Response to comment by Referee #1: Nili Harnik

Review of revised version of "Dynamics of stratospheric wave reflection over the North Pacific" by Schutte et al.

The authors have addressed many of my comments and the paper reads tighter and the motivation is clearer now. However, there are a few points that are still unclear, and in some ways misleading, that should be improved before publication.

We would like to thank you for your detailed and thoughtful review. We greatly appreciate the time and effort you have invested in providing constructive feedback. Below, we copied your comments in *italic* **and address your comments point by point in bold blue.**

Main points:

1) The emphasis on the role of the stratosphere in the introduction and abstract is a bit misleading. The focus of the analysis is on understanding the tropospheric and lower stratospheric evolution of the positive-negative heat flux dipole.

The abstract refers to negative v'T' events as Stratospheric Wave Reflection events which "involve the upward propagation of planetary waves, which are subsequently reflected downward by the stratospheric polar vortex." (1st sentence of the abstract).

The first few paragraphs of the introduction discuss a downward effect of the stratosphere on the troposphere, specifically, via downward wave reflection, and including how to diagnose downward reflection events. I am not sure, however, that the negative v'T' events discussed here are classical downward reflection events in the sense of an upward wave pulse propagating to the stratosphere, then reflecting back down from a reflecting surface. At least, the data shown does not necessarily support this. Rather, it shows that the combination of a stratospheric wave 1 and a westward propagating tropospheric medium scale wave packet which is also developing downstream, combine to give a dynamical evolution of upward wave activity flux over Siberia and downward over Canada.

In addition some of the results do not fit this chain of events - for example the sentence on lines 281-282 : "The overall Rossby wave activity mostly remains close to its climatological average and only increases in the stratosphere after the end of reflection events (Fig. 6 b)." I would expect the wave activity to increase in the stratosphere before reflection events, and to increase in the troposphere after the waves are reflected downwards, if the scenario assumed a priori in the introduction is true. Rather, this result (though see comment on figure 6 below) maybe supports the notion that the negative v'T' is due to a superposition of stratospheric and tropospheric waves which have different sources and phase speeds.

The only suggestion for a classical evolution of upward propagation to the stratosphere followed by a downward propagation downstream is found, to my mind, in figure A8 which shows the stratospheric phase tilt changes from westward with height to vertical with height.

Reflection events, as defined in our study via meridional eddy heat flux anomalies over Siberia and North Canada, have been strongly connected to stratospheric dynamics in earlier work (e.g., Matthias and Kretschmer, 2020; Messori et al., 2022; Millin et al., 2022). While the events are defined at 100 hPa, the dynamics of the stratospheric polar vortex at higher levels play a crucial role in enabling reflection, for example by creating a vertical reflective surface, which is also present during the events defined via the reflective index (Fig. 2 and its discussion in Messori et al., 2022). Simultaneously, the lower stratosphere remains essential for diagnosing upward and downward propagating Rossby waves using our reflective index. Unlike indices that solely diagnose anomalous downward wave activity flux, the reflective index used here captures both upward and downward wave flux (Matthias and Kretschmer, 2020).

As you noted, Figure A8 provides evidence of the stratospheric phase tilt transitioning from westward to vertical with height, which is characteristic for downward wave reflection. Our analysis also suggests that the stratospheric wave-1 anomaly acts as a mediator, while the smaller-scale waves (e.g., wave-3 and 4) from the troposphere are reflected. The role of wave-1 aligns with the concept of vortex stretching, as discussed in Cohen et al. (2022). This connection between wave-1 and wave-3 and 4 highlights the role of the stratosphere in organizing and reflecting waves back to the troposphere, supporting our interpretation of these events as stratospheric downward wave reflection. Nevertheless, we will acknowledge in lines 381-385 in the discussion that the observed structure in v'T' anomalies potentially arises from the superposition of stratospheric and tropospheric waves.

Regarding the comment on lines 281–282, we would like to thank you for spotting this inconsistency. We agree that Rossby wave activity increases in the stratosphere before the onset and in the troposphere during reflection events, which is apparent in Fig. 6b, as well. We will adjust the description in lines 281-282 accordingly. Nevertheless, it is important to differentiate between the overall Rossby wave activity and the subset of waves actively undergoing reflection. Waves that are reflected downward may not significantly increase overall stratospheric wave activity because they might be only a small fraction of the entire wave spectrum and potentially don't remain in the stratosphere long enough to be pronounced or accumulate there. Instead, these waves return to the troposphere, contributing to surface anomalies rather than persistent stratospheric signals. This contrasts with the period around the end of reflection events, where the blocking signal of the AKR regime results in enhanced wave activity and waves might remain longer in the stratosphere, possibly breaking or dissipating instead of being reflected downwards.

We appreciate your observations and adjust the discussion of Figure 6 also with respect to later comments.

2) The discussion of the validity of the spectral diagnostics (lines 304-313) is convincing to some level but not for all the points it is used for. Specifically, it is not convincing enough to justify using it for figure 6.

More explicitly:

Line 145 refers to figures 5 and A2 but these figures do not really show the diagnostic is able to capture daily time scale variations. On the other hand, figure 3 shows the Hovmöller diagram alongside ISP_west, and it does seem like ISP captures the temporal evolution of phase speed, though maybe the change from stationary to westward phase speed is sharper in the Hovmöller diagram than in ISP. Figure 7 also makes such a comparison, and the spectral diagnostic captures the broad features but maybe not as nicely as in figure 3.

A better test maybe would be to look at specific events and compare the time evolving spectral diagnostics with a corresponding Hovmöller diagram (which is not a composite), and show that these match for a few events.

- Figure 6: I find the use of the diagnostic potentially problematic for this figure, especially conclusions about detailed daily-timescale evolution, c.f. comments like that made on line 297: "and in the stratosphere a few days later". I am not convinced the temporal resolution is good enough. Moreover, as fig A7 clearly shows, that stratosphere is dominated by smaller zonal wavenumbers than the troposphere, meaning that the significant ISP_west enhancement is occurring for larger frequencies in the troposphere than the stratosphere. Can't this, by itself, lead to differences in the timing of statistical significance of the signal?

I expect the spectral diagnostics can only point out changes on coarser time scales, thus it is more convincing to use for onset - end comparison plots like figure 5, given that the phase propagation lasts for quite a few days, as does the stationarity of the anomalies during the first part of the events.

Thank you for pointing out the need to clarify our comparison. In line 145, we intended to compare the spectral characteristics shown in Figure 5a–c with the behavior of specific waves depicted in Figure A2. Specifically, the large-scale waves exhibit distinct differences in behavior between the onset and end of reflection events, as highlighted in the harmonics of large-scale waves in Figure 5a–c. We will highlight that these figures complement each other, with Figure A2 providing additional insights into wave propagation during the onset and end. Following your suggestion, we will also refer to Figures 3 and 7, which show that the spectral diagnostics broadly capture the temporal evolution of phase speed. Instead of discussing this relation in further detail in section 2.3., we decided to elaborate on it at the end of section 3.1.3.

We acknowledge the concern regarding the ability of the diagnostic to capture daily timescale variations. Thus, we computed a Hovmöller diagram for one specific reflection event (Fig. R1). While interpreting daily changes in spectral diagnostics may have some limitations, the agreement between the Hovmöller diagrams and ISP_west supports our conclusion that the space-time spectra can capture meaningful changes in Rossby wave behavior, even on shorter timescales.

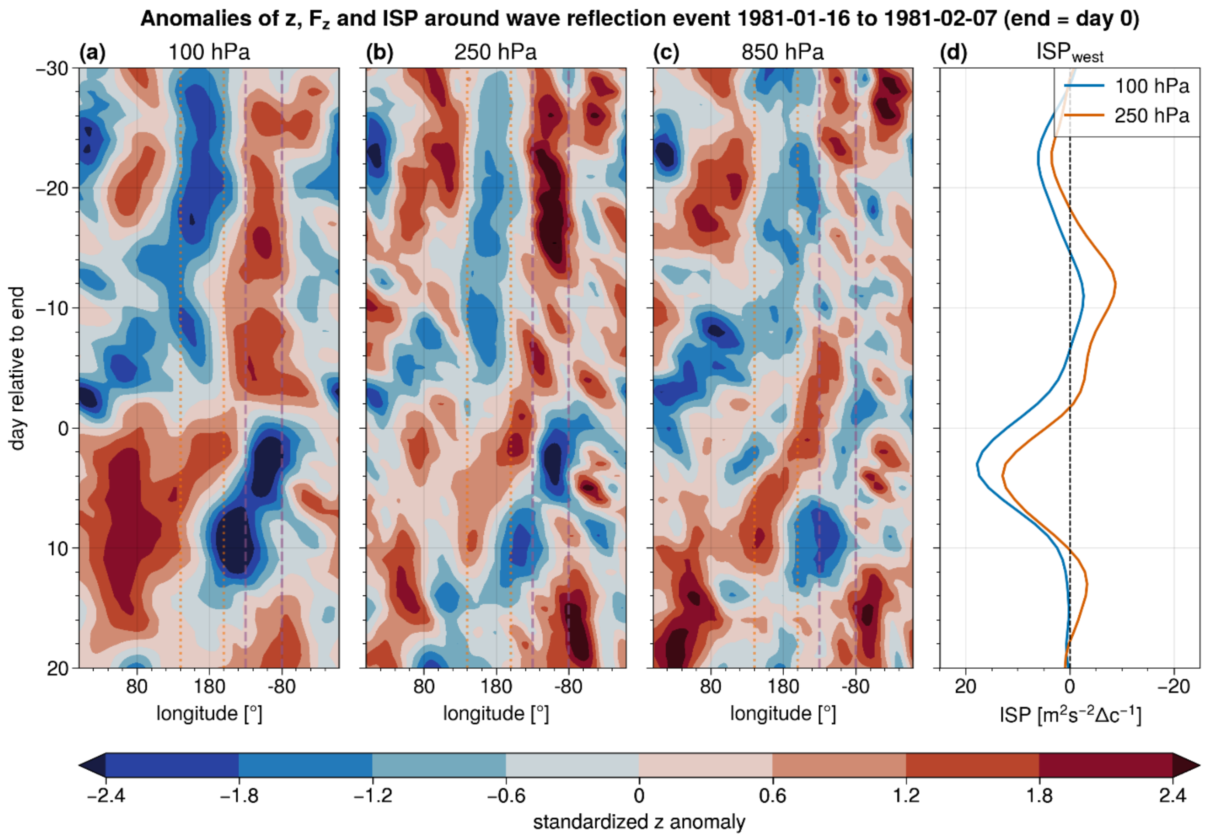

Figure R1. Hovmöller diagram of standardized anomalies of geopotential height averaged between 45◦N - 75◦N centred around the end date of one reflection event at (a) 100 hPa, (b) 250 hPa and (c) 850 hPa in shading. (d) Time series of ISP for westward-propagating Rossby waves at 100 hPa and 250 hPa with the x-axis being flipped, so that enhanced activity of westward-propagating Rossby waves lies to the left of the zero line. The vertical lines mark longitudes of the Siberian (orange, dotted) and Canadian (purple, dashed) domains.

We appreciate your observation regarding the temporal resolution and the potential influence of different wave frequencies between the troposphere and stratosphere. While the spectral diagnostics shown in Figure 6 may not fully support detailed daily-timescale conclusions, their ability to capture the broader temporal evolution of wave activity remains robust. We will adjust the statement on line 295-297 to reflect a more cautious interpretation to: "Additionally, westward-propagating Rossby waves become more active in the troposphere and stratosphere around 1 week before the end of reflection events. This matches temporally with …" Furthermore, we will adjust the discussion on lines 284-285.

Minor comments

line 188 - how do you deduce Rossby wave breaking from the figures?

We did not directly deduce Rossby wave breaking from the figures, but rather speculate on a potential mechanism that could decrease the downward pulse. Specifically, it is possible that upward-propagating Rossby waves may either break or become absorbed after some time, instead of being reflected. This mechanism could potentially contribute to the end of reflection events, and we will clarify this distinction in the manuscript.

line 251 - I would check references by Randel and co-authors from the 1980s which studies medium scale waves in the southern hemisphere for a tropospheric example which is maybe more relevant to the case studies here. Specifically, there is: Randel, W. J., and J. L. Stanford, 1985: An Observational Study of Medium-Scale Wave Dynamics in the Southern Hemisphere Summer. Part II: Stationary-Transient Wave Interference. J. Atmos. Sci., 42, 1189–1197, https://doi.org/10.1175/1520-0469(1985)0422.0.CO;2.

Thank you for suggesting the reference by Randel and Stanford (1985), which is a relevant addition. We will include it in line 251.

Figure 4- hard to see the green contours

Thank you for pointing this out. We will increase the size of the green contours for better clarity (see example in Figure R2). This adjustment will be applied to Figures 4, A6, and A17.

line 268- the reference to waves 2-5 in figure 5c is confusing because there changes in these wavenumbers are not statistically significant.

While the reduction of spectral power in wavenumbers 2-5 is not statistically significant according to our relatively strict testing procedure, which accounts for the false discovery rate, we believe it is still worth mentioning this well-pronounced tendency. We will clarify in the text that this part of the signal is not statistically significant.

There are too many appendix figures - it is hard to follow the paper when the reader is referred to these figures so much. This impression is strengthened by the fact that the appendix figures are not referred to in the order of appearance. specifically, Fig A9, A16, A17 appear earlier than the reference to figures before them.

We will reorganize the appendix figures to ensure they are referred to in the order of appearance, by switching positions of Fig. A9 and A8 and by placing Fig. A16 and A17 in the correct position. While the appendix contains a large number of figures, many were included in response to reviewer comments to provide additional clarity and support for the analysis. To

support our methodology and analysis, we would like to keep the appendix figures available for future readers.

Line 281: the following statement -" and only increases in the stratosphere after the end of reflection events (Fig. 6 b)." I am puzzled by this- I would expect the wave activity to increase in the stratosphere before reflection events, and to increase in the troposphere after the waves are reflected downwards. This maybe supports the notion that the negative v'T' is due to a superposition of stratospheric and tropospheric waves and not wave activity actually going down from the stratosphere to the troposphere... see major comment 1.

If waves are reflected back downward, it is possible that we do not observe anomalously high Rossby wave activity in the stratosphere because the waves do not remain there long enough. In contrast, after the end of reflection events, waves may instead propagate through a greater depth of the stratosphere, leading to the observed increase in wave activity. Additionally, reflection events are associated with higher wave activity near the surface about one week before their end, which coincides with decreasing surface temperatures over North America. We have also addressed similar concerns in response to the first major comment in more detail.

Figure 6, The discussion of this figure on lines 291-295 is confusing. Lines 291-295 took several re-reads for me to figure out what the authors are trying to say, specifically due to some of the implied causality words (can be understood by, a result of). Are you implying that the westward phase propagation in the lower stratosphere upper troposphere is consistent with the stratospheric waves vertical phase tilt changing from a westward to a vertical one (as is expected in downward wave reflection), with the phase of the wave not changing too much at 10mb?

Thank you for pointing this out. We apologize for the lack of clarity in our discussion. We appreciate your careful reading and will rewrite these sentences to: “The westward propagation of large-scale anomalies in the lower stratosphere and upper troposphere coincides with a shift of Rossby wave phase lines, that typically tilt westward with height, to a more vertical orientation over the North Pacific during stratospheric wave reflection (Fig. A7). This change in vertical phase tilt is consistent with a more pronounced enhancement of eastward phase speeds at higher stratospheric levels compared to those below (Fig. 6 a).” This way, the discussion should better convey that the westward phase propagation in the lower stratosphere and upper troposphere aligns with the stratospheric wave's vertical phase tilt changing from westward to vertical, as expected during downward wave reflection. In Figure A8, one can also see that the phase of the wave doesn't change too much at 10 hPa during reflection events.

In addition, the total ISP subplot (6b) does not seem to match the eastward and westward ISP plots 6c and 6d, especially at positive time lags - shouldn't it be some sort of sum of the two? At the same time, I am not sure how the information in figure 6 adds to the discussion, thus I would consider dropping this analysis altogether.

We would argue that Figure 6b aligns reasonably well with the average of 6c and 6d, particularly when considering that ISP_east typically has more weight due to the climatological prevalence of eastward-propagating Rossby waves. Since this figure displays the temporal evolution of spectral metrics and provides an overview of their vertical structure, we would like to keep Figure 6 in the manuscript to complement the results from Figure 5.

Section 3.2

- I think a plot like figures 4 or A17 for the PT-AKR transition would be useful to see.

The overview of PT-AKR transition in form of a plot like Figure 4 also highlights the similarity between reflection events and the regime transition (Fig. R2). To avoid adding additional

appendix figures, we believe Fig R2 does not add substantial additional information beyond that contained in the Hovmöller plots (e.g., Fig. 7).

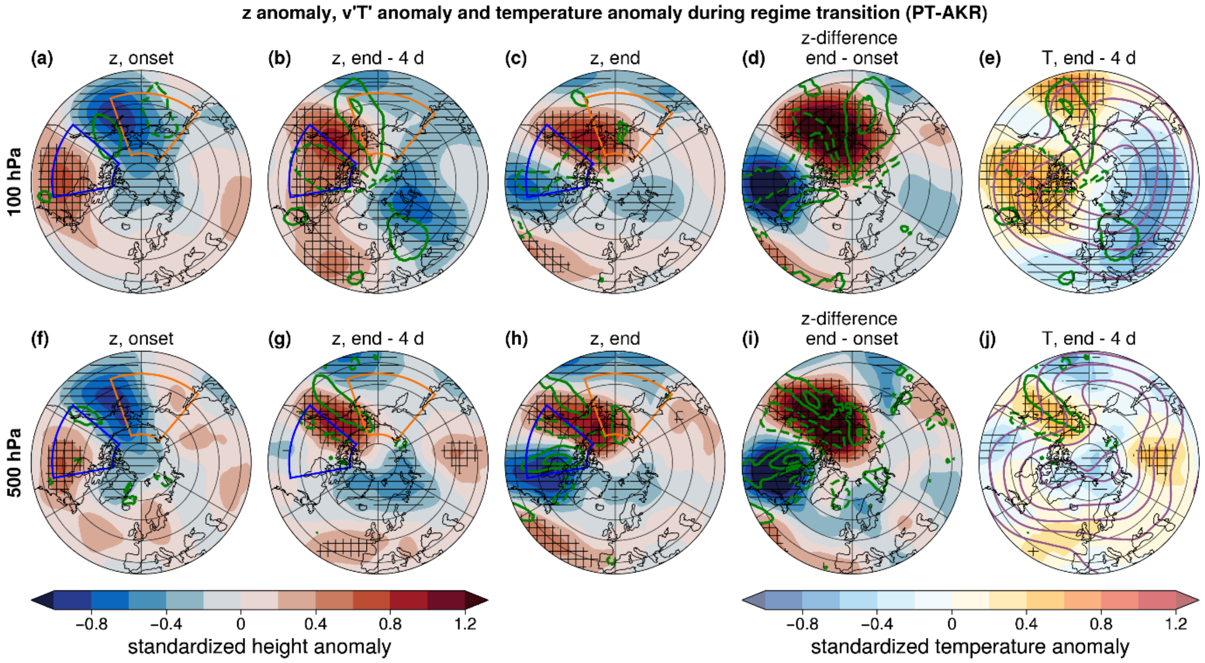

Figure R2. *Geopotential height anomalies in shading and v'T' anomalies in green contours (a, f) during onset, (b, g) 4 days before end, (c, h) at the end date and (d, i) difference between onset and end of PT-AKR regime transition events at 100 hPa (first row) and 500 hPa (second row).The central date of PT is denoted as onset and the central date of AKR as end of the regime transition events. Horizontal hatching marks significant negative geopotential height anomalies and cross-hatching significant positive anomalies. (e, j) Temperature anomalies in shading, geopotential height field in purple and v'T' anomalies in green 4 days before end.*

Lines 342-343 - discussion of figures A11-A12 refers only to differences in the stratosphere, but I would say that also the tropospheric evolutions are different- there is essentially no westward phase speed for the regime transitions in these figures outside of reflection events (A12), and only a very weak westward phase propagation for those with a reflection event (A11).

We agree that there are also some differences between reflective and non-reflective regime transitions in the tropospheric evolutions, specifically with respect to the phase speed, but the most pronounced differences are found in the stratosphere. This is connected to weather regimes being defined on the tropospheric level of 500 hPa, and expanding on the tropospheric differences here would go beyond the scope of the discussion in lines 342-343, which we have therefore decided not to extend. While the PT-AKR regime shift outside of reflection events could be more related to the superposition and interference of waves, it is likely, that we observe the weak westward-propagation during reflection events due to the additional influence of the stratosphere. Nevertheless, there is also a weak tendency of the ridge to propagate westward outside of reflection events at 250 hPa (Fig. A12).

Sentence starting at the end of line 343, to 345: I am confused. I assume the authors mean to point out the small region of significant difference in the region of 250mb waves 3-4 phase speeds that protrudes into the contoured region of phase space that dominates climatology in figure A14 which does not appear in A13? I would state this reference to A13 vs A14 explicitly, but this is contrary to what A11 vs A12 show for the 250mb level...

Yes, we are referring to the small region of significant difference for westward-propagating waves 3 and 4, as seen in Figure A14 f. Even though this signal is non-significant for regimes

during reflection events in Figure A13 f, the tendency is still evident for PT-AKR regime transitions during and outside of reflection events. Therefore, we attribute this part of the anomalies in the Rossby wave spectra during reflection events to the PT-to-AKR weather regime shift. Despite the more stationary setup outside of reflection events, we can still observe the tendency of the ridge to propagate westward (Fig. A12 b). The westward propagation is even more pronounced for PT-AKR regime transitions during reflection events (albeit being still slow in Fig. A11), which is also reflected in the higher amplitude of anomalies for westward-propagating waves-3 and 4 (Fig. A13 f). Even though these anomalies are not significant, the signal is also represented in the respective Hovmöller diagram (Fig. A11 b).

Discussion

The reasoning in the two sentences on lines 381-385 is not clear. Specifically, the way this sentence is phrased implies that the westward propagation results from downward reflection. However, it is possible that the westward propagation results from internal tropospheric free Rossby wave dynamics, and its superposition with stratospheric stationary waves could give a signature of downward reflection.

We agree that the phrasing is misleading and could imply that the westward propagation is solely a result of downward reflection. We will rephrase the sentences to clarify that the westward propagation could also arise from internal tropospheric free Rossby wave dynamics, with its interaction and superposition with stratospheric stationary waves contributing to the observed signature. They read now: “The westward propagation of medium-scale Rossby waves in the upper troposphere could be linked to internal tropospheric free Rossby wave dynamics. Their interaction and superposition with planetary-scale waves from the stratosphere may contribute to the observed signature of downward reflection. Indeed, we observe the enhancement of westward-propagating wave-1 during stratospheric wave reflection events, which suggests that the evolution of v'T' anomalies may be influenced by this coupling between stratospheric and tropospheric waves.”

I think maybe a schematic might help summarize the results more clearly.

Thank you for the suggestion! We have created a summary figure (Figure R3) that we will include in the manuscript.

Appendix figures:

Figure A7 - *Title should be changed* - *this is not an evolution, rather a longitude height section breakup to different wavenumbers.*

Thank you for pointing out this mistake. We will correct the title.

Figure A18 - *I don't find the signal strong enough to be convincing. The variability is so much stronger…*

We agree that there is a large variability in 100 hPa zonal wind, but there is also large variability at upper-level levels (Figure A5 in Messori et al., 2022). Thus, there are probably some cases, where wave breaking and the subsequent vortex deceleration occurs, but there is likely also a large number of cases, where other dynamics dominate the behavior of the stratospheric polar vortex, and we don’t see the slow-down of 100 hPa zonal wind. As mentioned in lines 388 -390, this is just one potential mechanism.

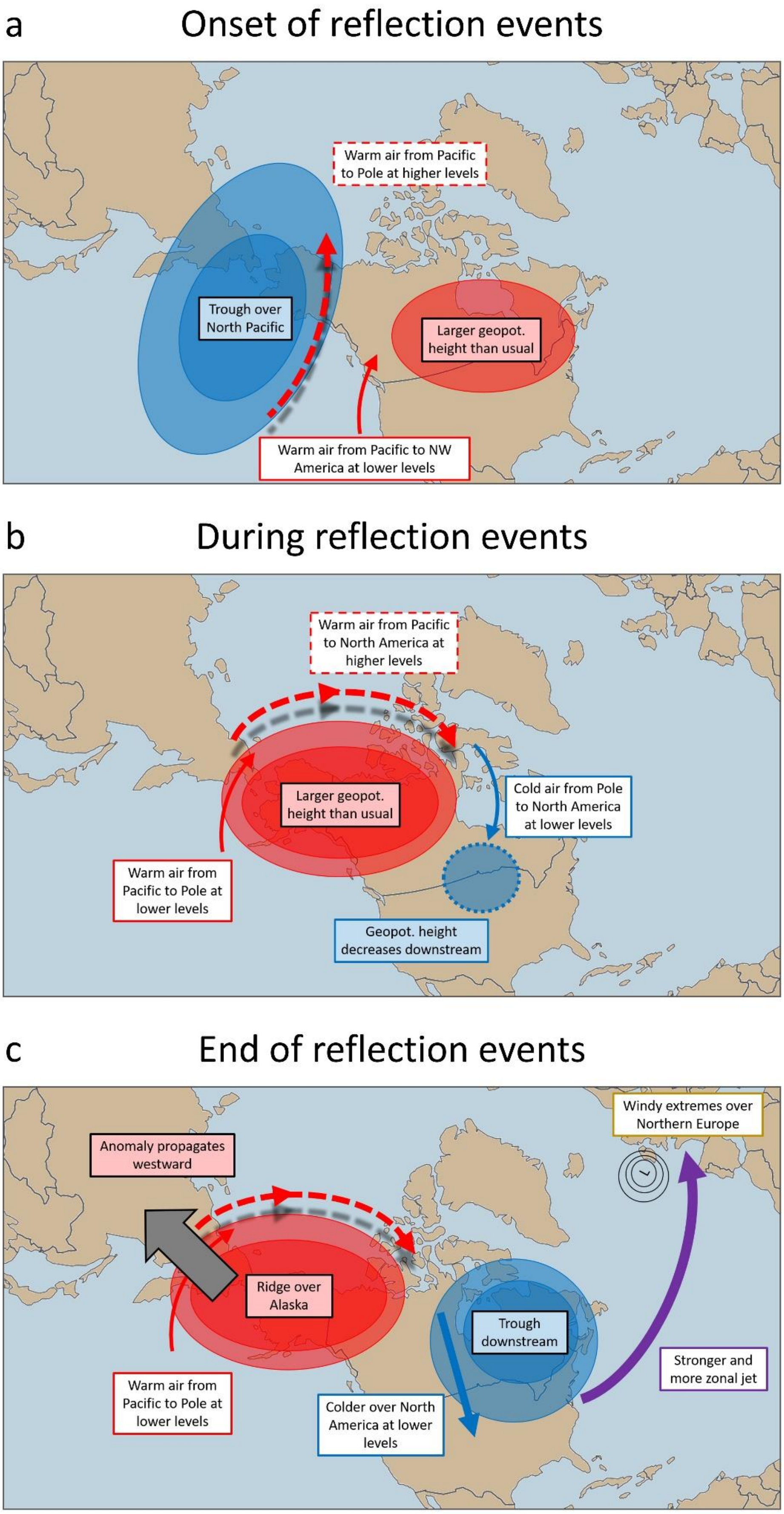

Figure R3. *Summary figure of reflection events.*

References

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