https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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The counter-intuitive link between European heatwaves and atmospheric persistence

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Abstract. Warm temperature extremes can lead to devastating societal impacts, thus, the ability to understand and predict these events is vital to minimising their potential impact on society. We investigate the link between warm temperature extremes in Europe and anomalously persistent atmospheric circulation patterns for both winter and summer, along with some possible driving mechanisms. We assess atmospheric persistence leveraging concepts from dynamical systems theory, with this more mathematical approach being reconciled with the conventional meteorological view of persistence. We find that wintertime warm spells are typically associated with persistent zonal advection. Contrary to intuition, we find neither evidence of a link to anomalously persistent circulation patterns, nor a strong signal for warm temperature advection for summertime heatwaves. We thus argue that atmospheric persistence is not a necessary requirement for summertime heatwaves, and that local effects could play a much more important role than large-scale warm temperature advection for these events.

1 Introduction

Heatwaves routinely exact a heavy toll on society, including increased mortality, aggravation of droughts, crop failure, damages to infrastructure and power outages (Muthers et al., 2017; Ouzeau et al., 2016; Adélaïde et al., 2021). A notable example was the 2003 European heatwave, which led to an estimated approximately 40,000 excess deaths, and economic damages of roughly 13 billion EUR (Garcia-Herrera et al., 2010; De Bono et al., 2004). Moreover, in most areas of the world these events are expected to become increasingly severe under anthropogenically-forced climate change (Seneviratne et al., 2012; Perkins-Kirkpatrick and Gibson, 2017; Seneviratne et al., 2014). For example, extremely hot summers are expected to become increasingly likely throughout this century (Christidis et al., 2015). In Europe, the Mediterranean region is projected to experience an increase in the frequency and duration of heatwaves, whilst south-central Europe is expected to experience a pronounced increase in the amplitude of heatwaves (Fischer and Schär, 2010). Furthermore, heatwaves are expected to be associated with a dramatic rise in damages to infrastructure over the next century (Forzieri et al., 2018). Uncommonly high temperatures can also have widespread impacts during the winter season. Wintertime warm spells can lead to significant disruptions in ecological systems,

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for example by causing plants to exit dormancy too early in the season, potentially leaving them vulnerable to subsequent cold spells (Ladwig et al., 2019). Some livestock are also highly sensitive to changes in the freeze-thaw cycle (Furberg et al., 2011). Consequently, understanding and predicting summertime heatwaves and wintertime warm spells is critical to minimising their potential societal impacts.

Wintertime European warm spells are often associated with zonal flow (Slonosky and Yiou, 2002). A wintertime zonal flow results in warm and moist air from the North Atlantic being transported to Europe. Summertime heatwaves are instead typically associated with atmospheric blocking over the Euro-Atlantic sector (Rousi et al., 2022; Lupo, 2021; Schaller et al., 2018). A summertime blocked flow over the North Atlantic leads to weakened zonal flow and more pronounced meridional flow, favouring the southerly advection of very hot airmasses to Europe, for example during the 2003 and 2010 heatwaves as discussed in Miralles et al. (2014). Cassou et al. (2005) notes that another regime, namely the Atlantic low with an associated ridge over southern continental Europe, can also be correlated with heatwaves. Following the same principle as for blocking, this configuration leads to weakened zonal and strengthened meridional flow over southern Europe. In addition to the advection of warm air, other physical mechanisms can lead to heatwaves, including radiative forcing and subsidence (Zschenderlein et al., 2019). Indeed, the latter study finds the effect of temperature advection to be almost negligible for summertime European heatwaves, in contrast with earlier literature.

Blocking has been diagnosed both as a localised atmospheric feature (Davini et al., 2012; Tibaldi and Molteni, 1990; Sousa et al., 2021), and as a weather regime representing one of the recurrent states of the North Atlantic atmospheric circulation (Hannachi et al., 2017). In both cases, blocks are typically regarded as very persistent atmospheric flow patterns, which can last for several days up to a few weeks (Drouard et al., 2021). Current understanding of the link between blocks and summertime heatwaves intuitively suggests that the more persistent the block, the longer the heatwave lasts and the more intense it can potentially become (Schaller et al., 2018).

The persistence of a block as diagnosed using feature-based detection algorithms is often imposed by the algorithm itself (e.g. by requiring a minimum persistence to define a feature as a block (Schwierz et al., 2004; Davini et al., 2012)). Moreover, it focuses on the feature itself as opposed to the larger-scale atmospheric flow pattern, and often allows for the center of the block to move a significant distance over the block's lifetime and for the block's intensity to vary, provided it stays above a given threshold. The persistence of blocking as diagnosed by weather regimes provides an indication of the larger-scale atmospheric persistence, as the whole Euro-Atlantic region is typically considered. However, weather regimes provide a very coarse-grained partitioning of atmospheric variability, most often into four reference states (Michelangeli et al., 1995). Different timesteps assigned to the 'blocked' regime can therefore display relatively large differences in the atmospheric flow pattern.

More recently, the persistence of blocking has been considered from the angles of Rossby wave activity or fixed points in a dynamical system. The former approach considers blocking as a manifestation of planetary wave breaking (Pelly and Hoskins,

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2003; Masato et al., 2012; Barnes and Hartmann, 2012) or resonance of specific phase-locked waves (Petoukhov et al., 2013; Kornhuber et al., 2020). Two notable heatwaves, the 2003 European heatwave and the 2010 Russian heatwave, were associated with anomalously persistent circulation patterns associated with phase-locked Rossby waves leading to persistent blocks (Kornhuber et al., 2017). The latter approach applies mathematical tools from dynamical systems theory to the atmosphere, and interprets North Atlantic atmospheric variability as having a number of stationary states, or fixed points. The conventional view considers two such states, namely blocked and zonal flows (Legras and Ghil, 1985), with this approach being further developed by Mo and Ghil (1987). The dynamical properties and transitions between these two states can then be used to infer their persistence.

A further development stemming from dynamical systems theory leverages the concept of atmospheric recurrences, or analogues – namely the fact that the atmosphere displays configurations similar to ones it has displayed in the past. Unlike weather regimes where a very large number of timesteps is assigned to a given regime, analogues are typically defined quite stringently, such that each timestep only has a limited number of analogues. Leveraging the notion of the extremal index, namely a measure of clustering in extreme value theory (Section 3.2.2 Lucarini et al., 2016; Moloney et al., 2019), it is possible to use analogues to estimate the persistence of a given atmospheric configuration. When applied to the North Atlantic, this approach has highlighted zonal flows as being highly persistent – more so than blocked flows. This was shown by Faranda et al. (2017) and Faranda et al. (2016) for the full year, and Messori et al. (2017), for the winter season. A similar conclusion was drawn by Hochman et al. (2021), who, using the extremal index, identified the zonal weather regime as one of the most persistent in a 7-regime classification. There is therefore an apparent discrepancy between blocking as a persistent atmospheric feature (Petoukhov et al., 2013; Legras and Ghil, 1985) and blocking as a transient feature of an atmosphere whose persistent state is one of zonal flow (Faranda et al., 2016, 2017; Messori et al., 2017; Hochman et al., 2021).

In this study, we adopt a dynamical systems viewpoint to illustrate the link between both summertime heatwaves and wintertime warm spells in Europe, and atmospheric persistence in the Euro-Atlantic sector. In doing so, we will attempt to reconcile the different views highlighted above on the persistence of blocked and zonal flows. The remainder of the paper is structured as follows: Section 2 details the datasets and methods used for the analysis, Section 3 shows composites of the atmospheric configurations associated with heatwaves, an analysis of the persistence of these configurations and composites of possible driving mechanisms for heatwaves, namely temperature advection and radiative forcing. Section 4 discusses these results and finally Section 5 presents the conclusion of this paper.

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2 Data and methods

2.1 Data

We use the ERA5 reanalysis dataset from the European Centre for Medium Range Weather Forecasts (ECMWF) (Hersbach et al., 2020) over 1978–2018. The specific variables used were temperature at 2m (t2m), geopotential at 500 hPa (Z500), surface sensible heat flux (SSHF) and mean sea level pressure (SLP), all at a horizontal spatial resolution of 0.25°. The SSHF was selected for the noon time step and the accumulated values divided by the accumulation period as per ECMWF's online data documentation. Daily means were calculated from hourly data, except for Z500, which was calculated from 6-hourly data due to the much larger size of pressure-level variables. Our Euro-Atlantic domain spans 30–70 °N, 345–45 °W. The anomalies for each variable were computed relative to a daily climatology smoothed with a 31 day running mean.

2.2 Definitions

We define heatwaves at single gridboxes following Alvarez-Castro et al. (2018), that is 5 or more consecutive days with temperature anomalies above the 90th percentile of the local distribution. We also define regional heatwaves over the British Isles, Scandinavia, central Europe (Germany), western Russia (Russia), Iberia and the central Mediterranean (Mediterranean) (Zschenderlein et al., 2019), by requiring that at least five percent of the land grid boxes in the region must experience a heatwave, as defined above, for a given day. The regions are shown by black boxes in Fig. 1. The summer season is defined as June–September (JJAS) and the winter season is defined as December–March (DJFM). For the remainder of this paper we will use the term warm spell to refer to a set of days which satisfy the above definition for a heatwave and which occur during the winter season. The temperature advection was investigated using the baroclinic vector, $\boldsymbol{B}$, defined as follows:

$$\boldsymbol{B} = \nabla SLP \times \nabla t2m \tag{1}$$

with units $[hPaK(^{\circ}lat \times ^{\circ} lon)^{-1}]$, as in Faranda et al. (2020a). We define reference directions of north, east and downwards for the cross product, thus $\boldsymbol{B}$ is oriented in the downwards direction. If we consider the magnitude of $\boldsymbol{B}$, namely B, and define positive values as corresponding to the downwards direction and negative values corresponding to the upwards direction, these then correspond to warm and cold air advection, respectively (Faranda et al., 2020a).
Statistical significance at a level of $p = 0.05$ was tested for each grid box in the composite plots in Sections 3.1 and 3.2 using a two-sided test to assess the uncertainty of the location of the true mean using a cluster bootstrap method (Cameron et al., 2008). This method was used because we want to study the entire duration of the heatwave, yet the days within a given heatwave are highly correlated. The same cluster bootstrap method was used to assess significance for the box plots in Section 3, however this time a one-sided test was used to test for negative θ anomalies. Sensitivity tests for the definition of heatwaves and warm spells can be found in the Appendix A.

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2.3 Atmospheric persistence computation

We calculate atmospheric persistence based on the SLP field over the full Euro-Atlantic domain considered here. SLP was chosen as opposed to Z500 due to the long term trend in Z500 fields related to the trend in surface temperature (Faranda et al., 2020b). We define persistence as θ^{-1}, where θ is the extremal index (Moloney et al., 2019) and persistence is in units of timesteps. Persistence is an estimate of the average number of consecutive recurrences, or analogues, for a given atmospheric state. In other words, it quantifies how long a given state of the atmospheric circulation will remain similar to itself. The computation of θ depends on the definition of recurrences, which we identify here as follows:

1) The Euclidean distance between the SLP maps for each day and all others in the data set is computed. Thus, for any given day we can quantify how 'similar' it is to any other day.

2) Of these distances, the smallest 5 percent ($q = 0.95$), as recommended by Süveges (2007) are selected as analogues, that is the days that are most similar to the given day.

3) A generalised Pareto distribution is fit to the negative log of the analogue distances to ensure that the distribution of negative log distances converges (Ferro and Segers, 2003).

After this requirement is satisfied, θ can be estimated using the methodology of Süveges (2007), which improves estimates of the extremal index compared to the earlier method of Ferro and Segers (2003). In practice this is performed using the package Robin (2021). Sensitivity tests for both the domain and the threshold for analogue selection (q) can be found in the Appendix A.

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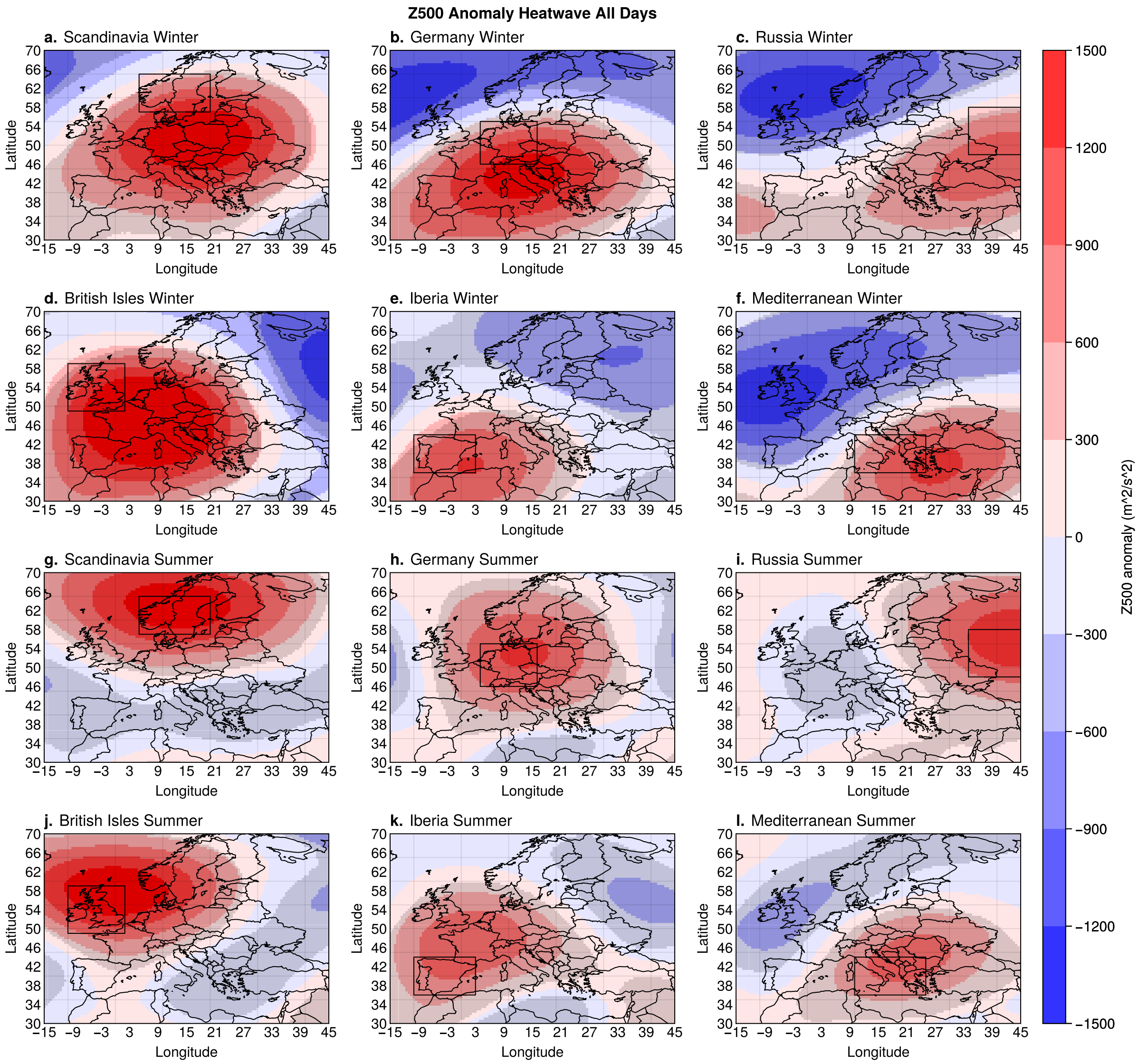

Figure 1. Composite Z500 $[m^2s^{-2}]$ anomalies during warm spell/ heatwave days in (a,g) Scandinavia, (b, h) Germany, (c, i) Russia, (d, j) British Isles, (e, k) Iberia, (f, l) Mediterranean, during winter (a–f) and summer (g–l). Statistical significance is assessed as described in Section 2 and shown with grey stippling.

3 Results

3.1 Characterising Atmospheric Persistence during European Heatwaves

We first examine the atmospheric configurations associated with regional European warm temperature extremes in the extended winter and summer seasons (Fig. 1).

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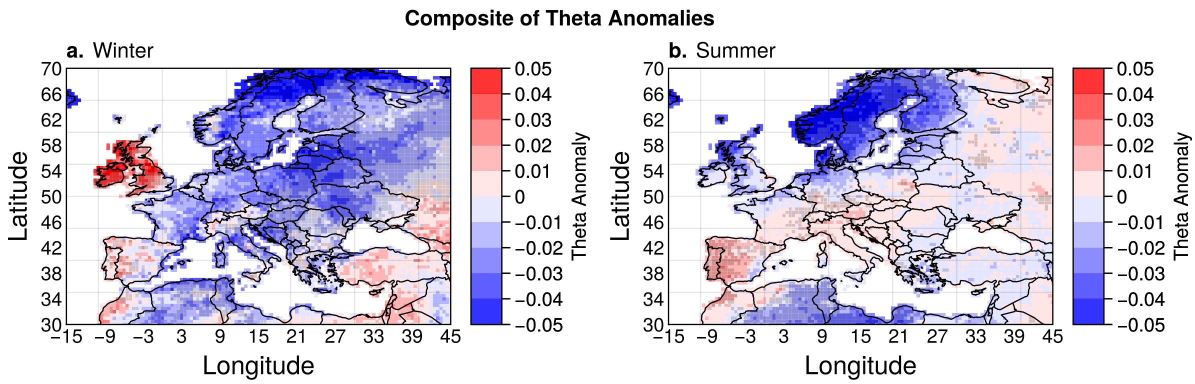

Figure 2. θ $[days^{-1}]$ anomalies for all warm spell or heatwave days for each grid box, during winter (a) and summer (b). Statistical significance is assessed as described in Section 2 and shown with grey stippling.

In winter (panels a – f) we see that the warm spell regions are typically located on the northern edges of areas of positive geopotential anomalies, with anticyclonic structures located so as to favour advection from the warm/wet southern flank of a zonal flow towards the regions of interest. During summer, in the more northern regions, namely Scandinavia, Germany, Russia and the British Isles (panels g – j), the Z500 anomalies are reminiscent of canonical blocked configurations, with an anticyclonic structure located so as to block zonal flow towards the areas of interest. In the Iberian and Mediterranean regions (panels k, l) the Z500 anomalies show a high pressure core located in the vicinity of the respective region, albeit with a smaller magnitude than in the northern regions. These configurations are consistent with those discussed in Zschenderlein et al. (2019) for the summer season.

Next, we examine the persistence of the configurations associated with heatwaves by considering first a composite of θ anomalies for heatwaves on a grid box by grid box basis, then the anomalies of θ during heatwaves on a regional scale (Figs. 2 and 3 respectively).

Negative θ anomalies dominate during winter (Fig. 2a). In other words, when temperatures are anomalously high at most European locations, the concurrent atmospheric configuration is anomalously persistent. The exceptions are the British Isles, which show positive θ anomalies, and Iberia which shows near-zero anomalies. In summer, negative θ anomalies are only present over Scandinavia and part of the British Isles, with the remaining regions showing weak and mostly non-significant anomalies (Fig. 2b). Focusing on regional heatwaves, Fig. 3 shows that wintertime heatwaves are associated with significantly enhanced atmospheric persistence in all regions except the British Isles and Iberia. In summer, only heatwaves in the British Isles and Scandinavia match significant negative theta anomalies, while all other regions show near-zero or weakly positive theta anomalies.

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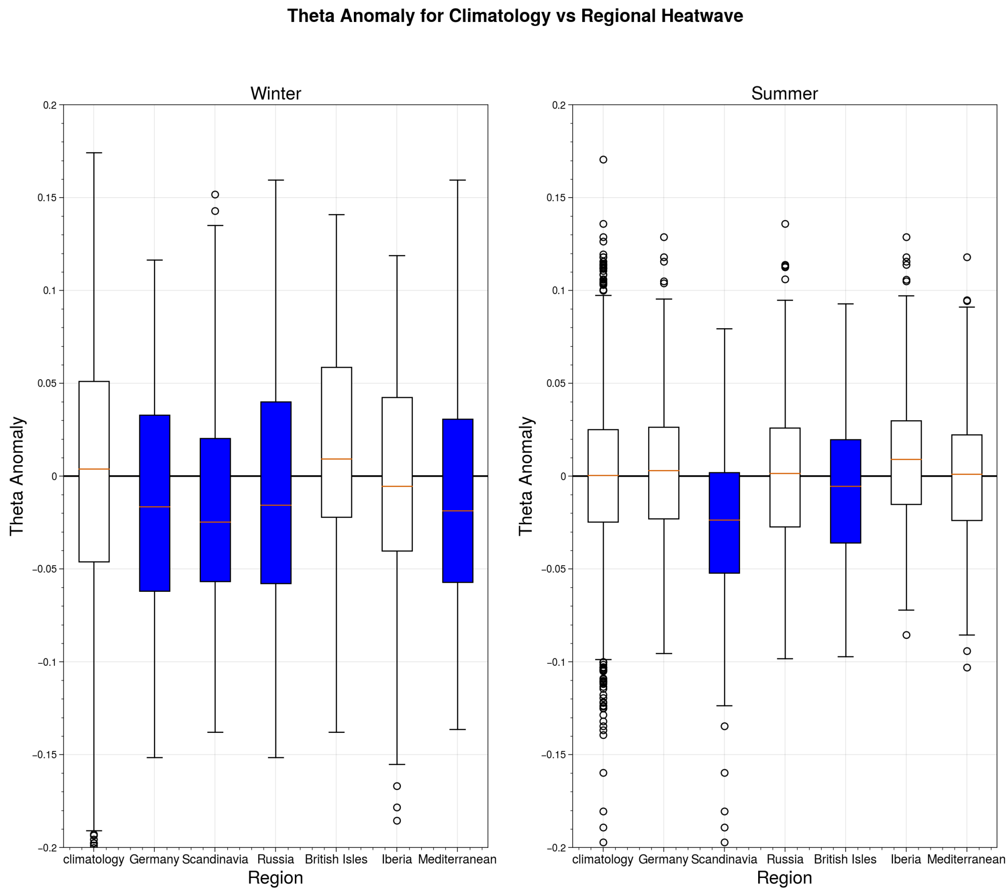

Figure 3. Box plots of θ $[days^{-1}]$ anomalies for all heatwave or warm spell days in the considered regions. Blue boxes indicate statistical significance, assessed as described in Section 2.

3.2 Characterising summertime heatwaves and wintertime warm spells in Europe

The results presented in Section 3.1 above are somewhat counter-intuitive, and appear in contrast with the conventional view of summertime heatwaves being driven by persistent blocks. To better understand this discrepancy, we investigate further the physical characteristics of heatwaves and warm spells during summer and winter.

Panels a–f in Fig. 4 show composites of B (surface temperature advection) during wintertime warm spells, generally pointing to a dominant role of warm air advection towards the region of interest during warm spells. This is consistent with the zonal flows highlighted in Fig. 1, which correspond to advection of comparatively warm oceanic air towards the continent. Panels g–l in Fig. 4 show a weaker signal for surface temperature advection during summertime heatwaves, suggesting that in many cases the advective component can only explain part of the observed large temperature anomalies. We also note that especially

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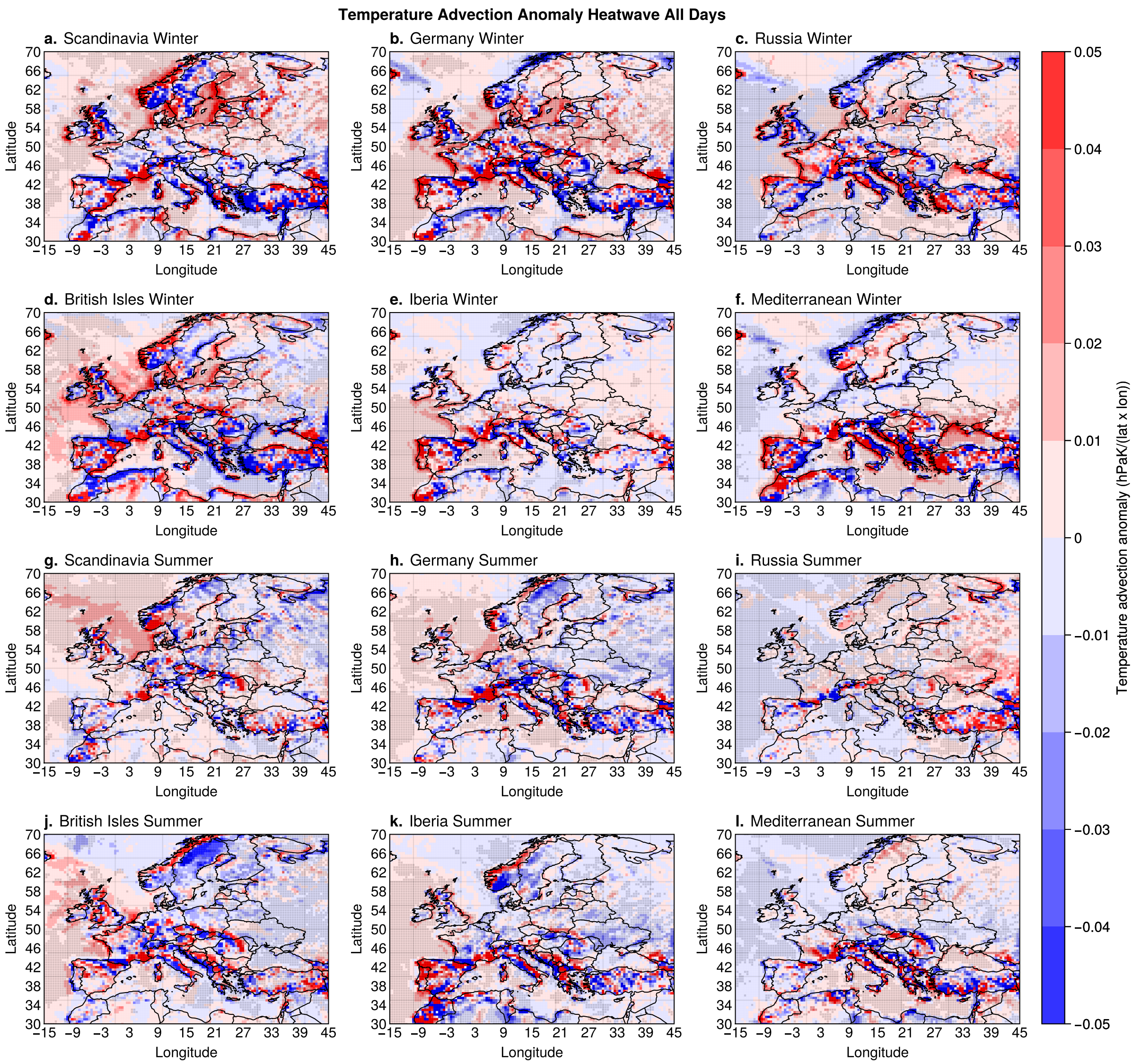

Figure 4. B $[hPaK(^{\circ}lat \times ^{\circ}lon)^{-1}]$ composite anomaly, corresponding to surface temperature advection, during warm spell and heatwave days in (a, g) Scandinavia, (b, h) Germany, (c, i) Russia, (d, j) British Isles, (e, k) Iberia, (f, l) Mediterranean, during winter (a–f) and summer (g–l). Positive anomalies, denoted by the colour red, represent warm advection, whilst the colour blue corresponds to cold air advection. Statistical significance is denoted with grey stippling and assessed as described in Section 2.

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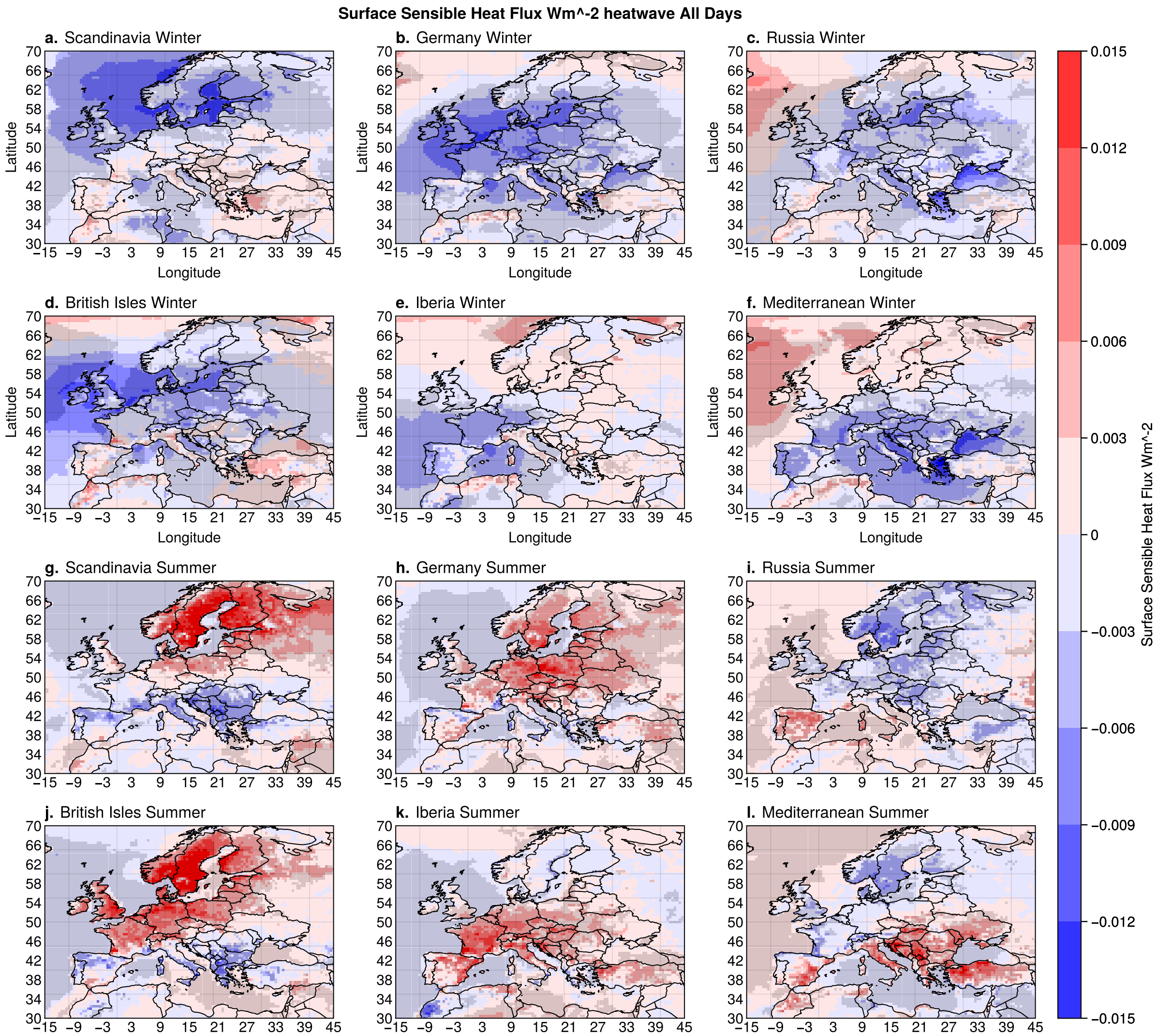

Figure 5. SSHF [Wm^{-2}] composite anomalies during during warm spell and heatwave days in (a, g) Scandinavia, (b, h) Germany, (c, i) Russia, (d, j) British Isles, (e, k) Iberia, (f, l) Mediterranean, during winter (a–f) and summer (g–l). Statistical significance is denoted with grey stippling and assessed as described in Section 2.

Iberia and the Mediterranean show a clear orographic signal in both seasons Fig. 4 e, f, k and l. This could suggest the possible importance of advection over topography for engendering large temperature anomalies.

Fig. 5 shows composite SSHF anomalies during heatwaves. Positive anomalies imply an upward flux – in other words the surface heats the air above it whilst negative anomalies imply the air above the surface is warmer than the surface itself. During wintertime (Fig. 5a–f), the widespread negative anomalies indicate that a relatively warm atmosphere helps warm the surface,

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consistent with a large role for temperature advection. The one exception is Russia, although we observe warm air in the Black Sea and Baltic Sea regions during warm spells in the Russian region. Anomalies over land are comparatively weak. During summertime heatwaves (Fig. 5g–l), there are widespread positive anomalies in Scandinavia, Germany and the British Isles, while weaker yet positive signals are found over the Mediterranean and the western part of Iberia, and no clear positive signal is found over Russia. We interpret the negative winter and positive summer SSHF signals shown in Fig. 5, in combination with the strong advective signal in winter and comparatively weak signal in summer (Fig. 4), as providing evidence that, whilst warm temperature advection is critical for wintertime warm spells, radiative forcing plays an important role in European summertime heatwaves.

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4 Discussion

We find that the conventional view of summertime European heatwaves being associated with persistent blocking (Petoukhov et al., 2013; Legras and Ghil, 1985) appears at odds with a quantification of atmospheric persistence based on dynamical systems theory (Faranda et al., 2017). Our results show a link between summertime heatwaves and persistent atmospheric configurations only in Scandinavia and the British Isles, and even then with modest persistence anomalies up to approximately 3 hours for the median θ anomaly in these regions. Thus, we argue that heatwaves can occur under persistent atmospheric conditions, but this is not a requirement. This is consistent with the findings of Faranda et al. (2017), who presented evidence that blocking is not associated with high persistence when considering the full year, whilst Faranda et al. (2016) argues for zonal flows being more persistent than blocked flows in winter. Our work also connects to that of Lucarini and Gritsun (2020), who show that the onset and decay of blocking corresponds to structurally unstable states. In the context of dynamical systems, structural instability means that the entire system is highly sensitive to perturbations, and a small perturbation can lead to instantaneous qualitative changes between states. In the current analysis, the system would be the atmosphere and the mathematical equations which govern it, and a state would correspond to an instantaneous map of some representative variable. This means that the persistence of a state, which is analogous to the expected time between qualitative changes in atmospheric states, is also highly sensitive to perturbations, and thus a link between blocking and anomalously persistent atmospheric configurations is not expected.

There is thus a clear discrepancy between the analytical, quantitative definition of persistence used here and the conventional view we have referred to numerous times. When blocking is defined using feature detection algorithms, persistence is defined as the duration of a coherent structure (often a reversal of the meridional gradient in Z500 or some other atmospheric variable). However, this structure may to some extent move and/or change in intensity. When a weather regime perspective is taken, a relatively wide range of different atmospheric patterns may be clustered into the same regime. The feature-based view of blocking thus allows for changes in the location and/or intensity of the block, and additionally potentially overlooks other atmospheric structures in the region of interest, which may still be very relevant for the overall dynamics, in particular at the offset of the block when the system is sensitive to small perturbations. Conversely, the weather regime view may define relatively different regional atmospheric patterns as belonging to the same continuous succession of blocked regime days. Our analytical view of persistence considers the whole regional atmospheric variability – like the weather regimes approach – yet is based on a small number of analogues (5% of all days in the data set). We thus suggest that the approach we adopt here could provide a more robust view of atmospheric persistence. Indeed, it allows for a more nuanced view of atmospheric variability and provides a rigorous and mathematically precise definition of persistence, supported by well-established mathematical theories.

The criterion of persistence and its link or lack thereof to heatwaves and warm spells can perhaps be better understood when one considers the underlying dynamics and their relevant spatial scales. Wintertime warm spells have previously been associated with persistent atmospheric configurations leading to warm air advection (Messori et al., 2017), which our findings

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partly support. Figs. 3 and 4 indeed show anomalously persistent configurations and advection being linked to warm spells in Scandinavia and the Mediterranean, whilst in the British Isles and Iberia we detect anomalous advection, but not anomalously persistent configurations linked with warm spells. We suggest that this could be because warm oceanic air does not need to travel far to lead to warm advection in these regions. Our results provide evidence that warm spells in Germany and Russia are linked with persistent atmospheric configurations, but showed only a moderate to weak advection signal, suggesting that other mechanisms could contribute to wintertime warm spells there. Literature discussing the drivers of heatwaves during summer mentions both radiative forcing and soil moisture as two key factors (Pfahl, 2014). Our results show a clear radiative signal associated with summertime heatwaves, while temperature advection appears to play a smaller role than during wintertime warm spells. This is supported by Zschenderlein et al. (2019), who also claim that warm temperature advection plays a weak role in summertime heatwaves. We conjecture that summertime heatwaves have multiple driving and trigger mechanisms with local effects, for example adiabatic and diabatic processes as discussed in Zschenderlein et al. (2019) and Bieli et al. (2015), who investigated summer and the full year respectively. These mechanisms play a greater role than in winter, where the persistent advection of warm oceanic air appears to be a leading process. We suggest that, for heatwaves predominantly driven by radiative or local effects, it is not a necessary requirement to have highly persistent large-scale atmospheric configurations. We contrast this to advectively driven warm spells, where warm air must be transported large distances from the ocean, for which the large-scale structure of the atmosphere must remain qualitatively similar for longer periods of time. The investigation of the relationship with soil moisture, whilst interesting, may prove to be a rather complex undertaking in a dynamical systems framework due to the different time scale on which it operates relative to atmospheric motions, and is left to future studies.

We illustrate our argument by considering two case studies, namely the September 2002 and June 2015 heatwaves in Germany. These were selected as they displayed the single days with the most negative and positive θ anomalies respectively, for heatwaves in the region, and thus make for a visually immediate example. Fig. 6 shows the Z500 configurations for the two identified days in the top row, and two days later in the bottom row. We have calculated the Euclidean norm for each pair of days, to empirically illustrate that after two days, the high θ (low persistence) case has a Z500 configuration further away from the initial day than the low θ (high persistence) case. Nonetheless, a visual appraisal suggests that in both cases a blocking algorithm would detect a blocked flow persisting for several days, as there is a clear perturbation of the meridional Z500 gradient in all four panels. These two case studies highlight that it is possible for heatwaves to occur during either high or low persistence atmospheric configurations, and that the persistence as quantified using dynamical systems theory can be related to the intuitive concept of ‘similarity’ of spatial atmospheric configurations. This supports our conclusion that highly persistent configurations are not a necessary criterion for European summertime heatwaves to occur.

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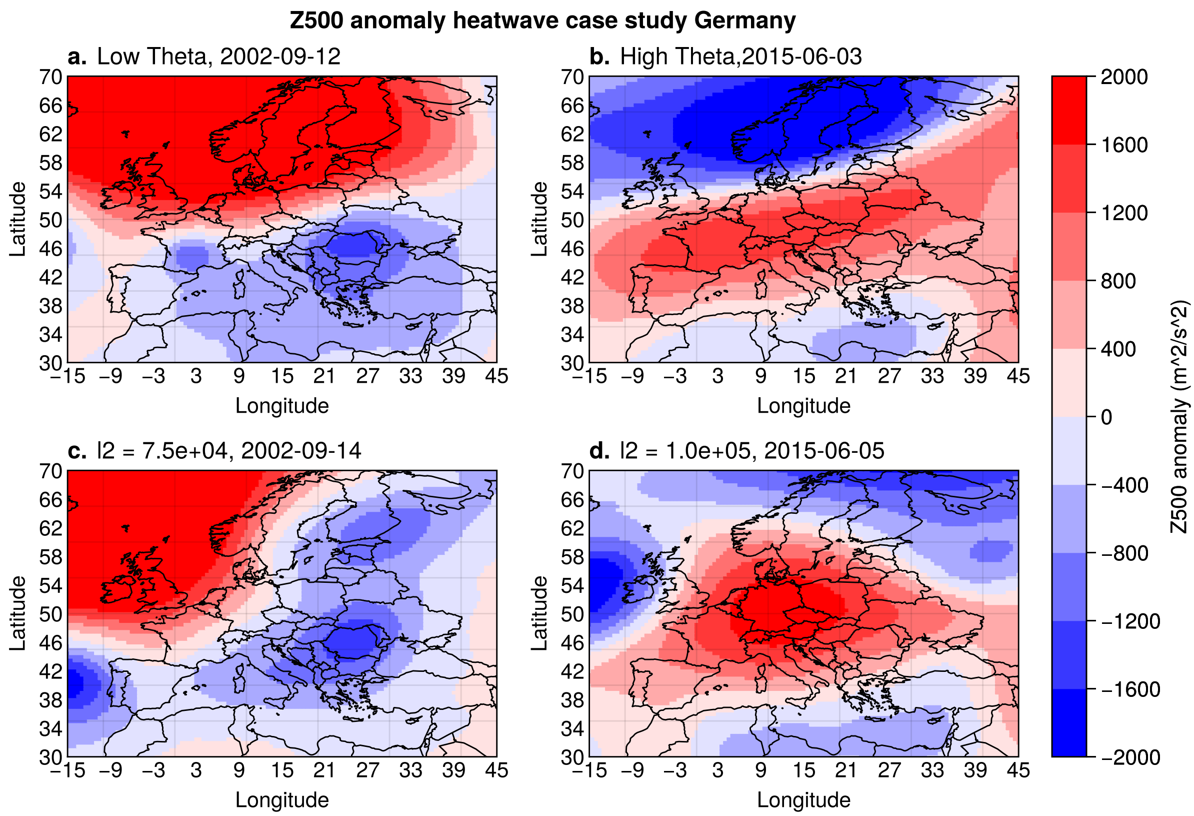

Figure 6. Z500 maps corresponding to the days with the highest and lowest θ within all days which are classified as days where there is a heatwave in the region Germany. Panel titles in (c), (d) show a lead time of 2 days to the respective high and low θ heatwave days, with the values corresponding to the euclidean distance between the initial and 2 day lead SLP maps for each case.

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5 Conclusions

We have analysed atmospheric persistence associated with European summertime heatwaves and wintertime warm spells. We define persistence using a robust quantitative approach issued from dynamical systems theory. Our results point to wintertime warm spells being associated with anomalously persistent atmospheric configurations, supporting previous investigations on the topic (Messori et al., 2017). During summer, however, our results appear to contrast the conventional view of heatwaves being associated with very persistent blocked configurations in the Euro-Atlantic sector. We find that atmospheric configurations associated with heatwaves, on average, do not correspond to anomalously persistent configurations. Our findings are consistent with recent work by Lucarini and Gritsun (2020) who also identified blocking as a structurally unstable state and thus not necessarily a persistent configuration.

We ascribe the different atmospheric persistence characteristics of summertime versus wintertime warm temperature extremes to their different driving mechanisms. We found a far weaker signal for temperature advection in summer than in winter. This is consistent with the results of Zschenderlein et al. (2019) and Bieli et al. (2015), who investigated summer and the full year respectively, and suggested that advection may play a role driving heatwaves in summer, yet is likely only one of several driving mechanisms. We indeed found a strong radiative signal for summertime heatwaves.

We have further attempted to reconcile the discrepancy between the dynamical systems and conventional views of atmospheric persistence associated with heatwaves. The dynamical systems persistence considers a fixed spatial domain, and has a relatively stringent definition of what 'similar' means in terms of atmospheric configurations. Such a dynamical systems definition is thus more sensitive than the alternative definitions to changes in the regional atmospheric configuration, and additionally rests on a mathematically rigorous and precise definition of persistence.

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Appendix A: Sensitivity Analysis

The sensitivity of the results to the domain used to calculate θ was tested by investigating a westward-shifted domain, see Fig. A1. Here the only notable differences were for the Iberia region during winter and Mediterranean region during summer, with a westward-shifted domain resulting in a significant negative θ anomaly. Sensitivity to heatwave/ warm spell duration was tested by considering 3 and 7 day minimum duration requirements, see Figs. A2, A3. Here we find that the Mediterranean no longer shows a significant negative θ anomaly during wintertime warm spells in both cases, and Russia no longer shows a significant negative θ anomaly for the 3 day warm spell definition. We also note that the British Isles no longer show a significant negative θ anomaly during both summertime cases, although the quantitative difference is small. The sensitivity to the temperature threshold was tested by considering temperatures above the 95th percentile, see Fig. A4. The only qualitative differences was found for Russia and the Mediterranean in winter, and the British Isles in summer, where clear, significant negative theta anomalies were no longer seen. Sensitivity to the number of recurrences selected during the computation of θ was tested by considering $q = 0.97$ and $q = 0.99$, shown in the upper and lower panels of Figs. A5 and A6 respectively. Here, Russia and Germany no longer show statistically significant negative θ anomalies during wintertime warm spells for both q values. In summary, wintertime warm spells appear to show some, albeit small, sensitivity in all tests, whilst the results for summertime heatwaves appear quite robust. None of the sensitivity tests, however, affect our qualitative conclusion that anomalously high atmospheric persistence is more closely associated with winter warm spells than with summertime heatwaves.

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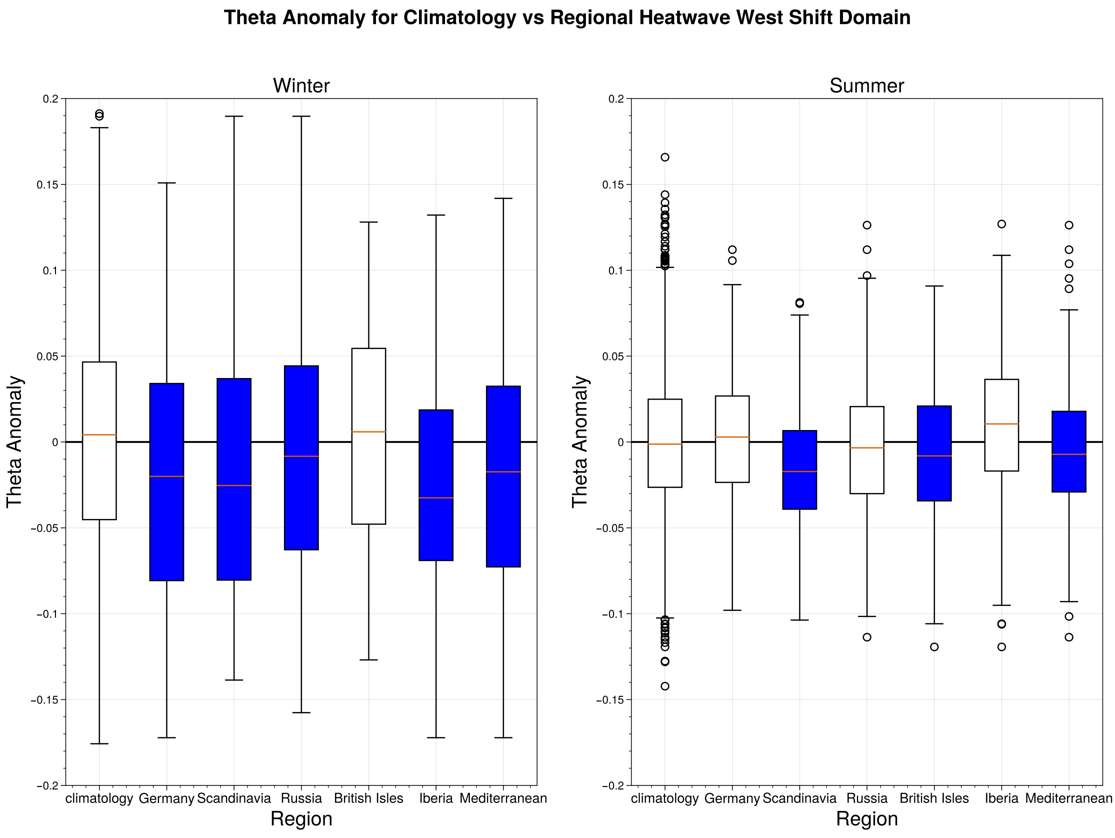

Figure A1. Theta anomaly box plots comparing a West shifted domain from 310W to 35W to the standard domain from 345W to 45W.

https://doi.org/10.5194/esd-2022-50
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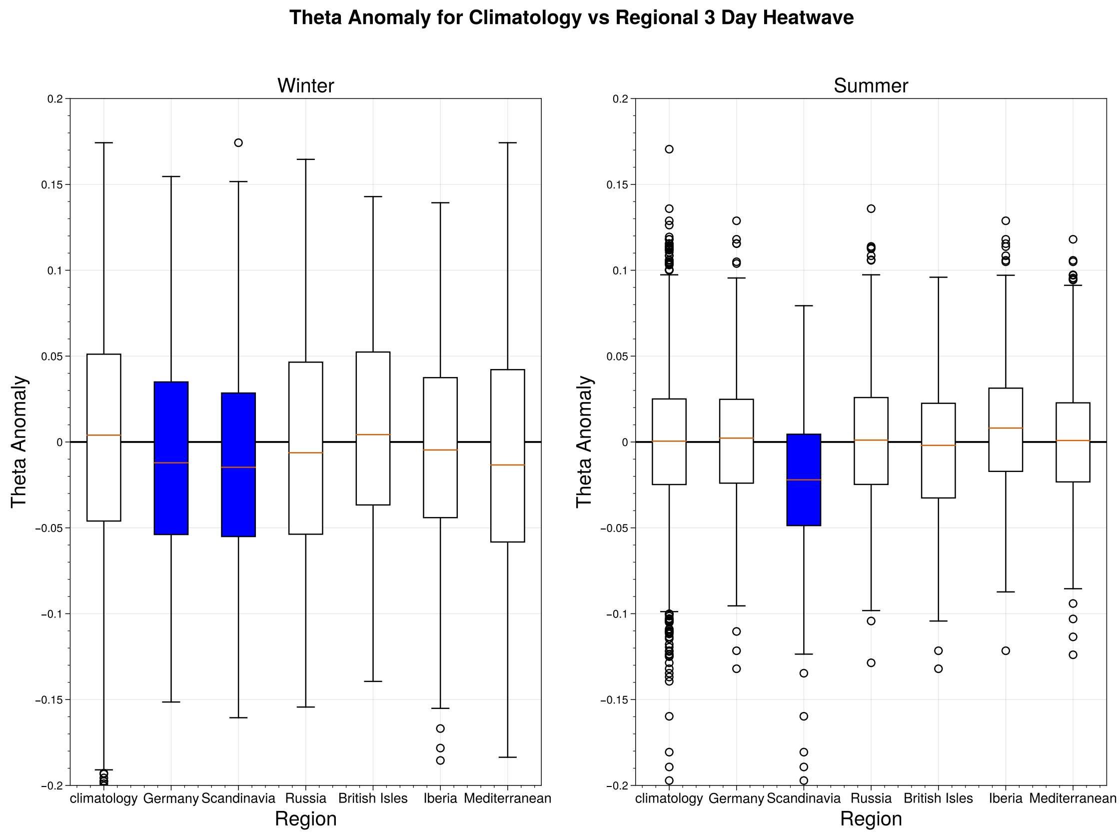

Figure A2. Theta anomaly box plots for a heat wave or warm spell of at least 3 days in duration.

https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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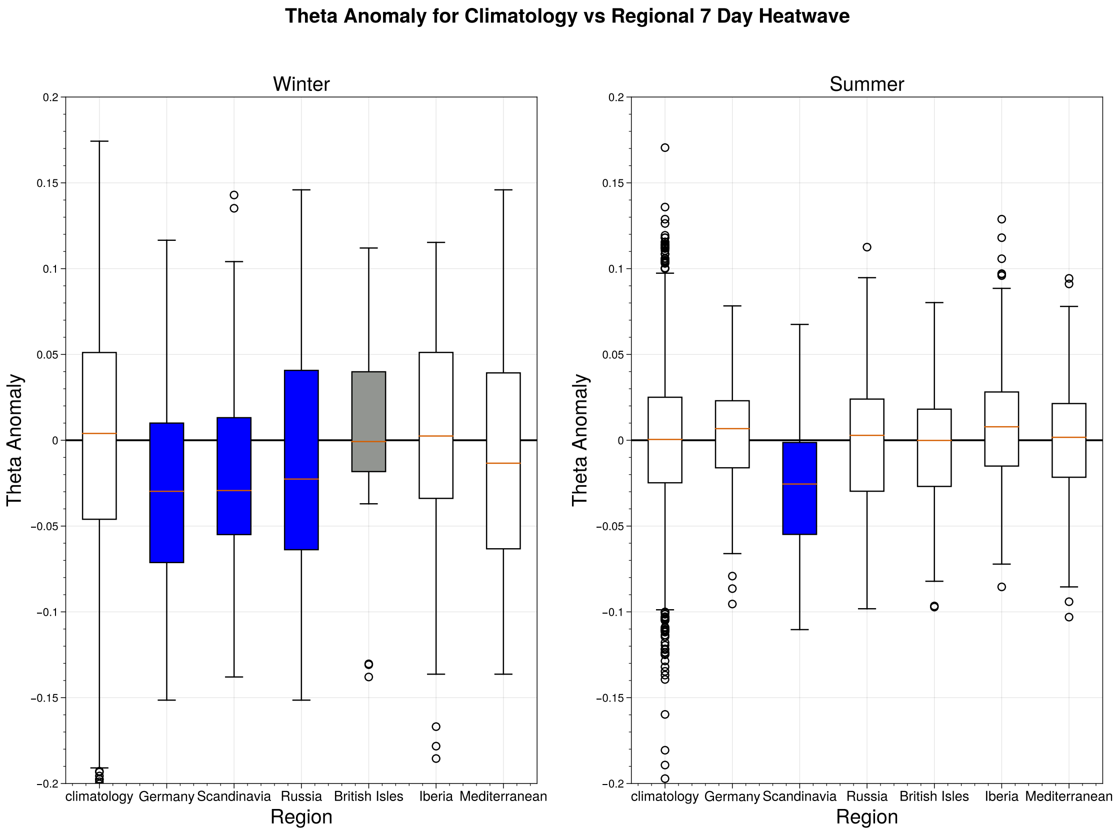

Figure A3. Theta anomaly box plots for a heat wave or warm spell of at least 7 days in duration, grey indicates a small sample size insufficient for significance testing.

https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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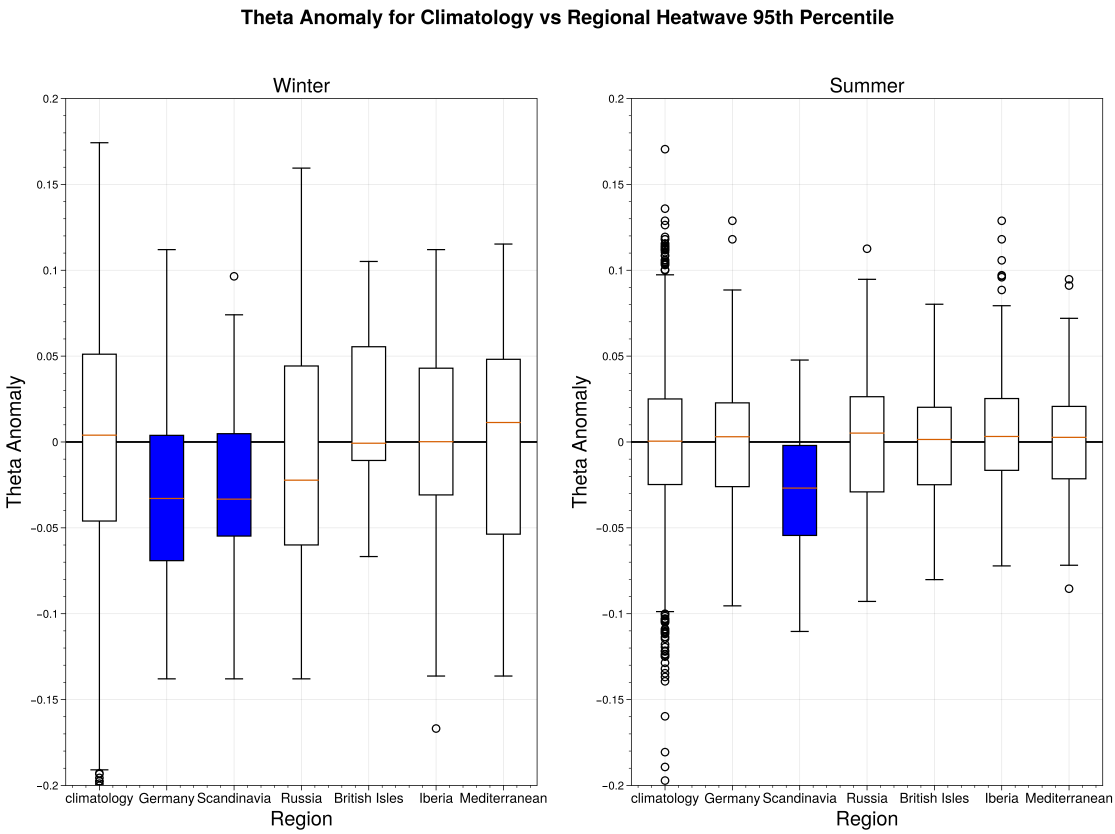

Figure A4. Theta anomaly box plots for a heatwave or warm spell with temperatures above the 95th percentile.

https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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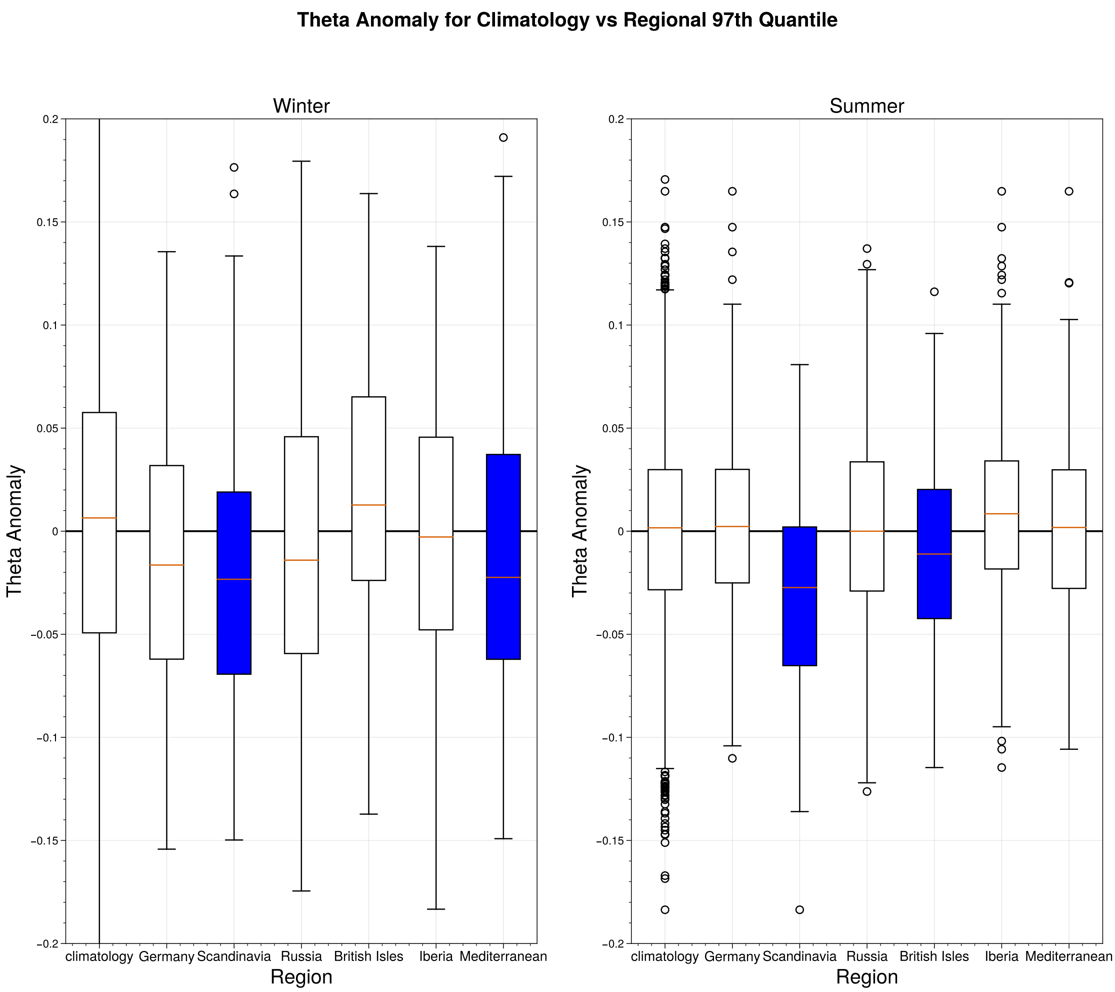

Figure A5. Theta anomaly box plots for different theta threshold values, namely the 97th percentile, which corresponds to a different number of analogues considered.

https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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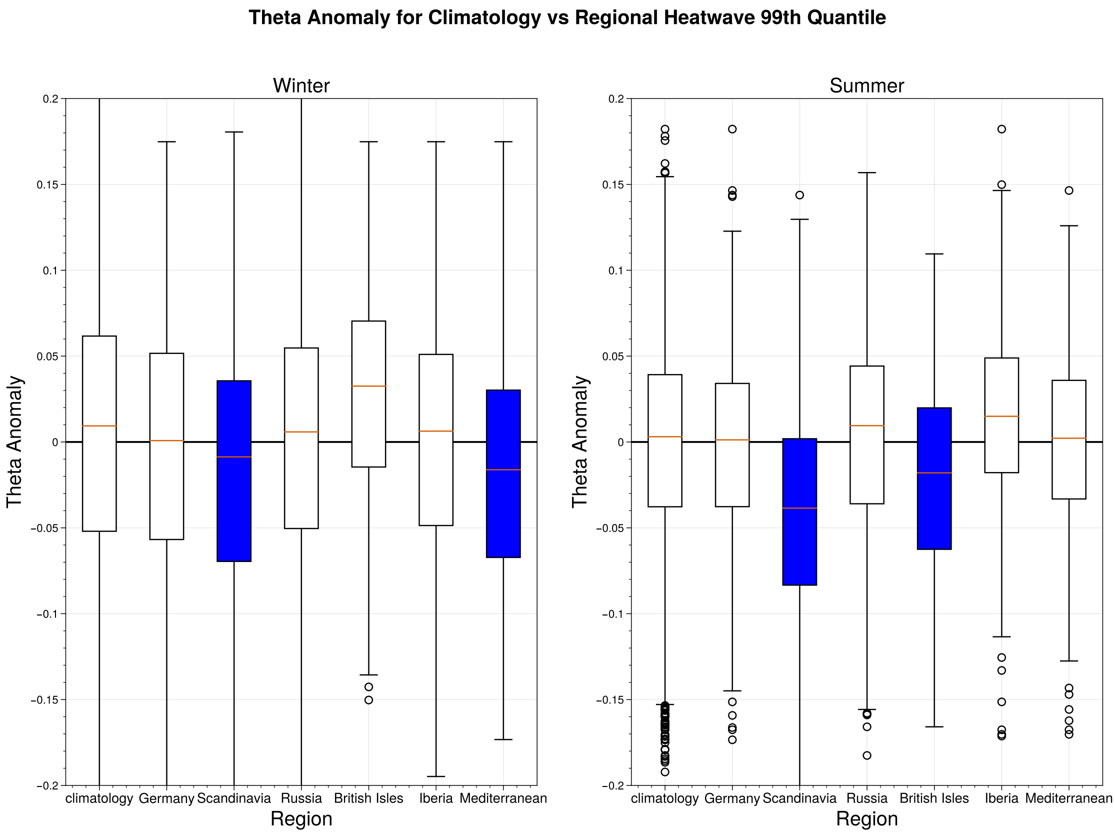

Figure A6. Theta anomaly box plots for different theta threshold values, namely the 99th percentile.

https://doi.org/10.5194/esd-2022-50
Preprint. Discussion started: 16 November 2022

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Author contributions. EH and GM designed the study. EH carried out the analysis and drafted the first version of the manuscript. All authors contributed to structuring the analysis and reviewing the manuscript.

Competing interests. One author is a member of the editorial board of this journal, Earth System Dynamics. The peer-review process was guided by an independent editor, and the authors have no other competing interests to declare.

Acknowledgements. This work was supported by the EU International Training Network (ITN) European weather extremes: drivers, predictability and impacts (EDIPI) project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 956396.

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