

Article

Historical Analysis of Heatwaves in China Based on Complex Network Theory

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Abstract

Under global warming, the frequency and intensity of extreme heat events have increased markedly, having widespread impacts on terrestrial ecosystems and human society. Based on daily maximum temperature observations across China during 1961–2020 and high-resolution ERA5 reanalysis datasets, this study constructs a heatwave synchronization network by integrating event synchronization and complex network theory. The spatiotemporal variations of heatwave occurrence and synchronization during 1961–2020 are systematically investigated. The results reveal a pronounced increase in heatwave frequency across China, with the number of heatwave events during 1991–2020 nearly doubling compared with that in 1961–1990, and the most prominent increase occurring in South China. Although the large-scale spatial pattern of heatwave synchronization remained relatively stable, node connectivity increased substantially, with persistently high values over Northwest China and an evident strengthening trend across North China and the Huang–Huai region in recent decades. Concurrently, heatwave events during the later period were generally accompanied by drier soil conditions, reduced latent heat flux, and enhanced sensible heat flux, indicating strengthened land–atmosphere coupling during heatwave events. These findings provide new insights into the spatiotemporal evolution of heatwave synchronization and contribute to a better understanding of large-scale heatwave hazards under a warming climate.

Keywords: heatwave changes; complex networks; event synchronization

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1. Introduction

In recent decades, global warming has led to a substantial increase in the frequency, intensity, and duration of extreme heat events, posing serious challenges to natural ecosystems and human societies [1–4]. As a region highly sensitive to climate change, China has experienced a warming rate exceeding the global average [5]. Observational evidence shows a continuous rise in summer hot days, accompanied by more frequent and widespread high-impact heatwaves [6–8]. These changes have had profound impacts on agriculture, energy supply, public health, and urban infrastructure [9–14]. Understanding the spatiotemporal characteristics and underlying mechanisms of heatwaves in China is therefore essential for improving climate risk assessment and developing effective adaptation strategies.

Previous studies have extensively examined the spatiotemporal evolution of heatwaves and their underlying physical drivers, providing valuable insights into long-term variability and the climatic background of extreme events in China [15–18]. However, most studies rely on station-based or grid-based analyses that focus on local characteristics such as frequency, intensity, and duration [19–21]. While effective in capturing regional trends, these approaches are limited in their ability to characterize interregional linkages, synchronization, and dependence structures of extreme events. Consequently, the large-scale spatial coherence and compound risks of heatwaves remain insufficiently understood.

In recent years, complex network approaches have emerged as a powerful framework for investigating multiscale and nonlinear interactions within the climate system [22,23]. In this framework, geographical locations are represented as nodes, and statistically significant relationships between climate events are treated as links. This enables the identification of spatial organization patterns, key hub regions, and pathways of coordinated variability. Such methods have been successfully applied to extreme precipitation, climate teleconnections, and early warning signals of tipping points, demonstrating clear advantages in capturing the spatial coherence and systemic risks of extreme climate events [24–26].

Despite these advances, the synchronization structure of heatwaves and its evolution under future climate scenarios remain poorly understood, particularly over large and climatically diverse regions such as China. In particular, how heatwave co-occurrence patterns evolve under different emission pathways, and how these patterns are linked to land–atmosphere feedback processes, has not been systematically investigated. Addressing these questions is crucial for understanding the emergence of spatially compound and synchronized heatwave risks.

To address these gaps, this study constructs a heatwave synchronization network over China based on the event synchronization method using daily maximum temperature observations from 1961 to 2020. By integrating ERA5 reanalysis data, we further analyze key variables associated with heatwave events, including daily maximum and mean temperature, sensible and latent heat fluxes, and soil volumetric water content, to characterize the land–atmosphere conditions accompanying heatwave events. This study aims to provide a comprehensive understanding of the spatiotemporal evolution and synchronization characteristics of heatwaves in China and to identify the environmental conditions associated with their observed changes over the past six decades.

2. Materials and Methods

2.1. Definition of Heatwaves

There is no universally accepted standard for defining heatwaves in existing studies [27–30]. In this study, a relative threshold method was used to define heatwaves: at a given grid point, the daily maximum temperature must exceed a specified threshold for at least three consecutive days [31]. The threshold was set as the 90th percentile of the daily maximum temperature time series for each grid point, calculated as a single value from all days in May–September over 1961–2020. Although this fixed-threshold approach may underestimate heatwave occurrences in the early and late warm season, it was adopted to identify genuinely extreme heat events in terms of absolute temperature across the warm season, rather than temperature anomalies relative to individual calendar-day climatology.

Based on the above definition, each heatwave episode was regarded as an individual event. Following previous studies [32,33], heatwave number, defined as the total number of heatwave events occurring at each grid point during May–September, was used to characterize heatwave activity and served as the basis for the subsequent event synchronization analysis.

2.2. Event Synchronization and Network Construction

Event synchronization is an efficient, nonparametric method for quantifying the synchrony and temporal lag between event time series while accounting for dynamic delays. Owing to its nonlinear nature, it has been widely used to analyze the co-occurrence of extreme events. Here, it is applied to measure heatwave synchrony across regions.

In this study, for grid point i and grid point j , the time lag τ_{ij}^{od} is defined as:

$$\tau_{ij}^{od} = \frac{\min\{t_i^o - t_i^{o-1}, t_i^{o+1} - t_i^o, t_j^d - t_j^{d-1}, t_j^{d+1} - t_j^d\}}{2} \quad (1)$$

where $t_i^o(t_j^d)$ represents the occurrence time of the o -th(d -th) heatwave event at grid point $i(j)$, and $t_i^{o-1}(t_j^{d-1})$ and $t_i^{o+1}(t_j^{d+1})$ denote the occurrence times of the preceding and subsequent heatwave events at the same grid point, respectively.

Following previous studies [31], a maximum lag window of 3 days ($\tau_{\max} = 3$) is adopted in this study. Within this lag window, to determine whether grid points i and j experience a synchronized event during a given period, the following conditions must be satisfied:

$$q_{ij} = \begin{cases} 1, & \text{if } |t_i^o - t_j^d| < \tau_{\max} \text{ and } |t_i^o - t_j^d| < \tau_{ij}^{od} \\ 0, & \text{others} \end{cases} \quad (2)$$

where τ_{ij}^{od} is defined as half of the minimum temporal spacing between each event and its neighboring events at the two grid points, ensuring that only isolated event pairs are considered synchronized.

Therefore, in this study, the total number of synchronized heatwave events between grid points i and j , denoted as ES_{ij} , is given by:

$$ES_{ij} = \sum_{o=1}^{e_i} \sum_{d=1}^{e_j} q_{ij} \quad (3)$$

Here, e_i and e_j represent the total number of heatwave events occurring at grid points i and j , respectively. To quantify the synchronization strength of heatwaves between grid points i and j , denoted as Q_{ij} , this study defines it as follows:

$$Q_{ij} = \frac{ES_{ij}}{\sqrt{(e_i - 2)(e_j - 2)}} \quad (4)$$

A value of $Q_{ij} = 1$ indicates that heatwave events at grid points i and j are completely synchronized.

After calculating the synchronization strength, a heatwave synchronization matrix with a dimension of 4189×4189 was obtained. To construct an undirected complex network, following previous studies, this study assumes that a connection exists between two nodes only if their synchronization value falls within the top 5% of all synchronization values, as shown below:

$$A_{ij} = \begin{cases} 1, & \text{if } Q_{ij} > \theta \\ 0, & \text{others} \end{cases} \quad (5)$$

Here, A_{ij} indicates whether a network edge exists between grid points i and j , and θ represents the 95th percentile threshold of all synchronization strengths in the matrix. Following previous studies on climate synchronization networks [31], the strongest 5% of links were retained to construct the heatwave synchronization network. This threshold has been widely adopted to preserve the dominant synchronization structure while minimizing weak and potentially spurious connections.

2.3. Data

In this study, daily maximum temperature data were obtained from the China Surface Temperature Gridded Dataset (V2.0, $0.5^\circ \times 0.5^\circ$), provided by the China Meteorological Administration (CMA), covering the period 1961–2022. These data were used to identify heatwave events and analyze their spatial and temporal characteristics.

Land–atmosphere variables, including sensible heat flux, latent heat flux, and volumetric soil water content, were obtained from the ERA5 reanalysis dataset at a spatial resolution of $0.5^\circ \times 0.5^\circ$. Consistent with previous studies on drought–heatwave interactions, volumetric soil water content in the 7–28 cm soil layer was used to represent near-surface soil moisture conditions.

Anomalies of daily maximum temperature, sensible heat flux, latent heat flux, and volumetric soil water content were calculated relative to their respective climatological means during May–September over the period 1961–2020. Using a common climatological baseline allows direct comparison of anomaly patterns between different periods and variables.

3. Results and Discussion

3.1. Historical Changes of Heatwaves in China

In recent years, with the intensification of global warming, the frequency of heatwaves in China has shown a significant increasing trend [34]. Figure 1 illustrates the changes in heatwave events across different regions of China over two consecutive 30-year periods from 1961 to 2020. During 1961–1990 (Figure 1a), heatwaves were mainly concentrated in the middle and lower reaches of the Yangtze River in east-central China and Xinjiang in northwestern China, occurring on average about twice per year. After 1991–2020 (Figure 1b), heatwave occurrences increased markedly in most regions, with cumulative events over the 30-year period reaching or exceeding 60, representing a multiple-fold increase. Pronounced regional differences were observed. Guangdong Province in southern China experienced the most pronounced increase, whereas the middle and lower reaches of the Yangtze River and Xinjiang in northwestern China showed relatively smaller growth. This trend is closely linked to multiple physical mechanisms. On the one hand, the rise in global temperatures has elevated the baseline surface temperature, making extreme heat events more likely to occur [35]. On the other hand, large-scale atmospheric circulation anomalies, such as the strengthening or westward expansion of the western Pacific subtropical high, can cause persistent subsidence, reduced cloud cover, and decreased precipitation, thereby enhancing surface heat accumulation [36–38]. Local factors also play an important role: urban heat island effects, soil dryness, and reduced vegetation cover can amplify warming, extending heatwave duration [39,40]. Furthermore, abnormal summer land–sea thermal contrasts may alter regional wind patterns, inhibiting cold air intrusions and further prolonging high-temperature events [41]. The combined influence of these factors has collectively driven the significant increases in both the frequency and intensity of heatwaves across China.

Compared with the substantial increase in heatwave occurrences over the past 60 years, the heatwave synchronization network also exhibited noticeable changes in its spatial organization during the most recent 30 years. During 1961–1990 (Figure 2a), the overall node degree of the heatwave synchronization network was relatively low. Regions with high node degrees were mainly concentrated in Northwest China, particularly eastern Xinjiang and adjacent areas, indicating that heatwave events in this region were more likely to occur synchronously with other parts of China. Moderate node degrees were observed in North China and the Huang–Huai region in eastern China, suggesting intermediate levels of regional synchronization. In contrast, the middle and lower reaches of the Yangtze

River and South China generally exhibited relatively low node degrees, indicating that synchronized heatwave events were primarily confined to neighboring regions rather than extending over large spatial scales. During 1991–2020 (Figure 2b), node degrees increased across most regions of China, and both the spatial extent and intensity of high-connectivity regions became more pronounced. Northwest China remained the primary synchronization center, while regions with relatively high node degrees expanded toward surrounding areas. Meanwhile, node degrees in North China, Northeast China, and the Huang–Huai region also increased, forming a medium-to-high connectivity belt extending from western to eastern China. Although South China continued to exhibit relatively low node degrees, local synchronization strengthened compared with the earlier period, indicating enhanced regional connectivity of heatwave events. Overall, compared with 1961–1990, the heatwave synchronization network during 1991–2020 was characterized by higher node degrees, an expansion of highly connected regions, and stronger interregional synchronization. To further quantify these changes beyond the spatial maps, the frequency distributions of node degrees for the two study periods are presented in Supplementary Figure S1. The distribution shifts toward larger node-degree values during 1991–2020, demonstrating that the enhancement of heatwave synchronization occurred across much of the network rather than resulting from a redistribution of only a few highly connected nodes. These spatial characteristics are broadly consistent with previous studies suggesting that regional differences in atmospheric circulation and land surface conditions influence the spatial coherence of heatwave events across China. In particular, persistent circulation over Northwest China has been reported to favor large-scale synchronous heatwave development, whereas the more complex circulation environment over southern China may limit synchronization over broader spatial scales [42–46]. It should be noted, however, that these physical processes are discussed here as possible interpretations based on previous studies rather than direct causal evidence derived from the present analysis.

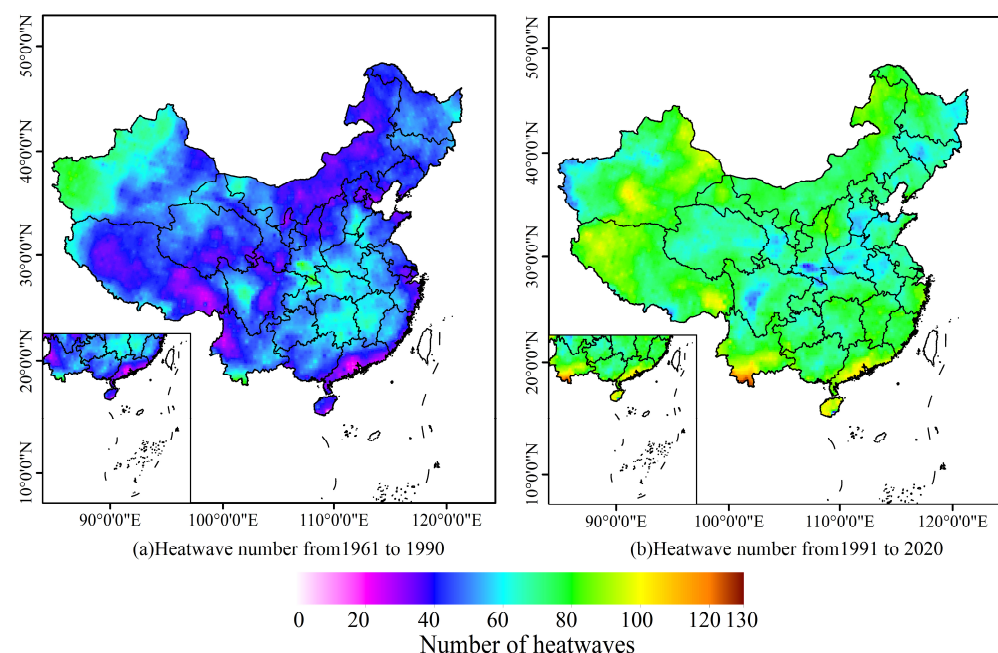


Figure 1. Spatial distribution of heatwave occurrences in China during 1961–2020: (a) shows the total number of heatwave events across China during 1961–1990; (b) shows the total number of heatwave events during 1991–2020.

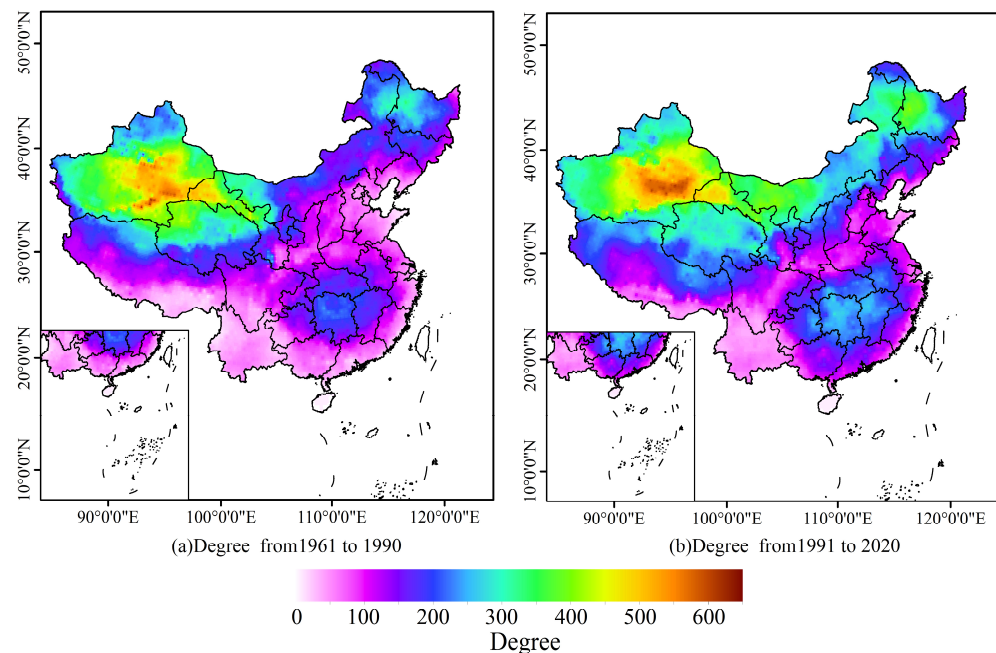


Figure 2. Spatial distribution of node degree in the heatwave synchronization network over China during 1961–2020: (a) shows the degree distribution of the Chinese heatwave synchronization network for the period 1961–1990; (b) presents the corresponding degree distribution for 1991–2020.

To further examine whether the observed changes represent an overall enhancement of the network rather than a redistribution of highly connected nodes, the distributions of node degrees for the two periods are compared in Supplementary Figure S2. The rightward shift of the degree distribution during 1991–2020 indicates that the increase in node connectivity is widespread across the network.

3.2. Analysis of Factors During Heatwave Events

By comparing heatwave occurrences and the node degree distribution of the synchronization network across China during 1961–1990 and 1991–2020, we identified pronounced interdecadal differences in heatwave characteristics. To further compare the environmental conditions associated with heatwave events in these two periods, we analyzed changes in daily maximum and mean temperatures, latent and sensible heat fluxes, and soil volumetric water content. The objective of this analysis is to characterize the climatic background accompanying the observed changes in heatwave characteristics, rather than to directly explain the topology of the synchronization network.

Although the spatial pattern of daily maximum temperature anomalies during heatwave events remained broadly similar between 1961–1990 and 1991–2020 (Figure 3), the magnitude of the anomalies became generally larger during the later period. Approximately five days before heatwave onset, daily maximum temperatures across most regions of China were already above the climatological mean, with anomalies of approximately 2 °C. The largest positive anomalies occurred in the middle and lower reaches of the Yangtze River, suggesting the presence of a pronounced pre-heating signal prior to heatwave onset. During heatwave events, positive temperature anomalies expanded across nearly the entire country, with particularly large anomalies in northern China. In contrast, relatively smaller anomalies were observed in Yunnan, Guangxi, and Guangdong, which is consistent with the regional climatic background reported in previous studies [47]. Following heatwave cessation, the positive anomalies weakened rapidly, and daily maximum temperatures generally returned to near pre-event conditions within several days. Overall, despite the relatively stable large-scale spatial pattern of daily maximum temperature anomalies,

heatwave events became more frequent during 1991–2020. In northern China, local daily maximum temperature anomalies exceeded 10 °C during some heatwave events, indicating stronger thermal extremes than those observed during the earlier period. To complement the spatial maps, the frequency distributions of daily maximum temperature anomalies are presented in Supplementary Figure S3. Compared with 1961–1990, the distributions for 1991–2020 exhibit an overall shift toward larger positive anomalies, providing quantitative evidence that heatwave events in the later period were generally accompanied by stronger temperature anomalies.

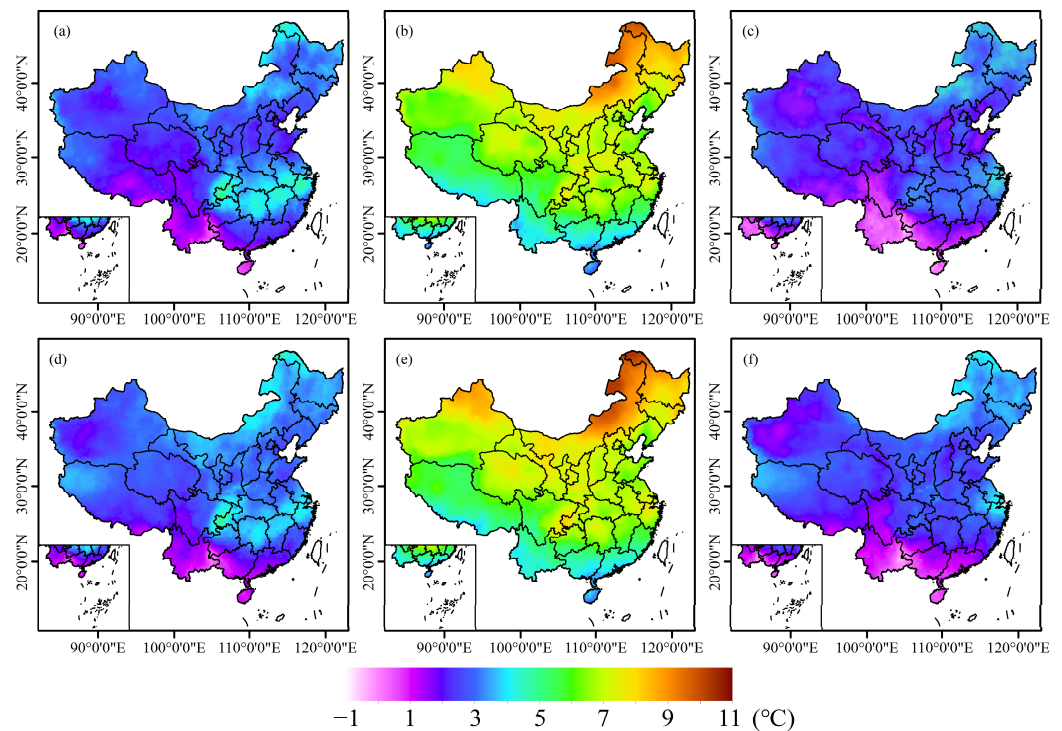


Figure 3. Spatial distribution of daily maximum temperature anomalies (°C) during heatwave events in China, 1961–2020: (a–c) show anomalies for 1961–1990, and (d–f) show anomalies for 1991–2020; (a,d) depict anomalies five days before heatwave onset; (b,e) show anomalies during heatwave events; (c,f) show anomalies five days after heatwave cessation.

Compared with changes in daily maximum temperature, anomalies in daily mean temperature during heatwave events are more pronounced (Figure 4). Five days before heatwave onset (Figure 4a,d), some regions already exhibited anomalous mean temperatures, with the middle and lower Yangtze River region showing relatively high positive anomalies. During heatwave events (Figure 4b,e), mean temperature anomalies increased nationwide. This phenomenon was especially pronounced during the first 30-year period (1961–1990), particularly in northern China, where daily mean temperatures during heatwaves exceeded normal values by 15 °C or more. Combined with the analysis of daily maximum temperatures, this indicates that during the earlier period, heatwaves in northern China were long-lasting, with nighttime temperatures remaining relatively high rather than dropping substantially. In the latter 30-year period (1991–2020), although nationwide mean temperature anomalies also increased during heatwaves, the magnitude of the increase was lower than in the earlier period. After heatwave cessation (Figure 4c,f), mean temperature anomalies across China returned to pre-heatwave levels. To complement the spatial distributions shown in Figure 4, the frequency distributions of daily mean temperature anomalies are presented in Supplementary Figure S4. Compared with 1961–1990,

the distributions for 1991–2020 indicate generally larger temperature anomalies during heatwave events, providing a quantitative summary of the interdecadal changes.

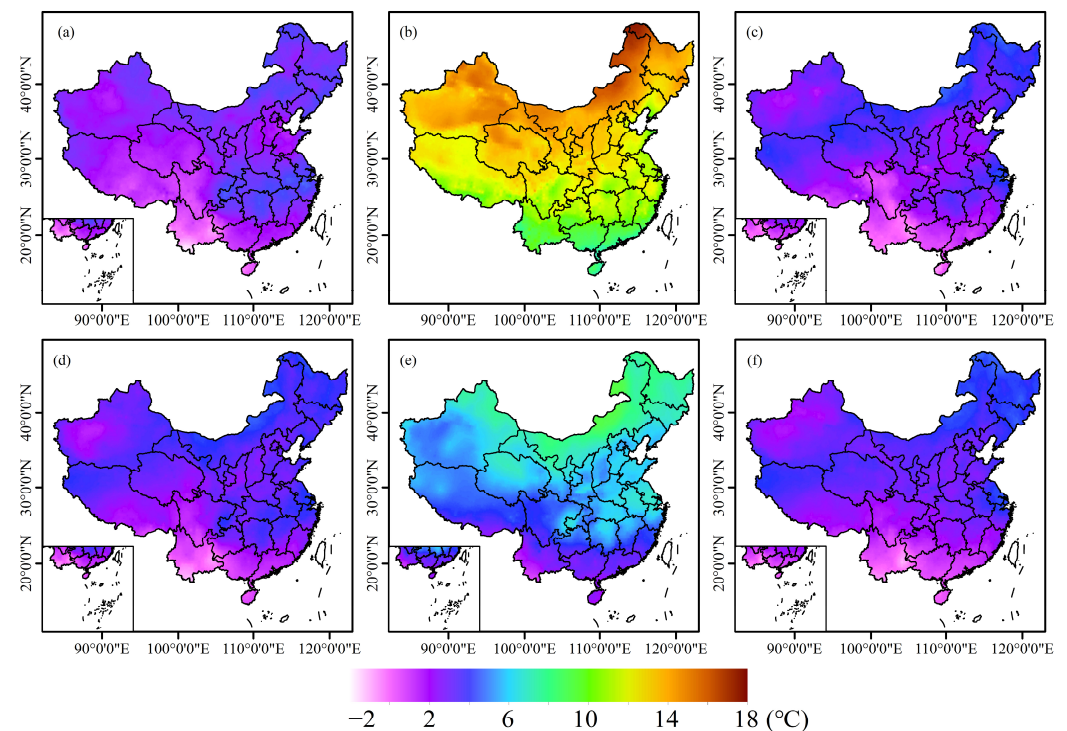


Figure 4. Spatial distribution of daily mean temperature anomalies (°C) during heatwave events in China from 1961 to 2020: (a–c) show the anomalies during heatwaves for 1961–1990, and (d–f) show those for 1991–2020; (a,d) represent daily mean temperature anomalies 5 days before heatwave onset; (b,e) represent anomalies during heatwave events; (c,f) represent anomalies 5 days after heatwave termination.

To better understand the potential drivers of heatwave occurrence, we analyzed the anomaly evolution of sensible heat flux, latent heat flux, and soil volumetric moisture before, during, and after heatwave events. This analysis reveals the critical role of land-surface energy partitioning and moisture conditions in the initiation and persistence of heatwaves.

Before the onset of heatwave events, soil volumetric water content exhibited predominantly negative anomalies over most regions of China (Figure 5a,d), particularly in the middle and lower reaches of the Yangtze River and South China, indicating relatively dry land-surface conditions prior to heatwave development. Averaged over all grid cells, the mean soil volumetric water content anomaly decreased slightly from $-0.014 \text{ m}^3/\text{m}^3$ during 1961–1990 to $-0.015 \text{ m}^3/\text{m}^3$ during 1991–2020. During the same period, latent heat flux was characterized by negative anomalies (Figure 6a,d) (mean values of -0.686 and -0.641 W/m^2 , respectively), whereas sensible heat flux remained below its climatological mean (Figure 7a,d) (-0.264 and -0.246 W/m^2 , respectively), reflecting persistent changes in surface energy partitioning under dry conditions. During heatwave events, soil volumetric water content remained below its climatological mean across much of China (Figure 5b,e), with the national mean anomaly changing from $-0.0315 \text{ m}^3/\text{m}^3$ during 1961–1990 to $-0.0333 \text{ m}^3/\text{m}^3$ during 1991–2020. Correspondingly, the mean latent heat flux anomaly changed from -0.655 to -0.626 W/m^2 (Figure 6b,e), while the mean sensible heat flux anomaly remained similar (Figure 7b,e) (from -0.337 to -0.332 W/m^2). Although these interdecadal differences are relatively small, the spatial distributions remain highly consistent between the two periods, suggesting that the environmental conditions accom-

panying heatwave events have changed only modestly despite the substantial increase in heatwave occurrence. This result is consistent with previous studies indicating that reduced soil moisture suppresses evaporative cooling and modifies surface energy partitioning during heatwaves [48–50]. However, the present analysis characterizes concurrent changes in these variables rather than establishing direct causal relationships between land-surface processes and heatwave evolution. After heatwave termination, soil volumetric water content and latent heat flux partially recovered in some regions (Figures 5c,f and 6c,f), although negative anomalies generally persisted for several days. The national mean soil moisture anomaly changed from -0.0203 to $-0.0219 \text{ m}^3/\text{m}^3$, while latent heat flux anomalies remained nearly unchanged (Figure 7c,f) (approximately $-0.404 \text{ W}/\text{m}^2$) between the two periods. Sensible heat flux anomalies became slightly weaker after heatwave termination (from -0.137 to $-0.095 \text{ W}/\text{m}^2$). To complement the spatial maps, Supplementary Figures S5–S7 present the frequency distributions of these variables. The distributions provide quantitative evidence that the two study periods exhibit highly similar spatial characteristics, with only modest shifts toward drier soil conditions during 1991–2020. Therefore, the purpose of this analysis is not to demonstrate fundamental changes in land–atmosphere processes, but rather to characterize the environmental conditions accompanying the observed increase in heatwave occurrence and the relatively stable spatial organization of the heatwave synchronization network.

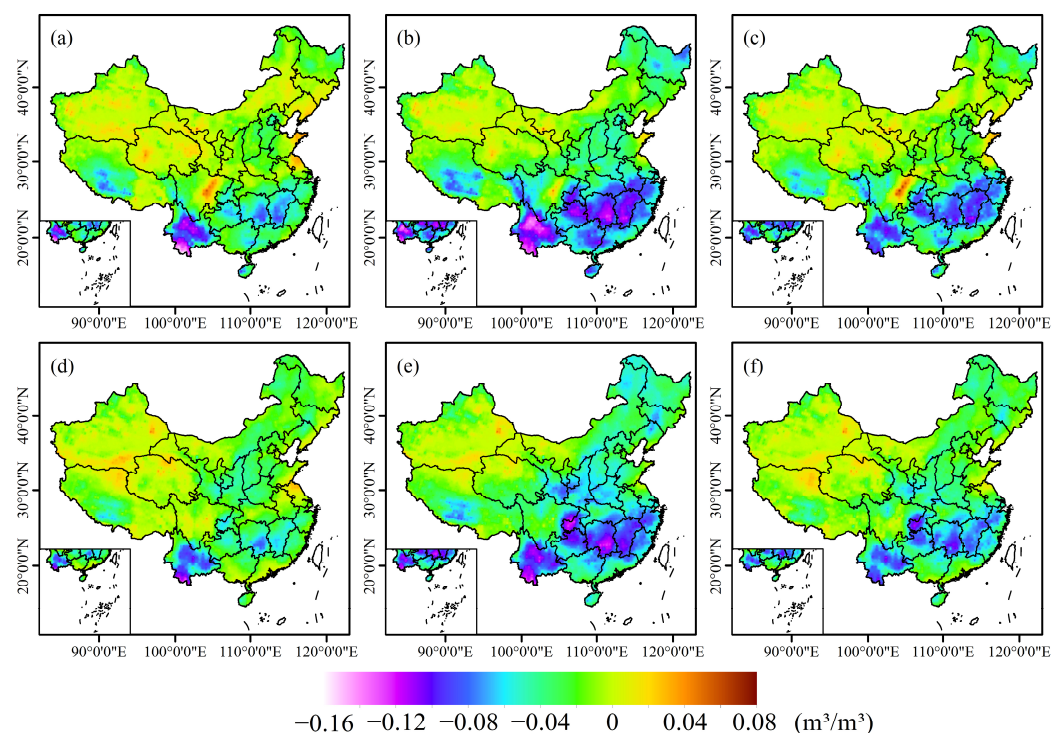


Figure 5. Spatial distribution of soil volumetric water content anomalies (m^3/m^3) during heatwaves in China from 1961 to 2020: (a–c) show the anomalies for the 1961–1990 period, and (d–f) correspond to the 1991–2020 period; (a,d) depict anomalies 5 days prior to heatwave onset; (b,e) depict anomalies during the heatwave; (c,f) depict anomalies 5 days after the heatwave ended.

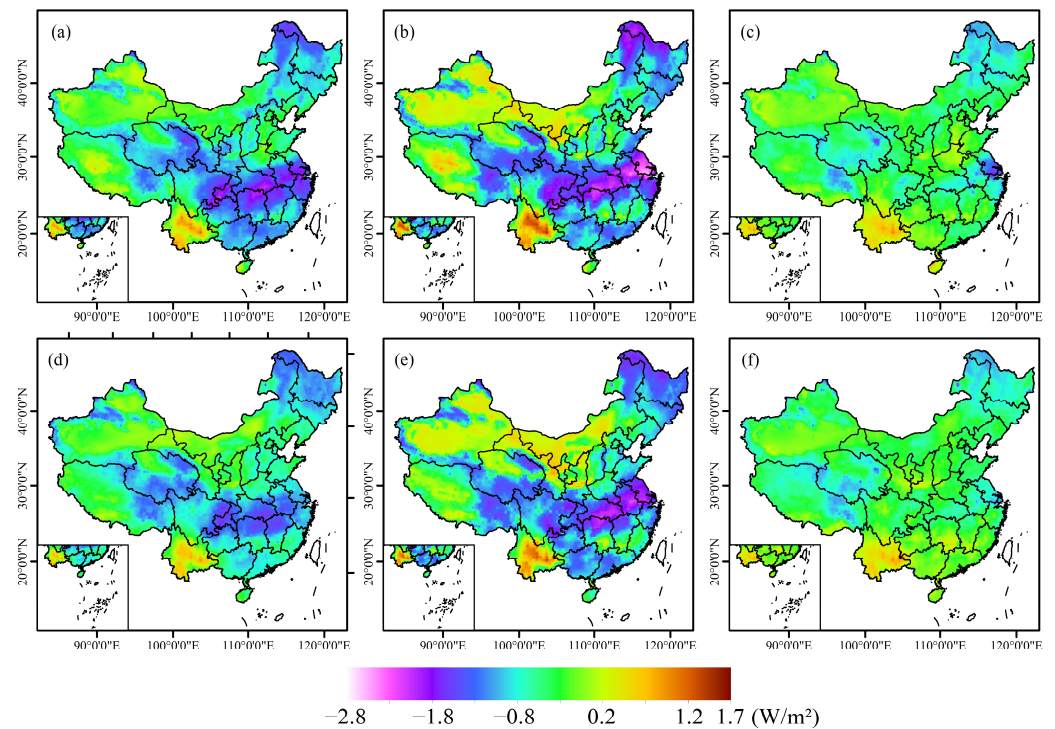


Figure 6. Spatial distribution of latent heat flux anomalies (W/m^2) during heatwaves in China from 1961 to 2020: (a–c) show the latent heat flux anomalies for the 1961–1990 period, and (d–f) correspond to the 1991–2020 period; (a,d) depict anomalies 5 days prior to heatwave onset; (b,e) depict anomalies during the heatwave; (c,f) depict anomalies 5 days after the heatwave ended.

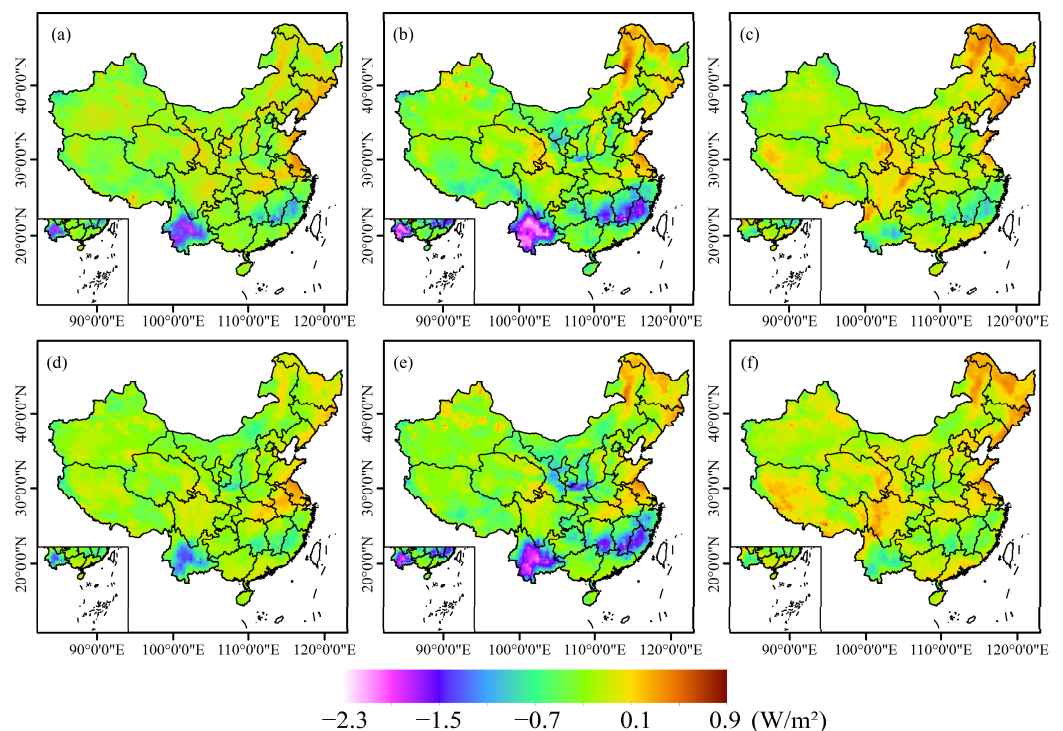


Figure 7. Spatial distribution of sensible heat flux anomalies (W/m^2) during heatwaves in China from 1961 to 2020: (a–c) show the sensible heat flux anomalies for the 1961–1990 period, and (d–f) correspond to the 1991–2020 period; (a,d) depict anomalies 5 days prior to heatwave onset; (b,e) depict anomalies during the heatwave; (c,f) depict anomalies 5 days after the heatwave ended.

4. Conclusions

Using event synchronization and complex network analysis, this study investigated the spatiotemporal evolution of heatwave occurrence and synchronization across China during 1961–2020. The results show that heatwave occurrence increased markedly across most regions of China, particularly after 1990. In contrast, the large-scale spatial pattern of the heatwave synchronization network remained relatively stable, although node connectivity increased and high-degree regions expanded. These findings indicate that climate warming has been accompanied by more frequent heatwave events and enhanced network connectivity, while the large-scale organization of synchronized heatwave events has remained largely persistent.

Compared with previous studies, which have mainly focused on changes in heatwave frequency, intensity, or duration, this study examined the spatial synchronization characteristics of heatwaves from a complex network perspective. The results demonstrate that, despite substantial increases in heatwave occurrence, the large-scale synchronization pattern of heatwaves across China has remained remarkably stable over the past six decades. In addition, the analyses of temperature, soil moisture, and surface heat flux anomalies indicate that the environmental conditions accompanying heatwave events also exhibit relatively persistent spatial characteristics between the two study periods. These findings provide a complementary perspective for understanding the large-scale organization of heatwave hazards and identifying regions that play an important role in the spatial evolution of synchronized heatwave events.

Several limitations should be acknowledged. First, heatwaves were identified using a fixed 90th-percentile threshold calculated from May to September during 1961–2020. Although this approach facilitates comparisons among regions and emphasizes genuinely extreme heat events, it may underestimate heatwave occurrences during the early and late warm season. Second, the synchronization network was constructed using the strongest 5% of synchronization links following previous studies. Although this threshold has been widely adopted in climate network analyses, future studies should further evaluate the sensitivity of the network topology to different threshold selections. Third, this study primarily employed node degree to characterize the synchronization network. Additional graph-theoretical metrics, together with atmospheric circulation diagnostics, land–atmosphere interaction analyses, and moisture transport analyses, would provide a more comprehensive understanding of the mechanisms governing heatwave synchronization. These improvements will further enhance the robustness and physical interpretation of heatwave synchronization analyses under a changing climate.

Overall, this study demonstrates that event synchronization networks provide an effective framework for investigating the large-scale organization of heatwave events and offer new insights into the spatial evolution of heatwave hazards under ongoing climate warming.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16147082/s1>, Figure S1. Statistical distribution of heatwave number during 1961–2020. (a) Statistical distribution of heatwave number during 1961–1990. (b) Statistical distribution of heatwave number during 1991–2020. Figure S2. Statistical distribution of degree during 1961–2020. (a) Statistical distribution of degree during 1961–1990. (b) Statistical distribution of degree during 1991–2020. Figure S3. Statistical distribution of daily maximum temperature anomalies (°C) during heatwave events in China, 1961–2020. a–c show anomalies for 1961–1990, and d–f show anomalies for 1991–2020. a,d depict anomalies five days before heatwave onset; b,e show anomalies during heatwave events; c,f show anomalies five days after heatwave cessation. Figure S4. Statistical distribution of daily mean temperature anomalies (°C) during heatwave events in China from 1961 to 2020. a–c show the anomalies during heatwaves for 1961–1990, and d–f show

those for 1991–2020. a,d represent daily mean temperature anomalies 5 days before heatwave onset; b,e represent anomalies during heatwave events; c,f represent anomalies 5 days after heatwave termination. Figure S5. Statistical distribution of latent heat flux anomalies (W/m^2) during heatwaves in China from 1961 to 2020. a–c show the latent heat flux anomalies for the 1961–1990 period, and d–f correspond to the 1991–2020 period. a,d depict anomalies 5 days prior to heatwave onset; b,e depict anomalies during the heatwave; c,f depict anomalies 5 days after the heatwave ended. Figure S6. Statistical distribution of sensible heat flux anomalies (W/m^2) during heatwaves in China from 1961 to 2020. a–c show the sensible heat flux anomalies for the 1961–1990 period, and d–f correspond to the 1991–2020 period. a,d depict anomalies 5 days prior to heatwave onset; b,e depict anomalies during the heatwave; c,f depict anomalies 5 days after the heatwave ended. Figure S7. Statistical distribution of soil volumetric water content anomalies (m^3/m^3) during heatwaves in China from 1961 to 2020. a–c show the anomalies for the 1961–1990 period, and d–f correspond to the 1991–2020 period. a,d depict anomalies 5 days prior to heatwave onset; b,e depict anomalies during the heatwave; c,f depict anomalies 5 days after the heatwave ended.

Author Contributions: X.Q. was responsible for methodology design, data processing, and manuscript editing. A.F. and X.Z. contributed to the revision and optimization of the manuscript. J.Q. supervised the experimental analysis. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: In this study, we used the daily maximum temperature data from the China surface temperature gridded dataset ($0.5^\circ \times 0.5^\circ$ resolution, V2.0), covering the period 1961–2022, provided by the China Meteorological Administration. Sensible heat flux, latent heat flux, and soil volumetric water content data were obtained from the ERA5 reanalysis dataset, also at a spatial resolution of $0.5^\circ \times 0.5^\circ$. Following previous studies on drought and heatwaves, soil volumetric water content in the 7–28 cm layer was selected for analysis (<https://cds.climate.copernicus.eu/datasets> (accessed on 20 June 2026)). MATLAB2022b was used for data analysing, and Arcmap10.8 was used for plotting. The code used in this study is available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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