines? Please clarify.

Yes, we have added a note saying this in the text: "...period between the MFW and the split (between the two vertical dashed lines in Figure 14)..."

22) p16l19-21: "In fact, as seen in Figure 13, a coherent mass of air from the blue vortex persisted into April – represented in Figure 15 by the individual purple points labeled "transient". I guess these transient vortices are those seen in the supplementary animation and labelled 4, 5, 6, 7 and 8 at the 490 K. If yes, please mention it.

You are correct, and we have added text pointing this out and referring to the animation in the discussion of Figure 14 (was Figure 15).

23) p18l8: "one previous winter.". Please recall which winter it is.

We have added this information: "...one previous winter (2012/2013, Figure 2d--f)..."

24) P20l1-2: "This is particularly interesting given reported differences between years with early and late Arctic final warmings, which have not, in general, accounted for the suddenness of those final warmings (e.g. Waugh and Rong, 2002; Akiyoshi and Zhou, 2007);". In recent studies on Frozen-In Anticyclones (FrIACs), tracer transport was linked to the suddenness/abruptness of final warmings (see e.g. Allen et al. (2012), Thiéblemont et al. (2013) or Thiéblemont et al. (2016)).

This is a very good suggestion; indeed we were remiss in not mentioning these studies. We have added a brief discussion of FrIACs following sudden/abrupt final warmings in this paragraph.