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Shifting the urban heat island clock in a megacity: a case study of Hong Kong

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Abstract

With increasing levels of urbanization in the near future, understanding the impact of urbanization on urban heat islands (UHIs) is critical to adapting to regional climate and environmental changes. However, our understanding of the UHI effect relies mainly on its intensity or magnitude. The present study evaluates the impact of urbanization on UHI duration changes by comparing three stations with different rates of urbanization, including highly developed and developing urban areas throughout Hong Kong, from 1990–2015. Results show that the 26 year average UHI intensity in highly urbanized regions is much higher than that in developing areas, and the 26 year average of UHI duration is similar. Over the past 25 years, however, UHI duration has increased only in developing urban areas, from 13.59–17.47 hours. Both earlier UHI starting and later UHI ending times concurrently contribute to the UHI effect being experienced for a longer duration. The differences in UHI duration change between the two areas are supported by population and by night light changes from space. Increasing night light, which suggests enhancements in the economic infrastructure, occurred only in the developing urban areas. Our results suggest that changes in UHI duration should be included in an assessment of regional climate change as well as in urban planning in a megacity.

1. Introduction

Urbanization refers to a dominant anthropogenic force that affects regional climate and environmental change in urban areas (United Nations Department of Economics and Social Affairs 2014). During the second half of the 20th century, dramatic urbanization additionally contributed to warming in relation to greenhouse gases, especially in populated regions such as Beijing, Seoul, Tokyo, Houston, Toronto and other cities (Saitoh et al 1996, Streutker 2002, Kim and Baik 2005, Rinner and Hussain 2011, Jacobson et al 2015). The concept of higher temperatures in populated regions is defined as an urban heat island (UHI) (Oke and Maxwell 1975). Changes in radiative and thermal properties such as thermal conductivity, emissivity, reflectivity, and heat capacity over the urban land surface regulate changes in the surface energy balance, which often leads to temperatures in urban areas higher than that in surrounding rural areas (Kalnay and Cai 2003, Jones et al 2008, Zhao et al 2014). As levels of urbanization and population growth increase in the near future (Grimm et al 2008, Buckley et al 2008), exact assessments of the impact of urbanization on UHIs are critical to improve urban planning in populated regions.

Since the 19th century (Howard 1820), many studies have focused on the impact of urbanization on UHIs. Oke (1982) showed that urban temperatures are higher than rural ones and that a UHI attains a maximum temperature at night or during the early morning; UHI has thus been called a ‘nocturnal phenomenon’. However, in desert cities such as Phoenix, Arizona, the boundary layer temperatures in the urban area are much lower than in rural surroundings because of the high albedo (Jin et al 2005). Relative cooling in urban areas rather than in rural areas is observed in the morning and in the early afternoon by studying the atmospheric boundary-layer (Theeuwes et al 2015). The UHI effect also varies according to season; Beijing, for example, has the highest seasonal mean canopy UHI intensity of the entire urban area in winter (1.65 °C) and the lowest in summer (0.85 °C) (Yang et al 2013). Furthermore,
the canopy temperature difference between urban and rural areas can be different due to different land cover types of the city’s surrounding areas (Weng et al. 2004, Rinner and Hussain 2011, Stewart and Oke 2012).

Although many previous studies have revealed various features of UHIs, most have focused on the intensity of the UHI effect (e.g. the magnitude of temperature difference between urban and rural areas). Our understanding of the temporal variability of UHI is very limited. In this study, we define the UHI duration as the total hours of which the UHI intensity value is positive (i.e. number of hours when the urban temperature is higher than the rural temperature). UHI duration could be an important concept for studying the urbanization effects on energy consumption and related environmental issues such as urban carbon emission. Santamouris (2014) suggested that the annual increase of the cooling degree hours resulted in a considerable increase in energy use. It is also known that the cooling load of typical urban buildings is on average 13% higher compared to similar buildings in rural areas (Santamouris 2014). A study in London found an apparent relationship between the UHI effect, energy use, and CO₂ emissions. As such, the longer duration of the UHI effect could lead to an increase in energy use and CO₂ emissions. Urban infrastructure can be affected by the duration of high temperatures. Sen and Roesler (2014) showed that the temporal information (i.e. duration of the UHI effect in this study) is an important factor in understanding the life cycle of urban pavement. Consequently, the study of UHI duration as well as intensity should be considered in understanding urbanization effects and future urban planning and management.

In this study, we focus on Hong Kong (HK), a metropolitan area located on the south coast of China. It is a highly populated region: the population is 7.4 million in 2017, with a density of over 6300 people per square kilometer. HK is the fourth most densely populated region in the world, after Macau, Monaco, and Singapore (Monkkonen and Zhang 2011, Census and Statistic Department 2017). Over the past few decades, HK has achieved rapid economic growth and global integration and has become a high-tech industrialized economy (Index of Economic Freedom 2017). As a highly populated city, HK experiences the UHI effect (Giridharan et al. 2005, Fung et al. 2009, Siu and Hart 2013). By focusing on HK, we can gain new insights into the role of human activities with regards to UHI duration changes in rapidly changing urban areas.

### 2. Methodology

#### 2.1. Data set

To study UHI duration, we mainly analyzed hourly temperature data sets from the HK Observatory (Hong Kong Observatory 2015). Although there is no universal method to classify representative urban and rural stations, the World Meteorological Organization provides principles for establishing suitable sites in urban and rural areas (Plummer et al. 2003, World Meteorological Organization 2008, 2010). Based on the availability of hourly data and on previous studies, we selected three different stations: Hong Kong Observatory Headquarters (HKO), Lau Fau Shan (LFS), and Ta Kwu Ling (TKL) (Leung et al. 2004, Fung et al. 2009, Memon et al. 2009, Yim and Ollie 2009, Lam 2010). The detailed information for each station is shown in table 1 (Hong Kong Observatory 2015, Siu 2011). HKO is situated in the highly-developed area of HK, indicating urbanization effects in a stable developed urban area. LFS is located in a newly developing urban area. TKL is in a developing urban area. Finally, we selected the TKL station as a reference rural station in HK. After checking all missing data sets in several stations in HK we excluded stations that have too many missing values. Our final dataset includes three representative stations, focused on the period 1990–2015. There is no data missing from HKO, 1.69% missing from LFS, and 1.61% missing from TKL. These minuscule fractions of missing data do not affect our results.

To support the changes in UHI duration related to urbanization, two identical data sets, population statistics and night light from space, were analyzed. Population is one of the most vital factors in urbanization (Oke 1973, World Health Organization 2017). To understand the relationship between UHI duration change and the urbanization process, annual population data from every district in HK from 1997–2015 was

| Station name | Hong Kong Observatory Headquarters (HKO) | Lau Fau Shan (LFS) | Ta Kwu Ling (TKL) |
|--------------|------------------------------------------|--------------------|--------------------|
| Coordination | 22°18’07” N, 114°10’27” E               | 22°28’08” N, 113°59’01” E | 22°31’43” N, 114°09’24” E |
| Elevation    | 32 m                                     | 31 m               | 15 m               |
| Land use     | Built ratio: 74.3%                       | Built ratio: 47.3%  | Built ratio: 17.5%  |
| Vegetation   | Vegetation ratio: 25.7%                  | Vegetation ratio: 25.6% | Vegetation ratio: 82.5% |
| Water        | Water ratio: 0%                          | Water ratio: 27.1%  | Water ratio: 0%    |

Table 1. The stations’ information including coordination, elevation and land use information.
obtained from the HK government statistics department. Some recent studies have suggested that night light could be a strong indicator for showing the extent of urbanization (Meng et al. 2014, Mellander et al. 2015, Gao et al. 2015, Li et al. 2016). In this study, we used night light data (1992–2013) from the US Air Force’s Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) and from the US Department of Commerce’s NOAA National Geophysical Data Center (NGDC). The DMSP program is designed to capture information about global weather and weather systems. The satellites have onboard sensors designed to detect moonlight (and even starlight) that is reflected off clouds (since clouds are difficult to identify at night). When the sky is clear, there are no clouds obstructing the view, and the instrument detects the light emanating from the surface of the Earth (Elvidge et al. 1997). The light can be from several sources but is primarily the result of electric-powered illumination (Mellander et al. 2015). The range of the nightlight data is from 0–63, with the saturation point determined by a limitation in the sensor itself. It is measured in ‘Gains’, a measurement unit for how much light per unit area is detected by a photomultiplier (light intensifier instrument) of the sort used by the DMSP satellites.

2.2. Definition
According to previous studies, UHI intensity is defined as the difference between urban temperature and rural temperature (Oke 1973, Kalnay and Cai 2003). The UHI intensity values in the present study are the temperature differences between the HKO and TKL stations and between the LFS and TKL stations. UHI duration is the total number of hours of positive UHI intensity in one day (i.e. red colors in figure 1). The start time is set as the beginning hour of the duration, usually in the afternoon, and the end time is set as the last hour of the duration, usually in the late morning of the next day.

2.3. Analysis
Based on the hourly data, the monthly average of hourly UHI intensity for the entire 1990–2015 period was calculated. This calculation has been denoted by a clock-like circle that is labeled in increments from 0–23 in one day. The period was separated into two sub-periods to see the decadal changes in UHI duration. The early one is the period from 1990–1999, and the later one is the period from 2006–2015. After calculating the UHI intensity values for the two sub-periods at HKO and LFS, we estimated the average duration of the two sub-periods and the duration start and end timing. The statistical significance of the difference in UHI duration start and end timing between the two time periods was evaluated by the bootstrapping method (Davison and Hinkley 1997, Efron and Tibshirani 1994).
3. Results

3.1. UHI intensity and duration
Figures 1 and 2 display the monthly climatology of hourly UHI intensity from 1990–2015 at HKO and LFS, respectively. The grey background in the clocks represent the nighttime and the white background for the daytime. The daytime here is the total amount of sunshine. Information for sunrise and sunset times for each month is from the Civil Aviation Department Hong Kong (2015). At the HKO station, which is the main station in the HK area, the UHI clocks show clear positive UHI intensity in the nighttime. For example, in January, positive UHI intensity occurred from 5 pm–11 am the next day, and in July, it occurred from 6 pm–8 am the next day. The UHI intensity maximum value in one day usually appeared during the nighttime, especially before sunrise (in May–September from 3 am–6 am, in other months from 5 am–8 am). The UHI intensity therefore shows apparent seasonal variability. UHI intensity is higher during the late autumn and winter seasons (i.e. November–January) and relatively lower during the late spring and summer seasons (i.e. March–August). For instance, in December, UHI intensity is greater than 3 °C for 9 hours per day. However, in May, the maximum UHI intensity was only approximately 1.5 °C. Our results corroborate previous studies from HK, which found higher UHI intensity in winter. Leung et al (2004) mentioned that during 1947–2002, the UHI intensity of annual mean temperature in winter was 0.21 °C and in summer was 0.12 °C. Chan and Ng (1991) also pointed out that for minimum temperature, UHI intensity was 3.2 °C in winter and 1.8 °C in summer. The seasonal variations in UHI over Hong Kong are related to the seasonal climate characteristics of the region (Memon et al 2009, Wong et al 2011). During the summer monsoon, humid air arrives in the HK region. However, during the winter, the climate is relatively dry. This could explain the higher UHI intensity observed in the winter.

The diurnal and seasonal variations in positive UHI intensity at the LFS station are generally consistent with those at the HKO station. Positive UHI always occurred in the nighttime. Relatively high UHI intensity was observed in the colder months. Maximum UHI intensity was approximately 0.7 °C in July but was twice as large in December at approximately 1.5 °C. However, in general, the magnitude of UHI intensity of LFS is less than that of HKO. For instance, maximum UHI intensity at LFS reached only about 1.5 °C, which occurred in December from 7–8 am. The maximum UHI intensity values from February–September at LFS were almost all less than 1 °C. These values were less than half the UHI intensity at HKO during the same time period.

The daytime cooling (negative UHI intensity) in the daytime occurs both in the heavily developed station HKO and developing station LFS. The negative UHI in urban areas during daytime could be explained...
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...relative humidity. Figures 1 and 2 show that at both area, the UHI effect has a negative relationship with tern (Hong Kong Observatory 2015); the wind comes in HK are largely determined by the monsoonal pat-tern (Hong Kong Observatory 2015); the wind rarely comes from the sea. Wind patterns in the spring. One of the reasons could be that in the spring, wind also brings moisture from the sea surface. Memon et al (2009) found that in the HK area, the UHI effect has a negative relationship with relative humidity. Figures 1 and 2 show that at both stations, summer daytime cooling periods are longer than in winter. In HK, the rainy and warm seasons are in the same period. In tropical and sub-tropical areas, the humidity (dry/wet) is more important than the temperature (cool/warm) for the UHI effect (Roth 2007). The cooling impact can be stronger during the wet season (summer), leading to longer cooling periods.

There are also some differences between the two stations. HKO daytime cooling is stronger than that at LFS in the spring. One of the reasons could be that in the spring, wind rarely comes from the sea. Wind patterns in HK are largely determined by the monsoonal pat-tern (Hong Kong Observatory 2015); the wind comes from the southwest (the same direction as the sea) in the summer, from various directions in the autumn, and from the northeast (from inland) in the winter and spring. However, because of massive urbanization in Shenzhen (one of the largest cities in China), the sea breeze is enhanced during the winter, affecting the western part of HK where LFS is located (Lu et al 2010). As a result, it is only during the spring when there is little wind from the southwest (from the sea). This could be one of the reasons explaining the lower daytime cooling effect during spring (March, April, May).

We defined UHI duration as the number of hours in a day with positive UHI intensity values. Figures 1 and 2 show the durations of the UHI effect per month at two stations (i.e. the number of the red bars in a clock). At HKO, in January, the UHI duration started at 5 pm and ended at 11 am the next day and lasted approximately 18 hours. At HKO, UHI duration was longest during the winter season (e.g. 18 hours for January) and shortest during the summer season (e.g. 14 hours for July). Like the HKO station, UHI duration at LFS showed clear seasonal variability. The longest UHI durations were observed in March, April, January and December (e.g. 18–19 hours), whereas the shortest UHI duration was observed in July (e.g. 13 hours).

3.2. UHI duration change

In the previous section, based on the climatology of UHI intensity, we obtained the climatology of UHI duration for the period 1990–2015. Here, to see the changes in UHI duration over time, we chose two time periods: 1990–1999 and 2006–2015. Figure 3 shows the UHI durations for the two time periods and the differences in UHI duration between them. At HKO, UHI duration apparently did not change for all months, suggesting stabilized diurnal variations in UHI over time. For instance, in winter, UHI duration during the earlier period (1990–1999) (e.g. 19 hours) is mostly the same as that during the later period (2006–2015). However, as opposed to the HKO station, a difference in UHI duration at the LFS station between the two time periods is noticeable. Changes in UHI duration for 6 months in a year show a statistically significant difference. For example, the UHI duration increased by more than 7 hours in February, by about 6 hours in March, and by nearly 5 hours in May and June. These results suggest that diurnal variations in UHI intensity at the LFS station have changed over time. Specifically, the duration of extra warming in urban areas has increased over time.

To understand the cause of UHI duration changes, we compared the changes in the start and end times of UHI duration of two time periods (figure 4). At HKO (figure 4(a)), both the start and end times of UHI

![Figure 3. Changes in UHI duration between 2006–2015 and between 1990–1999 at HKO (a) and LFS (b).](image-url)
duration difference values were near zero. However, in contrast to the HKO station, the start and end times of UHI duration at LFS changed over time. In February, the start time advanced by 2.9 hours, and the end time was delayed by 4.6 hours, thus lengthening the UHI duration by 7.5 hours. Deviations also existed; in March, for example, the duration increased about 6 hours, but on average, the start time was nearly 6 hours earlier and end time more than 2 hours later, which would represent an increase of more than 8 hours. The error line presenting the standard deviation of each value is also shown. Both an earlier start time and later end time led to the longer duration in developing urban areas. Larger changes occurred in February, March and during the summer compared with other months, which is consistent with the result shown in figure 3(b).

4. Discussion and conclusions

This study found clear changes in UHI duration in the LFS region over time but not in the HKO region. The different features of UHI duration change between the two regions could be explained by different stages of urban development, such as urbanization rates (i.e. stabilized vs developing urban). Among several indicators of urbanization, such as land use, infrastructure level, and employment rate, population is the most basic indicator of the urbanization rate (United Nations Department of Economic and Social Affairs 2014). Population could be an obvious phenomenon to indicate rapid development. Thus UHI duration could be enhanced due to population changes. Figure 5 shows the changes in population from 1997–2015 in the districts where stations are located. The population in the LFS region increased by 607,200 in 2015, whereas that of the HKO region showed no apparent change.

Although night light was not a fundamental element for judging urbanization levels, it is widely used to detect urbanization across the globe and is a popular indicator in recent urbanization impact studies (Fung et al 2009, Mellander et al 2015, Gao et al 2015, Li et al 2016). Figure 6 shows changes in night light over the entire HK region from 1992–2013. On a spatial map, positive changes in night light (e.g. an average level increase of 0.62 annually) is observed in the LFS.
Figure 6. Spatial patterns of night light changes from space for the period between 1992 and 2013. The range is from –0.99 to 1.70.

region, whereas negative changes in night light are observed in the HKO region. In accordance with positive changes in population (figure 5), the increased level of night light in the LFS area reflects an increase in habitation and human activities compared to the past (figure 6), indicating a timely, evolving urbanization stage in LFS and a stabilized urbanization stage in the HKO region. Consequently, two different indicators of urbanization support the results of the present study.

UHI duration information can provide us with a reference for urban development planning. A lengthening of the UHI duration indicates a longer period of extra warming in an urban area. This longer period of warming would influence both the fundamental and vital elements of the urban ecosystem and human daily life. For example, the energy bureau needs to adapt to new situations, as UHI duration changes in both daily and seasonal levels can lead to increases in electricity consumption (Auffhammer and Mansur 2014, Christenson et al 2006, Cowie and Blamire 1998). As urban air quality could be altered by changing UHI duration, the government needs to adjust its policies and procedures (Grimm et al 2008, Jacob and Winner 2009, Ramanathan and Feng 2009, Tai et al 2010, Cao et al 2016). Longer periods of hot weather require that more attention is paid to self-protection and that governments implement increased and longer-lasting emergency measures (Patz et al 2005). The assessment of the urban infrastructure life cycle needs to be more accurate by considering the UHI duration (Sen and Roesler 2014) to avoid unexpected events and give a better understanding about the relationship between urbanization and the UHI effect.

In conclusion, changes in the UHI effect over time should be considered to gain a better understanding of the impact of urbanization on the environment and on climate change. In particular, in addition to the old concept of UHIs that considers intensity, UHI duration (e.g. start, end, and persistence of UHIs during the day) should be understood. In this study, we focused only on areas in HK; however, UHI duration changes must be further examined in all world megacities, such as New York, Tokyo, and Seoul, to provide more targeted urban planning advice that addresses regional climate change.

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