### Investigating the urban heat and cool island effects during extreme heat events in high-density cities: A case study of Hong Kong from 2000 to 2018

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#### Abstract

Urban heat island (UHI) and cool island (UCI) effects are well-known and prevalent in cities worldwide. An increasing trend of extreme heat events has been observed over the last few decades and is expected to continue in the foreseeable future. In this study, warm periods (May to September) of 2000–2018 were examined to acquire a comprehensive understanding of the UHI and UCI characteristics for the case study of Hong Kong, China. Twenty-two weather stations in Hong Kong were classified into four categories, namely urban, urban oasis, suburban, and rural, with reference to the local climate zone (LCZ) scheme, to analyze UHI and UCI phenomena during extreme heat and non-extreme heat situations. One representative type of extreme heat events was considered in this study: three consecutive hot nights with two very hot days in between (2D3N). Results show that both the UHI and UCI effects are exacerbated during extreme heat events. Using the concept of the UHI degree hours (UHIdh) and UCI degree hours (UCIdh), their spatial patterns in Hong Kong during extreme heat and non-extreme heat situations were mapped based on multiple linear regression models. It is found that the predictor variable - windward/leeward index is a significant influential factor of both UHIdh and UCIdh during extreme heat events. The resulting UHIdh and UCIdh maps not only enhance our understanding on the spatial pattern and characteristics of the UHI and UCI during extreme heat events, but could also serve as a

Abbreviations: 2D3N, three consecutive HNs with two HDs in between; EH, extreme heat (EH) event; HD, very hot day; HDHN, when both HD and HN happen on the same day; HN, hot night; LCZ, local climate zone; MLR, multiple linear regression; non2D3N, normal summer days without 2D3N events; non-EH, non-extreme heat (non-EH) event; nonHD/HN, normal summer days without any individual HDs, HNs and their combinations; UCI, urban cool island; UCIdh, UCI degree hours; UHI, urban heat island; UHIdh, UHI degree hours.

useful reference in climate change adaptation, heat-health risk detection, cooling-energy estimation and policy making.

#### **KEYWORDS**

extreme heat events, heat waves, high-density cities, observational weather data, urban cool island, urban heat island

### **1** | INTRODUCTION

Urban temperatures at the micro-scale can be influenced not only by synoptic and meso-scale weather conditions (Morris and Simmonds, 2000; Brazel et al., 2007) but also by the land use/land cover of the area and its surrounding environment (Oke, 1973; Oke et al., 1991; Coutts et al., 2007; Rogers et al., 2019). The urban heat island (UHI) is one of the most well-known urban climate phenomena which describes the on average higher temperatures experienced in downtown areas than in rural areas, especially under clear sky and calm wind conditions (Oke, 1973; Oke, 1982). A negative UHI, known as an urban cool island (UCI), may also occur in the early daytime after a nocturnal UHI (Morris and Simmonds, 2000; Erell and Williamson, 2007; Haashemi et al., 2016; Rasul et al., 2017; Yang et al., 2017). Both UHI and UCI effects have been widely observed and reported in the literature. Oke (1982) provided a detailed discussion and explanation of UHI genesis and development. Many research studies have been conducted in hundreds of cities to examine this urban-rural air (or surface) temperature anomaly and measure the UHI magnitudes, the majority of which have been conducted on calm and clear (or less cloudy) nights (e.g., Oke, 1973; Stewart, 2011). Because the main causes of the UHI relate to the differences in surface structure and land cover, Stewart and Oke (2012) developed a new classification scheme called local climate zones (LCZ), based on the surface structure (height and spacing of buildings and plants) and surface cover (pervious or impervious). It was developed to refine the UHI assessment and enable a cross-comparison of UHI studies among cities worldwide. The LCZ scheme includes ten 'built' and seven 'natural' types (LCZ) (Stewart and Oke, 2012).

As a result of climate change, an increasing trend of extreme heat (EH) events has been observed over the last few decades worldwide (HKO, 2015; Luo and Lau, 2017; Ortiz *et al.*, 2019; Ramamurthy *et al.*, 2017; Ramamurthy and Bou-Zeid, 2017; Rogers *et al.*, 2019) and is expected to continue in the near future and threaten people's lives by increasing heat-related mortality and morbidity (Goggins *et al.*, 2012; Wang *et al.*, 2019). Such impacts on health are amplified in urban areas, as an increasing

number of people is living in cities and due to the UHI effect (Heaviside et al., 2017). Approximately 60% of the world's population currently lives in cities. According to the UN's recent projection on future urban population, this percentage is increasing, and more high-density megacities are expected in the next 20-30 years (UN, 2018). The UHI can also interact with the more frequently occurring EH events, as some studies have shown that UHIs are enhanced during EH events (Li et al., 2016; Rogers et al., 2019). Recent studies show that citizens, especially senior citizens, are more vulnerable to EH than villagers because they could experience greater heat health risks, particularly from heat exposure due to the UHI effect (Goggins et al., 2012; Heaviside et al., 2017). However, little is known about the UHI mechanism and how the UCI effects behave under EH events in high-density cities. This critical knowledge gap is worth investigating thoroughly.

Several modelling and observational studies have demonstrated interactions between UHIs and heat waves (Li and Bou-Zeid, 2013; Li et al., 2015; Ramamurthy et al., 2017; Ramamurthy and Bou-Zeid, 2017; Zhao et al., 2018). Modelling studies typically explore only one or a few specific extreme events owing to limitations in computational resources and their modelling set-up. However, since there are few cities with intensive weather station networks that obtain long-term measurements, it is usually difficult to gain a comprehensive and spatial understanding of UHIs during EH events. Researchers can only rely on observational records from one pair of representative urban and rural stations or very few weather stations. Hence, some factors that may influence the UHI and UCI, such as urban form, urban greenery, and natural landscape information, may not be easily considered in their studies (Rogers et al., 2019). In addition, the metadata and information of the station surroundings are often not available. Therefore, it is difficult to cross-compare their study results. Furthermore, different analysis methods and event definitions may result in seemingly contradictory results for the UHI during EH events. While some studies reported an intensified UHI effect (Li et al., 2015; Founda and Santamouris, 2017; Ramamurthy and Bou-Zeid, 2017; Zhao et al., 2018; Fenner et al., 2019; Jiang et al., 2019),

some have observed an unchanged or even reduced UHI effect (Zhou and Shepherd, 2010; Scott *et al.*, 2018; Rogers *et al.*, 2019).

The purpose of this study is to obtain a comprehensive understanding of the UHI and UCI under EH events in high-density cities based on observational weather data. The main research questions are whether the UHI and the UCI would be exacerbated during EH events and how much (in degrees) and for how long (in hours) the urban temperature varies during these events. The city of Hong Kong, China, was selected as the case study. First, weather stations of the Hong Kong Observatory, the meteorological authority of Hong Kong, were classified into four categories, namely urban, urban oasis, suburban, and rural, rather than the traditional urban-rural station types. Long-term observational records from one representative station in each category were then used to analyse the UHI and UCI phenomena during EH and non-extreme heat (non-EH) events. Environmental factors, including wind speed and wind direction, were also considered in the analysis. Finally, the spatial pattern of the UHI degree hours (UHIdh) and UCI degree hours (UCIdh) in Hong Kong during EH and non-EH situations were mapped based on multiple linear regression (MLR) models.

### 2 | METHODS

### 2.1 | Study area

Hong Kong is located on the coast of southern China and is surrounded by the South China Sea on all sides except the north. It is known as a high-density city, given its high population density and heavily developed downtown areas. Its current urban population density is approximately 6,000 people/km<sup>2</sup>, while for some extremely dense districts, the population density could reach 15,000 people/km<sup>2</sup> (Census and Statistics Department, 2019). Most downtown areas of Hong Kong are characterised by high-density high-rise buildings and deep street canyons. In these areas, the average building height is approximately 60 m, and the heightto-width ratio (H/W ratio) of the street can be as high as 4. In Hong Kong, urban areas occupy less than a quarter of the total land area; a large area of greenery and forests have been protected in country parks which make up about 40% of the total land area (Hong Kong Gov, 2019). Hong Kong has a subtropical climate characterised by hot and humid summers and relatively mild winters. Affected by global climate change and local urbanisation, Hong Kong has experienced a significant long-term warming trend in the last century, with

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more severe and frequent extreme high temperature events (Wong *et al.*, 2011). Future projections also suggest an even warmer climate and more frequent occurrence of extreme temperatures ahead (HKO, 2015). The UHI effect in Hong Kong has received much attention from both local government and design practitioners (HKGBC, 2018). However, a traditional way of assessing the UHI and UCI using urban-rural temperature anomalies may not be able to fully capture the complex effects of urbanisation due to the different urban morphologies and natural landscapes. There has also been a general deficiency in the investigation of the UHI and UCI during EH events, as well as the quantification of related heat health risks, due to the lack of long-term multistation measurements.

### 2.2 | Field observations in Hong Kong

In Hong Kong, the Hong Kong Observatory has made various meteorological measurements (such as temperature, rainfall, pressure, and relative humidity) at its headquarters in the Tsim Sha Tsui area, the heart of the Kowloon Peninsula, since 1884. The advent of the automatic weather station network since the mid-1980s has further expanded the areal coverage and enhanced the temporal resolution of meteorological observations in different parts of Hong Kong (Lee, 2016; Lee *et al.*, 2018). In this study, among over 50 staffed and automatic weather stations with air temperature measurements (Figure 1a), 22 weather stations were selected based on the following four criteria:

- Have sufficiently long data records covering the whole study period from 2000;
- Include air temperature measurements for the quantification of UHI/UCI;
- They are located within 100 m of the mean sea level, so that altitude-induced temperature variations can be avoided.
- They are situated on the ground and not on top of building structures, as rooftops may be subjected to different wind flow regimes and temperature gradients (WMO, 2008).

Although fulfilling the above criteria, the station at the Hong Kong International Airport was also excluded from the study because of its unique station environment on a paved artificial island and proximity to heavy air traffic.

Hourly measurements of air temperature (at approximately 1 m from the ground) and surface wind (at 8–42 m from the ground, available at 16 of the selected stations)



**FIGURE 1** (a) Locations and classification of the weather stations of the Hong Kong Observatory. The map uses a Transverse Mercator projection. Stations having considerable influences by the sea are marked with double asterisks in their labels (e.g., WGL\*\*). (b) GIS-based local climate zone (LCZ) map of Hong Kong (Wang *et al.*, 2018) [Colour figure can be viewed at wileyonlinelibrary.com]

were obtained for subsequent analyses. To facilitate the classification of stations (described in Section 2.3), a comprehensive understanding of the station environments in terms of surface cover fractions, vegetation characteristics, and urban geometry was acquired by assimilating administrative building data, land use maps, and satellite images in a Geographic Information System (GIS) (Kwok *et al.*, 2020).

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### 2.3 | Classification of weather stations

Weather stations are often grouped into classes, such as 'urban' or 'rural', for conducting systematic climate analyses and quantifying the UHI. Previous local studies have classified the weather stations of the Hong Kong Observatory according to their surrounding environments (Siu and Hart, 2013), populations (Lau and Ng, 2013), and their characteristics in daily temperature cycles (Mok et al., 2011). In this study, the classification of stations was based on the LCZ scheme (Stewart and Oke, 2012). Because of the highly heterogeneous surface covers around each station, and the fact that physical processes occur at different scales and thus have different 'circle of influences', the surface cover and geometric properties were first calculated for each of the selected stations at four buffer diameters: 100, 250, 500, and 1,000 m. With reference to the standard look-up table (Stewart and Oke, 2012), the corresponding LCZs were assigned to describe the surrounding environments of the stations (see part 1 of Supporting Information). Note that this LCZ classification is based only on the immediate environment of the stations. The stations were then classified into four categories (Figure 1a): urban (built-type LCZs for all four buffers), urban oasis (LCZ changes from

land cover type to build type as the buffer increases), suburban (land cover type LCZs for a majority of buffers), and rural (land cover type LCZs for all four buffers). In addition to the commonly used urban, suburban, and rural categories, an urban oasis category was added to consider the full spectrum of station environments present in Hong Kong, where stations are often set up in open and vegetated parks within the city. Finally, to allow a simpler and clearer presentation of the UHI analysis during EH situations, one representative station was chosen for each category, as shown in Figure 2 and Table 1. The four stations are the Hong Kong Observatory Headquarters (HKO), King's Park Meteorological Station (KP), Tseung Kwan O (JKB), and Tsak Yue Wu (TYW), which represent the urban, urban oasis, suburban, and rural classifications, respectively. These stations also measure a full range of meteorological variables and are likely to be free from direct climatic influences by the sea. The representativeness of HKO as an urban station and TYW as a rural station has been supported by previous UHI studies (Memon et al., 2009; Mok et al., 2011; Siu and Hart, 2013). To provide an overall description of the heterogeneous land cover and complex urban morphology of Hong Kong, as well as to facilitate the understanding of the subsequent analyses in this paper, the



### environments within the four buffers of the representative weather stations: (a) HKO – urban, (b) KP – urban oasis, (c) JKB – suburban, and (d) TYW – rural. Dash lines are different buffer diameters, within which the LCZ listed in Table 1 was determined (image source: Google Earth) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Station

Local climate zone for each buffer diameter					
100 m	250 m	500 m	1,000 m		
5 – Open mid-rise	4 – Open high-rise	1 – Compact high-rise	4 – Open high-rise		
D – Low plants	D – Low plants	4 – Open high-rise	4 – Open high-rise		
A – Dense trees	9 – Sparsely built	A – Dense trees	D – Low plants		
D – Low plants	A – Dense trees	A – Dense trees	A – Dense trees		
	Local climate zone for each of the second se	Local climate zone for each buffer diameter100 m250 m5 - Open mid-rise4 - Open high-riseD - Low plantsD - Low plantsA - Dense trees9 - Sparsely builtD - Low plantsA - Dense trees	Local climate zone for each buffer diameter100 m250 m500 m5 - Open mid-rise4 - Open high-rise1 - Compact high-riseD - Low plantsD - Low plants4 - Open high-riseA - Dense trees9 - Sparsely builtA - Dense treesD - Low plantsA - Dense treesA - Dense trees		

GIS-based LCZ map of Hong Kong with a resolution of 100 m (Wang *et al.*, 2018) is shown in Figure 1b.

### 2.4 | Extreme heat events in Hong Kong

In Hong Kong, EH events are also referred to as extreme hot weather events, which are mainly described by two key metrics adopted by the Hong Kong Observatory, namely 'very hot day' (HD) and 'hot night' (HN). According to the definition of the observatory, an HD has a daily maximum temperature higher than 33°C, while an HN has a daily minimum temperature higher than 28°C at the HKO station (HKO, 2019).

### 2.4.1 | Defined extreme heat events and non-extreme heat events

In this study, hourly weather records were used, and the numbers of HD and HN were identified based on the hourly temperature dataset from the HKO station. While using the hourly data instead of daily maximum/ minimum temperature data in counting HD/HN will result in a bit more HN and less HD because of data resolution issues, the inter-annual variations and overall longterm trends of HD/HN of these two counting approaches are generally in line with each other (not shown).

In a previous study, Wang *et al.* (2019) examined the association between mortality risk and extreme hot weather events in Hong Kong. They found the strongest association for EH events characterised as three consecutive HNs with two HDs in between (2D3N). Thus, the 2D3N combination, containing at least 72 hr of extreme hot weather, was adopted as the representative EH event in this study, given its significant heat-health impact.

After identifying the EH events (2D3N) in the summer season (May–September), there are still some single HDs and HNs in the so-called non2D3N dataset. Hence, to measure the pure normal summer weather conditions, the nonHD/HN were identified by eliminating all individual HDs and HNs from May to September. NonHD/ HN was used as the non-EH event in this study. Based on hourly observations from the HKO station, there were 21 2D3N events during the study period. A total of 78 days were identified as 2D3N days, that is, EH days, from the HKO data for the study period. The remaining 2,829 days were considered non2D3N days. Single HD and HN days were then excluded to obtain pure nonHD/ HN measurements, giving 2,271 days of non-EH events for the study period.

The inter-annual variations in UHI/UCI intensities during EH and non-EH events were further studied in Section 3.4, and the temporal evolution of UHI/UCI during both events was further investigated. As such 2D3N events cannot be found in some years, another type of EH event, HDHN which means both HD and HN occur on the same day, were used to compare against non-EH events (nonHD/ HN). Note that HDHN was only used in Section 3.4 to represent EH events due to the unavailability of 2D3N events for some years and generally represents EH weather conditions. Our results further show that the variations of UHI/UCI are very similar between 2D3N and HDHN, and between non2D3N and nonHD/HN (e.g., Figure 4 and Figure S3.1). Thus, the manuscript mainly presents and examines the defined EH (i.e., 2D3N) and non-EH (i.e., nonHD/HN) events. Other results for non2D3N and HDHN are shown in the Supporting Information.

### 2.4.2 | Study period

To determine the study period, the number of HD, HN, and EH days was first calculated from 1971 to 2018 (Figure 3). Linear trends were estimated based on the ordinary least squares method. Both HD and HN showed increasing trends over the past ~50 years, with the number of HN days increasing faster than on HD days. The linear trend of HN days was 0.56 days per year (p < .01), which nearly doubled that of HD days at 0.29 days (p < .01) from 1971 to 2018. However, after 2000, there has been a further rise in the rate of increase in the trends of HD and HN, especially for HDs which increased from around 5 days per year to more than

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FIGURE 3 Annual statistics of (a) very hot day (HD) and hot night (HN); (b) EH event days in Hong Kong [Colour figure can be viewed at wileyonlinelibrary.com]



**FIGURE 4** The average diurnal temperature profiles of the four selected stations for (a) EH, (b) non-EH and (c) the hourly temperature difference between EH and non-EH ( $\Delta T_{\text{EH-nonEH}}$ ) [Colour figure can be viewed at wileyonlinelibrary.com]

20 days per year. The linear trend of HD days is 1.23 days per year (p < .01) from 2000 to 2018, slightly higher than that of HN at 1.02 days per year (p < .01). The dramatic change in HD and HN also promoted the occurrence of EH events, which became more frequent after 2000. The increasing trend of EH days was 0.64 days per year (p < .01) from 2000 to 2018. Hence, this study focuses on the 18-year period between 2000 and 2018, where there is an adequate number of both weather stations in use and the appearance of EH events.

### 2.5 | UHI and UCI calculation

As HD and HN are mostly observed from May to September in Hong Kong (Chan *et al.*, 2012), the hourly data from May to September from 2000 to 2018 were used

to analyse the UHI and UCI effects during EH and non-EH events.

Data from the 22 selected stations with hourly measurements from the year 2000 were examined, and four representative stations (Table 1) were used to analyse the typical diurnal temperature profiles and quantify the UHI for different station categories. The diurnal cycle of UHIs in urban (HKO), urban oasis (KP), and suburban (JKB) stations were calculated against the rural (TYW) station. The average diurnal temperature profiles, the absolute values of UCI/UHI degree hours (cf. next section), and warming/cooling rate were calculated accordingly. To further investigate the evolution of UCI/UHI during the EH events, the hourly temperature profiles of the first 72 hr during the EH events were also computed for the four representative stations. The results are presented in Section 3.

# 2.6 | Mapping UHI and UCI degree hours

In this section, spatial mapping was conducted to understand the spatial patterns of UHI and UCI during EH and non-EH events in Hong Kong. Using the data in the period of 2000 to 2018 at 22 stations described in Section 2.3 and 2.5, both the urban heat island degree hours (UHIdh) and urban cool island degree hours (UCIdh) under EH and non-EH scenarios were calculated (Yang *et al.*, 2017). The unit of the UCIdh and UHIdh is °C h.  $\Delta T_{r-u}(t)$  is the temperature difference between the rural and urban air temperatures at time *t*. The UCIdh and UHIdh of a day can be defined as

$$UCIdh = \int_{\min(\Delta T_{r-u} \ge 0)}^{\max(\Delta T_{r-u} \ge 0)} \Delta T_{r-u}(t)dt$$
$$UHIdh = \int_{0}^{24} |\Delta T_{r-u}(t)| dt - UCIdh$$

Spatial mapping aims to investigate the variation in UHIdh and UCIdh among locations. To quantify the relative difference between stations, air temperature data from a representative rural station, TYW (mentioned in Section 2.3), was used as the rural baseline for the UHIdh and UCIdh calculations for all 22 stations. Land use regression (LUR) - a buffering analysis and regressionbased spatial mapping technique was adopted to generate spatial maps of UCIdh and UHIdh in a GIS. Previously, this technique was used in the UHI spatial investigation (Shi et al., 2018) and the estimation of the spatial variability of extreme hot weather conditions in Hong Kong (Shi et al., 2019a). Briefly, a group of urban morphological parameters (Shi et al., 2017) and landscape metrics (Shi et al., 2019b) were calculated based on building data (Kwok et al., 2020) and LCZ map of Hong Kong (Wang et al., 2018) using four buffer diameters (100, 250, 500, and 1,000 m which are consistent with the classification of weather stations in Section 2.3). The calculated data were used as candidate predictor variables for the four response variables (UCIdh and UHIdh under the EH and non-EH scenarios). Corresponding MLR models were developed. The detailed methodology of this geospatial mapping technique and regression modelling is explained in the third part of the supporting information. As a result, spatial data layers were generated based on the above mean regression models by overlaying geospatial layers of predictor variables in GIS. The data were aggregated at the tertiary planning unit (TPU, a spatial unit in the urban planning system of Hong Kong) level to generate the final spatial maps. The results of the

EH and non-EH are shown in Section 3.6, while the results of non2D3N and HDHN are shown in part 3 of the Supporting Information.

# 2.7 | Relationship between UHI and wind speed/direction

The potential relationships between UHI intensity and wind speed were derived using a statistical analysis examining *p*-values, and Pearson correlation coefficient R between averaged hourly UHI intensity and wind speed over the study period under EH and non-EH events at each of the three non-rural stations for both daytime (07:00-18:00 Local Time, UTC + 8) and nighttime (19:00-06:00 Local Time, UTC + 8). In addition, frequency-distribution analysis and mean wind-direction calculations were performed on the dataset to delineate the prevailing wind direction under the EH and non-EH events (see Section 3.5, the results under HDHN and non2D3N can be found in part 4 of Supporting Information).

### 3 | RESULTS AND ANALYSIS

#### 3.1 | Diurnal temperature profiles

The diurnal temperature profiles of the four representative stations during EH and non-EH events were examined (Figure 4). Despite the differences in magnitude, the temperature profiles for the different scenarios showed similar patterns. During the day, the temperature was the highest at the rural station, while during the night, the temperature was the lowest at the rural station. Such profiles form a strong daytime UCI and nighttime UHI in the urban areas of Hong Kong, which will be further described in Section 3.2. It is obvious that the temperature profiles are higher overall for EH days than for non-EH days (Figure 4a,b).

The difference in the diurnal temperature profiles between EH and non-EH events was further computed to quantify the temperature anomalies during EH events (Figure 4c). During the daytime, the increase in temperature (around  $4^{\circ}$ C) during EH events is the largest for the suburban station JKB. The increase in temperature during EH events for the rural station TYW was also higher than that of the urban (i.e., HKO) and urban-oasis (KP) stations. The change in the daytime temperature was the lowest for the KP station, which was slightly lower than that of the HKO station. However, during the night, the increase in temperature at the rural station was very subtle. The amplitude of the temperature increase for the other three 'urban' stations is comparable, all around 2°C. In summary, the temperature rise during the EH events was higher in the day than in the night, and the rural and suburban stations showed the largest temperature increase during the day.

# 3.2 | UHI between extreme heat and non-extreme heat events

The analysis of diurnal temperature profiles suggests different temperature variations during EH events between stations with different environmental characteristics, which resulted in distinct UHI profiles during EH events (Figure 5a,b). Generally, during the EH events, both the daytime UCI and nocturnal UHI were stronger than those of the non-EH days. The daytime UCI at the urban station HKO and urban-oasis station KP are both magnified as the daytime warming rate at the rural station is much larger in the EH days (Figure 5c,d). However, the suburban station JKB shows a slightly smaller daytime UCI, as the warming rate of this station is also higher during the EH days. The daytime UCI in HKO is similar to KP during EH days and larger than KP during non-EH days.

As the temperature differences vary throughout the day, the degree hour approach (Yang *et al.*, 2017) was also used here to describe the UCI and UHI quantitatively (Table 2). The nocturnal UHI shows a similar pattern such that the highest UHIdh is found for the urban station and the lowest for the suburban station. The UHIdh during EH events for all three stations increased by more than 50% compared to that during non-EH days, with the largest increment of more than 100% for the suburban station.



**FIGURE 5** The diurnal UHI profiles of the 3 representative stations for (a) EH, (b) non-EH, and the warming/cooling rate of the 4 representative stations (c) EH and (d) non-EH periods [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 The averaged UHI and UCI degree hours (UHIdh, UCIdh) during EH and non-EH days

Event types	Degree hours	Urban (HKO)	Urban-oasis (KP)	Sub-urban (JKB)
EH	UHIdh (°C h)	49.47	39.96	28.12
	UCIdh (°C h)	7.29	7.28	2.46
Non-EH	UHIdh (°C h)	28.42	20.56	11.43
	UCIdh (°C h)	4.09	3.04	4.39



**FIGURE 6** 72-hour temperature profiles of the 4 selected weather stations (a) and the calculated UHI and UCI (b) [Colour figure can be viewed at wileyonlinelibrary.com]

In summary, the results show a strengthened daytime UCI and nocturnal UHI in the urban and urban oasis stations. For the suburban station, the nocturnal UHI was much stronger during EH days than during non-EH days. However, unlike the other two stations, the daytime UCI is slightly smaller in the JKB during EH events.

# 3.3 | 72-Hour evolution of UHI during the EH events

To further investigate the evolution of the UHI during the EH events, the 72-hour temperature profiles were analysed to demonstrate the change in UHI along with the development of EH events (Figure 6). This shows a warming trend throughout EH events. Taking the second day as an example, the daytime temperatures were higher than the previous day for all four stations (Figure 6a). The magnitude of warming was similar during the day, so the daytime UCI remained similar for the three consecutive days (Figure 6b). However, the nighttime temperatures at the rural stations for the 48th to 54th hour were cooler than the previous day, while the other three 'urban' stations were higher. This results in a growing nocturnal UHI throughout these EH events.

### 3.4 | UHI and UCI intensity changes over the study period

The temporal evolution of the differences in UHI/UCI intensities during EH and non-EH days, as indicated by HDHN and nonHD/HN, was further examined over the study period. The HKO and TYW stations are referred to as urban and rural stations, respectively. As described in the previous section, it is observed that the daytime temperature is cooler at the urban station HKO than at the rural station TYW. This negative temperature difference between the HKO and TYW stations was quantified by the UCI intensity in Figure 7b. Similarly, the positive temperature difference at night was quantified by the UHI intensity, as shown in Figure 10a. The averaged, along the 10th and 90th percentiles, UHI intensity, are



**FIGURE 7** Annual result of UHI intensity (a) and UCI intensity (b) under HDHN and nonHD/HN periods, and the yearly differences in both UHI and UCI intensity between HDHN and nonHD/HN (c) over 2000–2018. Shadings in (a) and (b) are 10–90% intervals of the data [Colour figure can be viewed at wileyonlinelibrary.com]

compared here (Figure 7a,b). The differences in both UHI and UCI intensity between EH and non-EH are becoming smaller, especially for the UCI trend (Figure 7c). This finding shows that an intensified warming trend could be found in the urban area of Hong Kong, as the temperature variations in non-EH days are closer to EH days. This echoes the results of the Hong Kong Observatory (HKO, 2015). Potentially, such changes may cause higher heat stress and more heat health risks in downtown areas of Hong Kong, even under normal summer days.

### 3.5 | Wind speed and direction analysis

For the wind environment of Hong Kong, the background winds are dominated by the monsoon systems most of the time. In winter, the northeast monsoon brings cold and dry continental air to Hong Kong. In summer, Hong Kong is hot and humid, largely due to the maritime air associated with the southwest monsoon. In general, the summer wind speed is lower than the winter wind speed or annual wind speed (Lam, 2011). However, with a complex topography, there are large variations in sheltering from and exposure to winds over different parts of Hong Kong. Moreover, due to rapid urbanisation over the past five decades, land use changes and high-rise high-density building development have further changed the local climate conditions of the city, so more calm and weak wind situations could be observed in downtown areas. Based on the observed wind data, it was found that there is a significant decreasing trend in urban wind speed in downtown areas over the past few decades, while the wind speed in rural areas remains relatively constant (Lai et al., 2014; Peng et al., 2018).

In general, in this study, according to wind data from the four representative stations, the prevailing summer winds are mainly from east to southeast at the HKO and KP, mainly due to the channelling effect, as both are located at the north bank of the Victoria harbour. The wind flow observed at JKB and TYW is largely affected by the surrounding complex hilly terrain, so in summer, mainly south to south-westerly, can be observed at JKB while rather diverse wind directions at TYW.

# 3.5.1 | Wind direction on extreme heat and non-extreme heat days

Frequency distribution analysis was employed to determine whether the wind direction influences the strength



**FIGURE 8** Relative frequency distribution of wind speed and direction on non-EH and EH days during daytime and nighttime at (a) HKO – urban (b) KP -urban-oasis (c) JKB – sub-urban (d) TYW- rural stations (on the figures, MS, mean speed; MD, mean direction and CW, percentage of calm wind [<0.5 m/s]) [Colour figure can be viewed at wileyonlinelibrary.com]

of hourly UHI/UCI during EH and non-EH events, as shown in Figure 8.

The wind direction patterns at the HKO (urban) and KP (urban-oasis) are quite similar in both daytime and nighttime, as they are both influenced by similar surrounding topographical conditions, the channelling wind effect along the Victoria Harbour, and urban morphology. The wind directions at both stations on the EH and non-EH days were distinct. Mean south-easterly winds  $(104^{\circ}-132^{\circ})$  are dominant on non-EH days during the daytime, while a significant change in direction to westerlies  $(251^{\circ}-264^{\circ})$  can be observed on EH days (see Figure 8a,b). Although a lower wind speed is observed at night, the wind direction pattern is similar to that during the daytime at the same station.

At the sub-urban station (JKB), the observed wind direction was largely different from the urban and urbanoasis-type stations. The mean wind direction during daytime on non-EH days is from south-easterlies (116°), which changes further south to 164° on EH days (see Figure 7c). At this station, the wind direction during nighttime on non-EH days is highly variable, although the mean direction is south-easterlies (134°), while southwesterly (215°) wind is observed on EH days (see Figure 8c).

Weather observations at the rural station (TYW) reveal that daytime wind direction on non-EH days is

highly variable, as shown in Figure 8d; however, the dominant direction is south-easterlies (137°). On EH days, the wind direction is mainly southwesterlies (210°). At nighttime, wind direction in both EH and non-EH periods remained north-easterlies ( $60^{\circ}-65^{\circ}$ ).

# 3.5.2 | Wind speed and UHI on extreme heat and non-extreme heat days

Among the four studied stations, stronger daytime and nighttime wind speeds at the urban (HKO) and urbanoasis (KP) stations relative to observations at the suburban (JKB) and rural (TYW) stations may be related to the relative inland location and complex terrain of the latter two. There is a significant (at 95% confidence interval) negative relationship between wind speed and UHI/UCI irrespective of the EH condition and time of the day, generally implying strengthened UHI/UCI intensity with lower wind speed. This observation is comparable with those in previous studies in Hong Kong (Yang et al., 2017), Beijing (Li et al., 2016), Australian cities (Rogers et al., 2019), and Greece (Founda and Santamouris, 2017), where lower wind speed contributes to the intensification of UHI and/or UCI and vice versa. However, the magnitude of the relationship (*R*) varied, as shown in Table 3.

Station/EH event types	Nightime (UHI)		Daytime (UCI)			
	Urban (HKO)	Urban- oasis (KP)	Sub- urban (JKB)	Urban (HKO)	Urban- oasis (KP)	Sub- urban (JKB)
EH	-0.80*	-0.88*	-0.79*	-0.68*	-0.77*	-0.81*
Non-EH	-0.51*	-0.68*	-0.91*	-0.74*	-0.85*	-0.87*

 TABLE 3
 Pearson correlation coefficient (R) between wind speed and UHI/UCI during EH and non-EH days

\*Significant at 95% confidence level.

**FIGURE 9** The spatial maps of UCIdh and UHIdh in Hong Kong under EH and non-EH events at TPU level [Colour figure can be viewed at wileyonlinelibrary.com]



# 3.6 | Spatial patterns of UHI and UCI during extreme heat events

Following the method described in Section 2.6, four MLR models (UCIdh and UHIdh in EH and non-EH scenarios) were developed. These resultant models explain approximately 80-90% of the variations in UCIdh and UHIdh in different scenarios. Although this study only included weather stations below an elevation of 100 m, the elevation is still one of the most significant influential factors of both the UCIdh and UHIdh in all scenarios based on the LUR modelling results (see the Supporting Information). Similar findings to previous studies were also observed in this study: (a) The quantity of wooded landscape of trees (quantified by NDVI and the areal proportion of the landscape occupied by dense trees) were found to be influential factors. (b) In a high-density urban context, the aggregation of compact building clusters – the classes LCZ 1 and LCZ 4 as defined by the LCZ (Wang et al., 2018), increases the UHIdh in all scenarios. (c) The most notable finding is that the predictor variable, windward/leeward index, is identified as a significant influential factor of both UHIdh and UCIdh in the EH days. The windward/leeward index quantifies the spatial relationship between the ground surface slope

aspect and wind direction; therefore, it has been used as an indicator of the wind environment (Böhner and Antonić, 2009). The presence of wind-related predictors in the EH event models is reasonable, as significant relationships exist between wind speed and UHI intensity (as discussed in the wind analysis in Section 3.5).

Based on the resultant regression models, a group of spatial maps of UCIdh and UHIdh under the EH and non-EH events were generated, as shown in Figure 9. As observed from the resultant spatial maps, the UCIdh values were found to be higher in the TPU which generally have higher elevation and with highly vegetated areas spatially occupying most of the zone. This spatial pattern is reasonable because there are fewer anthropogenic impacts and influences on the natural environment in these sparsely populated TPUs. The findings from the spatial maps are also consistent with a previous study in Hong Kong (Yang et al., 2017) that UCI still exists but significantly decreases in high-density built-up areas of the city. Notably, the overall UHIdh level of the EH scenario was higher than that of the non-EH scenario (-Figure S3.1). Moreover, the contrast between the lower percentile values and higher percentile values of UHIdh also increased under the condition of EH events. The above findings indicate that UHI intensifies during EH



**FIGURE 10** (a) Diurnal temperature profile of two inland stations (HKO and TYW) and two coastal stations (LFS and EPC) during EH periods; (b) difference in diurnal temperature profile between EH and non-EH events based on the temperature records of four selected stations [Colour figure can be viewed at wileyonlinelibrary.com]

events, especially in high-density urban environments. Spatially, higher UHIdh values were strongly associated with high-density built-up downtown areas. During the EH events, the deterioration of the thermal environment in high-density areas was more obvious than that in other areas. The spatial dependence of UHIdh and UCIdh on urban morphology and natural landscapes indicates the impact of urban planning and design on the thermal environment in high-density cities.

#### 4 | DISCUSSION

# 4.1 | General analysis on the UHI and UCI characteristics

This study quantifies the UHI and UCI during EH and non-EH days in Hong Kong. The results show that the changes in both the intensity and duration of UHI and UCI are significant during EH events compared to non-EH days. During EH events, the typical nocturnal UHIs in Hong Kong, as measured at the HKO station, are warmer by up to approximately 1.7°C, while the UCIs are cooler by up to approximately 0.7°C. The number of UHIdh and UCIdh increased by 59% and 54%, respectively. Based on the analysis of weather records for different station types, it was found that more urbanised areas have both higher UHI and UCI intensities.

Previous studies have suggested an enhanced UHI during EH periods due to the increased net radiation, sensible heat, and anthropogenic heat (Ao *et al.*, 2019),

decreased wind speed, and less latent heat cooling (Li and Bou-Zeid, 2013) during EH periods. Our study shows that both the daytime UCI and nocturnal UHI are enhanced during the EH periods in Hong Kong, suggesting that heat storage may play an important role in determining the synergistic interactions between UHI and EH events in high-density cities. Increased heat storage ratios in urban areas during EH events have been reported (Sun et al., 2017). Such heat storage in the urban area slows down the rate of warming during the daytime (Figure 5d-f). The difference in the warming rates between urban and rural areas is much larger during the EH periods, resulting in an even stronger daytime UCI. Concurrently, the nocturnal cooling rate in the urban area is also smaller, producing a much stronger nocturnal UHI during EH events. Further analysis of the wind revealed a stronger negative relationship between UHI and wind speed in the urban and urban-oasis stations on EH days, suggesting that weakened ventilation exacerbated UHI on EH-days. Another factor that may exacerbate the UHI in summer is the anthropogenic heat released from air conditioning (Ohashi et al., 2007; Yang et al., 2019), as space cooling is a major energy consumption of the building sector in Hong Kong (EMSD, 2019). A recent study showed that the cooling energy demand increased by 80-140% owing to EH events in Hong Kong in recent years (Morakinyo et al., 2019). This would potentially contribute to further intensifying the UHI in Hong Kong, as shown by the intensified UHIdh during the night at all three stations. However, the increased UCIdh does not necessarily suggest the contribution of anthropogenic

heat during the daytime. During EH events, the increased heat storage in the morning hours may overcompensate the potential increase in urban air temperatures due to increased anthropogenic heat, resulting in a stronger UCIdh. Such contrast between daytime UCI and nighttime UHI may require further investigations.

The interactions between UHI and EH events could also be responsive to the background climate (Zhao et al., 2018), city size (Ramamurthy and Bou-Zeid, 2017), and location to identify EH events (Fenner et al., 2019). The UHI effect during heatwave periods tends to be stronger in larger cities than in smaller cities, such as New York (Ramamurthy and Bou-Zeid, 2017) and Melbourne (Rogers et al., 2019). Moreover, the highresolution simulations of EH in New York further suggest that the EH event duration lasts longer in the denser and taller built-up areas than in the sub-urban and lower built-up areas (Ortiz et al., 2019). Our study results echo the previous findings, as we found that the enhancement of UCI/UHI was observed mainly in high-rise and compact built-up areas in Hong Kong, that is, LCZ1 to LCZ4 (Figure 1b).

Moreover, as Hong Kong is a coastal city, there are a certain number of weather stations located at the seafront or close to the ocean. In this study, stations surrounded by >30% of water cover within 1 km buffer were considered to have substantial influence from the sea (as shown in Figure 1a, and Section 1 of Supporting Information). The diurnal temperature profiles of these stations were also examined during the EH and non-EH periods. Figure 10 shows the diurnal temperature profiles at urban station HKO and rural station TYW, together with another urban station LFS and rural station EPC, both having >30% water cover within their 1 km buffers. The impact of water on urban station LFS is less apparent, as the two urban stations HKO and LFS are very similar. The results show a much narrower diurnal temperature profile at both LFS and EPC, probably because of the influence of the sea, given the large thermal inertia of water bodies (Yang et al., 2020) and the sea breeze effect (Giridharan et al., 2007; Ramamurthy and Bou-Zeid, 2017; Rogers et al., 2019). The difference between EH and non-EH events at these stations was also smaller.

# 4.2 | Intra-urban UHI and UCI variation and potential implications

Much of the earlier UHI or UCI studies undertaken around the world were limited to measuring the temperature difference between urban and rural areas, typically measured under conditions with clear sky and calm wind. This is a typical way to explore UHI and UCI.

However, there is little detail about the intra-urban variation in UHI and UCI magnitude under EH conditions. Such spatiotemporal information is needed, especially in UHI applications for heat stress adaptation management. For example, for heat-health studies, it is critical to know the location and severity of hotspot and cool-spot areas during EH events because the decision of corresponding heat risk prevention and heat-health intervention actions depends on them. Currently, most heat-health risk assessments adopt Crichton's conceptual definition of risk triangle (Crichton, 1999), in which the spatial information of hot weather conditions is essential for generating the hazard layer. Directly extracting weather data from the closest monitoring locations introduces biases and uncertainties, as the fine-scale intra-urban variability of ambient air temperature is not well considered. Using UHIdh and UCIdh as indicators, this study generated spatial map layers of UHI and UCI under EH conditions, which could reduce the aforementioned biases and spatial uncertainties and thus improve the robustness of heat-health risk assessment and the reliability of risk maps.

Another example is the daily demand and peak load estimation of the energy consumption. The energy sector needs to carefully plan ahead and regulate the power generation and transmission in order to meet the daily energy demand cycle and peak load, especially during EH events (Miller et al., 2007; Cheung et al., 2016). More precise information about the spatiotemporal characteristics of the UHI and the UCI in cities would be useful for the energy sector to make better-informed decisions on energy management. In Hong Kong, buildings account for nearly 90% of the electricity used and over 60% of the carbon emissions (EnB, 2017). Cooling energy consumption accounts for a large portion of the total energy consumption. Therefore, the findings of this study could provide reference information for stakeholders and policymakers to formulate relevant recommendations and measures for building energy saving and efficiency management.

# 4.3 | Relationship between wind and UHI and UCI effects

As stated earlier, Hong Kong predominantly experiences warm moist southerly winds throughout the summer as a monsoon-influenced subtropical climate. However, the analysis for the selected four weather stations revealed that there was a noticeable difference in wind direction between the non-EH and EH days. On non-EH days, south-easterly winds are dominant across all stations; on EH days, wind primarily comes from the west to southwest direction, which may be due to the presence of the positive surface pressure and extreme hot weather conditions mainly caused by anticyclone circulation over the south China region (Luo and Lau, 2017). In addition, the local wind environment in Hong Kong is greatly influenced by both complex hilly topography and highdensity high-rise urban morphology (Ng et al., 2011). Hence, the urban wind environment is complex in Hong Kong based on the differences observed among the urban/urban-oasis, suburban, and rural stations. In addition, the land-sea breeze effect and its relationship with the UHI and UCI effects are not included in the study as they have strong seasonal characteristics in Hong Kong (Lu et al., 2009). It is more prominent under light background wind conditions in autumn and winter. In summer, the southerly background flow masks the sea breeze effect (Wang et al., 2017). Thus, the slight changes in wind direction, which relates to the existence of the landsea breeze interaction, may also exacerbate the magnitude of the UHI during the heatwave (Founda and Santamouris, 2017; Ramamurthy et al., 2017; Ramamurthy and Bou-Zeid, 2017; Ao et al., 2019).

The UHI intensity and wind speed on non-EH days were less correlated at the urban and urban-oasis relative to the suburban area where a significantly high correlation coefficient was found (see Table 3). However, the strength of the UHI/wind speed relationship is higher under the EH conditions in urban and urban-oasis stations, especially during prolonged events due to the combined effects of accumulated heat over the region and heat storage in the urbanised areas, as observed in other cities such as Beijing (Li *et al.*, 2016) and some American cities (Ramamurthy and Bou-Zeid, 2017). This is similar to observations in three Australian cities (Melbourne, Perth, and Adelaide), where local winds have a limited effect on the regulation of the UHI during EH events (Rogers *et al.*, 2019).

In terms of UCI, the contribution of wind speed to its intensity is generally higher on non-EH days and lower on EH days. Similar to the observations in Beijing (Li et al., 2016), but for UCI, the daytime UCI at all three stations exhibited a negative relationship with the wind speed, which suggest that the lower wind may further weaken the sensible heat flux at the urban station where daytime surface temperature is usually lower due to the much stronger heat storage effect (Yang et al., 2017). However, the strength of the relationship shown in Table 3 reveals a relatively weak relationship at the urban station and higher at the suburban and urban-oasis stations. As the urban station HKO is located within the densest districts in Hong Kong, other factors such as high anthropogenic heat release and the stronger heat storage effect may play a role here.

#### 5 | CONCLUSION

Based on observational data, the UHI and UCI effects during EH and non-EH events were investigated in this study, to evaluate the interaction of EH events and urban effect in a high-density city of Hong Kong. Classifying weather stations into urban, urban oasis, suburban, and rural types is found to be a useful approach in capturing intra-urban temperature variations and is able to consider the surrounding environment of stations in the quantification of UHI and UCI. This study further highlights the spatial pattern of the UHIdh and UCIdh under EH and non-EH events and shows that the compact building clusters of urban areas contribute to the increased UHIdh, especially at night during EH events. Local wind directions on EH days are in accordance with the average summer records of the Hong Kong Observatory, while the direction on non-EH days is significantly different across the four stations. This finding indicates the uniqueness of the wind directions on non-EH days. In terms of wind speed, negative correlation between UHI/UCI and wind speed on EH and non-EH days and at both daytime and nighttime was found. However, a stronger negative relationship was found at nighttime in the urban and urban-oasis stations on EH days, unlike non-EH days, suggesting that weakened ventilation exacerbated UHI on EH-days, especially at nighttime. As such, we conclude that improved ventilation has the potential to mitigate UHI and prevent its exacerbation with EH events.

The number of hot nights and very hot days in Hong Kong has increased significantly in the last few decades. Moreover, according to future climate change predictions conducted by the Hong Kong Observatory (HKO, 2015), the frequency and severity of EH events are expected to increase in the future. Thus, it is important to apply the results from this study to urban design, cooling energy management, and heat-health action plans.

A limitation of this study is that only four representative stations and their weather records were employed for detailed UHI/UCI analysis and diurnal temperature profiles. In addition, the sample size for EH events is much smaller than that for non-EH days, which covers a wide range of weather conditions. There is a need to further analyse the interaction of UHI/UCI with other changes in meteorological factors such as solar radiation, precipitation, humidity, and cloud conditions, which could be different between EH and non-EH events. Based on the lessons learned from this study, we plan to further investigate specific single EH events, such as the 18 consecutive very hot days in May 2018 (HKO, 2018) and 20 consecutive very hot days in July 2020 (HKO, 2020).

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**Chao Ren:** Conceptualization; formal analysis; funding acquisition; investigation; writing-original draft; writing-review & editing. **Kai Wang:** Conceptualization; formal analysis; investigation; visualization; writing-original draft; writing-review & editing. **Yuan Shi:** Formal analysis; investigation; visualization; writing-original draft; writing-review & editing. **Yu Ting Kwok:** Formal analysis; investigation; visualization; writing-original draft; writing-review & editing. **Tobi Morakinyo:** Formal analysis; investigation; visualization; writing-original draft; writing-review & editing. **Tsz-cheung Lee:** Investigation; writing-original draft; writing-original draft; writing-original draft; writing-review & editing. **Yuguo Li:** Investigation; writing-original draft; writing-review & editing.

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### SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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