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Estimates of the impact of extreme heat events on cooling energy demand in Hong Kong

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ABSTRACT

To better understand the relationship between energy consumption, and prevailing climatic condition, the present study uses Hong Kong's observed air temperature records, end-use electricity consumption, and population datasets to: (a) investigate the spatial pattern of cooling energy requirement i.e. cooling degree days on a typical normal and extremely hot summer day using co-kriging geospatial mapping technique; (b) analyze the annual trend of cooling degree days in the city; and (c) quantify the impact of extreme heat events on the summer cooling energy requirements. Results revealed reasonable predictability of city-wide cooling degree days with the co-kriging method which uses two covariates i.e. “elevation of the weather station” and “building volume density within the 1000 m radius neighboring area”. Homogeneity and heterogeneity in cooling degree days' distribution were found during the summer daytime and nighttime, respectively indicating the method's ability to delineate the urban heat island effect with increased magnitude during extreme heat events. Quantitatively, the extreme heat events increased cooling degree days by 80–140% depending on the event type, a range consistent in recent years (2011–2015). Lastly, we provided the implications of our findings to building and urban design; and future energy planning.

1. Introduction

1.1. Background of study

The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) revealed the indisputable warming of the earth's surface up to about 0.9 °C since the late 19th century [1]. This abrupt change is driven largely by increased anthropogenic greenhouse gas emissions since the pre-industrial era caused by economic and population growth, and urban development with impacts in almost all sectors of human living including agriculture, aviation, road transportation, water resources and energy [2]. Coupled with the current rate of urbanization, global warming and urban heat island (UHI) effect have been attributed as two of the causatives of increasing energy demand and consumption especially during the summer period of most tropical and subtropical cities or countries [3,4]. In fact, the intensification of higher ambient temperature induced by global climate change in recent years has resulted in increased cooling energy consumption across the world [5,6]. Santamouris [7] estimated the average Global Energy penalty per unit of surface and degree of UHI intensity as 0.74 kWh/m^2/K while the average total energy load of representative buildings consumed for heating and cooling purposes increased by 11% between 1970 and 2010. Akbari [8] found increases in air temperature explain 5–10% of urban peak electric demand, with a typical rise of 2–4% for every 1 °C rise in daily maximum temperature over 15–20 °C in the United States. However, the demand of cooling or heating energy varies across climate zones; in cold countries, where heating energy demand is higher, less energy will be required for buildings' heating during winter while buildings' cooling energy demand increases in tropical countries during hot summer [2,9]. Thus, the high outdoor ambient temperature will significantly influence energy consumption by

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increasing the demand for refrigeration and air conditioning; and reducing space heating demand [10]. This observation is raising public awareness concerning energy use and climate change implications and helped generate a lot of interests in having a better understanding of energy consumption and its correlations with the prevailing weather conditions. With the continued global climate change and urbanization rate, cities will become more susceptible to extreme heat events in which it is very likely hot days and nights; and intensity and frequency of heatwaves will further increase in the future as projected by IPCC [11]. This directly implies higher energy demand and consumption if human thermal stress will be tamed and desirable human thermal comfort in indoor spaces will be actualized.

1.2. Relationship between ambient temperature and cooling energy requirement

Climate has been long understood as a major influencing factor of energy consumption in cities [12] with air temperature leading the ranks of the climatic factors even as others such as relative humidity, solar radiation cannot be underemphasized [13,14]. Studies across the globe and subtropical climates especially had shown an increasing trend of temperature and summer discomfort over the past decades, and consequently, more cooling energy demand is anticipated [15]. To estimate the heating and cooling demands at different spatial scales, degree-days method described as the most simple, and practical of all other methods is widely used for measuring the influence of climate, i.e. severity of winter and summer conditions on heating and cooling requirements [16,17]. The degree days basically provide an understanding of the thermal needs and energy consumption patterns of a building, city and region [18]. It is subdivided into the heating and cooling components i.e. Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) and can be defined thus [17]: HDDs is the sum of the difference between the outdoor temperature and a selected base temperature, taking into account only positive values while CDDs is calculated from temperatures above the base temperature. The base temperature is defined as the outdoor temperature above or below which thermal equilibrium is reached in the building, i.e. no need for heating or cooling as the case may be and varies across climatic regions and different building types [19]. The use of degree-day methods in the citywide and building-scale energy analysis is presented in several studies, e.g. Refs. [20–24]. Thus, the present study will adopt this approach in investigating the spatio-temporal trend of cooling energy requirement during the typical and extremely hot summer period in Hong Kong.

1.3. Motivation and objective of study

An overview of end-use energy consumption in Hong Kong [25] revealed highest electricity consumption in the summer months (June–September) in two dominant sectors (residential and commercial) most of which are used for space cooling and refrigeration suggesting the role of ambient mean temperature as an undoubted determinant of residential and commercial electricity consumption. In the wake of future climate, the Hong Kong Observatory has projected long term increasing trend in air temperature which could signal more electricity consumption especially for space cooling. While previous studies [12,26,27] have studied the trend of CDD in Hong Kong, they used a single station data, i.e. Hong Kong Observatory headquarters at Tsim Sha Tsui of the Kowloon Peninsula. The unarguable reason is mainly that is its long years of record dated back to 1885 and its location in an urban area which implies the urban effect is accounted for in the temperature record. However, since the mid-1980s, more automatic weather stations have been installed across the city paving the way to address the insufficient information on the spatial distribution of intra-urban temperature difference variations and other derived variables such as cooling or heating degree days [28]. The spatial understanding of CDD for instance will enhance climate-responsive urban planning and design and sustainable urban living thus help the Government make an objective and targeted action for the most vulnerable areas.

Furthermore, Fung et al. [29] studied the temperature dependence of the monthly energy consumption for the period from 1990 to 2004 and indicated that temperature rise resulted from global warming and local urbanization could have implications on the energy sector of Hong Kong. Lee et al. [12] extended the study by attempts to identify the monthly variation of energy consumption and the correlation between energy consumption and climate factors in Hong Kong using the monthly energy consumption data and meteorological observations from 1970 to 2009. They found CDD had a significant positive correlation with electricity consumption in both residential and commercial sectors in warm months and the consumption per unit CDD increased from the 1970s to the 2000s, probably due to the higher living standard and the increased popularity of air-conditioning during this period. Futuristically, the projected increase in the mean temperature denotes a significant increase in the frequency and intensity of extreme heat events by the end of the 21st century which may have consequent implications on the future energy demand provided the current energy consumption pattern is not altered.

Meanwhile, the previous studies as described above have averaged-out the role of extreme heat events on cities' or building energy consumption while the scientific evidence of energy requirement on extremely hot days or events will aid futuristic energy planning since the frequency and intensity of the very hot weather events are projected to increase under either medium-low or high emission scenario. Thus, in the present study, the summer CDD trend analysis will be extended to 2015 from 1970 while the impact of extreme heat events on cooling energy requirement will also be investigated. Thus, a more comprehensive understanding of extremely hot weather in an urban environment and implication on energy consumption will be acquired and documented. These are in addition to the better understanding of the spatial variation of Hong Kong's summer cooling requirement under typical and extremely hot weather using spatial interpolation techniques.

2. Data and methods

2.1. Study area

Hong Kong (22°16′50″N, 114°10′20″E) has a monsoon-influenced subtropical climate characterized as hot-humid in the summer with maximum daily air temperature often reaching 31 °C or above but could reduce to 26 °C in urban and 24 °C in rural areas at night with high humidity [30,31]. Under the combined effect of global climate change and local urbanization there is a long term increasing trend in the average temperature in Hong Kong. Trend analysis of the annual mean temperature data from 1885 to 2017 showed an average rise of 0.12 °C per decade with a faster rate observed in the latter half of the 20th century, reaching 0.18 °C per decade during 1988–2017 [32,33]. More critically, more frequent extreme heat events such as very hot days and hot nights have been observed in Hong Kong since the inception of her urbanization in the 1960s [34–36] and projected increasing trend is throughout the

21st century [11,31]. The annual count of very hot days and hot nights has increased significantly from the 19th to 20th century with an expected further increase in the 21st century [34]. Consequently, building energy demand and consumption is on the increase and may further increase in response to future climate change.

2.2. Data description, selection and distribution

The methodological framework of this study is presented in Fig. 1, it highlights the main research steps taken to actualize the objectives of this study. Several datasets have been obtained and summarized in Table 1 which also contains the purpose or usage of each dataset. For the purpose of long-term trend analysis and estimation of CDD, we obtained summer months' (i.e. June, July, August, and September) hourly air temperature data from 1970 to 2015 of the Hong Kong Observatory Headquarters (HKOHq) station, the oldest of all Hong Kong's weather stations which has continuous record of temperature data since 1885 apart from a break during World War II from 1940 to 1946 and located at the urban area [37]. Similarly, for the historical trend analysis of electricity consumption, summer end-use monthly electricity consumption data of same period (1970–2015), cumulative (or single point data) for Hong Kong was obtained from the Census and Statistics Department (C&SD) of Hong Kong while the annual population data (1970–2015) in Hong Kong from C&SD was used to calculate the monthly consumption per capita.

For the purpose of geospatial mapping of CDD across the city, hourly air temperature data of summer month from 40 other air temperature stations (making a total of 41) was obtained from the Hong Kong Observatory. The 41 stations can represent both city and rural environments of Hong Kong (Fig. 2). The commencement date of data recording of each station differs, thus for uniformity, we selected data from 2011 to 2015 because these years have a complete database of temperature for all stations, and more extreme hot records have been recorded in these years and thus used for spatial mapping of the summer CDD.

2.3. Definitions of extreme heat events (EHEs) and calculation of cooling degree day

In Hong Kong, the Hong Kong Observatory defines the very hot day (VHD) and hot night (HN) respectively as days with daily maximum temperature $\geq 33\,^{\circ}C$ and daily minimum temperature $\geq 28\,^{\circ}C$. In this study, as the data analysis of CDD is on an hourly basis, to minimize the instantaneous temperature effect, the VHD (HN) was identified using the hourly temperature dataset, i.e. at least 1 h of daytime maximum (minimum) temperature $\geq 33\,^{\circ}C$ ($28\,^{\circ}C$). To characterize prolonged extreme heat event, at least three consecutive VHDs (3VHDs), and at least two consecutive HNs (2HNs) were selected and analyzed [38]. These temperature thresholds are in accordance with the 95th percentiles of T_{max} ($32.8\,^{\circ}C$) and T_{min} ($28.2\,^{\circ}C$) estimated from 2007 to 2014 temperature data in Hong Kong, and consistent with the 95th (or above) percentile threshold method for defining heat waves, an approach adopted in estimating the heat-related mortality data in many cities and countries [38,39]. For estimating the cooling energy requirement during the typical and extreme summer period in Hong Kong, average CDD per hour was calculated for days without any of the extreme heat event or reference condition hereafter named Non-Event Days (NED) and compared with the corresponding extreme heat period (VHD, HN, 3VHDs and 2HNs) to estimate the impact of Extreme Heat Events (EHEs) on CDD in Hong Kong.

$$CDD_{NED} = \frac{1}{N}\sum_{i=1}^{JJAS}(T_i - T_b)_{NED} \quad \left(for\ T_b > T_i\, ,\ (T_i \ - \ T_b) = 0\right) \tag{1a}$$

$$CDD_{EHE} = \frac{1}{N}\sum_{i=1}^{JJAS}(T_i - T_b)_{EHE} \quad \left(for\ T_b > T_i\, ,\ (T_i \ - \ T_b) = 0\right) \tag{1b}$$

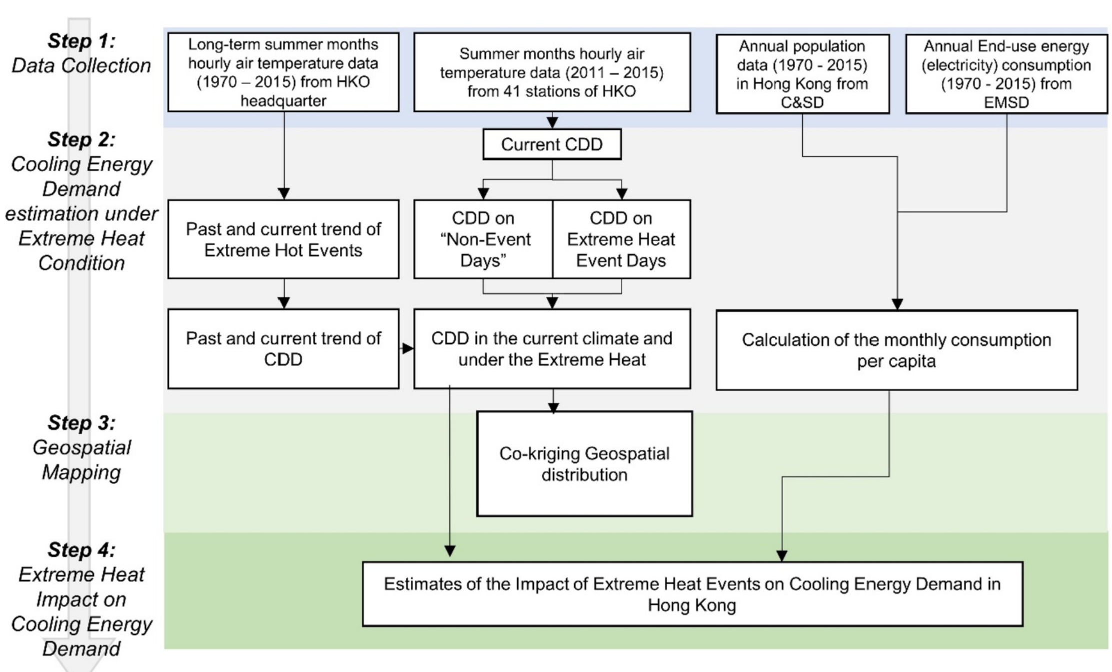

Fig. 1. Methodological flowchart on the study.

Table 1
Summarized list and description of the applied dataset for this study.

Data type and source	Data period	purpose and description
Hourly air temperature (Hong Kong Observatory)	1970–2015	This long-term dataset is only available for the HKO Headquarter station. It was used as representative data for the trend analysis CDD and estimation of relationship with space cooling energy consumption
Hourly air temperature (Hong Kong Observatory)	2011–2015	Data available for all weather stations in Fig. 3 for the stated period and therefore applied for geospatial interpolation of Citywide CDD.
End-use Energy (Electricity) consumption (Energy and Mechanical Services Department, HKSAR)	1970–2015	Available data is cumulated over Hong Kong
Population (Census and Statistics Department, HKSAR)	1970–2015	Available data is cumulated over Hong Kong

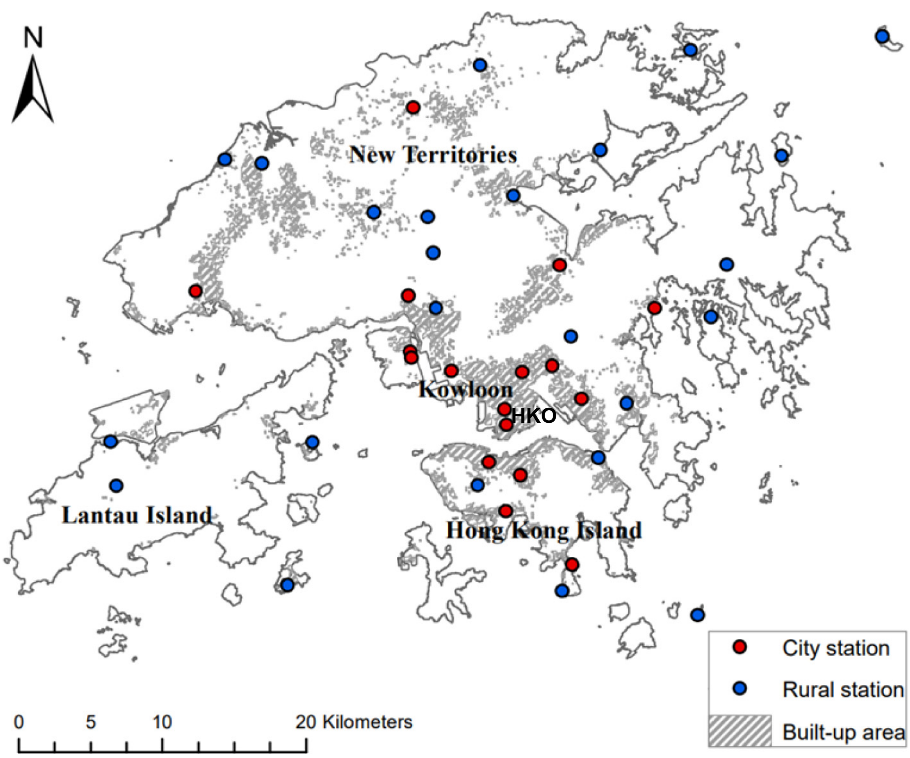

Fig. 2. Distribution of the Hong Kong Observatory stations.

To estimate the impact of each of the EHE on cooling energy requirement, the relative difference (%) between CDD during each EHE and corresponding NED was calculated thus:

$$EHEI(\%) = \left(\frac{CDD_{EHE} - CDD_{NED}}{CDD_{NED}}\right) \times 100 \quad (2)$$

where:

CDD_{NED} = Cooling Degree Days on a Non-Event Day (NED) during the ith hour of the day (07:00–18:00) or night (19:00–06:00) of the summer months i.e. JJAS- June, July, August and September
CDD_{EHE} = Cooling Degree Days on an EHE day or period (i.e. VHD, HN, 3VHDs or 2HNs) during the ith hour of the day or night
T_i = actual air temperature at the *i*th hour of the day or night
T_{base} = is defined as the temperature at which a building reaches thermal equilibrium with the incoming energy and the environment i.e. the base temperature above which cooling will be required which is 26 °C for this study following Ministry of Housing and Urban-Rural Development in China (2005) [12].
N = Total number of hours
$EHEI(\%)$ = Extreme Heat Event Impact on cooling energy requirement

2.4. Geospatial analysis technique

As mentioned earlier, the long-term air temperature monitoring data are acquired from the local authority – HKO. The air temperature is only monitored by the sparsely-built monitoring network as such the CDD could only be calculated at the locations of 41 weather stations. However, a fine-grained spatial estimation of CDD is necessary for analyzing the spatial trend of CDD on "EHE" and "Non-EHE" days in Hong Kong. Therefore, the spatial analysis needs to be performed to provide the continuous spatial estimation of CDD. Kriging and co-kriging are two spatial interpolation methods that have been widely used to create spatially continuous

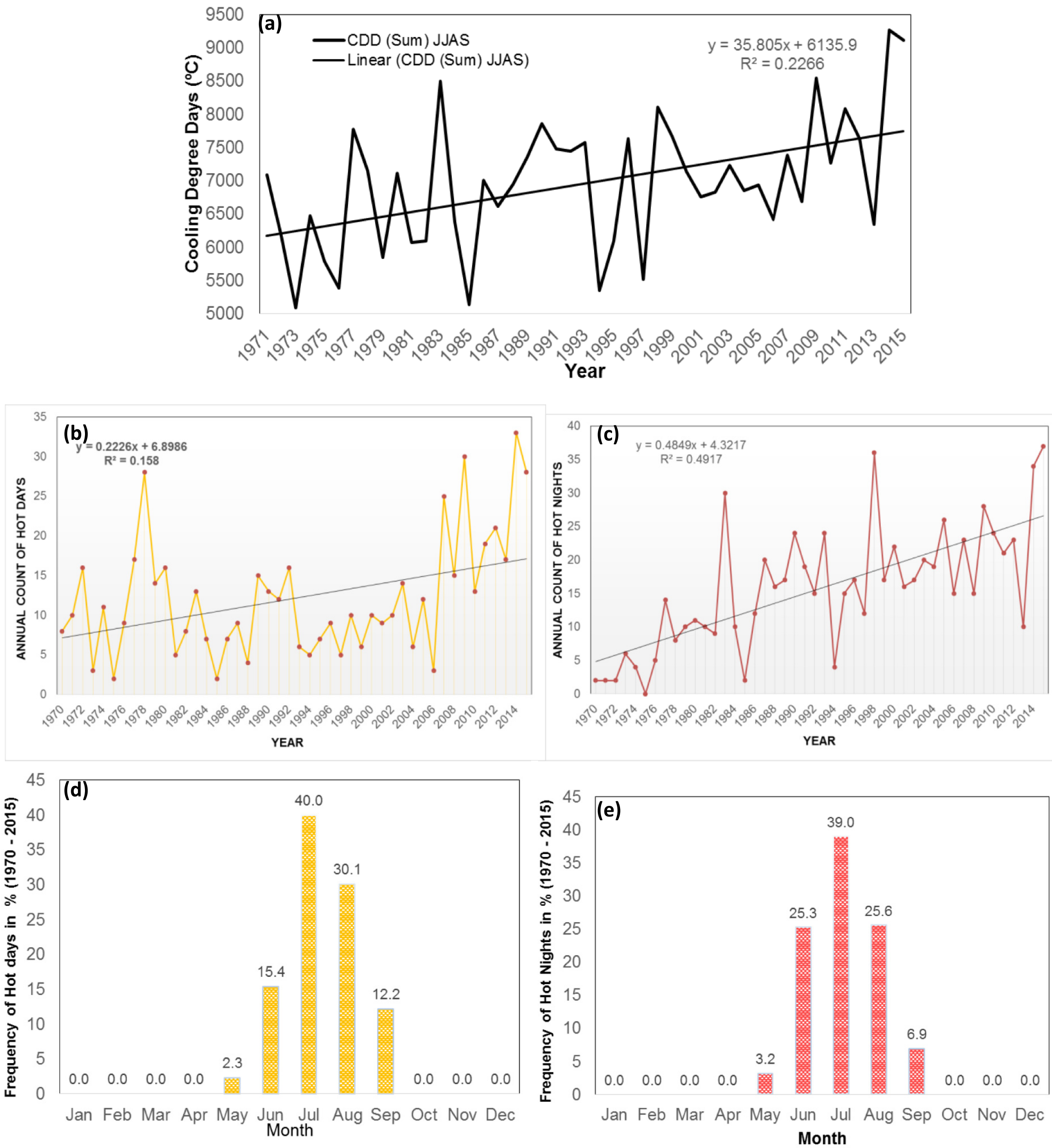

Fig. 3. (a) Time series of summer Cooling Degree-Day (June–September) season from 1970 to 2015. Annual count of (b) Very Hot Days and (c) Hot nights from 1970 to 2015. Monthly average distribution of (d) Very Hot Days (f) Hot Nights.

climate-related data [40]. They estimate the value of a variable or indicator of interest at an unmonitored location based on the values at neighboring monitored locations by fitting a semi-variogram model which is a function of spatial distance. Based on the context of the present study, the semi-variogram model is shown as follows:

$$\hat{\gamma} = \frac{1}{2n(d)} \sum_{s_i - s_j = d} (T_{si} - T_{sj})^2 \tag{3}$$

where $\hat{\gamma}$ is the semi-variogram. Each two weather monitoring stations (at the geo-location s_i and s_j) are paired by the model. T_{si} and T_{sj} are the temperature data monitored by the two stations at s_i and s_j. d is the spatial distance between stations s_i and s_j. $n(d)$ is the total amount of the pairs of all 41 monitoring stations. Co-kriging spatial interpolation method is well-known and described in Cressie (1993). Compared with the kriging, it allows additional predictor variables that exhibit inter-correlations with the variable of interest, which possibly produces better prediction performance than kriging method [41]. This could be particularly helpful in exploring the underlying influence of urban topography on urban climate-related parameters. Previously, the co-kriging method has been tested in Hong Kong for spatial prediction of air temperature at different spatial scales [28,42]. In the present study, co-kriging is adopted to estimate the spatial distribution of CDD over Hong Kong. To take the spatial heterogeneity of the urban topography and morphology into consideration, the elevation of the weather station and building volume density were used as the covariates for improving the robustness of spatial interpolation results. To account for the influence of urbanization in the surrounding area, the averaged building volume density within the 1000 m radius neighboring area was calculated and used as a covariate. The 1000 m-search radius is determined based on the spatial resolution used in the previous study of air temperature spatial mapping over Hong Kong [40].

3. Results

3.1. Trends of cooling degree days and extreme heat events in Hong Kong

Fig. 3(a) shows the variation of summer (June to September) CDD at the HKOHq station from 1970 to 2015. The increasing trend with an $R^2 = 0.23$ and significant at a 95% confidence interval was observed. An average increase of 35 °C per year for CDD was observed from the regression equation. The maximum value of 9000 °C was observed in the summer year of 2013 while a minimum of 5000 °C was observed in 1973. A bigger value signifies higher summer temperature and consequently higher energy consumption for space cooling by air conditioning. The trend is generally consistent with the increasing pattern of mean temperature observed at the same station under the combined influence of global warming and local urbanization [12]. Over the same time period of 1970–2015, Fig. 3(b and c) shows an increasing trend of extreme heat events (i.e. very hot days, VHD and hot nights, HN counts using hourly data) in Hong Kong. The results reveal an increase of 0.2 VHD/year ($R^2 = 0.16$, statistically significant at 95% confidence level) and 0.5HN/year ($R^2 = 0.49$, statistically significant at 95% confidence level) within the period even as the trend in the recent years shows a more significant rate of increase. Considering the monthly distribution of VHD and HN within the same period as presented in Fig. 3(d&e), 97% and 98% occurred within the typical summer months classified as for June, July, August, and September. The monthly distribution revealed about 40% of the total annual VHD and HN occurred in July; and usually more HN (25%) than VHD (15%) occurred in June while more VHD than HN occurred in both August and September. However, recent observation suggests the occurrence of EHE signatures in earlier months, especially May. For instance, in May 2018, 15 consecutive VHD (17–31 May 2018) was recorded including 5 HN and less than 5 mm of rainfall within the period in Hong Kong [43].

3.2. Spatial variation of CDD and comparison between 'EHE' days and 'NED'

The previous section has given an overview of the trends of summer mean temperature and CDD in Hong Kong using a long-term dataset of the HKOHq station. Here we present the spatial distribution of the summer CDD per hour of the day, daytime (07:00–18:00) and nighttime (19:00–06:00) using the co-kriging spatial interpolation method. Some previous studies [20,21,44] have applied contour interpolation in mapping CDD in the respective cities even though the accuracy of the resultant data relative to actual is often not reported. Another attempt has been made to construct the spatial map from point observations based on multiple regression [48]. It allows the incorporation of geographical factors (longitude, latitude, and elevation, etc.) as the spatial predictors, to produce spatial maps. In the present study, to improve the spatial prediction, we have applied the co-kriging method with two covariates i.e. "elevation of the weather station" and "building volume density within the 1000 m radius neighboring area", the later accounts for the influence of urbanization. Cai et al. [28] shows the comparison of the accuracy of geospatial interpolation of intra-urban temperature variation under extreme hot weather over Hong Kong using ordinary kriging and co-kriging methods. The co-kriging approach (which incorporates digital elevation model information, sky view factor and the vegetation cover information) provided better spatial predictability of extremely hot weather and their spatial patterns than ordinary kriging method. Hence, we present geospatial maps of CDD of Hong Kong using co-kriging method (see Fig. 4). The maps collage allows for comparison between hourly CDD on Non-Event Days (NED), Extreme Heat Event Days (EHE) i.e. isolated Very Hot Day (VHD), Hot Night (HN), and prolonged high temperature cases i.e. at least 3 consecutive Very Hot Days (3VHDs) and at least 2 consecutive Hot Night (2HNs). Fig. 4(a) shows the spatial interpolation of daily averaged CDD on NED with $R^2 = 0.88$ (see Fig. 5), most areas and districts experience a daily average CDD of 1–2 °C/h while the highly urbanized areas such as the Kowloon and a portion Hong Kong Island experienced 2–3 °C/h suggesting the influence the urban heat island effects and dense urbanization on CDD while areas around the Tai Mo Shan (station elevation about 950 m) observed lowest CDD of 0–1 °C/h. Considering the daytime and nighttime conditions separately, we found homogeneity and heterogeneity CDD distribution, respectively. For daytime, an average of 2–3 °C/h was observed across the city. The open urban settings i.e. less sky obstruction of the New Territories, areas void of high-rise buildings or high mountains commensurate the urban heat island effects in the urbanized Kowloon and the western Hong Kong Island areas during the daytime on NED. On typical EHE days and period, the daytime CDD increased considerably across the city. For instance, on typical VHD, it ranges between 4 and 6 °C/h which further increased to 5–7 °C/h during the daytime of prolonged high temperature cases characterized as 3VHDs with a mapping accuracy of 77% and 72% for VHD and 3VHDs, respectively (see Fig. 5). Clearly, the low urban density areas i.e. the new territories are more vulnerable to heat hazard although when population density is considered higher cooling energy will be consumed in the Kowloon and west Hong Kong Island areas. During the nighttime on NED, CDD of 1–2 °C/h and 0–1 °C/h was found in urbanized and less urbanized areas, respectively and with a mapping accuracy of 63% and 62% (see Fig. 5). The nighttime distribution pattern further echoes the effect of urban heat island due to intense urbanization in the Kowloon Peninsula and Hong Kong Island. At nighttime, CDD increased from 0 to 2 °C/h on a typical summer night to 1–3 °C/h on typical HN and 2HNs with reasonable prediction ($R^2 = 0.70$ and 0.90 for HN and 2HN, respectively (see Fig. 4). Again the effect of urbanization was clearly noticed and the higher values were mostly found at the highly dense urbanized Kowloon Peninsula and Hong Kong Island characterized dense urban canyons which is capable of trapping heat i.e. lower night time cooling rate in the urban area, and reduce wind speed leading to generally higher nighttime temperature in urban areas during prolong high temperature condition i.e. 2HNs. Overall, Table 2 summarizes the impact of the built environment on the cooling energy requirement by comparing the absolute average CDD between urban and rural stations. Generally, the built environment contributes to the increase in CDD on both event and non-event days, however, this impact is stronger at nighttime in both cases. The daytime contribution of the built environment across the city landscape weakens when the heat events persist for more than a day. The reverse is true for the nighttime where an increase in the impact of the built environment was observed with increase length of hot nights indicating heterogeneity. The features indicate the vulnerability of

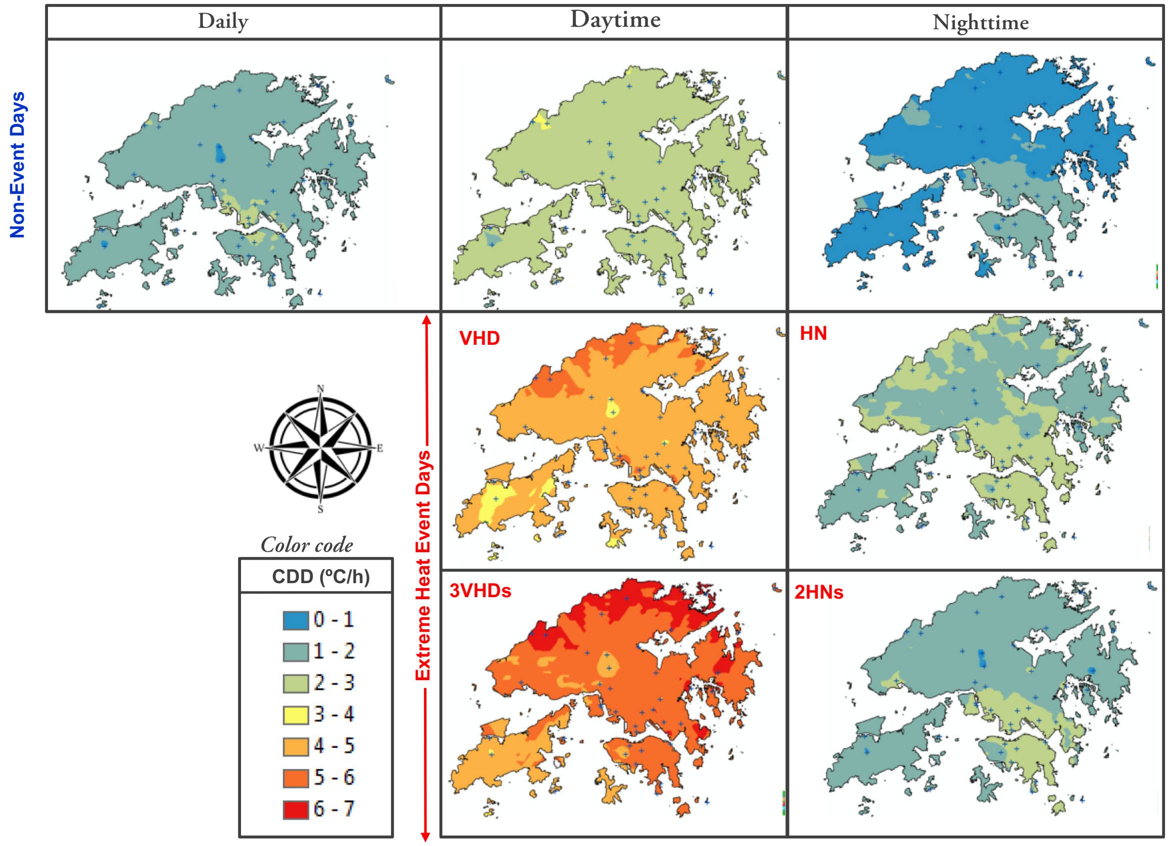

Fig. 4. Spatial variation of average summer cooling degree days per hour on typical non-event and extreme heat event days from 2011 to 2015.

this area to nighttime heat hazards and consequently, higher energy demand and consumption to attain desirable thermal comfort.

3.3. *Quantifying the impact of extreme heat events on cooling energy requirement*

In this section, we have estimated the impact of Extreme Heat Event (EHE) on cooling energy demand in Hong Kong, we calculated the relative difference (%) in CDD on EHE days/period relative to a corresponding Non-Event condition using Eq. (2) i.e. Extreme Heat Event Impact, EHEI. This aims at having an outlook on energy demand and consumption during extremely hot weather and the consequent need for energy planning as the frequency and intensity of extreme heat events is on the increasing trend. To analyze this impact, we only used data from HKOHq which is representative of the dense urban area where the majority of the population live. Here, we present the average value for recent years (2011–2015). The monthly distribution of the EHEI for each of the EHE class is shown in Fig. 6 (a) which revealed the highest impact of 3VHDs across all months except in September when its absence and that of 2HNs implies zero impact while the other two have up to 120% EHEI during that month. The yearly average per EHE class is shown in Fig. 6(b) which indicates about 80% and 100% CDD increase on a typical VHD and Heatwave period (3VHDs), respectively. Similarly, nighttime CDD increase by 80% during HN and 2HNs. On the annual scale (Fig. 6(c)), for all EHE combined relative to NED between 2011 and 2015, CDD increased from between 80% and 140%. Clearly it can be understood that energy consumption for space cooling can increase between 80% and 140% during EHE depending on the intensity of the event in the year under consideration.

3.4. *Relationship between electricity consumption and space cooling*

To understand the relationship between electricity consumption, space cooling and CDD, we first applied the population figure over the study period and the average air-conditioning end-use proportion which ranges between 35 – 36% and 29–34% for residential and commercial sector, respectively between 2005 and 2015 [25] as a correction factor to convert the 'electricity consumption' to 'electricity consumption for space cooling per capita' before correlating with CDD. Results of the correlation and regression statistics are shown in Fig. 7 and Table 3. Initial analysis with all datasets (1970–2015) pooled revealed a weak relationship between CDD and space cooling electricity consumption. Even though the statistical relationship is significant at 95% confidence level, the R and R^2 are somewhat low i.e. 0.36 and 0.13; 0.28 and 0.1; and 0.31 and 0.1 for residential, commercial and both sectors combined, respectively. Further subdivision of the dataset to decadal scale reveals an increase in the strength of the relationship between space cooling energy consumption and CDD; For instance, between 1970 and 1999, the slope (i.e. space cooling electricity consumption per capita per degree of CDD) is 0.06–0.14; 0.06–0.09 and 0.12–0.21 for residential, commercial and both sectors combined, respectively with accompanying statistically significant R and R^2. However, since the beginning of this century, all indicators of relationship have strengthened and significant at 95% confidence level. In recent years, per capita space cooling energy consumption is 0.38 kWh/°C, 0.22 kWh/°C, and 0.59 kWh/°C for residential, commercial and both sectors combined, respectively while the $R = 0.74–0.89$ and $R^2 = 0.56–0.79$. Minimal uncertainty of ±0.01 kWh/°C, ±0.02 kWh/°C, and ±0.18 kWh/°C was observed for

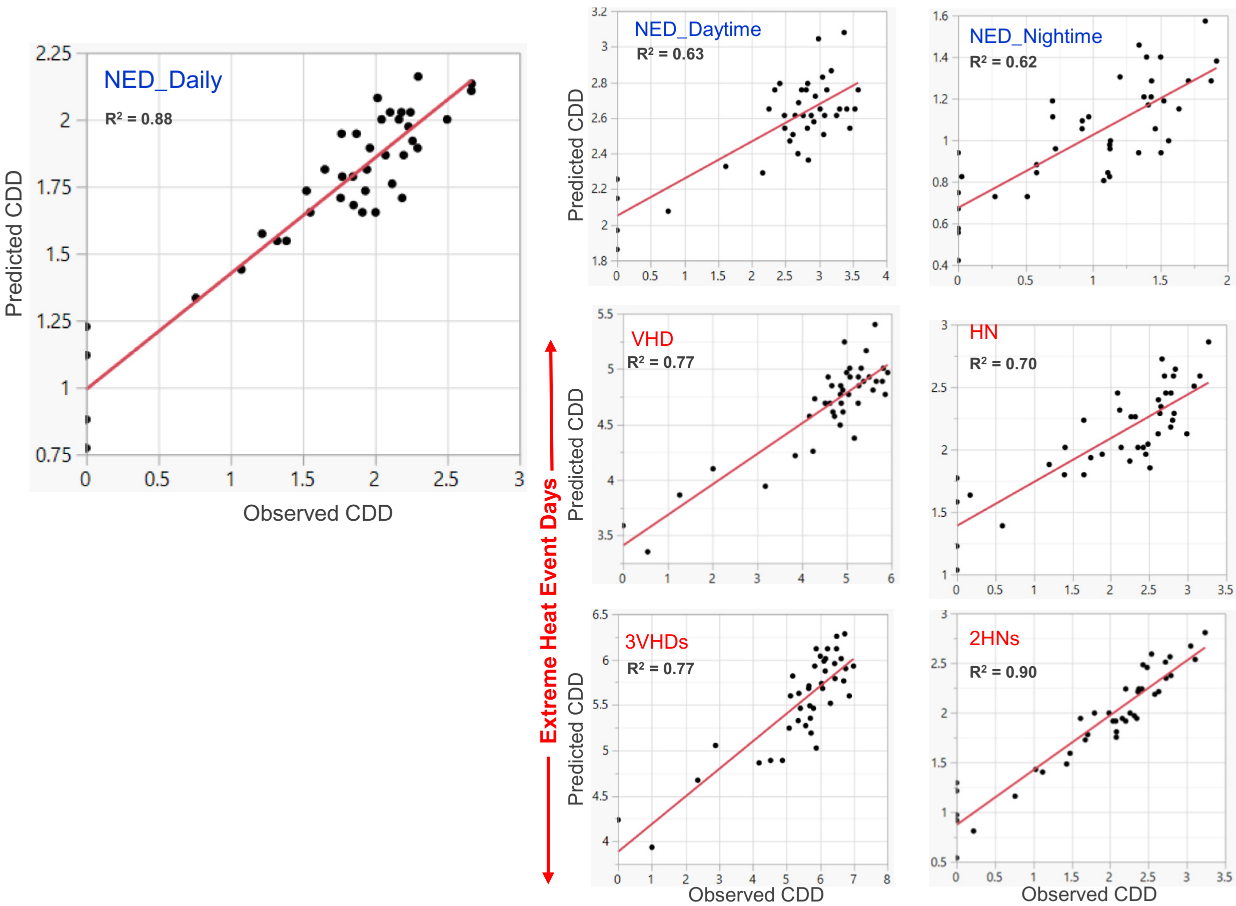

Fig. 5. Co-kriging spatial interpolation performance.

Table 2
Impact of the built environment on cooling energy requirement.

Average CDD (°C/h)	Non-Event Days			Extreme Heat Event Days			
	Daily	Daytime	Nighttime	VHD	3VHDs	HN	2HNs
Urban Stations	2.14	3.0	1.44	5.2	6.0	2.72	2.54
Rural Stations	1.61	2.5	0.83	4.2	5.1	1.83	1.66
Impact of Built Environment (%)	32.9	20.0	73.5	23.8	17.6	48.6	53.0

residential, commercial and both sectors combined, respectively if full range of air-conditioning end-use proportion in recent years were considered. In general, our finding is similar to reported a previous study which also revealed a significant positive correlation with electricity consumption in warm months and the consumption per unit CDD increased from the 1970s to the 2000s and attributed the pattern to higher living standard and the increased popularity of air-conditioning during in recent decades [12].

4. Implications to city planning and green building design

4.1. Implications and recommendations for city planning

One of the major findings from this study is the increasing trend of cooling degree days in Hong Kong and the strength of its relationship with space cooling electricity consumption. Our analysis reveals that in the most recent years, per capita space cooling electricity consumption per unit CDD is 0.38 kWh/°C,0.22 kWh/°C, and 0.59 kWh/°C for residential, commercial and both sectors combined, respectively. These two sectors contribute largely to a whopping 90% of the total electricity consumed by buildings in Hong Kong [32]. The recent closer relationship has been associated with rising income and living standards in Hong Kong [12] thus space cooling cost affordability for the majority has resulted in a rapid increase in the number of air-conditioners used in Hong Kong in the last two decades [45]. This is evident by the increasing saturation rates of the air conditioner which stood at 51% for public residential buildings to 87.1% and 92.8% by 1999 in public and private residential buildings respectively [46,47]. Moreover, the ownership level of air conditioners in both public and private residential buildings were 1.67 and 2.66 units per household respectively [12]. Therefore, implementation of energy saving measures at residential and commercial buildings levels is inevitable as Hong Kong seeks to meet her 2025 energy saving target. More so, the increasing strength of the predictability of cooling requirement with the length of the prolonged heat days during the day and night (Fig. 6) indicate a strong contribution of the built environment to urban heat and cooling energy requirement. This is due to the

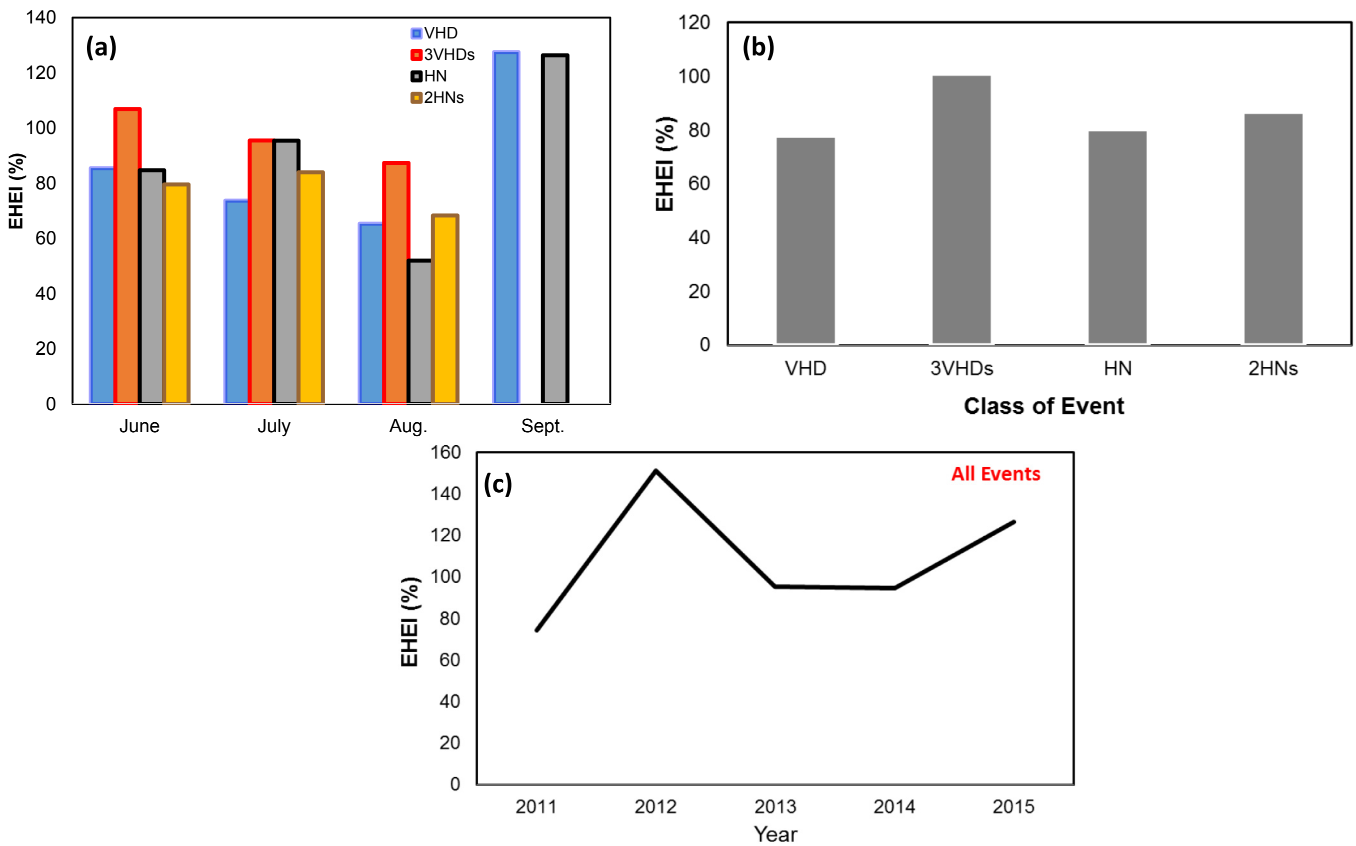

Fig. 6. Impact of EHE on cooling energy requirement (CDD) between 2011 and 2015.

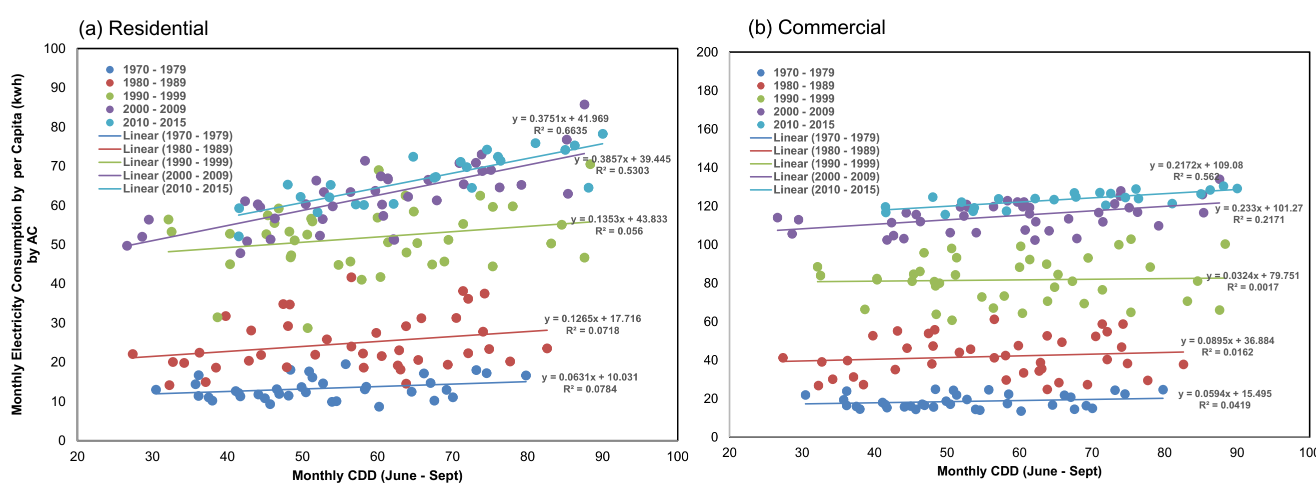

Fig. 7. The relationship between monthly electricity consumption for space cooling per capita and month cooling degree days.

urban heat island effect especially in the nighttime, higher cooling energy requirement in the downtown areas i.e. areas with compact and high density urban morphology than that in rural areas in Hong Kong. On average, the difference ranges between 20 −74% and 17−53% on events and non-event days, respectively as indicated in Table 2. The fast urbanization experienced in Hong Kong between the 1970s to the 2010s [48] i.e. urban sprawl and population increases might have contributed to this corresponding increases in space cooling electricity consumption as the years grow by. Thus, an urgent and proper climate-sensitive planning and design action to mitigate the UHI effect is needed. To ensure energy saving, conscious effort in both demand and supply sides must be in place because energy-efficient building designs are poised to help lower the energy demand and reduce emissions as discussed below.

4.2. Recommendation for green buildings design and sustainability

On the demand side, the Hong Kong Green Building Council (HKGBC) BEAM Plus assessment offers independent assessments of building sustainability performance. The assessment [49,50] gives

Table 3
Correlation statistics between monthly energy electricity consumption for space cooling per capita and monthly cooling degree days.

Decades	Slope (kWh/°C)	R	R^2	Significant?
(a) Residential				
1970–1979	0.06	0.28	0.08	No
1980–1939	0.13	0.27	0.07	No
1990–1999	0.14	0.23	0.06	No
2000–2009	0.39	0.72	0.53	Yes
2010–2015	0.38	0.81	0.66	Yes
1970–2015	0.53	0.36	0.13	Yes
(b) Commercial				
1970–1979	0.06	0.20	0.04	No
1930–1939	0.09	0.12	0.02	No
1990–1999	0.03	0.04	0.002	No
2000–2009	0.23	0.47	0.22	Yes
2010–2015	0.22	0.74	0.56	Yes
1970–2015	0.76	0.28	0.03	Yes
(c) Residential + Commercial				
1970–1979	0.12	0.24	0.06	No
1930–1989	0.21	0.19	0.04	No
1990–1999	0.17	0.13	0.02	No
2000–2009	0.62	0.65	0.42	Yes
2010–2015	0.59	0.89	0.79	Yes
1970–2015	1.29	0.31	0.10	Yes

credits and incentives to spatial planning and building designs actions for building energy efficiency. For residential buildings, average solar irradiance of all facades must lower than 395 kWh/m^2/April–October; site permeability of 20% relative to nearby buildings/obstructions; 20% of the habitable space can utilize natural ventilation; Overall Thermal Transfer Value (OTTV) of habitable spaces is less than or equal to 30 W/m^2; and the Vertical Daylight Factor (VDF) of habitable spaces are 50% more than the baseline requirements are recommended and rewarded. Also, for all building types excluding residential, consideration of: built form and building orientation for enhanced energy conservation; optimum spatial planning to enhance energy conservation; building permeability provisions of building features to enhance the use of natural ventilation; and provision of: fixed or movable horizontal/vertical external shading devices; and movable external shading devices for major atrium facade windows or skylights are all included in the guidebooks [49,50]. While the listed recommendations ensure both building energy efficiency and indoor thermal comfort, we opined that revision to include:

(1) Because of the higher daytime cooling degree days in open or low density areas, heterogeneous insulation factor within the city could be adopted i.e. buildings in less dense areas like new territories should be more insulated as they are more susceptible to incident radiation;
(2) Given the number of existing (or older) buildings in the Hong Kong's urban landscape, energy conservation measure through retro-commissioning and retrofitting of should be expedited as the number of these buildings will still be dominant (36%) by 2050 and their total replacement make take up to the end of this century;
(3) Given the projected increase in the mean temperature, frequency of extreme hot weather and consequent increase in future cooling energy demands in the future climate if the current energy consumption pattern persists. Thus, energy saving targets may not be actualized if more stringent benchmarks and passive design recommendation are not introduced early enough. For instance, the set point temperature which is currently at 24–26 °C depending on building use may increase as the ambient air temperature increases under the influence of climate change and frequency/intensity of extremely hot weather and which will also lead increased cooling energy. For instance, Li et al. [16] deduced that due to climate change and associated adaptation, higher set point temperature of 27–28 °C will be possibly acceptable in the future as experienced in Japan in 2005 when occupants of central government ministry buildings were asked to adjust the summer air conditioning setpoint to 28 °C until the beginning of September [51];
(4) Greening from building to urban scales cannot be overemphasized: Several studies from Hong Kong and elsewhere have shown through measurements and numerical simulation the importance of greening measures in reducing energy demand. With the strong contribution of local climatic condition as revealed from our findings, it can be deduced that the reduction of local environmental air temperature can help reduce heat transfer into the building thus reducing demands for cooling. One way of achieving this is in compliance with the prescribed greenery coverage ratio. Depending on the gross floor area, 20–30% greening coverage ratio should be actualized as recommended by the Sustainable Building Design Guideline also known as APP-152 [52]. A recent study [53] have numerically found the implementation of 30% GCR in a 500 × 500 km^2 neighborhood of Hong Kong to reduce CDD by up to 1 °C and equivalent to 3000 kWh energy saving and $450 in cost on a typical summer day. Also, implementation of green roof especially in Hong Kong urban neighborhood has the potential to reduced electricity peak demand by up to 5% especially in low density areas [54]. Other studies [55,56] have shown that vertical greening system is capable of reducing radiant load and reducing buildings annual cooling energy consumption. Lastly, there is a need to understand the social behaviour pattern in order to enhance public education and relevant energy saving design/measures, in particular during extreme heat events.

On the supply side, carbon emissions due to energy use in the built environment should be further reduced to help combat climate change in addition to savings from the demand side. Buildings can be used as vehicles or platforms actualize this and improve the proportion of renewable in the projected fuel mix for electricity generation in 2020 which currently stands at has 3–4%. Undoubtedly, renewable plays an important role in the decarbonisation of the electricity sector and meeting Hong Kong's 2025 Energy saving targets. Therefore, support and implementation of renewable energy infrastructure such as solar cooling for building applications especially in the New Territories areas with low rise buildings will be hugely beneficial. This is because solar-powered air conditioning systems can provide desirable energy performance while addressing the increases in electricity use as a result of increasing summer cooling requirements as observed in our analysis.

5. Conclusion

This study has provided a spatial understanding of cooling energy requirement on "Non-Event Days" and days of "Extreme Heat Events" in Hong Kong using co-kriging geospatial mapping technique as compared with ordinary kriging approach. It also aimed at investigating the annual trend of cooling degree days in the city while quantifying the impact of extreme heat events on the summer cooling energy requirements. Based on our findings, improved predictability of city-wide cooling degree days with the co-kriging was observed and thus recommended ahead of the ordinary kriging and contour mapping methods. The recommended method is capable of capturing the urban heat island effect as homogeneity and heterogeneity in cooling degree day's distribution was found during the summer daytime and nighttime, respectively. We also found the extreme heat events increased cooling degree days by 80–140% depending on the event type, a range consistent in recent years (2011–2015). Findings from this study provide building professions and energy/environmental policy makers with relevant information about the likely order of magnitude changes in energy consumption especially in the building sector in order to encourage the implementation of sustainable and resilient mitigation measures such as prescribed in section 4. Although the present work was conducted for subtropical climates, the study framework is applicable in other locations with similar or different climates. Also, the current work's aim is to quantify the contribution of climatic factor only to cooling energy requirement, In future work, fine-scale energy consumption, social behaviour pattern, economic factors, building footprint data, climate change and population density dataset could be utilized where available for spatial estimation of per capita space cooling per cooling degree days in the current and future climate.

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