Response to Referee #3

(Referee comments: https://doi.org/10.5194/egusphere-2023-2916-RC3)
Manuscript: Yessimbet, K., Steiner, A. K., Ladstädter, F., and Ossó, A.: Observational perspective on SSWs and blocking from EP fluxes, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2916, 2024.
The structure and content of the referee's comments are duplicated below in regular font. The authors' responses are in bold. Line numbers used in our responses refer to the original ACP Discussions paper. Text updates in the revised manuscript are in grey.

This paper examines the use of GNSS radio occultation (RO) data for investigating key features of sudden stratospheric warmings (SSWs). The authors grid RO data following established techniques and then calculate geostrophic winds from this gridded product. Wave diagnostics – meridional heat flux and Eliassen-Palm (EP) flux – are then extracted from these data. SSWs are identified and classified based off these data, and the evolution of wave forcing and vertical coupling are shown. The authors provide thorough discussion about this evolution for sets of known SSW types: displacement and split events, and reflecting and absorbing events. They acknowledge their sample size is small, but find evidence in support of previous work that displacement events are followed by North Pacific blocking and split events are followed by North Atlantic blocking.
The work is presented well, though the authors could consider some rearrangement of two figures. This work strictly uses observational data – along with dynamical theory – which is still somewhat novel. Other observational studies have looked at more limited samples or other features of SSWs such as only the stratospheric fields. And the thorough, deep analysis of a small, but representative set of events provides useful information for the community. The authors adeptly touched on several outstanding issues in our understanding of the wave-mean flow interaction and stratosphere-troposphere coupling that occurs around SSWs.
However, the manuscript would benefit greatly from additional work on a few topics. These are mostly related to how the GNSS data compare with other, well-studied data sets and what the GNSS data provide that is new.

We thank the reviewer for reviewing our manuscript and for providing constructive comments and advice on how to improve it. We also thank the reviewer for the positive comments on our manuscript, which emphasized the value and novel aspects of our work.

1) Details of the GNSS RO data are missing. As the authors surely know, the RO method observes bending of signals through the atmosphere, which is foremost related to changes in density. This knowledge can then be used to derive geopotential height and pressure to a high degree of accuracy through the hydrostatic equation. Following this, temperature may be calculated, but only by assuming no moisture – i.e., “dry temperature.” This is a reasonable assumption in the stratosphere but will lead to large inaccuracies in the tropospheric fields. Given how much of the discussion and results rely on temperature below 300 hPa, the authors should address the limitations of its

use. This is covered in the references they cite but the reader of this work would benefit from additional, relevant information here.
Alternatively, accurate temperature and humidity fields may be derived from RO using one-dimensional variational analysis. But it's not clear if the authors used such a product, in which case the limitations of that needs to be addressed.

Thank you for pointing to this. We included more information on the GNSS RO data retrieval, variables, and characteristics. In our study, we use physical temperature based on a moist-air retrieval, and not the "dry" temperature.

In this regard, the following text is added in the Data Section at Line 76:
The GNSS RO method is based on the detection of radio signals transmitted by GNSS satellites, which are refracted by the Earth's atmosphere as they propagate through it to Low Earth Orbit (LEO) satellites. The measured signal phase changes are converted to bending angle profiles, and further to refractivity by an Abel transform. At high altitudes, the Abel integral requires initialization with background data. Thermodynamic parameters are then computed under the assumption of a dry atmosphere ("dry" parameters). In moist air conditions (lower to middle troposphere, specifically in the tropics), the retrieval of (physical) temperature or humidity requires prior knowledge of the state of the atmosphere (e.g., Kursinski et al. 1995; 1996). Due to the involved background data, the retrieved RO temperature data exhibit larger uncertainties in lowermost moist parts of the troposphere and at high altitudes (above about 30 km). For an overview of the retrieval process and the involved structural uncertainties see, e.g., Steiner et al. (2020). The RO measurements are of very high quality with minimal structural uncertainty within the UTLS region, as highlighted by Scherllin-Pirscher et al. (2017) and Steiner et al. (2020).

In this work, we use geopotential height and physical temperature as a function of pressure, processed by the Wegener Center for Climate and Global Change (WEGC) with the Occultation Processing System (OPS) version 5.6 (Angerer et al., 2017; Steiner et al., 2020).

Geostrophic wind fields can be derived from RO geopotential height fields (Scherllin-Pirscher et al., 2014; 2017). RO geostrophic wind and gradient wind fields were found to capture all main wind features in our study. Compared to atmospheric analyses winds, differences are in general small (2 m/s) except near the subtropical jet (up to 10 m/s). There, RO winds underestimate actual winds due to the geostrophic and gradient wind approximations while RO retrieval errors have negligible effects (Scherllin-Pirscher et al., 2014).

We included the following new references in the revised manuscript:
Kursinski, E. R., and G. A. Hajj, K. R. Hardy, L. J. Romans, and J. T. Schofield, 1995: Observing tropospheric water vapor by radio occultation using the Global Positioning System. Geophys. Res. Lett., 22, 2365–2368, https://doi.org/10.1029/95GL02127.

Kursinski, E. R., Hajj, G. A., Bertiger, W. I., Leroy, S. S., Meehan, T. K., Romans, L. J., Schofield, J. T., McCleese, D. J., Melbourne, W. G., Thornton, C. L., Yunck, T. P., Eyre, J. R., and Nagatani, R. N.: Initial Results of Radio Occultation Observations of Earth's Atmosphere Using the Global Positioning System, Science, 271, 1107–1110, 1996.

At Line 76, we also edited the sentence "We use temperature and geopotential height profiles…":

In this work, we use geopotential height and physical temperature as a function of pressure, processed by the Wegener Center for Climate and Global Change (WEGC) with the Occultation Processing System (OPS) version 5.6 (Angerer et al., 2017; Steiner et al., 2020).

2) RO profile density may be an important topic to document for this study, but no details are given. RO missions and profile counts vary with time, but some measure of the sampling density should be given. Given the nature of RO sampling, this can likely be well-represented by zonal mean statistics. It would also be useful for the authors to document the occurrence, or likely rarity, of grid points that are missing RO profiles.

Regarding the number of RO profiles used in our study, we added Figure S1 (in Supplementary Information)/R3.1 showing the zonally averaged monthly distribution of RO profiles used in our studies. We have also added more detailed information in the manuscript in Line 82:

The number of daily RO profiles from different missions varied over the period from 2006 to 2019, with the highest number of profiles from 2007 to 2010 (> 2500 profiles per day) and a decrease in the number of profiles (from more than 2500 to less than 2000 profiles) from 2012 onwards (Figure S1) due to the exceeding of the lifetime of some of the RO missions (Fig. 5, Angerer et al., 2017).

Thus, in the range of vertical pressure levels from 10 to 850 hPa, there are fewer than 10 missing grid points in the daily gridded fields, with the number increasing towards the surface.

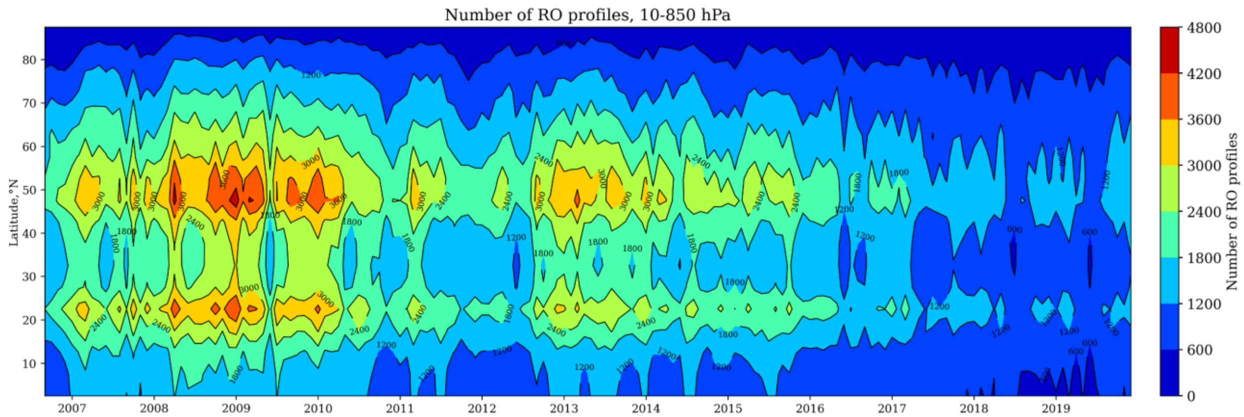

Figure R3.1. Zonal distribution of the monthly number of the RO profiles averaged over 10 to 850 hPa for the period from September 2006 December 2019.

3) Limited comparisons with reanalyses may be a real benefit to the manuscript. As it stands, the manuscript doesn't give the reader a sense of what the relatively high vertical resolution of the RO observations adds to our understanding of SSWs. This is most evident in the tropopause inversion layer (TIL) results. Details of the Brunt Vaisala frequency N^2 would seem to be most sensitive to vertical resolution, and RO may be able to provide additional insight, but it's not clear what that is.

Some comparison of N^2 with, say, ERA5 for all or a limited sample of SSWs may support the authors' claims on the benefits of the high vertical resolution of RO observations.

Additionally, the authors might consider adding one or two sentences about how their diagnosed dates of the SSWs compare with other, reanalysis-based studies.

Thank you for this suggestion. During our analysis, we compared our RO-based parameters with parameters based on reanalyses (ERA5 and NCEP), e.g., zonally averaged parameters such as zonal-mean zonal wind ($\overline{u}$), and eddy meridional heat flux ($\overline{v'T'}$). Figures S2,3 (also here R3.2,3.3) provide a comparison of these parameters and show consistency between RO and ERA5 both in the stratosphere and upper troposphere, confirming the reliability of RO-based dynamics.

As you suggest, we also include Figure S4/R3.4 depicting the Brunt Väisälä frequency computed from RO and ERA5 (averaged over 75-90°N), which shows high consistency in terms of main patterns and magnitude between RO and ERA5. Small differences (of around 10%) in N^2 are observed mainly in the tropopause region between 200 hPa and 300 hPa and in the stratosphere. It should be noted that we chose to compare with ERA5 because it is arguably the most advanced and commonly used reanalysis product, however, ERA5 assimilates RO data. RO data has a high vertical resolution, while the daily gridded field is

smoothed in the horizontal and over time due to weighted averaging. Therefore, it is not straightforward to interpret the differences in detail.

However, for our study we decided to take an observational perspective and chose to use GNSS RO observations for the analyses as the dataset resolves the relevant features to provide information on the stratosphere–troposphere coupling.

We added information about the comparison of parameters between RO and ERA5 in the manuscript on Line 123:
In our analysis, we also made comparisons of key parameters between RO and reanalyses (e.g., ERA5), such as the zonally averaged parameters, zonal-mean zonal wind and $\overline{v'T'}$ (Figure S2 and S3), confirming the consistency and the reliability of the RO-based dynamics.

For better clarity with respect to the observations we revised the first and last paragraph of the discussion section, it reads now:
The main objective of this study was to characterize the synoptic and dynamic conditions of SSWs and to investigate the link to blocking events from an observational perspective. We used GNSS RO observation for these analyses as the dataset resolves the relevant features to provide information on the stratosphere–troposphere coupling.

In conclusion, our findings underscore the applicability of GNSS RO for the exploration of atmospheric circulation dynamics. Due to its high vertical resolution, GNSS RO has the potential for studying the interplay between tropopause structure and wave activity propagation. A detailed study of the relationship between tropopause structure and wave activity propagation relevant to SSW events should be investigated in future GNSS RO studies.

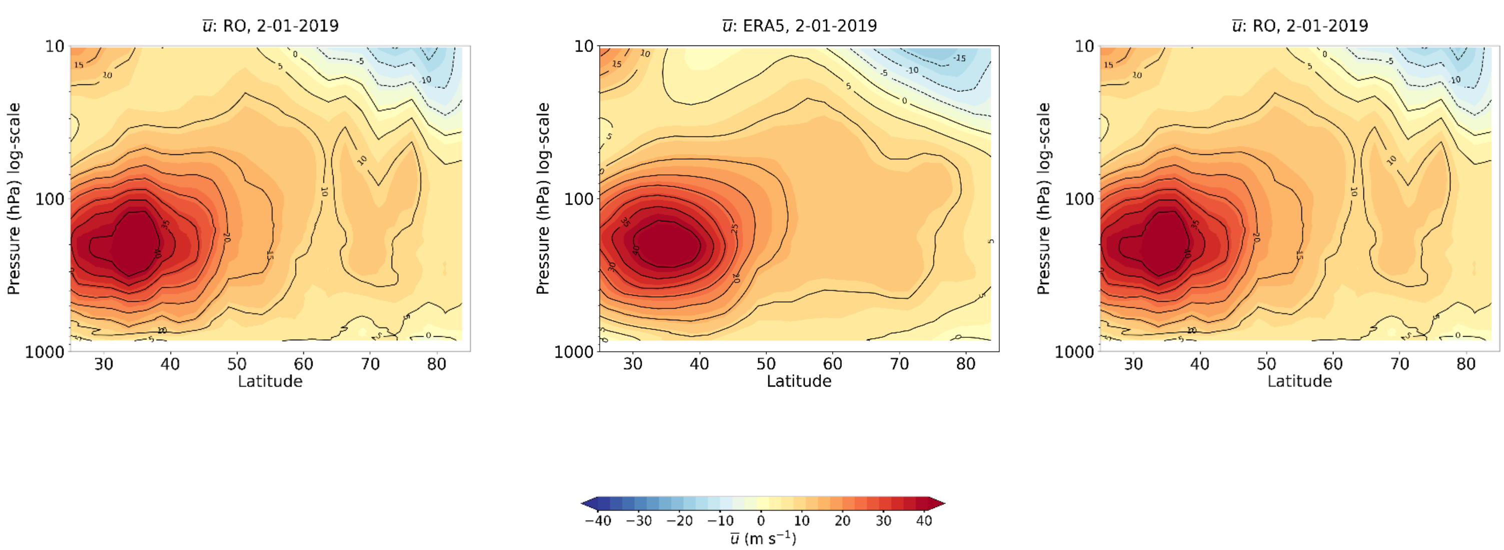

Figure R3.2. Zonal-mean zonal wind computed from RO (geostrophic wind; left) and ERA5 (real wind; right) and their difference for an exemplary day.

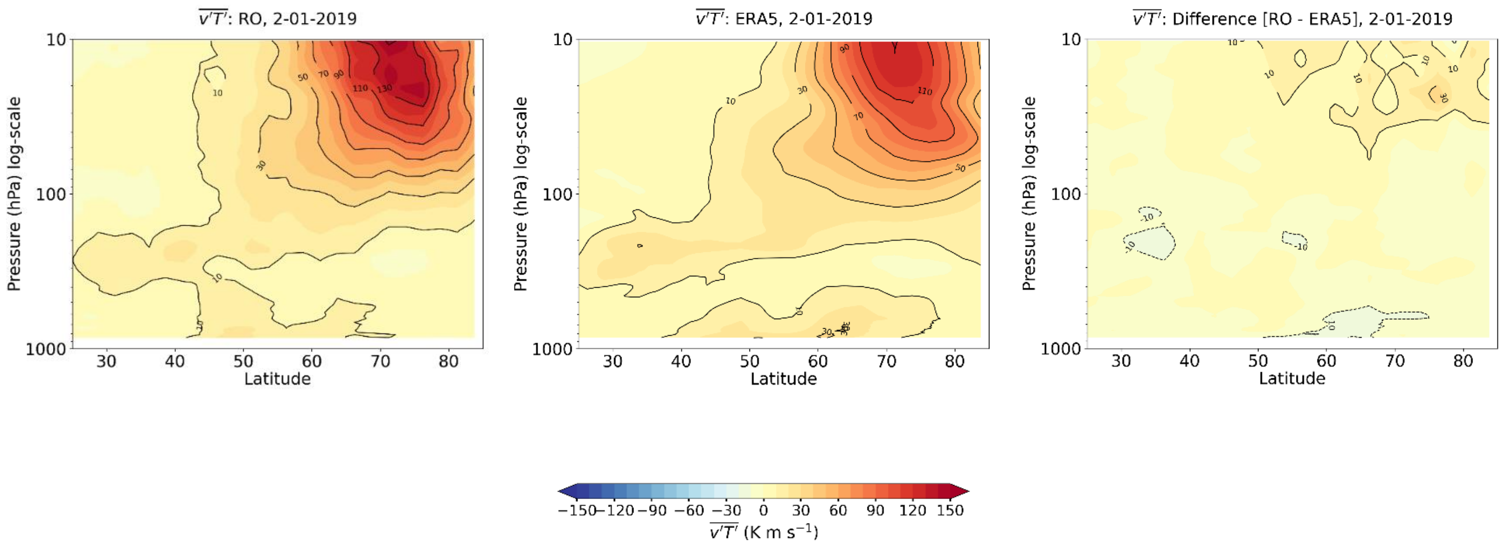

Figure R3.3. Eddy meridional heat flux computed from RO (using geostrophic meridional wind; left) and ERA5 (using real meridional wind; right) and their difference for an exemplary day.

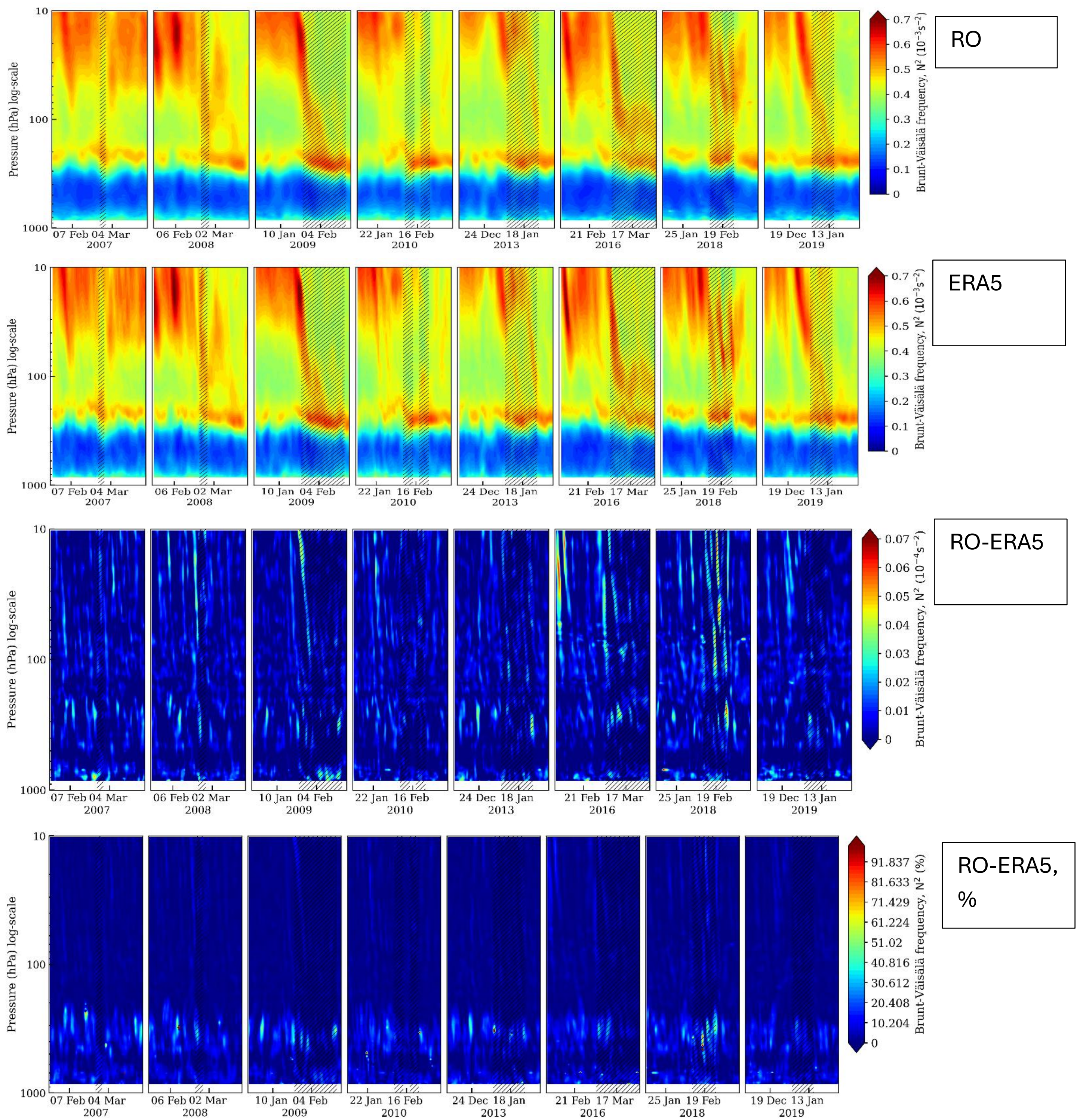

Figure R3.4. Brunt Väisälä frequency computed from RO (upper plot) and ERA5 (middle plot) and their difference (second lower plot) and difference in percentage (lowest plot) averaged over 75-90° N within a +/- 30 day timeframe relative to each of the SSW events

from 2007 to 2019. Hatched regions indicate dates when the zonal-mean zonal wind at 60° N and 10 hPa is negative.

Regarding the diagnosed dates of SSWs, we added the following sentence at Line 130:
The diagnosed central SSWs are compared with the list of major midwinter SSWs in the reanalysis products of the SSW Compendium dataset (NOAA CSL, 2024).
In the reference section we cite the SSW Compendium:
NOAA CSL: Chemistry & Climate Processes: SSWC, https://csl.noaa.gov/groups/csl8/sswcompendium/majorevents.html

4) Line 96: The citation to Scherllin-Pirscher et al. (2014) is not included in the references section.
The citation to Scherllin-Pirscher et al. (2014) is already included in the references section.

5) Figures 6 and 7 could benefit from vertical stacking into two rows of 4 panels. As they're presented, some of the details are squished into a narrow space.
Fig. 6 is a final combination of 8 detailed figures already shown for each SSW event in the study (e.g. Fig. 3d, Fig. 5d, Fig. A2d, etc.). We therefore decided to leave Fig. 6 as it is. In Fig. 7 the main patterns seem to be clear. Also, for the sake of consistency with Fig. 6, we decided to keep Fig. 7 as it is.

6) Line 114: Suggest starting a new paragraph at "A standard algorithm…"

We started a new paragraph at "A standard algorithm…".

7) Line 150: This final sentence of this paragraph feels more appropriate in the previous section with other definitions.

We moved this sentence to the Method Section on Line 130.

8) Line 155: Recommend "concurrent with" rather than "due to" as the heat flux is a proxy for the wave activity flux that drives the zonal wind reversal.

Thank you. We changed the words "due to" to "concurrent with".

You may consider a similar slight wording change on line 199: "led to a deceleration."

We changed the wording from "led to deceleration" to "resulted in a slowing down".