Review of "Cold spells induced by slow and amplified atmospheric waves" by Babaei et al.

General assessment

This concise manuscript focuses on the connection between Rossby waves and surface cold extremes, with the aim of systematically connecting such extremes with specific wave properties (i.e., amplitude, speed). To achieve this objective, a geometric method to track individual ridges and troughs is proposed and employed. The main outcome of the study emphasizes the equatorward advection of cold air by slow-moving, amplified ridges as crucial for cold spell occurrence.

First of all, I believe that the manuscript needs to be substantially revised, so that the novelty of the approach and of the results can be made more visible and assessed more properly. This can be done by:

1) extending the description of the ridge/trough tracking method, including a specific case study where, at different time steps, the wave properties and their connection with the occurrence of a cold spell are explicitly shown;

2) reworking the motivation of the study and the exposition of the results to highlight novel aspects, as the role of advection by slow-moving, amplified waves is a rather known mechanism for the occurrence of cold spells (e.g., Bieli et al. 2015; Fragkoulidis and Wirth, 2020; Roethlisberger and Papritz, 2023; Tuel and Martius, 2024, just to cite a few recent ones). In this sense, the performed analysis does not add (at least from reading the current version of the manuscript) much novel understanding.

In addition to the novelty aspect, there is some ambiguity concerning the type of Rossby waves that are analyzed in this study, as the reader is often left wondering whether stationary or transient (e.g., Rossby wave packets, RWPs) waves are being considered.

Given the conceptual and methodological unclarities, I conclude that publication in Weather and Climate Dynamics can only be granted after the resubmission of a substantially reworked manuscript: this would point to a recommendation between "Rejection" or, if the handling editor sees it fit, of "Reconsideration after major revision". More specific suggestions and requests for clarification are listed below.

We sincerely appreciate the reviewer's feedback and the detailed comments provided. We have substantially revised the manuscript to address the reviewer's concerns. The description of the developed ridge/trough tracking method is extended to include a specific case study. The entire introduction, results, and conclusion are rewritten to better address the novelty aspects of the work. The text is revised to clarify the type of Rossby waves analyzed in our study, removing ambiguity. Below, we offer a point-by-point response to each individual comment.

Major points

1. Need for a clearer explanation of the methodology, involving a real case study: If one of the aim of this paper is to introduce the novel methodology to track Rossby waves, the space dedicated to it is too short to actually appreciate its improvement with respect to other metrics. It would really help if the general explanation were to be complemented by a "real" case study, so that the approach can be actuallly understood. I would also suggest to incorporate some parts from the Supplementary Text in the main to improve the explanation. The explanation of the methodology is complicated to follow and the Fig. 1 does not help much to understand it, in particular for the part about the amplitude of the waves. A possibility would be to include a modified version of Fig. S3 as part of the panel in Fig. 1, removing the Fig. 1b. Furthermore, to better support the statement that the developed metric provides a "unique methodology compared to other metrics" (line 236), a comparison -even qualitative, but specific- with other metrics would be needed.

Thank you for your insightful feedback. We have rewritten the entire methodology to include a real case study and incorporated the Supplementary Text into the main manuscript. In the sentence that includes the “unique methodology compared to other metrics” statement, we highlighted that our metrics could evaluate changes in ridge and trough independently in a warming world. Additionally, we compared our developed metric with a modified version of the Cattiaux et al. (2016) metric. This comparison was previously located in the supplementary text, but we moved it to the main manuscript. In the revised text, we created a new section titled “Wave metrics” before the result section, which is now section 4. This section specifically addresses the speed and amplitude of the ridges and troughs.

3 Wave metrics

3.1 Trough and ridge speed

In order to investigate the role of large-scale waves, a Fourier decomposition of geopotential height (gph) is employed to separate the field into distinct harmonic waves based on the zonal wave number. The combination of the first five waves is regarded as an estimation of large-scale waves (Z1–5; solid line in Fig. 1a); these are planetary or Rossby waves (except possibly at high latitudes, where it may be argued that their wave length are too short for the categorization as Rossby waves). We estimate the speed of atmospheric wave zonal propagation by utilizing a ridge and trough tracking algorithm (Fig. 1a). Small amplitude ridges and troughs are ignored since they are often short lived (red stars in Fig. 1a). This is accomplished by considering a threshold for the gph at each local maximum (ridge) and local minimum (trough): At each time step (3-hourly) and latitude, the gph at the ridge (trough) position must be greater (less) than the gph at 30° to the west and east of the ridge (trough) position by at least 8% of the Z1–5 amplitude (see blue texts and arrows in Fig. 1a). The Z1–5 amplitude is defined as the difference between the highest ridge and the lowest trough at all longitudes around a latitude circle at each time step and latitude. These criteria were carefully chosen after multiple experiments to ensure that all large waves are tracked while minor waves are neglected. Nonetheless, in all the experiments, as long as the thresholds do not suppress large waves, the drawn overall conclusions regarding wave speed changes remain unchanged for other parameter settings. We track each local ridge and trough in time over longitudes to find the ridge and trough speed, respectively. Also, we save all local ridge latitude and longitude (RLL) and trough (TLL) positions. At each latitude, ridges and troughs are labeled according to their positions (longitude) and are tracked to the next time step by searching for the nearest ridge or trough within a 12-degree limit both to the west and east of their location (Fig. 1b). If no corresponding feature is detected within this range, the ridge or trough is considered to have decayed. Conversely, if a new ridge or trough appears without a corresponding feature in the previous time step, it is considered to have formed.

Note that the ridge and trough speeds as defined here are not the same as the phase or the group speed. Phase speed represents the speed of individual wave numbers, whereas the group velocity is the propagation of the wave «envelope». These are both different from the trough and ridge velocity of combined waves as investigated here. Consequently, here we will refer to the examined velocity simply as the wave speed or the speed of ridges and troughs, intentionally avoiding the terms phase speed or group speed.

Fig. 2 displays the probability for the positions of ridges and troughs for winter climatology, as well as the climatology positions of decay and formation of these features. Most often three major ridges and three major troughs can be seen throughout winters (Fig. 2 and supplementary Fig. S5). The three main ridges are located over the west coast of North America (hereafter, WNA ridge), the western flank of the Tibetan Plateau (hereafter, TP ridge), and the North Atlantic Ocean (hereafter, NAO ridge, at low latitude over the middle part, and at high latitude over the eastern part of the ocean). The three main troughs are located over Eastern North America (hereafter, ENA trough), the eastern Mediterranean (hereafter, EMed trough), and East Asia (hereafter, EAsia trough). The daily speed of these six major ridges and troughs is determined by summing their 3-hourly values across their respective longitudinal ranges (Fig. 1c). The speeds of the ridges over 180°W–90°W, 60°W–30°E, and 30°E–120°E are added to calculate the daily speeds of the WNA ridge, the NAO ridge, and the TP ridge, respectively. The daily speeds of the ENA trough, EMed trough, and EAsia trough are also found by taking the sum of the speeds of the troughs over 120°W–30°W, 0°E–90°E, and 90°E–180°E, respectively (Fig. 1c).

Ridges and troughs typically form upstream of their climatological positions and decay downstream of them (Fig. 2). The WNA ridge, NAO ridge, and ENA trough exhibit stronger formation and decay at high latitudes compared to mid-latitudes, indicating that these ridges and troughs tend to persist longer in the midlatitudes. The TP ridge and EMed trough show large formation and decay at mid-latitudes, likely due to their interaction with the complex orography. Nonetheless, the likelihood of their decay and formation remains significantly lower than their climatological existence, indicating persistency of the ridges and troughs (Fig. 2). The EAsia trough forms more strongly at midlatitudes, while its decay is more pronounced at higher latitudes. Over the Pacific Ocean, there is one ridge and one trough formation center, both of which decay downstream from their formation center. As can be seen from the climatological position of ridges and troughs, there is no strong ridge or trough in these locations, suggesting that these features are short-lived.”

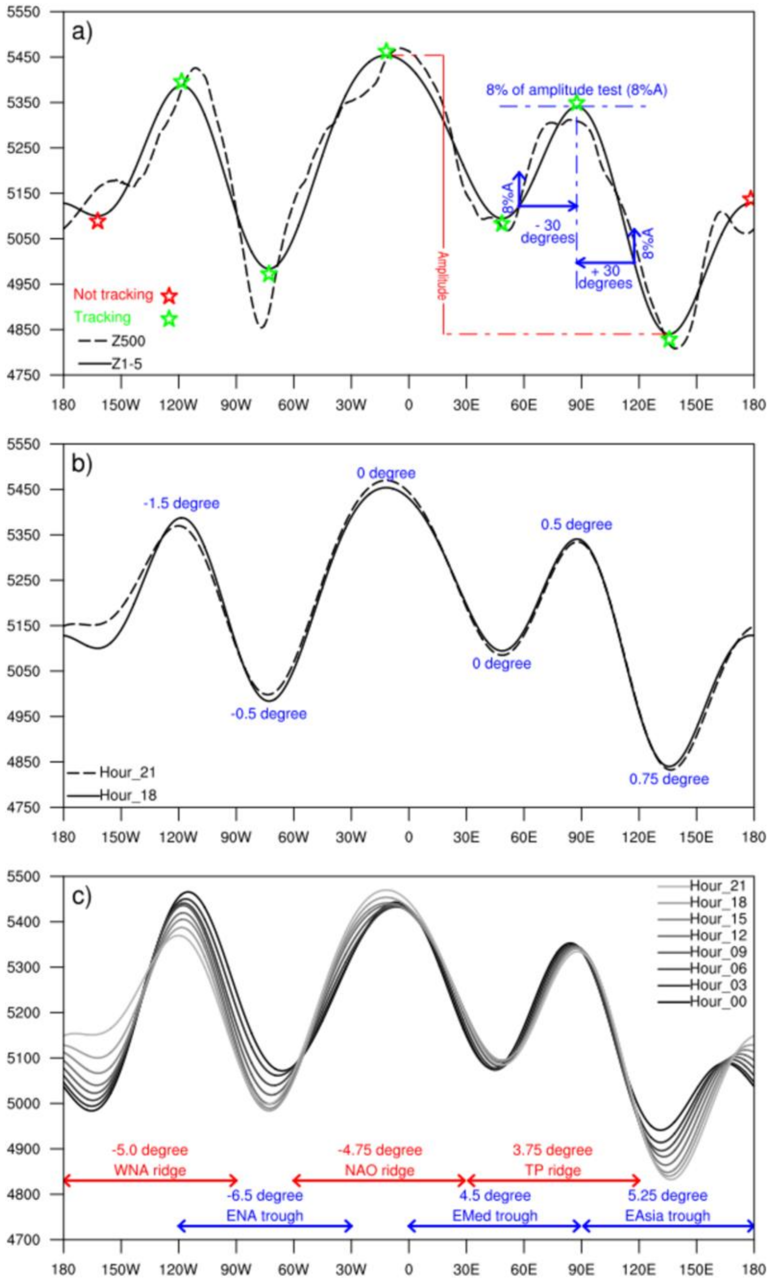

Fig. 1 The 500 hPa geopotential height field (Z500; dashed, black line) and the sum of the first five zonal Fourier-decomposed waves of Z500 (Z1–5; solid, black line) for a randomly selected time step (January 7, 2003) at 60°N. The blue text and arrows are associated with a threshold metric that identifies the strength of the ridges and troughs (see method for more information). Based on this threshold, three ridges and three troughs (green stars) are high and deep enough, respectively, for being detected by the tracking algorithm. In this time step, the tracking algorithm will ignore one ridge and one trough (red stars) that do not meet this threshold. b) The Z1–5 for two consecutive time steps (3 hours) and the changes in the ridges' and troughs' longitudinal location between these time steps. c) The Z1–5 for one day (8 time steps) and the calculated longitudinal shifts of each ridge and trough over the entire day.

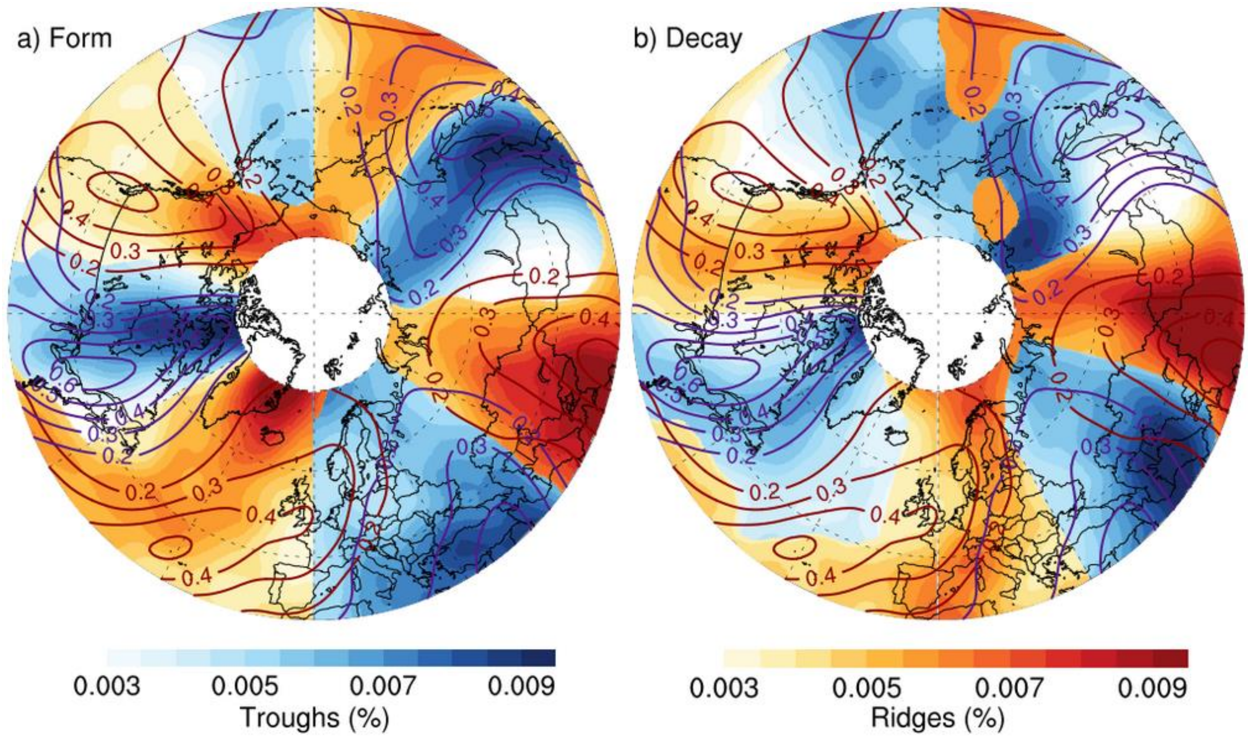

Fig. 2 The probability of ridges and troughs and their formation and decay as a function of location. Shown with contours are the probability (in percentage) of 300 hPa ridges (brown) and troughs (purple) during winter climatology as a function of location. The red (blue) shading indicates the climatological probability a) formation and b) decay of ridges (troughs) as a function of location. To show both ridges and troughs in a single plot, priority is given to the stronger feature. A Gaussian function, using a weighted running average over eight degrees in latitude and over an equal distance in longitude, is used to smooth the probabilities.

3.2 Trough and ridge amplitude

Several metrics have been developed to study the waviness of the atmosphere (e.g., Francis and Vavrus, 2012; Barnes, 2013; Hassanzadeh et al., 2014; Chen et al., 2015; Cattiaux et al., 2016; Geen et al., 2023), many of which rely on the meandering of the 500 hPa isohypses (lines of constant gph) as a proxy. Considering the variations of wave amplitude with different isohypse — e. g. associated with the seasonal variability and poleward shift due to global warming (Barnes, 2013) — selecting an appropriate isohypses are critical. To address these challenges, Cattiaux et al. (2016) derived isohypses from the daily average of the gph at 500 hPa between 30°N and 70°N, hereby varying in time. They regarded the meandering of these isohypses as an indicator of the waviness of the atmospheric flow at 50°N.

Here we focus on identifying changes in waviness at each latitude and at 300, 500, and 850 hPa, which requires some modification of the Cattiaux et al. (2016) approach: For a given study region, the most common isohypse at each time step and latitude is taken as the zonal average of the gph over half of the hemisphere centered on the center longitude of each study region. Then, the meridional wave extent for that latitude is defined as the meridional extent of the associated isohypse determined by calculating the difference between the maximum latitudinal location and the minimum location of that isohypse (total gph isohypse extent; TIE). By focusing on half of the hemisphere, it is ensured that at least one full ridge and trough are included within the region. In a similar way, the meridional extent of the first five Fourier decomposition wave numbers of gph (Z1-5) is calculated (planetary isohypse extent; PIE). During cold spells in the defined regions, both TIE and PIE demonstrate the same significant pattern of changes (not shown). This shows the modest impact of small waves on the wave amplitude changes during cold spells. Therefore, we only consider the results of the meridional extent of Z1-5.

Some isohypses have unconnected subparts (see Fig. 3a), referred to as cut-off low and cut-off high, which might lead to interpretation errors in the wave amplitude. For instance, in Fig. 3a, at high latitudes (around 85°N), the most common isohypse is 8300 m, and at these latitudes, the waviness of this isohypse is small. But, due to a cut-off low of this isohypse at midlatitudes, the estimated wave amplitude at 85°N is large. Moreover, the PIE does not specify the separate contribution to the wave amplitude from ridges and troughs. Understanding these contributions is critical, especially during cold spells, as it helps determine which parts of the wave—ridge or trough—having the greater impact.

Hence, we here propose an alternative metric where the meridional extent of the Z1-5 ridges and troughs are measured separately (Fig. 3b). The meridional extent of the ridge is given as the latitudinal difference between the RLL and the isohypse determined by the zonal average of the Z1–5 over a 90-degree longitude range centered at the RLL (Fig. 3b, red line); hence, the meridional extent of a ridge at a given latitude is obtained as the difference between that latitude and the latitude of the first cross of the isohypse when moving northward along the longitude of the RLL. The employed method does not take into account the possible meridional tilting of waves. To address this, at 300 hPa, the wave amplitude is calculated for all longitudes within the 90-degree longitude range. The highest value obtained is then considered the meridional amplitude of the ridge. While the highest value often yields slightly larger wave amplitudes than that obtained at the RLL, the overall conclusions regarding changes in wave amplitude during cold spells remain the same for both approaches (not shown). Therefore, to reduce computational usage, we used the amplitude at the ridge position. The meridional extent of troughs are obtained in a similar way but moving southward from TLL.

The estimated meridional amplitudes of a given ridge (trough) is highly influenced by the longitudinal range over which the zonal average of the Z1–5 is taken for determining the isohypse. Using a smaller longitude range yields an isohypse value closer to the value of Z1-5 at RLL (TLL), which can lead to small amplitudes. Using a large longitude range might yield an isohypse that cannot be found near the RLL (TLL), resulting in a missing value for the amplitude. Therefore, after conducting multiple experiments, the 90-degree threshold is chosen. Nonetheless, despite the arbitrariness of the meridional wave amplitude when defined this way, its magnitude exhibits a consistent latitude-dependent pattern and comparable bands of significance in both the climatology and cold-spell cases, which is important and sufficient for this study.

To compare the results of the refined method with PIE, considering the total wave amplitude, the average of the amplitude of the ridges plus those of the troughs over half of the hemisphere centered at each study region is calculated (ridge-trough isohypse extent; RTIE). For climatology, the RTIE amplitude (supplementary Fig. S4, gold lines) is nearly half of the PIE amplitude. During cold spells, there are likewise many similarities between the RTIE and the PIE, yet they have some important differences. During cold spells, the PIE amplifies over a wider latitude range compared to the RTIE. This could be attributed to the influence of cut-off lows or cut-off highs on the amplitude of distant locations.

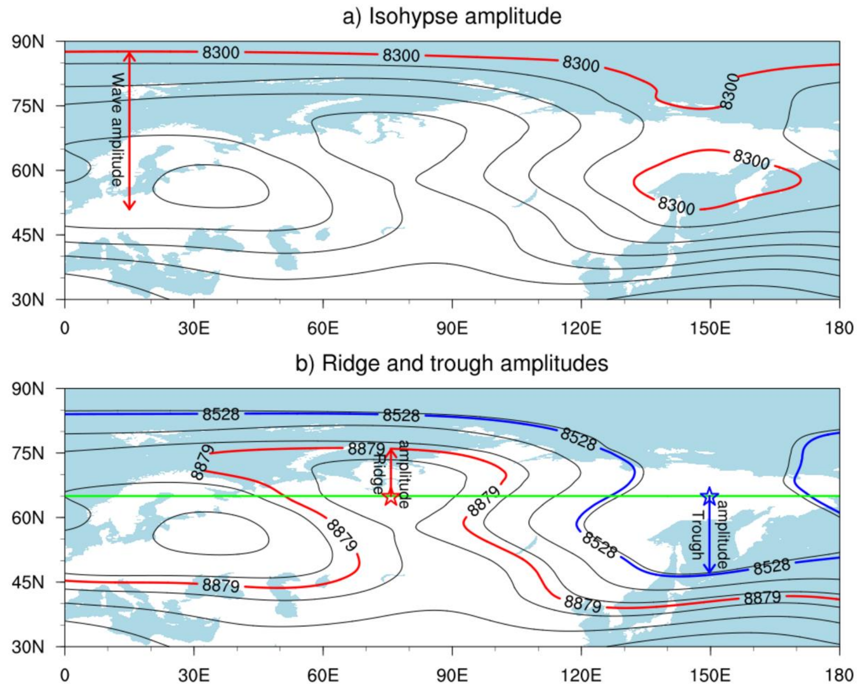

Fig. 3 The sum of the first five zonal Fourier-decomposed waves of the 300 hPa geopotential height field (Z1-5) for a randomly selected 3-hourly time step (January 4, 2016, at 18:00). a) The 8300 isohypse and its amplitude are highlighted; b) The ridge (red arrow) and trough (blue arrow) meridional amplitudes at the ridge (red star) and trough (blue star) center at latitude 65°N (green line).

The 8879 isohypse (red line) and the 8528 isohypse (blue line) are determined by the zonal average of the Z1-5 over a 90-degree longitude range centered at the ridge and trough positions, respectively, at 65°N.

2. Novelty aspect: the results section is quite short and does not focus too much on the novel aspects: it needs to be reworked to include more specific analysis, ideally by contrasting two/three different regions or groups of regions with analogous characteristics, rather than only showing the average. Topics that might be deepened include, for instance, the potential importance of retrograding patterns (whose presence is hinted in Fig. 3), the specificity of Northern Siberia (l. 132) or the Rossby wave dynamics during low- vs high-latitude cold spells. Some paragraphs in the Results section, furthermore, belong more to the Introduction than to the Results part (e.g., l. 141-147,l. 156-167), making it unnecessary lengthy and further blurring the explanation. In addition to the Results part, the conclusions do not stand out as novel enough: maybe, for a start, the authors can elaborate on the aspects in which this study provides a different perspective than, e.g., Fragkoulidis and Wirth (2020) who also concluded that "persistent [...] cold extremes are associated with an above-normal RWP amplitude and a below-normal RWP phase speed."

We appreciate the reviewer's concern regarding the novelty of our work. However, the primary objective of our paper is to provide a general overview of the role of ridges and troughs in the formation of cold spells in mid-latitude regions. To the best of our knowledge, no other research has specifically focused on this topic. To maintain clarity and focus, we intentionally limited the details provided for each region to ensure that readers grasp the key objectives of our research. Future studies can explore each region in greater detail.

Our research takes a global perspective on the formation of cold spells, in contrast to other studies, such as Fragkoulidis and Wirth (2020), as mentioned by the reviewer, which concentrate solely on one region. Hence, while Fragoulidis and Wirth (2020) shows that wave amplitude and speed play a role in developing cold spells in central Europe, we demonstrate that the wave amplitude increase and speed reduction are fundamental drivers of cold-spell formation, in general. Additionally, we demonstrate the contributions of ridges and troughs using a daily lag analysis, whereas Fragkoulidis and Wirth's (2020) discussion relies on the time averages of speed and amplitude over an area encompassing the cold-spell region. By doing so, we offer a comprehensive overview of the atmospheric behavior before and during cold spells. We emphasize the significance of the locations of the upstream ridge and downstream trough in the formation of cold spells. These findings are part of our broader perspective. However, we now incorporate more information about regional behavior to address the referee's concern. In addition, the conclusion is revised to highlight the novelty of our work and to compare our results with those of other studies.

The paragraphs that appear to fit better in the introduction have either been relocated to that section or removed from the manuscript.

In the results section, we replaced Fig. 3 in the manuscript with composites from regions in North America and Europe (Fig. 4 in this text). This choice was made because the upstream ridge and downstream trough are similar for the selected regions in each composite. Since we are using data from only one day of each cold spell event, there is insufficient information to plot results for each region separately. Therefore, we will not present the retrograding pattern for Northern Siberia which include only one region and hence too few cases for a statistical analysis. The text in the manuscript regarding Fig. 3 is updated as follows.

We added the following paragraphs to the Results section:

"Fig. 4 shows the retrograding patterns of ridges and troughs before and during cold spells for the composites of regions in North America and Europe. This choice is based on the similarity of the upstream ridge and downstream trough in the selected regions for each composite. In North America, cold spell regions are predominantly located in the vicinity of the WNA ridge. In North America, before cold spells occur, the ridge encompasses a broad area, including the cold-spell regions (Fig. 4a). At the start of cold spells, the upstream ridge becomes more localized in the western side of the cold-spell regions (Fig. 4e). This pattern provides northerly wind flow from the Arctic toward the cold-spell area (supplementary Fig. S6). In Europe, most of the cold spell regions are primarily located in the vicinity of the EMed trough. Similar to North America, before cold spells occur, the ridge encompasses a wide area (Fig. 4b), indicating that cold or warm anomalies are not concentrated to specific locations. However, with the onset of cold spells (Fig. 4f), ridges and troughs become more concentrated, with a ridge positioned upstream and a trough located within the cold-spell regions (Fig. 4f). Hence, associated with cold spells, roughly the same type of regional-scale circulation pattern is found in both North America and Europe. These findings highlight the critical role of the nearest upstream ridge and downstream trough in the formation of cold spells.

For Northern Siberia, the downstream trough amplifies at a positive time lag several days after the cold spells (supplementary Fig. S9i), indicating that the amplified trough cannot be responsible for the cold spell in this region. This is consistent with the formation of cold spells in Northern Siberia being due to diabatic processes (Röthlisberger and Papritz, 2023). Nonetheless, the upstream ridge amplifies and slows down prior to the onset of cold spells in this region (supplementary Fig. S9i)."

The updated version of the conclusion section:

"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. 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 et al., 2018; 2020) and amplified (e.g., Jolly et al., 2021; Fragkoulidis et al., 2020) Rossby waves contribute to cold spells 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 shifting the location of waves relative to climatology can result in a cold air advection to the cold region. Our findings highlight the critical importance of wave location, emphasizing the need to consider potential shifts in 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 focused 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 the dynamical drivers of them (Xu et al., 2024). In this context, we have developed two tools designed to identify the amplitude and speed of atmospheric waves, which can be utilized in future research to unravel the dynamical drivers of various extreme events. Furthermore, these metrics may help clarify the impact of AA 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."

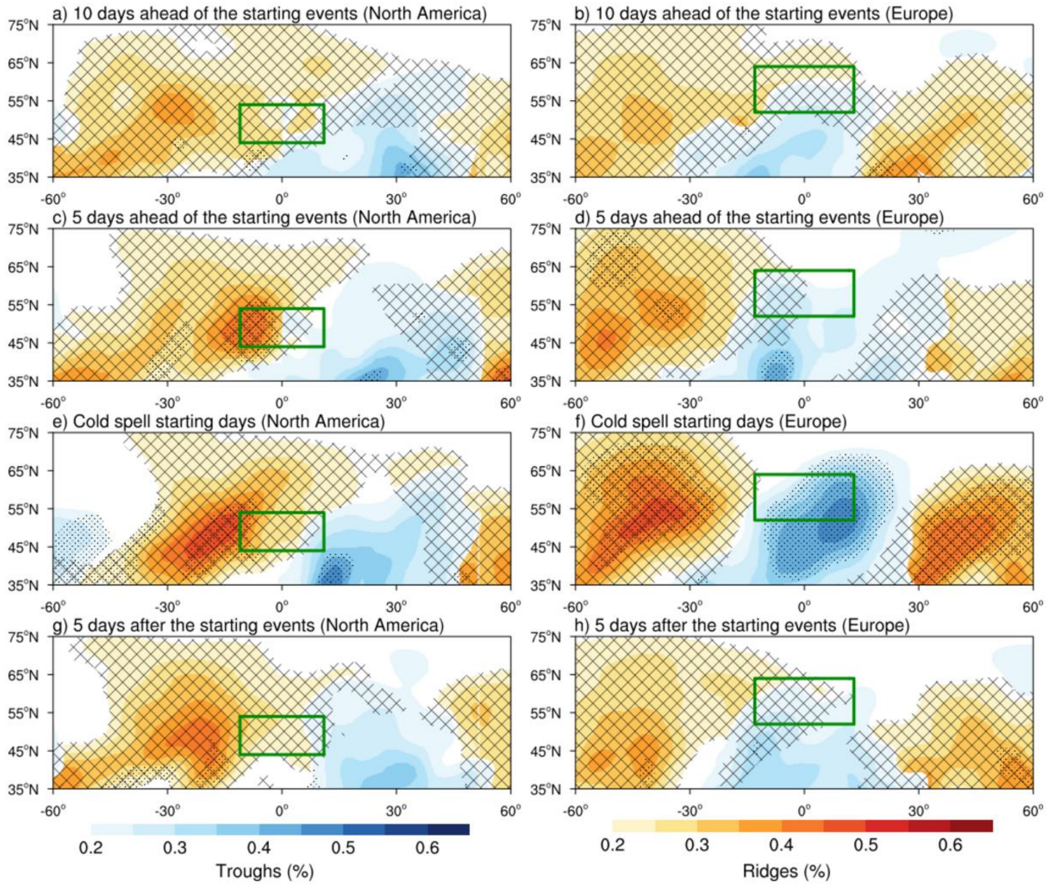

Fig. 4 The probability of ridges and troughs at 300 hPa as a function of location and time relative to the start of the cold-spell events. Shown with shading are probabilities (in percentage) of ridges (red) and troughs (blue) for different time lags averaged over all cold spells in study regions relative to the center of the cold-spell region. The panels on the left correspond to the composite of cold spells in North America (R01, R02, and R03), and the panels on the right correspond to the composite of cold spells in Europe (R04, R05, R06, R07, and R08). To show both ridges and troughs in a single plot, priority is given to the stronger feature. The hatched areas represent grid points where ridges are occurring, and dots indicate regions where ridges and troughs during cold spells are significantly different from the climatology at the 95% confidence level. The green box shows the average latitude and longitude span of the cold spell regions. A Gaussian function, using a weighted running average over eight degrees in latitude and over an equal distance in longitude, is used to smooth the probabilities. a), b) 10 days ahead of the starting cold spells; c), d) 5 days ahead of the starting cold spells; e), f) cold spell starting days; and g), h) 5 days after the start of cold spells.

3. Theoretical issue about the nature of the waves involved in cold spells: as far as I understand, the authors identify three main ridges and troughs over the Northern Hemisphere, corresponding to the stationary waves resulting from orography, land-sea contrast and eddy/mean flow forcing, and interpret the occurrence of cold spells as a shift in their position (as discussed in detail, e.g., in Supplementary Text "Wave location", at lines 96-115, a paragraph that helps the interpretation and that would fit more appropriately in the Results part). However, when performing the analysis, what is being tracked are transient ridges and troughs (more or less slow-moving) of fundamentally different origin that the ones by stationary wave theory: instead, they would be physically closer to RWPs. Although the authors might object that filtering on low wavenumbers (Z1-5) allows to consider longer waves than RWPs, most of the considered regions are located at high latitudes and, thus, baroclinic RWPs would project on similarly low wavenumbers due to the meridians getting closer and closer together towards the North Pole. Consequently, the interpretation of dynamics in terms of amplification/deepening of the six stationary wave features (ENA, EAsia, EMed, WNA, TP, NAO) is not well posed. On the other hand, what is being tracked are the transient features evolving on top of the stationary waves, whose presence should be considered more explicitly to explain the dynamics and remove ambiguities in interpretation.

Our objective is to enhance the trackability of ridges and troughs. To achieve this, we focused on the first five wavenumbers. This approach allows ridges and troughs to remain in their original locations (Fig. 1a) while filtering out smaller variations. As a result, instead of numerous local maxima and minima that are closely spaced, we obtain five distinct large ridges and troughs, facilitating their tracking. We also agree with the referee that at high latitudes, even low wavenumbers could represent synoptic-scale waves (Rossby wave packets). Therefore, in the manuscript, we become clearer about the use of the terminology of planetary waves (see the first paragraph of section 3.1, modified in response to point 1 of this review). Nonetheless, planetary waves (also at mid-latitudes) can exhibit transient behavior (e.g., Blackmon et al., 1984; Baggett and Lee, 2015; Graversen and Burtu, 2016), as is also shown in our results (Fig. 4b in the manuscript), specifically between 35°N and 45°N, where the first five wavenumbers represent planetary waves.

To further assess the impact of planetary waves on the formation of cold spells, we repeated our analysis, limiting the wavenumbers to those with wavelengths greater than 6000 km. This approach allowed us to isolate planetary waves across all latitudes. The results are presented in the following figure, which is similar to supplementary Fig. S8 but shows composites of Z1-5 waves larger than 6000 km only. As shown, over most latitudes there are little differences between the two ways of achieving the wave composite. However, there are some differences at higher latitudes. Between 68°N and 75°N, only wavenumbers one and two have wavelengths greater than 6000 km, which means that ridges and troughs derived from a combination of these two wavenumbers may not accurately represent the true location of the upstream ridge and downstream trough, in particular compared to the situation at lower latitudes. Therefore, we cannot argue about the impact of the upstream ridge and downstream trough on cold spells at these latitudes based on the condition of a minimum wavelength of 6000 km and will continue to use the full package of Z1-5, providing consistency across latitudes.

Nonetheless, in the updated manuscript, we avoided the terminology of planetary waves. These ridges and troughs may purely represent planetary waves at lower latitudes or a combination of planetary and synoptic waves at higher latitudes. As stated in the manuscript (lines 160-161), Rossby wave packets combine the ridge and trough into a single unit, and it remains unclear how these wave features contribute individually to the wave anomaly.

We will transfer the supplementary text regarding "wave location" to the main manuscript.

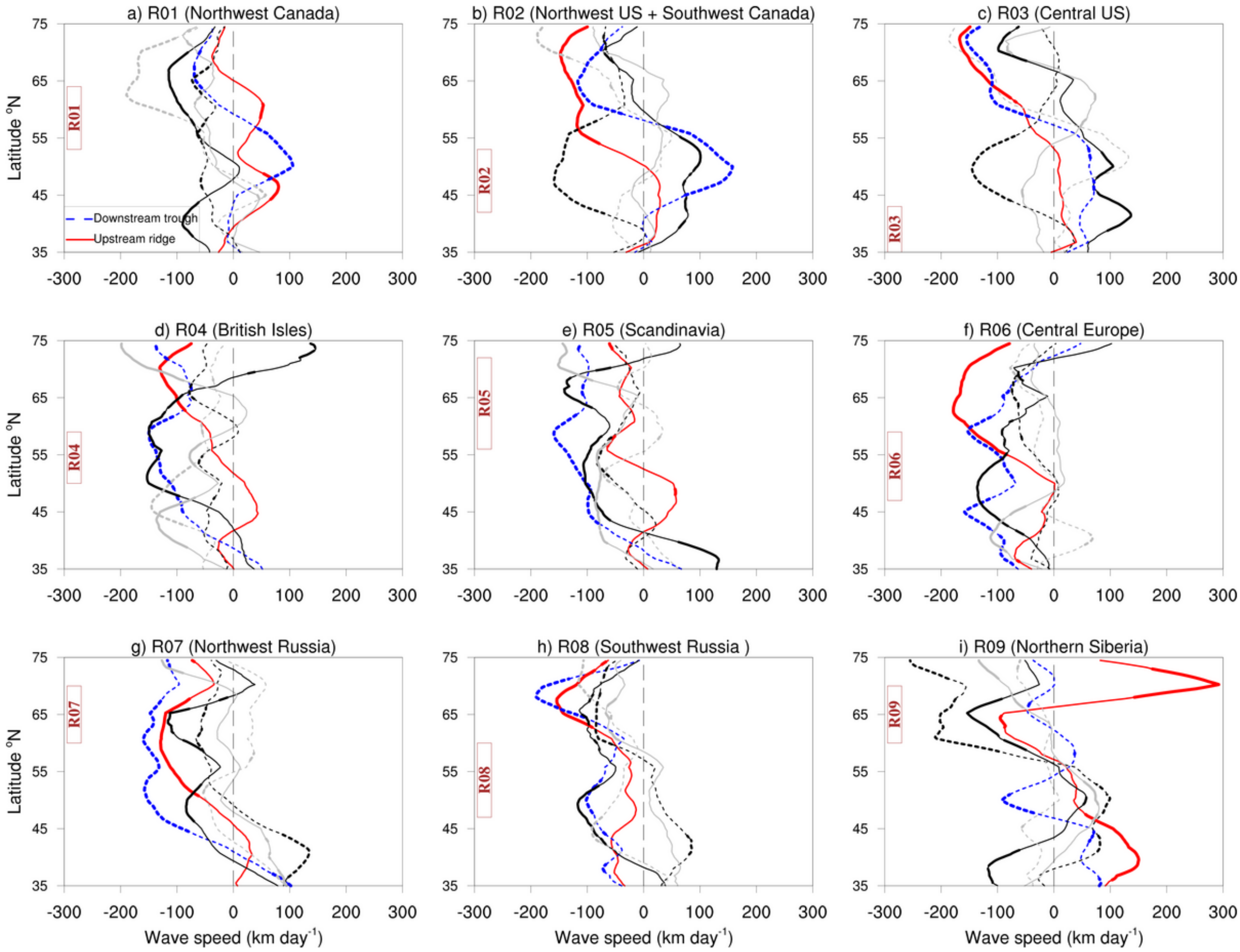

Fig. 6 As supplementary Fig. S8, but for Z1-5 with wavelengths greater than 6000 km only.

4. Excessive reminders to the Supplementary Information: the readers are often sent to look at the Supplementary information, often without additional explanation of how the linked content is relevant for the logical flow of the manuscript (l. 101-102, 132, 149, 167). Given that the manuscript now is quite short, I would suggest the reader to enrich the description of the method and the analysis of the results with material from the Supplement, properly introduced and discussed. Some detailed suggestions are scattered across the review.

Thank you for your comment. Most of the Supplementary Information is moved to the main manuscript.

Specific comments

l. 4-5 and following: what is the difference between "planetary wave" and "local wave dynamics" (line 4-5)? Are the ridges and the waves being tracked and analyzed part of the local or of the planetary?

In the manuscript, we used the term "planetary wave" to describe the behavior of all ridges and troughs, while "local wave dynamics" referred specifically to those near the location of the cold spell. As you noted, this terminology caused some confusion. In the revised manuscript, we have been careful with these terms. For instance, we have revised sentences in lines 4-5 to this:

"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."

l. 15: "influenced by pressure differences": this sound imprecise, in which sense "influenced"? Would "local and planetary vorticity gradients" be more adequate? Also, the Holton and Hakim (2013) textbook is cited three times in the manuscript, would it be possible to add more specific literature?

This sentence is removed from the manuscript. We rewrote the entire introduction following the request of Referee #1, including more specific literature.

l. 25: in which sense negatively tilted troughs are "generated through strengthening of the wind shear"? Do the authors refer to meridional wind shear in a context of LC1/LC2 life cycles and/or of Rossby wave breaking?

This sentence is removed from the manuscript.

l. 33-38: "Cold spells and heavy snowfalls across the Northern Hemisphere have increased" is a misleading statement, and the presence of few regional trends cannot mask the overall decrease in their intensity and frequency (e.g., Easterling et al. 2016, van Oldenborgh et al., 2019), and their occurrence is predicted to globally decrease according to climate projections (e.g., IPCC 2021, Fig. SPM.9). The purported examples in the following lines are anecdotal and not necessarily representative of a broader trend. The answer might be more nuanced for heavy snowfall (e.g., O'Gorman, 2014; Quante et al., 2021), but snowfall is a more complex phenomenon than cold spell as it involves moisture changes, and is anyway not the main focus of this article.

Thank you for the clarification. We have removed the argument regarding increasing snowfall from the manuscript. Additionally, we have discussed this section more thoroughly.

“The frequency of extreme events has risen in recent decades due to anthropogenic warming (IPCC; Seneviratne et al., 2021), and these events are likely to become more intense and break the previous extreme records by a large margin in the following decades (Fischer et al., 2021). In addition, despite the warming Earth, cold spells in some regions of the Northern Hemisphere have recently increased (e.g., Cohen et al., 2021; Cohen et al., 2024), although, in general, cold spells are projected to become less frequent by the end of the century (IPCC, Seneviratne et al., 2021), and the likelihood of experiencing the strongest historical extreme cold spell events is expected to diminish (Ribes et al., 2025).”

l. 46: the citation of van Mourik et al. (2025) needs to be contextualized a bit more: first of all, because the authors of that study question in their limitation whether rapidly moving "blocks" (as diagnosed by their methodology) actually represent cases of atmospheric blocking, and secondly because in the conclusions of that paper is written that "In winter, the coldest temperatures are associated with quasi-stationary blocks", so there is no particularly visible "inconsistency" (l.48).

The argument about the inconsistency is removed from the manuscript. The sentence citing van Mourik et al. (2025) is also revised to:

“It is argued that slow propagation of atmospheric blocking, identified using a blocking cell-tracking algorithm, lead to significant surface temperature anomalies (van Mourik et al., 2025).”

l. 66: a more detailed explanation of the logic behind the choice of the regions would be helpful here, ideally moving some parts of the Supplementary Information here and by adding a figure showing the "cold anomaly contribution to the historical extreme cold days".

Thank you for the suggestion. We will expand the explanation of the logic behind our choice of regions by incorporating details from the Supplementary Information. Additionally, we will include a figure that illustrates the "cold anomaly contribution to the historical extreme cold days" for clarity in the supplement (Fig. 7 in this text). Our argument will continue to be based on the Cold Wave Magnitude Index daily (CWMId), as this index quantifies occurrences of cold spells while considering their durations, intensities, and relevant climatological factors (Morlot et al., 2023). Nonetheless, both show the same results.

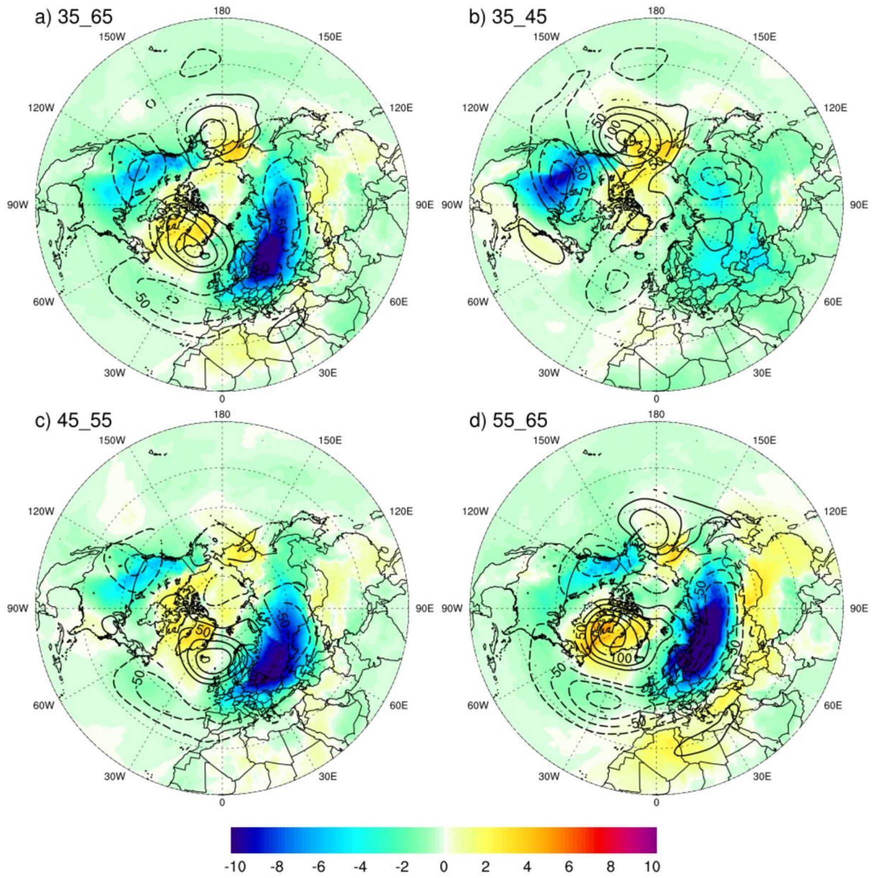

Fig. 7 Same as supplementary Fig. S1, but for the cold anomaly contribution to the historical extreme cold days.

l. 83: in which sense "bottom-trough" and "top-ridge"?

Referee #1 also mentioned this, and he suggested using “ridge and trough tracking,” which is implanted in the text.

l. 85-87: difficult to follow, would it be possible to mark the +/- 8% lines in Fig. 1a to visualize how it is computed?

The sentence is revised to avoid ambiguity:

“At each time step (3-hourly) and latitude, the gph at the ridge (trough) position must be greater (less) than the gph at 30° to the west and east of the ridge (trough) position by at least 8% of the Z1–5 amplitude (see blue texts and arrows in Fig. 1a).”

The 8% of the Z1–5 amplitude is already marked in Fig. 1a with blue arrows. We also updated Fig. 1; please see the modified version of the methodology in response to the major point one.

l. 92: would it be possible to see the lat/lon tracks of the ridges/troughs tracked using this method?

Yes. We are saving the locations of ridges and troughs at each time step, which enables us to observe how their positions in latitude and longitude evolve over time. However, our primary goal in this study is to examine how their speed and amplitude contribute to the formation of cold spells. We may conduct further research on their latitude and longitude trajectories in the future.

l. 101: what is the nature of these interpretation errors?

The argument is removed from the manuscript.

Fig. 2: It is not clear whether the contours are representative of the winter climatology or of vertical extremes, as from the caption one would expect a double set of contours. Also, what are "vertical extremes"?

This picture only shows the probability of the winter climatological positions of 300 hPa ridges and troughs. We used "vertical extremes" to show that we only depict the ridges' maximum and the troughs' minimum. We have removed it from the manuscript.

l. 169-173: if the trough speed is computed only over trough regions, what is the value attributed to "trough speed" in Fig. S8 (and consequently in Fig. 4) for cold spells occurring over the UK (R04) or the NW US (R01) that are located almost completely under a ridge? It would be great if these longitude bands were to be shown explicitly in a Figure.

We considered broader longitude bands for each ridge and trough to avoid missing them during cold spells. For instance, the ENA trough in its climatological position is mainly observed between 100°W and 45°W (Fig. 2 in the manuscript). However, during the cold spell over Northwest Canada (R01), this trough can be seen even at 120°W (supplementary Fig. S6 a). Therefore, we defined its longitude bands as extending from 120°W to 30°W. To enhance clarity, as you suggested, the longitude bands are added in Fig. 1c (in this text). Please see the modified version of the methodology in response to the major point one.

Fig. 4: I find interesting that at low latitudes troughs decelerate during cold spells (as discussed at line 191), but at the same time the ridge move significantly faster. I am wondering whether this puzzling aspect is due to the averaging across different regions: looking at Fig. S8 it seems that this behavior is related particularly to N Siberia and US cold spells, but could not figure out the logic of it. Could the authors explain more in detail what is happening? Would it make sense to have separate discussion for some peculiar regions?

Thank you for your thorough investigation; we have also observed this phenomenon. In all regions, the upstream ridge is moving faster at low latitudes, but this pattern is stronger and significant only in Northern America and northern Siberia. We are uncertain about the reasons behind this pattern, and further research is needed to explore it.

The following text is added to the result section:

"At low latitudes, the upstream ridge moves faster, which mainly results from cold spells in Northern America and northern Siberia. The underlying reasons for this pattern can be explored in future research."

l. 224-231: the ambiguity between stationary and transient waves is also well visible in this concluding paragraph, where the word "wave" is used sometimes to mean Rossby wave packets (e.g., citing Fragkoulidis 2018) and sometimes in terms of climatological stationary waves (l. 228). This leaves quite some confusion in the reader about what has been the object of this study, whether stationary or transient waves: the use of tracking approaches would indicates focus on the latter type, but the emphasis on the climatological wave-3 pattern points towards the former.

The entire conclusions section, including this paragraph, is rewritten to avoid ambiguity. Please see the response to the major comments 2 and 3.

Grammar/Technical/Typos

L. 39: increase. Also, increase in what? Frequency, intensity, etc...

We add frequency in this sentence.

l. 60-69: consider starting the paragraph with the full sentences starting between lines 65-69 and then explain why IPCC regions were not chosen.

The entire argument about IPCC regions, due to Referee #1's suggestion, is removed from the manuscript.

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