Authors response:

We are thankful to both reviewers for their thorough comments. We have added a few paragraphs to the introduction to better clarify previous studies that are relevant to this manuscript and to elucidate remaining research questions that this study focuses on. A few graphs have been updated to have higher resolution and to include statistics, as suggested by the reviewers. We have used more clear language to highlight the novelty and main findings of this study. We applied most of the reviewer's suggestions and provide justification for those that we did not include. We believe that the quality of this manuscript has been greatly improved by these reviews.

Our detailed responses are given below, as well as comments on the full manuscript.

To facilitate reading of our responses and tracking changes in the full manuscript, we have labeled each of the reviewer's comments using the following labels:

List of labels:

reviewer 1 (Kris Wargan) :
- General comments (GC+#)
- Specific comments (Spc+#)
- Technical corrections (Tc+#)

reviewer 2 (Simon Chabrillat):
- General comments (GCC+#)
- Tables and figures comments (TF+#)
- Minor Comments and typos (MC+#)

We also used different fonts, sizes and colors: Reviewer comments are in black in Calibri font, our written responses are in blue in Calibri font, and the updated text in the manuscript is in cyan in Time New Roman font using a small font size.

Review of

Analyzing ozone variations and uncertainties at high latitudes during Sudden Stratospheric Warming events using MERRA-2

submitted to ACP by Bahramvash Shams et al. (doi: 10.5194/acp-2021-646, 2021)
S. Chabrillat, BIRA-IASB, October 2021

General Comments

This study provides an interesting overview of the 6 SSW events which happened over the Arctic since 2004. Its main strength is the consistent usage of a leading reanalysis (MERRA-2) to compare the dynamical variabilities of these events and their relationships with the corresponding distributions of ozone. All analyzed fields (temperature, winds, ozone) come from the same reanalysis system, for all 6 events as well as for the climatology extracted from years with no SSW. This provides good confidence in the methodological consistency and in the validity of comparisons across the different years. This contribution to the field is sufficiently substantial to warrant publication in ACP after some revisions as outlined below.

These revisions may be considered minor because they probably do not require any new calculation (yet, see major comments 2 and 4). A general revision of the text is certainly necessary to address the first major comment.

Major Comments

The text should be improved w.r.t. consideration of related work and appropriate references. Citations do not seem very well used: it is difficult to see the links between specific results and specific references because these are always provided in groups. Not being an expert on SSWs, I often wondered what results are new and what results have already been published (e.g. for specific years or using less consistent datasets).

Here are a few ideas and missing references to remedy this shortcoming:

GCC1: How does MERRA-2 relate with other available reanalyses? ACP has a whole special issue

about the SPARC Reanalysis Intercomparison Project (S-RIP) explaining that several similar reanalyses are available (Fujiwara et al., ACP, 2017) with different performances w.r.t. ozone (Davis et al., ACP, 2017) and providing, on a topic related to SSW, an assessment of ozone mini-hole representation in reanalyses over the Northern Hemisphere (Millán and Manney, 2017). The CAMS reanalysis (Inness et al., ACP, 2019) assimilated very similar ozone data as MERRA-2 and has been extensively validated (Wagner et al., doi:10.1525/elementa.2020.00171, 2021).

Response: We added a sentence to show results from Davis et al., ACP, 2017, emphasizing that in the mid-stratosphere MERRA-2 has the best agreement with observations compared to other reanalysis data. However, their comparison study does not focus on northern high latitudes, which emphasizes the value of the comparison portion of our study. In this paper, we provide evidence to show the high accuracy of MERRA-2 stratospheric ozone estimation in the Arctic, which justifies our results and analysis.

> "MERRA-2 is shown to have the best agreement with stratospheric ozone observations compared to other reanalysis data (Davis et al, 2017)."

Wagner et al. evaluated the CAMS reanalysis using some observations and concluded higher uncertainty in stratospheric ozone over high latitudes. Although the intercomparison of different reanalysis data is an important topic, we believe it is out of scope of this publication. A further study should include CAMS compared with other reanalysis data, similar to Davis et al., ACP, 2017.

GCC2: An extensive review about SSWs was published 8 months before the submission of this manuscript (Baldwin et al., 2021). Yet it is cited only to give the general definition of these events. This is a pity, because if would have be easy to contrast original results with results that are already discussed in this review.

Response: We agree with the general point of the reviewer with regard to highlighting the novelty and the need to clarify our research compared to previous studies. We added some paragraphs in the introduction that review previous work related to SSW and their impact on trace gases and then clarified the exact research questions that this study will focus on, including its novelties and how this study complements previous studies. However, the major discussion of Baldwin et al, 2021 concerns different theories and possible mechanisms that drive SSWs, as well as their impacts on different atmospheric layers. The discussion on stratospheric ozone is short and is only one small section of their paper. Thus, we have included citations of this paper with regard to the general definition of SSWs.

> “From 2004 to 2020, six major SSWs persisted (persistent easterly winds at 60ºN 10hPa) for more than two weeks with each of these events having significant impacts on Arctic ozone. Since 2004, the number of stratospheric observations has increased, and various studies have focused on individual SSWs, their evolution, and their impact on trace gases. For example, Siskind et al. 2007 investigated trace gas (CO) descent from mesosphere to the upper stratospheric layers during the SSW event in 2006, using the Navy Operational Global Atmospheric Prediction System–Advanced Level Physics, High Altitude (NOGAPS-ALPHA) model, along with observations from the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER). Manney et al. (2008a) investigated the evolution of the SSWs in 2004 (minor) and 2006 by focusing on the transport of traces gases, including CO, H_2O, and N_2O using Microwave Limb Sounder (MLS), SABER, and ACE-Fourier Transform Spectrometer (ACE-FTS) at Eureka Canada. The evolution of the 2008 SSW and its associated changes in ozone and water vapor over northern Europe and, specifically, Bern, Switzerland was studied using the ground-based microwave radiometer and ozone spectrometer measurements, as well as MLS and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements and meteorological data from reanalysis systems (Flury et al. 2009).
>
> Manney et al. (2009b) used MLS and GEOS-5 data to discuss the dynamics and evolution of trace gas transport (CO, N_2O, H_2O) during the 2009 SSW event with a split polar vortex and compared it to the 2006 SSW with a displaced vortex. They confirmed a more rapid changes in trace gases during the split vortex event compared to displaced vortex, similar to a previous study by Charlton and Polvani (2007). Tao et al, (2015) showed the significant impact of dynamical forcing in variability of N_2O and O_3 during the SSW in 2009, using chemical Lagrangian Model of the Stratosphere (CLaMS) simulations and tracer-tracer correlation.
>
> Using CALIPSO and trace gas data (N_2O, HCL, HNO_3, CLO, and O_3) from MLS, and MERRA meteorological fields, Manney et al. (2015) showed that during the 2013 SSW, the persistent spring vortex, after it split in the lower latitudes and was exposed to sunlight, caused record ozone depletion in the Northern Hemisphere. Schranz et al. (2020) investigate the impact of the SSW in 2019 on ozone and H_2O over Ny-Ålesund, Norway, in particular, and the northern

hemisphere, in general, by analyzing the ground-based microwave radiometers, MLS measurements, MERRA-2 and climate simulations.

de la Cámara et al. (2018) analyzed the climatological impact of SSWs and their associated changes in stratospheric transport using ERAI reanalysis and WACCM simulations. They showed the associated changes in residual circulation and isentropic mixing and emphasized the impact of mixing on atmospheric composition in the lower stratosphere. The composite mean ozone changes during SSWs and associated chemical and dynamical conditions is also discussed by de la Cámara et al. (2018b).

While the above summarizes the studies that have looked at individual or composite SSW events the relative magnitude and extent of these events and their specific impact on ozone have not been compared to each other. How do the observed changes in Arctic ozone during each of the SSWs compare with the simulated climatology? If there are major differences associated with these events, do they fit into certain categories? What physical parameters modulate the different impacts of SSWs on Arctic ozone?

To our knowledge, no previous study has investigated these questions. Therefore, this study investigates the dynamical variability and ozone variations at northern high latitudes (between 60°N and 80°N) using the MERRA-2 dataset, both in the zonal average and within a specific geographical region during six persistent, major SSWs. We show that the magnitude, geographical extent, and timing of ozone changes are connected more closely to the averaged polar vortex shape before the SSW event rather than the final form of the vortex after breakdown (split vs displacement). We also show there is strong correlation between changes in average equivalent potential vorticity (EPV) and ozone column changes during these SSWs at high northern latitudes.”

GCC3: The manuscript nicely highlights the differences between elongated and displaced polar vortices prior to SSWs in the Northern Hemisphere. Has this distinction already been discussed w.r.t. ozone distribution in the Arctic stratosphere?

Response: We highlighted the novelty of the study more clearly throughout the manuscript. One of the novelties of this study is showing ozone changes due to SSWs are connected to the averaged polar vortex shape before the SSW, which led us to categorize them as either elongated or displaced. These averaged polar vortex indexes are different, though often related to, from split and displaced vortex breakdown conditions. As observed in the SSWs in 2018 and 2019, the polar vortex splits and the 15-day average polar vortex before that event is elongated. Other events such as those in 2013 and 2019, first displace and then split. However here we consider the displacement as the 15-day average, which is displaced and not elongated.

In our abstract:

“This study shows that the average shape of the Arctic polar vortex before SSWs influence the geographical extent, timing, and magnitude of ozone changes. The SSWs exhibit a more significant impact on ozone over high northern latitudes when the average polar vortex is mostly elongated as seen in 2009 and 2018 compared to the events in which the polar vortex is displaced towards Europe. Strong correlation (R2=90%) is observed between the magnitude of change in average equivalent potential vorticity before and after SSWs and the associated averaged total column ozone changes over high latitudes. This paper investigates the different terms of tracer continuity using MERRA-2 parameters, which emphasizes the key role of vertical advection on mid-stratospheric ozone during the SSWs and the magnified vertical advection in elongated vortex shape as seen in 2009 and 2018.

Additional text to section 5, page 17:

> "The averaged polar vortex state we refer to in this study is different, though often related to, split and displaced vortex morphology discussed in previous literature (e.g., Charlton and Polvani 2007). As seen during the SSWs in 2018 and 2009, in which the polar vortex split, the 15-day average polar vortex before those events is elongated. Other events, such as those in 2013 and 2019, first displace and then split. However, here we consider them displaced SSWs if the 15-day average EPV prior to the event is displaced and not elongated. Previous studies focused on the connection of the type of polar vortex breakdown to its impact on the speed of trace gas transitions (Charlton & Polvani (2007); Manney et al. 2009b). This study investigates the modulation of the magnitude and extent of ozone changes, and the results show that the average EPV shape before the vortex breakdown is more influential than the final form of polar vortex breakdown."

In section 6, page 23:

> This study shows that the larger geographical extent and magnitude of ozone changes during SSWs with elongated polar vortex is tied to magnified vertical advection during these events.

In section 7, page 24:

> "The variability in impact of SSWs on high latitude ozone is analyzed, two different patterns are found, and the possible dynamical mechanisms involved, are studied."

Conclusion, page 26:

> "This study shows that the averaged vortex shape before the SSWs is an important modulator of the magnitude and extent of ozone changes over high northern latitudes."

GCC4: The manuscript also highlights "the key role of vertical advection on mid-stratospheric ozone during the SSWs". Doesn't vertical advection also play a key role on mid-stratospheric ozone at other times and in other regions? What references have discussed this question?

Response: The global distribution of ozone concentration in the stratosphere cannot be understood without the influence of the Brewer-Dobson circulation (e.g., Hartmann and Garcia, 1979; Garcia and Solomon, 1983; Plumb, 2002), the advective part of which can be described by the residual velocities (v^*,w^*). In fact, its existence was first hypothesized by Brewer (1949) and Dobson (1956) trying to understand the distribution of ozone and other trace gases in the stratosphere.

The point of our paper is that during SSWs, the rapid changes in ozone are dominated by alterations in the vertical advection and horizontal eddy transport (M_y) rather than by other possible influences (horizontal advection, vertical mixing, chemical reactions, etc.)

Brewer A. W. (1949): Evidence of a world circulation provided by the measurements of helium and water vapor distribution in the stratosphere- Q. J. R. Meteorol. Soc., 75, 351-363.

Dobson, G. M. B. (1956): Origin and distribution of the polyatomic molecules in the atmosphere. Proc. R. Soc. London, Ser. A 236, 187-193.

Garcia, R. R. and Solomon, S.: A numerical model of the zonally averaged dynamical and chemical structure of the middle atmosphere, J. Geophys. Res., 88, 1379

Hartmann, D. L. and Garcia, R. R.: A Mechanistic Model of Ozone Transport by Planetary Waves in the Stratosphere, J. Atmos. Sci., 36, 350–364

Plumb, R. A.: Stratospheric Transport, J. Meteorol. Soc. Japan. Ser. II, 80, 793–809, https://doi.org/10.2151/jmsj.80.793, 2002.

GCC5: P.5, line 21 that "...temperature, the northward wind (v), vertical pressure velocity (ω), potential temperature (θ, calculated from temperature and pressure), and potential vorticity (PV) are extracted from the pressure-level MERRA-2 dataset."

The pressure-level dataset has a coarser vertical resolution than the model-level (i.e. sigma-pressure) dataset. Since the TEM analysis (Figs 11-12) involves vertical derivatives, it should be performed on dynamical variables which are retrieved on model levels. Is it the case?

Response: To have the finest vertical resolution for the comparisons with observations, MERRA-2 ozone at the model levels is used (GMAO, 2015a). To investigate dynamical mechanisms, using pressure-level data facilitates estimation of variables such as PV and potential temperature and consequently ozone at the pressure levels is used for associated analysis. We converted the pressure coordinate to geopotential height to estimate the derivatives for further analysis.

> "To have the finest possible vertical resolution for the comparisons with observations, MERRA-2 ozone at the model levels is used (GMAO, 2015a). Other dynamical variables such as temperature, and the northward and vertical wind velocities (v, ω), are extracted from the pressure-level MERRA-2 dataset (GMAO, 2015b), which facilitates the calculation of variables such as potential vorticity (PV) and potential temperature (θ)."

GCC6: Figures 3 and 4, and related discussion (especially p.13, lines 12-17): How different are the corresponding diagnostics for years with no SSWs? Maybe one would obtain exactly the same biases and standard deviations of differences?

On these figures and throughout the text: the usual terminology is not "difference ratios" but "relative differences" or "normalized mean biases" and "standard deviations of the differences". See e.g. Lefever et al. (2015, doi:10.5194/acp-15-2269-2015).

Response: We agree that using relative differences is best and have updated the terminology to relative differences throughout the whole text.

For the comparisons, we had performed the comparison of non-SSW years in our preliminary stage of this study and the standard deviation of stratospheric ozone are lower and over the tropospheric layer the same level of uncertainties is seen. However, as during SSWs ozone fluctuations are larger, this study focusses on comparison of MERRA-2 and observation during these altered situations. This specific validation justifies our analysis of using MERRA-2 for analyzing ozone during highly variable periods and on the other hand the high accuracy of data during the highly fluctuated time also prove the performance of non SSW years.

GCC7: P.19, lines 4-5: “The positive temperature anomalies in mid stratospheric layers start a few weeks before the SSWs in the 4 cases of a displaced vortex (2006, 2008, 2013, and 2019).” But from the definition of the SSW (p.3 line 1) one of the two conditions to identify a SSW is an abrupt and intense increase of stratospheric temperature. Yet Figure 9 shows that the increase in temperature was not abrupt on these 4 years (those with displaced polar vortices). So one wonders how your algorithm for SSW identification could identify 2006/01/21, 2008/02/22, 2013/01/06 and 2019/01/02 ? I am also confused by the next sentence:

“On the other hand, the intrusion of the positive temperature anomalies to mid stratospheric layers is almost coincident with SSWs in the 2 elongated vortex cases.”

But seeing the definition of SSWs, shouldn’t this be a feature of all SSWs?

I think that this should be clarified not only in the author’s response but also in the revised manuscript.

Response:

We clarified the definition of SSW as below:

> SSWs are defined by a reversal of the climatological westerly wind circulation, which typically coincides with an abrupt and intense stratospheric temperature increase”

Moreover, it should be noted that the definition is based on reversal of 60 N, 10 hpa zonal mean zonal wind. On the other hand, the cross-section plots are the anomalies of average temperature profile based on averages over the 60 to 80 N with respect to the climatology profile of non-SSW years. A substantial temperature increase (around 10-30 K) below 50 km is evident within approximately 10 days prior to all events in the zonal average.

Tables and figures TF1

TF1: Table 1: What is the “full PCO” in “%full PCO uncertainties”? Does it mean “Partial Column of Ozone”? But for what pressure range? Or maybe that is the TCO?

Do these uncertainties (two rightmost columns) come from Bognar et al. (2019) or are they a new result of this paper?

Response: we defined the PCO in the main body text as partial column ozone. But to facilitate the read and comprehension of the table we also included it table caption. As comparison are limited by ozonesondes maximum height which is around 30 km on average.

The text is updated:

> full PCO is replace by “% PCO uncertainties (Ground -30 km)”

TF2: Figure 1: Add a box for the Greenland sector; stretch the color scale towards the reds in order to increase the contrasts

Response: Greenland box is added. For this plot we have used standard “viridis” color map. “viridis” is among linear space colormaps that prevent misinformation by using non linear space among colors and adding non realistic contracts. Moreover the hues used in “viridis” have unique pairs in grayscale which makes it readable for different color blindness.

TF3: Figure 2: Add a sentence to the caption, e.g. “**The vertical red lines highlight the dates of the 2008 and 2009 SSWs**”.

Response: we added the quat to the caption.

TF4: Figures 3 and 4: re-formulate the captions to obtain similar captions while avoiding the words “difference ratios”. Consider: “**Normalized mean biases and standard deviations of MERRA-2 with respect to ozonesondes/FTIR observations** ”.

Response: we updated the text throughout the whole text and captions to use relative difference. And the caption of figure 4 use previous caption:

> Same as Figure 3 but for relative differences of FTIR retrieved ozone from MERRA-2. Statistical summaries ofthe MERRA-2 and NDACC comparisons in four layers of ground to 8 km, 8km-15km, 15km -22km, and 22km- 30kmfor each station are shown on top of each plot.

TF5: Figure 5: totally unreadable, even at maximum zoom on a large screen! You must change the layout of the figure to decrease the margins around each map and increase its relative area and increase the resolution of the bitmap or (better) save these maps as vector-oriented graphics (PDF). Please clarify the caption: “Mean values of the TCO anomalies...”

Response: the figure is updated and has a higher resolution! The caption is clarified.

> The anomaly TCO average over 15 days prior (alphabet1, first and third columns) and 15 days after to each SSW (alphabet2, second and forth columns) compared to climatology on non SSW years.

TF6: Figure 8: Please remind in the caption, for the casual reader: “...averaged over ~~the zonal averaged~~ **latitude band 60°N-80°N** and **over the** Greenland sector **(60°N-80°N, 10°W-70°W)**.”

Response: it is applied.

TF7: Figure 10: How different is the time evolution of w* on a year with no SSW? One expects smaller and less perturbed values, but by how much? Consider adding the same figure but from the climatology of years with no SSW

Response: In the NH, the vortex is very rarely undisturbed, for the wave forcing is relatively strong (at least compared to the SH) throughout the winter. However, the values of w* 40 to 30 days before SSWs in Fig. 10 should be characteristic of an "undisturbed" vortex situation.

TF8: Figure 11: these plots should not show results below 15 km because these results cannot be discussed since

"Considering the larger uncertainties of ozone estimation in MERRA-2 below 15 km, and the possibility of larger uncertainties in dynamic parameter estimations, this study does not analyze the impact of the dynamics on ozone in the lower stratosphere." (p. 21, lines 17-20).

Response: The plot is updated to 15km to 30 km.

Minor Comments and typos MC1

MC1: P.1, line 17: clarify "**During SSWs**, changes in..."

Response: the text is updated.

MC2: P.3, lines 10-11: "... many other factors such as lower stratosphere conditions, the geometry of the polar vortex, the gradient of potential vorticity (PV) at the edge of the polar vortex, and synoptic systems at lower altitudes (Tripathi et al. 2015, de la Cámara et al., 2019; Lawrence and Manney, 2020). Changes in momentum deposition associated with these processes leads to..." These are not "processes". Maybe "conditions" or "dynamical states"?

Response: the text is updated.

"…dynamical states lead to …"

MC3: P.4, lines 15-16: improve transition with next paragraph, e.g.
"This study investigates **dynamical variability and** ozone variations **above the Arctic** (between 60°N and 80°N) **both** in the zonal average **and above a specific region**, during six SSWs using the MERRA-2 dataset."

Response; the whole paragraph is revised as discussed in response to GC3.

MC4: P.4, line 20: this is the first occurence of "Greenland sector" so you should move here your definition of this region (currently on p.16) and also draw the corresponding box on Fig. 1.

Response: it is added.

MC5: P.5, lines 7-10 and 22-23: this attempt to define the MERRA-2 reanalysis and its assimilation system is not correct. Reanalysis systems use only one model, here GEOS5; a well-designed reanalysis does not have any variations in models nor in methods of analysis – only in assimilated datasets of observations. See e.g. Fujiwara et al. (ACP, 2017) for a general yet correct description of reanalysis systems such as MERRA-2.

Response: the text is updated to apply the reviewer comment:

> "A variety of data sets are incorporated into a general circulation model to create 3-dimensional MERRA-2 ozone datasets with a time-frequency of 3 hours (Wargan et al., 2017; Gelaro et al., 2017)."

> "In reanalysis products such as MERRA-2, methods of analysis, model uncertainties, and observations cause uncertainties in the products (Rienecker et al. 2011)."

MC6: P.6, lines 5-6:
"...atmospheric dynamics, displaced/split polar vortex, and hemispherically asymmetric conditions during SSWs may cause unusual nonlinearity in ozone flux/transport terms." What do you mean by "unusual nonlinearity"?

Response: We clarified the text.

> "Moreover, the anomalous atmospheric dynamics, displaced/split polar vortex, and hemispherically asymmetric conditions during SSWs may cause complexity and additional uncertainties in estimation of ozone flux/transport terms."

MC7: P.7, lines 16-18: "Having the ability to resolve the fine structure of solar radiation spectra allows the retrieval of a variety of trace gases using the NDACC solar FTIR. However..."
This sentence is irrelevant for this paper – consider removal.

Response: As suggested we removed the sentence.

MC8: P.7, line 21-22: this citation of Bognar et al. (2019) does not seem to belong here as they validate satellite instruments – not ground-based instruments?

Response: As suggested we removed Bognar et al. (2019).

MC9: P.8, line 1: "More details ~~of~~ **on** the ozone retrievals at Eureka"

Response: the sentence is updated.

MC10: P.8, lines 16-17: "However, the vertical resolution of the remote sensing retrieval is often not similar to the model grid points...". Consider instead:

"Since the the vertical resolution of the remote sensing retrieval is **much coarser than the vertical resolution of the model**..."

Response: This is a general statement, as some remote sensing data such as MLS have high vertical resolution, however it might not match the model levels, for one-to-one comparison. We rephrased the sentence as below:

> Since, the vertical resolution of the FTIR retrieval does not match to the vertical resolution of the assimilation system.

MC11: P.8, eq. (1): Do x_s , x_h and x_a represent vertical profiles of ozone **mixing ratios**? Please clarify.

Response: we updated the text as bellow: where x_s is the final smoothed profile, x_h is the reanalysis estimated profile, and x_a and A are the a priori and averaging kernel of ozone mixing ratio for the retrieval respectively.

MC12: P.8, line 26: "The smoothing method effectively linearizes the ozone from the model..."

I do not understand. How can ozone, or even its mixing ratio, be "linearized" ?

Response: we rephrased the sentence to clarify.

> The smoothing method effectively applies the sensitivity of the retrieval to the ozone mixing ratio profile from the reanalysis using the averaging kernel and the priori information to create comparable profiles. (Rodgers and Connor, 2003).

MC13: P.10, lines 15-16: "the lack of net chemical production in the assimilation model should not dramatically impact our conclusions."
Could heterogeneous chemistry losses happen in Polar Stratospheric Clouds prior to the SSWs?

Response: The chlorine activation requires sunlight, so during Nov, Dec, and Jan when dominant parts of the high latitude is dark, these reactions are small. The significant ozone depletion in the Arctic occurs in undisturbed springtime when both conditions of cold stratosphere and sunlight are met. The text is updated to clarify more.

> "The contribution of dynamical and chemical drivers of ozone anomalies varies throughout the year. During springtime, both dynamical resupply and chemical depletion strongly modulate ozone changes. Assuming an isolated polar vortex and neglecting isentropic mixing, a previous study showed a similar magnitude of influence from chemical ozone depletion processes and dynamical ozone supply during the springtime (Tegtmeier et al. 2008). However, Strahan et al. (2016) used a chemistry and transport model to show that dynamical processing affects ozone changes by a factor of two more than chemical processing during March. However, chemical processes are not significant drivers of ozone changes in the middle stratosphere from November to February in the Arctic because of the polar night (de la Cámara et al. 2018b). Moreover, it has been shown that during years with SSWs, Arctic ozone depletion is significantly diminished (Strahan et al. 2016). However, if prior to or during the SSWs, the polar vortex moves outside of the region of the polar night (to lower latitudes), ozone depletion will occur as shown in the 2013 SSW by Manney et al. (2015). By limiting our analysis to latitudes between 60ºN to 80ºN, this impact is minimized in our analysis."

MC14: P.11, lines 15-20: this is a pure repetition of details already given in the caption of the figure. I recommend to keep this in the figure caption and to remove it here.

Response: we removed the repetitive text and here is the updated sentence:

> The results and statistics of comparisons between ozonesondes and MERRA-2 are depicted as the relative differences in Figure 3.

MC15: P.11, lines 23-24, consider:
"the 5km-10km **layer** includes **the** upper troposphere **and the** lower**most** stratosphere (UTLS), while the 10-30km layer includes the lower **middle** stratosphere."

Response: It is applied.

MC16: P.12, line 2: "MERRA-2 ~~is shown to be~~ **appears** unable to retrieve..."

Response: based on other suggestions, this sentence is rephrased as:

> The extreme low ozone values near the surface are not represented in MERRA-2 as it does not include bromine chemistry.

MC17: P.13, line 1: "...contain the most column ozone...".

Consider instead: "...**contribute most to the total ozone column**..."

Response: It is applied.

MC18: P.13, line 24-25: re-write the sentence. Consider e.g. :
"...our primary analysis is focused on the mid-stratospheric layers **which contribute most to the TCO and** ~~because this is~~ where the measurements are most reliable ~~which also has the dominant density of ozone.~~"

Response: It is applied.

MC19: P.14, lines 8-12: please split this sentence in several parts to make it clearer. Specifically, I understood only later on that you plot and discuss **the <u>mean values</u> over the 15 days prior to the SSW and over the 15 days that follow**. Please state this clearly already here and also in the caption of Fig.5.

Response: It is applied.

MC20: P.14, lines 22-23: do you mean
"The easterly winds lasted 16 days ~~during~~ **after** the major warming on 22 February." ?

Response: It is applied.

MC21: P.16, line 8: what do you mean by “semi-symmetrical shape”?

Response: it is updated to a Fairly symmetrical shape around the arctic.

MC22: P.16, lines 21-23: if we zoom on Fig.15 to the maximum possible and on a large screen, we can see (despite the insufficient resolution of the figure) that this characterization does not hold for the 2019 SSW. See also major comment on unreadability of Fig. 5.

Response: The figure is updated to have higher resolution. The text is updated to emphasize on the importance of Greenland sector as climatologically being isolated by polar vortex to provide an image of regional impact of SSWs in comparison to the zonal average.

> As the Greenland sector is one of the critical regions that is climatologically isolated by the polar vortex

MC23: P.17, line 3: “the Greenland sector exhibits a very strong isolated stratospheric air circulation during wintertime...” Consider instead: “**The air masses above the Greenland sector are more strongly isolated than at other Arctic longitudes**”.

Response: It is updated

MC24: P.17, line 7: “...and the Greenland sector ~~during~~ from 40 days before to 60 days after each SSW...”

Response: It is updated

MC25: P.17, line 14: “The climatological polar vortex position is located over the Greenland Sector (Figure 1)”. I do not agree: the center of the climatological vortex, as shown on Figure 1, is above Ny Alesund which is sligthly outside (East) of the Greenland sector as defined here.

Response: we updated the text to be more clear. It is True that Ny Alesund is at the center of the climatology of the polar vortex, and Greenland sector is one area that is located inside the polar vortex. The location of Ny Alesund is very close to the area that we used for the Greenland sector thus in the mid stratospheric analysis it follows the same pattern for the most part.

> The Greenland Sector is located inside the climatological polar vortex area is located over (Figure 1)

MC26: P.17, lines 18-19: “... over the Greenland sector ~~by~~ **with a** larger drop ~~in~~ of EPV **in this region than in** ~~compared to~~ the zonal **mean**.”

Response: It is updated.

MC27: P.18, lines 1-2: "In all SSWs ~~the magnitude of percent increased~~ **relative increase** of the TCO is higher over the Greenland sector compared to the zonal average with the exception of 2006..." Is this significant? It seems to me that the values above Greenland are barely larger than at other longitudes.

Response: the wording is updated. Commenting on the significance of the relative difference over Greenland is difficult to make. The Greenland sector as an area under the climatological polar vortex has lower TCO during the undisturbed winter with strong polar vortex. Thus, after the polar vortex break down and transition of enriched ozone air to high latitude it exhibits a higher relative TCO increase. However, in some study cases, during years with minor SSWs prior to the major SSWs, the TCO fluctuates even over the climatological polar vortex area which prevents a significant difference in relative increase of TCO over the Greenland compared to zonal average.

Our conclusion is on the significant influence of elongated cases on relative TCO increase over the Greenland sector compared to displaced cases.

> "Compared to the 40-day average of TCO prior to the SSW, the highest percent zonal TCO increase of 29% is observed for one of the elongated polar vortex SSWs in 2009. The relative increase in TCO over the Greenland sector (blue line) is higher compared to the zonal average (orange line). The Greenland sector is climatologically inside the polar vortex area and has a lower TCO value during strong polar vortex which consequently exhibits higher relative increase after the vortex break down and mixing. However, dynamically disturbed winters such as years with minor SSWs before the major SSWs hinder the higher relative TCO increase over the Greenland sector compared to the zonal average. For instance, in 2006, the polar vortex weakened around 25 days before the major SSW (first column Figure 7, TCO 2006) due to a minor SSW, which coincides with the averaged TCO (solid line) increase compared to the climatology (dashed line) as seen in the second column Figure 7 (TCO 2006). The earlier timing of the positive anomaly caused a lower value in the TCO change after the event. The relative TCO increase over the Greenland sector exhibits a higher value during elongated polar vortex SSWs with 37% in 2018 and 31% in 2009. More details of physical mechanisms that cause variability in ozone during SSWs is discussed in section 6."

MC28: P.18, lines 5-12: is this paragraph useful or interesting? Consider deletion.

Response: It is deleted.

MC29: P.18, lines 22-23: split the sentence: "...for both the zonal averaged and the Greenland sector. As expected the structures of ozone anomalies are smoother in the zonal average compared to the Greenland sector ~~compared as shown in Figure 8~~."

Response: It is updated.

MC30: P.18, lines 24-25: this sentence is very unclear. Are you still comparing the Greenland sector with the zonal average? Please re-write.

Response: As we removed a paragraph that talked about recovery based on your suggestion (MC28:). This sentence is also irrelevant and is removed.

MC31: P.18, line 26: “The shortest impact on TCO ~~belongs to~~ **happened in** 2008...”

Response: It is updated.

MC32: P.19, lines 15-17: “...which leads to **poleward** advection of low EPV air parcels poleward. The conservation of EPV causes anticyclonic circulation, which gradually drives easterly the zonal mean zonal winds, and leads to **the** displacement or splitting of the polar vortex.”

Response: It is updated.

MC33: P.20, line 1, consider: “Occurrences of minor SSWs ~~are evident by~~ **can be seen through** the early appearance”

Response: It is updated.

MC34: P.20, line 8, consider: “The suppressed wave activity ~~creates preferable conditions for~~ **leads** to the recovery of...”

Response: It is updated.

MC35: P.22, line 7: Section 7 provides a summary, with only the last paragraph providing a conclusion. Hence the title of this section should be “**Summary and conclusion**”.

Response: It is updated.

MC36: P.22, line 13: “**The** MERRA-2 reanalysis...”

Response: It is updated.

MC37: P.22, lines 24-25, consider: “From 5km to 10km, ~~a non-significant (higher standard deviation)~~ negative mean bias exists in all sites (-8% to 15%) **but it is not significant due to the larger standard deviation.”**

Response: It is updated.

MC38: P.23, line 1: please describe “G-5km (<20%)” properly, with words

Response: It is updated.

Around 20% standard deviation of relative differences is observed at G-5 km.

MC39: P.23, line 8: “These results emphasize the high quality of MERRA-**2 at least after 2004, the year when MLS data became available**.” This is important!

Response: It is updated.

MC40: P.23, lines 9-10: “Higher uncertainties in the UTLS are also expected because MLS has **a dominant contribution in the MERRA-2 reanalysis and a** lower sensitivity at lower altitudes ~~and the dominant contribution of MLS in MERRA-2 reanalysis~~”

Response: It is updated.

MC41: P.23, line 22: “The TCO increases rates and the magnitude of changes in EPV after these cases are large and the intrusion of positive temperature anomalies to the mid stratosphere is coincident with **these** SSWs dates.”

Response: It is updated.

MC42: P.24, lines 3-5, consider: “A strong **cor**relation is observed between the magnitude of change in the averaged EPV ~~15 days after compared to 15 days before~~ around the SSW, and the magnitude of TCO change for the same period for all six studied SSWs.”

Response: It is updated.

MC43: P.24, lines 6-15: “The Greenland sector is one of the critical regions that is impacted by negative TCO **anomalies** before the elongated polar vortex in 2009 and 2018; positive TCO **anomalies** occurs before displaced SSWs. To identify the similarities and differences of zonal versus the regional impact of SSWs on ozone, the analyses are applied over the Greenland sector as well as the zonal average. The general structure of the vertical ozone anomaly **over** the Greenland sector is similar to the zonal **structure**. However, as expected the ozone anomaly over the zonal average is smoother than over the Greenland sector which results in a more magnified TCO increase over Greenland. The increased rate over the Greenland sector is between 15% in 2006 to 38% in 2018, while the zonal average ranges between 8% in 2008 to 29% in 2009. Moreover, **the** TCO exhibits a faster recovery to the climatology values over this region compared to the zonal average.”

Response: It is updated.

MC44: P.24, line 26: not understandable – please re-write:
“The faster recovery of zonal temperature and ozone at middle stratosphere within 30 days is recorded for 2008 with the shortest duration easterly zonal mean zonal winds.”

Response: It is updated.

> The fastest recovery of zonally averaged temperature and ozone at middle stratosphere happen in 30 days for 2008.

MC45: P.25, line 3-6: “In conclusion, the MERRA-2 dataset is shown to capture **the** ozone variability in the middle stratosphere and provides dynamical information to investigate the impact of SSWs. The impact of SSWs on ozone and the role of vertical advection is shown to be more intense in 2009 and 2018 with an elongated polar vortex compared to **the** displaced ~~vortex~~ **vortices** in 2006, 2008, 2013, and 2018.”

Response: It is updated.

MC46: P.25, last sentence: “the dramatic ozone increases over high latitudes during SSWs points to consequences of these events on the global earth system and possible environmental/ecosystem changes that could be investigated in future studies.”
This is a quite vague statement, and I am skeptical as the timescales for environmental/ecosystem changes are much longer than those due to SSW perturbations. Maybe it is possible to conclude instead with the changes in SSW occurences that are expected from climate change?

Response: we updated the final statement based on suggestion:

> “Although there is no consensus across future climate simulations on whether SSW occurrences will increase or decrease in response to increased greenhouse gas concentration (Ayarzarguena et al. 2018, 2020), many simulations show a significant change. The dramatic ozone increases over high latitudes during SSWs points to the consequences and implications for ozone if the rate of SSW increases in future.”