“The Life Cycle of Upper-Level Troughs and Ridges: A Novel Detection Method, Climatologies and LagrangianCharacteristics”

Reply to review #2

Dear Irina,
Thank you very much for your time and effort you put into this review. We very much appreciate the comments that helped us to improve the paper. Please find below our specific replies.

Reviewer: My major comment has already been picked up by another reviewer: I would also like to see justification of the geopotential level used to identify troughs/ridges and, possibly, how results differ between levels. I can see a point in using an Hgt level as opposed to, e.g., PV, as Hgt levels are readily available in most model outputs, making this approach useful for analysis of, e.g., CMIP6 models. However, troughs/ridges are often seen as upper-level phenomena, while 500 hPa lies in the middle of the troposphere.

Authors: Geopotential height at the 500 hPa level has traditionally been used for analysis of troughs and ridges. It is still widely used for forecasting purposes and also in research. Because of its historical significance, we have used it in this study for demonstration purposes.

In the revised version, we added the results for the 300 hPa level as a supplementary figure and we also comment on notable differences where appropriate. The combination of the quasi-geostrophic forcing of vertical motion by the Q vector, which is formulated using geopotential height, and the geopotential-based troughs and ridges result in a powerful research tool. We see however also the merits of using potential vorticity for input data. The user of our research tool is free to choose any other suitable variable or level as input data depending on the specific research question to be addressed.

Reviewer: Abstract: It is said that tracking allows analysis of evolution of troughs/ridges. However, in my view, this paper does not present such analysis. Either remove this statement from the abstract (it can be kept in the description of the method) or add analysis of their life cycle.

Authors: It is correct, we do not show an explicit example in this manuscript. We changed the sentence in the abstract to “(…) *could be* used to study the temporal evolution of the trough or ridge orientation”. Thanks for pointing this out.

Reviewer: p1, l.21-25: Add a figure showing a trough and a ridge.

Authors: Good idea, we now reference Fig.1.

Reviewer: p2, l.18: define E vector here.

Authors: We added the E vector definition.

Reviewer: p.4, l.9-16: This part needs to be illustrated - draw a figure showing vectors discussed here

Authors: We added such a figure.

Reviewer: p.5, l28: give a brief description of Q vector here first, not only a reference.

Authors: We added a brief description of the Q vector.

Reviewer: p.6, l22: can the absence of troughs be a result of northern boundary at 70N? Could it be that troughs extent further north and the part to the south of 70N is below the threshold on the length?

Authors: Our statement that troughs are absent at the end of the North Atlantic storm track was inaccurate. It is the center over the UK and over eastern Europe that is associated with development at the end of the North Atlantic storm track. We corrected this statement.

Reviewer: p.5, l. 32: The map at 06 UTC also suggests a significant trough in the Mediterranean, but it remains undetected. Is it due to the thresholds? In this case, some sensitivity test should be shown to justify the selection of thresholds.

Authors: The case study was chosen intentionally to highlight the difficulties arising from the need to define thresholds. The presented case was not used for the tuning of the thresholds. There is unlikely an ultimate answer to this question, because when we decrease the threshold in this case, we will find another where we would tend to increase it again. We do not want to show the perfect example in our study. We want to be transparent about this issue. We discuss for this reason the role of the thresholds in the corresponding section. In general, the patterns seen in the climatologies are robust, but the amplitude of detection frequencies depend on the used threshold. This holds true for all object-based feature detection algorithms.

Reviewer: p.6, l. 17: Is it frequency of trough area of trough axes?

Authors: Here we use the trough objects corresponding to the through area. We added this information.

Reviewer: p. 7, l.1: To confirm that Greenland troughs are more transient can you built pdfs of trough lifetime characteristics (propagation speed and lifetime) in regions of interest (over Greenland, Pacific that is discussed later and a reference region).

Authors: The Figure below shows the winter climatology of the trough lifetime at each grid point. The lifetime at Greenland is reduced compared to downstream of the Rocky Mountains or compared to East Europe and Russia. We added the figure as supplement to our manuscript.

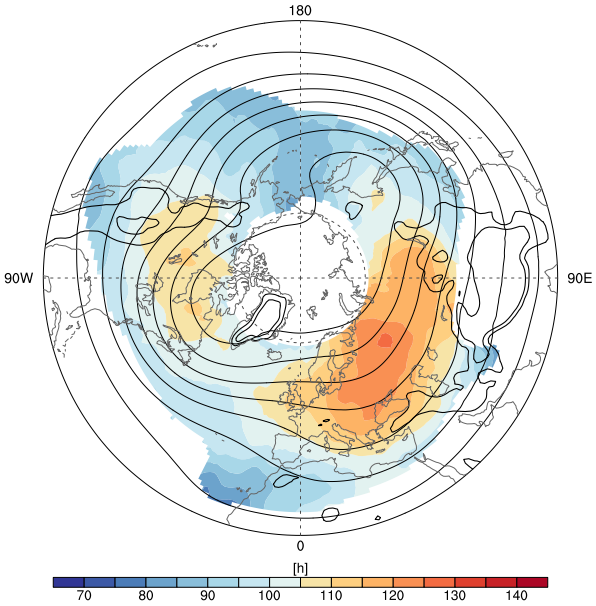

Figure 1: Mean lifetime of troughs during the extended winter period (Nov–Mar).

Reviewer: p7, l28-30: Given the difference in frequency of troughs and ridges, did you think of applying different thresholds for their identification. Troughs and ridges can be seen as advection of cold and warm air and, due to the variable air density, typical curvature of hgt may vary.

Authors: This is a very interesting suggestion, but we do not find a difference in the curvature between through and ridges. Climatologically, the curvature varies between the lower threshold of 0.05 degrees/km to 0.13 degrees/km for troughs and ridges. In midlatitudes both have a mean curvature of 0.1 degrees/km. However, we did some experiments with a latitude dependency of the thresholds, but did not consider this approach further as it is mainly relevant for regions that we have excluded (<20S and >70N) from our data.

Reviewer: p.8: Can you think of reasons why there is no cyclone maximum near the Iberian Peninsula associated with a peak in trough frequency and Rossby wave breaking? I suggest that these conditions in the upper (middle) troposphere produce cut off lows not visible on the surface.

Authors: Yes, we agree. It is likely cut-off low formation that is taking place in this region. We added this information.

Reviewer: p.8, l34: Despite equatorward shift of troughs off the West coast of the US in summer, the ridges shift poleward during summer (something that one would have expected). Can you discuss what may cause summer poleward shift of troughs in this region?

Authors: We assume that PV streamer formation is more common in this region. Consider the schematic below from Thorncroft et al. (1993). If PV streamer formation, or cut off

formation, is more common (upper panel), the more equatorward elongating troughs will result in a more equatorward displaced.

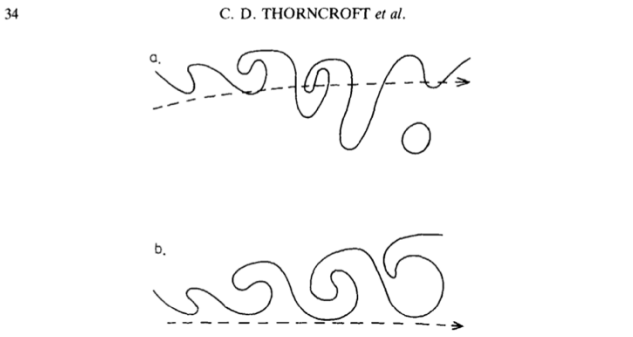

Figure 12. Schematic of a PV-theta contour in an Atlantic storm track sharing its main characteristics with (a) an LC1-type life cycle and (b) an LC2-type life cycle. The dashed line marks the approximate position of the mean jet at each stage.

Reviewer: p.10, l33: The text refers to Fig 6, which shows mean orientation of ridges and troughs. This plot is supposed to illustrate the 'dominance' of those systems in the Pacific, however, I think the frequency should be shown instead.

Authors: Ok, we corrected the sentence since "dominance" is misleading. We want to highlight however the fact that the preferred orientation is now cyclonic over most parts of the Pacific, while this is not the case during the shoulder months. We do not refer to the frequency, but to the preferred orientation regardless of the frequency.

Reviewer: p.11: Did you test longer backward trajectories? Do troughs/ridges have life cycles? It will be nice to see some analysis on this. Are back trajectories in fig. 7 b,c sensitive to the stage of their development?

Authors: We did not test longer backward trajectories, but it is good to see that this section triggers a lot of interesting questions and further suggestions from both reviewers. We consider longer trajectories to be in particular useful for Z300-based troughs and ridges.

We agree that troughs and ridges have a life cycle. However, while we do know their age, it appears to us not as particularly meaningful to release the trajectories from features of similar age. Cyclones, for example, are often categorized according to their genesis, maximum deepening, maximum intensity, maximum decay and lysis. Such a definition can be based on, for example, changes in SLP along each cyclone track. We do not have a similar convention for troughs and ridges. A proper definition of the life cycle stages of troughs and ridges would be required on which the community agrees. This section "only" explores the now new possibility of using the trough and ridge objects as trajectory start location in a "proof-of-concept" fashion. It is not indented to be a complete analysis. We agree that a complete analysis would be very interesting, with different levels and different trajectory lengths, for a complete 30-year period and for different life cycle stages on both hemispheres. All of these questions would easily fill one or two completely new studies and we cannot perform them in this paper.

Reviewer: p.12: A histogram of north/south displacements might be interesting. It is worse noticing that fig. 8a,b and e,f are in good agreement with each other, i.e. decent

corresponds to a reduction in potential temperature. However, then the statement that the downward motions occur along isentropic surfaces sloping equatorward is questionable (though I like to think that the flow is along isentropes).

Authors: We agree, there is on average a mild decrease in potential temperature so the motion is not fully isentropic, but quasi-isentropic. This reduction is found along trajectories that exhibit also a weak downward motion of 0-100hPa in 24 hours starting from the 500 hPa level and we therefore speculate that this is due to radiative cooling. We corrected this statement in the revised manuscript.

Reviewer: p.12, l2: what is the difference between a trough with closed geopotential isolines and a cyclone at that level?

Authors: Yes, it could be a deep surface cyclone or cut-off low with no surface signature, but we want to treat those distinct from "pure" troughs and ridges and the algorithm thus labels the former as closed-contour or closed troughs and the latter and open troughs. Although the distinction between closed and non-closed (open) troughs is somewhat arbitrary, it also matches with a human forecaster's perspective. And, as stated in the manuscript, it is also partly the aim of our approach to mimic the geometric view of a human forecaster.

Reviewer: p14, l.10: Is the code available online?

Authors: We are happy to share the data and the code. As is the case for all our feature-based climatologies, the data will be provided at http://eraiclim.ethz.ch (see Sprenger et al. 2017 for a full list of available climatologies; note that we are in the transition to ERA5 data) and the Fortran and Python codes will be made available on request.

- Sprenger, M., et al. 2017: Global Climatologies of Eulerian and Lagrangian Flow Features based on ERA-Interim. Bull. Amer. Meteor. Soc., 98, 1739–1748, https://doi.org/10.1175/BAMS-D-15-00299.1

Reviewer: Abstract: "methods that detect the initiation phase of upper-level Rossby wave development" - did you mean Rothlisberger et al. 2016 paper or another? I could not find a paper on this in the references.

Authors: Yes, this was missing, we added a reference to the introduction.

Reviewer: p1, l.22: for a good reason.

Authors: Corrected.

Reviewer: p1, l.24: replace enchanted with increased.

Authors: Corrected.

Reviewer: p2, l.3: re-phrase to read better.

Authors: We tried to simplify the sentence.

Reviewer: P6, l19: change to 'Altai' (multiple times in the paper). Not sure whether this is still east Asia. Perhaps, Far East is better.

Authors: We changed the wording consistently to "Altai". Maybe Far East is a bit ancient. We removed East Asia as suggest and no consistently refer to Altai (the latter is partly in East and Central Asia).

Reviewer: P.6, l20: remove 'slightly'

Authors: Removed.

Reviewer: Fig. 3, 4: On my screen continents are barely visible. As for elevated areas, I suggest either marking them with a different colour or hatching.

Authors: We did some experiments with hatching, but turned out to look rather patchy in the printed version. We will make sure, together with the editing team, that during the typesetting the quality of the continents will be increased. We did not use the high-quality figures for the initial submission and will submit higher-quality figures to the editorial office.

Reviewer: p.11, last line: I am not sure why you say 'pushing air', I guess it is being pushed. Perhaps 'moving air' is better.

Authors: Yes, perhaps "moving air" is better, we replaced "pushing air" with "moving air".

Reviewer: p.12, l6: remove 'most'

Authors: Corrected.

Reviewer: p.12, l3: change 'ore' to 'or'

Authors: Corrected.

Thank you for the helpful comments!