Response to Referee #1

(Referee comments: https://doi.org/10.5194/egusphere-2023-2916-RC1)
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. 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.

In this paper, the authors examined eight major boreal Sudden Stratospheric Warming (SSW) events between 2007 and 2019 to understand the vertical coupling between the troposphere and stratosphere, as well as the relationship between SSWs and blocking events using Global Navigation Satellite System (GNSS) radio occultation (RO) observations. They classified the eight SSW events into two types of groups, i.e., "reflecting" events and "absorbing" events; two events fell into the former group, while the other six events fell into the latter one. The reflecting events were found to be displacement-type SSWs with a downward propagation of wave activity from the stratosphere to the troposphere during vortex recovery, accompanying the formation of blocking in the North Pacific region. On the other hand, the absorbing events were found to be split-type or mixed-type ones, showing the subsequent formation of blocking in the Euro-Atlantic region. The authors also showed an enhancement of the polar tropopause inversion layer as the result of SSWs, which was stronger for the absorbing events. These results are consistent with former studies and can actually reinforce the former results. For this point, the authors describe that "these results could help clarify the open question of whether split or displacement events trigger consistently different reactions in the tropospheric circulation, on which there is not yet consensus in the scientific community" (L366-367). If so, the authors should try to make dynamical discussions to answer this question as far as possible. Hence, I recommend the paper be revised with attention to the following details.

We thank the reviewer for reviewing our manuscript, and for all the valuable comments and suggestions on how to improve it.

We included some more discussion on L366-367:

Nevertheless, we show that SSW reflecting/absorbing events differ in the magnitude of the downward impact (manifested e.g., in TIL variability, downward propagation of easterly wind and temperature anomalies) and correspond to specific divergent tropospheric responses. Reflecting events connected to vortex displacement are observed to trigger downward wave propagation inducing blocking over the North Pacific region while absorbing events connected to vortex split are associated with blocking over the North Atlantic and upward wave propagation. The magnitude of the downward impact may be one of the factors to consider in addressing the open question of whether displacement or split events trigger different responses in the tropospheric circulation.

Specific Comments:

(1) L.154-156: In this analysis, eddy meridional heat fluxes are estimated at 100 hPa, while zonal mean zonal winds are calculated at 10 hPa. What does the two-day lag mean in this case? Please add comments on this point.

The two-day lag between two consecutive heat flux pulses may indicate that the propagation of the upward wave activity (initial pulse) was somehow suppressed and then continued again, which looked like there were two two-day lagged heat flux pulses. This is part of a larger research question, namely, what enhances or suppresses the propagation of upward wave activity around 100 hPa. As for the mean zonal wind, which generally weakened due to these two pulses, it strengthened shortly during the two days between the heat flux pulses. In this regard, we added the following text in the manuscript in Line 156:

The two-day lag between these two pulses may be an indication that the upward wave activity was suppressed and then resumed.

(2) L.159, 164: "Fp" should be "F_p"

Thank you for noticing it. We corrected it in the text.

(3) L.189-191: Negative eddy meridional heat fluxes mean the occurrence of downward propagation of wave activity. As discussed in Kodera et al. (2016), downward propagation of wave activity could enhance meandering of zonal flows, which gives a favorable condition for blocking occurrence. Therefore, the development of the North Pacific blocking might be seen during the negative eddy meridional heat flux peak. In order to more clearly see the relationship between the downward wave propagation and the blocking occurrence, I recommend the authors to make 3-d analyses by the use of 3-d wave activity fluxes, such as Plumb's (1985) one. As in Kodera et al. (2013), it might be shown that downward propagation of wave packets over North America induces a ridge over the North Pacific as well as a trough over eastern Canada in the upper troposphere.

Thank you for the suggestion. We computed the 3D Plumb flux, according to Plumb (1985) (eq. 5.7) and we added a figure in the Appendix B (Fig.B1) showing its evolution during the SSW of 2008 (see Fig.R1.1 below). On 12-14 January, upward wave activity is enhanced over Eurasia with a clear westward tilt of the geopotential height anomalies. Starting from 21-23 February 2008, and particularly on 27-29 February we observe downward propagation of wave activity between around 250°E and 300°E (longitudinal range of North America) along with a trough centered over 300°E (longitudinal position of eastern Canada) and a positive barotropic geopotential height anomaly between 150°E and 200°E (North Pacific). This is observed together with the eastward tilt of the trough which is associated with Rossby wave downward propagation. This picture is also in agreement with Kodera et al. (2008). This, in

turn, induced the formation of the North Pacific ridge, which then led to the formation of the North Pacific blocking.

We added more details in the manuscript at Line 205 (on new paragraph):

In addition to the EP flux analysis, to further examine the evidence for the relationship between the downward propagation of wave activity and the North Pacific blocking, we analyzed the evolution of the 3D Plumb flux (Fig. B1). Starting from 21-23 February (Fig. B1b), and particularly on 27-29 February 2008 (Fig. B1c), a downward propagation of wave activity is observed between about 250°E and 300°E along with a trough centred over 300°E and a positive barotropic geopotential height anomaly between 150°E and 200°E (North Pacific). This is observed together with the eastward tilt of the trough, implying downward propagation of the Rossby waves, aligning with the findings of Kodera et al. (2008). This in turn induced the formation of the North Pacific ridge, which then led to the formation of the North Pacific blocking.
And the new reference in the text is:
Plumb, R. A.: On the three-dimensional propagation of stationary waves. J. Atmos. Sci., 42, 217−229, https://doi.org/10.1175/1520-0469(1985)042<0217:OTTDPO>2.0.CO;2, 1985.

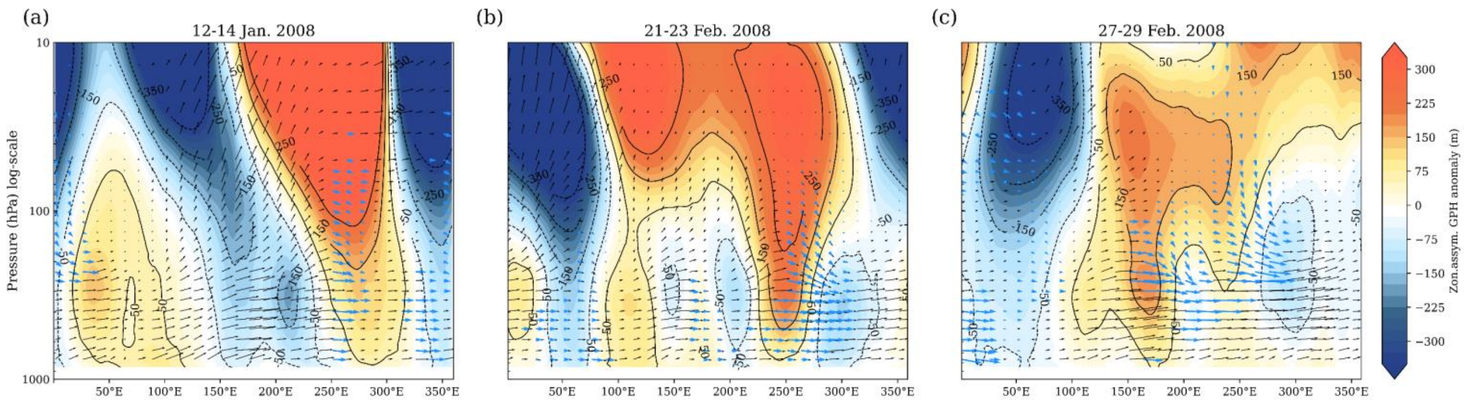

Figure R1.1. Evolution of the vertical and zonal components of the 3D Plumb flux (arrows), shown for the SSW 2008: before the SPV displacement (12-14 Jan.), during its displacement (21-23 Feb.) and during its recovery (27-29 Feb.) The vectors are plotted for every 5th longitude and pressure level. Blue vectors denote where the vertical component of Plumb flux is negative. Shading indicates the zonally asymmetric component of the geopotential height anomaly.

(4) L.195-204: For the reflecting events, easterlies remain only in the upper stratosphere and westerlies still dominates the lower to middle stratosphere with a maximum in the lower stratosphere, as seen Fig. 3. In such a situation, refractive index squared might be negative in the upper flank of the westerly maximum. If so, it could be a favorable condition to wave reflection

for upward propagating wave packets from the lower atmosphere, as discussed by Perlwitz and Harnik (2003). Could the authors add any discussions on this point?
We added the following discussion in the manuscript at Line 199:

From 21 to 23 February, it can be observed that easterly winds are already present in the upper stratosphere, while westerly winds prevail in the middle and lower stratosphere. According to Perlwitz and Harnik (2003) and Kodera et al. (2008), this negative wind shear indicates favourable conditions for the reflection of upward propagating wave packets. When these wave packets encounter a transition from lower regions where westerly winds support their upward propagation to easterly winds that oppose it, an effective barrier to upward propagation is formed and results in the reflection of part of the wave energy.

We included the new reference in the reference section:

Perlwitz, J., and Harnik, N.: Observational evidence of a stratospheric influence on the troposphere by planetary wave reflection. J. Climate, 16, 3011–3026, https://doi.org/10.1175/1520-0442(2003)016<3011:OEOASI>2.0.CO;2, 2003.

(5) L.244-263: As for the absorbing events, downward descending easterlies attain to the lower stratosphere, as shown in Fig. 5, which brings about a negative signal of the Northern Annular Mode in the troposphere and generally gives a favorable condition for blocking occurrence. In this case, upward wave packets, which could be occasionally originated from blocking highs, would supply easterly momentum to maintain warming events. Such a positive feedback mechanism seems to occur in these events. I also recommend the authors to make 3-d analyses here in order to show the details, as in Comment (3). In this case, it is interesting whether to see features that continuous upward wave packets originated from blockings might contribute to the continuation SSWs.

Thank you for the suggestion. As in comment 3, we included Fig. B2 in the Supplementary Information and here below (as Fig. R1.2), showing the Plumb flux evolution for the main dynamic phases of one of the absorbing SSW events (2019 event). Indeed, it can be observed that wave activity is enhanced and directed outward from the North Atlantic blocking which is barotropically related to the positive geopotential height anomaly in the stratosphere. This suggests that the North Atlantic block may have emitted some of the wave packets into the stratosphere, thereby contributing to vortex weakening and further SSW development.
In this regard, we added the following text in the manuscript in Line 268:

To further investigate the relationship between the North Atlantic blocking and the details of wave activity propagation, the 3D Plumb flux evolution and vertically resolved geopotential height anomalies are shown in Fig. B2. Along with the onset of North Atlantic blocking formation, it can be observed that the wave activity is enhanced outward from the positive geopotential height anomalies centred between 50°W and 0°. This suggests that wave

packets originating from the North Atlantic block propagate into the stratosphere, thereby contributing to vortex weakening and further SSW development.

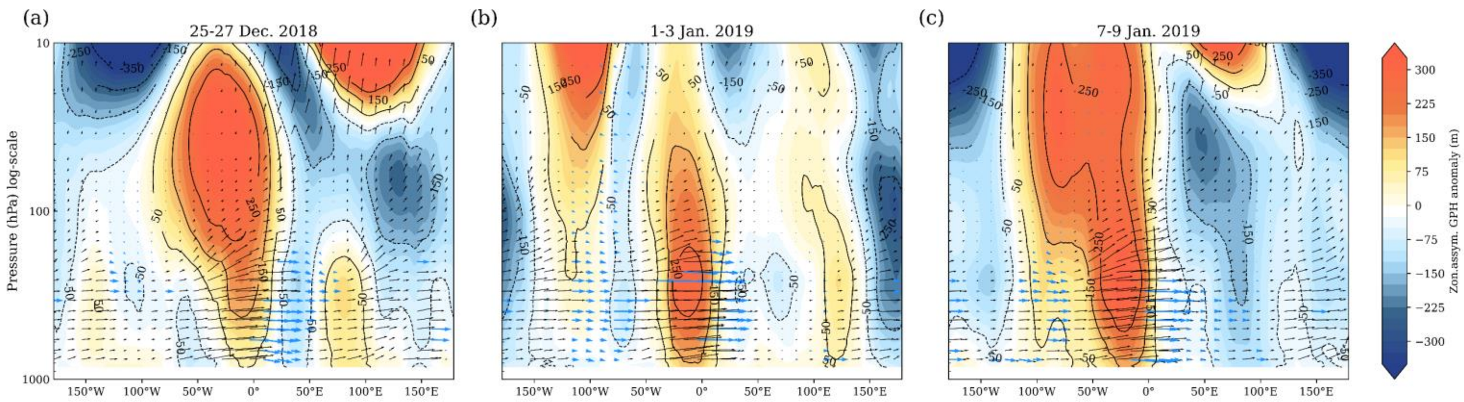

Figure R1.2. Evolution of the vertical and zonal components of the 3D Plumb flux (arrows), shown for the SSW 2019: during the SPV displacement (25-27 Dec2018.), during its split (1-3 Jan.) and after the split (7-9 Jan.) The vectors are plotted for every 5th longitude and pressure level. Blue vectors denote where the vertical component of Plumb flux is negative. Shading indicates the anomaly of the zonally asymmetric component of the geopotential height.

(6) L.325-329: Since influences induced by the absorbing events can reach the UTLS region and make large temperature anomalies there, the polar tropopause inversion layer would be more evidently enhanced. Please add further discussions on this point.

We added the following discussion in the text at Line 328:

This shows that the absorbing SSW events 2009-2019 had stronger and more prolonged impact (in terms of thermal heating) on the UTLS and the enhancement of the polar TIL than the reflecting events in 2007 and 2008.

References:

Kodera, K., Mukougawa, H., and Itoh S.: Tropospheric impact of reflected planetary waves from the stratosphere, Geophys. Res. Lett., 35, L16806, https://doi.org/10.1029/2008GL034575, 2008.

Perlwitz, J., and Harnik, N.: Observational evidence of a stratospheric influence on the troposphere by planetary wave reflection. J. Climate, 16, 3011–3026, https://doi.org/10.1175/1520-0442(2003)016<3011:OEOASI>2.0.CO;2, 2003.

Plumb, R. A.: On the three-dimensional propagation of stationary waves. J. Atmos. Sci., 42, 217−229, https://doi.org/10.1175/1520-0469(1985)042<0217:OTTDPO>2.0.CO;2, 1985.