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Increasing Compound Heat and Precipitation Extremes Elevated by Urbanization in South China

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Compared with individual events, compound weather and climate extremes may impose more serious influences on natural systems and human society, especially in populated areas. In this study, we examine the changes in the compound precipitation events that follow extremely hot weather within several days during 1961–2017 in South China by taking the Guangdong Province as an example. Additionally, we assess the impacts of urbanization on these changes. It is found that extreme precipitation events in Guangdong are often preceded by hot weather, with an average fraction of 28.25%. The fraction of such compound events is even larger in more populated and urbanized areas such as the Pearl River Delta (PRD) region. Moreover, our results reveal significant increases in the frequency and fraction of the compound extreme heat and precipitation events. These increases are especially stronger in more developed areas (e.g., PRD), and their increasing trends tend to accelerate in recent decades. Furthermore, the local urbanization contributes to 40.91 and 49.38% of the increases in the frequency and fraction of the compound events, respectively. Our findings provide scientific references for policy-makers and urban planners to mitigate the influences of the compound heat and precipitation extremes by considering their increasing risks under the context of global climate change and local urbanization.

Keywords: compound events, extreme precipitation, heatwave, urbanization effects, long-term trend, climate change, South China

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INTRODUCTION

Global warming increases the occurrence probability of climate extremes in worldwide ranges, and these climate events seriously impact human communities and the natural environment (IPCC, 2014; World Economic Forum, 2019). For example, heatwaves and heavy precipitation are more harmful to human health (Matthies and Menne, 2009; Lin et al., 2015), agriculture (Wreford and Adger, 2010; Sun et al., 2014), economy (Kjellstrom, 2015; Zhang et al., 2017b), and public infrastructure (McEvoy et al., 2012). For instance, heatwaves increased the death rate by 2,300 folds (136,000 deaths) from 2001 to 2010, compared with the last decade of the 20th century (World Meteorological Organization, 2013). Additionally, precipitation extremes resulted in the devastating floods in the Yangtze River of China in 1998, which caused thousands of deaths and missing country-wide (Orsolini et al., 2015). Furthermore, these resultant influences of climate extremes have been proved to be exacerbated due to global warming (Liu et al., 2020a; Perkins-Kirkpatrick and Lewis, 2020).

Extreme climate and weather events often occur simultaneously or sequentially within a short period of time, known as compound events (Leonard et al., 2014). As a combination of two or more extremes (e.g., preconditioned heat and subsequent extreme precipitation), compound events often result in larger impacts than individual events (Zscheischler et al., 2018; Weber et al., 2020). Moreover, the hazards resulting from interacted climate extremes may further intensify the magnitude and severity of the risks caused by individual events (Leonard et al., 2014; Alizadeh et al., 2020). For instance, the compound high-temperature and severe precipitation events have vital effects on plants during the growing season (Madden and Williams, 1978). A compound event with low temperatures, strong wind, and following extreme precipitation in Queensland of Australia caused the deaths of half a million cattle (Cowan et al., 2019). While most existing studies paid much attention to individual events, few focused on compound events with magnified impacts compared to the individual events (Weber et al., 2020).

In addition to global warming, local urbanization significantly affects changes in regional weather and climate extremes. During the urbanization process, land use/land cover (LULC) changes such as the transformation from vegetation to impervious surfaces accelerate the variations in surface temperature and increase the frequency and duration of severe precipitation events (Pielke Sr et al., 2011; Sun et al., 2019; Lin et al., 2020). Furthermore, LULC changes affect the original energy balance generating a prominent phenomenon, i.e., urban heat island (UHI), making urban areas warmer than surrounding rural areas (Oke, 1982; Zhou et al., 2004; Jones et al., 2008; Luo and Lau, 2018). Urbanization and the associated UHI can deteriorate extreme heat and heavy precipitation events under a warming climate (Stone, 2012; Oleson et al., 2015; Yu and Liu, 2015; Zhang et al., 2018). For instance, Luo and Lau (2018) estimated that urbanization accounted for nearly 30% of the increases in average extreme heat stress in the urban areas of eastern China. The rising numbers of heatwaves may increase mortality in urban regions (Li et al., 2013; Mishra et al., 2015). Liang and Ding (2017) found that urbanization is conducive to enhance the frequency and intensity of heavy precipitation events on urban stations, thus further increasing the total precipitation. Although previous studies have linked increasing extreme events to urbanization and its associated UHI effects (Yang et al., 2017a; Luo and Lau, 2017), the possible physical mechanisms underlying these linkages have not been revealed and warrant further investigations.

China has been experiencing rapid urbanization since the 1970s, and its urban population proportion increased from 18.4 to 58.52% during 1961–2017 (National Bureau of Statistics of China, 2018). Under global climate change and rapid region urbanization in China, the characteristics in terms of frequency, duration, and intensity of extreme weather and climate events have been drastically intensified in most parts of China (Ren and Zhou, 2014; Yang et al., 2017b; Sun et al., 2019). For example, Ren and Zhou (2014) estimated that urbanization contributed to 37.8% for tropical nights and 12.8% for summer days in China during 1961–2008. In particular, Yang et al. (2017b) suggested that urbanization accounts for more than one-third of the increase of the intensity of heat extremes in East China, and urbanization tends to have stronger effects on cold and warm nights than the daytime extremes in this region (Sun et al., 2019). These effects are especially stronger in urbanized and populated areas, such as the Beijing-Tianjin-Hebei (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD) region (Zhang et al., 2017a; Peng et al., 2017). As one of the most populated and urbanized areas, South China suffers from the impacts brought by both frequent extreme hot weather and intense precipitation events (Wang et al., 2019), which pose remarkable impacts on public health in this area. Nevertheless, the temporal and spatial changes in compound heat and extreme precipitation in South China, along with the possible effects of urbanization on these changes have not been reported in the literature.

In this study, therefore, we investigate the changes in sequentially compound precipitation events with preconditioned hot weather in South China, and evaluate the contribution of local urbanization to these changes. The remainder of this paper is structured as follows. Section *Materials and Methods* introduces the study area, data, and methods. The examinations of the changes of compound events and urbanization effects are presented in Section *Results*. Section *Conclusion and Discussions* summarizes the main findings of this study.

MATERIALS AND METHODS

Study Area

In this research, we examine the changes in compound extreme heat and precipitation events in South China, by taking Guangdong Province as an example since it possesses the densest population and is the most urbanized province in South China. It is characterized by a subtropical monsoon climate with hot-humid summer and cool-dry winter. Guangdong has experienced rapid urbanization and industrialization since the commence of China's economic reform and opening-up policy (Xiong et al., 2012). Among all provincial units of China, Guangdong has been holding the largest Gross Domestic Product (GDP) since 1989. Its urbanization level reached 69.85% in 2017. Of Guangdong, the PRD region (as denoted by the red boundary in **Figure 1**) exhibits the highest urbanization level of 85.29% and the largest population density (Statistics Bureau of Guangdong Province, 2017). Moreover, this area has been severely suffering from dramatic increases in extreme weather and climate events over the past decades (Chen et al., 2015; Lin et al., 2019).

Data

In this study, the compound extreme heat and precipitation events are derived from daily maximum temperature (T_{max}) and daily precipitation. Observations recorded at 86 meteorological stations in Guangdong from 1961 to 2017 are

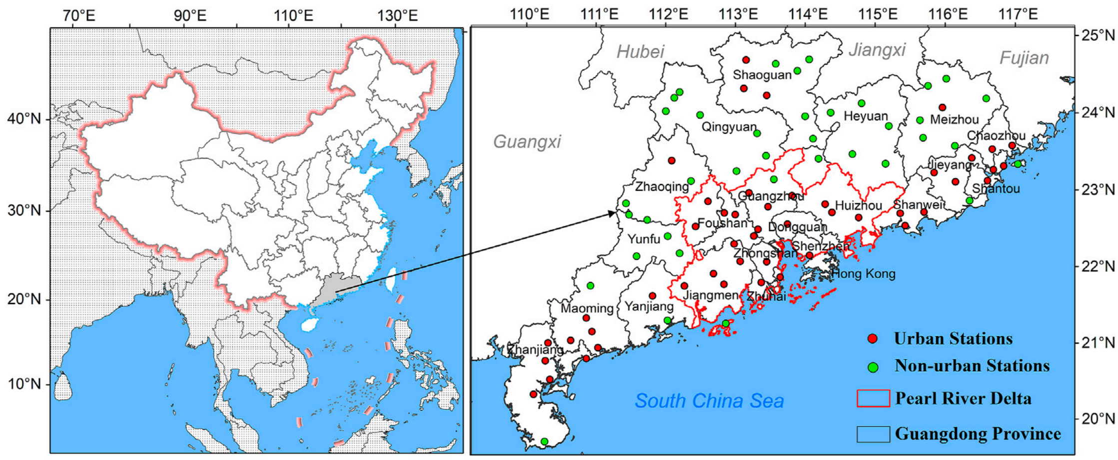

FIGURE 1 | Locations of the meteorological stations in Guangdong Province of South China. Urban and non-urban stations are marked as red and green dots, respectively. PRD is marked by the red boundary.

obtained from the China Meteorological Data Service Center (http://data.cma.cn). The raw data have been homogenized using a statistical approach proposed by Xu et al. (2013). Their temporal inhomogeneity has been evaluated by the Easterling-Peterson method (Li et al., 2004; You et al., 2010). In this study, stations with ≥3 missing days in any month from June to August are excluded.

Definition of Compound Events

Compound events are defined as comprising a combination of two or more different extremes occurring coincidentally or sequentially within a certain period of time (Mueller and Seneviratne, 2012; AghaKouchak et al., 2014; Leonard et al., 2014; Wahl et al., 2015). These extremes are considered contributing to complex interactions of multiple hazards such as widespread wildfires (Witte et al., 2011), large-scale air pollution (Konovalov et al., 2011) to human society/ecosystems (Weber et al., 2020). In this study, compound heat and precipitation extremes are defined for each station individually. An extreme precipitation event is first detected when daily precipitation is larger than the 90th percentile value for all rainy days (≥0.1 mm) in the summers of the reference period of 1961–1990. Then the compound event is counted if the extreme precipitation event is preceded by an extreme heat event within three days. Here, a heat event is defined when daily T_{max} is larger than the 90th percentile of the reference period. To quantify the compound events, we adopt a probabilistic metric by using the fraction of the compound events accounting for all extreme precipitation events in a calendar year.

Statistical Methods

In order to evaluate the possible influences of urbanization on compound events, we classify all meteorological stations into urban and non-urban types, as suggested by previous studies (Mishra et al., 2015; Luo and Lau, 2018; Wang et al., 2019). Stations are tagged as urban type if they are located in urban areas or urban buffers of 25 km that have a population more than 250,000; otherwise, they are classified as non-urban type. The urban area extents are derived from the DeLorme World Base Map dataset (https://www.baruch.cuny.edu/confluence/display/geoportal/ESRI+International+Data), which has been validated by the urban extents extracted from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Mishra et al., 2015).

The urbanization effects are quantified by calculating the differences in the trends between the urban and non-urban series (Ren and Zhou, 2014; Luo and Lau, 2019b). The urban (non-urban) series of the frequency and fraction of compound events are obtained by averaging all urban (non-urban) stations. The secular trend of the series of compound events is estimated by the conventional linear regression, and its significance is evaluated by the modified nonparametric Mann-Kendall (mMK) test. The mMK method considers the autocorrelation in the time series to provide an unbiased evaluation of the trend (Hamed and Rao, 1998). It has been widely used in hydrological and climatological studies (e.g., Luo and Lau (2019a); Sa'adi et al. (2019))

RESULTS

Climatology of Compound Events

Based on the above definition, we search for the compound events at all stations from 1961 to 2017, and obtain the multi-year mean frequency and fraction of these events. As shown in **Figure 2**, compound events with extreme precipitation and hot days have occurred in all parts of Guangdong. On average, 28.25% of extreme precipitation events are preceded by a heat extreme within three days, and the study area experiences 1.26 compound events per year. The frequency and fraction of compound events demonstrate obvious spatial variations across the study area. Specifically, compound events are more prominent in densely populated and highly urbanized areas such as PRD, in which the highest frequency and fraction of compound events are observed. The PRD region has 1.49 compound events per year, and 31.81% of its precipitation

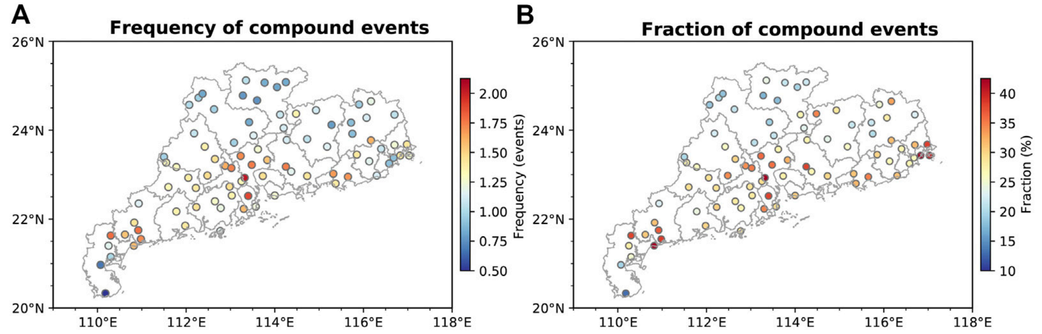

FIGURE 2 | Spatial distribution of mean **(A)** frequency and **(B)** fraction of compound events in Guangdong Province from 1961 to 2017.

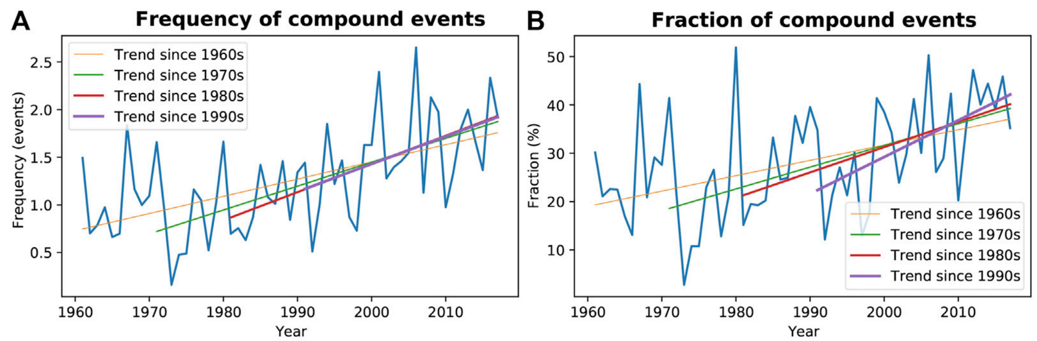

FIGURE 3 | Time series of regional mean **(A)** frequency and **(B)** fraction of compound events in Guangdong Province from 1961 to 2017. Straight lines denote the corresponding linear trends in different subperiods.

extremes occur following a previous extreme heat day within a short period. The larger (smaller) frequency and fraction in more (less) urbanized areas indicate that local urbanization may increase the occurrence of compound events.

Nearly all stations have experienced the compound events (with the frequency of compound events > 0). This result is in accordance with the findings of Hao et al. (2013) that heat and precipitation extremes have co-occurred in the high latitudes and tropical regions. The spatial variations of the compound heat and extreme precipitation events are highly consistent with the distribution of the urban and non-urban stations, i.e., compound events tend to occur more frequently at the urban than non-urban stations.

Spatial and Temporal Changes of Compound Events

To understand the temporal evolution of compound events, we calculate the regional mean frequency and fraction of compound events by averaging all stations (**Figure 3**). Both the frequency and fraction show dramatic increasing trends, i.e., statistically significant at the 0.05 level. The regional mean frequency of compound events has increased by 0.18 events per decade, and the fraction has risen by 3.17% per decade over the study period. It indicates that the probability of extreme precipitation events following a heat event tends to increase.

It is also shown in **Figure 3** that the increasing trends of the compound frequency and fraction tend to be accelerated since the 1960s. The magnitudes of the trends are 0.25 and 4.49% per decade during 1971–2017 for the frequency and fraction of compound events, respectively. These trend magnitudes become larger during 1981–2017, i.e., 0.30 and 5.23%, respectively. The trends remain significant and continue to increase till at least the 1990s, since which the frequency and fraction increased by 0.29 and 7.60%, respectively. These results suggest that the increasing speed of the proportion of extreme precipitation that follows a heat event has elevated.

Figure 4 depicts the spatial distribution of the secular trends of the frequency and fraction of compound events at the individual station during 1961–2017. Compound events exhibit increasing tendencies in measure of frequency (fraction) since the 1960s at nearly all stations, of which 55.81% (56.98%) are significant at the 0.05 level. The upward trends show regional disparities with stronger magnitude in more populated and urbanized areas and weaker in less developed regions. In particular, the PRD region with the densest population and highest urbanization level has the most substantial increasing tendency, whereas other less urbanized areas such as the northern parts of Guangdong possess relatively weaker trends. These features indicate that the residents living in PRD are facing intensifying threats induced by compound heat-precipitation events. More substantial intensification of compound events in faster-

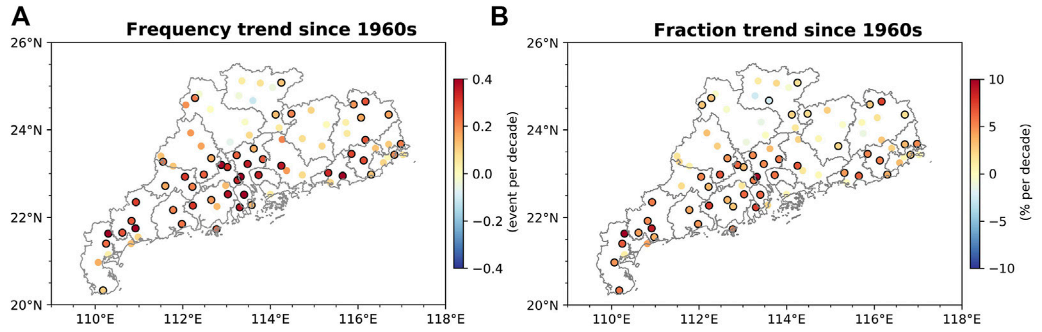

FIGURE 4 | Spatial distribution of the trends in the **(A)** frequency and **(B)** fraction of compound events in Guangdong Province from 1961 to 2017. The black circle indicates significance at the 0.05 level.

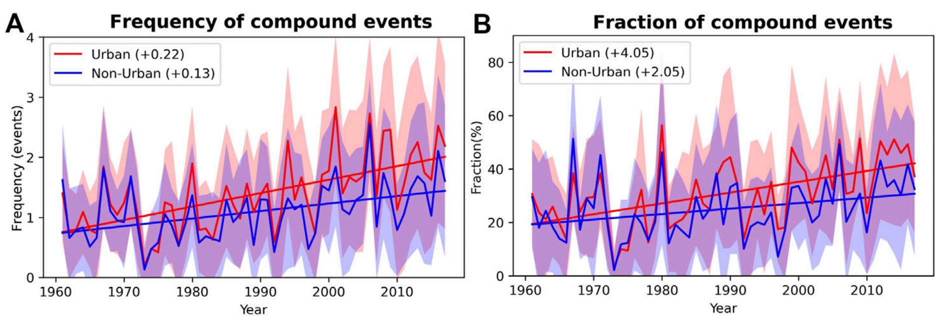

FIGURE 5 | Time series of regional annual mean **(A)** frequency and **(B)** fraction of compound events from 1961 to 2017 for urban (red) and non-urban (blue) stations. The pink (cyan) shading indicates the mean ± standard deviation of frequency and fraction of compound events for urban (rural) stations. The straight lines indicate their corresponding linear trends (unit: event per decade and % per decade for the frequency and fraction, respectively).

urbanized areas implies that the urbanization process possibly plays an important role in accelerating this phenomenon.

The trends of compound heat-precipitation events revealed above are consistent with the findings of Scherrer et al. (2016) in such a way that the increasing trends of hot days and heavy precipitation were found in warmer places. Hao et al. (2013) used the Coupled Model Intercomparison Project phase 5 (CMIP5) climate model to simulate concurrent wet and warm events, and demonstrated that those events increased significantly in high-latitude and tropical regions (Hao et al., 2013). The reason for the increasing trend of compound events in South China is likely that the preconditioned extreme hot weather with higher temperature leads to increased higher evaporation rates and vapor content, thus accelerating the hydrological cycle under the context of global warming (Menzel and Bürger, 2002). Moreover, the preceded heat can enhance the moisture flux and the convective available potential energy (CAPE) and thereby provide a suitable environment for extreme precipitation and flooding in several subsequent days (Zhang and Villarini, 2020). In our study, we also find that the upward trends of frequency and fraction of the compound climate events in South China became even steeper from 1990 to 2017. A possible reason for the acceleration since the 1990s is that the increased Tibetan Plateau snow cover and sea surface temperature in the equatorial Indian Ocean boosted the precipitation in South China (Wu et al., 2010).

Urbanization Effects and Contribution

To quantify the impacts of urbanization on the increases in the frequency and fraction of compound events, all stations are categorized into urban and non-urban types (**Figure 1**), and we calculate the annual mean values for the two types of stations from 1961 to 2017 (see **Figure 5**). Both the urban and non-urban areas exhibit rising trends in terms of the compound frequency and fraction. It is noteworthy that the urban stations (as shown in pink shading) exhibit even steeper trends than those in the non-urban areas (as shown in cyan shading), demonstrating a remarkable contribution of urbanization. The frequency (fraction) of compound events in the urban and non-urban areas increased by 0.22 events (4.05%) and 0.13 events (2.05%) per decade, respectively. The differences in the trend between the urban and non-urban regions are 0.09 events for the compound frequency and 2.00% for the compound fraction. Since possible influences by other impact factors such as global warming and large-scale circulations are comparable at the local scale, the differences between trends for the urban and non-urban regions mainly result from local urbanization. Accordingly, we estimate that urbanization accounts for 40.91% (49.38%) of the total increasing trend in the frequency (fraction) of the compound events in the urban region.

These results indicate that the urbanization process tends to exert intensifying impacts on compound heat-precipitation events. Previous studies such as Chen et al. (2015); Wang et al. (2018) found that the PRD region experienced much stronger precipitation compared to its surrounding rural areas and attributed this difference to urbanization. Other studies have also confirmed that urbanization can affect extreme precipitation by influencing UHI (Oke, 1982; Dixon and Mote, 2003), urban canopy (Miao et al., 2009), and urban aerosols (Han and Baik, 2008). Specifically, UHI effects can be enhanced by the increases in anthropogenic heat release, as suggested in many modeling studies by the Weather Research and Forecasting (WRF) model coupled with the Urban Canopy Model (UCM) (Feng et al., 2012; Chen et al., 2014; Yang et al., 2019). The urban development enhances the total thermal discomfort hours by 27% in the urban core areas of YRD, and anthropogenic heat release and urban land use change contribute nearly equally to this change (Yang et al., 2019). Warmer temperature in urban areas enhances the disturbance above the ground and strengthens the upward motion and convective activities (Collier, 2006). Moreover, urban canopy disturbs the water vapor and energy balance in urban boundary layers and impacts heavy convective precipitation by increasing the surface roughness, which reduces surface wind, bifurcates the approaching moist air mass upward, and then aggregates them in the downwind of urban areas (Cotton and Pielke, 2007; Zhang et al., 2014). Additionally, extreme precipitation is contributed by the interactions of urban aerosols with radiation and clouds (Liu et al., 2020b). Urban aerosols absorb and scatter solar radiation to generate condensation nuclei, which can influence deep convection and hence precipitation (Li et al., 2011; Liu et al., 2020b). Consequently, via these processes, the local urbanization provides favorable conditions for extreme compound heat and precipitation events.

CONCLUSION AND DISCUSSIONS

In this study, we investigate the changes in sequentially compound extreme heat and precipitation events during 1961–2017 in South China and quantify the contribution of urbanization to the long-term changes of this type of extreme weather for the first time. Our results indicate that extreme precipitation events in South China are often preceded by hot weather within three days, and demonstrate that the local urbanization exerts significant impacts on this compound extremes event.

The compound heat and precipitation extremes occur frequently in South China and they are more frequent in more populated and urbanized regions such as PRD. The increases in the frequency and fraction of the compound events are observed almost everywhere in Guangdong, especially in the PRD region. Similarly, Zhang and Villarini (2020) found that compound heat stress and flooding extremes in the central United States become more frequent, and these increasing compound events may lead to greater societal and economic impacts. In our research, we demonstrate that the increasing trends of compound heat and precipitation extremes in China also tend to accelerate in recent decades. This result is also consistent with the study by Scherrer et al. (2016), who found increasing trends in hot temperature and heavy precipitation extremes in Switzerland, while the upward trends of compound heat-precipitation events have not been linked to human activities such as urbanization. These studies collectively suggest that compound heat-precipitation events have increased in many parts of the world, posing increasing threats to human society and the natural environments. A better understanding of such events is urgently warranted and thus of great significance to improve the forecast, prediction and mitigation of the compound weather and climate disasters.

Previous studies have shown that urban expansion plays an important role in extreme precipitation, and urbanization contributes to nearly 50% of the increase in the heatwave frequency in the PRD region of South China (Luo and Lau, 2017; Wang et al., 2018). However, these studies only considered individual extreme events, without examining the extreme events that occur simultaneously or sequentially within a short period of time. Our present study provides the first examination of the changes in compound heat-precipitation events in South China and quantifies the urbanization effects on these changes by classifying the stations into urban and non-urban ones. Chen et al. (2021) has studied another type of compound event, i.e., sequential flood-heatwave events across China, and found that anthropogenic forcings contributed greatly to these compound extremes. Nevertheless, to what degree local urbanization influences the compound events has not been evaluated and needs to be further investigated.

In this study, we estimate that the contributions of urbanization to the increases in the frequency and fraction of compound heat-precipitation events are 40.91% and 49.38%, respectively. It is noteworthy that the frequency and fraction of compound event in urban areas increase more steeply than in non-urban areas. Our results demonstrate a prominent urbanization contribution by local human activities to these compound events. Local urbanization contributes to nearly half of the increases in the frequency and fraction of compound events. It is thus suggested that future mitigations to climate change and disasters should take more consideration of urban planning and the increasing threats by compound weather and climate extremes.

Additionally, previous observational and modeling studies revealed various mechanisms underlying the urbanization effects on regional or local climate change, such as UHI (Dixon and Mote, 2003; Chen et al., 2014), urban canopy (Miao et al., 2009; Chen et al., 2011), and urban aerosol effects (Han and Baik, 2008; Jin et al., 2010). Many studies have used WRF model simulations to qualify the urbanization effects on climate (Feng et al., 2012; Yang et al., 2014; Zhang et al., 2018; Yang et al., 2019). This modeling approach may broaden our understanding of the mechanisms of compound events and the urbanization effects. In our future work, we shall use climate modeling to conduct a deeper investigation of the processes associated with the compound heat-precipitation events and reveal the mechanisms underlying the urbanization effects on these events. It is also of great interest to examine how these compound event will change in the future under different scenarios of emission and socio-economic development, i.e., via analyzing the projections of phase six of the Coupled Model Intercomparison Project (CMIP6). Moreover, as it remains unclear how compound heat-precipitation events changed in other climate regimes beyond South China, compound extremes in other urbanized and populated areas of China such as YRD and BTH also warrant investigations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YZ and ML design the research. SW and ML conduct the analysis. All authors discuss the results and edit and review the manuscript.

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