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A New Global Lagrangian Analysis of Near-Surface Temperature Extremes

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Key Points:

- This global Lagrangian study assesses how horizontal transport, vertical transport, and diabatic heating contribute to temperature extremes
- The study quantifies these contributions based on deviations from their climatological values
- The findings suggest that, globally, horizontal transport is the dominant factor in the formation of both warm and cold extremes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Temperature extremes strongly affect the society and the environment, yet a complete physical understanding of their formation mechanisms is still lacking. Specifically, the relative importance of the three key processes—horizontal advection, subsidence accompanied by adiabatic warming, and diabatic heating—remains controversial. This paper presents a global quantification of the contributions from these processes to near-surface temperature extremes using the Lagrangian framework. Two Lagrangian potential temperature anomaly decompositions are applied: one based on the full fields of the respective terms, and the other one based on the anomaly fields of the respective terms (i.e., deviations from their corresponding climatologies). The results from the decomposition based on full fields mostly align with those of a previous study, while the decomposition based on anomaly fields offers a different assessment of the roles of the different processes. Most importantly, horizontal transport is attributed the primary role for both extremes globally.

Plain Language Summary Temperature extreme events can have serious impacts on the society and the environment. However, a full understanding of how temperature extremes form in the Earth's atmosphere is still lacking. What remains especially unclear is whether temperature extremes result from horizontal or vertical transport of air masses or from the heating and cooling of these air masses on their way. This study takes a global approach to assess the roles of these processes in the formation of warm and cold extremes. By tracing the evolution of air masses, the study evaluates the contribution of each process. Following a previous approach, the analysis suggests that warm and cold extremes form quite differently: While horizontal transport appears to dominate the formation of cold extremes globally, warm extremes seem to result from a variety of processes. However, the current study then reveals that, when considering deviations from climatological conditions for each process, anomalies in the horizontal transport dominate the formation of both warm and cold extremes. Thus, globally, horizontal transport appears to be the key factor in the formation of both extremes.

1. Introduction

Temperature extremes, both warm and cold, have a wide-ranging impact on the society and the environment. They can strain energy systems (e.g., Añel et al., 2017; Thornton et al., 2016), threaten public health (e.g., Conlon et al., 2011; Forzieri et al., 2017; Gasparrini et al., 2015), and cause agricultural and economic losses (e.g., García-Herrera et al., 2010; Lesk et al., 2016). Given the socio-economic importance of such temperature extremes, scientists have aimed to develop a comprehensive physical understanding of the processes driving these extreme events. However, this understanding still lacks a scientific consensus on the relative importance of the processes believed to be crucial for the formation of temperature extremes.

Cold extremes have primarily been attributed to the horizontal advection of cold air (e.g., Bieli et al., 2015; Garfinkel & Harnik, 2017; Schneider et al., 2015; Tuel & Martius, 2024), with diabatic cooling sometimes also considered important (e.g., Hartig et al., 2023; Papritz, 2020; Turner et al., 2013). In contrast, warm extremes seem to be more diverse in terms of their underlying mechanisms. Horizontal advection of warm air, adiabatic warming in subsiding air, and diabatic heating have all been identified as key contributors (e.g., Hochman et al., 2021; Hotz et al., 2024; Miralles et al., 2014; Schumacher et al., 2022; Sousa et al., 2019; Zschenderlein et al., 2019). Yet, assessing the relative importance of the different processes remains challenging, and a comprehensive global understanding of their relevance is only about to emerge. A major step forward in this direction was made by Röthlisberger and Papritz (2023a, 2023b), who conducted the first global quantification of hot and cold extremes, considering all the three processes involved. They employed a novel Lagrangian diagnostic, in which the temperature anomaly changes of an air parcel are tracked separately for each individual process and accumulated along its trajectory. Based on this approach, Röthlisberger and Papritz (2023a, 2023b)

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concluded that advection dominates cold extremes globally, while warm extremes show high spatial variability in the contributions from the three processes, with no single process clearly dominant across the globe.

Röthlisberger and Papritz' Lagrangian temperature anomaly decomposition approach is valuable in that it quantifies the extent to which each individual process has acted on an air parcel to form a final anomaly. However, in some respects, the approach may fail to address the key question of which process is actually most relevant to the formation of a given temperature anomaly. One could argue that a particularly large contribution from one term may be irrelevant if a large contribution from this term is a typical feature, that is, part of the climatology. This issue was recognized by Mayer and Wirth (2025), who proposed an alternative decomposition based on anomalies of the individual terms. This decomposition addresses the arguably most relevant question, namely: What is unusual about the processes' contributions in situations where temperatures are unusual? Focusing on two specific regions and episodes, Mayer and Wirth (2025) showed that, for warm extremes, the anomaly based decomposition can lead to substantially different conclusions about the relative importance of the processes compared to the original decomposition. This finding raises the question of to what extent the decomposition based on anomaly fields might change the conclusions of Röthlisberger and Papritz (2023a, 2023b) regarding the role of the three processes in the formation of temperature extremes on a global scale.

In this paper we present a new global analysis of near-surface warm and cold extremes with respect to their contributions from horizontal transport, vertical transport, and diabatic heating. We apply both a Lagrangian decomposition based on full fields, similar to that of Röthlisberger and Papritz (2023a, 2023b), as well as a decomposition based on anomaly fields. We follow Mayer and Wirth (2025) and gain the Lagrangian information required by means of Eulerian tracer advection (Mayer & Wirth, 2023). We will show that our results from the decomposition in terms of full fields mostly align with those of Röthlisberger and Papritz (2023a, 2023b), who used trajectory calculations to determine the contributions, while the decomposition in terms of anomaly fields offers a rather different assessment, especially with regard to warm extremes.

2. Methods and Data

2.1. Lagrangian θ' Decompositions

In this study, the Lagrangian potential temperature anomaly decomposition from Mayer and Wirth (2025) is employed. The decomposition is based on five terms: (a) horizontal transport along climatological horizontal potential temperature gradients, (b) vertical transport along climatological vertical potential temperature gradients, (c) diabatic heating of the air parcel along its trajectory, (d) the local rate of change of the climatological potential temperature due to seasonality, and (e) a pre-existing potential temperature anomaly. The full contributions from the first four terms can be described via the following Lagrangian integrals:

$$\theta_{\text{hor}}(\mathbf{x}, t) = \int_{-\infty}^t -\mathbf{v} \cdot \nabla_{\text{h}} \bar{\theta} e^{-\lambda(t-t')} dt', \quad (1)$$

$$\theta_{\text{ver}}(\mathbf{x}, t) = \int_{-\infty}^t -\frac{\partial \bar{\theta}}{\partial p} \omega e^{-\lambda(t-t')} dt', \quad (2)$$

$$\theta_{\text{dia}}(\mathbf{x}, t) = \int_{-\infty}^t \frac{D\theta}{Dt'} e^{-\lambda(t-t')} dt', \quad (3)$$

$$\theta_{\text{sea}}(\mathbf{x}, t) = \int_{-\infty}^t -\frac{\partial \bar{\theta}}{\partial t'} e^{-\lambda(t-t')} dt', \quad (4)$$

where \mathbf{v} and ω are the horizontal and vertical winds, respectively, θ is potential temperature with $\bar{\theta}$ its climatology, ∇_{h} is the horizontal gradient, and p is pressure. The integrals accumulate information along the trajectory of the air parcel that happens to be located at location \mathbf{x} at time t . The accumulation involves an exponential weighting as one goes backward in time along the parcel trajectory. The decay time associated with the exponential weighting is governed by the parameter λ and effectively determines the timescale of accumulation. The fifth term, the pre-existing potential temperature anomaly, θ_{pre} , reflects the accumulation of the four other terms from earlier times,

that is, up to about λ^{-1} before the considered point in time (see the term R in Equation 6 in Mayer and Wirth (2025)).

Based on the aforementioned terms, a given potential temperature anomaly θ' can be decomposed into the contributions from the respective processes. In Mayer and Wirth (2025), two different approaches for this decomposition have been employed. The first approach is based on the full fields of the respective terms, following the approach of Röthlisberger and Papritz (2023b):

$$\theta' = \theta_{\text{hor}} + \theta_{\text{ver}} + \theta_{\text{dia}} + \theta_{\text{sea}} + \theta_{\text{pre}}. \quad (5)$$

In contrast, the second approach is based on the anomaly fields of the respective terms, that is, deviations from their corresponding climatologies (denoted with primes):

$$\theta' = \theta'_{\text{hor}} + \theta'_{\text{ver}} + \theta'_{\text{dia}} + \theta'_{\text{sea}} + \theta'_{\text{pre}}. \quad (6)$$

The two decompositions 5 and 6 capture slightly different aspects of the formation of temperature anomalies. Both are mathematically sound, although they are somewhat complementary. As we will argue, selecting decomposition 6 over 5 will offer a more meaningful approach to understanding anomalous temperatures, as it eliminates the atmosphere's climatological behavior, which is of limited use in explaining anomalies. In the following, we apply both decompositions to warm and cold near-surface temperature extremes globally to analyze how the two decompositions differ in the relative importance they assign to the respective processes.

For the accumulation timescale λ^{-1} we selected 3 days for warm extremes and 7 days for cold extremes. This choice reflects the typical Lagrangian lifetimes of temperature anomalies, which have been found to be approximately 3 days on average globally for warm extremes (Röthlisberger & Papritz, 2023b), and somewhat longer for cold extremes (Röthlisberger & Papritz, 2023a). Note that the choice of a fixed and static parameter for λ is a limitation of our approach, as it cannot account for individually varying lifetimes of anomalies. However, experimenting with different values of λ has shown that the main findings of our paper do not sensitively depend on the exact choice of the parameter. In particular, the results for the decomposition in terms of anomaly fields proved to be quite insensitive to the precise value chosen.

In the following analysis, θ_{hor} , θ_{ver} , and θ_{dia} will be referred to as the process terms. The seasonality θ_{sea} is usually small and will be neglected. For further details regarding the θ' decompositions the reader is referred to Mayer and Wirth (2025).

2.2. Eulerian Tracer Advection With Relaxation

The integrals in 1–4 are obtained using the tracer advection method by Mayer and Wirth (2023). A key feature of this method is that it provides the required time-accumulated Lagrangian information directly as gridded fields available at any time step. The method is based on the offline advection of passive tracer fields including a relaxation term. A separate tracer is required to get a solution for each of the integrals. The term θ_{pre} is computed from 5 as a residuum. For more information on the tracer method and its use in calculating the terms in the θ' decomposition the reader is directed to Mayer and Wirth (2023, 2025).

2.3. Data

This study is based on ERA5 reanalysis data (Hersbach et al., 2017, 2023) for the period 2010–2022. The θ' contributions are derived from global data at every second model level up to model level 50 with a horizontal resolution of 1° and a temporal resolution of 3 hr. The θ' contributions are obtained every 3 hr and then aggregated to daily means. The fields cover the entire global domain up to the tropopause; however, this study only presents near-surface fields. For this purpose, all fields have been averaged gridpointwise over a layer with a vertical extent of 50 hPa following the topography. Climatologies of any variables are computed by individually averaging each day of the year, followed by smoothing these day-specific temporal averages with a centered 31-day running average. Daily anomalies are calculated as differences from these daily climatologies.

2.4. Definition of Warm and Cold Extremes

For warm (cold) extremes we chose the following simple definition. Warm (cold) extremes are defined as days that exceed (fall below) the 90th (10th) percentile of the daily mean near-surface potential temperature anomaly distribution during the warm (cold) season. The warm (cold) season is defined as the period of the year when the climatological daily mean near-surface potential temperature surpasses (is below) the 75th (25th) percentile. The identification of warm and cold extremes is performed for each grid point individually and results in 119 warm and 119 cold days per grid points. For additional information on the timing of the warm and cold seasons and the number of independent extreme events, see Figure S1 in Supporting Information S1.

3. Results

3.1. Decomposition in Terms of Full Fields

We begin by presenting the results of our potential temperature anomaly decomposition in terms of full fields, both for warm and cold extremes. In this context, we compare our results with the findings of Röthlisberger and Papritz (2023a, 2023b), whose analysis was limited to the hottest and coldest day of each year in a 42 yr period. We expect overall good consistency with their results, but differences in the selection of warm and cold extremes and in the decomposition methods (see Mayer and Wirth (2025)) are likely to lead to some deviations.

To start with, Figure 1 shows the average near-surface potential temperature anomaly during warm extremes and its decomposition in terms of full fields. We find strong geographical variations in the contributions from the three process terms. Horizontal transport (Figure 1a) is positive in most of the extratropics, particularly in the storm track regions, and negative in the subtropics and mid-latitude land areas; it dominates the θ' decomposition in the mid-latitude storm tracks, Greenland, and over Antarctica (green in Figure 1f). Vertical transport (Figure 1b) is positive everywhere except in regions with pronounced orography, with the largest positive contributions along coastal areas on the western sides of continents and over subtropical oceans, where it dominates the θ' decomposition (blue in Figure 1f). Diabatic heating (Figure 1c) is positive over land, excluding ice sheets, and negative over oceans, with maxima in dry regions like western Australia and western Africa. In many tropical and subtropical land regions, diabatic heating dominates the θ' decomposition (brown in Figure 1f). The pre-existing potential temperature anomaly (Figure 1d) is overall positive and particularly large over northern Eurasia, Greenland, and Antarctica, consistent with a larger mean Lagrangian age of the potential temperature anomalies in these regions (Röthlisberger & Papritz, 2023b). Substantial positive contributions from multiple processes are evident in several areas, such as northern Eurasia and eastern Canada, where all three processes contribute similarly (purple in Figure 1f). Overall, vertical transport is the dominant process over the ocean (Figure 1g), whereas diabatic heating prevails over land (Figure 1h).

Next, Figure 2 shows the average near-surface potential temperature anomaly during cold extremes and its decomposition in terms of full fields. Horizontal transport (Figure 2a) is negative across most areas, and notably large negative contributions—sometimes even exceeding the magnitude of the final anomaly—are found in the storm track regions. Here, horizontal transport is often the only negative contributor and its strong contributions are partially offset by the other terms (see also Röthlisberger and Papritz (2023a)). Vertical transport (Figure 2b) mostly contributes positively, except in elevated regions, with maxima over the oceans. Diabatic heating (Figure 2c) is negative over the mid-to-high latitude Northern Hemisphere continents, the ice sheets, and parts of the tropical oceans, with the largest negative contributions in Siberia and Antarctica. In contrast, diabatic heating is positive over the extratropical oceans, with particularly large values in the storm track regions. The contribution from the pre-existing potential temperature anomaly (Figure 2d) is generally negative, but relatively small compared to the other terms. Globally, horizontal transport dominates the θ' decomposition, both over the ocean and over the land (Figures 2g and 2h). In summary, we find a gradual transition from cold extremes mostly driven by diabatic heating in the climatologically coldest regions (brown in Figure 2f) to cold extremes dominated by horizontal transport (green in Figure 2f) in climatologically warmer regions.

Overall, the findings for both warm and cold extremes are in good agreement with the results from Röthlisberger and Papritz (2023a, 2023b) (also see Figures S2 and S3 in Supporting Information S1), with only minor differences being apparent. These differences appear mostly in areas with pronounced orography, likely due to the challenge of accurately computing the temperature gradients in these regions (Röthlisberger & Papritz, 2023b). Additional differences occur in regions where the pre-existing term dominates, suggesting a link to the longer timescale over

Decomposition in terms of full fields
warm extremes

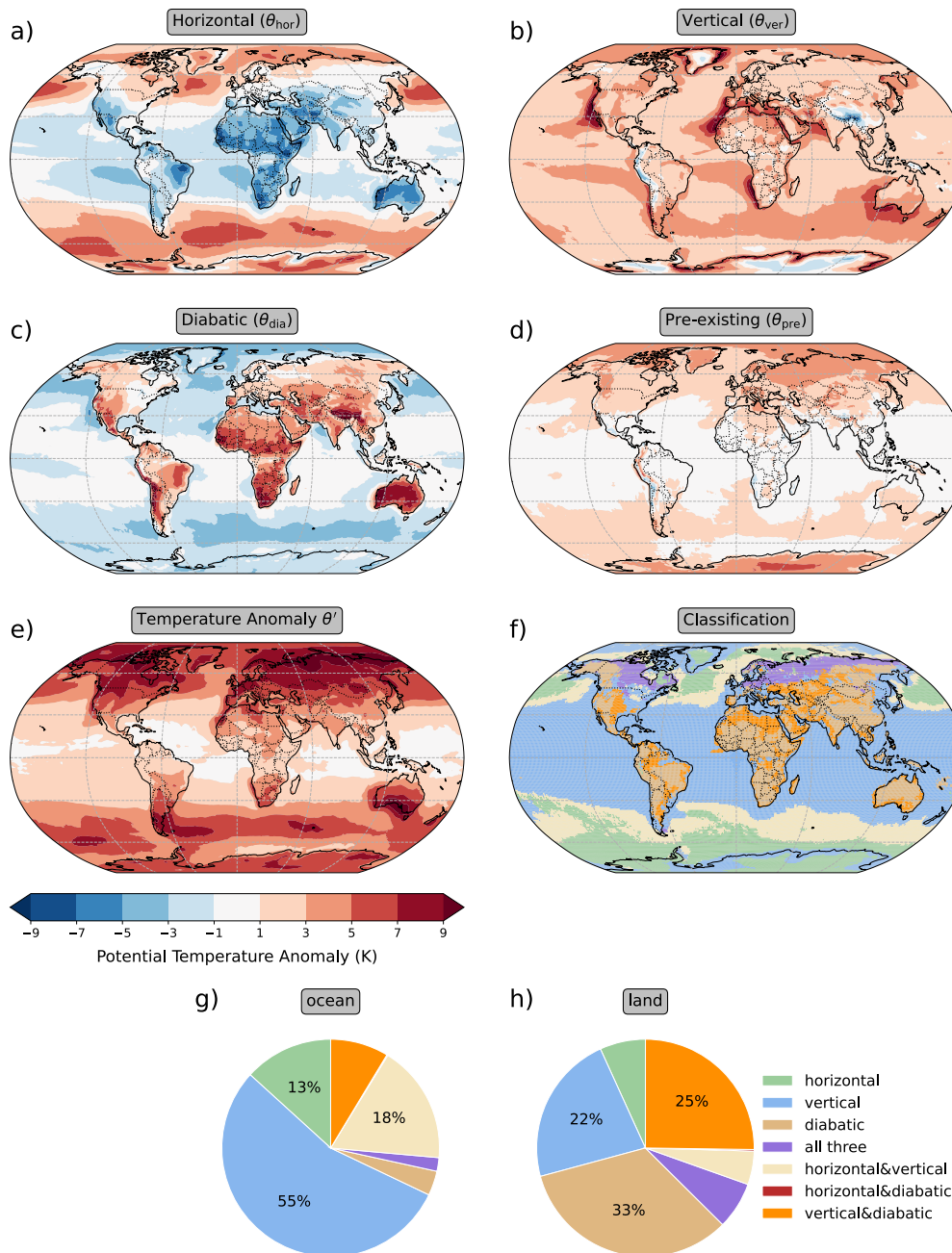


Figure 1. The average contributions from (a) horizontal transport, (b) vertical transport, (c) diabatic heating, and (d) pre-existing anomaly to the average near-surface potential temperature anomaly (e) during warm extremes in 2010–2022 at each grid point. Contributions are given in terms of full fields. In (f), all grid points are categorized based on their θ' composition, following the categorization from R othlisberger and Papritz (2023b). The figure depicts the category that occurs most often across all hot days. Green, blue, and brown colors represent regions where either horizontal transport, vertical transport, or diabatic heating dominates, whereby a process is considered dominant if its contribution is the only positive one or if it is at least twice as large as the contribution from the second most important process. In purple regions, no single process dominates, but all three contribute positively to the anomaly. Light brown, red, and orange regions also lack a dominant process, but show positive contributions from two processes, with the remaining one being negative. The pie charts depict the occurrence frequency for each category across all hot days over (g) land and (h) ocean grid points, with a cosine-based area weighting applied to compensate for the meridian convergence towards high latitudes.

Decomposition in terms of full fields
cold extremes

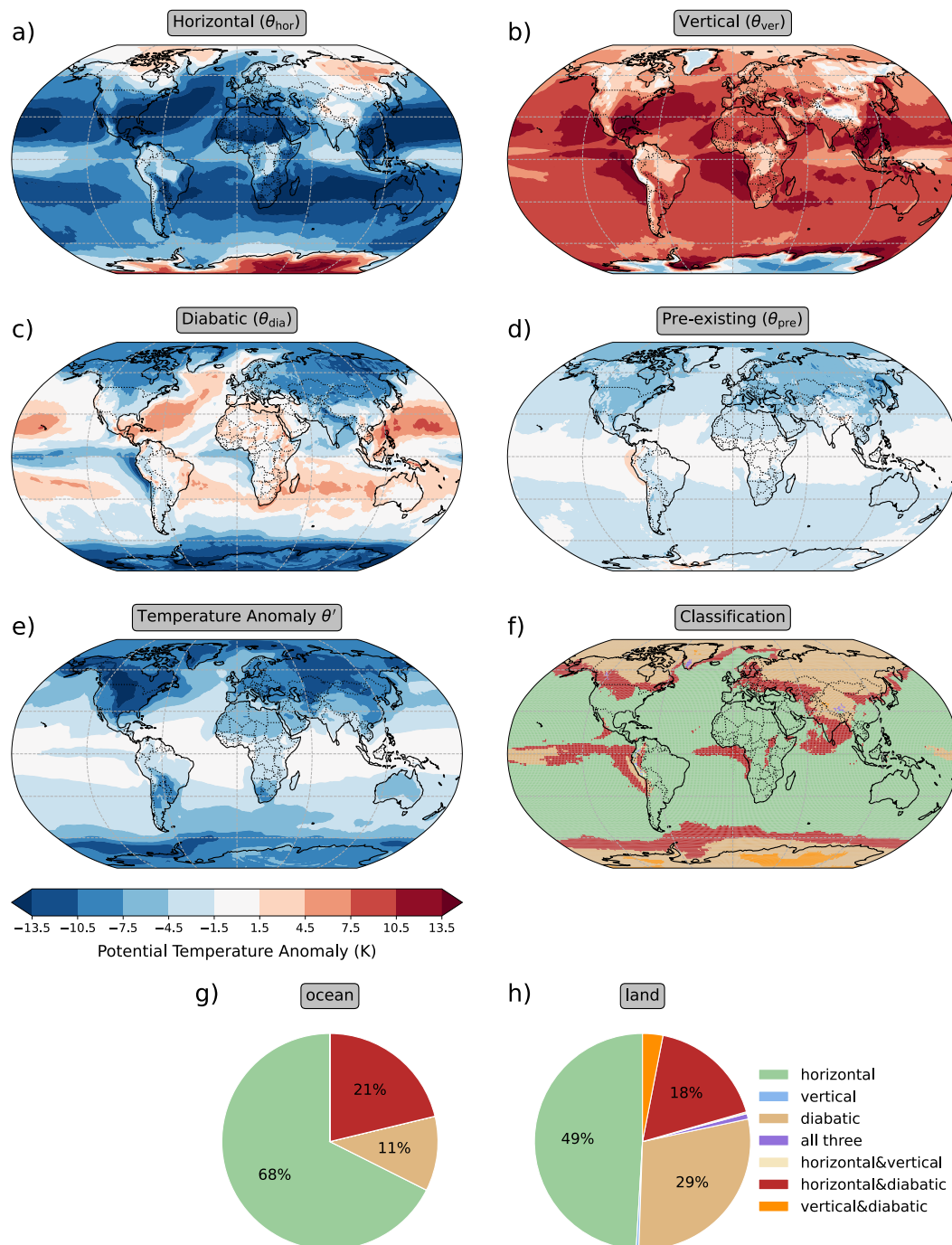


Figure 2. Same as Figure 1, except for cold extremes.

which the anomalies form in these regions (Röthlisberger & Papritz, 2023b). However, the overall good agreement with Röthlisberger and Papritz (2023a, 2023b) suggests that the process terms in our potential temperature anomaly decomposition do capture the key processes of anomaly formation similarly to theirs, despite some differences in the decomposition approaches, and in particular, our additional pre-existing anomaly term.

3.2. Decomposition in Terms of Anomaly Fields

Now we turn to the decomposition in terms of anomaly fields and analyze to what extent this decomposition differs from the decomposition in terms of full fields. This analysis is motivated by the fact that many characteristics of the process terms described earlier are largely inherent to the climatological behavior (see Figures S4 and S5 in Supporting Information S1) and, as such, may not be useful in “explaining” an *anomalous* behavior (temperature). For instance, it was diagnosed that diabatic heating during warm extremes is substantially positive over large parts of the continents and, thus, contributes substantially to warm extremes there. However, this diabatic heating is not unique to warm extremes, but also applies to the warm season as a whole (see Figure S4c in Supporting Information S1). Consequently, a decomposition that focuses specifically on the unusual behavior of the process terms may provide a more effective framework for “understanding” unusual temperatures.

Figure 3 depicts the decomposition in terms of anomaly fields for warm extremes. Most notably, the decomposition in terms of anomaly fields differs from the one in terms of full fields in the role of horizontal transport (Figure 3a). While horizontal transport showed negative contributions in many parts of the Earth in the decomposition in terms of full fields, the decomposition in terms of anomaly fields reveals positive contributions almost everywhere, except in a few tropical regions. The decomposition in terms of anomaly fields accounts for the fact that horizontal cold air transport is “normal” across large areas near the Earth’s surface (see Figure S4a in Supporting Information S1) and, therefore, represents the absence or reduction of this cold air transport as a positive contribution in the decomposition. Contrary to horizontal transport, the contribution of vertical transport (Figure 3b) is smaller in the decomposition in terms of anomaly fields compared to the decomposition in terms of full fields, such that noticeably more areas occur where vertical transport contributes negatively. The decomposition in terms of anomaly fields takes into account that most air masses near the surface could only have arrived there through subsidence (indicated as overall positive contributions in the climatology, see Figure S4b in Supporting Information S1), and provides a positive contribution only if the subsidence is stronger than usual. Diabatic heating (Figure 3c) is still mostly positive over land and negative over oceans, though its magnitude is noticeably smaller compared to the decomposition in terms of full fields.

Overall, the shift to the decomposition in terms of anomaly fields yields a new and somewhat different assessment of the dominant formation processes of warm extremes globally. Most importantly, horizontal transport controls most of the extratropics (green in Figure 3f) and parts of the subtropics and tropics. Moreover, the dominant role of vertical transport in the subtropical and tropical oceans is limited to lower latitudes compared to the decomposition in terms of full fields. Diabatic heating (brown in Figure 3f) remains the dominant process in many tropical and subtropical regions, but similar to vertical transport its dominance over land is confined to lower latitudes compared to the decomposition in terms of full fields. Instead, diabatic heating now prevails in parts of the tropical ocean. Globally, horizontal transport dominates, both over the ocean and over the land (Figures 3g and 3h).

Finally, Figure 4 presents the decomposition in terms of anomaly fields for cold extremes. Most importantly, the role of vertical transport (Figure 4b) is assessed differently compared to the decomposition in terms of full fields. That is, vertical transport now reveals substantial negative contributions, primarily over Siberia, Canada, and the northern polar regions. These occurrences of negative contributions from vertical transport are a major difference compared to the decomposition in terms of full fields, which does not allow vertical transport to contribute negatively to cold extremes in non-elevated regions. Thus, the decomposition in terms of anomaly fields opens up the possibility for vertical transport to actually contribute in an amplifying way to a cold anomaly—in distinct contrast to the decomposition in terms of full fields. In certain areas, vertical transport even dominates the formation of cold extremes (blue in Figure 4f). In contrast to vertical transport, the role of horizontal transport (Figure 4a) does not differ substantially from its role in the decomposition in terms of full fields. As before, its contribution is negative in most regions across the globe. Overall, the magnitude is smaller compared to the decomposition in terms of full fields; however, horizontal transport still constitutes the major formation process for cold extremes globally (Figures 4g and 4h). Interestingly, with the shift to the decomposition in terms of anomaly fields, diabatic cooling (Figure 4c) loses its role as key formation process for cold extremes in the coldest regions, where substantial diabatic cooling is typical during the cold season (see Figure S5c in Supporting Information S1). In contrast, diabatic cooling becomes the leading process for cold extremes in parts of the tropics (brown in Figure 4f).

Decomposition in terms of anomaly fields
warm extremes

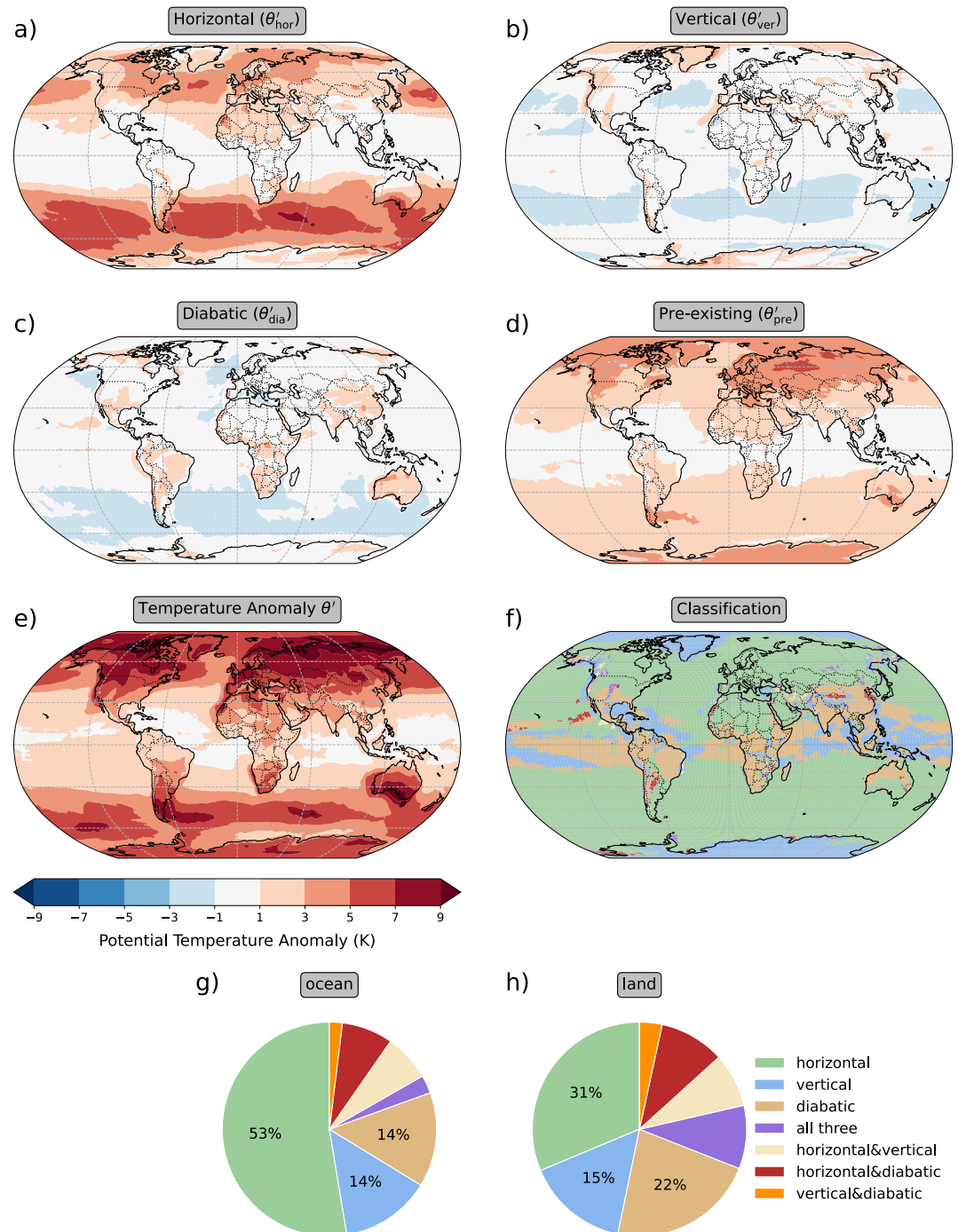


Figure 3. Same as Figure 1, but the contributions are now depicted in terms of anomaly fields.

4. Discussion and Conclusions

This paper presents a new global quantification of the roles of horizontal transport, vertical transport, and diabatic heating for the formation of near-surface warm and cold temperature extremes based on a new Lagrangian

Decomposition in terms of anomaly fields
cold extremes

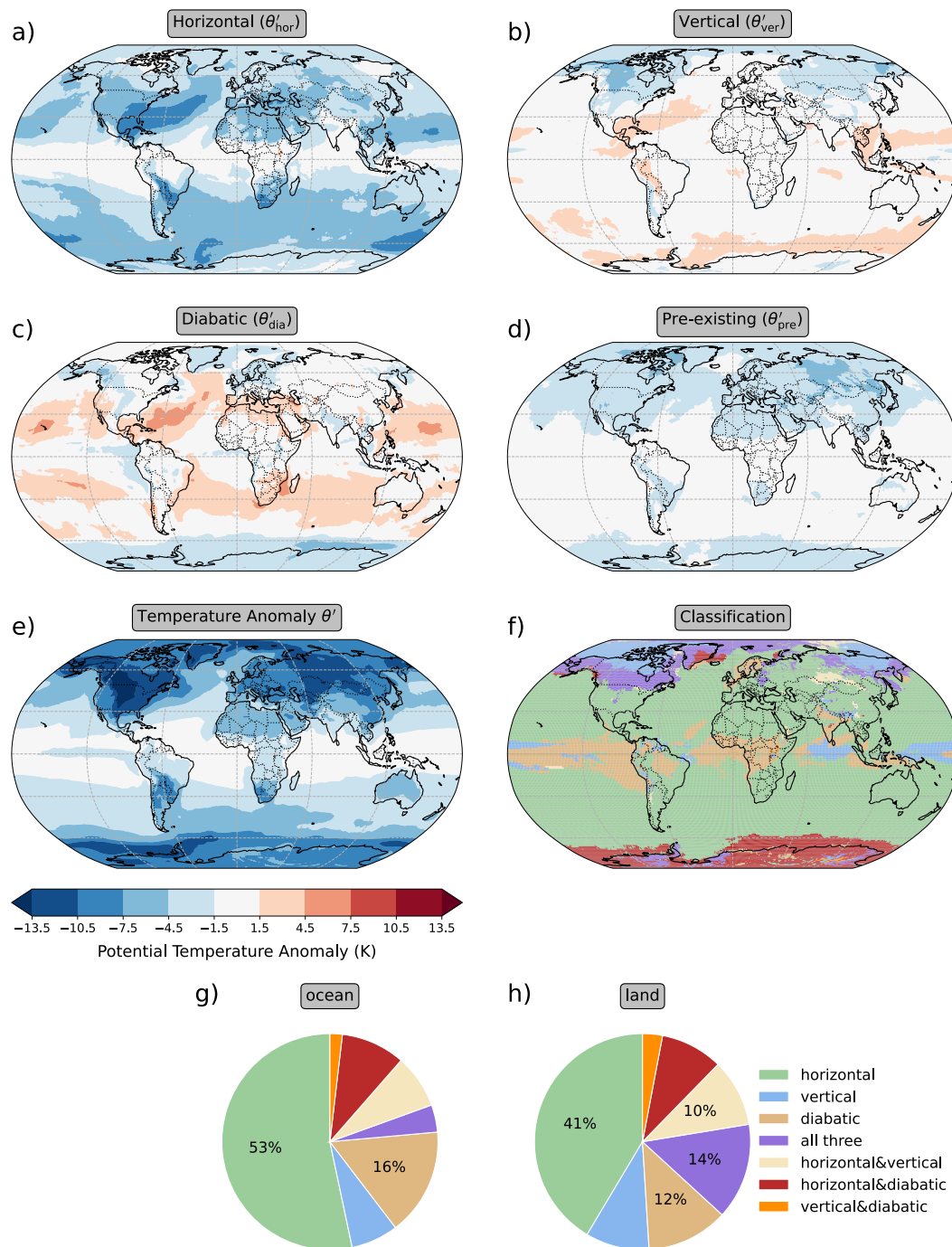


Figure 4. Same as Figure 2, but the contributions are now depicted in terms of anomaly fields.

temperature anomaly decomposition. As a first step—and to connect with existing literature—we applied a decomposition based on the absolute contributions of the respective processes, which yielded results largely similar to Röthlisberger and Papritz (2023a, 2023b) for both warm and cold extremes. The similarity of these results not only confirms our approach but also reinforces the findings of Röthlisberger and Papritz (2023a,

2023b), establishing them on a broader statistical basis. This quantification assigns distinctly different roles to the various processes in the formation of warm and cold extremes. In particular, on a global scale, horizontal transport is attributed an important role only in the formation of cold extremes, but not in the formation of warm extremes.

However, we then showed that the relative importance of the three processes is assessed substantially differently on a global scale when a new quantification based on anomaly fields of the respective terms is applied. The new quantification was motivated by the finding that many aspects of the processes' contributions are associated with the atmosphere's climatological behavior and, as such, may offer limited value in understanding anomalous temperatures. In the new quantification, horizontal transport emerges as a key contributor not only to cold extremes, but also to warm extremes across large parts of the globe. This finding thus extends the findings of Mayer and Wirth (2025) beyond the two specific regions they studied. In general, the quantification in terms of anomaly fields emphasizes the dominance of horizontal transport in the generation of temperature extremes and deemphasizes the role of diabatic heating.

Our new quantification extends the quantification by Röthlisberger and Papritz (2023a, 2023b) by interpreting the contributions from the respective processes with respect to their climatological behavior—a behavior that yields contributions substantially different from zero. More precisely, the new quantification systematically describes the highly anomalous temperatures during hot and cold extremes in terms of anomalies in the underlying process terms. In doing so, it addresses the arguably truly interesting question of what exactly is anomalous in situations where temperatures are highly anomalous—a question we believe the quantification in terms of absolute fields narrowly misses.

Despite some limitations in our method, such as the presence of a pre-existing anomaly which leaves room for some unexplained anomaly and uncertainty in our results, we believe this study represents an important step forward in advancing our understanding of the formation of temperature extremes. For the first time on a global scale, the study makes a clear attempt to quantify, from a Lagrangian perspective, the unusual behavior during temperature extremes through capturing the unusual behavior of the process terms—arguably a crucial, if not the most crucial, element in understanding the formation of temperature extremes.

Conflict of Interest

The author declares no conflicts of interest relevant to this study.

Data Availability Statement

The code to reproduce the data analysis and all figures of this article is available at <https://doi.org/10.5281/zenodo.17100492> (Mayer, 2025a). The data is available at <https://doi.org/10.5281/zenodo.15827328> (Mayer, 2025b) and the tracer advection code used to create the data is available at <https://doi.org/10.5281/zenodo.14773247> (Mayer, 2025c). All results are based on the ERA5 reanalysis (Hersbach et al., 2017, 2023) from the European Center for Medium-Range Weather Forecasts (ECMWF) provided by the Copernicus Climate Change Service (C3S). The results contain modified Copernicus Climate Change Service information 2024. Neither the European Commission nor the ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

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