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EDITORIAL

The continuing trend of air warming and humidifying in Kowloon, Hong Kong—is there an effective intervention?

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Abstract
The Kowloon Peninsula, an urban area of Hong Kong, might be one of the most studied cities in terms of urban climate in the world. Both annual mean urban air temperature and humidity have been on the rise following the continual increase in the building volume and continual reduction in the average wind speed in the urban canopy layer. The observed urban warming and humidifying phenomena are a direct result of the city form (i.e., the city shape and size), including the building height and density. We call for a system-of-systems approach to be adopted in urban climate studies.

Keywords Urban heat island, Urban moisture island, City design, Urban overheating, Urban form

The phenomena

While preparing this editorial, an extreme event in which a maximum temperature of 41.1 °C was recorded in Beijing. This was the hottest day recorded in Beijing for June and the second-highest reading in Beijing since reliable records began (Rong 2023). The June heatwave affected nearly half of the population in China. Indeed, there have been increasing trends of regional heatwaves globally (Perkins-Kirkpatrick and Lewis, 2020). The well-known urban heat island phenomenon (Oke 1982) describes a setting in which the urban air temperature is higher than its rural counterpart, and when the urban heat island phenomenon occurs during a regional heatwave, a city becomes even warmer.

The annual mean air temperature in Kowloon, an urban area in Hong Kong, has been found to increase more rapidly than that at a corresponding rural site (i.e., 0.23 °C per decade between 1961 and 2017 at Hong Kong Observatory (HKO, urban) versus 0.12 °C per decade between 1989 and 2017 at Ta Kwu Ling (rural) (Wang et al. 2021), suggesting urban warming in Kowloon. Urban warming, a rising mean air temperature over a period of years, is different from an urban heat island. If there was no city in the Kowloon area, the air temperature would be expected to increase at a rate similar to the regional climate warming rate. The possible additional warming rate (urban air warming minus local rural air warming) might only be explained by local urban factors. Urban warming is a suspected phenomenon in Hong Kong, as there have been discrepancies between the estimated regional air warming rate and the observed air warming rate at Ta Kwu Ling. The surface air warming rate has been reported to be 0.08 °C per decade globally since 1880 (0.18 °C per decade since 1981) (Lindsey and Dahlman 2023) and 0.24 °C per decade since 1951 in China (Sun et al. 2022). According to NOAA (2023), the air temperature has risen by 0.1–0.2 °C per decade in the Pearl River Delta region since 1901 and by 0.2–0.3 °C per decade since 1993.

In addition, urban air has become more humid, increasing by 0.25 g/m^3 per decade at HKO between 1961 and 2017 (Wang et al. 2021). The air temperature and humidity at HKO increased from 1961 to 2017 by 1.5 °C and 1.4 g/m^3, respectively. The contribution of moisture to the equivalent air temperature has increased appreciably. An important urban factor is the continual increase in the building volume (i.e., building height and/or building density), which has led to a continual reduction in the average wind speed in the urban canopy layer; i.e., a continual weakening of the wind (Peng et al. 2018).

Extreme heat or overheating in Hong Kong affects human health and the comfort and energy efficiency of buildings (Guo et al. 2017; Shi et al. 2019). Many efforts, such as city ventilation and an air ventilation assessment initiative (Ng 2009) and a building energy efficiency programme (Chan and Yeung 2005; Ma and Wang 2009), have been made over the past 20 years but have failed to halt the trends of urban warming and humidification.

We thus consider whether we are targeting the wrong causes, whether we have not done enough, and whether it is possible to develop an effective intervention.

Why have we failed to stop the urban warming trend?

The Kowloon Peninsula, an urban area of Hong Kong, might be one of the most studied cities in terms of urban climate in the world. The peninsula lies in the eastern Pearl River Delta of the South China Sea, to the north of Hong Kong Island. Hong Kong is one of the most densely populated cities in the world. The fact that urban warming interventions have not been successful even in such a well-studied city is alarming. With the aim of designing city climate as we have designed indoor climate in buildings, our team has carried out numerous studies on the mechanisms of heat, moisture, and air transport within and across urban boundaries, as cited below. These studies might explain two aspects of why we have failed to stop the urban warming trend, although most discussions below are still qualitative in nature.

First, an urban cool island and an urban heat island co-exist in Kowloon, with the former occurring during the day and the latter occurring mainly at night. This has been mechanistically explained by the appreciable heat storage effect of building envelopes (Yang et al. 2017). If not for the storage effect of building envelopes, it would be difficult to explain the co-existence of island effects, as during the day, the anthropogenic heat due to air conditioning and traffic might be highest and the solar heat gain in the urban canopy layer would also be highest, and the urban air temperature should thus be much higher than its rural counterpart. The total building envelope area can be 4 to 10 times the land surface area that the city occupies; i.e., on 1 square metre of land, there are 4 to 10 square metres of building envelope, which can absorb heat during the day and release heat at night. In addition, an appreciable release of heat from building fabrics and other impermeable materials at night suggests a worsening urban heat island effect. This is exactly what has been observed and explained. Note that the thermal storage effect reduces the daily temperature variation. If we were to insulate all building exterior envelopes and all streets to avoid any heat storage, the urban heat island intensity would also increase in dense cities at daytimes.

To demonstrate such a mechanism of urban heat storage, Wang et al. (2018) carried out a year-long hourly monitoring of air temperature in a stone forest having a spatial scale of a few kilometres and areas of high and densely distributed stones (representing high-rise urban buildings) and areas of low and sparsely distributed stones (representing low-rise urban buildings). The average air temperature in the 'urban' forest areas with low and sparsely distributed stones was higher than the air temperature in nearby 'farmland' areas, which was consistent with observations for low-rise and sparse cities in the United States. In 'high-rise' and dense stone forest regions, a cool island was observed during the day and a heat island at night. Considering there was almost no anthropogenic heat release in the stone forest, the only available explanation was the daily storage and release of heat by the stones. The major heat gain during the day was the solar heat gain in the stone canopy layer. The similarity of the average daily air temperature profiles of the high-rise and densely distributed stone areas and Kowloon suggests a similar heat storage effect. Most importantly, although not recognised at the time of the study, even without anthropogenic heat, the same observed heat/cool island phenomenon suggests that reducing anthropogenic heat alone would be insufficient to stop the rising trend of urban warming in Kowloon, which is an unfortunate and undesirable finding.

Our discussion does not imply that reducing anthropogenic heat is not useful. Anthropogenic heat from air conditioning systems and vehicles increases the urban air temperature, but it is insufficient to produce a heat island with the level of intensity as observed in Kowloon. This suggests the importance of the solar heat gain in the urban canopy layer and the insufficient removal of heat by other means, such as city ventilation.

Second, urban air has its own wind system, with a larger city having a greater length scale of the urban wind system. For a long time, we believed that urban air pollution and urban heat are highest when the background wind is calm, but it turned out to be wrong in Kowloon. Without wind flow, there might be reduced air exchange across the urban boundary. Theoretical small-scale and meso-scale modelling has suggested the formation of a heat dome for an isolated city located on flat terrain (Fan et al. 2017; Wang et al. 2019). In such a heat dome, thermal air flows converge at the city centre and rise. The rural air flows horizontally into the city at ground level, and through inversion, the rising plume bends and urban air spreads horizontally in all directions and then merges into the rural horizontal air flow, forming a dome. Under realistic settings, such an ideal dome flow might not exist, and the urban heat circulation is often referred to as urban heat island circulation. The heat dome has been found to be affected by the city shape. Asymmetric air flow circulation breaks down in an ideal square city (Fan et al. 2019). Owing to the longer diagonal length, there is stronger lower inflow through the four corners and weaker lower inflow through the four sides. The relationship is the opposite for upper outflows, with stronger side flows.

Kowloon Peninsula is surrounded by sea to both the west and east, with Hong Kong Island located to the south beyond Victoria Harbour. There are mountains to the north of Kowloon. Hence, the urban island circulation interacts with sea breezes and mountain air flows. Sea breezes cool the city of Kowloon. An analysis of the HKO monitoring data suggests that eastern Kowloon is hotter when there is a north-easterly wind than when there is no wind (Zhang et al. 2022), which contradicts our common belief that a condition of no wind results in the highest temperature. The warming effect of the north-east wind was recently explained in terms of a (mountain) downstream blocking phenomenon. The down-slope wind from the north-easterly mountain merges with the inflow of the urban heat island circulation, and the merged flow forms a large vortex between the mountain and the urban rising flow. The urban rising flow becomes virtually vertical and stable, and the urban area below warms.

Hong Kong has evolved into such a large climate entity that its self-generated urban island circulation has a height close to or even higher than the surrounding mountains. The need to grow an economy and increase innovation is thus seen to accelerate urban growth both horizontally and vertically. The growing problem of urban overheating is no longer a problem at the building or district scale but a problem that requires a solution at the city scale.

The need for a system-of-systems study of city forms

Our discussion so far suggests that the observed urban warming and humidifying phenomena are a direct result of the city form (i.e., the city shape and size), including the building height and density. Without changing the city form, identifying an effective intervention for urban climate change might be difficult. Traditionally, the development of resilient cities has focused on resilience against flooding and heavy rain, yet increasing heat resilience has become a major challenge. As cities become warmer and more humid, the air-conditioning systems in buildings need to run for longer with greater power. Thus, as more anthropogenic heat is released, more energy is used in response and more CO_2 is released in a vicious cycle.

This might be the right place to reiterate the importance of urban climate solutions, not just for the comfort and wellbeing of urban dwellers but beyond cities. Cities are human centres of economic activity and innovation. Without cities, there is no civilisation.

The global human population is projected to reach 9.7 billion by 2050, from 8 billion in 2022 (United Nations, 2022). More than half of the global population now lives in cities, and cities consume 75% of resources even though they occupy less than 3% of the Earth's surface. In some cities, the proportion of elderly people is expected to rise significantly We have built extensive buildings, street networks, and healthcare and commercial/business facilities in our cities. Materials are used to construct safe structures, and energy is used to drive and keep each building comfortable and healthy. By 2060, the global floor area of buildings is predicted to double. By 2050, two out of every three people, including 2.5 billion newly added, are likely to be living in cities. Eighty per cent of global economic growth is now in cities.

Kowloon is a high-rise city. The benefits of high-rise living are as obvious as the challenges. The land area effectively occupied by a typical family is much lower in a dense high-rise city than in a sparse low-rise city. We first consider a sprawling city with a land/building ratio of only 10%; i.e., the spacing between buildings is large and used for streets and other utilities. We assume that a family needs a floor area of 200 square metres in a single-story house. The land area by occupied one family is thus 2000 square metres. In contrast, for Kowloon, with an approximate land/building ratio of 50%, we consider a 30-storey high-rise apartment with each family again occupying a floor area of 200 square metres. Ignoring public spaces, 30 families can live in such an apartment block, and the land area occupied by one family is only 13 square metres. This is a 150-fold difference in the occupied areas between the two cities. High-density living thus reduces land use. However, dense high-rise cities face climate and environmental challenges.

Humans have exploited almost every habitable inch of land for food and materials. The majority of extracted materials are used to construct buildings and other urban infrastructure (OECD 2019). It is intriguing that the use of such construction materials in cities such as Kowloon blocks winds and stores urban daytime heat. Human-made materials now weigh more than all life on Earth (Elhacham et al. 2020). The per-capita mass of man-made materials has increased from 20 tons in 1900 to 150 tons in 2020, as estimated from data reported by Elhacham et al. (2020). Cities consume most of the man-made materials, produce most of the waste (pollution in air, water, soil, and sediment) and consume most of the energy while accounting for most of the greenhouse gas emissions. Without a city-scale solution to urban warming, there can be no global sustainability.

Is there an ideal city form that balances the needs for sustainability, wellbeing, and resilience? Most existing studies of city forms have considered one or only a few aspects of city design. For example, Hang and Li (2011) suggested that elevating all buildings above ground would significantly improve city ventilation, but this turns out to be unrealistic. The need for urban heat resilience is compounded by the global challenges of climate change, pollution and biodiversity loss. Development of future new city forms involve a holistic, multi-scale and integrated approach that consider several interdependent systems (e.g., land use, climate, atmospheric, energy, transportation, other infrastructure, industrial, economic, governance and other sociocultural systems). In addition, many of the same systems are involved in other societal challenges (e.g., climate change, renewable energy, adaptive infrastructure, disasters, pandemics, food insecurity and biodiversity loss, depending on the specific cities involved). We need to address these societal challenges simultaneously and not one at a time, using a system-of-systems (SoS) approach (Bi and Little 2022; Little et al. 2023). The integrated SoS approach would vary depending on the specific cities involved (the city form), but can help us make our cities more sustainable and resilient.

Without global sustainability, the development of an eventually effective solution to the problems of urban air warming and humidification might be in doubt. This calls for an SoS approach to be adopted in urban climate studies.

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