Editor:

Dear authors,

We do think with the referees that many aspects of your work have been clarified and that you addressed many of their concerns. However reviewer 2 has still a main concern about the impact of the trough/ridge detection methods on the results and suggests two options: 1) keeping the detection method as is but commenting more in the paper the difference with other detection methods 2) removing the climatology before detecting ridges/troughs. I think option 1) is fair and makes sense to me. Indeed, both the titles and abstract do not provide enough information about the characteristics of the method and the originality of the results. To do so, it would be important to explicitly say that you are focused on "planetary-scale Rossby waves". The keywork "planetary" never appears in the title or in the abstract so far whereas this is indeed the starting point of the detection method. Also I found particularly illustrative the choice of the words of reviewer 2 on the detection method: it mainly detects the "wobbling of planetary-scale Rossby waves". So I would recommend a more explicit title like "cold spells induced by wobbling of planetary-scale Rossby waves" or "cold spells induced by wobbling of planetary-scale atmospheric waves"

Another point that came to my mind when reading your paper (in particular the abstract and conclusions) is that the originality of the results is not clear to me or at least not properly emphasized. The fact that strong cold air advection from the pole leads to cold spells is already known but maybe this is the more systematic analysis of the Northern Hemisphere with your ridge/trough detection method that makes the results original. In other words, maybe all the previous studies were more dedicated to specific regions like the North American cold spells (Harnik et al. 2016; https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL070760 and references herein) or over Europe.

To summarize, I see two axes of improvements: (i) be more clear about the specificity of the detection method, in particular in the title/ abstract, but also when you present the method with respect to others (reviewer 2 mentioned Schemm et al., paper) (ii) be more explicit about the original aspects of the results in the abstract and conclusion.

Best regards,

Gwendal Riviere

We sincerely thank the reviewers and the editor for their valuable feedback. In response to Reviewer 2’s main concern regarding the impact of the trough/ridge detection methods on our results, we have carefully revised the manuscript to clarify the specificity of our detection approach and its distinction from other methods, such as that of Schemm et al. (2020).

In our initial submission, we used the term "planetary." However, Reviewer 2 argued that the first five zonal Fourier decompositions of the geopotential height field do not represent planetary waves at high latitudes. To acknowledge Reviewer 2's feedback, we will replace "planetary" with "large-scale."

For the paper's title, we have chosen “Cold spells induced by slow-moving and amplified large-scale ridge and trough.” This title accurately emphasizes the significance of our main findings (please see Fig. 9 in the main text), which indicate that ridges and troughs move slower and become amplified prior to the onset of cold spells.

We have revised the abstract, introduction, wave metrics, and conclusions to highlight the novelty and originality of our findings.

Updated abstract:

“Cold spells in the Northern Hemisphere mid-latitudes have been linked to Rossby waves. Yet the mechanisms by which **these large-scale** waves impact cold-spell formation remain unclear. Here we develop novel metrics to separately determine the amplitude and speed of **large-scale** ridges and troughs**, derived from the first five zonal Fourier decompositions of the geopotential height field. This approach allows us to** examine the behavior of **large-scale ridges and troughs** during winter cold spells. **These ridges and troughs mainly represent climatological features, which can be regarded as wobbling around their climatological positions due to interactions with background flow.** Our findings indicate that while ridges and troughs across the entire mid-latitudes experience significant changes during cold spells, the local ridge and trough near the cold spell's location play a major role in the development of these events. The nearest upstream ridge and downstream trough of the cold-spell region are located in a way that facilitates development of the extreme cold anomaly. This ridge and trough amplify and slow down, enhancing and prolonging southward advection of cold air from the Arctic into the cold-spell region. The slow and amplified upstream ridge and downstream trough occur several days before the region’s minimum temperature, suggesting these local wave anomalies induce cold-spell formation.”

Changes in the introduction:

Here, we aim to explore the linkage between cold spells, in particular those that are associated with the advection of cold air from the Arctic, and the amplitude and speed of **large-scale** ridges and troughs in the vicinity of cold spells. Cold spells are particularly of interest in the context of Rossby waves because these cold extremes are argued to be primarily driven by the large-scale advection of cold air from higher latitudes (Bieli et al., 2015; **Harnik et al., 2016;** Tuel and Martius, 2024; Mayer, 2025).

Changes in the “Trough and ridge speed” section:

This part: “The combination of the first five waves captures the major ridges and troughs of atmospheric waves (Z1–5; see the solid line in Fig. 3a for an example). These ridges and troughs exhibit transient behavior (Fig. 3b and c); they represent planetary waves in low latitudes and both planetary and synoptic-scale waves in high latitudes.” **Is changed to:** “The combination of the first five waves captures the large-scale ridges and troughs of atmospheric waves (Z1–5; see the solid line in Fig. 3a for an example). These ridges and troughs represent planetary waves in low latitudes and both planetary and synoptic-scale waves in high latitudes. The longitude position of these ridges and troughs at high latitudes aligns with the location of unfiltered gph data (Fig. 3a). However, in lower latitudes, the locations may not accurately represent the true positions of ridges and troughs in the unfiltered gph data. Nevertheless, since the main focus of this study is on high latitudes, where the wave structures are more accurately captured, the overall conclusions remain robust. In addition, the intention here is not to detect all ridges and troughs, but just those associated with the longest waves (Z1-5).”

This sentence: “Ridges and troughs typically form upstream of their climatological positions and decay downstream of them (Fig. 4).” **Changed to** “Ridges and troughs typically form upstream of their climatological positions, sometimes wobble around these locations for several time steps (or days), and subsequently decay downstream (Fig. 4).”

This paragraph is added to the end of the **"Trough and ridge speed"** section:

"The probabilities of climatological ridge and trough positions here differ significantly from those in Schemm et al. (2020), mainly due to differing detection methods. Schemm et al. (2020) identify ridges and troughs by comparing nearby grid points, while our method compares values across all longitudes at each latitude. Consequently, their probabilities are higher at high latitudes, where ridges and troughs are more distinct, but lower at low latitudes due to local gph flattening. Our method, however, shows larger probabilities at lower latitudes since it is defined to capture ridges and troughs at all latitudes. Additionally, the probabilities estimated by our method represent the likelihood of ridges or troughs occurring at a specific location, rather than over an area defined by exceeding a curvature threshold of the gph field as in Schemm et al. (2020); hence, the probabilities in our study are naturally much lower than those reported by Schemm et al. (2020)."

Updated conclusions:

The present study provides a comprehensive perspective on the formation of cold spells in the midlatitudes, demonstrating that increased wave amplitude and decreased speed are fundamental drivers of cold-spell development. **Here, the focus is on the role of large-scale Rossby waves in these cold spells. We utilized a novel ridge/trough tracking method that identifies large-scale ridges and troughs derived from the first five zonal Fourier decompositions of the gph field. Because our detection targets the large-scale (Z1–5) components, it primarily captures the slow wobbling of climatologically preferred ridges and troughs and may under-detect weaker, transient synoptic features, particularly at lower latitudes.**

Across all midlatitude regions, locally amplified and slowing ridges and troughs near cold spells appear important for the formation of these. Through a daily lag analysis, a cause-and-effect relationship between upper-level waves and extreme cold surface temperatures is revealed, indicating that upper-level waves are preceding cold spells and hence important for the development of these. Our findings support previous research conducted in a specific region, indicating that slow (e.g., Fragkoulidis and Wirth, 2020) and amplified (e.g., Jolly et al., 2021; Fragkoulidis and Wirth, 2020) Rossby waves contribute to cold spells in Europe. Moreover, we demonstrate the importance of ridge and trough development at each latitude within the mid-latitudes, whereas others (e.g., Fragkoulidis and Wirth, 2020) discuss daily averages of speed and amplitude over an area encompassing the cold-spell region. By focusing on latitude rather than averaging over a broader region, we determine that the slow and amplified waves are mostly in the vicinity or north of the cold spell regions.

Additionally, we discuss the importance of wave location in cold spell development, as different configurations of ridges and troughs, compared to their typical winter climatological positions, can result in a cold air advection from the north to the cold-spell region. Our findings highlight the critical importance of **large-scale** wave location **(Z1-5)**, emphasizing the need to consider potential shifts in **these** wave positions in a warming world. Such shifts could result in more frequent extreme events in certain areas, impacting local climates.

It is important to note that this research primarily focuses on the nearest ridge and trough relative to the location of cold spells. However, an upper-level anomaly can propagate both downstream and upstream (e.g., Simmons and Hoskins, 1979). Consequently, the anomaly that ultimately triggers the formation of cold spells may initially originate from a remote ridge or trough, and further investigation is required to explore each region in greater depth.

Considering the increasing frequency of heat waves, floods, and droughts due to climate change (IPCC; Seneviratne et al., 2021), there is a need to understand their dynamical drivers (Xu et al., 2024). In this context, we have developed two tools designed to identify the amplitude and speed of **large-scale** atmospheric waves, which can be utilized in future research to unravel the dynamical drivers of various types of extreme events. Furthermore, these metrics may help clarify the impact of Arctic amplification on the waviness and speed of Rossby waves. Our meridional wave amplitude metric provides a unique methodology compared to other metrics (Geen et al., 2023), as it could evaluate changes in ridge and trough independently in a warming world."

Reviewer #2

Please find my comments in the attached PDF. While I appreciate the efforts put by the authors in the revision and explain me some aspects I did not understand of the methodology, some important points of criticism that I raised in the previous review still stand open. I have reformulated them more concisely in this round of review, with the hope to improve clarity.

The authors have delivered a very thorough reply to my previous comments, further revising the manuscript to reduce misunderstandings and taking the time to explain the reasoning behind their methodological choices. These explanations have further highlighted issues with this work that had initially convinced me to propose this manuscript for rejection. However, I will give the authors a last chance to fix these standing issues in the manuscript through a revision focused on three specific points. After this final revision is addressed, I will be ready to either accept or reject the manuscript without further review. Please provide a point-by-point reply to the issues raised below.

We thank the reviewer for taking the time to read our manuscript once again and provide constructive feedback. Below, we offer a point-by-point response to your comments.

1) **The choice of limiting trough and ridge identification to the zonal wavenumbers between 1 and 5 (Z1-5) seems to result in unrealistic trough and ridge frequencies.** Considering only the first five Fourier harmonics of geopotential, without removing the time-averaged flow, leads to the systematic identification of the climatological, stationary ridges and troughs due to orography, land-sea contrast and other stationary wave forcing. Despite the reassurance of the authors that tracking is performed "across the entire hemisphere", ridge and trough tracking effectively happens only in the limited longitude sectors corresponding to those stationary waves (e.g., the Ridge over the Rockies, the troughs upstream of the two storm tracks). As visible in the genesis/decay frequency (and noticed by the other reviewer, too), the tracked features are indeed very likely to form to the west of the time-mean ridge/trough and decay right to the east of it with little chance of propagation across, e.g., a continent or an ocean basin. This is visible in the contours of Fig. 4 in the manuscript (pasted below). Furthermore, there is virtually no overlap between trough and ridge frequencies over most of the hemisphere: for instance, it looks like it is extremely uncommon to identify ridges over east Asia, or troughs over the North Atlantic --which are, on the other hand, rather common during winter and tied to, e.g., NAO+ and the Icelandic Low.

For comparison, I copy below a plot from Schemm, S., Rüdisühli, S., and Sprenger, M.: The life cycle of upper-level troughs and ridges: a novel detection method, climatologies and Lagrangian characteristics, Weather Clim. Dynam., 1, 459–479, https://doi.org/10.5194/wcd-1-459-2020, 2020. a reference (not cited yet in the manuscript) where one can also find the seasonal climatologies of (left) trough detection and (right) ridge detection frequencies for the cold season (Nov. to Mar.) in ERA-Interim reanalysis.

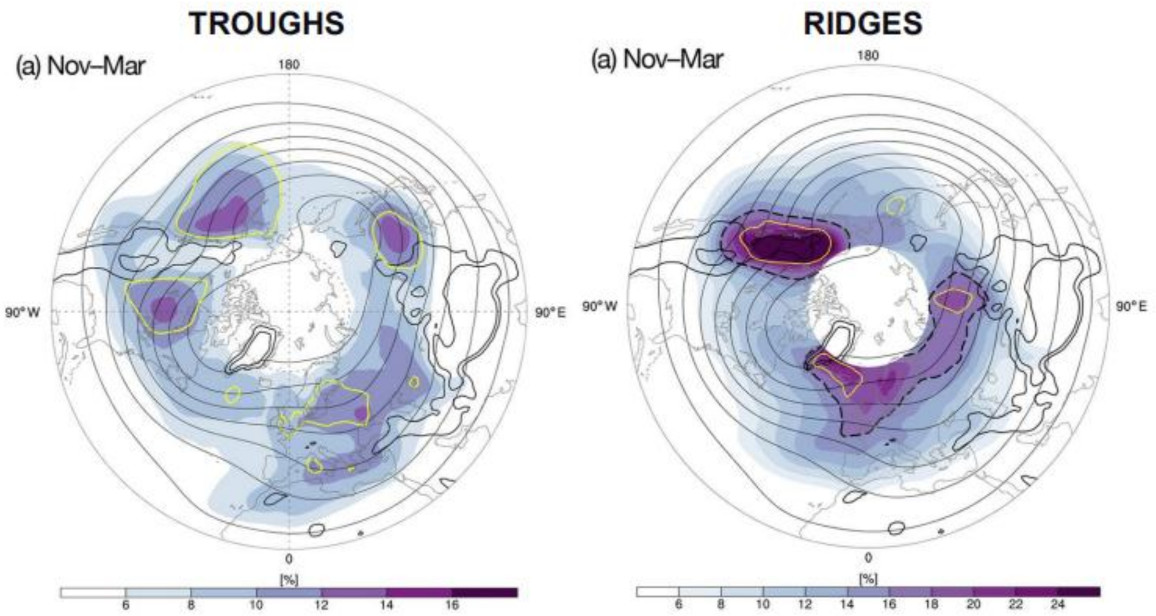

Figure 1 Probabilities of ridges and troughs as presented in Schemm et al. (2020).

In those plots by Schemm et al. (2020), troughs and ridges can be found at all longitudes. The zonal variations leading to relative minima and maxima in frequency also correspond (roughly) to the location of stationary ridges and troughs, but those relative extremes in frequency are not as sharp as in the current manuscript (with the exception maybe of the ridge over the Rockies). The presence of such defined ridge/trough regions in Fig. 4 is possibly due to a phase preference for some of the wavenumbers (1-5) involved in the filtering: for instance, assuming that the Rockies ridge projects on k=3, the k=3 would systematically projected on a ridge corresponding to the location of the Rockies and, with it, also the remaining two ridges and three troughs over the rest of the hemisphere will acquire fixed locations. Removing a zonally varying geopotential climatology could help attenuate this problem.

Thank you very much for providing the reference, which we were previously unaware of. We agree that limiting the analysis to only the first five Fourier harmonics of geopotential height may not capture all ridges and troughs, especially at low latitudes. In response, we have updated the manuscript to include a comparison of our method with that of Schemm et al. (2020) and have added a discussion on the limitations of our metric.

It is worth noting that Schemm et al. (2020) used geopotential data without removing the zonally varying climatology. The main reason for the differences between our ridge and trough occurrence probabilities (Fig. 4 in the main text) and those presented by Schemm et al. (2020) (Figure 1 in this response) may lie in the detection methodologies. Schemm et al. (2020) identify ridges and troughs by comparing grid points near these extremes, whereas our method defines ridges and troughs at each latitude by comparing values across all longitudes. As a result, their probabilities for ridges and troughs are greater at high latitudes (Figure 1 in this response), where ridges and troughs are more distinct compared to surrounding grid points. In contrast, their probabilities are lower at low latitudes due to the local flattening of geopotential height. Our method, however, shows larger probabilities at lower latitudes since it is defined to capture ridges and troughs at all latitudes. Additionally, the probabilities estimated by our method represent the likelihood of ridges or troughs occurring at a specific location, rather than over an area defined by exceeding a curvature threshold of the geopotential height field as in Schemm et al. (2020); hence, the probabilities in our study are naturally much lower than those reported by Schemm et al. (2020).

Furthermore, removing the zonally varying climatology does not necessarily improve the representation of transient ridges and troughs. In fact, this process can introduce artificial ridges and troughs, as illustrated in the schematic (Figure 2 in this response). We also reproduced Fig. 4 (in the main text) using data with the winter climatology removed (Figure 3 in this response), which supports this conclusion. Therefore, the results derived from climatology-removed data may be misleading.

Changes in the "Trough and ridge speed" section:

This part: "The combination of the first five waves captures the major ridges and troughs of atmospheric waves (Z1–5; see the solid line in Fig. 3a for an example). These ridges and troughs exhibit transient behavior (Fig. 3b and c); they represent planetary waves in low latitudes and both planetary and synoptic-scale waves in high latitudes." **Is changed to:** "The combination of the first five waves captures the large-scale ridges and troughs of atmospheric waves (Z1–5; see the solid line in Fig. 3a for an example). These ridges and troughs represent planetary waves in low latitudes and both planetary and synoptic-scale waves in high latitudes. The longitude position of these ridges and troughs at high latitudes aligns with the location of unfiltered gph data (Fig. 3a). However, in lower latitudes, the locations may not accurately represent the true positions of ridges and troughs in the unfiltered gph data. Nevertheless, since the main focus of this study is on high latitudes, where the wave structures are more accurately captured, the overall conclusions remain robust. In addition, the intention here is not to detect all ridges and troughs, but just those associated with the longest waves (Z1-5)."

This sentence: "Ridges and troughs typically form upstream of their climatological positions and decay downstream of them (Fig. 4)." **Changed to** "Ridges and troughs typically form upstream of their climatological positions, sometimes wobble around these locations for several time steps (or days), and subsequently decay downstream (Fig. 4)."

This paragraph is added to the end of the **"Trough and ridge speed"** section:

"The probabilities of climatological ridge and trough positions here differ significantly from those in Schemm et al. (2020), mainly due to differing detection methods. Schemm et al. (2020) identify ridges and troughs by comparing nearby grid points, while our method compares values across all longitudes at each latitude. Consequently, their probabilities are higher at high latitudes, where ridges and troughs are more distinct, but lower at low latitudes due to local gph flattening. Our method, however, shows larger probabilities at lower latitudes since it is defined to capture ridges and troughs at all latitudes. Additionally, the probabilities estimated by our method represent the likelihood of ridges or troughs occurring at a specific location, rather than over an area defined by exceeding a curvature threshold of the gph field as in Schemm et al. (2020); hence, the probabilities in our study are naturally much lower than those reported by Schemm et al. (2020)."

Added to the conclusions:

"Here, the focus is on the role of large-scale Rossby waves in these cold spells. We utilized a novel ridge/trough tracking method that identifies large-scale ridges and troughs derived from the first five zonal Fourier decompositions of the gph field. Because our detection targets the large-scale (Z1–5) components, it primarily captures the slow wobbling of climatologically preferred ridges and troughs and may under-detect weaker, transient synoptic features, particularly at lower latitudes."

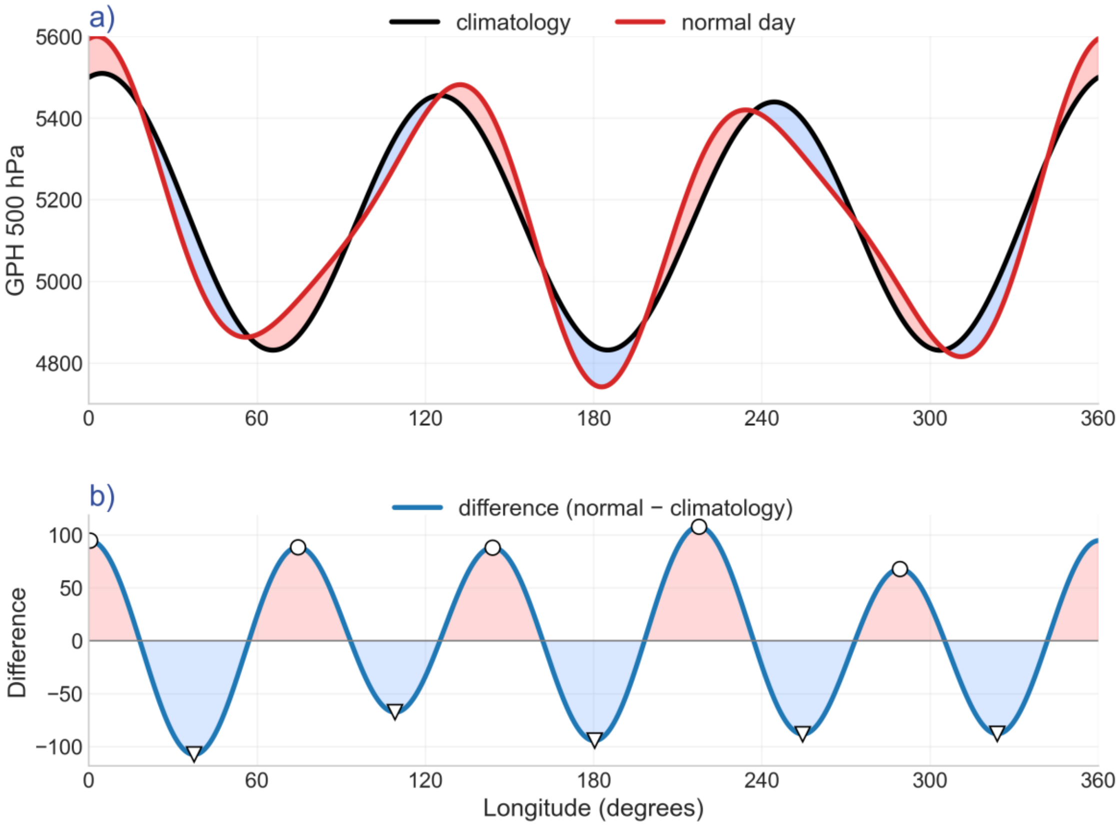

Figure 2 A schematic showing a) the geopotential height for a normal day and climatology at 500 hPa and b) the difference between the normal day and climatology.

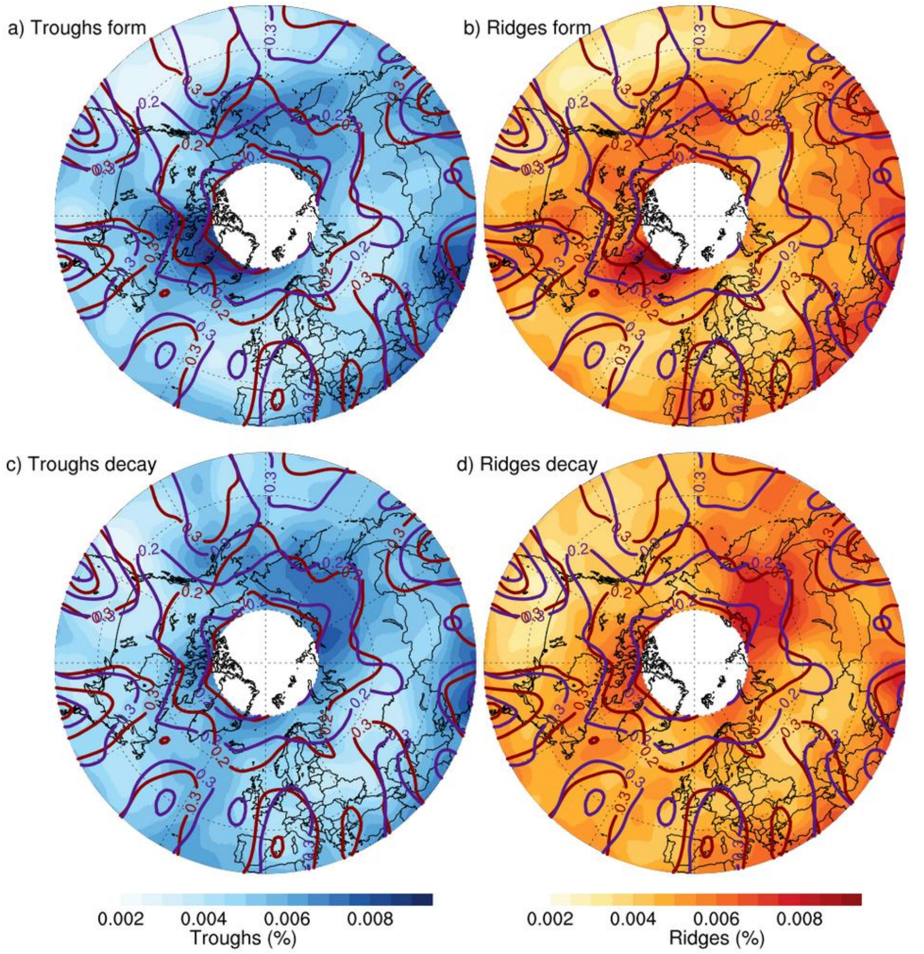

Figure 3 Same as Fig. 4 in the manuscript but using data with removed winter climatology (1981-2020).

2) Unlike what is suggested by the authors in their reply, I do not believe that "Rossby waves are stationary and have little or no transient behavior": instead, I am rather convinced that the Rossby waves identified following the methodology proposed in this study feature little or no transient behavior. The authors write in their reply that they "... tracked all ridges and troughs across the entire hemisphere and gave them a name for specific longitude sectors" and, later that they are tracking "transient troughs and ridges". This claim is true only in theory, because the presence of a climatological ridge would automatically weaken a trough eventually passing thereby, introducing a risk that the algorithm discards it more often than not. In the practice, what is being tracked is rather the "wobbling" of the same climatological ridges and troughs around their respective time-mean locations, superimposed with the passage of transient ridges and troughs (by constructive interference with the stationary wave). Climatological, supposedly stationary features can "wobble" because the flow in which they are embedded is not steady. For instance, the ridge upstream of the Rocky Mountains is generated by the interaction between the mountain chain and the background flow: as the latter changes with time, the shape of the resulting orographic wave can also be expected to change. Thus, it is well possible that a orographic wave might feature some degree of movement at synoptic time scales while still remaining anchored, of course, to the topographic feature generating it. This "wobbling" could explain the large negative displacements found in Fig. 3c, as it is quite rare to have a retrograding pattern moving westward at 3-4m/s across half of the hemisphere. **All those issues arise from the choice of performing the tracking on the Z1-5 filtered geopotential height field, obtained through a nonlocal mathematical operation like the Fourier transform.** I am also not aware of other studies who performed tracking of filtered Rossby waves at the scale of individual troughs and

ridges, and maybe there is a good reason for that. Furthermore, I am aware that the example brought by the authors their reply document (Fig. 1) would suggest a very good instantaneous match between filtered and unfiltered geopotential, and that those harmonics would represent the flow at high latitudes quite well… but the unrealistic longitudinal partition found in the climatological trough and ridge frequency keep me wondering about how the temporal evolution of the tracked feature actually looks like.

Since we are tracking the large-scale movement of the atmosphere (Z1-5), we did not expect circumglobal transient behavior. As you noted, these waves typically form upstream of their climatological positions, they may oscillate for several time steps (or days) around those positions, and ultimately decay downstream. We previously referred to this behavior as “transient,” but now we believe that terminology is misleading; instead, "wobbling," as you suggested, more accurately describes the phenomenon. We modified the “Trough and ridge speed” section and removed the reference to the transient behavior of Z1-5. Please refer to our response to your previous comment to review the changes.

Regarding “the unrealistic longitudinal partition found in the climatological trough and ridge frequency," please see our response to your previous comment.

3) The authors conclude (lines 323-327) that "Our findings highlight the critical importance of wave location, emphasizing the need to consider potential shifts in wave positions in a warming world." The sentence above only makes sense in a world where ridges and troughs, regardless of whether they are transient or stationary, can only be found in rather specific longitudinal sectors. This contradicts synoptic weather experience and previous studies. In synthesis, **the results discussed by the authors make sense in a Z1-5 world, but their applicability to the real world --where trough and ridges can be encountered across the whole hemisphere-- remains rather questionable**. This might be an issue when other regions are chosen for investigation: almost all regions chosen in Fig. 2 are located near a time-mean ridge or upstream of a time-mean trough.

Answer: Thank you for pointing this out. The sentence is revised to improve clarity regarding usage of Z1-5 data:

“Our findings highlight the critical importance of large-scale wave location (Z1-5), emphasizing the need to consider potential shifts in these wave positions in a warming world.”

From the comments above, I believe that the paper can be made acceptable only if

- the reader is informed explicitly and thoroughly of all the limitations that choosing a "Z1-5 approach" introduces on the distribution and properties of the tracked ridges and troughs, also by comparing it with pre-existing literature (e.g., Schemm et al. 2020);

We have addressed the reviewer’s concerns by thoroughly discussing all limitations introduced by the "Z1-5 approach" regarding the distribution and properties of the tracked ridges and troughs. This discussion includes a detailed comparison with Schemm et al. (2020) to provide comprehensive context. These changes ensure that the implications of our methodological choice are clear and transparent to the reader.

- or if the analysis is repeated removing a zonally varying climatology (I am aware that this might require more work, but it would help to dissipate doubts and clarify the approach; a re-submission might be indicated).

The results from removing the zonally varying climatology could potentially be flawed, as the anomalies may not represent actual positions of ridges and troughs. Please see our response to your first comment.