

Cross-Regional Synchronization of Northern-Hemisphere Heatwaves Using Dynamic Event Synchronization and Frequent Pattern Growth[†]

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Abstract

We integrate the dynamic event synchronization (DES) method to analyze temporal synchronization between regions with the frequent pattern growth (FP-Growth) pattern to extract significant spatial associations. The European Centre for Medium-Range Weather Forecasts ECMWF Reanalysis version 5 reanalysis data were partitioned into two 30-year intervals (1965–1994 and 1995–2024). First, inter-regional heatwave synchrony was measured using DES, and prevalent spatial associations were derived through the FP-Growth pattern. Comparative results show that the later interval yields twice as many association rules, a 34% decline in short-range linkages, and an 8% increase in long-range teleconnections—evidence of a transition from localized clustering toward transcontinental-scale heatwave synchronization.

Keywords: heatwave; dynamic event synchronization; ECMWF reanalysis v5 (ERA5); FP-Growth; spatial–temporal correlation



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1. Introduction

We investigated the spatiotemporal synchrony and cross-regional transmission patterns of heatwaves by integrating dynamic event synchronization (DES) with the frequent pattern growth (FP-Growth) algorithm. Since the 1950s, extreme heat events have become more frequent and intense across most land regions. According to the Intergovernmental Panel on Climate Change Sixth Assessment Report, heatwaves have not only increased in frequency and intensity but also exhibited simultaneous occurrences across regions, with North America, Europe, and parts of Asia often experiencing heatwave events concurrently [1,2]. To analyze such cross-regional synchrony of heatwaves, studies have commonly employed fixed time-window approaches to assess the co-occurrence of events in different areas. However, such approaches may fail to accurately capture the actual time differences between events, especially during periods with irregular occurrence frequencies, making it difficult to detect true synchrony [3]. In contrast, dynamic event windows can adjust the window length based on the actual time difference between events, offering more precise representation of synchrony across regions [4–6].

Heatwaves that occur across geographically distant regions may lead to cascading impacts, emphasizing the importance of understanding their synchronous characteristics for climate risk assessment [7]. Understanding whether heatwaves exhibit synchronous

characteristics has therefore become a critical issue in climate risk assessment. While most studies focus on detecting synchrony by observing whether multiple regions experience heatwaves within a similar timeframe [8], statistical methods are employed to evaluate the spatial correlation of climate variables across geographic locations, helping to elucidate the climatic mechanisms behind heatwave synchrony [9]. Moreover, a nonlinear relationship between the probability of extreme climate event synchrony and geographic distance is observed, with a turning point around 2500 km [10]. Considering that heatwaves are also driven by large-scale atmospheric circulation patterns, we adopted this distance threshold as the basis for distinguishing between long-range and short-range heatwave connections. Regarding spatial characteristics, adaptive filter techniques have been applied in some studies to explore short-range spatial synchrony [11].

Distinct from earlier approaches, we applied the DES method in combination with the FP-Growth algorithm, which is well-suited for efficient association rule mining and avoids candidate set generation [12]. This integrated framework captures nonlinear temporal relationships and extracts representative cross-regional transmission patterns of extreme events.

2. Materials and Methods

2.1. Definition of Heatwave Events

We defined heatwave-related events based on the following two criteria. The first type considers a heatwave event to occur at a grid point on a given day when the daily mean temperature exceeds the 95th percentile of historical summer daily means at that location. The second type, defined as an intense heatwave event, refers to a case where the temperature anomaly at a location (relative to the climatological mean for the same calendar day) exceeds 5 °C for five consecutive days starting from the initial day. The first criterion is expressed as follows [13]:

$$T(x, y, t) > \text{Percentile}_{95}\{T(x, y, t')\} \quad (1)$$

where $T(x, y, t)$ denotes the daily mean temperature at grid point (x, y) on day t , and $\text{Percent}_{95}\{T(x, y, t')\}$ is the 95th percentile of daily mean temperatures at that location during the historical period for calendar day t' (e.g., 1 July of each year). The second criterion is expressed as follows [14]:

$$A(x, y, t) = T(x, y, t) - T(x, y, t') \quad (2)$$

$$A(x, y, t + i) > 5, \forall i = 0, 1, \dots, 4 \quad (3)$$

where $T(x, y, t')$ represents the climatological mean daily temperature for calendar day t' (e.g., 1 July) at location (x, y) , computed over the historical reference period. If the temperature anomaly $A(x, y, t + i)$ exceeds 5 °C for five consecutive days ($i = 0, 1, 2, 3, 4$) starting on day t , then day t is marked as the occurrence of an intense heatwave event at (x, y) . Based on this criterion, the frequency and spatial distribution of intense heatwave onsets and their spatial distribution across all grid points can be further analyzed.

2.2. DES

We adopted the DES method that considers two regions to be synchronized if their event time difference falls within a permissible maximum delay window. The method dynamically adjusts the tolerance window based on the actual time differences between events, enabling a more precise identification of synchronized occurrences. Considering the potential lagged response of heatwave events, an appropriate maximum delay is applied in

order to capture possible cross-regional propagation characteristics. Unlike the original DES approach that calculates synchronization strength, we retained all pairs of synchronized events and organized them into daily events for subsequent analysis. Specifically, the events are defined as follows [15]:

$$grid_{i,j}(t) = \begin{cases} 1, & \text{if } \exists t_{a,i}, t_{b,j} \text{ s.t. } |t_{a,i} - t_{b,j}| \leq \Delta t_{max} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

$$events(t) = \{grid_1(t), grid_2(t), \dots, grid_k(t)\} \quad (5)$$

where $grid_{i,j}(t)$ is an indicator function that specifies whether the i -th and j -th grid location experiences synchronized heatwave events at time t . $t_{a,i}$ and $t_{b,j}$ is the occurrence time of the a -th and b -th heatwave events in grid i and j , respectively. Δt_{max} represents the dynamically adjusted tolerance window, set to 10 days in this study. $Events(t)$ represents the set of all grid points with synchronized heatwave events on day t . k is the total number of such grid locations. This event set serves as the input for the FP-Growth algorithm to extract cross-regional association rules of heatwave events.

2.3. Association Rule Mining of Heatwave Events (FP-Growth)

FP-Growth is an efficient frequent itemset mining algorithm designed to avoid the generation of a large number of candidate sets by constructing a tree-based data structure of frequent events [16]. In this study, each record represents the set of grid cells where synchronized heatwaves occurred on a given day, and the daily data are transformed into a Boolean format (1 indicating the presence of a heatwave in the grid cell). The procedure is as follows:

1. Building the tree structure

First, the occurrence frequency of each grid cell with heatwaves is counted across all records, and grid cells exceeding the minimum support threshold are selected as frequent events. For each record, only these frequent events are retained and inserted into the FP-Tree in descending order of their global frequencies. The FP-Tree, a type of prefix tree, efficiently compresses common patterns across multiple records and maintains the structural relationships of event occurrences through linked nodes.

2. Recursive pattern growth

For each frequent event, a conditional pattern base and corresponding conditional FP-Tree are constructed to recursively mine all event combinations that meet the threshold.

3. The resulting frequent itemsets are used to generate association rules, with support and confidence calculated as follows:

$$Support(grid_i, grid_j) = \frac{Count(grid_i \cap grid_j)}{N} \quad (6)$$

$$Confidence(grid_i \Rightarrow grid_j) = \frac{Count(grid_i \cap grid_j)}{Count(grid_i)} \quad (7)$$

where $Support$ represents the proportion of days both $grid_i$ and $grid_j$ experience heatwaves, $Confidence$ indicates the conditional probability of $grid_j$ having a heatwave given that $grid_i$ does, $Count$ denotes the total number of days, $(grid_i \cap grid_j)$ is the intersection of heatwave occurrences in $grid_i$ and $grid_j$, and N is the total number of days considered.

3. Results

We used ECMWF Reanalysis version 5 (ERA5) hourly temperature reanalysis data (summer, 1965–2024) for the Northern Hemisphere (20–80° N). The original 0.25° resolution data were resampled to a 5° × 5° grid, and the daily maximum temperature was extracted to focus on large-scale heatwaves and improve computational efficiency [17,18]. Figure 1 illustrates the spatial distribution of strong heatwave event onset days, identifying hotspot regions such as Eastern Europe and North America as the basis for subsequent analyses of heatwave propagation.

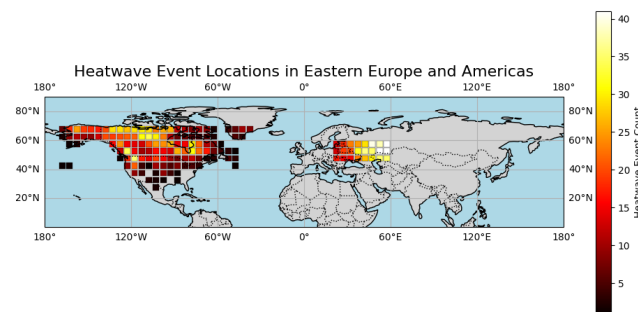


Figure 1. Heatwave event locations in Eastern Europe and North America.

After applying the DES method, heatwave events were transformed into daily event data, and the FP-Growth algorithm was used to mine cross-regional association rules. The minimum support and confidence thresholds were set at 0.03 and 0.2, respectively, to preserve more potential propagation patterns. The analysis focused on heatwave onset hotspots in Eastern Europe and North America, with the dataset divided into two periods (1965–1994 and 1995–2024) to examine temporal changes in the spatial extent of heatwaves. Figure 2 shows the confidence distribution when 52.625° N, 57.375° E is used as the heatwave onset point. Our results indicate that during the earlier period, the confidence distribution had a higher median and smaller overall variability. In contrast, the later period exhibited a lower median, yet displayed a pronounced increase in high-confidence outliers, indicating that heatwave propagation patterns have become more spatially dispersed, which may be attributable to climate change.

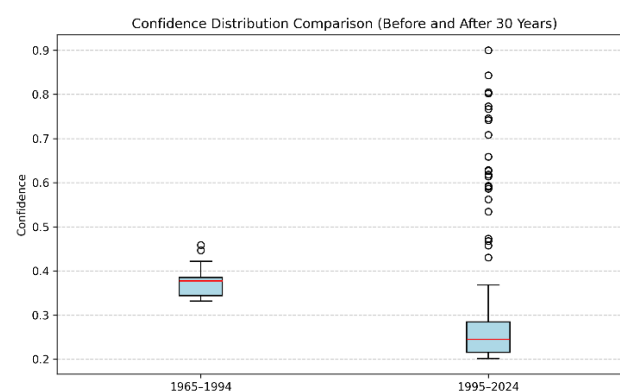


Figure 2. Confidence distribution comparison (before and after 30 years).

3.1. Eastern Europe

Based on the statistics of three major heatwave initiation points in Eastern Europe, heatwaves in the earlier period were mostly confined to neighboring regions, with a limited number of associations. In contrast, the later period shows a significant expansion of heatwave propagation, covering vast areas and exhibiting long-distance transmission. The propagation extends eastward to Siberia and the Far East, northward to the Arctic coastline,

and spans across Eurasia to include Canada, Greenland, and the Mediterranean region. Figure 3 illustrates the heatwave propagation paths and confidence distributions, further confirming this expansion trend. This phenomenon suggests that synchronous heatwave events may be influenced by larger-scale climate mechanisms, such as global warming, with the increase in confidence values further supporting this conclusion.

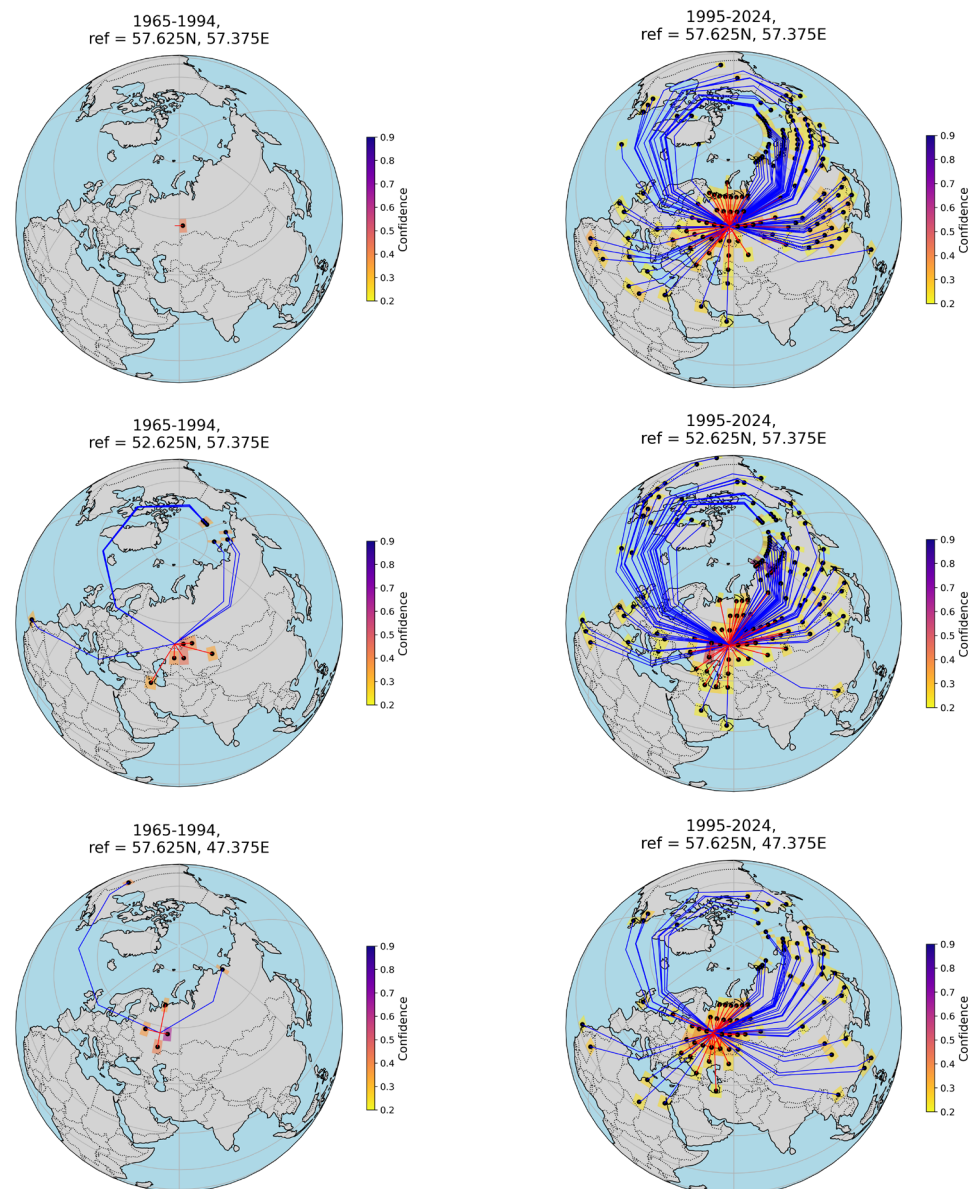


Figure 3. Data from Eastern Europe Heatwave Associations from 1965–1994 to 1995–2024.

3.2. North America

Based on the statistics of three major heatwave initiation points in North America, heatwaves in the earlier period were mostly confined to nearby regions, with fewer associations. In the later period, the propagation range expanded to include central North America, eastern Canada, and the Arctic. The transmission extended northward to the Arctic and southeastward to central Canada. Figure 4 illustrates the heatwave propagation paths and confidence distributions, further confirming this expansion trend. These results indicate that climate warming may be amplifying the impacts of heatwaves.

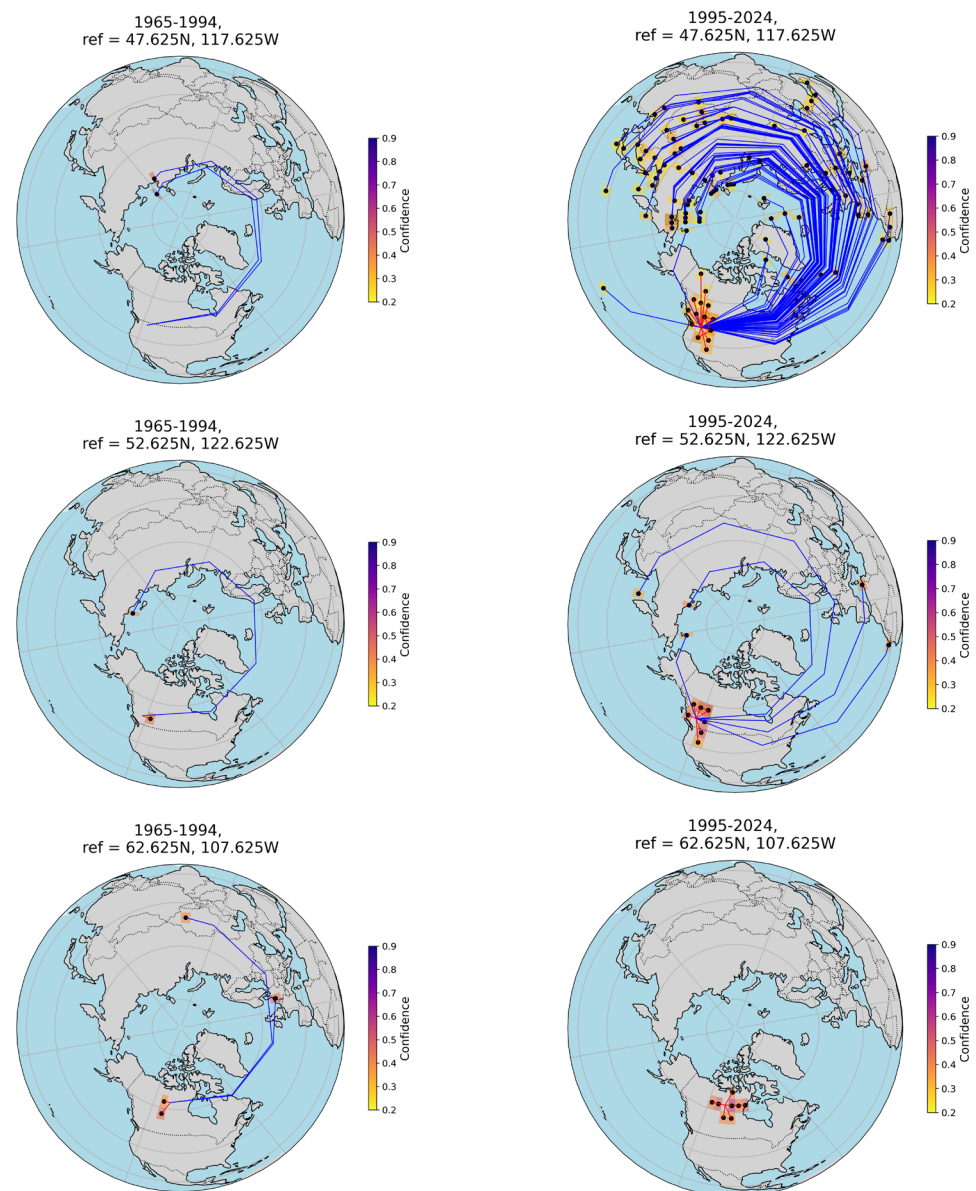


Figure 4. Data from North America Heatwave Associations from 1965–1994 to 1995–2024.

4. Discussion and Conclusions

We integrated DES with association rule mining (FP-Growth) to analyze the trans-regional propagation characteristics of summer heatwave events across the Northern Hemisphere during 1965–2024. The data were divided into an earlier period (1965–1994) and a later period (1995–2024), focusing on three major heatwave initiation points in Eastern Europe and North America for comparative analysis.

The results showed that the number of heatwave association rules in the later period increased by 198.4% compared with that of the earlier period. The proportion of long-distance associations rose by 8%, while short-distance associations decreased by 34%, indicating a shift from regional propagation patterns to more extensive transcontinental synchronization. This change reflects the enhanced large-scale climatic connectivity, likely driven by climate variability associated with global warming.

In the later period, heatwave initiation points in Eastern Europe exhibited propagation paths spanning Eurasia to the Arctic. Similarly, initiation points in North America expanded from being confined to surrounding regions to reaching central Canada and the Arctic.

These findings suggest that the range and stability of synchronized heatwave events have simultaneously expanded.

Overall, heatwave events are no longer confined to local regions but exhibit broader and more stable transregional propagation patterns.

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