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Higher Probability of Occurrence of Hotter and Shorter Heat Waves Followed by Heavy Rainfall

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Key Points:

- Detection, attribution, and future projection of a temporally compounding event—consecutive heat wave and heavy rainfall (CHWHR)
- For every four heat wave events, there is one subsequent heavy rainfall (CHWHR) within 7 days during 1981–2005 in China
- Shorter and hotter heat waves are more likely to be followed by heavy rainfall compared with those not followed by rainfall

Supporting Information:

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

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Abstract

The consecutive heat wave and heavy rainfall (CHWHR) events, defined as the occurrence of heat waves followed by heavy rainfall, can cause more damages than individual extremes. Nevertheless, this type of compound event has not been diagnosed systematically. Here we examine the occurrence of CHWHR events and underlying characteristics. We find 22% of land areas experienced statistically significant CHWHR events within 7 days in China during 1981–2005, with an average 26% of heat waves being followed by heavy rainfall (vs. 10% expected by chance). More importantly, the shorter and hotter heat waves are more likely to be followed by heavy rainfall than other heat waves. This phenomenon is associated with atmospheric convection and moisture convergence. In addition, climate projection shows the CHWHR events will occur more frequently and abruptly in China throughout the 21st century, which contribute to the increased compound risk of back-to-back heat waves and flash floods.

Plain Language Summary

Heat waves and heavy rainfall have profound impacts on humans, ecosystems and society. Despite the well-understood mechanisms of heat waves and heavy rainfall, current knowledge on the abrupt transitions from deadly heat waves to devastating downpours remains unclear as they are usually treated as isolated events in previous studies. In this study, we investigate the occurrence of heat waves followed by heavy rainfall in China by revealing the probability of occurrence and underlying mechanisms as well as future changes of compound extremes. We find that approximately for every four heat wave events, one of which was followed by heavy rainfall within 7 days during 1981–2005, which is much higher than that expected by chance. Furthermore, we highlight that the shorter and hotter heat waves are more likely to be followed by heavy rainfall compared with other heat waves. Such consecutive heat wave and heavy rainfall events are projected to occur more frequently in China under a warming climate. Our study offers meaningful implications for policymakers and stakeholders to better implement adaptation and mitigation solutions that can help reduce the negative consequences of this type of back-to-back extremes (consecutive heat wave and heavy rainfall events).

1. Introduction

Heat waves and heavy rainfall are regarded as two of the most frequent and widespread severe weather hazards (UNDRR & CRED, 2020; WEF, 2020). Heat waves are characterized by a period of abnormally high temperatures lasting three or more days, and heavy rainfall is a primary cause of flooding. Different from concurrent heat waves and droughts, heat waves and heavy rainfall are usually considered as isolated events, given that the two contrasting weather extremes seldom co-occur in the same place (Mukherjee & Mishra, 2021; Ridder et al., 2020). Nonetheless, there may be a lagged connection between heat waves and heavy rainfall in consideration of the interaction and mutual dependence between temperature and precipitation (Y. Chen et al., 2021; Liu et al., 2019; Zhang & Villarini, 2020).

There are a number of generally accepted hypotheses and evidence that show the potential of the compound occurrence of heat waves and heavy rainfall. For instance, it is projected that precipitation intensity will increase as the climate warms, which is primarily described by the Clausius-Clapeyron (C-C) relation, indicating that the atmospheric moisture-holding capacity will increase approximately 7% as per degree temperature rise (Trenberth et al., 2003). Despite the C-C rate scaling is not applicable to all regions around the world and lower or super C-C rates are observed elsewhere (Held & Soden, 2006; Lenderink et al., 2017; Lepore et al., 2015; Utsumi et al., 2011), the rising temperatures should increase the atmospheric water-holding capacity to some extent, which may result in more condensed moisture favorable for the occurrence of heavy rainfall (Molnar et al., 2015; Wang et al., 2017). Heat waves are often characterized by prolonged high temperature and high humidity in the lower atmosphere. The heat forcing combined with moist accumulation may contribute to atmospheric instability and trigger convection for precipitable water at the local scale (Berg et al., 2013; Fowler et al., 2021; Randall et al., 1992). As a result, water vapor convergence may be enhanced, leading to the occurrence of sudden heavy rain after the end of a heat wave. These hydrological processes and atmospheric dynamics could potentially lead to a consecutive heat wave and heavy rainfall (CHWHR) event. At a relatively large-scale, there may be a lagged connection between heat waves and heavy rainfall as a result of the thermodynamic effects, circulation shift and land-sea-atmospheric feedbacks (H. Chen et al., 2020; Deng et al., 2020; Fischer et al., 2007; Giorgi et al., 2011; Randall et al., 1992; Shang et al., 2020). The termination of a heat wave could be associated with a shift from a large-scale atmospheric blocking to circulation anomalies as well as monsoon oscillation, accompanied with thunderstorms, tropical cyclones or atmospheric rivers (Boschat et al., 2015; Raghavendra et al., 2019), potentially leading to the sudden occurrence of heavy rainfall after the end of a heat wave.

The compound occurrence of heat waves and heavy rainfall poses a critical challenge for the society responding to and preparing for extreme heat and flash flooding, which can cause even more damages than heat waves and heavy rainfall events individually (Kawase et al., 2020; Mukherjee & Mishra, 2021; Ruiter et al., 2020; Zscheischler et al., 2020). There is growing evidence that the sequential occurrence of heavy rainfall after the end of heat waves is likely to cause flash flooding, which can cause extensive damage to water quality, fundamental infrastructures, crop yields, and human livelihood. For instance, a heat wave was followed by heavy rainfall and flooding in 2019 in Australia, thereby leading to severe economic losses and environmental issues (Cowan et al., 2019; Zhang & Villarini, 2020). Similar abrupt alternations from preceding severe heat waves to thunderstorms and flash floods also occurred around the world, causing widespread socioeconomic losses (BBC News, 2020; Cappucci, 2019; ITV News, 2020). Therefore, exploring the probability of occurrence and evolution characteristics of compound heat wave and heavy rainfall events is crucial for revealing how these weather systems interact with each other and for improving the predictive skill of compound extremes under a warming climate. This is particularly important in China that is expected to experience more intense heat waves and heavy rainfall events throughout the 21st century (Deng et al., 2020; Sun et al., 2017; Wu et al., 2019).

Although a number of studies have been conducted to investigate heat waves and heavy rainfall events that occur in isolation (Day et al., 2018; Donat et al., 2016; Perkins-Kirkpatrick & Lewis, 2020), little effort has been made to examine the CHWHR events as well as their lagged connections. Furthermore, physical mechanisms and characteristics associated with the occurrence of CHWHR events remain unclear, hampering our understanding of spatiotemporal patterns and evolutionary processes of this type of compound hazards. In addition, little is known about the projected future changes of CHWHR events and associated compound risks in a warming climate.

Here, we explore the occurrence of CHWHR events and underlying mechanisms in China. Future changes in the probability of occurrence of CHWHR events are projected for the period 2075–2099 based on the high-resolution (25 km) Coordinated Output for Regional Evaluations (CORDEX-CORE) simulations. To the best of our knowledge, this is the first attempt to provide a systematic and thorough assessment of CHWHR events in a changing climate and an in-depth analysis of the lagged connections between heat waves and heavy rainfall. This study not only contributes to a deeper understanding of the new type of compound extremes (CHWHR) but also offers vital insights into the implementation of adaptation and mitigation solutions that can help reduce the negative consequences of CHWHR events.

2. Data and Methods

2.1. Data

A variety of datasets were used in this study, including gridded observations, reanalysis products, and model simulations. Observational data includes the daily gridded maximum temperature and precipitation at a spatial resolution of 0.5° × 0.5°, obtained from the China Meteorological Data Service Center (http://data.cma.cn/en). The gridded data was derived based on the interpolation of 2,472 station observations that cover the period from January 1, 1961 until now (Zhao et al., 2014). The large-scale atmospheric variables including convective available potential energy (CAPE), convective inhibition (CIN) and vertically integrated moisture divergence (VIMD), obtained from the European Center for Medium Range Weather Forecasts Reanalysis 5 (ERA5) (https://cds.climate.copernicus.eu/cdsapp#!/home), were used to assess potential physical processes associated with CHWHR events.

The high-resolution CORDEX-CORE regional climate models were used to project future changes in the probability of occurrence of CHWHR events in China (https://esgf-data.dkrz.de/search/cordex-dkrz). An ensemble of three model runs, including MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR and NCC-NorESM1-M from CORDEX-CORE were selected under the Representative Concentration Pathway (RCP) 8.5 that represented a high-emission scenario. All data were gridded to $0.5° \times 0.5°$. Our study covers a 25-year historical period from 1981 to 2005 and a 25-year future period from 2075 to 2099, with a focus on the extended summer season (May–September).

2.2. Identification and Characterization of CHWHR Events

The CHWHR events refer to the phenomenon of heat waves being followed by heavy rainfall within a prescribed temporal interval. It should be noted that we only considered the sequential occurrence of heavy rainfall after the end of a heat wave as a CHWHR event and did not consider the occurrence of heavy rainfall during heat waves. Considering the time lag that may exist between heat wave and heavy rainfall events, we selected potential impact-related intervals of 1, 3, and 7 days that represented a relatively short time span for identifying the CHWHR events. Heat wave and heavy rainfall events are identified separately when the corresponding index exceeds the predefined thresholds. A heat wave event is defined when its daily maximum temperature exceeds the 90th percentile of daily maximum temperature for at least three consecutive days during the extended summer season (May–September). This percentile is calculated for each location and each calendar day, using a 15-day moving window surrounding the calendar day during the 30-year baseline period (1961–1990). And a heavy rainfall event is detected when daily rainfall is higher than the 95th percentile of precipitation in wet days. The percentile-based thresholds used to identify heat waves and heavy rainfall events have been proved reasonable and consistent with previous studies (Casanueva et al., 2016; Perkins & Alexander, 2013; Perkins-Kirkpatrick & Lewis, 2020; Sun et al., 2017; Zhai et al., 2005) (Text S1).

The probability of occurrence of CHWHR events and the associated significance test (at the significance level of 0.05) as well as sensitivity assessment were conducted using the event coincidence analysis (ECA) framework which was widely adopted to quantify simultaneous or lagged coincidences between event time series (Donges et al., 2016; He & Sheffield, 2020; Siegmund et al., 2017; Zhang & Villarini, 2020) (Text S2). In this study, the CHWHR events are characterized by two indices: (a) heat wave duration (HWD), which is defined as the length of longest heat wave events and (b) heat wave magnitude (HWM), which is calculated based on the average temperature anomaly relative to the calendar day 90th percentile during heat wave events (Perkins-Kirkpatrick & Lewis, 2020) (Text S3).

3. Results

3.1. Probability of Occurrence of Historical CHWHR Events

Figure 1 presents the probability of occurrence of historical CHWHR events within a prescribed temporal interval in China during 1981–2005, which represents the fraction of heat waves followed by heavy rainfall within 1, 3, and 7 days. In general, 14% of land areas experience the CHWHR events (at the significance level of 0.05) within 1 day over China, which represents the worst-case scenario in which heavy rainfall occurs immediately 1 day after the end of heat waves, with an average 9% probability of occurrence of CHWHR events detected among all heat wave events (Figures 1a and 1b). When increasing the time interval to 3 days, the probability of occurrence is two times higher than those with a time interval of 1 day, with the probability of approximately 20% (Figures 1c and 1d). In terms of the frequency of CHWHR events within 7 days (Figures 1e and 1f), the probability of occurrence increases to 26%, indicating that for every four heat wave events, there is one heavy rainfall event that occurs within 7 days after the end of a heat wave. Furthermore, we highlight that the observed high probability of occurrence of CHWHR events cannot be a pure coincidence by an additional random experiment (Text S4), which is manifested in the cumulative

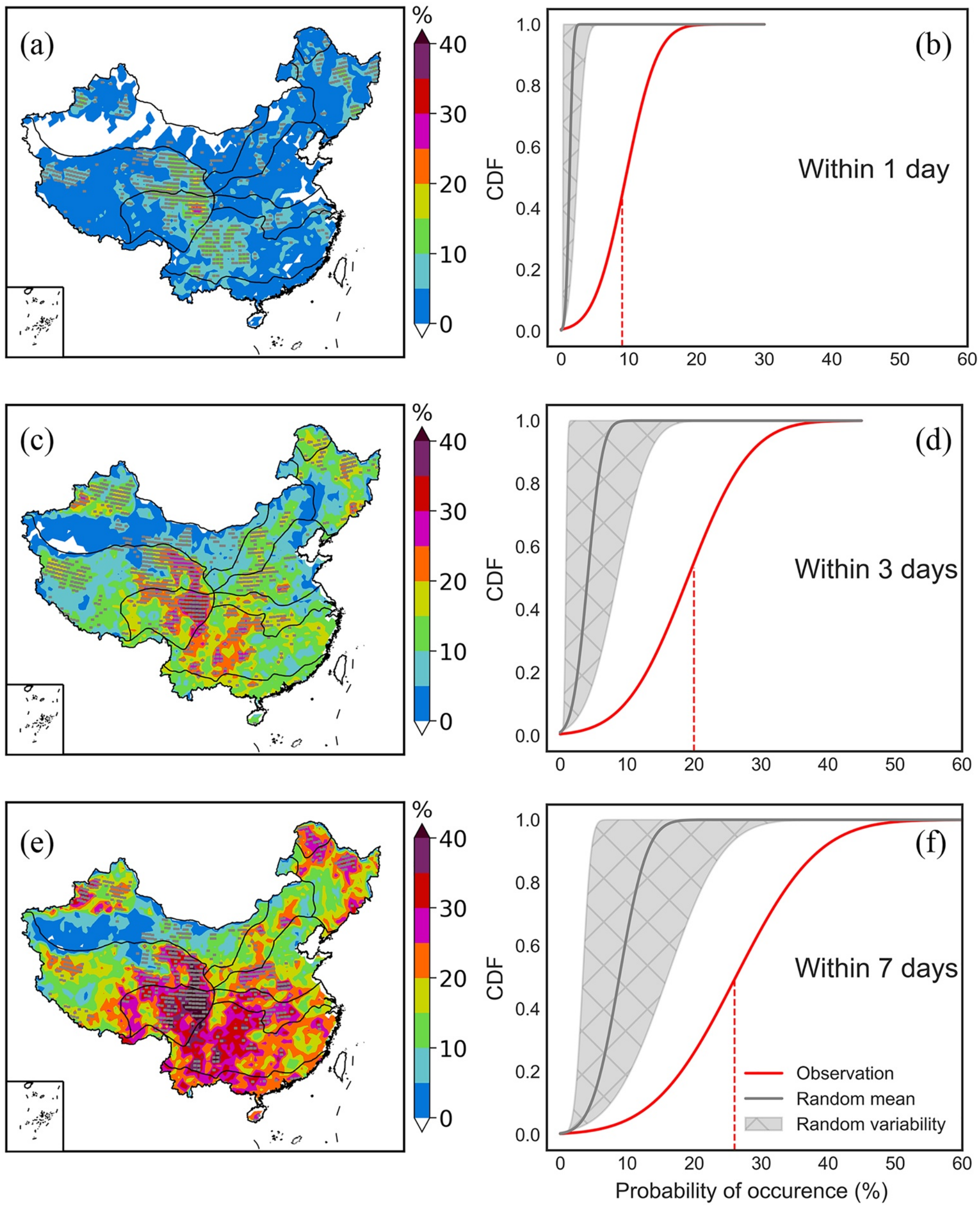

Figure 1. The spatial distribution (left column) and corresponding cumulative distribution function (CDF) (right column) of the probability of occurrence of consecutive heat wave and heavy rainfall (CHWHR) events within the prescribed temporal intervals (1, 3, and 7 days), indicating the fraction of heat wave events being followed by heavy rainfall within (a and b) 1 day, (c and d) 3 days, and (e and f) 7 days. The CDF plots in the right column show observed probability of occurrence CHWHR events (red) versus those expected by chance (gray), and its 95% confidence interval of random variability simulated by 1,000 times of bootstrap iteration (gray and hatched). Only statistically significant areas at the 0.05 level are hatched on maps and are considered in the CDF. The datasets used here are observational data for the period 1981–2005.

distribution function (CDF) subplots in Figures 1b, 1d, and 1f. As shown in Figure 1f, the probability of occurrence of CHWHR events in observation (red line) is much higher than that expected due to random coincidence (i.e., expected by chance) (gray line and hatched curve), with the 2.6-fold higher than that expected due to random coincidence (26% in observation vs. only 10% expected by chance) for CHWHR events within 7 days.

The probability of occurrence of CHWHR events shows spatial hotspots and regional variability across different climate regions in China (Figures 1a, 1c, and 1e; and Figure S1 of Text S5 for each subregion). There is a relatively high probability of occurrence of CHWHR events within 1 day during 1981–2005 (approximately 31%) located in Central and Southwest China, indicating that for every three heat wave events, one of which is followed by heavy rainfall (CHWHR events) with a 1-day lag (Figure 1a). When longer time intervals are considered, there are significantly increasing trends in the probability of occurrence of CHWHR events within 3 (Figure 1c) and 7 days (Figure 1e).

Our findings are consistent with observational evidence from previous studies of heat waves and heavy rainfall patterns (Chang et al., 2012; Deng et al., 2020; Sun et al., 2017; Tao & Ding, 1981). For instance, the hotspots detected over Central and Southwest China (around the Qinghai-Tibet Plateau) are related to the relatively high summer temperature and an abrupt increase in precipitation may be due to the sudden change of summer rain-bearing synoptic systems. These patterns are consistent with previous findings of the increasing magnitude and frequency of heat waves (Deng et al., 2020; Sun et al., 2017) as well as heavy rainfall and severe storms over the plateau and its surroundings in Central and Southwest China (Tao & Ding, 1981). The scattered patterns found in part of Northeast China may be associated with the combined effects of mid-latitude anticyclones and the western Pacific subtropical high (WPSH). The former relates to blocking weather patterns and typically leads to the occurrence of heat waves (Li et al., 2019; Petoukhov et al., 2013). The WPSH could cause the northward jump of subtropical high in summer, during which the monsoon may reach the northeast (Chang et al., 2012), transporting a great amount of moisture and thus setting a prerequisite for the occurrence of heavy rainfall after the end of heat waves.

3.2. Comparison Between Heat Waves Followed by and Not Followed by Heavy Rainfall

We examine the differences between characteristics of heat waves followed by heavy rainfall (i.e., CHWHR events) and those not followed by heavy rainfall within 1 day. There is a statistically significant difference in heat wave duration (HWD) and heat wave magnitude (HWM) between the abovementioned two types of events. In general, the shorter and hotter heat waves are more likely to be followed by heavy rainfall compared with those not followed by heavy rainfall (Figure 2). For the regions where the CHWHR events occurred during 1981–2005, a great proportion of regions (approximately 95% of total land areas) experienced the longest heat waves lasting less than 10 days (Figure 2a). For the areas without the occurrence of CHWHR events, however, heat waves tend to last for a relatively long time. Specifically, approximately 70% of land areas experienced longer heat waves for non-CHWHR events, with the duration of more than 10 days (Figure 2c). These findings are also manifested in the CDF of HWD (Figure 2e), as a clear shift to the left of the distribution of CHWHR events (red line) compared to those of heat waves not followed by heavy rainfall (green line). On the other hand, the HWM of CHWHR events, representing heat wave intensity, is generally higher than those heat waves not followed by heavy rainfall, with the largest anomalies located in northern China (Figures 2b and 2d). Unlike the HWD of CHWHR events which becomes shorter significantly (Figure 2e), the HWM of CHWHR events is not always higher than those not followed by heavy rainfall over China, especially for mild heat waves. In this study, we focus on the statistically significant areas with relatively high-intensity (exceed average anomalies of 3°C) in Figures 2b and 2f, which indicate increased excess heat accumulated during the CHWHR events. In other words, the higher HWM of CHWHR events is observed with the upper tail of the CDF shifted to the right, which demonstrates that the hotter heat waves are more likely to be followed by heavy rainfall (CHWHR events) compared with those not followed by heavy rainfall.

To further investigate synoptic preconditions when heavy precipitation occurs after heat waves in close succession, we evaluate atmospheric variables of CAPE, CIN and VIMD anomalies between heat waves followed by and not followed by heavy rainfall, with a focus on the conditions 1 day prior to the date of the occurrence of heavy rainfall following heat waves (Figure 3). As a crucial indicator of atmospheric instability, the CAPE appears to be relatively high in the northern and western parts of China (Figure 3a), which could potentially promote the development of convection and stormy weather (Brooks et al., 1994; Seeley & Romps, 2015; Wallace, 1975). CIN is another measurement of the amount of energy required for stormy weather and if CIN is too high, moist convection is unlikely to occur even though CAPE is high (J. Chen et al., 2020). This is manifested in the red box located in central China (Figures 3b and 3d) where heavy rainfall does not occur after heat waves since the higher CAPE is witnessed but the CIN is larger. The high CAPE combined with the low CIN provides favorable conditions for stormy weather, and thus can lead to

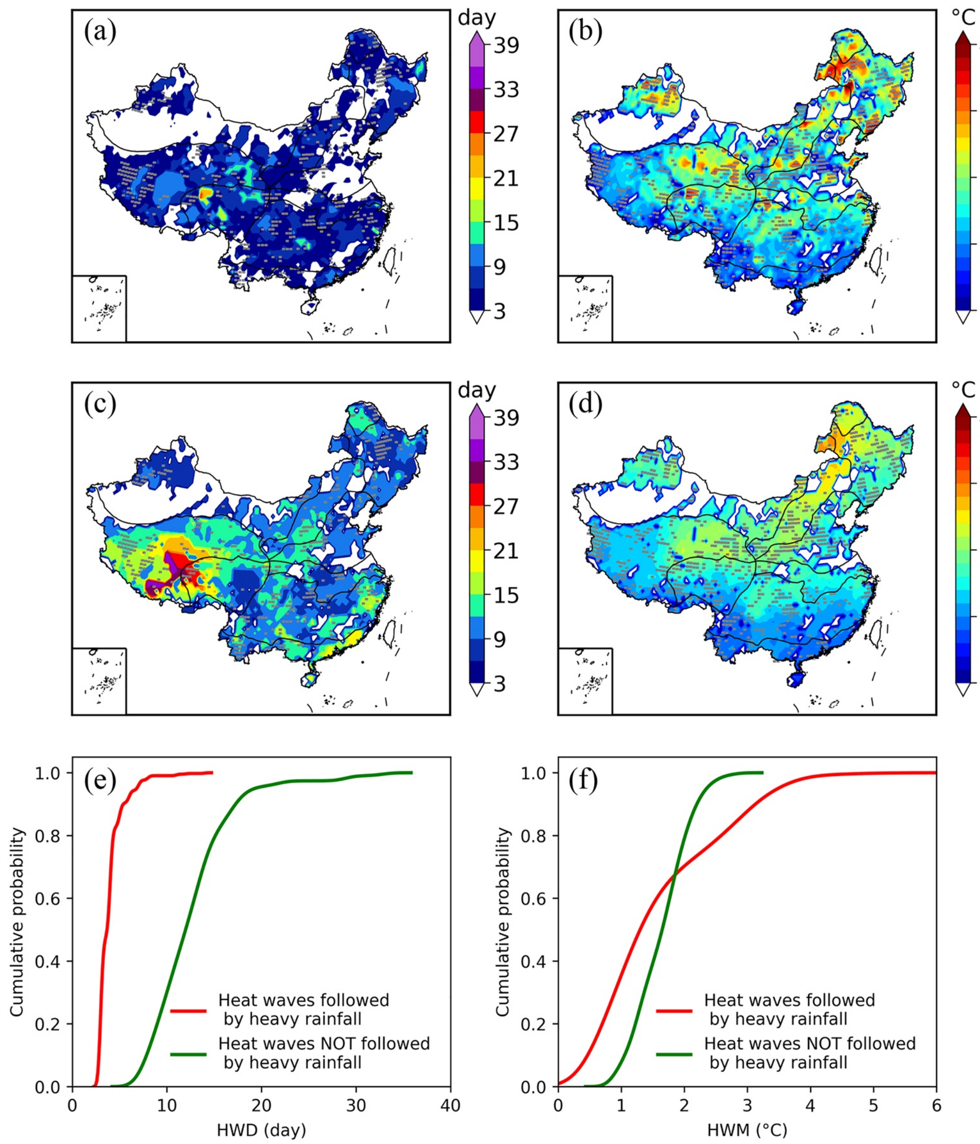

Figure 2. Comparison of heat wave duration (HWD, day) (left column) and heat wave magnitude (HWM, degree Celsius) (right column) between heat waves followed by and not followed by heavy rainfall: (a) HWD for those followed by heavy rainfall (i.e., CHWHR events); (b) HWM for those followed by heavy rainfall; (c) HWD for those not followed by heavy rainfall; (d) HWM for those not followed by heavy rainfall; (e) CDF of the HWD for heat waves followed by (red) and not followed by heavy rainfall (green); and (f) CDF of HWM for heat waves followed by (red) and not followed by heavy rainfall (green). Hatched areas are statistically significant at the 0.05 level, representing the regions where the differences of HWD or HWM between heat waves followed by and not followed by heavy rainfall are significant.

the sequential occurrence of heavy rainfall after the end of heat waves. We find that statistically significant differences (with the significance level of 0.05, as shown by hatched areas in Figure 3) in both CAPE and CIN exist between heat waves followed by heavy rainfall (CHWHR events) and those not followed by heavy rainfall, indicating that CAPE and CIN play an important role in the sequential occurrence of heavy rainfall within 1 day after the end of heat waves in China. With regard to the VIMD, the negative value of VIMD-derived from ERA5 indicates that moisture is converging, and for better visualization, we transformed the VIMD value from negative to positive. The larger values, as shown in the color bars of Figures 3e and 3f, suggest that more moisture is converging, which is conducive to the occurrence of heavy rainfall when the rainfall is preceded by a heat wave event. As shown in Figures 3e and 3f, there is a statistically significant

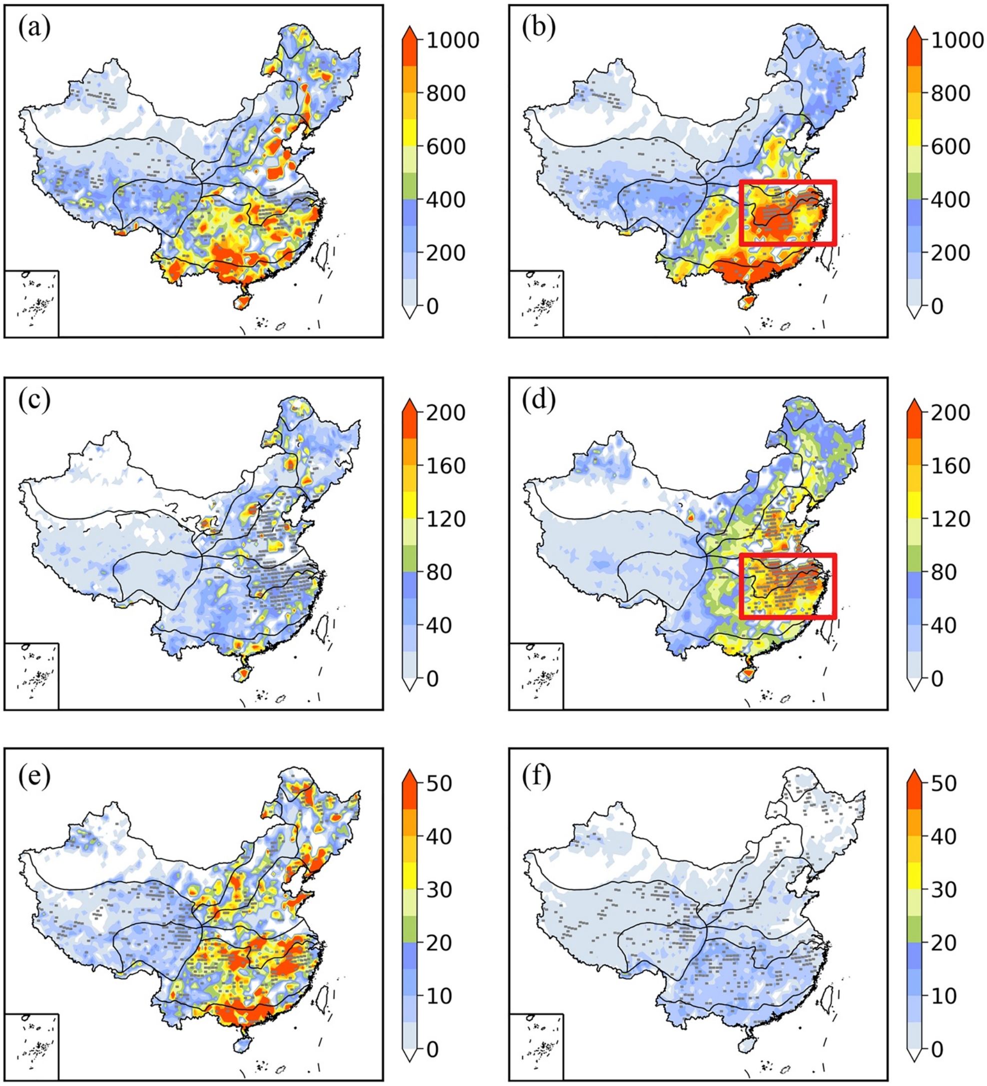

Figure 3. Distributions of three convection-related atmospheric variables: convective available potential energy (CAPE, J/kg) (top row), convective inhibition (CIN, J/kg) (middle row), and vertically integrated moisture divergence (VIMD, kg/m^2) (bottom row). Panels (a, c, and e) represent heat waves followed by heavy rainfall and panels (b, d, and f) represent heat waves not followed by heavy rainfall. Hatched areas are statistically significant at the 0.05 level.

difference in the VIMD anomalies between heat waves followed by and not followed by heavy rainfall, with increasing VIMD-derived water vapor convergence during the CHWHR events over China (Zhou & Yu, 2005). Based on previous studies assessing the importance of CAPE, CIN and VIMD on heavy precipitation, our findings highlight that the large-scale climate drivers of CAPE, CIN and VIMD anomalies play an important role in the successive occurrence of heat waves and heavy rainfall in China (CHWHR events).

3.3. Projection of Future Changes of CHWHR Events

Figures 4a–4c present the distributions of the risk ratios of CHWHR events relative to the historical period within the prescribed time intervals of 1, 3, and 7 days using CORDEX-CORE models (see Figure S2 and Text S6 for historical reproduction of CHWHR events). The risk ratio is defined as the ratio of frequencies of CHWHR events over a future 25-year period (2075–2099) to those in the historical 25-year period (1981–2005). In general, there is an increasing trend in the frequency of occurrence of CHWHR events by the end of the 21st century, with the risk ratio increasing significantly by a factor of 1–5 over most regions of China. Figures 4a–4c indicate that the land areas of increased CHWHR frequencies (i.e., risk ratios higher than

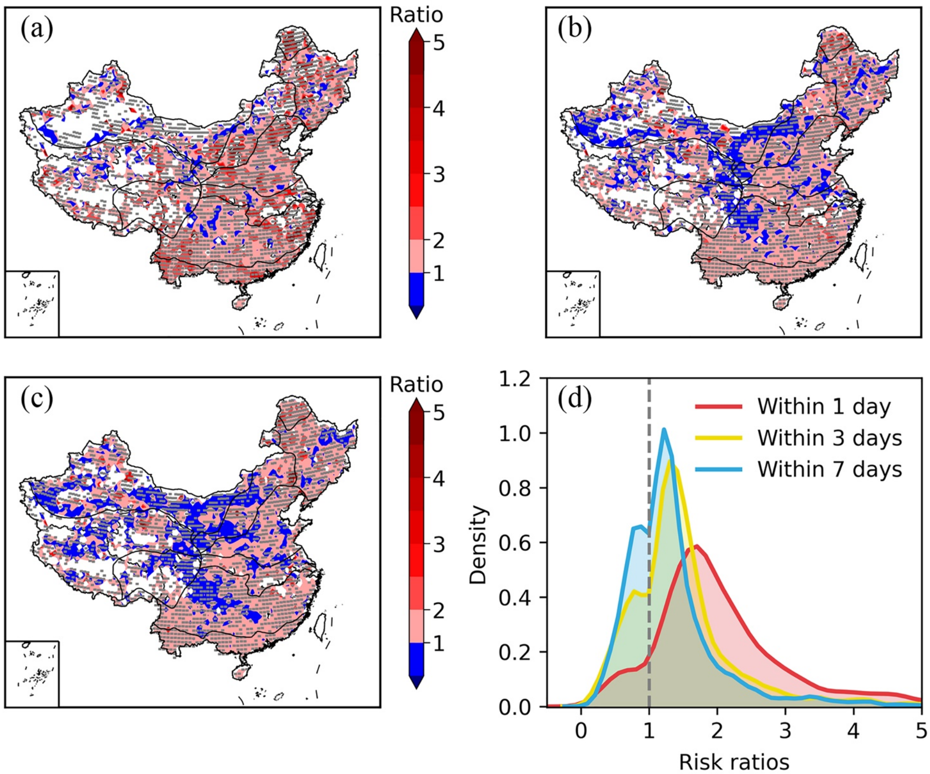

Figure 4. Projected future changes in the risk ratios of CHWHR events relative to the historical period: (a) heat wave events being followed by heavy rainfall within 1 day; (b) within 3 days; (c) within 7 days; and (d) density plot of grid cell distributions in the risk ratios of CHWHR events within 1, 3, and 7 days. Hatched areas are statistically significant for all three models.

1) decrease when the time intervals extend from 1 day to 3 days and then to 7 days, with a decreasing land proportion of 15%, 37%, and 31%, respectively (growing blue areas in Figures 4a–4c). This indicates that in the future, more CHWHR events will occur with the most rapid transition (from heat wave to heavy rainfall within only 1 day), which is largely attributed to a warming climate under the high-emission scenario. This projected trend is also observed by the corresponding cumulative probability of risk ratios of CHWHR events, as shown in Figure 4d, indicating that more heat waves are expected to be followed by heavy rainfall for the future period 2075–2099 relative to 1981–2005, especially for the worst-case scenario when heavy rainfall occurs abruptly one day after the end of heat waves.

4. Discussions and Concluding Remarks

Previous studies have examined heat waves and heavy rainfall events separately, yet their compound characteristics and future projections have not been investigated systematically. This study presents new evidence on a temporally compounding extreme in China, namely the consecutive heat wave and heavy rainfall (CHWHR). By coincidence detection and attribution analysis as well as climate projection, we reveal the probability of occurrence, underlying mechanisms, and future changes of CHWHR events. Although this study is focused on China, the proposed framework can also be applied to examine the occurrence of CHWHR events elsewhere around the world where reliable datasets with long-term records of temperature and precipitation are available.

Our findings indicate that approximately for every four heat wave events, there is one subsequent heavy rainfall (CHWHR event) within 7 days during 1981–2005. Furthermore, we find that the shorter and hotter heat waves are more likely to be followed by heavy rainfall compared with those not followed by. Such a new phenomenon is associated with three potential factors including CAPE, CIN, and VIMD that play vital roles in providing the favorable prerequisite for heavy rains and severe storms after heat waves, thereby resulting in the abrupt transition from heat waves to heavy downpours (or flooding). In addition, CHWHR events are projected to occur more frequently and abruptly in China by the end of this century, increasing the risk of consecutive heat waves and floods as the climate warms.

We verified that our findings are robust and consistent regardless of data sources, through the use of different datasets from the ERA5 reanalysis product and three CORDEX-CORE models including MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR and NCC-NorESM1-M (Text S7). As shown in Figures S2 and S3, the spatial patterns of the probability of occurrence of CHWHR events are generally consistent for the historical period 1981–2005, despite some small hotspots in observations are not well captured by ERA5 and regional models.

Considering the possibility that the shorter heat waves could tend to be hotter simply because of accumulation over fewer days, we conducted correlation analysis to examine whether there is a latent correlation between HWD and HWM. As shown in Figure S5, the R^2 value is 0.01, indicating no latent relationship between HWD and HWM, which further confirms the robustness of our findings. Hotter heat waves are associated with larger sensible heat flux, while the shorter-duration heat wave may be tied to abrupt water vapor convergence that can stop the persistence of oppressive heat waves. The larger heat forcing combined with abrupt moist accumulation, caused by the shorter and hotter heat waves, may contribute to atmospheric instability and trigger convection for precipitable water. These may help explain why the shorter and hotter heat waves are more likely to be followed by heavy rainfall compared with those not followed by heavy rainfall.

We have also investigated the possibility that a heat wave event may be temporally interrupted by a day or two of heavy rain and subsequently followed by another heat wave, which may interfere with the identification and significance of CHWHR events. Sensitivity analysis shows that the frequency of consecutive heat wave, heavy rainfall and another heat wave events turns out to be extremely low and the findings that shorter and hotter heat waves are more likely to be followed by heavy rainfall are not sensitive to the occurrence of a day or two of heavy rain that briefly drops the temperatures (Figures S6 and S7 of Text S8).

This study offers practical implications for policymakers and stakeholders adopting to mitigate the double threat of the abrupt transition from lethal heat waves to catastrophic downpours. This is especially important for the early warning and forecasting of compound extremes and flash floods (Boschat et al., 2015; Lau & Kim, 2012; Ruiter et al., 2020; Wasko, 2021), so that the society will be able to quickly respond to and prepare for the potential risk of a subsequent heavy rainfall (flooding) hazard when a short-duration but high-intensity heat wave is witnessed.

Data Availability Statement

All data in this study are publicly available. The daily gridded observations of maximum temperature and precipitation used in this analysis are available at https://data.mendeley.com/datasets/mz8hjgwn7z/1. The large-scale atmospheric variables of CAPE, CIN and VIMD are from ERA5 reanalysis that can be accessed via https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels. The CORDEX-CORE model outputs are accessible through https://esgf-data.dkrz.de/search/cordex-dkrz, with search constraints of EAS-22, REMO2015, MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR, and NCC-NorESM1-M.

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References

BBC News. (2020). *UK heatwave: Thunderstorms and flash floods after scorching heat*. Retrieved from https://www.bbc.com/news/uk-53760283

Berg, P., Moseley, C., & Haerter, J. O. (2013). Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, *6*(3), 181–185. https://doi.org/10.1038/ngeo1731

Boschat, G., Pezza, A., Simmonds, I., Perkins, S., Cowan, T., & Purich, A. (2015). Large scale and sub-regional connections in the lead up to summer heat wave and extreme rainfall events in eastern Australia. *Climate Dynamics*, *44*(7), 1823–1840. https://doi.org/10.1007/s00382-014-2214-5

Brooks, H. E., Doswell, C. A., & Cooper, J. (1994). On the environments of tornadic and nontornadic mesocyclones. *Weather and Forecasting*, *9*(4), 606–618. https://doi.org/10.1175/1520-0434(1994)009<0606:oteota>2.0.co;2

Cappucci, M. (2019). *Storms deluge New York City, abruptly ending sweltering heat wave*. Retrieved from https://www.washingtonpost.com/weather/2019/07/23/flooding-rain-deluges-new-york-city-abruptly-ending-sweltering-heat-wave/

Casanueva, A., Kotlarski, S., Herrera, S., Fernández, J., Gutiérrez, J. M., Boberg, F., et al. (2016). Daily precipitation statistics in a EURO-CORDEX RCM ensemble: Added value of raw and bias-corrected high-resolution simulations. *Climate Dynamics*, *47*(3), 719–737. https://doi.org/10.1007/s00382-015-2865-x

Chang, C., Lei, Y., Sui, C., Lin, X., & Ren, F. (2012). Tropical cyclone and extreme rainfall trends in East Asian summer monsoon since mid-20th century. *Geophysical Research Letters*, *39*(18). https://doi.org/10.1029/2012GL052945

Chen, H., Wang, S., & Wang, Y. (2020). Exploring abrupt alternations between wet and dry conditions on the basis of historical observations and convection-permitting climate model simulations. *Journal of Geophysical Research: Atmospheres*, *125*(9), e2019JD031982. https://doi.org/10.1029/2019JD031982

Chen, J., Dai, A., Zhang, Y., & Rasmussen, K. L. (2020). Changes in convective available potential energy and convective inhibition under global warming. *Journal of Climate*, *33*(6), 2025–2050. https://doi.org/10.1175/JCLI-D-19-0461.1

Chen, Y., Liao, Z., Shi, Y., Tian, Y., & Zhai, P. (2021). Detectable increases in sequential flood-heatwave events across China during 1961–2018. *Geophysical Research Letters*, *48*(6), e2021GL092549. https://doi.org/10.1029/2021GL092549

Cowan, T., Wheeler, M. C., Alves, O., Narsey, S., de Burgh-Day, C., Griffiths, M., et al. (2019). Forecasting the extreme rainfall, low temperatures, and strong winds associated with the northern Queensland floods of February 2019. *Weather and Climate Extremes*, *26*, 100232. https://doi.org/10.1016/j.wace.2019.100232

Day, J. A., Fung, I., & Liu, W. (2018). Changing character of rainfall in eastern China, 1951–2007. *Proceedings of the National Academy of Sciences*, *115*(9), 2016–2021. https://doi.org/10.1073/pnas.1715386115

Deng, K., Jiang, X., Hu, C., & Chen, D. (2020). More frequent summer heat waves in southwestern China linked to the recent declining of Arctic sea ice. *Environmental Research Letters*, *15*(7), 074011. https://doi.org/10.1088/1748-9326/ab8335

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., & Maher, N. (2016). More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, *6*(5), 508–513. https://doi.org/10.1038/nclimate2941

Donges, J. F., Schleussner, C. F., Siegmund, J. F., & Donner, R. V. (2016). Event coincidence analysis for quantifying statistical interrelationships between event time series. *The European Physical Journal Special Topics*, *225*(3), 471–487. https://doi.org/10.1140/epjst/e2015-50233-y

Fischer, E. M., Seneviratne, S. I., Lüthi, D., & Schär, C. (2007). Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters*, *34*(6). https://doi.org/10.1029/2006GL029068

Fowler, H. J., Lenderink, G., Prein, A. F., Westra, S., Allan, R. P., Ban, N., et al. (2021). Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth & Environment*, *2*, 1–122. https://doi.org/10.1038/s43017-020-00128-6

Giorgi, F., Im, E.-S., Coppola, E., Diffenbaugh, N. S., Gao, X. J., Mariotti, L., & Shi, Y. (2011). Higher hydroclimatic intensity with global warming. *Journal of Climate*, *24*(20), 5309–5324. https://doi.org/10.1175/2011JCLI3979.1

He, X., & Sheffield, J. (2020). Lagged compound occurrence of droughts and pluvials globally over the past seven decades. *Geophysical Research Letters*, *47*(14), e2020GL087924. https://doi.org/10.1029/2020GL087924

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, *19*(21), 5686–5699. https://doi.org/10.1175/JCLI3990.1

ITV News. (2020). *Two months' rain could fall in three hours as heatwave triggers thunderstorms*. Retrieved from https://www.itv.com/news/2020-08-10/two-months-rain-could-fall-in-three-hours-as-heatwave-triggers-thunderstorms

Kawase, H., Imada, Y., Tsuguti, H., Nakaegawa, T., Seino, N., Murata, A., & Takayabu, I. (2020). The heavy rain event of July 2018 in Japan enhanced by historical warming. *Bulletin of the American Meteorological Society*, *101*(1), S109–S114. https://doi.org/10.1175/BAMS-D-19-0173.1

Lau, W. K. M., & Kim, K.-M. (2012). The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. *Journal of Hydrometeorology*, *13*(1), 392–403. https://doi.org/10.1175/JHM-D-11-016.1

Lenderink, G., Barbero, R., Loriaux, J. M., & Fowler, H. J. (2017). Super-Clausius–Clapeyron scaling of extreme hourly convective precipitation and its relation to large-scale atmospheric conditions. *Journal of Climate*, *30*(15), 6037–6052. https://doi.org/10.1175/JCLI-D-16-0808.1

Lepore, C., Veneziano, D., & Molini, A. (2015). Temperature and CAPE dependence of rainfall extremes in the eastern United States. *Geophysical Research Letters*, *42*(1), 74–83. https://doi.org/10.1002/2014GL062247

Li, M., Yao, Y., Luo, D., & Zhong, L. (2019). The linkage of the large-scale circulation pattern to a long-lived heatwave over mideastern China in 2018. *Atmosphere*, *10*(2), 89. https://doi.org/10.3390/atmos10020089

Liu, X., Tang, Q., Liu, W., Yang, H., Groisman, P., Leng, G., et al. (2019). The asymmetric impact of abundant preceding rainfall on heat stress in low latitudes. *Environmental Research Letters*, *14*(4), 044010. https://doi.org/10.1088/1748-9326/ab018a

Molnar, P., Fatichi, S., Gaál, L., Szolgay, J., & Burlando, P. (2015). Storm type effects on super Clausius-Clapeyron scaling of intense rainstorm properties with air temperature. *Hydrology and Earth System Sciences*, *19*, 1753–1766. https://doi.org/10.5194/hess-19-1753-2015

Mukherjee, S., & Mishra, A. K. (2021). Increase in compound drought and heatwaves in a warming world. *Geophysical Research Letters*, *48*(1), e2020GL090617. https://doi.org/10.1029/2020GL090617

Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. *Journal of Climate*, *26*(13), 4500–4517. https://doi.org/10.1175/JCLI-D-12-00383.1

Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020). Increasing trends in regional heatwaves. *Nature Communications*, *11*(1), 3357. https://doi.org/10.1038/s41467-020-16970-7

Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnhuber, H. J. (2013). Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the National Academy of Sciences*, *110*(14), 5336–5341. https://doi.org/10.1073/pnas.1222000110

Raghavendra, A., Dai, A., Milrad, S. M., & Cloutier-Bisbee, S. R. (2019). Floridian heatwaves and extreme precipitation: Future climate projections. *Climate Dynamics*, *52*(1), 495–508. https://doi.org/10.1007/s00382-018-4148-9

Randall, D. A., Cess, R. D., Blanchet, J. P., Boer, G. J., Dazlich, D. A., Genio, A. D. D., et al. (1992). Intercomparison and interpretation of surface energy fluxes in atmospheric general circulation models. *Journal of Geophysical Research: Atmospheres*, *97*(D4), 3711–3724. https://doi.org/10.1029/91JD03120

Ridder, N. N., Pitman, A. J., Westra, S., Ukkola, A., Hong, X. D., Bador, M., et al. (2020). Global hotspots for the occurrence of compound events. *Nature Communications*, *11*(1), 5956. https://doi.org/10.1038/s41467-020-19639-3

Ruiter, M. C., Couasnon, A., Homberg, M. J. C., Daniell, J. E., Gill, J. C., & Ward, P. J. (2020). Why we can no longer ignore consecutive disasters. *Earth's Future*, *8*(3). https://doi.org/10.1029/2019EF001425

Seeley, J. T., & Romps, D. M. (2015). Why does tropical convective available potential energy (CAPE) increase with warming? *Geophysical Research Letters*, *42*(23), 10429–10437. https://doi.org/10.1002/2015GL066199

Shang, W., Ren, X., Duan, K., & Zhao, C. (2020). Influence of the South Asian high-intensity variability on the persistent heavy rainfall and heat waves in Asian monsoon regions. *International Journal of Climatology*, *40*(4), 2153–2172. https://doi.org/10.1002/joc.6324

Siegmund, J. F., Siegmund, N., & Donner, R. V. (2017). CoinCalc—A new R package for quantifying simultaneities of event series. *Computers & Geosciences*, *98*, 64–72. https://doi.org/10.1016/j.cageo.2016.10.004

Sun, Q., Miao, C., AghaKouchak, A., & Duan, Q. (2017). Unraveling anthropogenic influence on the changing risk of heat waves in China. *Geophysical Research Letters*, *44*(10), 5078–5085. https://doi.org/10.1002/2017GL073531

Tao, S., & Ding, Y. (1981). Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. *Bulletin of the American Meteorological Society*, *62*(1), 23–30. https://doi.org/10.1175/1520-0477(1981)062<0023:oeotio>2.0.co;2

Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society*, *84*(9), 1205–1218. https://doi.org/10.1175/BAMS-84-9-1205

UNDRR, & CRED. (2020). *Human cost of disasters: An overview of the last 20 years, 2000–2019*. UN Office for Disaster Risk Reduction (UNDRR), Centre for Research on the Epidemiology of Disaster (CRED).

Utsumi, N., Seto, S., Kanae, S., Maeda, E. E., & Oki, T. (2011). Does higher surface temperature intensify extreme precipitation? *Geophysical Research Letters*, *38*(16), a–n. https://doi.org/10.1029/2011GL048426

Wallace, J. M. (1975). Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States. *Monthly Weather Review*, *103*(5), 406–419. https://doi.org/10.1175/1520-0493(1975)103<0406:dvipat>2.0.co;2

Wang, G., Wang, D., Trenberth, K. E., Erfanian, A., Yu, M., Bosilovich, M. G., & Parr, D. T. (2017). The peak structure and future changes of the relationships between extreme precipitation and temperature. *Nature Climate Change*, *7*(4), 268–274. https://doi.org/10.1038/nclimate3239

Wasko, C. (2021). Review: Can temperature be used to inform changes to flood extremes with global warming? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2195), 20190551. https://doi.org/10.1098/rsta.2019.0551

WEF. (2020). *The global risks report 2020*. Retrieved from https://www.weforum.org/reports/the-global-risks-report-2020

Wu, S., Wu, Y., & Wen, J. (2019). Future changes in precipitation characteristics in China. *International Journal of Climatology*, *39*(8), 3558–3573. https://doi.org/10.1002/joc.6038

Zhai, P., Zhang, X., Wan, H., & Pan, X. (2005). Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate*, *18*(7), 1096–1108. https://doi.org/10.1175/JCLI-3318.1

Zhang, W., & Villarini, G. (2020). Deadly compound heat stress-flooding hazard across the central United States. *Geophysical Research Letters*, *47*(15), e2020GL089185. https://doi.org/10.1029/2020GL089185

Zhao, Y., Zhu, J., & Xu, Y. (2014). Establishment and assessment of the grid precipitation datasets in China for recent 50 years. *Journal of the Meteorological Sciences*, *34*(4), 414–420. (in Chinese). https://doi.org/10.3969/2013jms.0008

Zhou, T., & Yu, R. (2005). Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. *Journal of Geophysical Research*, *110*(D8). https://doi.org/10.1029/2004JD005413

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., et al. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, *1*(7), 333–347. https://doi.org/10.1038/s43017-020-0060-z