RESEARCH ARTICLE

Urban heat islands in Hong Kong: Bonding with atmospheric stability

Weiwen Wang1 | Bingyin Chen1 | Yong Xu2 | Wen Zhou3 | Xuemei Wang1

1Guangdong-Hong Kong-Macau Joint Laboratory of Collaborative Innovation for Environmental Quality, Institute for Environmental and Climate Research, Jinan University, Guangzhou, China
2School of Geographical Science and Remote Sensing, Guangzhou University, Guangzhou, China
3Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China

Correspondence
Weiwen Wang, Institute for Environmental and Climate Research, Jinan University, Guangzhou 511443, China.
Email: wwangeci@jnu.edu.cn

Abstract
A barrier to urban heat island (UHI) mitigation is the lack of quantitative attribution of the various contributions to UHI intensity. This study demonstrates the daily and seasonal dynamics of UHIs in Hong Kong, a subtropical high-density city. The nocturnal UHIs of the city are grouped according to various dynamic stability conditions (neutral, weak stable, and strong stable) of the boundary layer. Results indicate that the stronger the atmospheric stability, the more intense the UHI. The atmospheric anomalies linked to these stability classifications are hence revealed. In summer, nights of neutral (strong stable) stratification are controlled by low (high) pressure with rising (sinking) motion, less (more) precipitation, and lower (higher) air temperature at the surface. In winter, the influence of the large-scale circulation system of the East Asian winter monsoon is significant. In the upper layer, the East Asian jet stream retreats westward (is displaced northward) on nights with neutral (strong stable) atmospheric stratification. At the surface, southeast China is hot and humid on neutral nights, while on strong stable nights, the coastal regions of southeast China are dry, and East Asia is dominated by positive surface air temperature anomalies. Atmospheric anomalies are generally nonsignificant on nights with weak stable stratification in both summer and winter. These findings provide potential predictors for UHI intensity.

KEYWORDS
atmospheric anomaly, dynamic stability, Hong Kong, urban boundary layer, urban heat island

1 | INTRODUCTION

The main cause of urban heat islands (UHIs) is the modification of land surfaces with materials that effectively store short-wave radiation and reduce evaporative cooling (Voogt and Oke, 2003; Shi et al., 2018). A secondary contributor is waste heat generated by energy usage (Li and Zhao, 2012; Giridharan and Emmanuel, 2018). Much emphasis has been placed on documenting UHIs in modern climate studies, especially in megacities and urban agglomerations around the world (Stewart, 2011; Wang et al., 2014b; Chen et al., 2016; Goddard and Tett, 2019; Wang et al., 2020a; 2020b). Hong Kong is one such high-density megacity in the hot and humid subtropics.

The UHI effect in Hong Kong has been investigated extensively. Some studies have characterized the spatial pattern of UHIs in Hong Kong using land surface...
temperatures retrieved from remote sensing data (Fung et al., 2009; Liu and Zhang, 2011; Wong et al., 2016; Tsou et al., 2017), and others have evaluated the reliability of UHI intensity as an indicator of urban heating (Memon et al., 2009). Besides the intensity or magnitude of UHIs, the impact of urbanization on changes in UHI duration has been examined (Chen and Jeong, 2018). Urban planning strategies for adaptation to and mitigation of UHIs are of wide interest to the government and researchers in Hong Kong as well (Giridharan et al., 2007; Ng et al., 2012; Tan et al., 2016; Aflaki et al., 2017; Lin et al., 2017; Wang and Ng, 2018). Because Hong Kong is a coastal megacity, attention has also been paid to the interaction between UHI circulation and land–sea breezes (Wang et al., 2017), but studies of the linkage between Hong Kong UHIs and large-scale atmospheric contributors have rarely been undertaken.

In addition to urbanization and population density, recent studies have found that local background climate makes strong contributions to UHIs (Zhao et al., 2014; Manoli et al., 2019). UHIs are most apparent under weak wind and clear sky conditions, and studies on UHIs are consequently linked with atmospheric stability. Azevedo et al. (2016) performed UHI analysis under a range of atmospheric stability classes in a case study in Birmingham. Krüger and Emmanuel (2013) took atmospheric stability conditions into account in a UHI study and suggested that UHIs were not particularly affected by the choice of more stable conditions in a case study in Glasgow. Hu et al. (2013) noted that mechanical mixing associated with low-level jets played a critical role in moderating nocturnal UHI intensity in Oklahoma City.

The interaction between air pollution and UHIs has attracted increasing attention (Cao et al., 2016; Yang et al., 2020). In a short period, pollutant emissions usually do not fluctuate significantly. Contamination episodes are usually caused by calm weather with poor dispersion conditions. Therefore, it is crucial to find out what kinds of atmospheric circulation anomalies lead to a calm and stable atmospheric boundary layer. Taking Hong Kong, a high-density city in the highly urbanized Pearl River Delta, as an example, this study aims to clarify the connection between UHIs and atmospheric stability, and consequently the contribution of large-scale atmospheric circulation.

2 | DATA AND METHODOLOGY

2.1 | Observations and definition of UHIs in Hong Kong

In this study, we chose the Hong Kong Observatory (HKO) Headquarters as the urban site. The HKO is a representative urban weather station and a common choice for UHI studies in Hong Kong (Fung et al., 2009; Memon et al., 2009). However, HKO is located in an urban park and close to the coast, which may affect its characteristic as an urban site in UHI intensity estimation. Hence, the King’s Park (KP), which has little vegetation around, locates further away from the coast compared to HKO, but has a higher altitude (Figure 1 and Table S1, Supporting Information), is also used as the urban site to evaluate the UHI intensity in Hong Kong. There is no consensus on the most appropriate rural site in UHI studies (Das et al., 2011). But a comprehensive evaluation study points out that the most appropriate rural site to quantify UHI intensity in Hong Kong is Tsak Yue Wu (TYW) (Siu and Hart, 2013). We adopt this recommendation and take TYW as the rural site in calculating UHI intensity. A UHI is defined as the temperature difference (ΔT) between HKO and its rural counterpart, TYW. Hourly records from these two sites during 1996–2015 are utilized. Two seasons, summer (June–August) and winter (December–February), are investigated separately.

In addition, hourly wind speed and cloud cover observations from HKO, and global solar radiation records from King’s Park (KP) are further used for defining stability classifications. Cloud cover is available only from HKO and global solar radiation only from KP. The boundary layer structure above urban and rural areas during a UHI event is different (Barlow et al., 2014). We
use observations of wind speed, cloud cover, and solar radiation at the urban site to represent the urban boundary conditions of interest. Figure 1 indicates the locations of HKO and TYW on a land use map of Hong Kong (data source: http://data.ess.tsinghua.edu.cn/) (Gong et al., 2020). General information on the three sites is listed in Table S1.

### 2.2 Stability classifications

The planetary boundary layer is generally characterized by diurnal variation. The unstable boundary layer during the daytime is also known as the convective boundary layer, since turbulence there is usually convectively driven. At night under clear skies, outgoing longwave radiation cools the land surface and adjacent air above it. This cool layer of air forms the stable boundary layer, which is characterized by stable air with weak and sporadic turbulence. The oldest and, for a great many years, the most commonly used method for classifying atmospheric stability of the boundary layer was developed by Pasquill (1961), which categorized atmospheric turbulence into six stability classes called A, B, C, D, E, and F, with class A being the most unstable, class F the most stable, and class D neutral (Table S2).

In the Pasquill scheme, thresholds for wind speed and cloud cover are quantitatively specified, while thresholds for daytime insolation are categorized in qualitative terms of “strong,” “moderate,” and “slight,” which need to be transferred to specific values. Based on the diurnal cycle of global solar radiation, we chose 1200–1500 LST (UTC +8) when insolation is at its maximum for the calculation (Figure S1). The data are sorted into summer and winter, respectively. The 25th, 50th, and 75th percentiles are herein computed (Table S3). According to the Pasquill scheme (Table S2), daytime stability is classified. For example, when wind speed is lower than 2, classifications A and B are divided by the 50th percentile of solar radiation; when wind speed is between 2 and 3, classifications A and B are divided by the 75th percentile of solar radiation, classifications B and C are divided by the 25th percentile, and so on.

### 2.3 Atmospheric reanalysis and anomaly composite

Reanalysis data during 1996–2015, including the daily mean of geopotential height, zonal component of wind speed, omega (represents vertical movement), surface air temperature, and precipitation, are taken from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996). Daily anomalies derived from a smoothed mean daily cycle (June–August for summer and December–February for winter) are used to examine the atmospheric anomalies associated with local stability in Hong Kong. These daily anomalies are averaged in corresponding stability classes, and the Student’s t test is used to test their significance.

### 3 RESULTS

#### 3.1 Daily and seasonal dynamics

Figure 2 shows an isotherm plot of the annual UHI climatology of Hong Kong. The UHI magnitude is muted, as these are averages that include all types of weather conditions in their multiyear records. Nevertheless, it shows the daily and seasonal dynamics of UHIs well. The seasonal variation is related to daytime and nighttime length. Solar control of warming and cooling clearly sets the timing of the diurnal cycle. The close spacing of isotherms near sunrise and sunset defines the times of the most rapid decay and growth of UHIs, respectively. Generally, UHIs in Hong Kong are dominantly nocturnal during all months of the year, with the greatest...
magnitude in the winter and the smallest in spring. More importantly, they are positive during the nighttime but may be negative during the daytime. A general contributor to the negative daytime UHI intensity is canyon shading around urban sites (Oke, 1982). But the case in Hong Kong may be more complicated because of the combined effects of its coastal location and its high-rise and compact urban morphology (Wang et al., 2016). Yang et al. (2017) documented the daytime urban cool island phenomenon and its mechanisms in Hong Kong and reviewed the studies on the cause of this phenomenon worldwide. For examples, advection of warmer air to rural areas is the cause of daytime urban cool island in Beijing; dense urban structure and little anthropogenic heat is the cause in Adelaide; sea breeze and backdoor cold fronts are the contributor to the phenomenon in New York.

Here, the rural site is fixed at TYW, while UHI intensity is estimated by using two urban sites, HKO and KP. It is found that the daily and seasonal dynamics are similar when choosing the two different urban sites, but the daytime urban cool island is weaker, winter nocturnal UHI is stronger when KP is used as the urban site. Moreover, the isotherms are more intensive and change more frequently in Figure 2b than in Figure 2a. The differences are caused by the abovementioned different characteristics of HKO and KP that KP is located in a park with less vegetation and further away from the coast. The two urban sites have their own advantages and disadvantages. In order to keep up with previous studies, HKO is chosen as the urban site in the following analysis.

Urban warmth has several practical implications. In summer, the nocturnal UHI intensity is around 2–3°C in Hong Kong. This UHI magnitude means an exact requirement of electric power for artificial cooling (air conditioning) in this subtropical city, while negative UHI intensity in the daytime means energy savings, as less air conditioning is required. In winter, a UHI magnitude of more than 4°C means fewer cold nights. The diurnal cycle of air temperature at different sites and the UHI intensity calculated from different pairs of sites are shown in Figure S2.

3.2 | Urban heat island intensity according to stability

For nocturnal UHI, we take the maximum intensity during 2000–0600 LST for analysis. The correlation

![Figure 3](image-url)  
**Figure 3** Boxplots for nocturnal UHI intensity (the maximum value during 2000–0600 LST) in Hong Kong under neutral (class D), weak stable (class E), and strong stable (class F) atmospheric stability in (a) summer and (b) winter during 1996–2015

|              | Estimated coefficient | Standard error | t statistics | p-value      |
|--------------|-----------------------|----------------|--------------|--------------|
| Summer       | Intercept             | 5.82           | 0.07         | 79.16        | 0            |
|              | SPD                   | −0.3           | 0.02         | −16.11       | 1.28 × 10⁻⁵⁴ |
|              | CLD                   | −0.34          | 0.01         | −26.77       | 4.12 × 10⁻¹³³|
| Winter       | Intercept             | 8.25           | 0.1          | 85.04        | 0            |
|              | SPD                   | −0.3           | 0.03         | −8.84        | 2.27 × 10⁻¹⁸ |
|              | CLD                   | −0.65          | 0.02         | −41.91       | 1.1 × 10⁻²⁶⁶ |
coefficients of UHI intensity and meteorological parameters for Pasquill stability classification are listed in Table S4. During the nighttime, weak wind and clear sky represent dynamic stability. Significant negative correlations between nocturnal UHI intensity and the meteorological parameters demonstrate that the more stable the atmospheric boundary layer, the stronger the UHI intensity.

As shown in Figure 2, nocturnal UHIs in Hong Kong are generally positive. Based on the Pasquill stability classification scheme, nighttime dynamic stability in Hong Kong is classified into three classes, namely neutral (D), weak stable (E), and strong stable (F), using observed surface wind speed and nighttime cloud cover at HKO. As there are “gaps” between the thresholds of the Pasquill scheme, not all days are grouped into the stability classes. Of the total 1,840 summer nights, classes D, E, and F have 249, 237, and 336 nights, respectively, only 44.7% of the total summer nights. Of the total 1,805 winter nights, classes D, E, and F have 237, 303, and 559 nights, respectively, or 60.9% of the total winter nights. Boxplots for nocturnal UHI intensity in Hong Kong under the three nighttime dynamic stability classes during 1996–2015 are provided in Figure 3, further indicating that the more stable the stratification of the atmosphere, the stronger the UHI intensity. The median UHI

**FIGURE 4** Composite (a)–(c) geopotential height at 500 hPa (m), (d)–(f) omega at 850 hPa (Pa·s⁻¹), (g)–(i) precipitation (kg·m⁻²), and (j)–(l) surface air temperature (K) for neutral (class D), weak stable (class E), and strong stable (class F) atmospheric stratification stability on summer (June–July–August) nights in Hong Kong during 1996–2015. Color shading indicates regions that are significantly different from the mean at the 0.05 confidence level in the Student’s t test. The black dot denotes the location of Hong Kong.
intensity in Figure 3a (summer) for classes D, E, F is 2.2, 3.0, and 4.6°C, respectively, while in Figure 3b (winter), the median is 2.6, 4.1, and 7.1°C, respectively. There are significant differences in UHI intensity under different atmospheric stratification stabilities, whether in summer or winter.

Using multiple regression technique, a linear model is established to provide more intuitive information for quantifying the attribution of the atmospheric stability factors to UHI intensity. The estimated coefficients and diagnostics of the linear regression model are listed in Table 1. The reported p-values, which derived from the t statistics under the assumption of normal errors, are smaller than .05 for the intercept and all the predictors. In summer, nocturnal UHI intensity of Hong Kong can be estimated by

$$UHI = 5.82 - 0.3SPD - 0.34CLD,$$

where SPD and CLD represents wind speed and cloud cover, respectively. While in winter, it can be estimated by

$$UHI = 8.25 - 0.3SPD - 0.65CLD.$$

**FIGURE 5** Composite (a)–(c) u-wind velocity at 200 hPa (m s\(^{-1}\)), (d)–(f) geopotential height at 500 hPa (m), (g)–(i) precipitation (kg m\(^{-2}\)), and (j)–(l) surface air temperature (K) for neutral (class D), weak stable (class E), and strong stable (class F) atmospheric stratification stability on winter (December–January–February) nights in Hong Kong during 1995/1996–2014/2015. Color shading indicates regions that are significantly different from the mean at the 0.05 confidence level in the Student’s t test. The black dot denotes the location of Hong Kong.
According to the Pasquill stability classification scheme, surface wind speed and insolation are considered in dividing the daytime stability classes. The correlation coefficients in Table S4 suggest that daytime UHI intensities (calculated by the mean $\Delta T$ during 1200–1500 LST) do significantly correlate with the two meteorological parameters in classifying Pasquill stability. The negative correlations imply that the stronger the atmospheric stability, the more intense the UHI. However, the relationship between diurnal UHI and atmospheric stability will not be further discussed for two reasons: First, Figure 2 demonstrates that there is no robust daytime UHI in this city. The UHI value is climatologically negative—in other words, it is an urban cool island. Second, there are no appropriate thresholds to divide daytime insolation into “strong,” “moderate,” and “slight” for Pasquill stability classification. Although we have tested some thresholds for the classification as mentioned above, the uncertainty regarding the UHI itself leads to failure to establish a robust relationship between UHIs and atmospheric stability (as shown in Figure S3).

3.3 | Linking with large-scale atmospheric patterns

Using the composite technique with the Student’s $t$ test, Figures 4 and 5 illustrate the anomalies of atmospheric parameters for different nocturnal stability classes corresponding to the mean in summer and winter, respectively. In summer, nights with neutral stability in Hong Kong are controlled by low pressure with rising motion, less precipitation, and lower air temperature at the surface (Figure 4a,d,g,j). On nights with a strong stable atmospheric boundary layer, the situation is the opposite. Southeast China is controlled by high pressure and high surface air temperature; Hong Kong is surrounded by local sinking motion with dry anomalies (Figure 4c,f,i,l). On nights with weak stable stratification, atmospheric anomalies are generally nonsignificant (Figure 4b,e,h,k).

In winter, the influence of the large-scale circulation system of the East Asian winter monsoon (EAWM) is significant. In the upper layer, the East Asian jet stream (EAJS) retreats westward (is displaced northward) on nights with neutral (strong stable) atmospheric stratification in Hong Kong (Figure 5a,c). The middle-layer geopotential height corresponds to the displacement of the EAJS (Figure 5d,f). At the surface, southeast China is hot and humid on nights with neutral stability in Hong Kong (Figure 5g,j), while on nights with strong stable stratification, the coastal regions of southeast China are dry, and East Asia is dominated by positive anomalies of surface air temperature, but negative anomalies over the South China Sea are found (Figure 5i,l). Analogous to the situation in summer, atmospheric anomalies are generally nonsignificant on nights with weak stable stratification (Figure 5b,e,h,k).

4 | DISCUSSION AND CONCLUSIONS

The definition of UHIs is simple, but attribution is complicated. From a “bottom-up” perspective, urban morphological parameters such as impervious surface ratio, surface albedo, street canyon aspect ratio, and vegetation density are major predictors explaining UHI response (Kotharkar et al., 2019). From a “top-down” point of view, meteorological characteristics and synoptic conditions including precipitation, wind, cloud cover, fog, air pollution, and haze affect the intensity and magnitude of UHIs (He, 2018).

Taking Hong Kong as an example, this study demonstrates the daily and seasonal dynamics of UHIs in this high-density subtropical coastal city. The 2–3°C nocturnal UHI intensity in summer means an exact requirement of electric power for air conditioning, while the diurnal “urban cool island” in summer is a potential energy saver. In winter, a nocturnal UHI of more than 4°C implies fewer cold nights. As there are no unequivocal daytime UHIs, only nocturnal UHIs are grouped according to various dynamic stabilities of the boundary-layer atmosphere, namely neutral, weak stable, and strong stable. Results indicate that the stronger the atmospheric stability, the more intense the UHI. The traditional classification scheme proposed by Pasquill was adopted in this study. The method is simple but still widely used today, as it requires only surface meteorological observations (Kahl and Chapman, 2018).

Consequently, the atmospheric anomalies linked to the observed stability classifications are investigated. In summer, neutral nights with weak UHI intensity are controlled by low pressure with rising motion, less precipitation, and lower air temperature at the surface, while on strong stable nights with strong UHI intensity, the region is controlled by high pressure, and hot and dry air with sinking motion. In winter, the influence of the EAWM circulation system is significant (Wang et al., 2014a). In the upper layer, the EAJS retreats westward (is displaced northward) on neutral (strong stable) nights with weak (strong) UHI intensity (Wang et al., 2013). At the surface, meteorological conditions are adjusted according to the upper layer anomalies. The practical implication of these findings is to provide a quantitative predictor in the upper layer atmosphere for UHI intensity and hence lower the barrier to UHI mitigation.
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ORCID
Weiwen Wang https://orcid.org/0000-0002-1714-1008

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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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