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

Review by Nili Harnik

Recommendation: Major revisions

This paper examines the dynamics of North Pacific downward wave reflection events, in which the wave activity propagation is upward over the NW Pacific, zonal in the lower stratosphere and downward over E. Canada. These events have been studied in Messori et al (2022) which related them to N. American cold spells and a transition from a pacific Trough (PT) weather regime to an Alaskan Ridge (AKR) regime. In this paper the authors build upon this work and further examine the following things which Messori et al 2022 did not focus on:

The latitude-height-time evolution of meridional heat flux (alongside atmospheric temperature anomalies), Rossby wave activity and Rossby wave phase speeds based on a space-time spectral analysis, and surface wind extremes over Europe. The analysis was done with a focus on the onset and end of the Pacific reflection events. The main findings are a concentration of the heat-flux anomalies in the upper troposphere-lower stratosphere, with oppositely signed anomalies in the lower troposphere, and a clear signature of westward propagation of waves during the reflection event at all levels and for a range of zonal wavenumbers, and an increase in the occurrence of extreme wind events over Europe.

In addition, the authors also compare the heat flux and Rossby wave evolution of these events to regional geopotential height events of similar structure and compared the onset/end of reflection events to anomalies related to PT and AKR regimes, respectively. For both the regional geopotential height anomalies and PT/AKR regimes they find the above heat flux and Rossby wave anomalies, with some differences.

The results point out to interesting dynamics and the analysis raises lots of interesting questions. At the same time, the paper can be improved significantly by better motivating the specific calculations and scientific questions, in a way that can they tie the results into a more coherent story. Following are some more specific comments and some thoughts on possible ways to improve the focus of the work.

In addition the methodology needs to be explained better, and in the case of the phase speed analysis, also better justified.

Motivation:

The authors discuss various ways to detect downward reflection, specifically, the detection of localized vs global events, and discuss the importance of these events for extreme event. They then do on to state on line 53, as underlying motivation to the paper, that the physical mechanisms linking stratospheric wave reflection to the subsequent tropospheric anomalies are not completely understood. As part of their aim to develop a deeper understanding of the evolution of the flow during these events, they pose 3 questions. While the questions are answered in the paper, it is not realy clear why these are chosen, beyond the fact that the analysis done happens to answer them. The paper can be greatly imporved if some of the main dynamical questions regarding these waves are more explicitely posed, and the reasons for studying heat fluxes, Rossby wave activity, and weather regimes is explained.

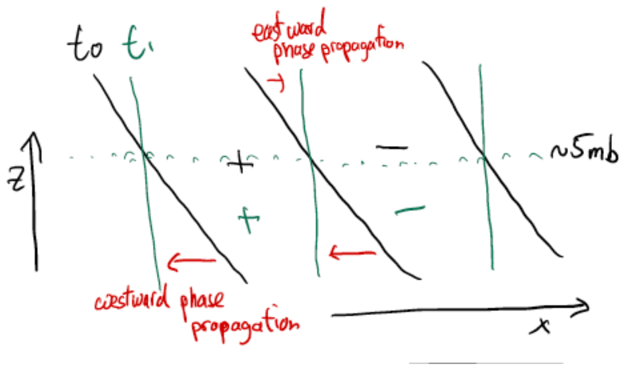
Question 1 specifically (*What is the vertical structure of the meridional eddy heat flux before, during and after reflection events?)* is not well motivated in my mind. Why did the authors choose to look at the vertical structure of heat fluxes and what do the results contribute to our understanding of these events?

The change in sign between lower and upper tropospheric heat fluxes, which accompanied the temporal change in sign, is interesting, but was not totally surprising to me because for the stratospheric case at least, it is related to the wave geopotential height (Φ) peaking in height (at the downward reflection level), e.g. Fig. 4 of Harnik and Lindzen (2001). This peak in Φ wave amplitude leads to the temperature waves having a node at the level at which Φ peaks ($T' \sim d\Phi'/dz$). This will lead to a change in sign of $v'T'$.

It seems that in this case the heat flux signature comes from the medium scale waves having such a node - this can be examined easily, and can thus give us a better understanding of where the downward reflection signal is coming from. Specifically, how much of the evolution is tropospheric vs stratospheric dynamics? Understanding this can lead to more understanding of the sources of their predictaiblity.

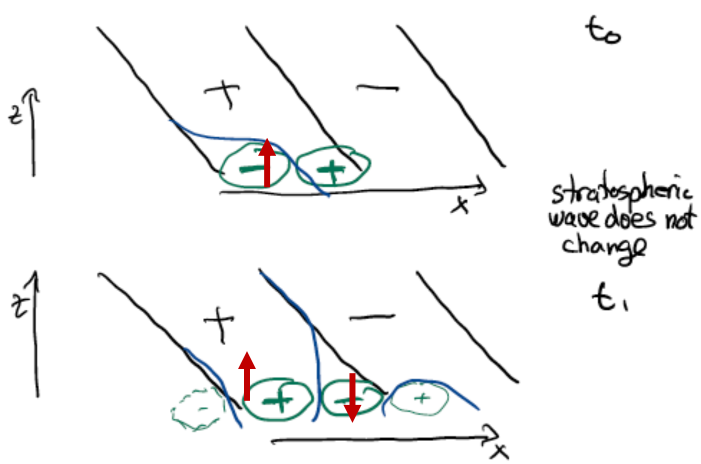
Another main result of the analysis is the westward phase speed of the waves during the downward reflection events. This again can be explained for the pure stratospheric wave reflection quite simply, but is more interesting in a way for the current case of the tropospheric waves propagating westward.

The following schematic shows how downard reflection natuarlly invovles westward phase propagation at lower levels (due to the vertical tilting of the phase lines of the wave). A westward phase speed on top and eastward on bottom is characteristic of a tilting of the climatologically westward tilted waves to a more vertical tilting



Longitude-height wave 1 geopotential height phase lines. The + is a high and - a low. The waves at t_0 (in balck) tilt westward with height, and at t_1 the tilt vertically, due to downward reflection. They stay in place at 5mb so that below, the phase lines shift westward.

I also thought of another option which can give a more tropospheric-induced donward reflection, as follows. The schematic below shows how a westward propagation of smaller scale tropospheric anomalies can lead to upward to the west - downward to the east wave propagation.



Longitude height plots of geopotential height at two timesteps.

The stratospheric waves (black) do not change. Only the tropospheric wave field (green) evolves. The total field, stratosphere plus troposphere is in blue - the red arrows are the corresponding vertical EP fluxes which are up when the phase lines tilt westward with height and down when they tilt eastward.

In this case the downward reflection occurrs due to the superposition of the waves and not due to a downward reflection of the wave 1.

Thinking of these two scenarios raises a few questions about the role of stratospheric wave 1 in these events - do these events involve both of the above scenarios or only one, or something else? See also my comments about the discussion section.

Following are some more major comments:

Methods:

The description of the analysis is partial and thus confusing:

In section 2.1 (line 77) you state that you deseasonalise all the variable except for the meridional wind. Why not the meridional wind? I assume you calculate v'T' from the full zonal anomalies before deseasonalising, and not using deseasonalized T' and non-deseasonalized v'..?

Section 2.3- the Space time Rossby wave spectra:

The deseasonalisation process is not explained clearly. Specifically, is ISP of equation 3 an anomaly or not. The right way is to calculate each of the quantities- S, ISP and Cp is using the full fields and only then calculate the anomaly from the climatological seasonal cycle. Maybe this is what is done but then please clarify in the text.

Another issue which is more fundamental is the ability of the spectral analysis to correctly resolve these relatively fast events, given that the spectra are calculated from 61 day time series (or shorted due to tapering). A possible way to check things is to compare just zonal spectra and then look at hovmoller diagrams of waves that dominate each time period to see if the results you get show similar changes of the wave phase speeds during the events.

Results:

Section 3.1.1

Figure 1 and its discussion:

As noted above, the change of sign of wave temperature anomalies, alongside no change of sign of the geopotential height, necessarily gives a change in sign of the heat fluxes, and this could be a result of the wave geopotential height structure. Have you looked at longitude-height plots of T' alongside v' or geopotential height? I think these would be very telling.

Also, regarding the negative v'T' anomaly which precedes the wave onset (fig 1a) and its corresponding positive v'T' - how much of this is due to the wave events occuring in bursts, meaning that preceding a wave event there is no heat flux, i.e. the upward flux starts after a period of "quiet", which is climatologically a negative heat flux anomaly.

Summary paragraph and specifically the statement starting on line 189: " *The oscillation of v'T' anomalies in the Siberian and Canadian domain originates from the westward propagation of negative v'T' anomalies"*

I assume this pertains to figure 2a. I find it hard to physically understand the propagation of v'T' anomalies, because it depends on two fields with a complex vertical structure (temperature). Specifically, a small change in the morphology of the plotted fields can change the appearance of the anomalies from a westward propagation to a simple standing oscillation, as in Figure A2a which shows temperature. Is this westward propagation meaningful in terms of a westward modal propagation? It could be resulting from a wave vertical structure change, rather than a modal propagation. Such questions can also motivate the space-time spectral analysis.

I think it will help to understand the phase propagation in terms of the wave geopotential height field evolution. The authors should consider switching the order of sections 3.1.1 and 3.1.2 - start with geopotential height anomaly evolution, and then examine how it manisfests in terms of v'T'.

Section 3.1.2:

Line 215 - figure 3d -

Repeating my comment from above: Is the ISP diagnostic able to capture the temporal evolution well given that it is based on spectra that are calculated from 61 day time series (or shorted due to tapering)? A possible way to check things is to compare just zonal spectra and then look at composites of the temporal changes of wave activity summed over the wavenumbers only.

Section 3.1.3

Here as well- the use of the spectral diagnostic for this specific problem needs more justification, specifically for figure 6 which shows a temporal evolution over a period which is of the same length as the date used for each of the phase speed calculations.

Here too, a zonal Fourier analysis can help - you can find the zonal wavenumbers which dominate each stage, and then look at the composited Hovmoller diagrams filtered only for the dominant zonal wavenumbers to see if the waves change their phase speed and how.

Also, anomalies in Cp shown in figures 5-6 do not necessarily indicate a westward propagation of the waves - a decrease in Cp can be due to specific zonal wavenumbers slowing down or propagating westward, but also to a weakening of the faster waves during a specific time period. How much do "background" synoptic waves affect the results of these figures?

Section 3.2:

The reference to the regimes and their transition in the context of the tropospheric waves westward propagation is interesting, and could be emphasized more in terms of the overall picture the authors have of what is going on. A more explicit motivation for this will improve the paper.

The lack of wave 1 dominance in the regime plots suggests maybe that wave 1 westward propagation is not crucial for the downward reflection signal to occur?

Discussion:

By better motivating the research questions, the discussion can be more focused. I am not sure how, but here is a possible flow of summarizing the results:

- The Pacific downward reflection events involve tropospheric medium scale waves, alongside planetary scale waves which dominate in the stratosphere.

- The tropospheric waves propagate westward during the events and also evolve downstream (is there also a clear westward propagation of the stratospheric wave 1?)

- This co-evolution leads to a specific evolution of heat fluxes.

- Given this picture, what is the role of the tropospheric wave evolution relative to the stratospheric wave evolution? Is it the downward reflection of stratospheric waves which causes the tropospheric waves to retrograde, or is it the westward propagation of the tropospheric waves which leads to a pattern of wave reflection? Is reflection from the stratosphere a contributing factor, or is it crucial for the occurrence of the wave reflection events defined by the regional 100mb v'T'?

Understanding the involvement of the stratosphere has implications for influences over Europe, and predictability.

Rereading the discussion, all of this is sort of mentioned but it does not come across as a coherent story, with one or two focusing questions.

Minor comments:

Lines 38-39- the reference to the wave reflection diagnostics of Harnik, Perlwitz, Shaw as

" *computationally intensive and may require data that are usually not a standard output of reanalysis products or climate models" is not quite right. The SVD time-lagged correlation* *is not time-specific (though the space-time spectra are not as well) while the wave geometry calculation takes a few seconds on a simple laptop, but it requires a linear stationary wave model which most people don't have, and can give quite messy results which are hard to interpret especially for the troposphere.*

line 85- remove the word "daily" - it sounds like you remove the daily mean for each day..

line 86 - change "as indicated by asterisks" to "which we denote by an asterisk"

line 103-105- definition of the regional signal. Why did you choose 100hPa?

Have you tried projecting on other levels, specifically in the troposphere, or on a vertical-longitude (latitude averaged) or on the regional 3D structure in the upper troposphere-lower stratosphere?

line 108-109: How many of these onset high-correlation dates are followed by a highliy-correlated end date, meaning how many events do you find which correspond to the wave reflecting life cycle do these include?

line 225: the use of the term "barotropic" in this context is confusing, because barotropic dynamics strictly speaking do not involve heat fluxes. I think it is more exact to say that the tropospheric part of the wave is equivalent barotropic, which is consistent with the heat fluxes being concentrated in the upper troposphere and stratosphere rather than in mid troposphere (and with the heat fluxes changing sign in the vertical).

Figure 3d: Why is the x axis is flipped? A quick skim of the figure suggests there are less westward propagating waves during the event.. at the very least note in the caption that the axis is flipped..

Line 242: why is an enhancement of eastward propagating wave indicative of the presence of an accelerated stratospheric flow?

Line 244: what do you mean by *deceleration* of Rossby waves? Do you mean the increase in westward Rossby wave activity? If so it is confusing. The change of a stationary feature to westward propagation is actually an "acceleration"...

Line 269: why do you state that it is these wavenumbers? figure 5 seems to indicate wave 2 has strengthened just as much as 3,4 and larger wavenumbers

Figure 5: Is the y axis plotted in equal distances of 1/k? So the slope is one over the frequency, or the period, right? These plots made me try and deduce the group speeds for

each period but its too complicated. Switching the x and y axes would make it easier but this is maybe not the focus of the paper, though the authors do indicate downstream development, which is essentially an eastward group propagation (alongside westward phase propagation).

Figure 7: The significant upward region in figure 7c is different from the downward reflection events. Can you explain this upward propagation and this difference?

Lines 305-307: I think the question of the ability of the spectral analysis to represent the temporally concentrated (episodic) events, rather than spatially localized events is more of an issue, because the spatial localization will simply be manifest as a projection on a few zonal wavenumbers. It would be good to see a similar analysis focusing on time localization rather than spatial localization..

line 369: remove the word "accelerating"

Also on line 369 it is stated: "*A key result of our analysis is the accelerating westward propagation of Rossby waves during reflection events. This may be explained by the slowdown of the circulation due to Rossby wave absorption in the stratosphere.*"

I am not sure what the authors mean. I can think of two things:

1) A deceleration of the zonal mean zonal winds will cause the wave phase speed to slow down. However, the authors do not show a slowdown of the flow in the troposphere or lower stratosphere where the phase speed change is taking place (I think), even though it is an easy thing to check. Messori et al (2022) shows for these events, they are accompanied by a slowdown of zonal winds in the stratosphere, but the westward phase speed anomalies do not occur at these levels.

2) Another possible meaning has to do with the westward propagation being due to the tilting of the waves to the vertical. In this case- the slowdown of zonal mean zonal winds which Messori et al (2022) showed that occurs in the upper stratosphere, could indeed lead to downward reflection (as shown in Perlwitz and Harnik, 2003).

The authors should better state what they mean.