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On the Definition of Extreme Evaporation Events

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Key Points:

- Evaporation extremes form clusters in time which can be studied as autonomous entities, that is, extreme evaporation events (ExEvEs)
- Extreme evaporation events have distinct physical properties and can behave differently compared to the total evaporation
- An event-based statistical framework is formulated that can help in the detection, characterization, and analysis of extreme evaporation

Supporting Information:

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

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Abstract Even though evaporation is a crucial component of the energy and water cycles, its extremes remain largely unexplored. To address this gap, this study introduces a statistical framework defining Extreme Evaporation Events (ExEvEs). We investigate their characteristics over Czechia, a country in Central Europe with increasing evaporation and examine their seasonal correlation with radiation and/or precipitation—the main drivers of land evaporation. Despite their statistical definition, ExEvEs are shown to have a physical basis, also evident in their onset and termination. We also observe that ExEvEs fluctuate differently than the average evaporation resulting to significant implications for water availability and regional water cycle's acceleration. The proposed event-based framework provides a systematic way to detect, characterize, and analyze evaporation extremes, which helps to improve our understanding of their drivers and impacts.

Plain Language Summary Evaporation plays a key role in the transfer of water and energy from Earth's surface to the atmosphere. Although the physical processes that govern it are well-understood, much less is known about its extremes. In this study, a statistical framework is introduced which defines its extremes as individual events with a beginning and an ending. By applying this methodological approach over Czechia, we can see that ExEvEs tend to form clusters of heightened evaporation lasting several days. In summer, these events are linked to sunny, dry conditions, while in winter, they are driven by wet weather and longwave radiation. Since 1981, the frequency and intensity of ExEvEs in Czechia have risen sharply, much more dramatically than overall evaporation. This increase has significant effects on the amount and speed of water exchange between land and atmosphere. The proposed framework provides a systematic way to identify, study, and understand evaporation extremes, shedding light on their causes, effects, and seasonal patterns.

1. Introduction

The study of extreme events has a long and well-established history in climate and hydrological research. Among the most extensively studied climatic extremes are those related to temperature and precipitation, due to their critical roles in the global energy and water cycles. Prolonged periods of extreme temperatures, known as heatwaves, significantly disrupt the surface energy budget, worsening drought conditions, elevating wildfire risks, and placing severe stress on natural ecosystems and human health. Similarly, extreme precipitation events play a crucial role in the water cycle, often leading to severe consequences for infrastructure and local economies through floods and landslides. Given the profound impacts of these events, it is essential to expand our understanding of other climatic extremes that also disrupt the energy and water cycles and pose risks to both ecosystems and human society.

Even though the importance of evaporation as a fundamental process in both the global energy and water cycles has been established by decades of research, its extremes have received surprisingly little attention. To date, only two studies have specifically focused on extreme evaporation (Aemisegger & Papritz, 2018; Bogawski & Bednorz, 2016). The former investigate regional fluctuations of extreme evaporation over land, while the latter goes one step further by demonstrating how large-scale oceanic evaporation can affect synoptic patterns and influence global atmospheric circulation. Except for these two studies only a few scattered references to extreme evaporation exist in the literature, such as the analyses of global evaporation and potential evaporation divergence (Liu et al., 2022), the downscaling of climatic extremes in model simulations (Yang et al., 2012), the generation of dry intrusions from increased speed winds (Givon et al., 2024), and the study of heavy precipitation over the Mediterranean (Winschall et al., 2014). Additionally, the notion of evaporation events can be found in the context of atmospheric moisture transport (Gimeno et al., 2012; Keune et al., 2022), but these are not explicitly connected to evaporation extremes. Therefore, an event-based framework for defining and studying extreme evaporation and its implications is still lacking.

The most likely reason for this is the general lack of long-term observations at daily scale, as well as the huge uncertainties and biases that have been reported to the simulated data products (K. Wang & Dickinson, 2012). Additionally, the strong coupling of evaporation with atmospheric temperature extremes (i.e., heatwaves) offers a plausible, more accurate, alternative with better spatio-temporal coverage and resolution. Therefore, when we study the impact of extreme atmospheric evaporative demand to soil moisture droughts, compound events or soil-atmosphere interactions, we usually resort to atmospheric temperature instead (Miralles et al., 2019; Seneviratne et al., 2010; Zscheischler et al., 2020). By doing so, we assume that temperature can fully describe and be associated to the soil water depletion, and most likely with this assumption we increase the estimation uncertainty. If we, instead, analyze evaporation fluxes and their extremes, we can overcome this limitation, since we will be directly estimating the transfer of water from land to the atmosphere. The increase in the amount and quality of high-resolution, global evaporation products during the last decade as well as the advances in the modeling domain, now allows for the first time to look deeper into extreme evaporation itself.

The objective of this study is to provide a new methodological approach for the study of extreme evaporation. We will see that evaporation extremes tend to cluster over time creating periods with persistent deviations above the mean state. These periods can be considered as events with their onset and termination triggered by external physical drivers. Hence, in the very same manner that we define and study heatwaves, we can formulate a framework that determines and analyzes extreme evaporation events (ExEvEs). To achieve this, we will first confirm the clustering behavior of evaporation by investigating its autocorrelation structure. After defining what constitutes an extreme evaporation event, we will investigate how they relate to the energy and moisture sources (radiation and precipitation) to justify that it is not just a statistical artifact. Then, we will discuss how the proposed framework can be implemented in a specific region and evaluate the additional insights gained in terms of evaporation temporal fluctuations, as well as their impacts in regional hydrological cycle and water availability. After this investigation, it will be easier to understand the potential impact of extreme evaporation events in current and future research, which is briefly discussed in the concluding paragraphs.

2. Materials and Methods

To analyze extreme evaporation events over land, the Global Land Evaporation Amsterdam Model (GLEAM) v3.7a was utilized at a 0.25° resolution and daily time scale for the period 1981–2022 (Martens et al., 2017). GLEAM has been widely applied in global evaporation analyses, making it a suitable choice for a representative case study on evaporation extremes. Additionally, the Collocation-Analyzed Multi-source Ensembled Land Evapotranspiration Data (CAMELE) was employed at the same spatio-temporal scale for validation due to its ensemble nature (Li et al., 2022). For downwelling shortwave/longwave radiation, precipitation, and temperature, the Multi-Source Weather (MSWX-Past) was used, a global gridded near-surface meteorological product (Beck et al., 2022). The original data product has a high spatiotemporal resolution of 0.1° and 3-hr time step 1979 to date. GLEAM and CAMELE were used at their original resolutions, while MSWX-Past was aggregated to daily time step and 0.25° resolution. All the data sets were upscaled through area-weighted averages and remapped through nearest-neighbor interpolation. The evaporation and precipitation data sets are freely available for download through the *evapoRe* and *pRecipe* packages, respectively (Vargas Godoy & Markonis, 2023).

The evaporation and radiation time series were transformed to z-scores over pentads at each grid cell to remove their seasonality. that is, each daily value was subtracted from the corresponding pentad mean and divided by the pentad standard deviation. Then, to determine the clustering strength of the time series, the evaporation autocorrelation structure was analyzed. Strong autocorrelation structure implies that the time series values change by small differences compared to their mean, favoring the formation of clusters in time. This behavior known as long-term persistence, long-term memory, or long-range dependence was first detected in streamflow (Hurst, 1956), and since then is also evident in many other natural and artificial systems (O'Connell et al., 2016). Here, the persistence strength is estimated through the Hurst coefficient (Maximum Likelihood Estimation method; Tyralis, 2016), with values close to one indicate long-term persistence (clustering), while weak or no autocorrelation results in a coefficient around 0.5.

The methodology was applied over Czechia (12–19°E and 48.5–51°N), a country in Central Europe characterized by a temperate oceanic climate (Cfb), with cool humid summers and drier winters. A constrained spatial domain was chosen to reduce climatic and land cover heterogeneity, thereby simplifying the investigation of the physical mechanisms involved. This controlled, well-characterized environment, known for its increasing evaporation trends as outlined in Section 4.1, allows us to better understand how these processes are represented by our methodological approach. Once validated, the insights gained can inform future applications on a global scale, where interactions between surface and atmospheric variables are more complex due to diverse land cover, climate zones, and other environmental factors.

Finally, to understand the interplay between evaporation and precipitation within and outside ExEvEs, we explored the changes in the daily residual of precipitation minus evaporation $(P - E)$ and the mean daily land-atmosphere water exchange $\left(\frac{P+E}{2}\right)$. The first metric corresponds to water availability over land, representing the wetness or dryness of the region, while the second serves as an index for water cycle intensification, further extending the formulation of Huntington et al. (2018).

3. Definition of Extreme Evaporation Events

3.1. Statistical Basis

To study extreme evaporation events as individual entities, we must first demonstrate that such events actually exist. To do this, we analyze the autocorrelation structure of the deseasonalized daily time series of evaporation (Figure 1a). The results show that the evaporation time series retains autocorrelation over a 10-day lag. For context, a typical stochastic process that exhibits clustering, such as the lag-1 auto-regressive Markov process (AR(1)), with similar statistical properties, converges to zero after about a week, while a time series without clustering would converge to zero after a single day (white noise). Therefore, evaporation exhibits long-term persistence, with a mean Hurst coefficient of approximately 0.85, indicating enhanced clustering and abrupt state shifts (Eichner et al., 2006; Koutsoyiannis, 2006). In terms of statistical characteristics, this suggests that evaporation time series form clusters of values that can be studied as distinct events.

To classify these events as extremes, they must represent above-average conditions, with at least one day of extreme evaporation. Hence, we define extreme evaporation events as periods of consecutive days with standardized evaporation above the 0.8 quantile, including at least one day above the 0.95 quantile. The use of z-scores is essential due to the strong seasonal patterns of evaporation in regions outside the tropics. We also tested alternative definitions to assess sensitivity to threshold selection, such as consecutive days above the 0.8 quantile without an additional threshold (similarly to the approach of Bogawski and Bednorz (2016)) or using quantile regression instead of fixed values for the mean and the 0.95 quantile (Table S1 in Supporting Information S1). While there were some differences in event detection based on the criteria used, significant overlap was observed in all cases examined (Figures 1b and 1c). These differences highlight that, as with any statistical approach, it is impossible to create an objective, all-encompassing definition of extreme evaporation events. Nevertheless, to study past and future changes, it is necessary to establish and apply a working definition for extreme evaporation events, despite its inherent subjectivity.

Using the aforementioned definition of ExEvEs, we detect an average of 13 events per year, which account for approximately 15% of the total water evaporated over Czechia during the 1981–2022 period. The average duration of an extreme evaporation event is around 3 days, with 1.4 extremes above the 0.95 quantile occurring on average. However, in extraordinary cases, events can extend for nearly a month, such as the 27-day event in January 2021 (Figure S1a in Supporting Information S1). As expected, the average intensity of ExEvEs is 50% higher than normal conditions (1.9 mm/day vs. 1.3 mm/day), and in the most extreme cases, intensity can be up to seven times greater. In terms of severity, an average of 5.2 mm of water is evaporated per event, with a maximum of 60 mm over 18 consecutive days in July 2006 (Figure S1b in Supporting Information S1), reflecting an average intensity of more than 3 mm/day for that event. As we will see bellow, the properties of ExEvEs are not static; they fluctuate significantly over time in response to changes in their physical drivers.

3.2. Physical Properties of the Extreme Evaporation Events

Do extreme evaporation events have distinct characteristics which could be linked to their physical drivers? To address this, we analyze the energy and moisture sources required for ExEvEs examining the conditions before, during, and after the event. The flux driving ExEvEs is ultimately controlled by surface-to-atmosphere gradients in energy and moisture states. By analyzing radiation, decomposed into shortwave and longwave components, as well as precipitation, temperature, and sensible heat flux we can understand how these variables collectively shape the extreme evaporation intensity (Figure 2).

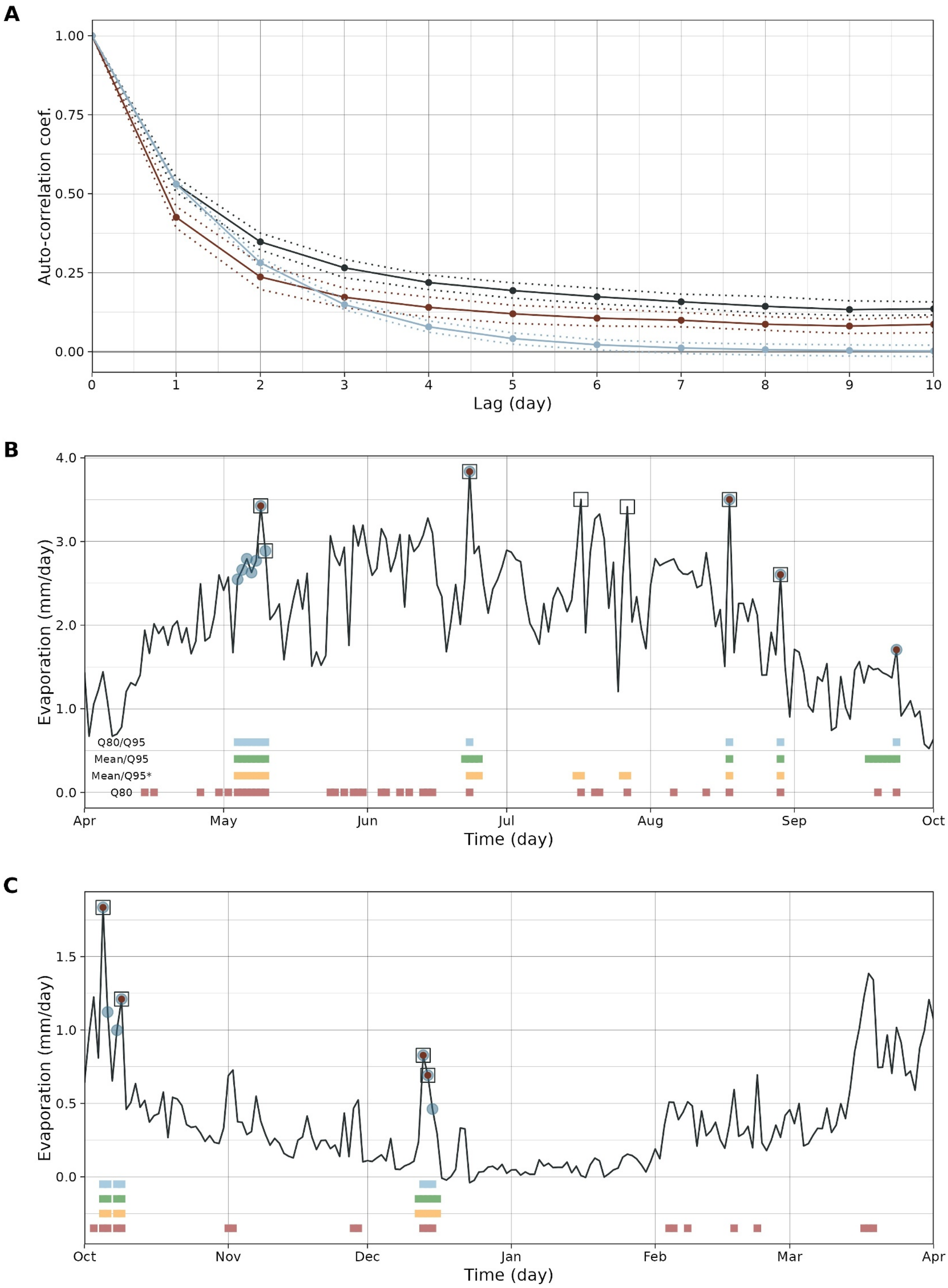

Figure 1. (a) Auto-correlation structure of standardized daily evaporation. Dark red line corresponds to mean auto-correlation coefficient for all grid cells of GLEAM data set (solid line) with 0.1 and 0.9 quantiles (dotted line). Dark blue line, similarly for CAMELE data set. Light blue line, represents the theoretical AR(1) stochastic process, again with 0.1 and 0.9 quantiles. (b) Comparison of different ExEvE definitions for the warm season (April—September) of 2003 over a random grid cell. Red circles correspond to standardized evaporation extremes (above the 0.95 quantile) and blue to the values of the ExEvE using the definition of this study. Rectangles correspond to quantile regression extremes. The ExEvEs for four alternative definitions appear on the bottom of figure. (c) As in panel (b) but for the cold season (October—March) of 2003–2004.

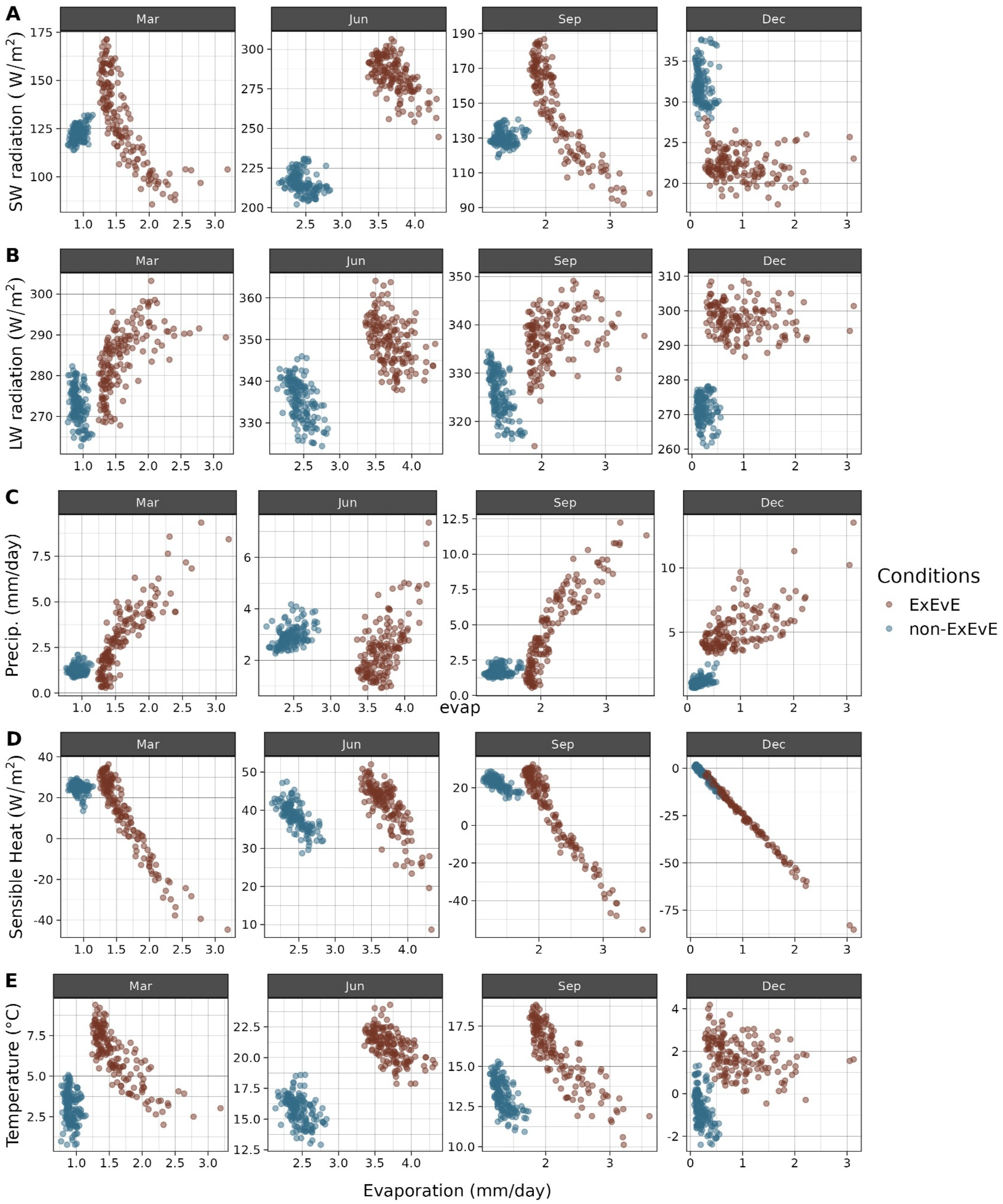

Figure 2. Relationship between evaporation and (a) downward shortwave radiation, (b) downward longwave radiation, (c) precipitation, (d) sensible heat, (e) temperature during ExEvEs and non-ExEvEs for March, June, September, and December.

Two seasonal patterns emerge. In summer, ExEvEs are linked to high shortwave and longwave radiation and low precipitation, conditions that intuitively support evaporation by providing the energy required for surface heating. These warm, sunny conditions enhance surface energy, increasing temperatures and the capacity for moisture to evaporate. However, a negative correlation between evaporation and shortwave radiation among ExEvEs suggests that more intense evaporation occurs under reduced solar energy, likely due to cloud cover associated with these events. The positive correlation between evaporation and precipitation among ExEvEs, further supports the clouded-sky interpretation, indicating that precipitation replenishes surface moisture, sustaining the high evaporation rates needed for extreme events. This pattern is also evident in the dynamic evolution of summer ExEvEs (Figure 3). During onset, shortwave radiation is elevated and precipitation is minimal, while by termination,

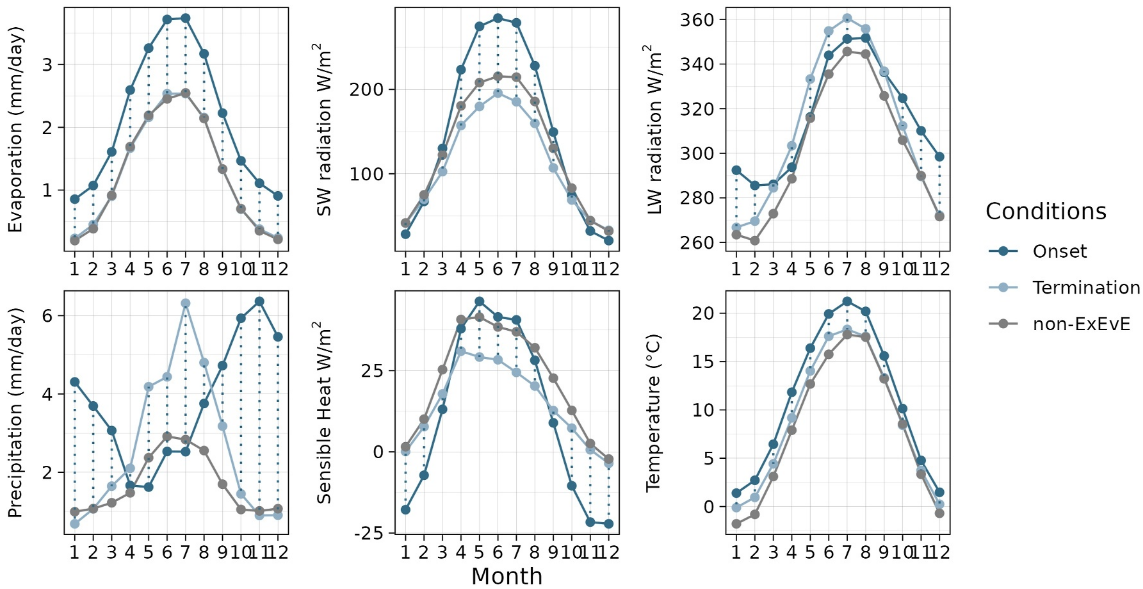

Figure 3. Monthly values of mean evaporation, shortwave radiation, longwave radiation, precipitation, sensible heat, temperature on the onset and termination of the ExEvEs and the non-ExEvEs average. Onset is defined as the first day of the event and termination the day after the last day of the event.

shortwave radiation declines and precipitation increases. Sensible heat flux is typical during onset, reflecting balanced energy partitioning, but becomes negative during termination as latent heat flux dominates, cooling the surface. Thus, while high shortwave radiation may be critical for triggering ExEvEs, moisture availability appears to play significant role as the events intensify.

In contrast, winter ExEvEs occur under low shortwave radiation and elevated longwave radiation, combined with high precipitation (Figure 3). These conditions, alongside higher-than-average temperatures and a consistent influx of atmospheric moisture, create favorable conditions for evaporation despite the limited contribution from direct solar heating. The positive correlation between evaporation and precipitation underscores the importance of moisture availability, while negative correlations with sensible heat flux indicate that most of the available energy is directed toward latent heat flux for evaporation. Notably, winter ExEvEs are consistently associated with above-freezing temperatures, suggesting the presence of liquid precipitation and either a lack of snow cover or snowmelt, which provides an additional source of moisture to sustain evaporation. The dynamic evolution of winter ExEvEs also reveals their dependence on moisture-driven processes rather than incoming solar radiation (Figure 3). Precipitation and longwave radiation peak during onset, ensuring the moisture and atmospheric heat needed for intense evaporation, but return to typical conditions by the termination phase. During onset, negative sensible heat flux indicates heat transfer from the atmosphere to the surface, while above-freezing temperatures support liquid precipitation or snowmelt as critical moisture sources. By termination, the reduction in precipitation highlights the end of external moisture contributions, while sensible heat flux stabilizes to typical levels, reflecting a balance in energy partitioning.

The differences between summer and winter events are evident, with each season reflecting unique facets of the intricate energy balance and moisture dynamics that drive extreme evaporation events. Even though causal directions cannot be definitively established, ExEvEs are clearly more than statistical artifacts of the evaporation time series. Instead, they are closely tied to incoming energy and moisture sources, as also illustrated in the three extreme winter and summer events shown in Figure S1 in Supporting Information S1. Furthermore, ExEvEs follow the fundamental theoretical and empirical concepts of land-atmosphere interactions, particularly regarding soil moisture dynamics (Brubaker & Entekhabi, 1995; Short Gianotti et al., 2019). Soil moisture, often seen as the primary state variable controlling the surface energy and water budgets, governs the transition between energy-limited and moisture-limited evaporation regimes (Haghighi et al., 2018), which could play a key role in the intensification of the summer ExEvEs. Additionally, the termination of the summer ExEvEs could be related to soil moisture-precipitation feedbacks (Tuttle & Salvucci, 2016), potentially driving cloud formation that concludes these events (Figure S1B in Supporting Information S1). This aligns with the concept of atmospheric water

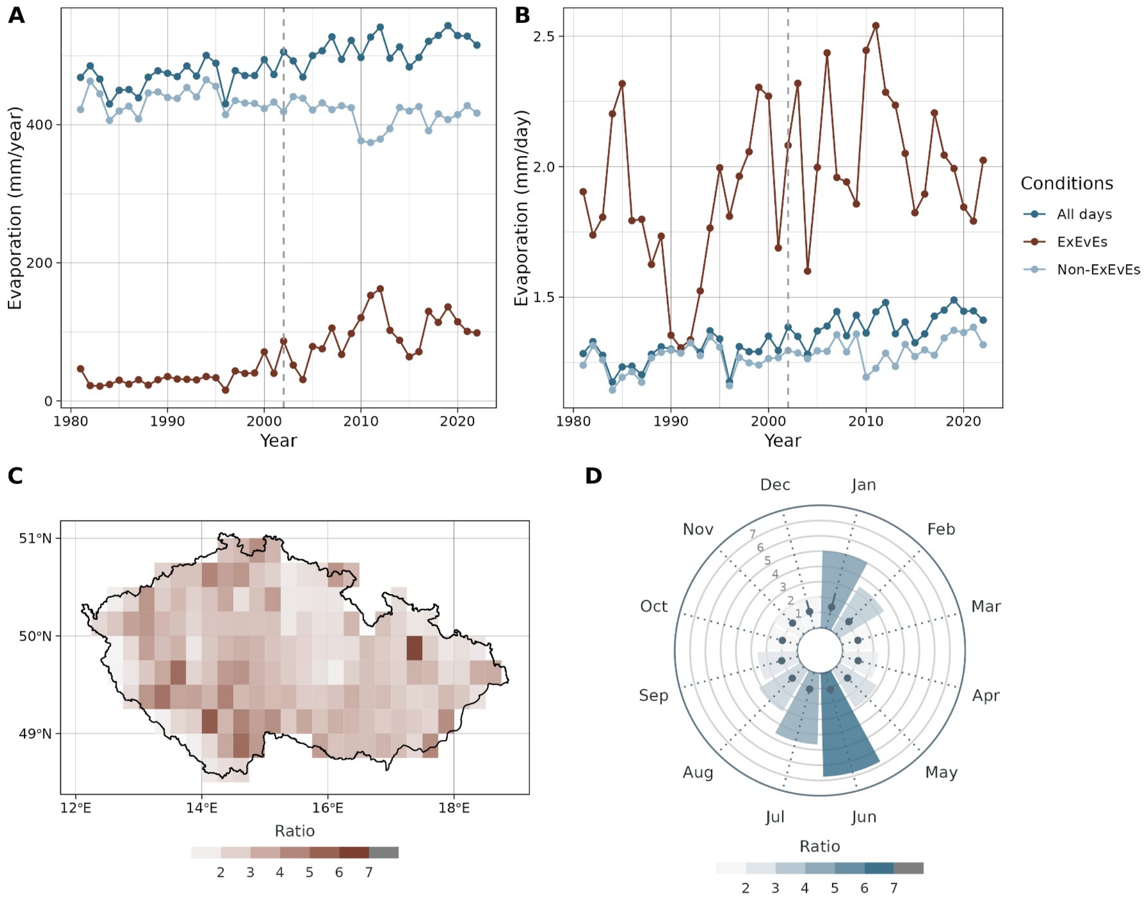

Figure 4. Temporal change of evaporation and its extremes. (a) Annual sum of evaporation for all days of the year, extreme evaporation evants, and non-extreme evaporation events. Vertical dashed line corresponds to year 2002. (b) As in panel (a), but for intensity. (c) Spatial distribution of ratios of ExEvEs evaporation in 2002–2022 versus ExEvE evaporation in 1981–2001. (d) As in panel (c) but for monthly values over the whole region. Bar plots indicate the ratio of ExEvE evaporation and points the evaporation ratio for all days. Error bars correspond to the 0.01 and 0.99 quantiles.

recycling, where elevated summer evaporation enhances atmospheric moisture, promoting precipitation that, in turn, sustains intense evaporation rates. Future research should explore these feedback mechanisms in greater depth to clarify the processes governing the onset, propagation and termination of ExEvEs.

4. Implementation of the Event-Based Framework at Regional Scale

4.1. New Insights Into Temporal Variability

With a framework in place to study extreme evaporation in an event-based structure, we now investigate how this approach can broaden our understanding of hydroclimatic change. Czechia presents a compelling case for this analysis, as evaporation has increased in recent decades (Vargas Godoy et al., 2024), alongside the prevalence of summer anti-cyclonic conditions (Lhotka et al., 2020). The region has been experiencing more sunshine during summer, a trend also reported in neighboring countries (Bogawski & Bednorz, 2016). Additionally, Czechia has been severely impacted by extreme droughts across Central Europe since the start of the century and can serve as a robust analog for the large-scale evaporation changes observed across central and northern Europe (Hanel et al., 2018). It remains to be determined how ExEvEs are linked to these observed fluctuations.

To investigate changes in ExEvEs, we divided our records into two 21-year periods, before and after 1 January 2002, and estimated the ratios of the monthly evaporation sums (Figure 4). Annual evaporation increased by 8.7%, shortwave radiation by 4.7%, and longwave radiation and precipitation by only 1% (Figure 4a). At the same time, extreme events became longer and more intense by approximately 10% (Figure 4b). One might assume that fluctuations in extremes would align with changes in the mean. However, when examining evaporation in terms of events, another key factor emerges: frequency. In our study, the frequency of extreme events increased by 130% annually, with some months, like June, showing a sixfold increase. Consequently, the rise in ExEvE frequency led to a reduction in non-ExEvE days (Figure 4a). It is important to note that the magnitude of the frequency increase depends significantly on the definition method used, with the quantile regression method yielding the lowest increase, as expected (Table S4 in Supporting Information S1). Other properties, however, were less sensitive to the definition choice, with changes ranging from −5% to 30% between the two periods. Nevertheless, while the change in the mean state of evaporation is not dramatic, the rise in the frequency of extremes is remarkable.

This rise becomes even more pronounced at finer spatial and temporal resolutions. Comparing the amount of water evaporated during ExEvEs before and after 2002, certain regions in the western half of the country experienced up to a sevenfold increase (Figure 4c). On a monthly scale, June, July, and January exhibited the most substantial changes, followed by August, September, and February (Figure 4d). When we combine both space and time, we find regions where evaporation within extreme events increased from as little as 1 mm/month to over 50 mm/month during summer months. In all these cases, monthly evaporation never increased by more than 20%, highlighting the stark difference between changes in monthly evaporation and shifts in the extreme values of its empirical distribution. Additionally, as the frequency of ExEvEs increased, the gaps between events diminished, resulting in chains of consecutive extreme events. It is no surprise, then, that summer droughts have exhibited an increasing trend in Czechia and Central Europe since the early 21st century (Markonis et al., 2021). For instance, during the 2018 drought, which peaked in late spring, seven ExEvEs occurred in less than two months (Figure S1c in Supporting Information S1). These events were briefly interrupted by precipitation lasting 1–3 days, only to resume as clear skies prevailed. The intertwined nature of evaporation and precipitation events raises important questions about the implications of ExEvEs for the regional water cycle, which will be analyzed in the final section of this study.

4.2. Decomposing Regional Water Cycle Intensification

Finally, to understand the impacts of ExEvEs on regional water cycle flows and storage, we examined the fluctuations in mean water exchange between land and atmosphere in relation to changes in the residual of precipitation minus evaporation(Figure 5). As expected, the entire region has shifted toward drier conditions, with an overall acceleration in water fluxes between land and atmosphere across 97% of grid cells (Figure 5a). However, when we decompose these changes within and outside ExEvEs, two opposing patterns emerge. Within evaporation events, the majority of grid cells (86%) have shifted toward wetter conditions, accompanied by accelerated water fluxes (Figure 5b). In contrast, outside of these events, we observe the opposite pattern: widespread decelerated drying across 96% of the area (Figure 5c). This acceleration-deceleration contrast is expected, as the rise in ExEvE frequency tripled the amount of water evaporated during ExEvEs, now accounting for one-fifth of annual evaporation. At the same time, while total precipitation only showed a modest 1% increase between the two periods, it doubled during ExEvEs. Thus, the dominant driver of water cycle acceleration occurs within ExEvEs, where more water is both evaporated and precipitated in shorter time spans.

It may seem counter-intuitive that an increase in ExEvEs results in wetter conditions. One possible explanation lies in the wet/dry ratio within ExEvEs. The number of wet days during ExEvEs did not change between the two periods, except in December and January. For the rest of the year, particularly during the summer months, the number of wet days remained constant. As the wet/dry ratio remained stable while the frequency of ExEvEs increased, the total annual precipitation within ExEvEs also increased. Another explanation can be found in the monthly fluctuations of evaporation and precipitation (Figure S2 in Supporting Information S1). While overall changes vary from month to month (Figure S2A in Supporting Information S1), a clear signal emerges within ExEvEs: consistent wetting due to increased precipitation in the cold season (September to March) and drying due to increased evaporation in the warm season (April to August; Figure S2B in Supporting Information S1). As the cold-season wetting outweighs the warm-season drying, the net effect is a shift toward wetter conditions. Therefore, we can interpret the wetting trend within ExEvEs as a result of increased evaporation during summer ExEvEs and increased precipitation generating ExEvEs in winter.

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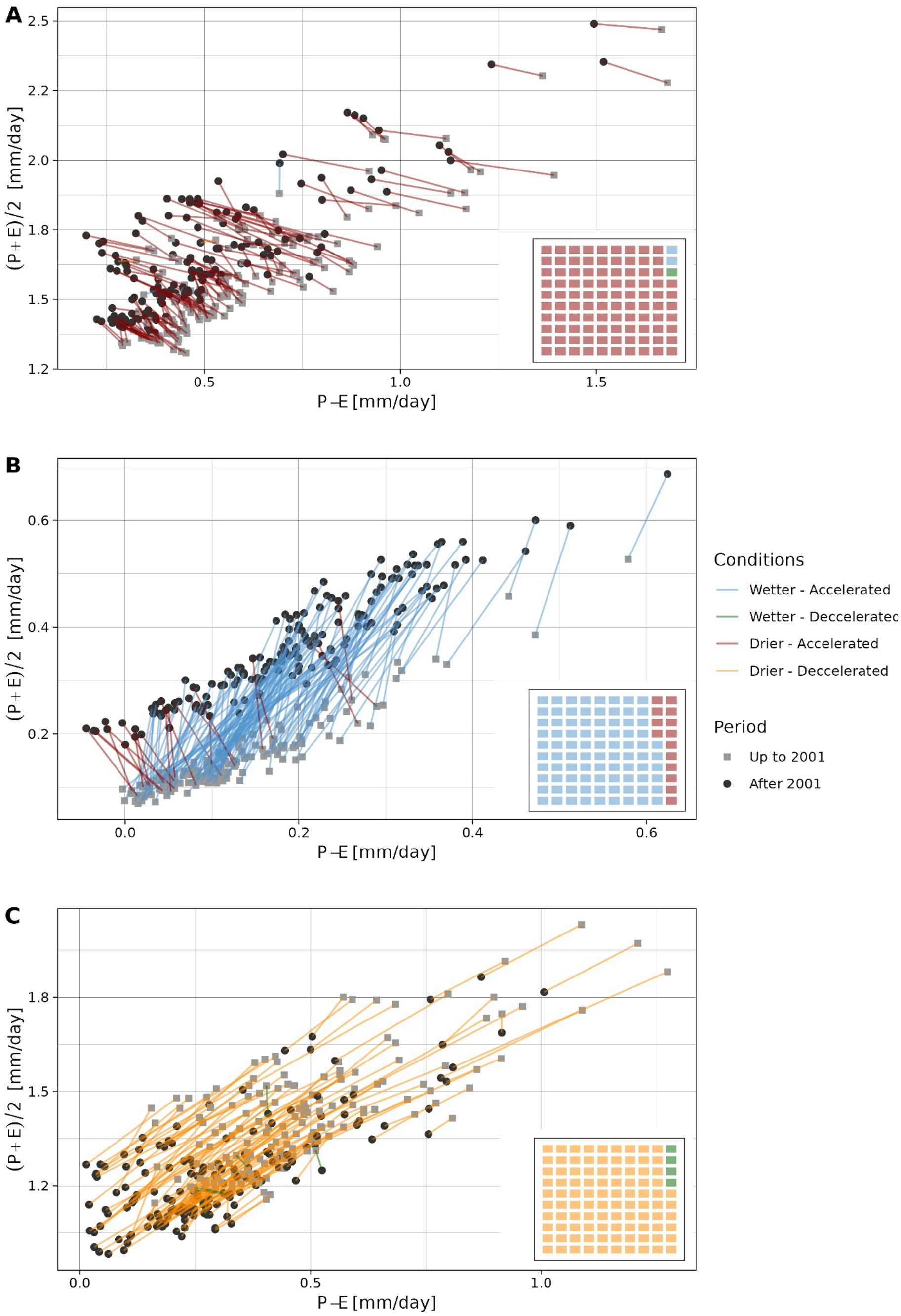

Figure 5. Changes in water availability over land and water cycle acceleration. Each point pair represents a grid cell. Water availability is estimated by the mean daily residual of precipitation minus evaporation ($P - E$), and water cycle acceleration/deceleration as the mean monthly land-atmosphere water exchange $\left(\frac{P+E}{2}\right)$ for: (a) All days. (b) Extreme evaporation events. (c) Days with normal conditions. Monthly values for whole Czechia can be found in Supplementary Information (Figure S2 in Supporting Information S1).

5. Discussion and Future Research

The motivation behind this study is to provide a new conceptual framework for analyzing extreme evaporation. The central idea stems from the strong temporal clustering observed in the evaporation process, which was applied to a region with undergoing substantial changes in its water cycle regime. The findings can be considered a first step toward empirically demonstrating that evaporation can be studied in terms of extreme events, which may behave differently than the mean state of the system, similar to temperature or precipitation extremes (Horton et al., 2016; Markonis et al., 2019).

However, several limitations should be noted before developing a comprehensive theory of ExEvEs. While the framework developed here is promising, its applicability across different climatic regimes remains an open question. Moreover, the study relies on a process-based model (GLEAM) for evaporation data, which carries its own assumptions and limitations. These factors highlight the need for further research to validate this framework in broader contexts and integrate observational data, for example, FLUXNET, to overcome current model-related limitations. Still, this study provides preliminary evidence that similar statistical properties, such as clustering, may exist for evaporation across all climate types (Figures S3-S4 in Supporting Information S1). Furthermore, the observed associations between energy sources (shortwave and longwave radiation) and water availability (precipitation) appear to be consistent across different climates (Figure S5 in Supporting Information S1), suggesting the potential generality of this framework for understanding extreme evaporation dynamics.

In addition, the ExEvE framework could affect ongoing research in numerous ways. For instance, in the study of (flash) droughts, where evaporative atmospheric demand plays a crucial role, an event-based approach to analyzing evaporation could enhance the understanding of their underlying drivers. Similarly, examining water depletion during extreme evaporation events could shed light on its impacts on plant productivity and the carbon cycle, particularly in terms of soil-plant-atmosphere interactions (C. Wang et al., 2019). By reversing the definition, the study of low evaporation extremes could improve our understanding of the preconditions for flood events, where reduced evaporative demand may play a crucial role (Massari et al., 2023). Perhaps most importantly, this framework could complement and extend existing research on soil moisture-atmosphere feedbacks, a critical aspect of land-atmosphere coupling and extreme events (Seneviratne et al., 2010). These examples highlight just a few of the promising avenues for future exploration, demonstrating the potential of the ExEvE framework to advance understanding of hydrological extremes and their broader implications.

To conclude, this study provides an important first step in the investigation of extreme evaporation events. However, much work remains to be done. While the findings highlight the potential of the ExEvE framework, much remains to be done. A deeper exploration of the physical processes driving extreme evaporation is essential to refine the conceptual framework and transition it from the empirical to the theoretical domain. Nevertheless, the methodological approach outlined here systematically identifies, characterizes, and analyzes evaporation extremes, providing valuable insights into their drivers, impacts, and seasonal variability. By laying the groundwork for studying extreme evaporation events, this framework opens promising pathways for exploring their broader implications for the global water cycle, ecosystem resilience, and socio-economic development.

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Data Availability Statement

In this work, all data come from previously published sources. Both evaporation data sets are presented in Martens et al. (2017) and Li et al. (2022), and are available at Rahmati et al. (2023). Downwelling shortwave/longwave radiation and precipitation, are presented in Beck et al. (2022) and are available at https://www.gloh2o.org/mswx/ . All the code used in the analyses, including any post-processing of the downloaded data sets can be found at Markonis (2024).

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