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Key Points:
• Unprecedented compound heat waves will occur on a regular basis in three urban agglomerations in China since mid-21st century under RCP8.5.
• The likelihood of unprecedented compound heat waves in a 1.5°C warmer world will halve compared to 2°C warming scenario.
• Population exposures to future unprecedented compound heat waves will increase by nearly 70, 90, and 60 million by the end of this century.

Supporting Information:
• Supporting Information S1

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Plain Language Summary
Extreme heat waves impose devastating impacts on human health, economy, and the environment. The risk of extreme heat stress tends to be higher in urban areas than in rural areas, due to greater population exposure and added heat stress from urban heat island. Compared to daytime- or nighttime-only heat waves, the risk of compound heat waves that combine scorching days and sweltering nights sequentially tends to be higher. Focusing on top three populous urban agglomerations in China, this study dissects summertime heat waves into three nonoverlapping types and identifies the strongest heat waves on record based on a universal metric of heat wave magnitude. Projections show that unprecedented compound heat waves will become the norm since around 2045 (2060), 2045 (2065), and 2030 (2040) in the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta, respectively, under RCP8.5 (RCP4.5) emission scenario. Enhancing heat hazards will translate into increasing population exposure of about 70, 90, and 60 million to unprecedented compound heat waves by the end of this century, which are concentrated on the highly urbanized areas, such as Beijing, Shanghai, Guangzhou, and Shenzhen. This study highlights the urgent adaptation and mitigation efforts for cities against compound heat waves in particular.

1. Introduction
Urban areas face formidable challenges associated with climate change. Despite covering a small proportion of the global land surface, urban areas currently accommodate more than 55% of the world’s population, and this proportion is projected to increase to 68% by 2050 according to the United Nations (2018). This is of concern because fast-growing and highly concentrated urban populations are vulnerable to extreme weather events such as severe heat waves (Ürge-Vorsatz et al., 2018). As global temperatures rise, the frequency, intensity, and duration of extreme heat waves are expected to increase (Meehl & Tebaldi, 2004; Mora et al., 2017; Russo et al., 2017) and likely exacerbated further by localized impacts associated with urbanization (Krayenhoff et al., 2018; Li & Bou-Zeid, 2013). Owing to the positive feedback of urban heat islands to
heat wave (Wang, Yan, et al., 2017), severe summer heat waves represent one of the deadliest disasters confronting cities. In addition, urban areas have more aging population and greater economic disparities, which give rise to more adverse health impacts of heat waves (Tan et al., 2010). Therefore, it is beneficial to assess future changes in extreme heat wave events and the associated risk to rapidly urbanizing areas, which is crucial for policy-making regarding urban sustainability.

Historical record-breaking heat waves have been investigated extensively, with attention to their physical drivers, for example, anthropogenic warming (Ma et al., 2017; Stott et al., 2004; Sun et al., 2014), atmospheric circulations (Black et al., 2004; Jézéquel et al., 2018), soil moisture-temperature feedbacks (Fischer et al., 2007; Miralles et al., 2014), and patterns of sea surface temperature anomalies (Chen et al., 2019; Feudale & Shukla, 2007; Wang, Tang, et al., 2017). Given the perceived seriousness of the impact of record-breaking heat waves on human society and natural ecosystems, it is especially important to project the future probability of occurrence of historically unprecedented heat waves. In China, increasing efforts have been devoted to the projections of future changes in different aspects of heat waves, for example, frequency, duration, and intensity (Guo et al., 2017; Sun et al., 2018; Wang et al., 2015, 2019), as well as to the associated population exposure (Huang et al., 2018; Li et al., 2019). However, few studies have focused on the future occurrences of severe heat waves with magnitude greater than historical record-breaking heat events witnessed by densely populated urban areas, primarily because of the lack of appropriate high-resolution observations and climate model projections. Moreover, most previous studies identified heat waves based on daytime high temperatures solely. However, this univariate definition may underestimate or even overlook the change and associated impact of compound heat waves, that is, with both extreme hot daytime and nighttime temperatures (Chen & Li, 2017; Zscheischler et al., 2018). Compared with the daytime-solely heat waves, compound heat waves combine the impacts of consecutive scorching days and sweltering nights, hence aggravate the burden of human thermoregulation and elevate the risk of human health (Kovats & Hajat, 2008). In this sense, historically unprecedented compound heat waves that arise from rare combinations of persistent hot days and hot nights pose the greatest challenge for the society and ecosystems.

A further hindrance for identifying the record-setting heat wave has been the limited robustness of traditional climate indices used to quantify the magnitude of heat waves, which is due to complicated spatiotemporal variations of heat waves. Up to eight heat wave indices have been proposed by the Expert Team on Climate Change Detection and Indices (Alexander et al., 2006; Sillmann et al., 2013), most of which are generally endemic to only the region, sector, or community affected (Perkins & Alexander, 2013). To address this issue, Russo et al. (2014) introduced a new Heat Wave Magnitude Index (HWMI) to facilitate comparison of the spatiotemporal variation of heat wave magnitude. Recognizing the saturation problem of the HWMI in representing heat wave magnitude, Russo et al. (2015) further developed an improved version of the HWMI, that is, the HWMI daily (HWMId), which they used to rank the top 10 European heat waves since 1950. Owing to its objectivity and universality, a growing number of studies have applied the HWMId to evaluate and project changes in the likelihood and magnitude of extreme heat waves (Dobricic et al., 2020; Dosio et al., 2018; Russo et al., 2016, 2019; Smid et al., 2019). However, most of these studies paid primary attention on the role of daytime high temperatures in HWMId. To our best knowledge, there is to date no quantitative study that has been conducted to estimate the magnitude of compound heat waves with HWMId, let alone on urban areas specifically.

In this study, we first categorized the summertime heat waves into three distinct types, that is, independent daytime or nighttime heat waves and compound heat waves. Then, we used the heat wave magnitude metric to identify historical record-breaking compound heat waves that occurred in three vast urban agglomerations in China. We then delineated the probability of occurrence of and areal exposure to historically unprecedented compound heat waves in the future, especially under 1.5°C and 2°C global warming scenarios. Further, we combined the information of future climate change with spatially explicit global population projections to estimate the fractions of land area and population that will be exposed to future unprecedented compound heat waves, under different demographic and climate scenarios.

The remainder of the paper is organized as follows. Section 2 provides the basic information of the study areas, data sources, HWMId, and analysis procedures. Section 3 presents main results, followed by further discussions and conclusion in section 4.
2. Materials and Methods

2.1. Brief Overview of Study Regions

The three vast urban agglomerations, that is, the Beijing-Tianjin-Hebei region (BTH; 114°–119°E, 37°–42°N), the Yangtze River Delta (YRD; 118°–125°E, 28.5°–33.5°N), and the Pearl River Delta (PRD; 111°–116°E, 20°–25°N), are the most developed and populated urban areas in China (see Figure S1 in the supporting information for their geographical ranges as defined in this study). The BTH is located in the North China Plain, including Beijing Municipality, Tianjin Municipality, and Hebei province. The YRD is a triangle-shaped megalopolis that comprises Shanghai Municipality, the provinces of Jiangsu, Zhejiang, and Anhui. The PRD is located in the Guangdong province in South China, which consists of nine large cities, including Guangzhou and Shenzhen. About 113, 154, and 63 million people are living in these three urban agglomerations in 2018, with total land sizes of about 218,000, 212,000, and 55,000 km² and urbanization rates of 65.8%, 67.4%, and 85.3% (National Bureau of Statistics of China, 2019; Yang et al., 2020). These three major urban areas account for more than 40% of China’s gross domestic product in 2018.

2.2. Observations and Projections

This study focuses on summertime (June–August) heat waves. Based on the high-resolution gridded climate observation data set of China (CN05.1), we delineated historical changes in heat waves over three vast urban agglomerations in China and identified record-breaking heat waves. The CN05.1 data set provides daily maximum, minimum, and mean temperatures and precipitation at high spatial resolution (0.25° × 0.25°) covering the period 1961–2015 over the mainland of China (Wu & Gao, 2013). This data set comprises quality-controlled climate records collected from more than 2,400 national meteorological stations in China. Based on an interpolation algorithm used to produce Climatic Research Unit data, the gridded climatology and daily anomaly of the variables contained within the CN05.1 data set were obtained using a thin-plate smoothing spline interpolation technique and an angular distance weighting method, respectively (Wu & Gao, 2013).

For historical simulations and future projections, high-resolution gridded daily maximum and minimum temperatures were obtained from the National Aeronautics and Space Administration’s (NASA’s) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data set (Thrasher et al., 2012, 2013). This data set comprises climate simulations and projections of 21 Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Table S1). A statistical downscaling technique, that is, Bias Correction Spatial Disaggregation, was used to generate the NEX-GDDP data set (Wood et al., 2002, 2004). In detail, this algorithm corrected most of the biases in climate model simulations with respect to climatology, variability, and trend by comparing historical climate simulations with the observations from the Global Meteorological Forcing Data Set developed by Sheffield et al. (2006). These adjusted data were interpolated to a finer resolution using the techniques of spatial disaggregation and observational constraints.

This data set is considered more consistent with realistic observations because most biases in the CMIP5 historical simulations and future projections have been removed by the comparison of historical simulations and observations (Thrasher et al., 2013). This data set includes daily outputs of historical climate simulations for 1950–2005 and future climate projections for 2006–2099 under two representative emission scenarios corresponding to moderate (RCP4.5) and high-end (RCP8.5) global warming at high spatial resolution (0.25° × 0.25°). It has been shown that the spatial patterns of temperature and precipitation extremes in China and its three vast urban agglomerations can be well reproduced by the NEX-GDDP data set (Bao & Wen, 2017; Yu et al., 2018).

We used a new data set of global spatially explicit fine-scale (spatial resolution: 0.125° × 0.125°) population projections at decadal intervals over 2010–2100 (Jones & O’Neill, 2016) to estimate future population exposure to future unprecedented compound heat waves. This data set has five alternative demographic scenarios corresponding to five representative Shared Socioeconomic Pathways (SSPs): SSP1 corresponds to a sustainable pathway representing the “Green Road” that implies low socioeconomic challenges to mitigation of and adaptation to climate change; SSP2 describes a future world following a middle path between SSP1 and SSP3 in terms of the spatial patterns of urbanization, population, and income growths, representing medium socioeconomic challenges to mitigation of and adaptation to climate change; SSP3 represents a pathway of regional rivalry with low international priority for addressing global environmental issues,
leading to high socioeconomic challenges to mitigation of and adaptation to climate change; SSP4 corresponds to a divided pathway with increasing inequality and stratification both across and within countries, implying low (high) socioeconomic challenges to mitigation of (adaptation to) climate change; SSP5 describes a pathway governed by fossil-fueled development with rapid growth of the global economy but high challenges to mitigation of climate change.

Among the various climate change and demographic scenarios of the RCPs and SSPs, we chose to use an integrated scenario of RCP4.5 and SSP1 to represent a future world with relatively low socioeconomic challenges to the mitigation of and adaptation to climate change. We also used a combination of RCP8.5 and SSP3 to frame a world moving toward an intense carbon emission future with high socioeconomic challenges to the mitigation of and adaptation to climate change. These combinations of climate change and demographic scenarios are consistent with the suggestion of van Vuuren and Carter (2014) for reconciling the new climate change scenarios (i.e., SSP) with the old (i.e., RCP). We bilinearly interpolated the historical simulation and future projection data from NEX-GDDP to the grids of CN05.1. We also spatially aggregated the projected size and spatial pattern of the future population according to the observation grids by summing the total population in the grids.

2.3. The Metric of Heat Wave Magnitude

In this study, we used an objective and universal metric to measure the magnitude of heat waves, that is, the HWMId, which comprehensively accounts for the intensity and duration in determining the magnitude and therefore the potential risk of heat waves. According to Russo et al. (2015), the procedure for calculation of the HWMId contains the following steps:

1. We identified a heat wave as a period comprising at least three consecutive hot extremes with daily maximum (Tmax) or minimum (Tmin) temperature exceeding its corresponding historical 90th percentile threshold (T90p). To avoid both the attenuation of the annual cycle of temperature thresholds when using a large moving window and the inhomogeneity in percentile-based indices of hot extremes associated with a fixed reference period (Zhang et al., 2005), the temperature threshold was determined by ranking the 15-day samples surrounding a specific calendar day (i.e., 7 days before and after; reflecting data for 15 × 55 = 825 days) within the entire historical period (i.e., 1961–2015). Hence, for a given day (d), its 90th percentile threshold (T90p) was derived from the data collection (DC) defined by:

\[ DC = \bigcup_{y=1961}^{2015} \bigcup_{i=d-7}^{d+7} T_y . d \]

2. We estimated the interquartile range of annual maximum Tmax or Tmin by the difference between the 25th and 75th percentiles of the yearly maximum Tmax or Tmin within the entire historical period (i.e., T_{x75p} − T_{x25p}).

3. We calculated the daily magnitude (M_d (T_d)) of all the consecutive days that comprise a heat wave as follows:

\[ M_d (T_d) = \begin{cases} \frac{T_d - T_{x25p}}{T_{x75p} - T_{x25p}} & \text{if } T_d > T_{x25p} \\ 0 & \text{if } T_d \leq T_{x25p} \end{cases} \]

4. We tallied up the M_d (T_d) of each heat wave days as the magnitude of a heat wave and defined the HWMId as the annual maximum magnitude of the summertime heat waves that occur in a given year.

With the incorporation of high-resolution observations and climate projections, this heat wave metric addresses a major barrier to comparative analysis of historical record-breaking heat waves and future changes in unprecedented heat waves with magnitude exceeding previous record-setting heat wave events in densely populated urban areas. For the observations, we constructed a regional mean HWMId for three vast urban agglomerations in China by weighting each grid’s HWMId series by the cosine of its central latitude. The record-breaking heat wave for each grid or region was determined as the one with the largest HWMId during 1961–2015. Using the same procedure as adopted for the observations, we calculated the
HWMId for each grid and each year from the historical simulations and future climate projections under the RCP4.5 and RCP8.5 scenarios.

2.4. Definitions of Independent and Compound Heat Waves

We defined independent daytime or nighttime and compound heat waves in summer as follows:

1. Independent daytime heat wave—at least three consecutive hot days without any accompanying hot nights (i.e., $T_{max} > 90th$ percentile and $T_{min} \leq 90th$ percentile). The magnitude of an independent daytime heat wave is calculated as the sum of the daily magnitudes of all the participating hot days.

2. Independent nighttime heat wave—at least three consecutive hot nights without any accompanying hot days (i.e., $T_{min} > 90th$ percentile and $T_{max} \leq 90th$ percentile). The magnitude of an independent nighttime heat wave is computed as the sum of the daily magnitudes of all the participating hot nights.

3. Compound heat wave—at least three consecutive days with simultaneous hot days and hot nights (i.e., $T_{max} > 90th$ percentile and $T_{min} > 90th$ percentile). The magnitude of a compound heat wave is the sum of the daily magnitudes of all the participating hot days and hot nights.

2.5. Areal and Population Exposures to Heat Waves

To reveal the changes in geographical extent of historical heat waves, we calculated the percentage of land areas experiencing a heat wave with an HWMId value within a given interval (i.e., 2–4, 4–6, 6–8, and $\geq 8$) for each year and each region. In detail, we summed the total area of heat wave-affected terrestrial grids, which were weighted by the cosine of their central latitudes. Based on this, we calculated the fraction of land areas exposed to different categories of heat waves with respect to the total land areas of three vast urban agglomerations in China. Using a similar method, we further projected the fraction of future land areas exposed to unprecedented compound heat waves with an HWMId value exceeding historical record-setting compound heat event for a given grid and specific model.

We estimated future population exposures to historically unprecedented compound heat waves by spatially aggregating the population numbers experiencing a compound heat wave with an HWMId value exceeding the historical record-breaking heat event. Given that the population projections were at decadal intervals, we calculated the decadal average of occurrence of future unprecedented compound heat waves for each grid and multiplied it by the population within that grid. Specifically, if a specific grid had no unprecedented compound heat wave over a specific decade, we considered that the population would not be exposed. In contrast, for a specific grid, if up to 10 historically unprecedented compound heat waves were projected for a given decade, the population exposure was considered equal to the population of that grid during that decade.

3. Results

3.1. The Changes of Compound Heat Waves in Three Vast Urban Agglomerations in China

Figure 1 shows the observed annual variations of regional mean HWMId of compound, daytime and nighttime heat waves in three vast urban agglomerations in China during 1961–2015. The magnitudes and their changes for different types of heat waves exhibited quite different characteristics. Compared to independent daytime and nighttime heat waves, the magnitudes of compound heat waves tend to be much larger, especially for the last three decades. For the BTH, the magnitudes of daytime and nighttime heat waves are pretty close. The magnitudes of daytime heat waves tend to be larger than those of nighttime heat waves in the YRD, especially during the early three decades. This situation is the opposite in the PRD.

The magnitudes of summertime compound heat waves have exhibited a general increasing tendency across the three vast urban agglomerations. The BTH and PRD have witnessed sharp increments in the magnitude of compound heat waves after the 1990s, before which compound heat wave was very weak or rare. Among the three urban agglomerations, the magnitudes of compound heat waves in the YRD tend to be larger than those in the BTH and PRD. This may be associated with the stable and abnormal western Pacific subtropical high (WPSH), which was the direct driver of the persistent and strong heat waves in the YRD (Chen et al., 2020).

The most severe heat waves on record in the BTH and YRD as identified by the HWMId were compound heat waves, which occurred in 2010 and 2013, respectively. According to previous literature, the extreme heat wave in July 2010 in the BTH persisted for more than 5 days (Wang et al., 2013) and caused excess...
mortality related to cardiovascular disease in Beijing (Yin & Wang, 2017). The Beijing Meteorological Bureau issued yellow-coded heat alert for this extreme heat wave. From middle-late July to mid-August in 2013, an extremely intense and persistent heat wave swept across a large swath of eastern China, including the populous and economically developed YRD. This severe heat wave caused record-breaking high temperatures in many cities within the YRD, including Shanghai, Hangzhou, and Ningbo (Wang, Yan, et al., 2017; Xia et al., 2016). Previous study suggested that this record-breaking heat wave led to an increase of 168.8% in heat-related illness in Ningbo (Bai et al., 2014). Comparatively, the record-breaking compound heat wave that occurred in 2015 in the PRD is moderate, with the HWMId value a bit smaller than the record-breaking nighttime heat wave that occurred in 1998.

3.2. Observed Changes in Areal Exposure to Different Categories of Heat Waves

The risks of compound heat waves are elevated not only on the increasing frequency and magnitude but also on the changes in areal exposure to different categories of heat waves. Despite strong variability, the fraction of land area experiencing severe and extreme compound heat waves (HWMId > 6) exhibited an upward trend in three vast urban agglomerations in China during 1961–2015 (Figure 2). This result implies that the areas affected by more severe compound heat waves have increased in three vast urban agglomerations in China, which could be associated with increased duration and intensity of compound heat waves due to general global warming (Perkins-Kirkpatrick & Gibson, 2017) and decadal climate variability (Su & Dong, 2019). Particularly notable is the evident difference in HWMId levels between the first and second three decades of 1961–2015, especially for the BTH and PRD.

There was almost no severe or extreme independent daytime heat waves observed in the BTH and PRD during 1961–2015. The affected areas of normal and moderate daytime heat waves first increased and then decreased in these two regions. For the YRD, the land areas exposed to daytime heat waves across the HWMId levels exhibited a decreasing tendency. Specifically, from 1990 onward it is almost impossible to observe extreme daytime heat waves in the YRD. The land areas exposed to normal and moderate nighttime heat waves in the BTH have increased by 2000. Then, the fraction of land areas experiencing normal
nighttime heat waves decreased rapidly in the BTH. By contrast, the areal exposure to normal and moderate nighttime heat waves in the YRD and PRD exhibited an increasing tendency.

Above results clearly suggest a rapid boom of compound heat waves in three vast urban agglomerations in China. The nighttime heat waves also show increasing trends in magnitude and affected areas but at a much smaller rate compared to compound heat waves. Given the dominance of compound heat waves and the perceived severity of above-mentioned record-breaking compound heat waves, in the following sections, we paid major attention to this type of heat waves and projected the occurrence of future unprecedented compound heat events in the three densely populated urban agglomerations.

3.3. Spatial Patterns of the HWMId of Record-Breaking Compound Heat Waves

Figures 3a–3c show the spatial patterns of the HWMId of the record-breaking compound heat waves over three urban agglomerations in China. These record-setting compound heat events are determined by the HWMId as shown in Figure 1. An obvious spatial heterogeneity can be seen in the heat wave magnitudes. For the record-breaking compound heat waves that occurred in the BTH and PRD, the northwest part of the regions witnessed the most severe heat events. However, in the major urban areas of these two regions, the HWMId of the record-breaking heat waves was relatively moderate. This implies that the HWMId of record-breaking heat wave is determined by multiple factors (e.g., the large-scale circulation structure, local climatology, intensity, and duration), which is not necessarily higher in central towns than in surroundings. By contrast, the record-breaking compound heat wave of 2013 in the YRD mainly occurred in the metropolitan areas, exhibiting a signature of urban-induced warming along the cities of Nanjing, Shanghai,
Hangzhou, and Ningbo. This may be partly associated with the dominance of WPSH, that is, stationary anticyclones, and with the positive feedbacks of urban heat islands to extreme heat wave (Wang, Yan, et al., 2017).

We noted that the HWMId of the record-setting compound heat wave in the PRD was lower than the other two urban agglomerations (Figures 1 and 3). To elaborate on the reasons for this, we compared the duration and the daily average magnitude (i.e., $\sum_{d=1}^{\text{duration}} \frac{Md}{\text{duration}}$) of all the consecutive days that comprise the record-breaking compound heat waves in the BTH, YRD, and PRD. As shown in Figure S2, the daily average magnitudes (especially for Tmax) of the record-breaking compound heat wave in the PRD were much smaller than those in the YRD and the BTH. In addition, the durations of the record-breaking compound heat wave in the PRD were relatively shorter than the case in the YRD (Figure S3). As a result, it was postulated that the lower HWMId of the record-breaking compound heat wave in the PRD can largely be ascribed to its small daily average magnitude for Tmax and relatively short duration.

The spatial patterns of the maximum HWMId of compound heat waves on record for each grid were similar to the patterns of record-breaking compound heat waves (Figures 3d–3f). It is reasonable that slight differences existed between them, because the maximum HWMId observed at a specific grid could be either associated with the record-breaking heat wave identified at a regional scale or could be linked to another local severe heat wave that occurred in other year. In the following sections, we projected future occurrence of unprecedented compound heat waves by comparing model-simulated regional mean HWMId with the observed record-breaking heat event, and quantified future areal and population exposures to unprecedented compound heat waves by comparing the model-projected HWMId with the observed maximum HWMId on record as shown in Figures 3d–3f for each grid and each model.
3.4. Future Occurrence of Unprecedented Compound Heat Waves

Figure 4 shows the projected changes in regional mean HWMId of compound heat waves for the three vast urban agglomerations in China. With global warming, all the models showed positive trends in the regional mean HWMId for the RCP4.5 and RCP8.5 scenarios. It implies that the likelihood of more severe compound heat waves will increase and that these three major urban areas will normally (i.e., future multimodel ensemble median HWMId is equal to or higher than the historically maximum regional mean HWMId value) experience unprecedented compound heat waves in the future. Historical record-breaking compound heat waves, such as the 2010 heat wave in the BTH, will become the norm since around 2045 (2060) under the RCP8.5 (RCP4.5) emission scenario (Figure 4a). The super heat wave event of eastern China occurred in 2013, which was identified as the most severe compound heat wave on record in the YRD, will become the norm since around 2045 (2065) under the RCP8.5 (RCP4.5) scenario (Figure 4b). The recent record-breaking compound heat wave in 2015 in the PRD will become the norm in this region after 2030 (2040) under the RCP8.5 (RCP4.5) scenario (Figure 4c). These results suggest that historically unprecedented compound heat waves will occur on a regular basis over all the three vast urban agglomerations in China since the middle of this century under the high-end emission scenario (RCP8.5). These timelines can be postponed by about 15, 20, and 10 years, respectively, under the moderate mitigation scenario (RCP4.5).

The increase in the regional mean HWMId is bound to greater areal exposure to unprecedented compound heat waves in the future. As shown in Figure 5, future projections under the high-end emission scenario (RCP8.5) suggested that the percentage of land area exposed to future unprecedented compound heat waves would increase rapidly in the three vast urban agglomerations in China. For instance, over 50% of the land area will normally experience unprecedented compound heat waves in the BTH, YRD, and PRD by around 2050, 2050, and 2030, respectively. If appropriate mitigation policies are not implemented, almost all the land areas of these three urban agglomerations in China will become normally exposed to future unprecedented compound heat waves by around 2090, 2070, and 2050, respectively. By contrast, if moderate emission mitigation actions are carried out (i.e., RCP4.5), the maximum areal exposure to unprecedented compound heat waves in the BTH and YRD will not reach 100% normally across the 21st century. For the PRD, however, all the land areas will be normally exposed to unprecedented compound heat waves by 2060 even if moderate mitigation policies are implemented.

The Paris Agreement sets a goal to hold the global mean temperature increase well below 2°C relative to pre-industrial levels (1861–1890) and pursue efforts to limit it to 1.5°C. As a result, it is beneficial to assess the probability of occurrence of and areal exposure to unprecedented compound heat waves for different levels of global warming and understand how 0.5°C more warming enhances the associated heat hazards. We calculated the multimodel ensemble mean global mean surface air temperature anomalies (relative to 1861-1890) based on the historical simulations and future projections under RCP4.5 and RCP8.5 scenarios from the climate models identical as those in the NEX-GDDP data set (Table S1). We determined the periods of the 1.5°C and 2°C global warming levels within the 20-year windows that are centered on the years when the global mean surface temperature exceeds respective warming levels (Figure S4 and Table S2). As shown in Figure 6, compared with the Intergovernmental Panel on Climate Change baseline period (1986–2005), the probability of occurrence of and areal exposure to unprecedented compound heat waves in the three urban agglomerations are projected to increase substantially in a 1.5°C and 2°C warmer world. These comparisons suggest a substantial increase in the risk of unprecedented compound heat events between the baseline and 1.5°C and 2°C warming periods. Compared with the results under 2°C warming scenario, the occurrence probability of and areal exposure to historically unprecedented compound heat waves in a 1.5°C warmer world will reduce by more than half in the BTH and YRD. In comparison with these two regions, the occurrence probability and areal exposure in the PRD under 1.5°C warming scenario will decrease by about a third as much as those in a 2°C warmer world.

We noted that the skewness of the multimodel projected occurrence probability of and areal exposure to unprecedented compound heat waves in the YRD is larger than other two urban agglomerations, especially for 2°C warming period. We found that this was associated with remarkably high probabilities projected by a handful of models, such as GFDL-CM3, MIROC-ESM, and MIROC-ESM-CHEM. All of them have remarkably high equilibrium climate sensitivity (Andrews et al., 2012; Forster et al., 2013). In addition, the intensity and duration of summer heat waves in the YRD are dominated by the WPSH. The intermodel spread in the...
Figure 4. Time series of projected regional mean HWMId in the (a) BTH, (b) YRD, and (c) PRD during 2020–2099. Solid green and brown lines denote the multimodel ensemble median projections under the RCP4.5 and RCP8.5 scenarios, respectively. Light green and brown shaded areas enclose the annual interquartile range of the multimodel ensemble for the RCP4.5 and RCP8.5 scenarios, respectively. Horizontal blue line marks the HWMId of record-breaking compound heat wave during the historical era (1961–2015). Vertical dashed green and brown lines locate the years, after which the historically unprecedented compound heat waves occur on a regular basis under the RCP4.5 and RCP8.5 scenarios.
Figure 5. Time series of projected fractions of land area exposed to future unprecedented compound heat waves in the (a) BTH, (b) YRD, and (c) PRD over 2020–2099. Solid green and brown lines denote the multimodel ensemble median projections for the RCP4.5 and RCP8.5 scenarios, respectively. Dashed green and brown lines show their corresponding 11-year running averages. Light green and brown shaded areas enclose the annual interquartile range of the multimodel ensemble for the RCP4.5 and RCP8.5 scenarios, respectively. Horizontal blue line marks the 50% areal exposure, and vertical dashed green and brown lines locate the years, after which the multimodel ensemble median exceeds or reaches a given areal fraction threshold (i.e., 50%) under the RCP4.5 and RCP8.5 scenarios.
response of WPSH to global warming is substantial (Chen et al., 2020), which may further enlarge the model-to-model differences in simulating the occurrence probability of and areal exposure to unprecedented compound heat waves in the YRD.

### 3.5. Population Exposure to Future Unprecedented Compound Heat Waves

Population exposure to future unprecedented compound heat waves was projected to increase substantially in three urban agglomerations in China (Figure 7). The projections under the scenario combining unmitigated emissions (RCP8.5) and rapid population growth (SSP3) suggested that the population exposure to future unprecedented compound heat waves in the BTH and YRD will increase from approximately less than 20 million per year in the 2010s to about 90 million per year by the end of this century (Figures 7a and 7b). For the PRD, the peak population exposure to future unprecedented compound heat waves will occur in the 2050s (Figure 7c), which is mainly attributable to a near 100% areal exposure to unprecedented compound heat waves since the 2050s in this region (Figure 5c). Afterward, with the decreasing tendency in the total population of this region (Figure S5), the population exposure will also decrease during the second half of this century. Under the high-end emission scenario, population increases of approximately 70 (from 18.6 million in the 2010s to 88.0 million in the 2090s), 90 (from 3.8 million in the 2010s to 93.5 million in the 2090s), and 60 (from 13.7 million in the 2010s to 71.4 million in the 2090s) million per year will be exposed to unprecedented compound heat waves by the end of this century (relative to the 2010s) in these three vast urban agglomerations in China.

If future world development were to follow a sustainable green road via moderately mitigated emissions (RCP4.5) and low population growth (SSP1), the BTH and YRD would still be expected to witness an increase in population exposure to historically unprecedented compound heat waves of approximately 30–40 million per year by the end of this century, which is much less than that under the high-end
emission scenario. In contrast, this moderate-mitigation scenario cannot substantially reduce the population exposure to future unprecedented compound heat waves in the PRD in comparison with the unsustainable climate and demographic scenarios (i.e., RCP8.5 and SSP3).

We note that the total population of the three vast urban agglomerations in China is projected to increase before the 2030s/2040s and to decrease sharply thereafter in all SSPs (Figure S5). However, the timings of the maximum urban population in these three urban regions lag the total population by approximately 20 years. This difference supports the continual growth in urban population exposure to future unprecedented compound heat waves throughout this century in the three vast urban agglomerations in China, as is evident from the spatial patterns of population exposure increase from the 2010s to the 2090s (Figure 8). Future great increases in population exposure will be clustered in highly urbanized and populated areas in the three vast urban agglomerations in China, such as the cities of Beijing, Shanghai, Guangzhou, and Shenzhen, which highlights the urgent need for more effective urban adaptation strategies to be adopted for the cities.

4. Discussion and Conclusions

In this study, we categorized the summertime heat waves into three distinct types, that is, independent daytime or nighttime heat waves and compound heat waves. We applied an objective and universal metric of heat wave magnitude (HWMId) to multiple data sets of high-resolution observations and multimodel simulations and projections. We found remarkable increases in the magnitudes of and areal exposures to compound heat waves over recent decades in the three vast urban agglomerations in China. We identified historical record-breaking compound heat waves with the largest magnitude at regional scale, which were well documented in previous literatures. We further quantified the areal and population exposures to future unprecedented compound heat waves with magnitude exceeding the most severe compound heat events on record in the three urban agglomerations in China. We found that future unprecedented compound heat waves will become the norm since around 2045 (2060), 2045 (2065), and 2030 (2040) under the RCP8.5 (RCP4.5) emission scenario in the BTH, YRD, and PRD, respectively.

It is important to note that the “new norm” of historically unprecedented compound heat waves will appear first in the PRD, followed by the BTH and the YRD. Future compound heat waves will have the fastest growth rate in magnitude in the PRD. The BTH, YRD, and PRD are located in midlatitudes, subtropical, and tropical regions, respectively. Due to relatively small temperature variability in tropical regions (e.g., PRD), even a moderate warming will lead to longer-duration heat waves in future (Dosio et al., 2018; Fischer et al., 2012). In contrast, in midlatitudes (e.g., BTH), where the synoptic variability of the temperatures is large, future temperature may be hard to exceed the historical percentile thresholds persistently, even with a more remarkable warming trend. In addition, as shown in Figure S6, due to small temperature variability, the interquartile ranges of annual maximum Tmax or Tmin (i.e., T_{x75p} − T_{x25p}) are much smaller.
in the PRD than those in the YRD and BTH. According to the definition of HWMId, smaller interquartile range of yearly maximum Tmax or Tmin would result in more remarkable increase in HWMId. As a result, we considered that the geographical variations in growth rates of future compound heat wave magnitudes among the three vast urban agglomerations in China are mainly associated with the regional disparities in summertime temperature variability. As shown in Figure S7, we found that the number of compound heat wave days will have the greatest increase, which means that compound heat waves will become the most common type over three vast urban agglomerations in China. In addition, the increasing rate of future compound heat wave days in the PRD will be much larger in comparison to the BTH and the YRD. All these results imply that the PRD will become a hot spot region of particular concern, which requires the implementation of timely and effective urban adaptation strategies against compound heat waves in particular.

The importance of limiting global warming to the 1.5°C Paris Agreement target is apparent when considering the increasing compound heat hazards over the major urban areas in China. The probability of occurrence of and areal exposure to historically unprecedented compound heat waves in the BTH and YRD will nearly double under 2°C warming scenario compared to 1.5°C warming level. By comparing projections under two combinations of climate and demographic scenarios, we found that significant fractions of areal and population exposures to future unprecedented compound heat waves could be reduced by taking sustainable green pathway with moderately mitigated emissions and low population growth. This would be particularly evident in the BTH and YRD. The maximum areal exposure to future unprecedented compound heat waves in the BTH and YRD under the RCP4.5 scenario will be no greater than 100% throughout

Figure 8. Spatial patterns of multimodel ensemble median changes in population exposure to unprecedented compound heat waves (the 2090s minus the 2010s) in the (a, d) BTH, (b, e) YRD, and (c, f) PRD for the integrated scenarios of RCP4.5 and SSP1 and RCP8.5 and SSP3, respectively.
the remainder of this century. This represents a critical time frame available for the design and implementation of effective urban adaptation actions in newly emerging metropolitan areas in these two urban agglomerations, such as the Xiong’an New Area in the BTH that is currently under construction.

Although this study focused only on the three vast urban agglomerations in China, the findings provide new insights into the spatiotemporal quantification of future changes in unprecedented compound heat waves, which could have broad implication regarding assessment of risk faced by urban areas throughout the world in relation to future extreme heat events. Some limitations of this study should be recognized. First, this study focused on the daytime-nighttime compound heat waves, which does not fully take into account the additively compounding effect of humidity on the magnitude of heat waves. One of the reasons is the lack of universal metric of heat wave magnitude that accounts for the combined effect of heat and humidity, although a few recent studies have drawn attention to the so-called humid heat waves in China (Freychet et al., 2020). In addition, there is no humidity data in the high-resolution observations and the NEX-GDDP data set. Further studies are needed to develop a new metric of heat wave magnitude that accounts for the additive impacts of heat and humidity. Second, despite the strengths of the NEX-GDDP data set in terms of its high spatial resolution and bias correction, all data in this data set were based on the outputs of CMIP5 climate models. Performing additional analyses with CMIP6 model outputs may provide some new findings. However, the spatial resolutions in most CMIP6 models are around or above 1°, which are too coarse to represent the spatial patterns of temperature extremes in the three urban agglomerations in China. Moreover, it was suggested that equilibrium climate sensitivity has increased substantially in most CMIP6 models (Zelinka et al., 2020). The plausibility of a higher climate sensitivity needs to be further verified. Third, urbanization-induced warming has not been explicitly resolved in the NEX-GDDP projections. Future urban development could further increase the magnitude of compound heat waves via enhanced urban heat island effects (Argüeso et al., 2014; Georgescu et al., 2013). In this sense, we reported only a conservative estimate of the increasing risk of unprecedented compound heat waves in the three vast urban agglomerations in China. Fine-resolution numerical modeling studies are required to fully take into account the warming effect of urbanization on the changing magnitude of compound heat waves in the rapidly developing urban areas.

In summary, in terms of hazards and areal and population exposures, our results suggest that future risks of unprecedented compound heat waves in the three most populous urban agglomerations in China will increase rapidly due to anthropogenic climate change. These increasing heat hazards pose challenges to the health, well-being, and livelihood of urban residents, not only in China but also in many other countries. Given that the cities are the major source of global greenhouse gas emissions and the biggest user of global energy, our findings underline the responsibility of the cities to undertake emission reduction commitments by implementing sustainable climate and energy action plans, which in turn can reduce the climate hazards in the urban areas where more than half of the global population live.

Data Availability Statement

Accesses to all the data sets are as follows: the NEX_GDDP data set can be downloaded from https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp website. The spatially explicit global population projection data are available online (https://sedac.ciesin.columbia.edu/data/set/popdynamics-pop-projection-ssp-2010-2100/data-download). The CN05.1 data set is available from the data producer upon reasonable request.

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