Review of Egusphere-2025-3867

The authors present an intersting manuscript about upper-tropospheric drivers of cold extremes. By assessing the meridional extent and the zonal propagation of the upstream ridge and the downstream trough separately, the study promises valuable insight on the role of the large-scale atmospheric dynamics for temperature extremes. The authors develop an original algorithm focused on planetary waves that could potentially complement existing analyses of synoptic-scale variability, such as Rossby wave packets, or hemispheric variability represented by Fourier harmonics. However, it remains unclear to what extent the results are sensitive to filtering choices and to the definition of the study regions. Significant improvements are therefore required to better justify and illustrate the choices underlying the development of this new algorithm.

We sincerely appreciate the reviewer's feedback and the detailed comments provided. We have expanded the methods section to clarify the filtering choices and the definitions of the study regions. Below, we offer a point-by-point response to each individual comment.

General comments

1. The introduction falls short in introducing the large variety of waviness and persistence metrics and the scientific discussion around their importance for weather and climate extremes. The first paragraph contains mostly textbook material (line 11-16). The second paragraph and in particular the first sentence (line 19-20) could have been expected at the very beginning. And the third paragraph contains mostly anecdotal evidence. On the other hand, the first paragraph of Section 3.2 (line 156-167) makes good material for the introduction. I suggest restructuring and extending.

The entire introduction is rewritten and expanded with several additional studies concerning the linkage between circulation and extreme events:

High-amplitude quasi-stationary Rossby waves may generate extreme weather events (e.g., Hoskins and Woollings, 2015; Fragkoulidis and Wirth 2020; White et al., 2022), and increase in temperature extremes in the mid-latitudes is argued to be linked to increased upper-atmosphere waviness (e.g., Fragkoulidis et al., 2018). An increase in meridional amplitude of Rossby waves may enhance the meridional exchange of warm and cold air, leading to the advection of cold air to the south and warm air to the north (Zschenderlein et al., 2018; Jolly et al., 2021). Some studies link extreme temperatures to a significant amplified circumglobal waviness based on wave amplitudes of individual wave numbers (Petoukhov et al., 2013; Screen and Simmonds, 2014), while others assert a robust correlation between local waviness and temperature extremes (Röthlisberger et al., 2016; Fragkoulidis et al., 2018; Fragkoulidis and Wirth, 2020). Studies based on the amplified circumglobal waviness argued that free-traveling synoptic waves of some specific wave numbers (6, 7, or 8) may be trapped within the midlatitude waveguide leading to extreme temperature events (Petoukhov et al., 2013; Kornhuber et al., 2017), whereas others caution against overemphasizing the significance of circumglobal waviness, suggesting that local climatic factors may play a more critical role in influencing temperature extremes (Teng and Branstator 2019).

Slow movement of Rossby waves may also lead to weather persistence, for instance in terms of blocking, which may develop into extreme weather events, such as floods, droughts, heat waves, and cold spells (Francis and Vavrus, 2012; Pfleiderer and Coumou, 2018; Riboldi et al., 2020; Jolly et al., 2021; Wicker et al., 2024). Extreme rainfall over Eastern Australia has been linked to slow-moving upper-level low-pressure systems (Barnes et al., 2023; Reid et al., 2025; Vries et al., 2025), and 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). The propagation speed of atmospheric blocking can impact the upstream and downstream of the block, in the way that rapidly westward-moving blocks lead to less persistent cold events in the upstream of the block, while slower westward-moving or quasi-stationary blocks lead to strong cold anomalies in the downstream of the block (Chen and Luo, 2017; Yao et al., 2017).

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).

Increases in extreme event frequency, specifically cold spells, have been linked to Arctic amplification (AA), a phenomenon by which the Arctic warms faster than the mid-latitudes (e.g., Francis and Vavrus, 2012; Cohen et al., 2014): the AA is weakening the jet stream, making the large-scale atmospheric waves more wavy (Francis and Vavrus, 2012; Coumou et al., 2015; Stendel et al., 2021); in addition, AA causes Rossby waves to become more stationary, resulting in an increase in the frequency of extreme weather (Francis and Vavrus, 2012). This hypothesis, however, has been questioned by several studies (e.g., Barnes, 2013; Screen and Simmonds, 2013; Blackport et al., 2022, 2024).

The dispute about the influence of the AA on planetary waves might stem from the sensitivity of waviness assessments to the applied metric (Geen et al., 2023), highlighting the need for improved and universal wave metric. Existing wave amplitude metrics, such as Rossby wave packets (e.g., Fragkoulidis et al., 2018; Röthlisberger et al., 2019), local jet waviness (e.g., Röthlisberger et al., 2016), and hemispheric variability (e.g., Petoukhov et al., 2013; Kornhuber et al., 2019), do not establish the role of the amplitude of each ridge and trough in temperature events. In addition, as far as the authors know, the speed of local ridges and troughs and their role in extreme events have not earlier been quantified. Some studies estimate atmospheric phase propagation by following grid points using lag-correlation in different bandpass-filtered geopotential height maps, tracking the maximum positive correlation center (e.g., Blackmon et al. 1984; Takaya and Nakamura 2001). Others derive phase-speed spectra for each zonal wavenumber by performing a space–time spectral decomposition of upper-tropospheric winds along latitude circles (e.g., Randel and Held 1991; Domeisen et al. 2018; Riboldi et al. 2020). A local approach is also used to estimate the speed of Rossby wave packets (e.g., Fragkoulidis and Wirth 2020; Fragkoulidis 2022). Here, we aim to explore the linkage between cold spells and the amplitude and speed of each ridge and trough. 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; Tuel and Martius, 2024). Hence, this study further investigates the role of individual ridges and troughs in causing cold spells.

2. The sentence in line 65-66 is key to the relevance of the present manuscript. I am surprised to see that the authors choose to move the evidence supporting this statement to the supplement; in particular, since the filtering choices as part of the detection algorithm seem justified by the location of the study regions relative to the climatological position of the troughs and ridges (Fig. 2). Without reading the supplement, it is not clear why these filtering choices are made. Retaining zonal wavenumbers 1-5 and the 30° longitude prominence criterion basically ensure that there will be exactly 3 troughs and 3 ridges (line 137).

Thank you for providing insightful feedback. We will transfer the evidence regarding cold spell region selection from the supplementary information to the main text for clarity.

We only consider the first five wave numbers to remove small variability from the ridges and troughs. In this way, we are enhancing the trackability of ridges and troughs. Additionally, the 30° longitude prominence criterion is intended solely to remove noise. Smaller waves typically develop over the Pacific Ocean and persist for less than several time steps (3-hourly). This information is also added in the paper. Please see the answer for the next comment.

In the text, we specifically mention "three major ridges and three major troughs," but this does not imply that only three exist; there may be additional ones.

3. No information on the tracking itself is provided. I assume that the detection algorithm is run at every time step and at every latitude. How are the troughs and ridges labeled and tracked in time? Do they from and decay in different places? How long do they persist? Is there some correspondence across latitudes? The

authors could provide much more detail. Figure 1a is helpful for illustration of the detection. I suggest producing a similar illustration for the tracking.

Detailed information on the tracking, formation, and decay of ridges and troughs is now added in the manuscript. We are saving the locations of ridges and troughs at each time step, which enables us to observe the correspondence of ridges and troughs across latitudes. However, our primary goal in our study is to examine how their speed and amplitude contribute to the formation of cold spells. We may conduct further research on their latitude trajectories in the future.

For better clarity, Fig. 1 in the text is updated to illustrate the tracking procedure. The following text is added to the description of the trough and ridge speed in the "Wave metrics" section. This section is newly created and includes both the speed and amplitude of the ridge and trough metrics.

"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.

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."

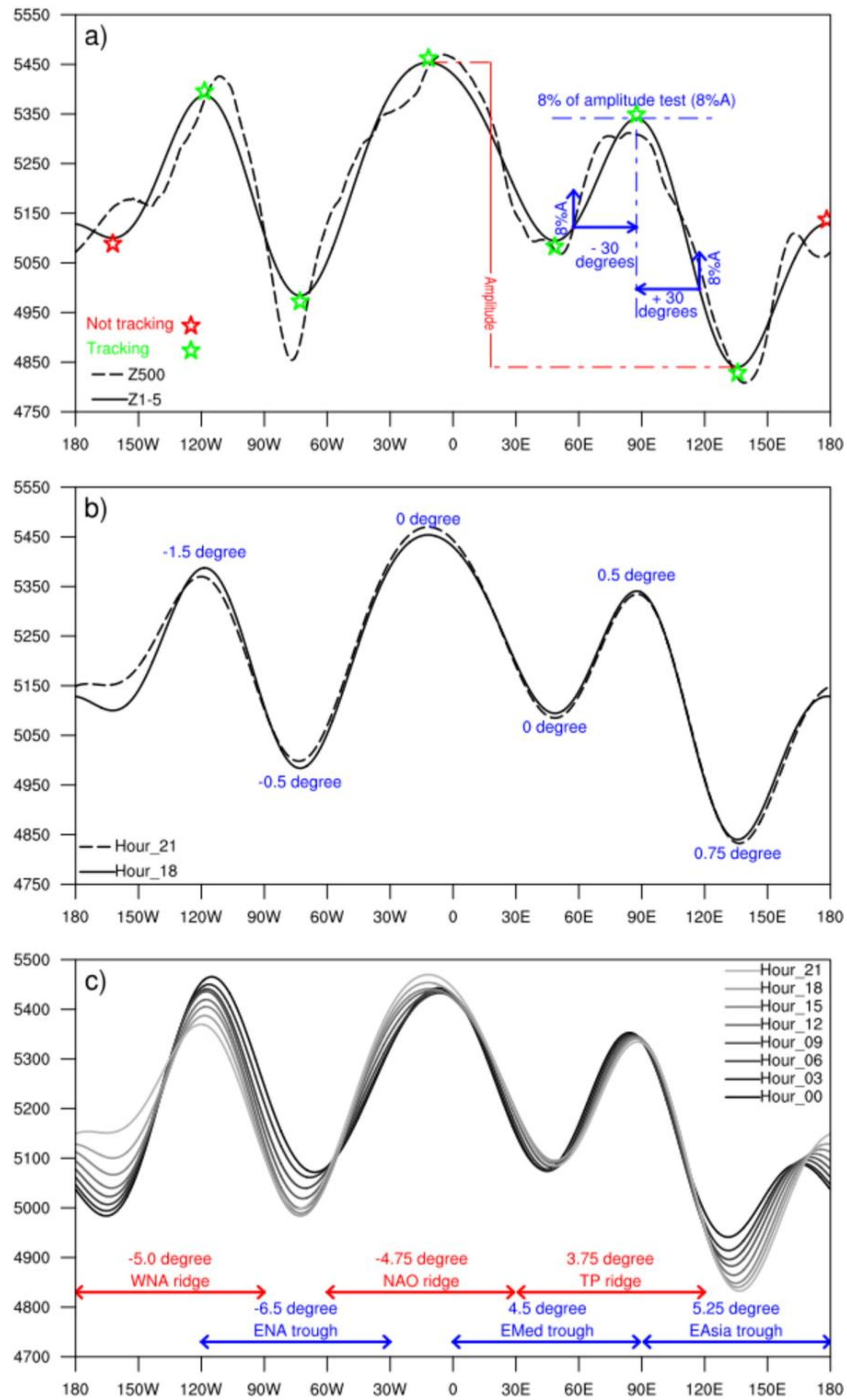

Fig. 1 The 500 hPa geopotential height field (Z500; dashed, black line) and the sum of the first five zonal Fourier-decomposed waves of Z500 (Z1–5; solid, black line) for a randomly selected time step (January 7, 2003) at 60°N. The blue text and arrows are associated with a threshold metric that identifies 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.

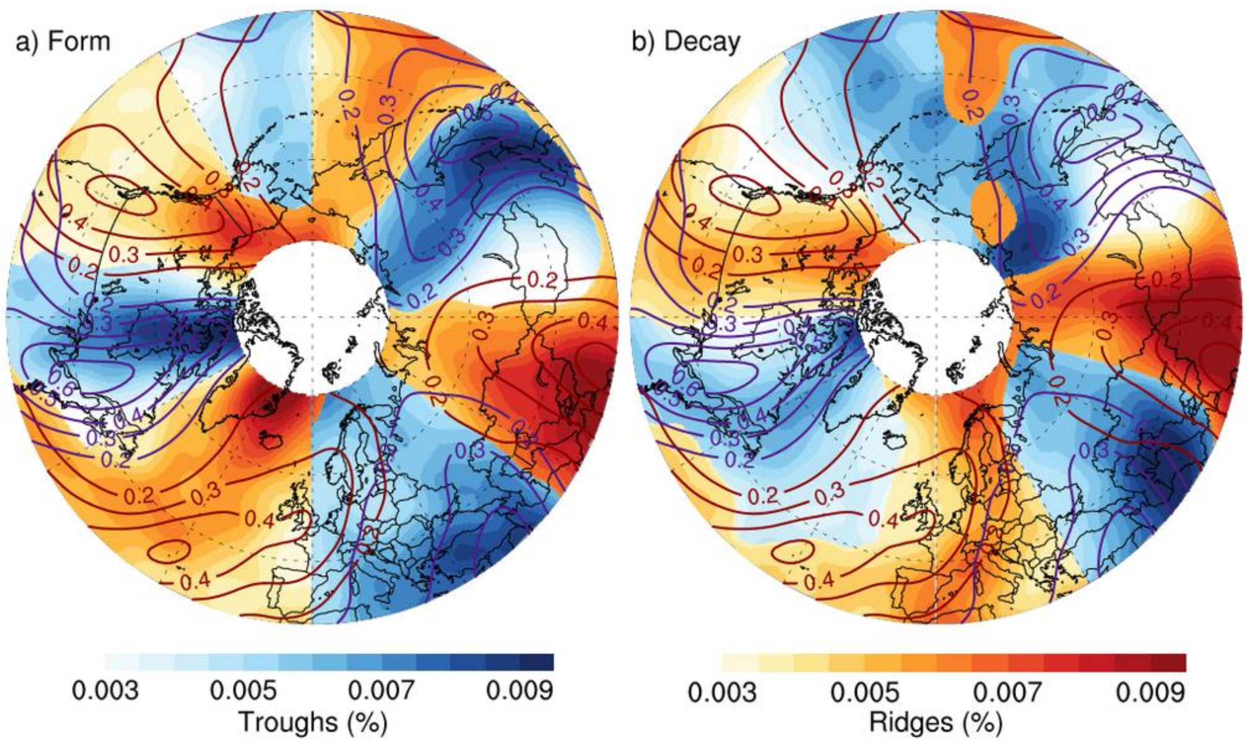

Fig. 2 The probability of ridges and troughs and their formation and decay as a function of location. Shown with contours are the probability (in percentage) of 300 hPa ridges (brown) and troughs (purple) during winter climatology as a function of location. The red (blue) shading indicates the climatological 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.

4. The lead-lag behaviour of wave amplitude and wave speed presented in Figure 5 looks very interesting in light of the literature introduced in line 194-211. However, I am afraid that averaging only over latitudes, that show a significant positive amplitude or a significant negative speed anomaly, compromises the informative value. The Figures S7 and S8 also show latitudes with a significant negative amplitude or positive speed anomaly as well as latitudes with not significance. Is there a lead-lag behavior at those latitudes?

Thank you for your deep investigation. As shown in Figs. S7 and S8, the significant latitude bands used in Fig. 5 are mostly located in the vicinity or to the north of the cold-spell regions, which could influence the transfer of Arctic cold air to these areas. The lead-lag behavior of other significant and non-significant changes in the upstream ridge and downstream trough depicted in the supplementary Figs. S7 and S8 is also examined, see Fig. 3 of this response. Based on their behavior, we updated the manuscript.

We added the following paragraphs to the Results section:

"The lead-lag behavior of other significant and non-significant changes in the upstream ridge and downstream trough (supplementary Figs. S7 and S8) is also analyzed (supplementary Figs. S10; Fig. 4 in this text). Their time lag either shows no significant changes or occurs after the upstream ridge and downstream trough's significantly positive amplitude and negative speed anomalies. However, there are some exceptions: During cold spells over North America (R01, R02, and R03), the lead-lag behavior of the upstream ridge anomaly at the lower midlatitudes (35N-50N) indicates that this ridge slows down at these latitudes before it does at other latitudes (supplementary Figs. S10a). For both Eastern European regions (R07 and R08), latitudes with a reduction in the upstream ridge amplitude (35N-40N; supplementary Fig. S7g and h) show strong negative amplitude anomalies weeks before the onset of the cold spell (supplementary Figs. S10b). This indicates that the ridge at lower latitudes tends to move zonally, which may weaken the mixing of warm tropical air with colder midlatitude air long in advance of the cold spell formation."

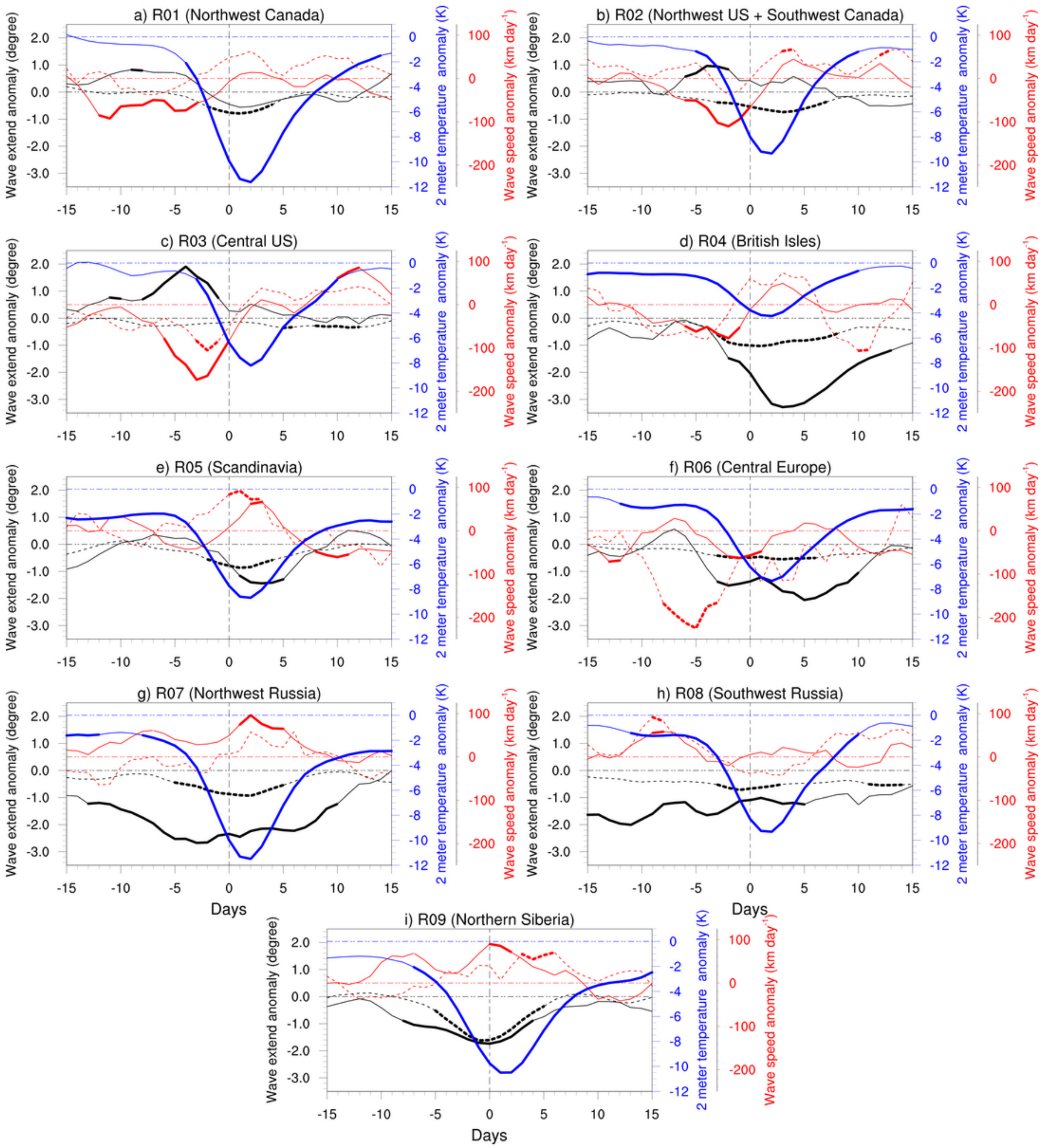

Fig. 3 As supplementary Fig S9 but based on the average over the latitude bands with a significant negative wave amplitude anomaly and a positive wave speed anomaly for each cold spell region. For regions with no significant negative wave amplitude anomaly and a positive wave speed anomaly, the latitudes with non-significant changes are averaged. The exceptions to these are mentioned in the text.

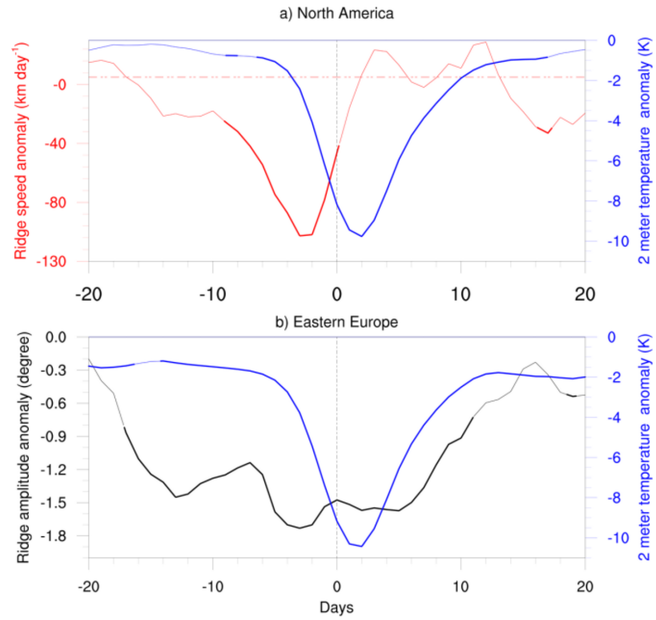

Fig. 4 Composites of anomalies relative to climatology for 2-meter temperature, ridge speed, and amplitude during cold spells over a) North America (R01, R02, and R03) and b) Eastern Europe (R07 and R08), as a function of time lag. The lag zero (zero on the x-axis) is the day that 30% of the land in each region experiences a cold spell. The blue line shows the composite of temperature anomalies averaged across each study region. The black and red lines represent the composites of the upstream ridge's amplitude and speed anomalies, respectively, in the vicinity of the cold-spell location. A five-day running average is used to smooth the lines. For North America, speed anomalies are calculated based on the average from 35°N to 50°N. For Eastern Europe, the amplitude anomaly is derived from the average over latitudes 35°N to 40°N. Bolded solid and bolded dashed lines indicate the difference to climatology significant on a 95% level.

Specific comments

• Line 14-16: The second half of this sentence is basic knowledge and not necessary as introduction of an article for WCD.

It is removed from the manuscript.

• Line 33-34: How does the statement on cold spells under global warming relate to the study by Ribes et al. (2025)?

We added the results of their research in the introduction. Please see the revised introduction.

• Line 60-64: The discussion of the IPCC regions does not seem relevant for the present manuscript.

It is removed from the manuscript.

• Line 79: It seems that Section 2.3 would be entitled more appropriately as “Trough and ridge speed”.

Changed to “Trough and ridge speed”

• Line 83: Why is the algorithm called “top-ridge and bottom-trough tracking” instead of a “ridge and trough tracking”?

Changed.

• Line 86: Is the prominence criterion of 8 % applied to every grid point or just the two grid points exactly 30 degrees to the west and to the east? I suspect the latter. And why is the value of 8 % chosen?

Yes. We worked with two grid points that are exactly 30 degrees to the west and 30 degrees to the east. 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)."

There is no specific reason for the value of 8%. We experimented with various thresholds, and regardless of our choice, the results remain consistent across the other thresholds. This point has already been addressed in the manuscript (lines 88-91).

• Line 101: I suspect that "the chaotic nature of the gph field" refers mostly to cut- offs. I am not whether chaos is the correct term here.

The argument is removed from the manuscript.

• Line 105: What do vertical extremes refer to in this context?

We used "vertical extremes" to show that we only depict the ridges' maximum and the troughs' minimum. We have removed it from the manuscript.

• Line 109: Which method is used for the manuscript? The method that takes account for meridional tilting?

We only applied the method that accounts for meridional tilting to test the sensitivity of our results at 300 hPa. This method requires significant computational resources. To clarify our approach, we revised the text:

"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."

• Line 117: Not even at the North Pole?

At midlatitudes, the corresponding isohypse definitely can be identified. However, as we approach the North Pole, the corresponding isohypse may not exist at higher latitudes.

• Line 119: What does consistent mean in this context?

The term "consistent" refers to the robustness of the results against the choice of longitude window used to define the isohypse. Sensitivity tests conducted with longitude ranges of 60°, 90°, 180°, and 360° reveal that the cold-spell composites display the same latitude bands of significant anomalies. Additionally, the climatological profiles maintain a similar latitude-dependent shape. The sentence is revised to improve clarity.

"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."

• Line 133: For some cases in Figure S2 the anticyclonic (cyclinic) anomaly lies rather poleward (equatorward) of the region.

The argument is removed from the manuscript.

• Line 137: Be more clear that these are the climatological position, not the troughs and ridges detected in the climatological-mean field.

Thanks for the reminder. The sentence is changed to “Fig. 2 displays the probability of the winter climatological positions of ridges and troughs.”

• Line 145-147: The “intrinsic relationship between relative and planetary vorticity” is not clear. The point that the conservation of potential vorticity gives rise to Rossby waves is textbook knowledge.

The sentence is removed from the manuscript.

• Line 151-153: Figure S6 shows the MCI and does not provide evidence for the role of temperature advection.

The argument about temperature advection is removed from the sentence.

• Figure 2 : The colorbar is missing a label. Also, I wonder whether the authors might want to display the mean geopotential height field for comparison with the trough/ ridge locations?

In the updated manuscript, we have decided to remove this figure because the information it contains is already included in the new Fig. 2 (in this text, Fig. 2). The revised version of the old Fig. 2 (in this text, Fig. 5) can be found in the following text.

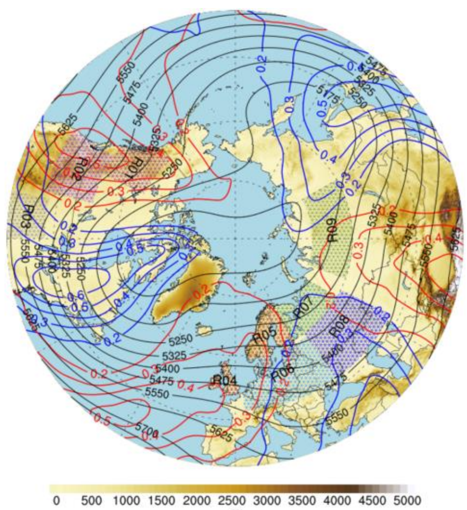

Fig. 5 The probability (in percentage) of the position of 300 hPa ridges (red contours) and troughs (blue contours) during winter climatology. The black contours indicate the winter climatology mean geopotential height field. The hatches indicate the chosen regions for the study on cold spells. A Gaussian function, using a weighted running average over eight degrees in latitude and over an equal distance in longitude, is used to smooth the probabilities. Shading shows the elevation above mean sea level (m).

• Line 168-173: Are the trough and ridge speeds and amplitudes calculated only in the longitudinal bands of their climatological position or across the globe?

The calculations are based on the longitudinal bands corresponding to their climatological and cold spell positions. The sentence is revised to improve clarity, and the longitude bands are added in a figure. Please see the response for your general comment number 3.

• Figure 3: What are “probabilities of vertical extremes in longitude and latitude”? And why do you show them in relative longitude but absolute latitude?

We used "vertical extremes" to show that we only depict the ridges' maximum and the troughs' minimum. We have removed it from the manuscript. The point is to show the reader that, despite the latitude of the cold spell location, the upstream ridge and the downstream trough relocate in the entire midlatitude. This terminology is also added to the text.

• Figs. S7 and S8: Related to the question above, are the troughs and ridges assessed in these figures (blue/red lines, black lines, grey lines) necessarily located in the longitudinal bands indicated lines 168-173?

Yes. We will include this text in the caption for Fig. S7:

“These ridges and troughs are the same as those in the methodology section, but here they are shown in relation to the cold spell's location.”

• Line 179: If I am not mistaken, an amplification of the ridge is determined by its meridional extent and, therefore, does not imply the development of higher geopotential height values.

The argument is removed from the manuscript.

• Line 182: The Figure S6 depicts the MCI, which is not directly related to temperature advection.

In this line, we did not argue about the temperature advection. The sentence is only about increasing the northward and southward winds during the cold spells.

• Line 193: “Causality” seems a misleading section title. I suggest something like “lead-lag analysis”

Done

• Line 198: I would not say that the mechanism is unclear. I suggest removing the sentence because it is not necessary to motivate the following.

Done

• Figure 4: Why is the wave speed all positive despite the westward propagation indicated by Fig. 3? Also, it does not seem to agree with Fig. S8.

These waves, during normal conditions, propagate both westward and eastward within a specific longitude range; however, their eastward propagation is generally more common than their westward propagation. During cold spells, their behavior is similar, but there are two notable differences: first, they are confined to a smaller longitude range (Fig. 2 in the manuscript), and second, they propagate at a slower speed (Fig. 3 in the manuscript). Despite this reduction in speed, their average behavior still favors eastward movement. Fig. S8 illustrates the anomalies from climatology, but Fig. 3 shows climatology and the average over cold spell days.

• Line 224-227: So far, the manuscript dealt specifically with troughs and ridges. But now the authors generalize to “Rossby waves”.

We clarified our terminology by changing "Rossby waves" to "troughs and ridges."

• Line 236: I recommend a reference to Geen et al. (2023) for the influence of Arctic amplification on waviness.

Added.

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