Response to Reviewers after 2nd review

Dear editor and reviewers,

Thank you very much for revising this manuscript a second time. The authors very much appreciate the comments and the positive feedback. Please find attached the answers to the comments of all three reviewers on our first revision of "How do different pathways connect the stratospheric polar vortex to its tropospheric precursors?". Although Reviewer 1 and 2 suggested to accept the manuscript as it, they included very minor comments and therefore we decided to also respond to these.

For your convenience we cited the reviewers' comments in separate sections and responded in bold font and indent. The line specifications in our responses refer to the track-changes file.

Reviewer 1

I thank the authors for a careful revision of their manuscript.

My initial concern about a potential confounding influence of ENSO on tropospheric features and the polar vortex has been addressed. No significant linear correlation between the ENSO 3.4 index and the polar vortex was found, supporting the proposed direct upward influence of an Atleutian low/ Ural high to the polar vortex.

In the initial manuscript, the authors investigated upward stratosphere-troposphere coupling by means of the Plumb flux, which I found difficult to interpret physically. In the revised manuscript, this was addressed by substituting the Plumb flux by the Eliassen-Palm flux, which in my view significantly improves the study's mechanistic reasoning.

The authors suggest that geopotential anomalies over the Ural and Atleutian area penetrate the stratospheric polar vortex via two distinct mechanisms. Anomalies over the Ural area are linked to vertical wave propagation. Atleutian pressure anomalies near the surface are linked to anomalies in the mid-troposphere of opposite sign, which reach up into the stratosphere and displace the polar vortex.
I appreciate the authors' explanation; however, I continue to ponder the feasibility of also reconciling the latter perspective with the concept of upward-propagating waves. For example, I could imagine the negative mid-troposphere geopotential anomaly over North America to stem from the vertical westward tilt of vertically propagating Rossby waves. Near the surface, anomalies might vanish due to presence of wavenumber 3 structures, as found by the authors.

> **We find the comment of the reviewer a worthwhile contribution to the interpretation of our results and added a comment in lines 314-316.**

If that was the case, the authors' conclusion "that the zonally-averaged planetary wave approach cannot explain all stratospheric variability" (l. 359) would be somewhat misleading.

Rather, the same picture could be described from different angles.
Nevertheless, I acknowledge that this is speculative, and I genuinely appreciate the authors's efforts and explanations. All my other comments have been satisfactorily addressed. Therefore, I am happy to recommend the manuscript for publication in its current form, leaving my thoughts as potential avenues for future investigations.

We agree that line 359 might be slightly misleading and therefore added additional explanation (cf. ll. 367-368).

Reviewer 2

Comments to the Authors
I would like to thank the authors for careful consideration of my comments and the comments of two other reviewers. I think that the revised manuscript clarifies points where I was was not fully convinced and I appreciate the authors testing some suggestions I made. I think that using the Eliassen-Palm flux benefited the study and made the results more robust. I therefore only have minute comments/typo corrections left, after which I see the manuscript ready to be published.

We kindly thank Reviewer 2 for the positive feedback on our revised manuscript and for pointing out some minute issues.

Minor comments
L104 maybe 'EP flux at 100 hPa'?

Thank you pointing out this mistake. We changed this throughout the manuscript.

L139 '..the qualitative agreement between ICON and ERA5 is given.' I am not sure that I understand the word 'given' in this context: given where? If you refer to some figures, please, provide the figure numbers, or, maybe, you mean 'is shown'/'can be seen (Figure xx)'/etc.?

We changed the word "given" to "shown" and added the reference to the figure (cf. l. 139).

L379 Appendix: 'amplittudes'

This was also corrected (l. 387).

Reviewer 3

This is my second review of this paper. My initial criticisms were that the paper didn't adequately discuss the previous relevant literature, and that if this previous literature were taken into consideration, the present paper makes mostly incremental progress. The paper is somewhat improved on both respects, however there is still much work to be done.

Several of the key results and figures are essentially updates of Garfinkel et al 2010 (already

cited). This includes the regression whereby the Aleutian low and Ural high are both used to predict vortex strength (termed the precursor index in the current paper), and also analyzing the wavenumber-decomposed EP flux associated with anomalies in the Aleutian Low and Ural high. As best as I can tell the results are in agreement with this previous work.

There is an improvement in the current draft in the discussion section, however this reviewer still thinks that too much time and attention is devoted to repeating analyses rather than focusing on the open questions still outstanding.

> **We want to thank Reviewer 3 for the feedback on our revised manuscript. The authors agree with R3 that the results are in good agreement with Garfinkel et al. (2010). We further highlight this in the revised manuscript (cf. ll. 358-359). However, we also want to point out that our study strongly focusses on the involved timescales without using fixed lead-lag times. This allows for more precisely determining the involved time scales in days for each step in the chain from surface anomaly -> vertical wave flux anomaly -> stratospheric NAM anomaly -> downward influence on troposphere. Additionally, we investigate the involved mechanisms for individual winter months and discuss differences between early and late winter (e.g., ll. 221-225). The innovative approach in Figures 7 and 8 enables a disentanglement of the coupling mechanisms for the Ural and Aleutian region, which nicely adds to the explanation using wavenumber theory. We furthermore want to point out, that these mechanisms have so far not been analysed with the ICON model. As this unified next-generation global numerical weather prediction and climate modelling system is envisaged for seasonal predictions in coming years, we want to stress the importance of investigating these coupling mechanisms in ICON.**

minor comments:

line 97 climatological -> planetary [climatological amplitudes are not modified by anomalies in the Aleutian low or Ural high region]

> **Thank you for pointing this out. This was corrected (cf. l. 97).**

figure 1 implies that the Aleutian low is not significantly correlated to the vortex strength, however the rest of the figures do suggest that there is a significant relationship.

> **This is related to the different methods. Fig. 1 is an introductory figure and based on a simple composite using the monthly mean NAM@10hPa to select years with a weak vortex in January (20th percentile), leading to only 9 events in ERA5. This small sample size in combination with the monthly averaging is connected to the difference in significance. The more sophisticated approach of Fig. 2 uses daily mean MSLP and NAM values for a regression. Also, for the ICON ensemble (40 events) we see a clear significant signal in the Aleutian region in Figure 1. Thus, hinting that the ensemble size in ERA5 might be too small. Additionally, we would like to point out, that small regions in Fig. 1 c) are statistically significant at the 95% level, i.e., in the Gulf of Alaska and towards the Kamchatka Peninsula.**

figure 4 and accompanying discussion: Please compare to Polvani and Waugh 2004

> **Thank you for pointing out this study. We now also compare our results to the results of Polvani and Waugh (2004) (cf. ll. 225-229)**