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

1. 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:
   - 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).
   - 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.

- 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?
- 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?

2. 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?

3. 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).

4. 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.

Tables and figures

- 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?

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

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

- 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*** ”.

- 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...”

- 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)***.”

- 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

- 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).

Minor Comments and typos

- P.1, line 17: clarify "***During SSWs***, changes in..."
- 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"?
- 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."
- 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.
- 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.
- 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"?
- 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.
- 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?
- P.8, line 1: "More details ~~of~~ ***on*** the ozone retrievals at Eureka"
- 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***..."
- P.8, eq. (1): Do x_s , x_h and x_a represent vertical profiles of ozone ***mixing ratios***? Please clarify.
- 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" ?
- 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?

- 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.
- 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**.**"
- P.12, line 2: "MERRA-2 is ~~shown to be~~ ***appears*** unable to retrieve..."
- P.13, line 1: "...contain the most column ozone...".
  Consider instead: "***...contribute most to the total ozone column...***"
- 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~~."
- 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 ***mean values 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.
- P.14, lines 22-23: do you mean
  "The easterly winds lasted 15 days ~~during~~ ***atfer*** the major warming on 22 February." ?
- P.16, line 8: what do you mean by "semi-symmetrical shape"?
- 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.
- 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***".
- P.17, line 7: "...and the Greenland sector ~~during~~ ***from*** 40 days before to 60 days after each SSW..."
- 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.
- 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***."
- 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.
- P.18, lines 5-12: is this paragraph useful or interesting? Consider deletion.

- 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~~."
- P.18, lines 24-25: this sentence is very unclear. Are you still comparing the Greenland sector with the zonal average? Please re-write.
- P.18, line 26: "The shortest impact on TCO ~~belongs to~~ ***happened in*** 2008..."
- 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."
- P.20, line 1, consider: "Occurrences of minor SSWs ~~are evident by~~ ***can be seen through*** the early appearance"
- P.20, line 8, consider: "The suppressed wave activity ~~creates preferable conditions for~~ ***leads to*** the recovery of..."
- 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**".
- P.22, line 13: "***The*** MERRA-2 reanalysis..."
- 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***."
- P.23, line 1: please describe "G-5km (<20%)" properly, with words
- 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!
- 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~~"
- P.23, line 22: "The TCO increase~~s~~ rates and the magnitude of change~~s~~ in EPV after these cases are large and the intrusion of positive temperature anomalies to the mid stratosphere is coincident with ***these*** SSWs date~~s~~."
- 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."

- 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.”
- 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.”
- 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.”
- 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?