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Spatial Analysis on Intra-Urban Temperature Variation under Extreme Hot Weather by Incorporating Urban Planning and Environmental Parameters: A pilot study from Hong Kong

Meng Cai[1], Chao Ren[1, 2, 3], Kevin Ka-Lun Lau[1, 3, 4] and Yong Xu[1]

[1]Institute of Future Cities, The Chinese University of Hong Kong, Hong Kong
[2]School of Architecture, The Chinese University of Hong Kong, Hong Kong
[3]Institute of Energy, Environment and Sustainability, The Chinese University of Hong Kong, Hong Kong
[4]Institute of Aging, The Chinese University of Hong Kong, Hong Kong

Abstract: The number of extreme hot weather events have raised significantly in Hong Kong. Due to urban heat island effect, urban thermal environment of Hong Kong has been deteriorated. However, there is limited spatial understanding of intra-urban temperature variation under extreme hot weather conditions and climate-sensitive design for reducing heat load in severe heat events. Thus, there is a need to analyse the spatial distribution of intra-urban temperature variation of extreme hot weather and the impact of urban environment parameters on intra-urban temperature differences. In this paper, firstly, hourly air temperature records from 40 Hong Kong Observatory stations from 2011 to 2015 were collected to analysis hot night and very hot day. Secondly, for spatially mapping the very hot days and hot nights, kriging, a geostatistical interpolation algorithm, was adopted. Thirdly, urban environmental parameters (digital elevation model information, sky view factor and the NDVI) were incorporated in co-kriging interpolation for a more comprehensive understanding of the correlation of extreme hot weather and their spatial patterns. The generated maps of very hot day and hot night can provide better understanding of intra-urban temperature differences under extreme hot weather events and help to create climate-sensitive design strategies to cope with climate change locally.

Keywords: extreme hot weather, intra-urban temperature variation, climate-sensitive design, high density city, climate change

Introduction

There is a growing number of heat waves since the end of the twentieth century and this growing trend will continue throughout the 21th century(IPCC, 2014). Hong Kong has more frequent extreme weather events such as very hot days and hot nights since its urbanization started in the 1960s(HKO, 2015). Urban thermal environment of Hong Kong has been deteriorated due to urban heat island effect. It's reported that Increase in 1 °C in hot days was associated with 6.82% increase in deaths in Hong Kong(Fung, 2004). As the number and duration of extreme heat events are likely to increase with climate change, it is important to obtain a more comprehensive understanding of extreme hot weather in urban environment. The conditions of extreme hot weather are generally based on the meteorological data acquired at ground-level meteorological stations(WMO& WHO, 2010). However, there is insufficient information on the spatial distribution of intra-urban temperature difference variations due to the limited coverage of the stations(WHO/Europe, 2004; WMO& WHO, 2010). Moreover, the problem is aggravated with the limited knowledge of the effect of urban environment on extreme hot weather and appropriate urban planning and design in the context of adapting and mitigating the extreme heat events. Therefore, there is an urgent need for better understanding of the spatial variation of extreme hot weather for more climate-responsive urban planning and design and hence more sustainable urban living.

This study aims to obtain a comprehensive understanding of spatial variation of intra-urban differences in temperature under extreme hot weather using spatial interpolation techniques. The understanding of the intra-urban temperature variation under extreme hot weather can help policy makers and urban planners to have a better understanding on the spatial distribution of the extreme hot weather, thus taking effective and targeted action for the most vulnerable areas. Also, the urban environment characteristics can contribute to the urban planning and building design for the resilience and adaption strategies of Hong Kong, therefore reducing the adverse impact of heatwaves at present and under climate change.

Materials and Methodology

Study Area

Hong Kong (22° 16’ 50” N, 114° 10’ 20” E), located on the southeast coast of China, has total area of about 1104 square kilometres covering Hong Kong Island, Kowloon and the New Territories and Islands. The terrain of Hong Kong is mountainous with steep slopes, where the elevation ranges from sea level to over 900m above sea level(Morton, 1995).

Hong Kong has monsoon-influenced subtropical climate, experiencing very hot weather in summer. Air temperatures typically reach 33 °C on the hottest summer days, cooling to 26 °C in urban and 24 °C in rural areas at night(Nichol et al., 2012). On one hand, the temperature is continuously growing. The annual mean temperature increased 0.12°C per decade from 1885 to 2015 in average. The rate of increase in average temperature reached 0.17°C per decade during 1986-2015(HKO, 2015). On the other hand, there are more frequent occurrence of the extreme hot weather in Hong Kong. The annual count of hot nights and very hot days has increased significantly, by 19 and 10 respectively from 1885 to 2015(HKO, 2015). Moreover, extreme temperature in Hong Kong further suggests that the number of extreme hot weather is expected to increase significantly in the 21th century (HKO, 2015).

Data

Hourly air temperature data from 40 air temperature stations of the Hong Kong Observatory in June, July, and August (the months defined as summer in Hong Kong) were used for mapping out the intra-urban temperature variation under extreme hot weather. The 40 stations can represent both city and rural environments of Hong Kong (Figure 1). The years 2011-2015 were selected for this study because the past five years have more extreme hot records and most complete database of temperature recordings available for Hong Kong. And also this is a pilot study. Later the findings will be applied to a case study with a longer study period.

Based on the findings of Hong Kong Urban Climatic Map project, urban morphology parameters include digital elevation model (DEM) information, sky view factor (SVF) and the normalized difference vegetation index (NDVI) were selected to capture and describe urban geographical and morphological characteristic(Ng et al., 2015; Ng et al., 2012; Ren et al., 2011). The intra-urban distribution of the temperature excess is largely dependent on local surface characteristics and previous studies have identified a link between these parameters and air temperature(Unger, 2008). Air temperature generally decreases with elevation and air temperature is often lower with higher altitude(HKO, 2017). SVF is important for the spatial variation of air temperature within the urban environment(Maru et al., 2015). Temperature studies in Hong Kong showed that places with higher greenery coverage often have lower maximum temperature than that with lower greenery coverage, in particular in summer(HKO, 2017).

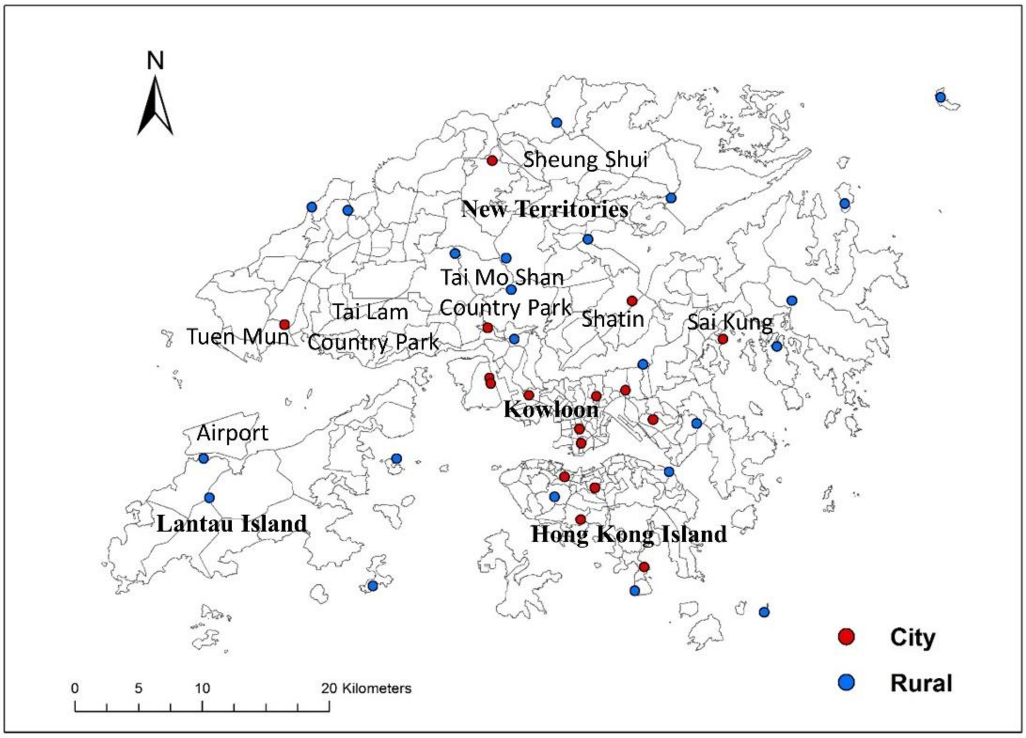

Figure 1. Distribution of the HKO stations.

Table 1. Urban Morphology Parameters.

parameter	resolution	year
SVF	1km	2009
DEM	1km	2009
NDVI	1km	2016

Kriging Analysis

In order to represent different levels of extreme hot weather, temperature classes defined by HKO were used (HKO, 2015). The classes are defined as hot nights (days with a minimum temperature of 28°C or above) and very hot days (days with a maximum temperature of 33°C or above). However, the existing definition of extreme hot weather in Hong Kong is inadequate in days with many hot hours but the minimum temperature less than 28° C. It cannot be classified as a hot night according to the HKO definition but it may still have high potential of heat hazard. In order to represent the heat hazard in a more objective and comprehensive way, the cumulative hours above 28° C and 33°C thresholds are chosen as measure for hot nights and very hot day.

First, the annual mean hot night hours and very hot day hours of each station over the ten years were counted based on the observatory data. The selected hazard measures at each site were plotted as point values in GIS. Second, a geostatistical interpolation algorithm, called kriging, was applied to map the very hot days and hot nights. The kriging interpolation expresses the spatial variation of the property in terms of the variogram, and minimizes the prediction errors which are themselves estimated(Oliver, 1990).

In addition, urban morphology parameters such as the SVF, NDVI and DEM also have influence on the spatial pattern of extreme hot weather. These factors were also involved in the interpolation process by co-kriging to gain a more comprehensive understanding of the correlation of hot weather and spatial patterns.

Result and Analysis

Very Hot Day and Hot Night between City and Rural Stations

According to the statistical results of the extreme hot weather under city and rural stations, it can be observed that city stations have higher mean, median very hot day hours and hot night hours than rural stations, indicating significant urban heat island (UHI) effect in Hong Kong and urban areas are more vulnerable to heat hazards(Landsberg, 1981; Oke, 1982, 2002). In addition, hot night hours have larger range and values than very hot day hours thus there are more extreme heat events during night time.

Table 2. Statistical results of the extreme hot weather between city and rural stations.

Hot weather indicator	City station	Rural station
Average very hot day hours	62.4	49.5
Median very hot day hours	48.1	37
Range of very hot day hours	11-190.6	0-149.8
Average hot night hours	527.8	223.8
Median hot night hours	533.6	202.8
Range of hot night hours	113.6-693.6	0-485

Spatial distribution of very hot day

The spatial distribution of the very hot days and hot nights was mapped and the potentially hot areas in Hong Kong identified by using kriging and co-kriging method (Figure 2&3). The most frequent very hot day hours occur in the north of the New Territories where most are rural areas according to the kriging mapping results. The number of very hot days is predominantly high in rural areas due to the more open settings without high-rise buildings or high mountains where there is better air ventilation and less sky obstruction, leading to persistently high temperature. More frequent very hot day hours are also identified in urban areas in Kowloon and the western Hong Kong Island. There are few very hot day hours in Lantau Island, Tai Mo Shan Country Park and the rest of the Hong Kong Island.

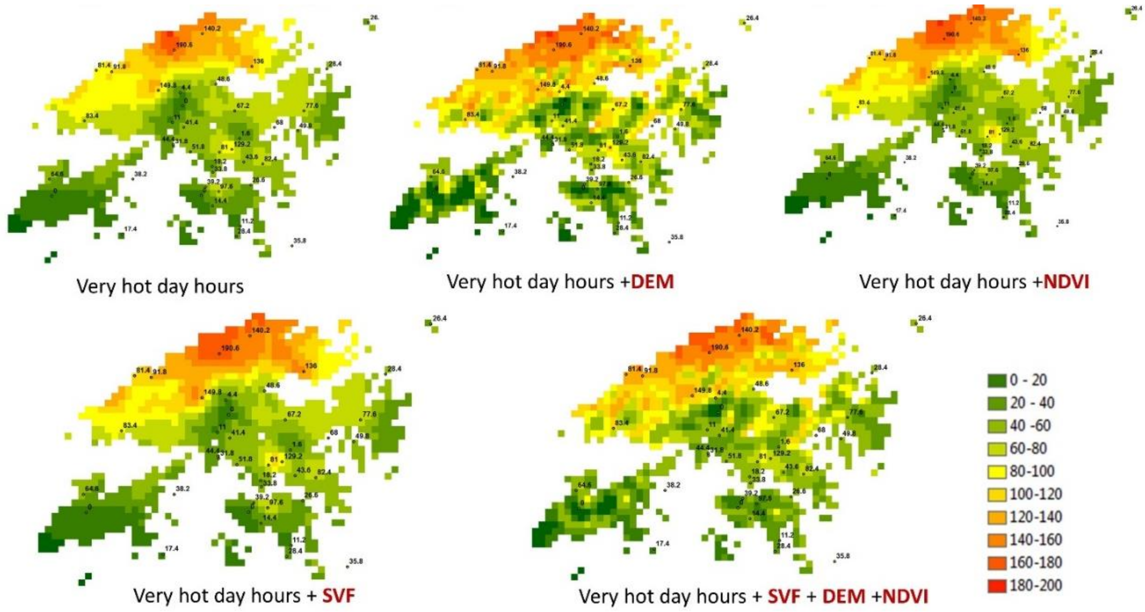

Figure 2. Mapping results of annual average very hot day hours (2011-2015).

The DEM information helps differentiating very hot day hours in the mountainous areas such as Lantau Island, Hong Kong Island and Tai Mo Shan Country Park. The mapping results are similar with the kriging mapping result after incorporating NDVI and SVF. However, more very hot day hours are detected in the west of the New Territories with relatively little vegetation coverage.

The results delineate more detailed spatial distribution of the extreme heat events after incorporating all the three urban environmental factors in the interpolation process. The high frequency of very hot day hours in the northern New Territories are more scattered than that of the original kriging mapping. Also, very hot day hours are also detected in Shatin, airport in the Lantau Island, which is not represented by the previous results. In addition, very hot day hours in Tai Lam Country Park are characterized as low by taking elevation into account. In particular, the lowest very hot day hours are located in the peak of the Tai Mo Shan Country Park which is the highest place in Hong Kong.

Spatial distribution of hot night hours

High hot night hours occur most frequently in urban areas such as Kowloon and Hong Kong Island while low hot night hours are located in the rural areas in Hong Kong. Dense development with tall buildings can affect the solar radiation, reduce wind speed and slow down night time cooling rate in the urban area, leading to generally higher night time temperature in urban areas when compared with rural stations(HKO, 2010). Also, the counts of hot nights are much greater than that of very hot day which indicates that night time extreme heat events are more frequent and severe than daytime extreme heat events.

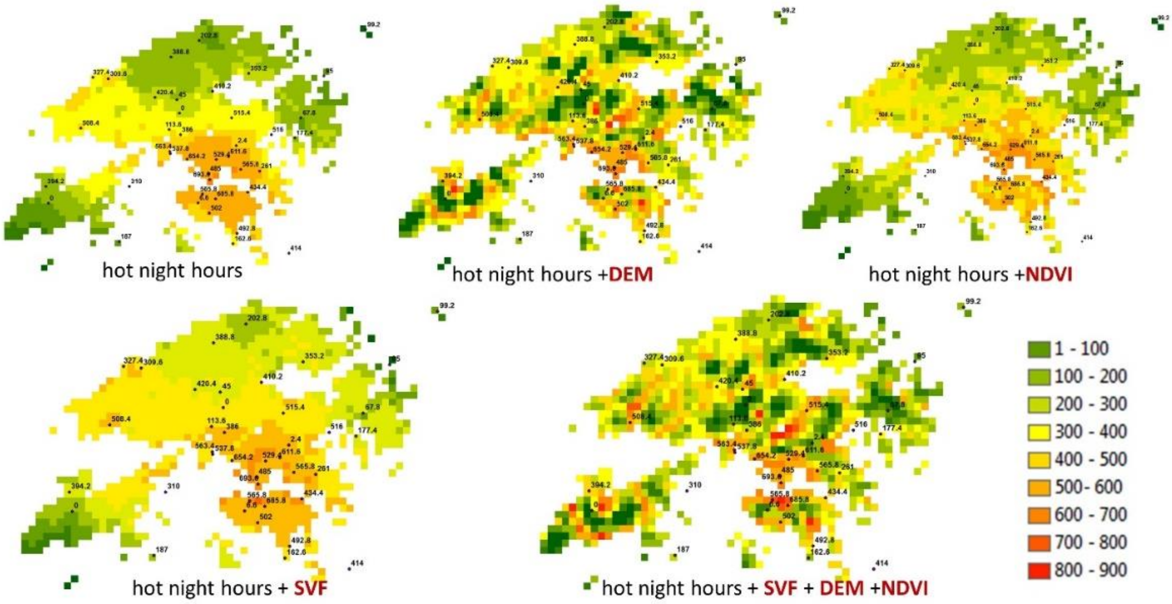

Figure 3. Mapping results of annual average hot night hours (2011-2015).

The range of hot night hours has been significantly increased after co-kriging using DEM information. Lowest values of very hot day hours have been detected in high-altitude locations such as Lantau Island and Tai Mo Shan Country Park due to their high environmental lapse rate. NDVI helps characterize hot night hour variation more detailed according to different greenery coverage. SVF increased the value of hot night hours in the whole New Territories in comparison with the original kriging mapping. Larger areas in urban areas such as Kowloon, Hong Kong Island and Shatin district are characterized as high very hot day hours by taking the three parameters into account. The co-kriging method also captured hot night hours in the west of the New Territories. The result is similar with the co-kriging mapping using DEM, demonstrating that DEM may have dominant impact on the spatial distribution of the extreme heat events in comparison of the other two parameters.

Conclusion

This study mapped the intra-urban temperature variation under extreme hot weather by incorporating DEM, SVF and NDVI based on the annual average very hot day hours and hot night hours from 40 weather stations in Hong Kong. It's found that urban stations have more frequent extreme hot weather than rural areas, indicating significant UHI effect in Hong Kong. In addition, there are more extreme heat events during night time in Hong Kong. Moreover, the north of the New Territories has more daytime extreme hot weather while urban areas in Kowloon and Hong Kong Island have more extreme heat events during night time. Finally, the co-kriging mapping incorporating all the three parameters delineates the spatial distribution of the intra-urban temperature under extreme hot weather in a more detailed and reasonable way.

Findings of the present paper contribute to a better understanding of the spatial variation of extreme hot weather in high-density urban environment. It also provides local-scale information for the selection of representative meteorological stations for heat wave warning system which the World Meteorological Organization and the World Health Organization jointly call for actions by the governments.

In future, we will interpolate average, minimum and maximum air temperature to further analyse the spatial pattern of extreme hot weather and map hourly average air temperature to understand the temporal variations of extreme heat events. We also plan to determine a more appropriate heatwave threshold, to select alternative index for the kriging interpolation (Glenn et al., 2017) and as well as to link the mapping result with heat-related mortality in Hong Kong for future enhancement of local heat health risk studies, thus ensuring a healthy urban living for local citizens.

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