Replies to the reviewers of "A Lagrangian analysis of upper-tropospheric anticyclones associated with heat waves in Europe" by Philipp Zschenderlein et al.

We thank the reviewers for their interest and the time they spent to review our manuscript. The comments were very constructive and helped us to improve the quality of the manuscript. The comments of the reviewers are given in black, our replies in green colour.

Review #1

In order to simplify the revision task, I organized my remarks taking into consideration the list of aspects suggested in the WDC review criteria, as follows:

1. Does the paper address relevant scientific questions within the scope of WCD?
The manuscript addresses interesting questions, concerning synoptic conditions and processes leading to the occurrence of heat waves in Europe, which, regarding the global warming and increasing frequency of positive temperature extremes, is scientifically relevant and perfectly comprises the scope of the journal Weather and Climate Dynamics.

2. Does the paper present novel concepts, ideas, tools, or data?
The concept of analyzing the role of diabatic heating for the formation and maintenance of upper-tropospheric anticyclones associated with heat waves, which was undertaken in the paper is novel and it was pursued with adequate modern methods of a Langrarian analysis. Authors defined the backward trajectories of air parcels in the days prior to heat waves and quantified diabatic processes along the trajectories, which influenced formation of anticyclones.

3. Are substantial conclusions reached?
Relevant, although surprising conclusions concerning the two source regions of air masses were obtained for heat waves in Central and Southern Europe. Described spatiotemporal variability of the diabatic processes influencing formation and conditions of anticyclones related to heat waves, seems to be one of the most important results.

4. Are the scientific methods and assumptions valid and clearly outlined?
Data and Methods section is well organized and clearly written. Description of all calculations and research procedures are complete and precise; all methods are adequate to the anticipated results.

Replies to comments 1-4: We thank the referee for his/her comments.

5. Are the results sufficient to support the interpretations and conclusions?
Interpretations and conclusions in general well correspond to the obtained results, however, some conclusions concerning other European regions than the three analyzed in the study in details (Central Europe, western Russia and Greece/ Italy) seem to be weekly documented. Other regions are addressed only in single paragraphs and figures (Fig. 1b and 5b). I would suggest to consider removing regions IB, BI and SC from the analysis.

We discuss results for the regions IB, BI and SC in more detail in the revised version and added the respective figures (Figs. S1-S8) to the supplementary material. Explicitly, we added the following paragraphs:

> *"Three days prior to the arrival of the air parcels in the heating branch over the Iberian Peninsula and the British Isles, most of them are located above the western North Atlantic in the middle and lower troposphere, but also over northwestern Africa and Spain (Figs. S1a,c). For Scandinavia, air parcels are located over the western North Atlantic and southern/central Europe in nearly equal parts (Fig. S1e). On the seven-day time scale, air parcels of the heating branch are distributed between North America and the western Atlantic (Figs. S2a,c), although the dichotomy in the trajectory origin for Scandinavia still exists (Fig. S2e). The results for the cooling branches are qualitatively similar to the other regions (Figs. S1b,d and S2b,d,f), while for Scandinavia, a large fraction of diabatically cooled air parcels is already located in the target area three days prior to arrival (Fig. S1f)."*

Motivated by second reviewer, we have changed the terminology of the two heating branches. Instead of western branch, we use remote branch and instead of eastern branch, we name it nearby branch. This terminology is also used in our replies.

> *"The dominant remote branch reaching anticyclones above the Iberian Peninsula and the British Isles is diabatically heated above the central North Atlantic (Figs. S3a,c), similar to anticyclones over Central Europe. Scandinavia is slightly more influenced by the nearby branch (Figs. S3e,f) and air parcels in this branch are diabatically heated above central and western Europe (Fig. S3f)."*

> *"Trajectory-centred composites for the remote branch reaching anticyclones over western Russia, as well as for both heating branches arriving over the Iberian Peninsula, British Isles, Scandinavia and Greece/ Italy can be found in the supplementary material (Figs. S4-S8). Overall, the composites are qualitatively similar to the already discussed ones, especially for the remote branches (Figs. 4-8a,b), and only differ with respect to the magnitudes of ML CAPE in the nearby branch. ML CAPE values for Greece/ Italy are comparable to those for western Russia, albeit in a smaller area (Figs. S8c,d), but generally lower for trajectories of the nearby branch reaching anticyclones over Scandinavia (Figs. S7c,d) or the British Isles (Figs. S6c,d). In addition, the upper-level ridge of the nearby branch reaching Scandinavia (Fig. S7c) is more pronounced compared to Greece/ Italy (Fig. S8c). A similar difference in the magnitude of the upper-level ridge is found for the remote branches (Figs. S7-8a)."*

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?
Please, see point 4.

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution?
Yes

8. Does the title clearly reflect the contents of the paper?
The title is adequate to the content.

9. Does the abstract provide a concise and complete summary?
Yes.

10. Is the overall presentation well structured and clear?
Yes.

11. Is the language fluent and precise?
Yes.

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?
Yes.

Replies to comments 6-12: We thank the referee for his/her comments.

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?
Some clarifying of figures seems to be needed, namely:
Fig. 1a – please adjust caption concerning PVU lines to the content of the map; it would be useful to put values on PVU isolines.

We added contour labels of the PVU lines and adapted the caption accordingly.

Fig. 1b – I would suggest to consider to delete Fig. 1b and eliminate from the analysis regions IB, BI and SC (please, see remarks in point 5).

See our reply to your comment 5.

Fig. 5a – in my copy the difference between 3d and 7d line is not distinct enough.

We adapted the line style for the 7d line and hope that they are now better discernible.

Fig. 5b – please, see comment in point 5.

See our reply to comment 5.

Fig. 7 and 8 – I would rather suggest to join the figures; please, note that captions are not complete (what does the black checked field mean?)

We think that two separate figures are more suitable, as they represent two branches with different mechanisms. Furthermore, with 6 panels, the images would be too small. We corrected the captions.

Fig. 10 – Please, adjust the caption (I can’t see the black dashed line in the picture).

We meant the black dotted circle, maybe the term "black line" was misleading, we changed it to "black dashed circle".

14. Are the number and quality of references appropriate?

The paper contains a reach list of references pertaining to both methods and comparable results.

Thank you.

15. Is the amount and quality of supplementary material appropriate?
There is no supplementary material.

We uploaded various figures to the supplementary material.

Review #2

This study follows Pfahl et al. (2015) and Steinfeld and Pfahl (2019) - most of the tools are used there – but this study targets heat-wave-associated upper-tropospheric anticyclones, which often can be weaker summertime continental anticyclones. Such target allows this study to find two heating branches: western (Atlantic, related to warm conveyor belt, stratiform precipitation) and eastern (continental, related to ML CAPE, convective precipitation, orographic lifting). The latter is not known in previous studies, potentially because analyses in previous studies (including the above two) might tend to be dominated by stronger oceanic blocking.
I find this study scientifically significant and methodologically sound. It may be well suited for publication if the presentation quality can be further improved and a couple of scientific comments below are addressed.

We thank the referee for his/her comments and agree with the referee's assumption that previous studies tend to be dominated by stronger oceanic blocking, while our approach clearly emphasises summertime continental anticyclones.

Please note that we changed the terminology of the western and eastern branches. We now use remote and nearby branch, respectively.

Major comments
1. (Line 281): As mentioned in line 358, trajectories do not resolve sub-grid scale convective processes. So, how is the eastern branch heated? Is it heated by the weaker stratiform precipitation?

With our discussion in lines 358-373 we noted that sub-grid scale convective ascent is not resolved in ERA-Interim. In order to explicitly resolve sub-grid scale processes with trajectories, the only way would be to run a high-resolution model with explicit convection and calculate online trajectories. Since this is not feasible for a nearly 40-year climatology, we have to live with some limitations in the representation of convective processes. However, in ERA-Interim, the effect of convection is parameterized (cf. Dee et al., 2011, section 3.1.1) and the trajectories will capture the bulk effect of latent heating by convection, even if they don't follow the rapid vertical ascent in convective updrafts. It is important to note that the composites (Figures 8 and 9) show remarkable differences concerning the feature frequencies and ML CAPE between the two branches. Also, the ratio between stratiform and convective precipitation differs. While stratiform precipitation dominates in the remote branch (Figure 8), convective precipitation dominates in the nearby branch, especially for western Russia (Figure 9). Hence, we assume that the precipitation in the remote (warm-conveyor belt) branch is predominantly heated by stratiform precipitation and the nearby branch (enhanced ML CAPE) by convective precipitation. Unfortunately, we are not able to identify whether parcels are heated by shallow-, mid-level or deep-convection. Since precipitation rates in the nearby branch are not very high in the composite, we assume that convection is mostly not very intense.

Since we explained this issue already in our discussion, we decided not to make any further amendments to the text.

2. I view the physical difference between the two heating branches is more about the heating mechanisms, less about where they are 3 days ago. Would it be cleaner to define the two branches based on their "locations of maximum diabatic heating", instead of where they are 3 days ago?

We performed a sensitivity study testing the new categorisation of the heating branches according to the "locations of maximum diabatic heating". Fig. R1 shows the location of maximum diabatic heating for heated trajectories reaching upper-tropospheric anticyclones over Central Europe. Some trajectories are heated above the North Atlantic and some over the European continent. At a first glance, it is difficult to find a clear longitude that separates the two heating branches, which is different to our approach, where locations three days prior to arrival are clearly separated (cf. Figs. 3a,c,e in the manuscript). Fig. R2 (left) shows a steady increase in the number of heated trajectories between 120°W and 18°W, followed by a sharper increase eastward of 18°W, which is somewhat more discernible for heated trajectories reaching anticyclones over Greece/ Italy (Fig. R2, right).

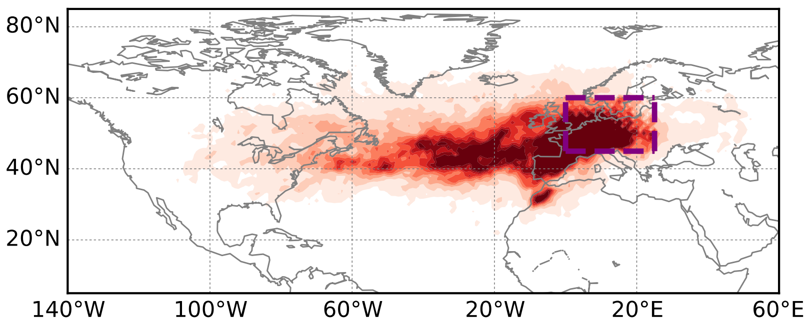

Figure R1: *Location of maximum diabatic heating for diabatically heated trajectories reaching upper-tropospheric anticyclones above Central Europe. Red colour shading shows trajectory counts per grid point.*

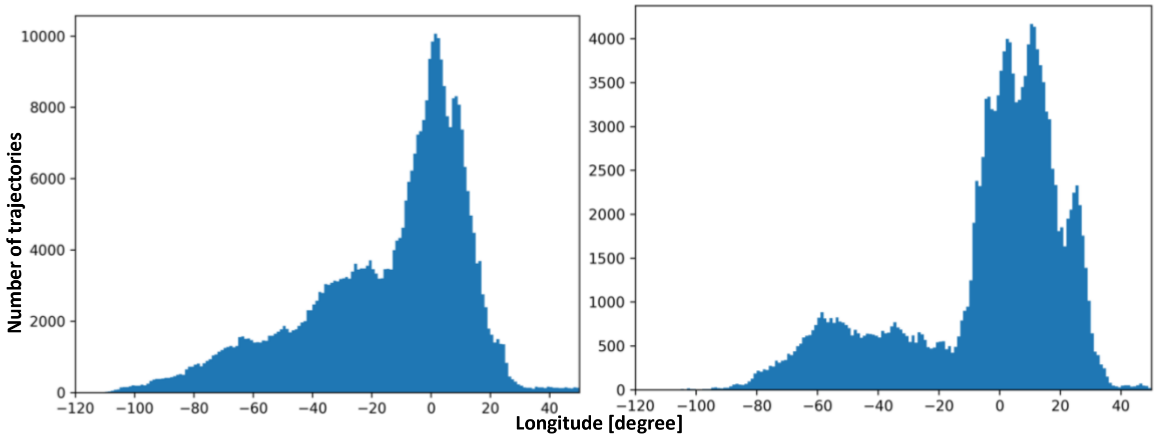

Figure R2: *Longitudinal distribution of diabatically heated trajectories reaching anticyclones over Central Europe (left) and Greece/ Italy (right).*

We have thus chosen 18°W as the longitude separating the remote and nearby branch. The resulting composites are qualitatively similar to our former approach (Fig. R3), although the magnitudes of the anomalies are slightly more pronounced, e.g. the WCB frequency is higher, and the area of convective precipitation is larger compared to our former approach, which is mainly due to the clearer geographical separation of the locations of maximum diabatic heating. Finally, we have looked at the temporal evolution of the two heating branches during the life cycle of the heat waves. The overall result is similar to the old approach (Fig. R4, left), although the relative difference between the remote and nearby branch during the onset is reduced. However, this result is highly sensitive to the definition of the longitude separating the two heating branches. When using 0°E as border, results for the life cycle are different (Fig. R4, right).

Overall, we conclude from this sensitivity analysis that pros and cons exist for both approaches. The advantages of the new approach, i.e. separation of the branches according to the location of maximum diabatic heating, is that the composites are clearer with respect to the feature frequencies. However, results are qualitatively similar to our original approach. The disadvantage of the new approach is that we introduce a new sensitivity, namely towards the separating longitude between the two branches. In our original approach, the longitude border can be identified more easily.

Therefore, we did not change the approach in our manuscript. However, we thank the reviewer for the undoubtedly useful suggestion.

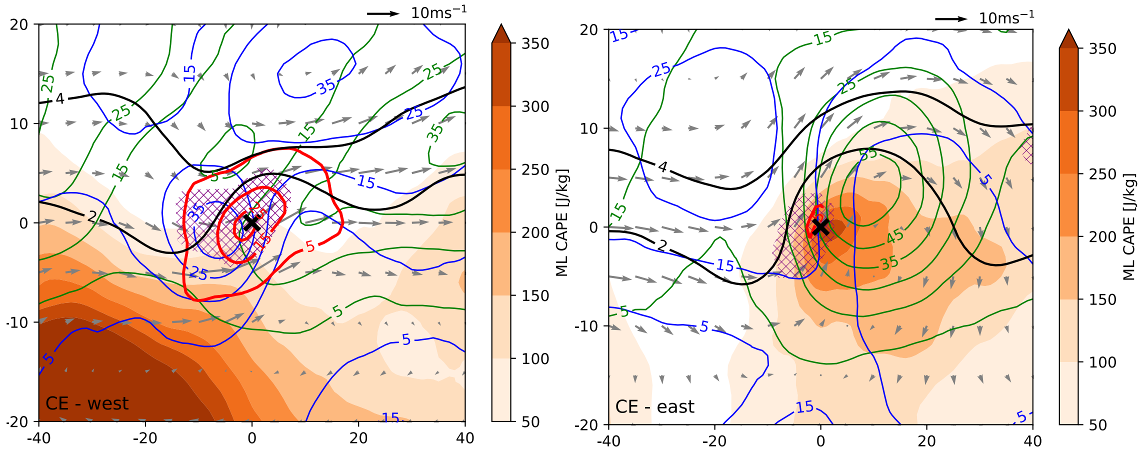

__Figure R3:__ Trajectory-centred composites around location of maximum diabatic heating for the remote (old: western) and nearby (old: eastern) branch reaching upper-tropospheric anticyclones above Central Europe. Colour definitions are the same as in the manuscript.

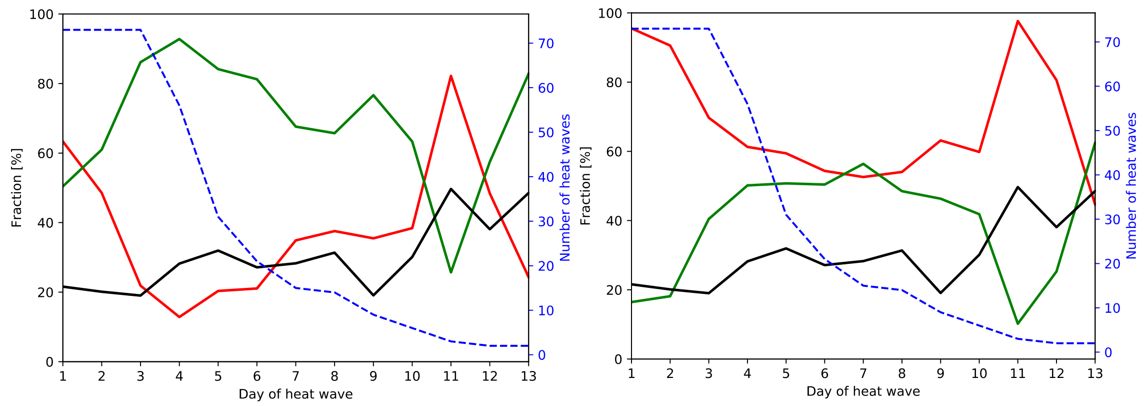

__Figure R4:__ Relative contribution of the two diabatic heating branches during the heat wave life cycle in Central Europe. The left plot shows results for 18°W as border between the remote and nearby branch, the right one for 0°E. Colour definitions are the same as in the manuscript.

3. The novelty of this study against related work is not explicitly emphasized enough. In introduction, readers might want to know the deficiencies in related works that you will be solving, and in what way you might expect your results to differ from theirs.
As mentioned in my summary: I view this study is novel in targeting heat-wave associated upper-tropospheric anticyclones. These anticyclones often collocate with heat waves [Roethlisberger et al. 2016, https://doi.org/10.1002/2016GL070944; Brunner et al. 2018, https://doi.org/10.1029/2018GL077837; Chan et al. 2019, https://doi.org/10.1029/2019GL083307], and are therefore continental anticyclones.
Line 57: Instead of throwing out all the key words, you can emphasize on heat wave anticyclone, saying that they often can be weaker summertime continental anticyclones and therefore may differ from global studies like Pfahl et al. (2015) and Steinfeld and Pfahl (2019), analyses in which might be dominated by more frequent oceanic blocking.
Line 60: Do you expect this study to be different and better than Quinting and Reeder (2017)? If so, please explicitly tell the difference.

Line 145: Again, lack of detailed studies of continental blocking could be the reason why this eastern branch is not known before. Could emphasize on that.

Thank you for the suggestions, we agree with your assessment. We emphasized the novelty of this study more explicitly in the introduction and added the suggested references.

The following aspects were added in the manuscript:

Regarding your comments on lines 57 and 60:

- *"Recent climatological studies on blocking tend to be dominated by oceanic blocking (Pfahl et al., 2015; Steinfeld and Pfahl, 2019), but heat waves are typically associated with summertime continental blocks (Röthlisberger et al., 2016, Brunner et al., 2018, Chan et al., 2019), which are typically weaker than wintertime blocks (Pfahl and Wernli, 2012). Also, the influence of latent heating on the formation of continental blocking may differ. Quinting and Reeder (2017) analysed trajectories reaching the lower and upper troposphere during heat waves over southeastern Australia. They emphasised the influence of cloud-diabatic processes over a baroclinic zone to the south of the Australian continent on the formation of upper-tropospheric anticyclones.*

  However, Quinting and Reeder (2017) did not analyse the life cycle of upper-tropospheric anticyclones, i.e. whether the role of diabatic heating differs between the formation and maintenance of these anticyclones. Since Quinting and Reeder (2017) focused on Australia and no similar study exists for Europe, we therefore aim to analyse the role of diabatic heating for the formation and maintenance of upper-tropospheric anticyclones associated with heat waves in different parts of Europe."

Regarding your comment on line 145 we added the remark that recent studies emphasized on oceanic blocks.

Minor comments

You don't have to, but I personally find the naming of western/eastern branch not intuitive enough. Is there a better alternative?

With respect to your comment 2, we changed the names of the western branch to "remote branch" and the eastern branch to "nearby branch".

The separation line of 30W is not repeatedly mentioned enough. Line 217: You might want to repeatedly remind readers that eastern means east of 30W and western means west of 30W, in this line and many other lines. Line 327: You might want to repeat in conclusions that 30W divides the two branches.

Thank you, we now repeat the separation at 30°W more often.

Line 9: "located southwest of the anticyclone" and "above western North Atlantic" are not mutually exclusive, consider saying "is located *over Africa/Europe* to the southwest. . ."

Thank you for the suggestion. We changed it to “is located over northwestern Africa/Europe to the southwest …”.

Line 22: Warming being “not spatially uniform” doesn’t seem to connect well with the idea of changes in “regional circulation patterns”.

We changed the sentence and only mentioned the changes in regional circulation patterns.

Line 26: This paragraph can start with a better topic sentence, saying that heat waves are associated with either an upper-tropospheric ridge or a blocking flow pattern.

Thank you for the suggestion, we slightly shortened the paragraph.

Line 27-28: In introduction, probably you don’t need to include the fine details of methods in previous research.

This is correct, we have left out the details.

Line 82: Would be good to exemplify upfront that for Central Europe, 72? heat waves lasted for at least 3 days are identified.

We added that 73 heat waves were identified for Central Europe.

Line 87: You might want to explicitly mention that your definition of upper-tropospheric anticyclone requires no temporal persistence (this is implied in line 122).

We now mention this in our manuscript.

Line 109: Might be good to be slightly clearer about the difference in method to Steinfeld and Pfahl (2019).

The main difference to Steinfeld and Pfahl (2019) is that in their study *all* trajectories experiencing diabatic heating of more than 2 K are categorised as “diabatically heated”, no matter how large the cooling is. This is mentioned in the revised manuscript.

Line 233: Might be useful to show the figure for the pressure of maximum diabatic heating.

We added a new figure showing pressure and timestep of maximum diabatic heating (the latter one was a supplementary figure before).

Line 270: Is the idea of Quinting and Reeder (2017) more like warm conveyor belts in the western branch? Or more like the eastern branch? Could be more explicit.

The idea is more like warm conveyor belts in the remote (old: western) branch. We added this in the revised version.

Figure captions: Proofreading or copy-editing is needed. (Plurals, Capital letters,

spaces, etc.)
Figure 7b caption line 6: Please note in caption that orange shading in 7b is not visible.

We deleted the sentence mentioning the orange shading.

Figure 8 caption: Please note in caption that WCB is not visible.

We added a comment on this to the caption.

Figure 8 purple hatching: Do you require total precipitation >= 2 mm/d? You might also want to remind readers that purple hatching in Fig. 8 is opposite to that in Fig. 7.

We completed the caption.

Technical corrections

Line 162: is found east of the *western* heating branch.

Corrected.

Line 224: over the *European* continent. . .

Corrected.

Line 236: *42* to 54 h

Corrected. Thank you for the careful reading.

Line 296: "About 70" -> "72"?

73 heat waves, corrected.

Line 297: a duration of *at least* three days

Corrected.

Line 332: Are there *three* source regions instead of two?

No, only two. The nearby heating branch and the cooling branch originate from a similar region (although from different pressure levels, but we would not see this as a different source region). We added the word *geographic* source regions to make this clear.

Line 376: Do you mean Rossby wave *packets*?

Yes, corrected accordingly.

Figure 3 caption line 4: boxes represents -> boxes represent

Corrected.

Figure 6 caption line 3: ... and Greece/ Italy (GI).

Added.

Figure 7 caption line 6: warm conveyor belts *(red)* frequency

Corrected.

Figure 8 caption line 2: grey shading -> purple hatching?

Corrected.

A Lagrangian analysis of upper-tropospheric anticyclones associated with heat waves in Europe

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Abstract. This study presents a Lagrangian analysis of upper-tropospheric anticyclones that are connected to surface heat waves in different European regions for the period 1979 to 2016. In order to elucidate the formation of these anticyclones and the role of diabatic processes, we trace air parcels backwards from the upper-tropospheric anticyclones and quantify the diabatic heating in these air parcels. Around 25-45% of the air parcels are diabatically heated during the last three days prior to their arrival in the upper-tropospheric anticyclones and this amount increases to 35-50% for the last seven days. The influence of diabatic heating is larger for heat wave-related anticyclones in northern Europe and western Russia and smaller in southern Europe. Interestingly, the diabatic heating occurs in two geographically separated air streams. Three days prior to arrival, one heating branch (~~western~~ remote branch) is located above the western North Atlantic and the other heating branch (~~eastern~~ nearby branch) is located over nortwestern Africa/ Europe to the southwest of the target upper-tropospheric anticyclone. The diabatic heating in the ~~western~~ remote branch is related to warm conveyor belts in North Atlantic cyclones upstream of the evolving upper-level ridge. In contrast, the ~~eastern~~ nearby branch is diabatically heated by convection, as indicated by elevated mixed-layer convective available potential energy along the western side of the matured upper-level ridge. Most European regions are influenced by both branches, whereas western Russia is predominantly affected by the ~~eastern~~ nearby branch. The ~~western~~ remote branch predominantly affects the formation of the upper-tropospheric anticyclone, and therefore of the heat wave, whereas the ~~eastern~~ nearby branch is more active during its maintenance. For long-lasting heat waves, the ~~western~~ remote branch regenerates. The results from this study show that the dynamical processes leading to heat waves may be sensitive to small-scale microphysical and convective processes, whose accurate representation in models is thus supposed to be crucial for heat wave predictions on weather and climate time scales.

1 Introduction

Among various kinds of natural hazards, temperature extremes and especially heat waves during summer impose large impacts particularly on human health (Horton et al., 2016; Watts et al., 2018). Anthropogenic climate change has already increased the number of heat wave days during the last decades (Perkins et al., 2012), which is in line with an overall global-scale temperature increase (Horton et al., 2015). ~~However, the warming is not spatially uniform (Field et al., 2014) and some~~ Some regions, e.g. Europe, encounter changes in the frequency, persistence and maximum duration of regional circulation patterns associated with extreme temperatures (Horton et al., 2015). It is therefore crucial to understand the processes that lead to the formation and maintenance of these circulation patterns.

Recently, Zschenderlein et al. (2019) provided an analysis of European heat waves in the time period 1979 to 2016, identified as regions with temperature anomalies exceeding both the 90$^{\text{th}}$ percentile of daily maximum temperatures and the 25$^{\text{th}}$ percentile of annual maximum temperatures for at least three days. In and in all subregions considered, from the Iberian Peninsula to western Russia, these heat waves were associated with either an upper-tropospheric ridge or a blocking flow pattern. Several earlier studies emphasised that heat waves in the midlatitudes are typically co-located with atmospheric blocking (Carril et al., 2008; Pfahl and Wernli, 2012; Stefanon et al., 2012; Pfahl, 2014; Tomczyk and Bednorz, 2019). Heat waves in Southern and Central Europe are often caused by intense subtropical ridges extending to Southern Europe (Sousa et al., 2018) or by a displacement of a North Atlantic subtropical high to Central Europe (Garcia-Herrera et al., 2010). Both blockings and intense ridges are associated with anticyclonic flow anomalies in the upper troposphere, and these anticyclones are essential for the persistence of the events and for the strong downwelling associated with intense adiabatic warming of the air parcels (Zschenderlein et al., 2019). Upper-tropospheric anticyclones can therefore be regarded as an essential dynamic precursor for the formation of surface heat waves. As a continuation of Zschenderlein et al. (2019), we here aim to investigate the formation of these anticyclones in a Lagrangian and potential vorticity (PV) framework.

Both blockings and subtropical highs are associated with negative PV anomalies in the upper troposphere (Schwierz et al., 2004). These anomalies are the result of isentropic advection of low-PV air or cross-isentropic transport of low-PV air along moist ascending air streams. The isentropic advection of low-PV air corresponds to (i) the mechanism introduced by Yamazaki and Itoh (2013), in which blocking is maintained by the absorption of synoptic-scale anticyclones or (ii) the quasi-adiabatic transport of air from lower latitudes, often ahead of extratropical cyclones (e.g. Colucci, 1985). Pfahl et al. (2015) and Steinfeld and Pfahl (2019) investigated, in a Lagrangian framework, the influence of diabatic heating on the formation and maintenance of blocking. Up to 45% of the air masses in northern hemispheric blocks experience latent heating by more than 2 K during the three days prior to their arrival in the block, and this percentage increases up to 70% when considering a seven-day period (Pfahl et al., 2015). The contribution of latent heating to the formation and maintenance of blocking is not uniform. Latent heating is more important for the onset than for the maintenance of the block (Pfahl et al., 2015). And in northern hemispheric winter, the contribution of latent heating is much larger for blocks over the oceans than for continental blocks, while in summer also continental blocks are substantially affected by latent heating (Steinfeld and Pfahl, 2019).

Latent heating due to condensation of water vapour is not only restricted to the formation of blocking, it generally influences the upper-level ridge building and amplification (e.g. Pomroy and Thorpe, 2000; Grams et al., 2011). In the midlatitudes, synoptic-scale latent heating occurs within moist ascending air streams from the lower to the upper troposphere, so-called warm conveyor belts (WCBs) (Green et al., 1966; Harrold, 1973; Browning et al., 1973). The outflow of the WCB produces negative PV anomalies at the level of the midlatitude jetstream and is therefore a key process for the upper-level ridge building (Madonna et al., 2014).

~~Only very few studies so far specifically investigated the role~~ Recent climatological studies on blocking tend to be dominated by oceanic blocking (Pfahl et al., 2015; Steinfeld and Pfahl, 2019), but heat waves are typically associated with summertime continental blocks (Röthlisberger et al., 2016; Brunner et al., 2018; Chan et al., 2019), which are typically weaker than wintertime blocks (Pfahl and Wernli, 2012). Also, the influence of latent heating ~~for~~ on the formation of ~~upper-tropospheric anticyclones related to heat waves in summer~~continental blocking may differ. Quinting and Reeder (2017) analysed trajectories reaching the lower and upper troposphere during heat waves over southeastern Australia. They emphasised the influence of cloud-diabatic processes over a baroclinic zone to the south of the Australian continent on the formation of upper-tropospheric anticyclones.

~~This study therefore focuses on~~ However, Quinting and Reeder (2017) did not analyse the life cycle of upper-tropospheric anticyclones, i.e. whether the role of diabatic heating differs between the formation and maintenance of these anticyclones. Since Quinting and Reeder (2017) focused on Australia and no similar study exists for Europe, we therefore aim to analyse the role of diabatic heating for the formation and maintenance of upper-tropospheric anticyclones associated with heat waves in different parts of Europe. We apply an impact-oriented perspective, meaning that we study a particularly impact-related type of upper-tropospheric flow anomalies. The following questions are addressed:

(1) What are typical source regions of low-PV air masses that constitute the upper-tropospheric anticyclones associated with European summer heat waves?

(2) Are there inter-regional differences in the contribution of diabatic heating to the formation of these anticyclones?

(3) Where and in which synoptic environment does the diabatic heating occur in airflows entering the anticyclones?

(4) Are there differences in the relevance of diabatic heating during the formation and maintenance of the anticyclones?

Section 2 provides an overview of the data and methods employed in this study. The results section 3 starts with a discussion of the origin of the air parcels arriving in the upper-tropospheric anticyclones followed by a comparison of different regions in Europe. Subsequently, the locations of strong diabatic heating and their synoptic environments are presented. The results section closes with a comparison of the formation and maintenance of upper-tropospheric anticyclones. In section 4, a summary of the main findings and avenues for further research are presented.

2 Data and Methods

This section first describes the identification of upper-tropospheric anticyclones and their connection to the heat waves at the surface. Secondly, the calculation of the trajectories and the identification of diabatic processes are outlined. If not noted otherwise, all analyses are based on the ERA-Interim reanalysis of the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011) on a 1° x 1° longitude-latitude grid. To be consistent with Zschenderlein et al. (2019), we use the period between 1979 and 2016.

2.1 Identification of upper-tropospheric anticyclones

We aim to assign the surface heat waves in the six European regions (dashed boxes in Fig. 1b) used in Zschenderlein et al. (2019) to upper-tropospheric anticyclones. For defining As an example, 73 heat waves are identified for Central Europe (Zschenderlein et al., 2019). In order to define upper-tropospheric anticyclones, we use a PV-approach introduced by Schwierz et al. (2004) that is based on the anomaly of the instantaneous, vertically averaged PV between 500 and 150 hPa with respect to the monthly climatology. To be identified as an upper-tropospheric anticyclone, the PV anomaly at a grid point must fall below -0.7 PVU (1 PVU = 10^{-6} K kg^{-1} m^2 s^{-1}). Pfahl and Wernli (2012) used this threshold for the definition of weak blocking and demonstrated that the link between weak blocking and northern hemispheric warm temperature extremes is particularly robust. We therefore choose the -0.7 PVU threshold for defining upper-tropospheric anticyclones. Note that our definition of upper-tropospheric anticyclones requires no temporal persistence in contrast to Schwierz et al. (2004) and is only constrained by the duration of the surface heat wave.

In a second step, we assign the upper-tropospheric anticyclone to the respective region. Exemplarily for Central Europe, Fig. 1a depicts a composite of the vertically averaged PV anomaly for all heat wave days. The composite shows a negative upper-tropospheric PV anomaly with small standard deviations over Central Europe. In order to study the formation of the corresponding anticyclones, we define a rectangular box enclosing the -0.5 PVU contour line in the composite (black solid box in Fig. 1a) and assign all upper-tropospheric negative PV anomalies in this box to heat waves in Central Europe. The respective boxes for the other regions are shown in Fig. 1b. All grid points with PV anomalies below -0.7 PVU in the respective box during heat wave days in the corresponding region (dashed boxes in Fig. 1b) are identified as upper-tropospheric anticyclones.

2.2 Backward trajectories

Seven-day backward trajectories, driven by three-dimensional ERA-Interim wind fields on 60 vertical model levels, are calculated at each six-hourly time step with LAGRANTO (Sprenger and Wernli, 2015) for every heat wave day. Trajectories are initialised in the upper-tropospheric anticyclone and started from an equidistant grid (Δx=100 km horizontally) and vertically between 500 and 150 hPa every 50 hPa with the additional criterion that the PV at the respective level must be less than 1 PVU. The latter excludes starting points in the stratosphere, similar to Steinfeld and Pfahl (2019). Physical parameters traced along the trajectories include temperature and potential temperature. The total number of trajectories is between 700,000 for Greece/Italy and nearly 2,000,000 for Scandinavia.

In order to quantify diabatic processes along the trajectories, we evaluate whether diabatic heating or cooling dominates. For that, we calculate the highest (θ_{max}) and lowest potential temperature (θ_{min}) along the backward trajectories over a three or seven day period. Diabatic heating is calculated as the difference ($\Delta\theta$) between θ_{max} and the preceding, i.e. closer to the origin, potential temperature minimum, whereas diabatic cooling is quantified as the difference ($\Delta\theta$) between θ_{min} and the preceding potential temperature maximum. If the diabatic heating exceeds the absolute value of the diabatic cooling, the trajectory belongs to the heating branch and vice versa. If the magnitude of diabatic cooling and heating are equal, the trajectory will be sorted in the cooling branch. This approach is similar to Steinfeld and Pfahl (2019), but differs in the categorisation of the diabatic heating and cooling brancheswith the difference that in their study all trajectories heated by more than 2 K are categorised as "diabatically heated", no matter how large the diabatic cooling is.

Figure 2 shows an example for a three-day period: the backward trajectory in Fig. 2a experiences stronger diabatic heating (red arrow in Fig. 2a) than cooling (blue arrow in Fig. 2a) and therefore belongs to the heating branch, whereas in Fig. 2b the diabatic cooling dominates and the trajectory is consequently sorted in the cooling branch.

2.3 Feature composites

To explore in which synoptic environment the air parcels in the heating regime are diabatically heated, we create composites of various features centred around the location of maximum diabatic heating. We show PV at 330 K, wind at 800 hPa, mixed-layer convective available potential energy (ML CAPE) and convective and large-scale precipitation. Whereas convective precipitation in ERA-Interim comes from the parameterised shallow, mid-level and deep convection, large-scale, i.e. stratiform, precipitation denotes the contribution coming from the cloud scheme (Dee et al., 2011). Flow features, i.e. blocks, cyclones and warm conveyor belts, are taken from Sprenger et al. (2017). In their climatology, weak atmospheric blocking is defined as a region where the anomaly of vertically averaged PV between 500 and 150 hPa is lower than -0.7 PVU and persists for at least five days (Schwierz et al., 2004; Croci-Maspoli et al., 2007). Hence, temporal persistence is required in addition to our definition of upper-level anticyclones. The region affected by a cyclone is defined as the region within the outermost closed sea level pressure isoline surrounding one or several local sea level pressure minima (Wernli and Schwierz, 2006). Warm conveyor belts are air parcel trajectories ascending more than 600 hPa in two days associated with a midlatitude cyclone (Madonna et al., 2014). A more detailed description of the three features is given in Sprenger et al. (2017). To assess, whether the occurrence of blocks, cyclones and WCBs is anomalous, we compare the frequencies of the three features during diabatic heating with their climatological frequencies. The anomaly is then defined as the difference between the observed frequency during heat wave days and the climatological frequency.

3 Results

3.1 Source regions of low-PV air masses

This section focuses on the origin of trajectories started from the upper-tropospheric anticyclones. To this end, density maps of trajectory locations at specific time steps are created, which show relative frequencies and are normalised such that the spatial integral over the whole distribution yields 100%. We only present the density maps for heat waves in Central Europe, Western western Russia and Greece/Italy because they exhibit the largest differences. Results for the other three regions, viz. Iberian Peninsula, British Isles and Scandinavia are shown in the supplementary material (Figs. S1-S2).

Three days prior to the arrival of the trajectories in the upper-tropospheric anticyclone over Central Europe, one part of the heating branch is located over the western North Atlantic and the other part over northwestern Africa in the middle and partly lower troposphere (Fig. 3a). The western North Atlantic is a typical source region of diabatically heated trajectories for the formation of atmospheric blocking, although the main source region in summer is shifted towards North America (Pfahl et al., 2015). In the blocking study by Pfahl et al. (2015), most of the backward trajectories were initialised over the North Atlantic to the west of Central Europe, which explains the westward shift of the source regions of diabatically heated trajectories compared to our study. Additionally, the western North Atlantic is the entrance region of the summer storm tracks (Dong et al., 2013) and therefore a region prone to diabatic heating. The second major source region over northwestern Africa (Fig. 3a) is not known as a source region for air parcels influencing the formation of blocking, presumably due to the stronger influence of oceanic blocks in other studies (e.g. Pfahl et al., 2015; Steinfeld and Pfahl, 2019), but appears to be important for the formation of summertime upper-tropospheric anticyclones in association with heat waves. Due to this separation of the heating branch into two distinct regions, trajectories in the heating branch located west and east of 30°W three days prior to the arrival in the upper-tropospheric anticyclone are analysed separately in the following and are hereafter denoted as the western and eastern remote and nearby heating branch, respectively.

Air parcels in the cooling branch related to upper-tropospheric anticyclones above Central European heat waves are located in the upper troposphere at around 300-400 hPa and mostly above northwestern Africa, but also over the North Atlantic and already within the upper-level anticyclone area three days prior to their arrival (Fig. 3b). These air parcels are then transported northwards to Central Europe along the western flank of the ridge associated with the heat wave. Pfahl et al. (2015) showed that the majority of the air parcels not influenced by diabatic heating (comparable to our cooling branch) are, three days prior to the arrival in the block, located to the east of the diabatically heated trajectories. This is also the case here when comparing the location of the cooling with the western remote heating branch (Figs. 3a,b).

Seven days prior to the arrival of the air parcels in the heating branch to Central Europe, most of them are located above North America and the western North Atlantic and to some extent above northwestern Africa. Compared to the three-day period, air parcels are located at lower altitudes (Fig. 4a). Generally, air parcels in the subtropics over the North Atlantic and Gulf of Mexico are located at lower altitudes compared to air parcels above the North American continent and towards the East Pacific. Air parcels in the cooling branch are at similar pressure levels compared to the three-day period, but more widely distributed compared to the heating branch with a maximum density above the North Atlantic (Fig. 4b). Similar to the three-day timescale, the major part of the cooling branch is found east of the remote heating branch.

The density maps for air parcels in the heating branch reaching Western western Russia exhibit two distinct differences compared to Central Europe. Firstly, the source regions of the heating branch do not show two clearly separated geographical maxima on the three-day timescale (Fig. 3c). In fact, the major part of this branch is located above the European continent and in the middle troposphere. However, on the seven-day timescale, a pattern of two geographical maxima emerges with the highest densities over the western North Atlantic and in the Mediterranean area (Fig. 4c). Secondly, more air parcels are already located in the vicinity of the target upper-level anticyclone indicating that the diabatic heating can occur more locally. The overall pattern of the cooling branch, however, does not reveal substantial differences compared to the pattern for Central Europe, although the maximum densities are generally shifted to the east (Figs. 3d and 4d).

Air parcels in the heating branch reaching the upper-troposphere above Greece/Italy predominantly originate from northwestern Africa during the last three days, in particular from the Atlas Mountains (Fig. 3e). Therefore, these anticyclones are strongly influenced by the ~~eastern~~ nearby heating branch, whereas on the seven-day timescale, most of the diabatically heated trajectories originate from the western Atlantic and North America (Fig. 4e). The majority of the air parcels in the cooling branch are located above the North Atlantic three and seven days prior to the heat wave, but some trajectories are located in the tropics south of 20°N at around 200 hPa (Figs. 3f and 4f) - an area which is climatologically influenced by upper-level easterly winds in summer (Fink et al., 2017). In this region and during this time of the year, organised convection in the from of huge mesoscale convective systems occurs in the ITCZ (InterTropical Convergence Zone) over the West African monsoon region. Their upper-level poleward outflow turns eastward to feed the subtropical jet over Northern Africa and the Mediterranean (cf. Fig. 1 in Lafore et al., 2010).

Three days prior to the arrival of the air parcels in the heating branch over the Iberian Peninsula and the British Isles, most of them are located above the western North Atlantic in the middle and lower troposphere, but also over northwestern Africa and Spain (Figs. S1a,c). For Scandinavia, air parcels are located over the western North Atlantic and southern/central Europe in nearly equal parts (Fig. S1e). On the seven-day time scale, air parcels of the heating branch are distributed between North America and the western Atlantic (Figs. S2a,c), although the dichotomy in the trajectory origin for Scandinavia still exists (Fig. S2e). The results for the cooling branches are qualitatively similar to the other regions (Figs. S1b,d and S2b,d,f), while for Scandinavia, a large fraction of diabatically cooled air parcels is already located in the target area three days prior to arrival (Fig. S1f).

3.2 Two diabatic regimes

We now compare the statistical distributions of the potential temperature changes in the heating and cooling branch. Changes in potential temperature during the last three and seven days prior to reaching upper-tropospheric anticyclones over Central Europe are shown as probability density distributions. For both the three- and seven-day period, the shape of the cooling branch features a Gaussian normal distribution, whereas the heating branch is more skewed (Fig. 5a). This skewness increases for the seven-day period, implying an overall higher magnitude of diabatic heating along the trajectories on this timescale. During the last three days, about 29% of the trajectories are influenced by diabatic heating and, consequently, 71% belong to the cooling branch (Fig. 5b). On the seven-day timescale, 42% of the trajectories are in the heating branch (Fig. 5b). Hence, diabatic heating along trajectories substantially influences the formation of upper-tropospheric anticyclones above Central Europe.

The majority of trajectories in the cooling branch slightly descend and are radiatively cooled in the free atmosphere, while most of the trajectories in the heating branch ascend (not shown). Overall, the diabatic heating is a more rapid process compared to the diabatic cooling (not shown). Therefore, the heating branch can be interpreted as a strongly cross-isentropic branch transporting low-PV air from the lower to the upper troposphere, whereas the cooling branch is a quasi-adiabatic process that advects low-PV air towards the upper-tropospheric anticyclone, in line with the analysis of Pfahl et al. (2015) and Steinfeld and Pfahl (2019) for blocks.

The cross-isentropic transport of low-PV air from the lower to the upper troposphere in the heating branch is stronger for western Russia. During the last three days, about 44% of the air parcels reaching upper-tropospheric anticyclones above western Russia are affected by the heating branch, which is the highest fraction among the different European regions (Fig. 5b).

For Scandinavia and the British Isles, about 35% of the air parcels are influenced by diabatic heating, which is slightly more than for Central Europe. The Mediterranean area, i.e. Greece/Italy and the Iberian Peninsula, however, is less influenced by the heating branch with only about 25% of the trajectories in this branch on the three-day timescale. During the last seven days, the relevance of the heating branch increases for all regions (Fig. 5b). The highest influence of the heating branch (about 50%) is found for trajectories reaching upper-tropospheric anticyclones above the British Isles, Scandinavia and western Russia. Interestingly, the increase of the fraction of diabatically heated air parcels from the three- to the seven-day period is smallest for western Russia, indicating that heat wave anticyclones in western Russia are less influenced by remote diabatic heating beyond three days prior to their arrival in the anticyclone.

Comparing the fraction of diabatically heated air parcels contributing to the formation of atmospheric blocks (Pfahl et al., 2015) with our findings, we conclude that the fraction is lower in our study. This can be explained by three main reasons: firstly, weather systems that are associated with diabatic heating such as extratropical cyclones and warm conveyor belts are climatologically less frequent during summer (Madonna et al., 2014). Secondly, Pfahl et al. (2015) defined blocking with a more pronounced negative PV anomaly, and because more intense negative PV anomalies are associated with stronger latent heating in WCBs (Madonna et al., 2014), the influence of diabatically heated trajectories is reduced in our study. Thirdly, the quantification of diabatic heating along trajectories of Pfahl et al. (2015) is slightly different, because they only quantified the contribution of diabatic heating to the formation of blocking and did not account for diabatic cooling.

3.3 Two geographically separated heating branches

In the remainder of this study, we further analyse the heating branches for heat wave anticyclones in three regions. Remember that heated trajectories located west (east) of 30°W three days prior to the arrival in the heat wave anticyclone belong to the remote (nearby) heating branches. We focus on Central Europe and Greece/Italy, which are affected by the ~~eastern and western~~ nearby and remote heating branches (Fig. 3a,e), and on western Russia, which is affected predominantly by the ~~eastern~~ nearby heating branch (Fig. 3c).

The spatial distributions of the locations of maximum diabatic heating along the trajectories for the ~~eastern and western~~ nearby and remote heating branches are shown in Fig. 6. These locations are defined as the geographical positions at the end of the maximum 6-h increase of potential temperature in the last three days prior to reaching the upper-level anticyclones. The ~~western~~ remote heating branch associated with anticyclones above Central Europe accounts for 50% of the whole heating branch. Most of its diabatic heating occurs over the central North Atlantic between 40°-50°N and 20°-40°W (Fig. 6a). Air parcels in the ~~eastern~~ nearby heating branch are diabatically heated over the European continent in a similar latitude band (Fig. 6b). For western Russia, only 8% of the heated trajectories are in the ~~western~~ remote branch and the strongest diabatic heating occurs over the North Atlantic, but also over Central Europe (Fig. 6c). The dominant heating branch reaching western Russia is the ~~eastern~~ nearby heating branch (92%, Fig. 6d). Most of the diabatic heating in this branch occurs over the European continent and mostly in the target area between 50° and 60°N. For Greece/Italy, 69 (31)% of the heated trajectories are assigned to the ~~eastern (western~~nearby (remote) heating branch. Air parcels in the ~~western~~ remote heating branch experience diabatic heating over the western North Atlantic (Fig. 6e). Local maxima of diabatic heating in the ~~eastern~~ nearby heating branch occur above the Atlas Mountains and the Alps (Fig. 6f), suggesting the importance of orographic ascent for the formation of upper-tropospheric anticyclones in this region. Overall, most of the diabatic heating in the ~~eastern~~ nearby heating branch occurs close to the target region, whereas the ~~western~~ remote heating branch is associated with more remote diabatic heating. Most of the trajectories are diabatically heated at around 400 hPa (~~not shown~~Fig. 7a), indicating that the air parcels are mostly heated due to latent heat release in clouds, as opposed to surface fluxes.

~~Although the western and eastern~~ The dominant remote branch associated with anticyclones above the Iberian Peninsula and the British Isles is diabatically heated above the central North Atlantic (Figs. S3a,c), similar to anticyclones over Central Europe. Scandinavia is slightly more influenced by the nearby branch (Figs. S3e,f) and air parcels in this branch are diabatically heated above central and western Europe (Fig. S3f).

Although the remote and nearby heating branches are geographically separated, it may be possible that the maximum diabatic heating occurs at the same time before arrival in the upper-tropospheric anticyclone. Around ~~48~~ 42 to 54 h prior to arrival, the ~~western~~ remote heating branch experiences the strongest diabatic heating (Fig.~~S1~~ 7b). On the contrary, trajectories in the ~~eastern~~ nearby heating branch are strongly heated between 24 and 36 h prior to arrival (Fig.~~S1~~ 7b). Hence, air parcels in the ~~western~~ remote branch are heated earlier compared to the ~~eastern~~ nearby branch.

To explore which synoptic systems lead to the ascent and latent heat release in the two different heating branches, we create composites of different fields and frequencies of blocks, cyclones and warm conveyor belts centred around the location of maximum diabatic heating. To emphasise the structure of the most pronounced heating, we only considered trajectories in the composites that are diabatically heated by more than 5 K during the last three days.

The composite for the air parcels within the ~~western~~ remote heating branch reaching Central Europe is presented in Fig. 8~~, the composites for the other regions are qualitatively similar (not shown)~~. The upper tropospheric circulation, represented by PV at 330 K, is characterised by a trough upstream of the maximum diabatic heating (Fig. 8a). At the surface, extratropical cyclones are frequently located west and north of the diabatic heating maximum. The position of the extratropical cyclones west of the heating maximum is slightly east of the upper-level PV trough, which corresponds to the canonical configuration of cyclogenesis at the leading edge of an upper-tropospheric trough. In the warm sector of these cyclones, where southwesterly winds prevail (Fig. 8a), lifting occurs according to quasi-geostrophic forcing (Holton and Hakim, 2013). Hence, it is meaningful that warm conveyor belts are found centred around the diabatic heating maximum and downstream of the extratropical cyclones (Fig. 8a). These ascending air streams release latent heat and lead to an increase of potential temperature. Therefore, the ~~western~~ remote heating branch is often influenced by cyclones in the North Atlantic storm track and latent heating in their warm conveyor belts.

Above the diabatic heating maximum, an upper-level ridge evolves and blocking frequencies are enhanced downstream (Fig. 8a). ML CAPE values are usually low in this branch. To the southwest of the diabatic heating maximum, ML CAPE values strongly increase due to climatologically higher sea surface temperatures in the western North Atlantic south of 30°N.

To assess, whether the occurrence of the three features in the North Atlantic region is anomalous for this time of the year, we compare the frequencies of the three features during the diabatic heating with their climatological frequencies. In general, the anomalies of all three features attain their highest values in the vicinity of or at the position of the diabatic heating maximum

(Fig. 8b). To the west and southwest of the diabatic heating maximum, the observed cyclone frequency is about 15 percentage points higher than the climatology, which is an increase by a factor of about 1.5. In contrast, the anomalies of the cyclone frequency to the north are smaller, although the observed frequency is similar (Fig. 8a). As a result of the enhanced cyclone occurrence, also the existence of warm conveyor belts is anomalously high (Fig. 8b). In accordance with the anomalously high cyclone frequency north and northwest of the diabatic heating maximum, the blocking frequency is anomalously low in this region. Downstream of the diabatic heating maximum, the blocking frequencies are higher and the cyclone frequencies lower than climatologically expected.

Steinfeld and Pfahl (2019) performed a similar composite analysis for the latent heating associated with blocks and found a more pronounced upper-level ridge pattern due to similar reasons as discussed at the end of section 3.2. Overall, the latent heating in the warm conveyor belts of extratropical cyclones is important for the formation of both atmospheric blocks and upper-tropospheric ridges associated with heat waves. Also Quinting and Reeder (2017) highlighted the role of cloud-diabatic processes and ascending air streams for upper-level anticyclones during heat waves in southeastern Australia. This is similar to the warm conveyor belts in our remote branches.

After discussing the synoptic conditions of the ~~western~~ remote heating branch, we now focus on the conditions of the ~~eastern~~ nearby heating branch. In this branch, the diabatic heating maximum is located below the western part of an upper-tropospheric anticyclone, which is much more pronounced compared to the ~~western~~ remote heating branch (Fig. 9a,b). In contrast, the frequency of both cyclones and WCBs at the position of maximum diabatic heating is reduced (WCBs are not visible in Fig. 9a,b; they occur with frequencies of less than 3%). Hence, the driving mechanisms of the latent heating differs between the two branches. The circulation at 800 hPa is more anticyclonic and much weaker in the ~~eastern~~ nearby compared to the ~~western~~ remote heating branch. The most substantial difference between the two heating branches is the enhanced ML CAPE in the ~~eastern~~ nearby heating branch (Fig. 9a,b), indicating the potential for convection. The absolute values of ML CAPE are, however, not extremely high, which may indicate that convection is efficiently depleting the ML CAPE. Additionally, according to ERA-Interim, most of the precipitation in the ~~eastern~~ nearby heating branch is indeed convective (Fig. 9a; more clear for western Russia in Fig. 9b), whereas precipitation in the ~~western~~ remote heating branch is predominantly stratiform (Fig. 8a). Cloud top temperatures derived from infrared ~~Satellite~~ satellite imagery are between -5 and $-9°$ C at the location of maximum diabatic heating (not shown). Hence, we assume that in the ~~eastern~~ nearby branch latent heating is driven by mid-level convection or deep convection that reaches from lower into mid levels.

The anomalies underline the importance of the enhanced blocking frequencies and ML CAPE values for the ~~eastern~~ nearby heating branch (Fig. 9c,d). Although the anomalies show also a small positive anomaly of cyclone frequencies (Fig. 9c,d), the absolute frequency (Fig. 9a,b) is lower compared to the ~~western~~ remote heating branch (Fig. 8a). Comparing the two regions, western Russia shows slightly higher anomalies of blocking frequencies and ML CAPE at the location of maximum diabatic heating (Fig. 9d). The ~~eastern~~ nearby heating branch has not yet been discussed in the literature on the formation of European blocking, but it appears to be relevant for the formation of upper-tropospheric anticyclones in association with heat waves in summer.

Trajectory-centred composites for the remote branch reaching anticyclones over western Russia, as well as for both heating branches arriving over the Iberian Peninsula, British Isles, Scandinavia and Greece/Italy can be found in the supplementary material (Figs. S4-S8). Overall, the composites are qualitatively similar to the already discussed ones, especially for the remote branches (Figs. 4-8a,b), and only differ with respect to the magnitudes of ML CAPE in the nearby branch. ML CAPE values for Greece/Italy are comparable to those for western Russia, albeit in a smaller area (Figs. S8c,d), but generally lower for trajectories of the nearby branch reaching anticyclones over Scandinavia (Figs. S7c,d) or the British Isles (Figs. S6c,d). In addition, the upper-level ridge of the nearby branch reaching Scandinavia (Fig. S7c) is more pronounced compared to Greece/Italy (Fig. S8c). A similar difference in the magnitude of the upper-level ridge is found for the remote branches (Figs. S7-8a).

3.4 Diabatic heating during the life cycle of heat waves

Here, we investigate the life cycle of the upper-tropospheric anticyclones associated with heat waves, i.e. the temporal sequence of the occurrence of the different heating branches. The contributions of the eastern and western nearby and remote heating branches and their relative importance with respect to the whole heating branch is quantified as a function of the duration of the heat waves. We concentrate on the results for Central Europe, because this region is equally affected by both branches. Due to the definition of the heat waves (cf. Zschenderlein et al., 2019), all events have a minimum duration of three days (Fig. 10). About 70 73 events have a duration of at least three days, but only two of them last 13 days. We therefore start with the discussion of the results for the heat waves with a duration up to six days and then elucidate the findings for the longer-lived heat waves. For the latter category, the results are likely less robust due to the small number of events.

During the onset of a heat wave, the western remote heating branch is of primary importance (Fig. 10). The formation of the upper-tropospheric anticyclone is therefore strongly affected by air masses that are diabatically heated in extratropical cyclones in the North Atlantic region. After the first two days of the heat waves, the eastern nearby heating branch with air masses originating from northwestern Africa and heated diabatically due to convection below the western part of the ridge gains relevance (Fig. 10), thus supporting the maintenance of the upper-tropospheric anticyclone. The fraction of trajectories in the whole heating branch, i.e. western and eastern remote and nearby heating branch together, with respect to all trajectories slightly increases during the maintenance of the upper-tropospheric anticyclone (black line in Fig. 10). Hence, the influence of latent heating increases during the life cycle of the events mainly due to an intensification of the eastern nearby heating branch. At first sight, this result is contradictory to the findings of Pfahl et al. (2015) and Steinfeld and Pfahl (2019), who showed that the influence of latent heating reduces during the maintenance phase of atmospheric blocks. However, the heating relevant for atmospheric blocking mainly occurs in trajectories similar to our western remote heating branch, and this branch looses relevance for the maintenance (up to day five) of upper-tropospheric anticyclones also here (Fig. 10).

Overall, the formation of upper-tropospheric anticyclones depends mainly on the latent heating within extratropical cyclones in the North Atlantic storm track, whereas the maintenance is related to air masses that are diabatically heated due to convection above western and central Europe. Although this pattern seems to be relevant for most of the heat waves, longer lasting heat waves show a different behaviour.

The maintenance of heat waves beyond six days duration is more influenced by the ~~western~~ remote heating branch compared to the maintenance of shorter lasting heat waves (Fig. 10). Note that these longer lasting heat waves occur only rarely, therefore results are variable from case to case and less robust. However, it seems that the ~~western~~ remote heating branch revives and has a comparable influence as during the onset of the heat wave. We therefore hypothesize that long-lived upper-tropospheric anticyclones cannot be sustained by the ~~eastern~~ nearby heating branch alone. Rather, cyclones over the North Atlantic and the associated latent heat release are relevant to maintain the negative PV anomalies in the upper troposphere above the heat wave areas. In addition, the fraction of the heating branch related to all trajectories increases for longer-lasting heat waves up to nearly 50%.

4 Conclusions

In this study, we analysed the contribution of latent heating to the formation and maintenance of upper-tropospheric anticyclones associated with heat waves in different parts of Europe. Based on heat waves identified in Zschenderlein et al. (2019), we calculated backward trajectories from the anticyclones and separated the trajectories according to their potential temperature changes. The heating branch was further subdivided according to the location of the air parcels three days prior to the arrival in the upper-tropospheric anticyclone into an ~~eastern and western~~ nearby and remote heating branch. Air parcels located west (east) of 30°W three days prior to the arrival belong to the remote (nearby) heating branch. In the introduction, we raised specific research questions that we aim to summarise for Central Europe with the help of Fig. 11.

1. What are typical source regions of low-PV air masses that constitute the upper-tropospheric anticyclones associated with European summer heat waves?

For Central European heat wave anticyclones, mainly two geographic source regions exist. Three days prior to reaching the upper-tropospheric anticyclones, air parcels in the cooling branch are located in the upper troposphere southwest of the target region, mainly distributed between Central Europe and the central North Atlantic, peaking over the northwest coast of Africa (Fig. 11, label 1). Air parcels assigned to the ~~eastern~~ nearby heating branch are located mainly between Central Europe and the northwest coast of Africa in the mid- to lower troposphere (Fig. 11, label 3), while air parcels in the ~~western~~ remote heating branch culminate between eastern North America and the western North Atlantic (Fig. 11, label 2) at similar altitudes.

2. Are there inter-regional differences in the contribution of diabatic heating to the formation of these anticyclones?

Around 25-45% (35-50%) of the air parcels are diabatically heated during the last three (seven) days prior to the arrival in upper-tropospheric anticyclones. The influence of diabatic heating increases towards northern Europe and western Russia and decreases towards southern Europe. While most regions in Europe are - with varying magnitude - influenced by both the ~~eastern and western~~ nearby and remote heating branch, western Russia is only influenced by one diabatic heating branch. The contribution of diabatic heating increases substantially on the seven-day timescale except for western Russia.

3. Where and in which synoptic environment does the diabatic heating occur in airflows entering the anticyclones?

For most regions in Europe, the diabatic heating occurs in two geographically separated moist ascending air streams. But the air streams differ not only in location, also the processes responsible for the diabatic heating are different. The ~~western~~ remote heating branch is influenced by an enhanced activity of extratropical cyclones and associated warm conveyor belts over the North Atlantic. Diabatic heating in this branch is accompanied by stratiform precipitation, in contrast to the ~~eastern~~ nearby heating branch, where convective-scale precipitation dominates. The moist ascent in the latter branch occurs closer to the target anticyclone in an environment of enhanced ML CAPE and is also aided by orographic lifting.

4. Are there differences in the relevance of diabatic heating during the formation and maintenance of the anticyclones?

The activity in the North Atlantic and the associated latent heat release in cyclones and warm conveyor belts are of primary importance for the onset of the upper-tropospheric anticyclones connected to the heat waves. Their maintenance is affected by the more local diabatic heating in the ~~eastern~~ nearby heating branch. For longer lasting heat waves, the ~~western~~ remote heating branch regenerates and becomes more relevant compared to days 3-5, implying that the ridge connected to the longer lasting heat wave cannot be sustained without the transport of low-PV air to the upper troposphere within extratropical cyclones.

One shortcoming of our approach is that our trajectory calculations are not able to resolve small-scale convective processes. Hence, we possibly underestimate the effect of convection especially in the ~~eastern~~ nearby heating branch and therefore the associated diabatic heating. Recently, Oertel et al. (2019) showed that embedded convection in warm conveyor belts can influence the synoptic-scale circulation and increase the isentropic PV gradient at upper-levels in addition to the slantwise WCB ascent. However, we assume that for our climatological analysis the source regions will not substantially change, because also the convective ascending parcels are located in the vicinity of the slantwise ascending WCB (Oertel et al., 2019) and we argue that convective parameterisation is tuned to capture the climatological bulk effects of deep convection on rainfall and latent heat release. For the the ~~eastern~~ nearby branch, especially in the Greece/Italy case, the pathway of individual trajectories affected by deep convection over the Atlas Mountains and the Alpes might be more uncertain due to the proximity of convection to the heat wave region. Weisheimer et al. (2011) noted that a revised formulation of the convective parameterisations in the ECMWF model improved the predictability of the 2003 European heat wave. Interestingly, air parcels arriving over Greece/Italy can originate from the upper-level easterlies over West Africa (see section 3.1). Pante and Knippertz (2019) show that explicit convection over West Africa improves forecast of upper-level fields over Europe at 5-8 days lead time. Thus, it would be interesting to calculate online, convection-permitting trajectories in high-resolution model simulations (e.g. Miltenberger et al., 2013) to study the impact of convection over the North African subtropics and over southern Europe on the formation of European heat waves.

Our results have relevant implications for both weather and climate dynamics. The processes discussed in our study need to be correctly simulated in both state-of-the-art numerical weather prediction and climate models. Diabatic processes affect the life cycle of Rossby wave ~~packages~~ packets and a misrepresentation of these processes can lead to reduced predictability (Rodwell et al., 2013). Grams et al. (2018) showed that a misrepresented warm conveyor belt in an upstream trough led to misforecasts in the onset of blocking situations over Europe. Also Rodwell et al. (2013) pointed out that convective situations in eastern North America led to a forecast bust over Europe. When considering a higher moisture content in the lower troposphere in a generally warmer world (Held and Soden, 2006), the latent heat release in cyclones or convective systems may increase. The stronger latent heat release stimulates the ascent of air streams that produce more significant negative PV anomalies in the upper troposphere (Madonna et al., 2014). Hence, model experiments quantifying the amplitude and the size of the upper-tropospheric anticyclones subject to a changing moisture content would be helpful to estimate the influence of global warming on the dynamics of European heat waves.

Author contributions. PZ carried out the analysis and SP, HW and AF gave important guidance during the project. PZ wrote the manuscript and all authors provided feedback on the manuscript.

Competing interests. The authors declare that they have no competing interest.

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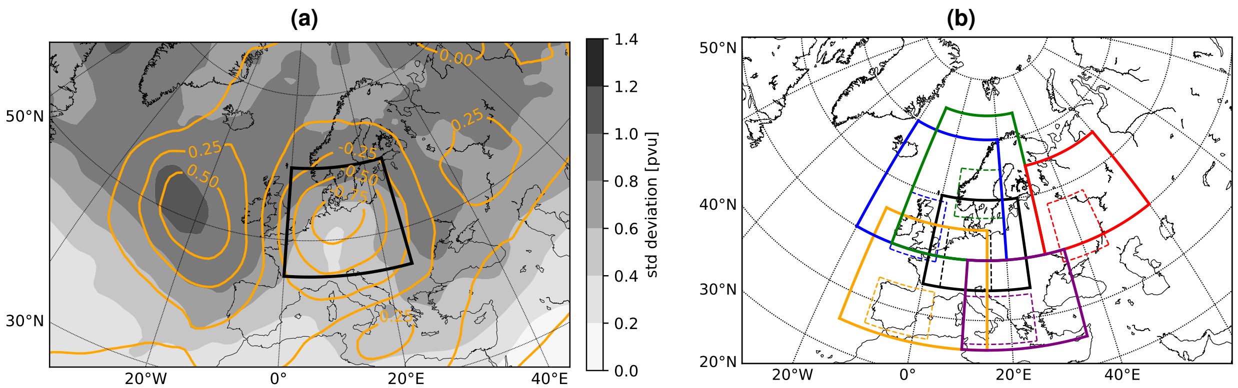

Figure 1. Identification of upper-tropospheric anticyclones. (a): Composite of the instantaneous, vertically averaged PV anomalies (VIPa) for all heat wave days in Central Europe. The contours show the mean of VIPa (in ~~0.25~~ PVU~~increments, 0 PVU line in bold, positive (negative~~) ~~anomalies solid (dashed)~~ and the shading shows the standard deviation of VIPa. (b): The solid boxes depict the regions where the upper-tropospheric PV anomalies are assigned to heat waves at the surface and the dashed boxes show the regions of the heat waves as defined in Zschenderlein et al. (2019): Scandinavia (green), western Russia (red), Greece/Italy (purple), Iberian Peninsula (orange), Central Europe (black, also in (a)) and the British Isles (blue).

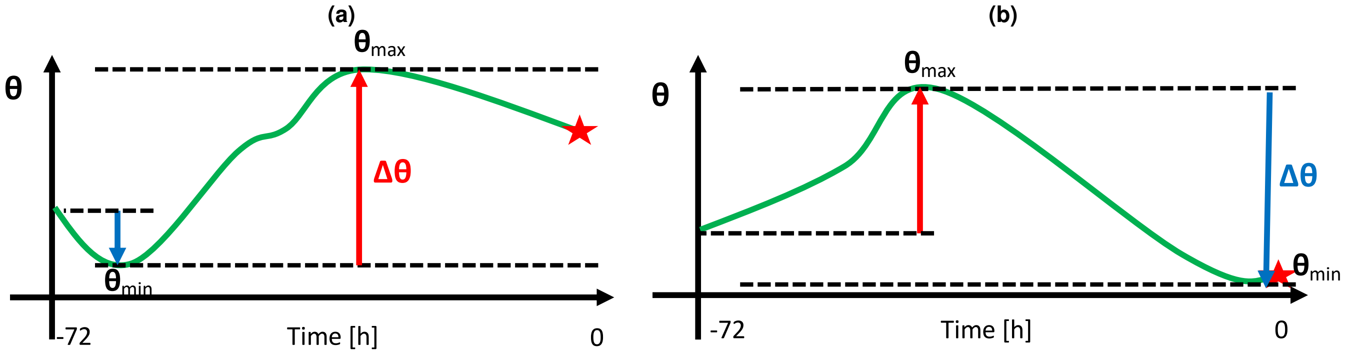

Figure 2. This schematic depicts the potential temperature change $\Delta\theta$ for a three-day period. The red star indicates the starting point of the backward trajectory. (a): Diabatic heating (red arrow) exceeds diabatic cooling (blue arrows). (b): diabatic cooling exceeds diabatic heating.

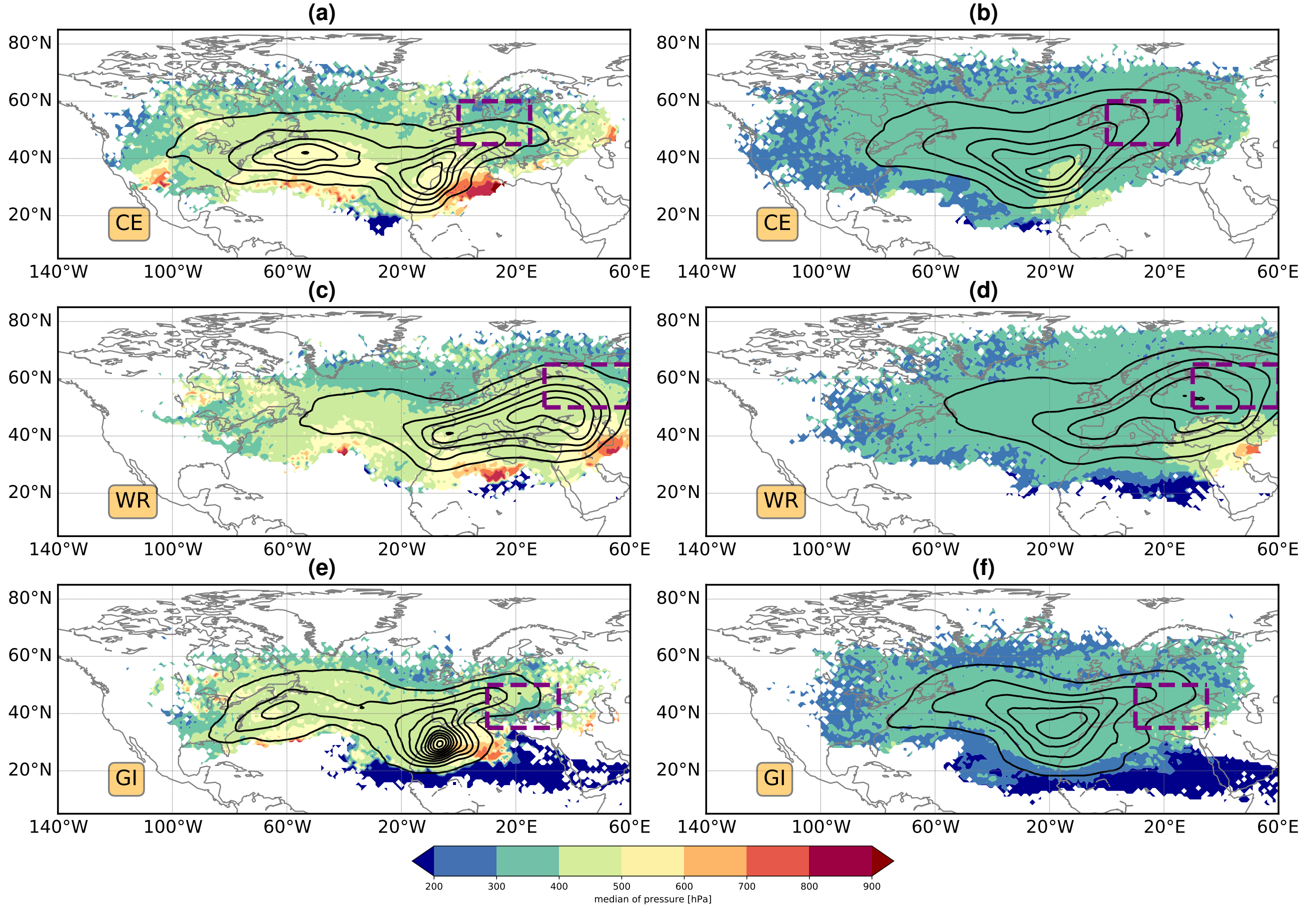

Figure 3. Spatial distribution of diabatically heated (left) and cooled (right) trajectories three days prior to arrival in the upper-tropospheric anticyclones for (a,b) Central Europe (CE), (c,d) western Russia (WR) and (e,f) Greece/Italy (GI). The colours indicate the median pressure of air parcels and contours display the air parcel density (starting from 1‰ per 10^5 km^2 in 2‰ increments). The dashed purple boxes ~~represents~~ represent the area in which upper-tropospheric anticyclones are associated with heat waves (cf. section 2.1 and Fig. ~~1~~1b).

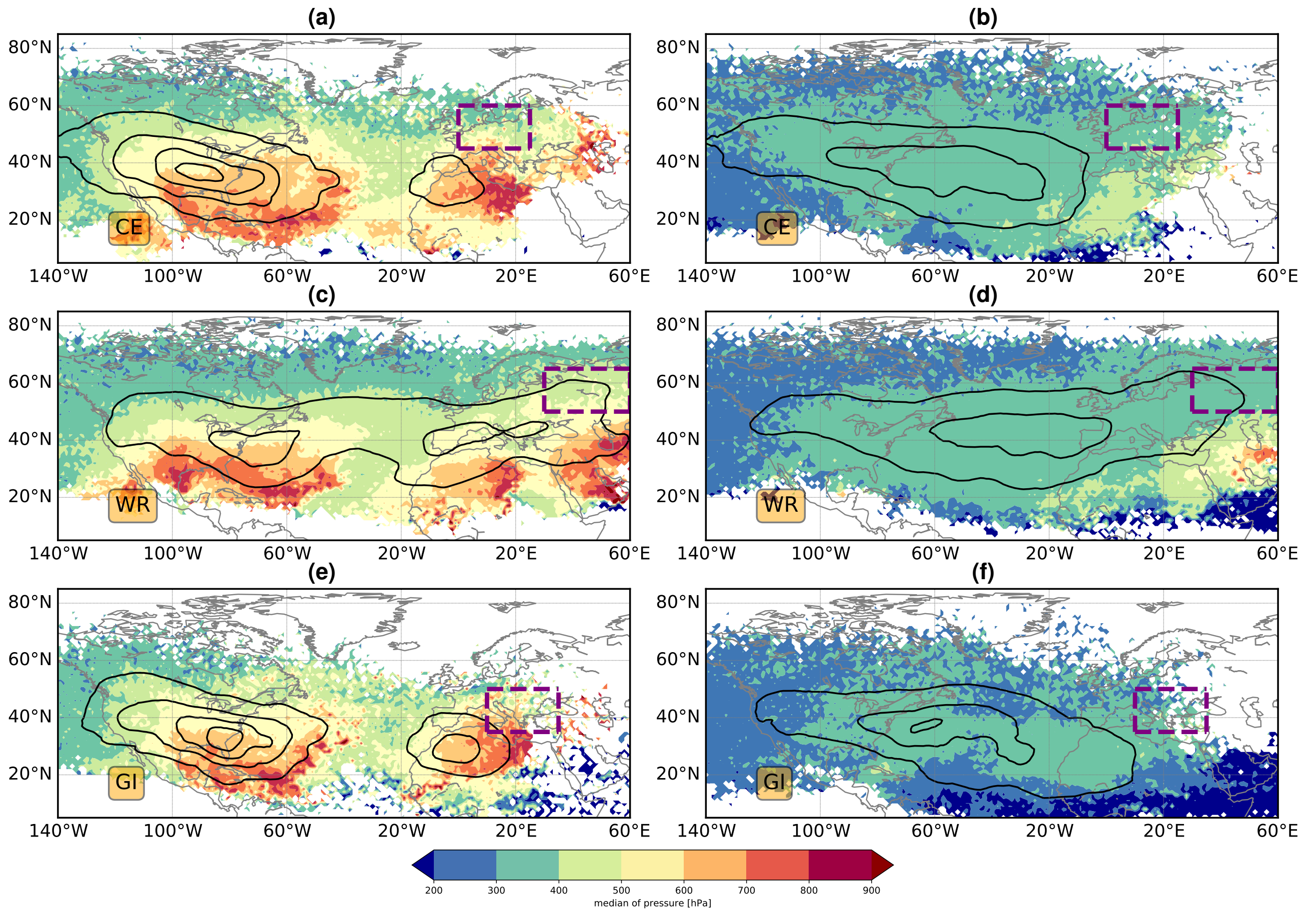

Figure 4. Same as Fig. 3, but for the last seven days.

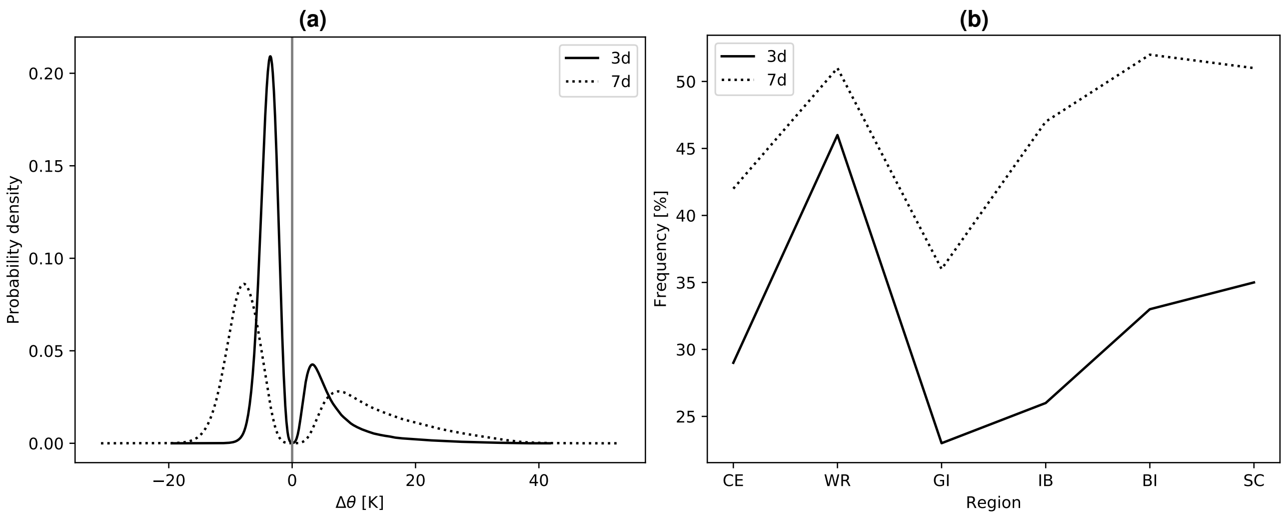

Figure 5. Diabatic processes in the heating and cooling branches three (solid line) and seven days (dashed line) before reaching upper-tropospheric anticyclones. (a): Probability density distribution of the potential temperature changes for air parcels reaching Central European heat wave anticyclones. The grey line denotes the 0 K border separating the heating and cooling branch. (b): Fraction of diabatically heated trajectories for all regions (CE: Central Europe, WR: Western Russia, GI: Greece/Italy, IB: Iberian Peninsula, BI: British Isles and SC: Scandinavia).

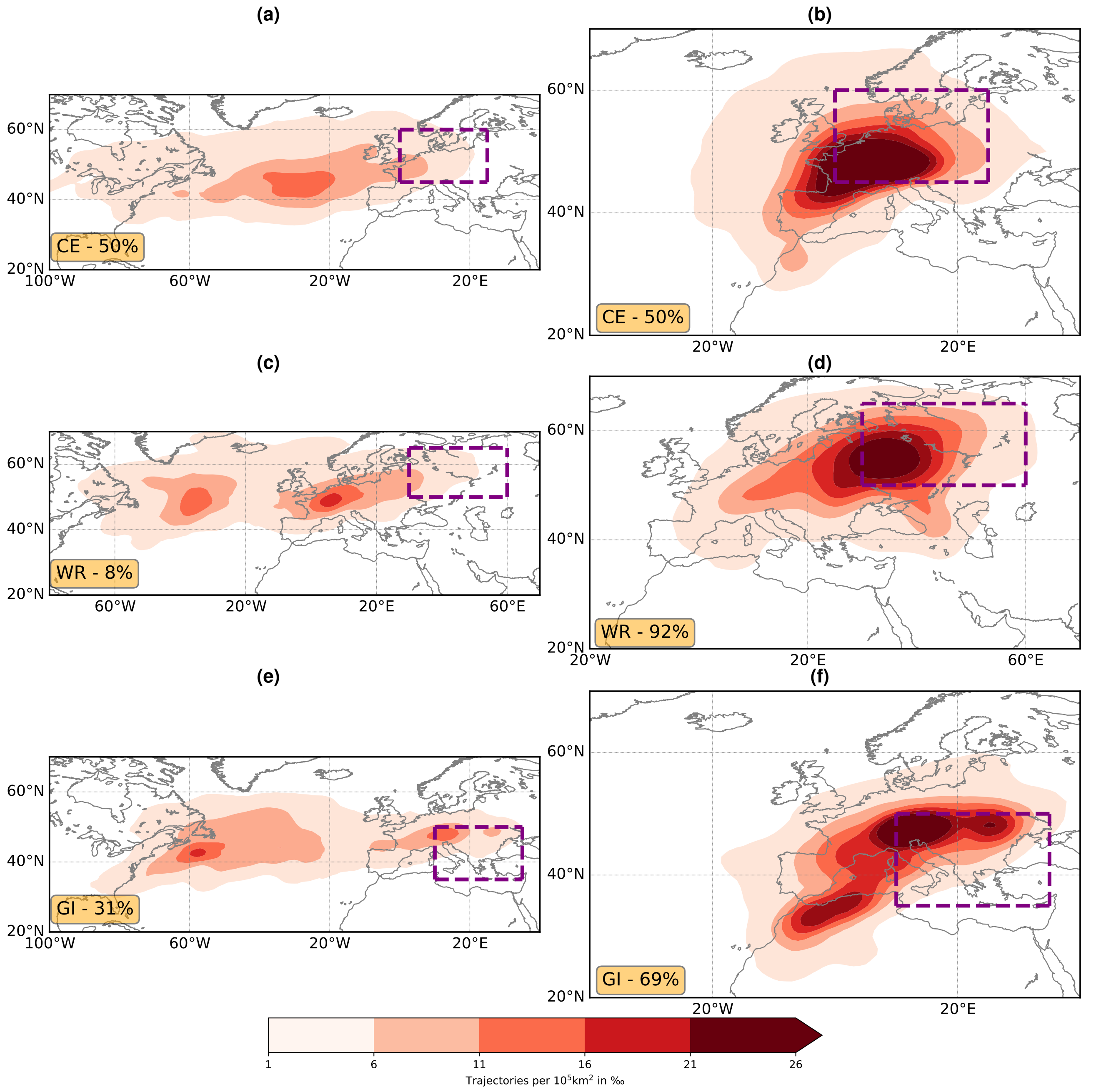

Figure 6. Geographic location of the maximum diabatic heating along trajectories for the ~~western~~ remote (left column) and ~~eastern~~ nearby heating branch (right column) during the last three days prior to reaching upper-tropospheric anticyclones above Central Europe (CE)~~and~~ , western Russia (WR) and Greece/Italy (GI). The percentages in the orange boxes denote the fraction of the ~~western~~remote/ ~~eastern~~ nearby heating branch with respect to the whole heating branch.

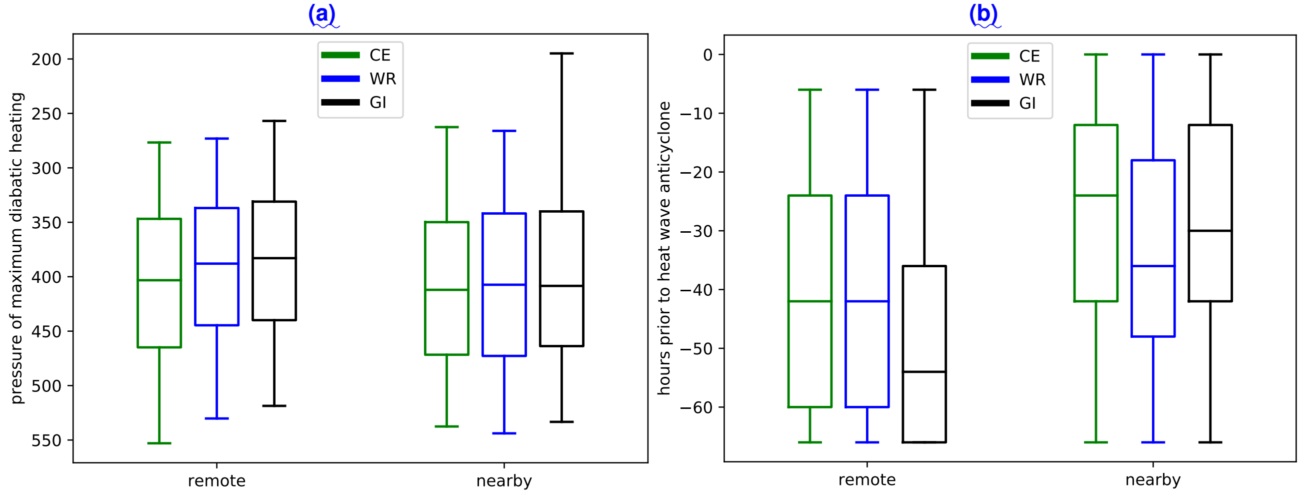

Figure 7. Pressure (a) and time (b) of maximum diabatic heating of trajectories in the two heating branches of the heat wave anticyclone over Central Europe (green, CE), western Russia (blue, WR) and Greece/Italy (black, GI). Horizontal lines denote the median, the boxes the interquartile range and the whiskers the 5th and 95th percentile, respectively.

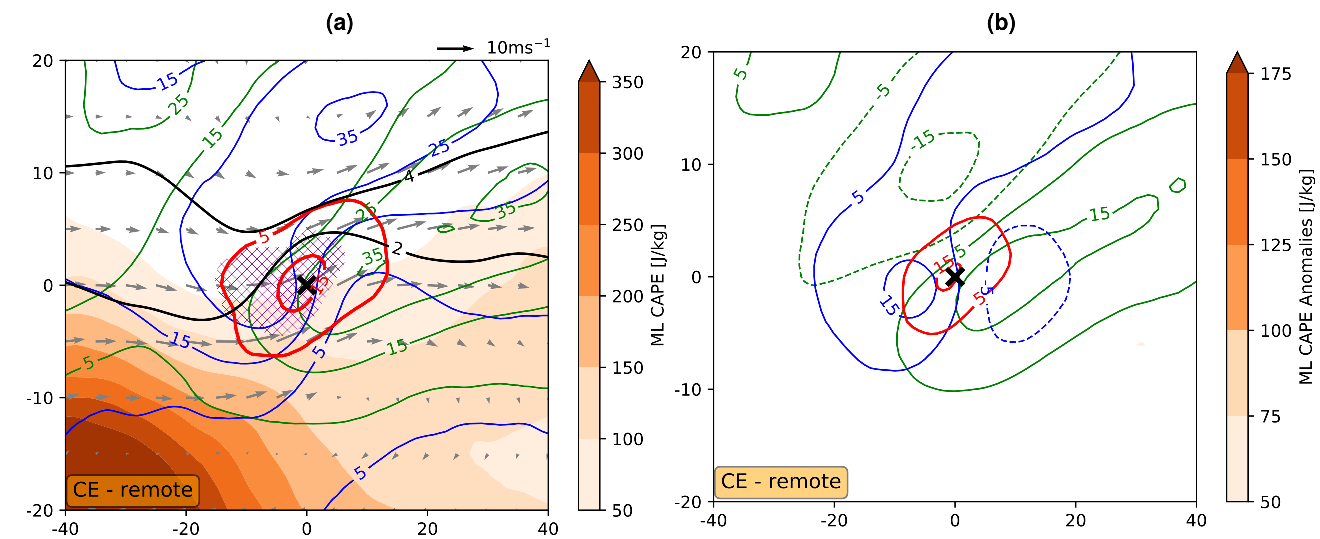

Figure 8. Composites centred around the position of maximum diabatic heating ~~of~~ for the ~~trajectories in the western~~ remote heating branch reaching upper-tropospheric anticyclones above Central Europe. (a): Frequencies of extratropical cyclones (blue), blocks (green) and warm conveyor belts (red) starting from 5% in 10% increments. The orange shading shows the ML CAPE (in J kg^{-1}) and the arrows the wind at 800 hPa. Black contours indicate PV (2 and 4 PVU contours) at 330 K. The purple hatching marks the region where the stratiform precipitation exceeds the convective precipitation (only for areas with total precipitation $\geq$ ~~2mm/~~2 mm d^{-1}). (b) Anomalies of cyclone (blue), blocking (green) and warm conveyor belt ~~frequency starting from 5 percentage points with 10 points increments. Orange shading shows ML CAPE anomalies~~ (~~in Jkg^{-1}~~red) frequency.

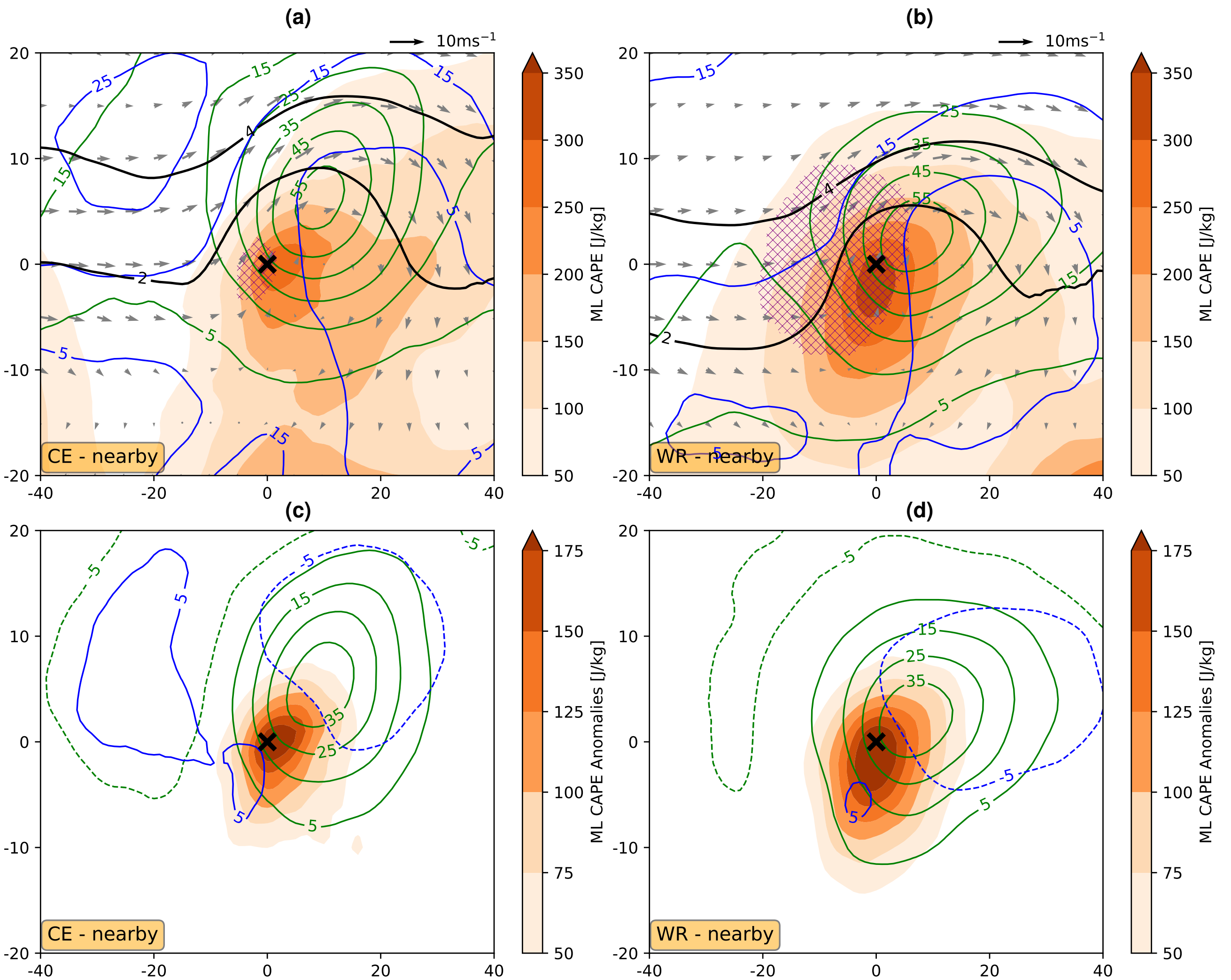

Figure 9. Same as Fig.~~7~~ 8, but for the ~~eastern~~ nearby heating branch ~~and~~ reaching Central Europe (a,c) and western Russia (b,d). Note that WCB frequencies are not shown because they are negligible in the nearby branch. The top row ~~show~~ shows the full fields and the bottom row the anomalies. The ~~grey shading~~ purple hatching marks, in contrast to Fig. 8, the area where the convective precipitation exceeds the stratiform precipitation (only for areas with total precipitation $\geq 2\,\mathrm{mm\,d^{-1}}$).

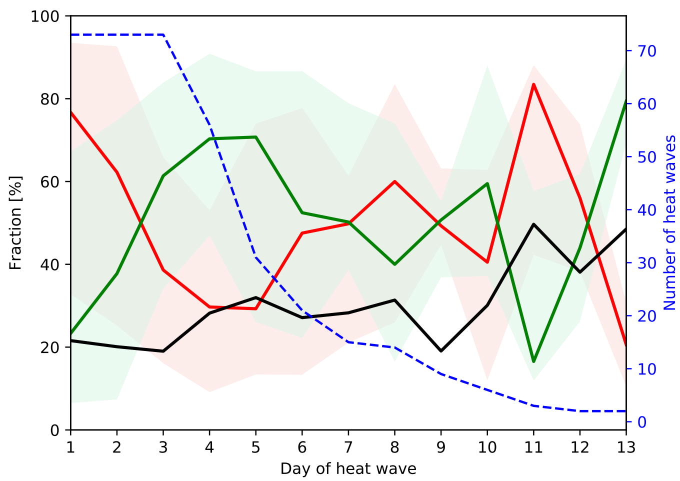

Figure 10. Latent heating during the life cycle of upper-tropospheric anticyclones connected to heat waves in Central Europe. The red (green) line shows the median contribution of the ~~western~~ remote (~~eastern~~nearby) heating branch to the whole heating branch, the shading represents the range between the 25th and 75th percentile. The median fraction of the heating branch relative to all trajectories is represented by the black line and the number of heat waves is indicated by the blue dashed line.

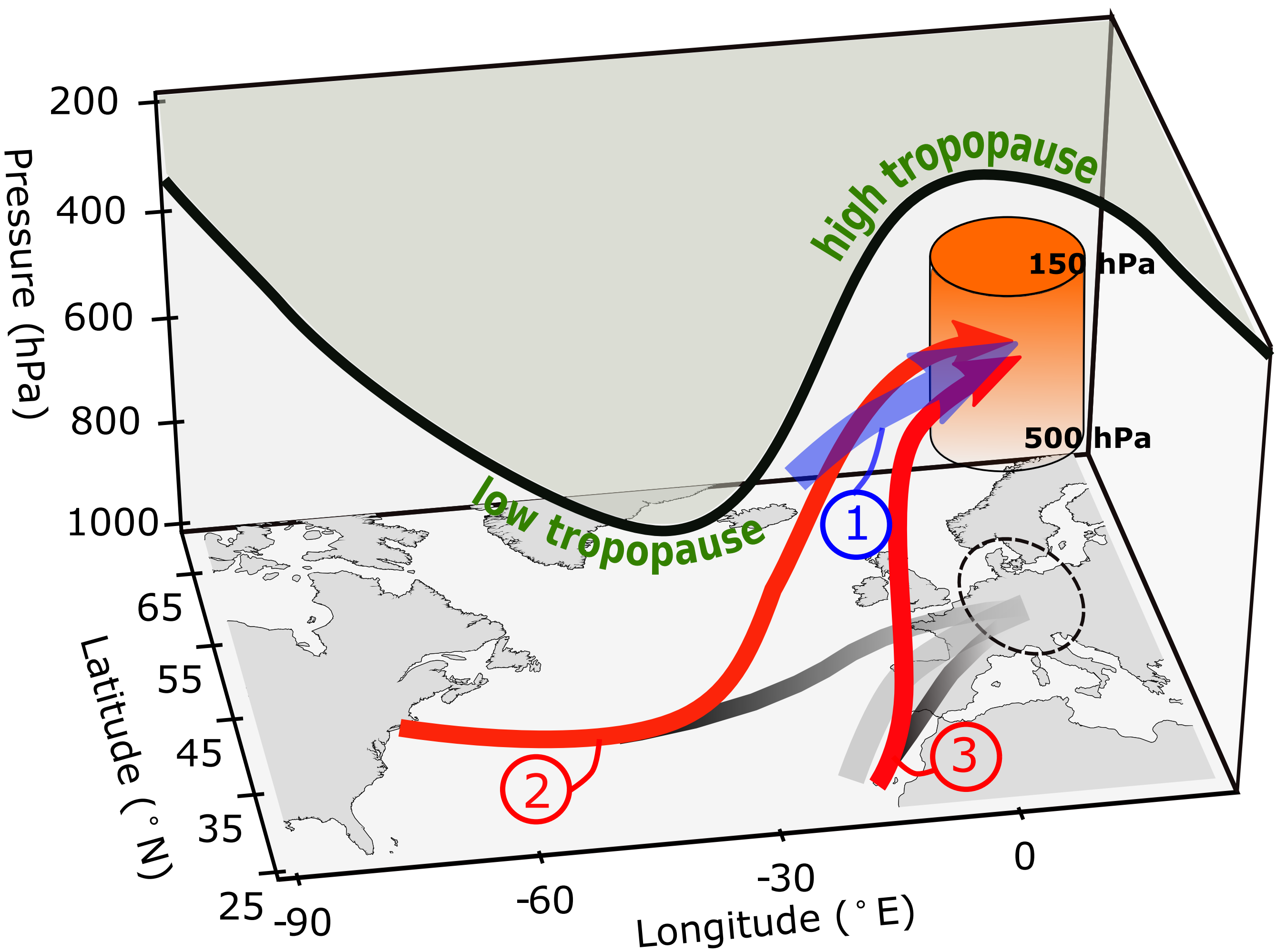

Figure 11. Schematic illustrating the pathway of the three air streams contributing to the upper-tropospheric anticyclone (red cylinder) above the heat wave in Central Europe (black dashed ~~line~~circle) during the last three days prior to arrival. Air stream 1 denotes the cooling branch and air streams 2 and 3 the ~~western~~ remote and ~~eastern~~ nearby heating branches, respectively. Grey-marked lines at the surface illustrate the projections of the arrows (~~brighter colours~~ lighter greys indicate a higher altitude of the associated air stream). The bold black line represents the dynamical tropopause. The arrow of air stream 1 is wider because this branch is less spatially coherent compared to air streams 2 and 3.