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LETTER

Wet-bulb temperatures reveal inequitable heat risk following climate change in Hong Kong

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Abstract

Rising temperatures will impact urban communities, which are growing as a proportion of the global population. However, the effects of increasing temperature may not be felt equally, with less wealthy neighbourhoods experiencing hotter thermal environments in some urban areas because of geographic location and tree cover. While relationships have been drawn between wealth inequality and temperature in urban areas, these rarely project into the future or combine humidity and air temperatures into 'wet-bulb temperature' at fine spatial resolution, which is more directly relevant to the human experienced environment. Here I present an analysis of present and future wet-bulb temperatures in Hong Kong, an economically developed subtropical city in South-East Asia. I couple census data with recently available 30 × 30 m resolution climate models to examine how the income of districts and their physical characteristics are correlated with human-experienced local temperatures. I uncover evidence of thermal inequity, with wealthier districts exhibiting cooler conditions than less wealthy districts. Projecting into the future using three different climate change scenarios I demonstrate that wet-bulb temperatures considered dangerous to human survival may be commonly experienced in Hong Kong by the end of the century. However, the wealthiest districts of Hong Kong are likely to have a thermal safety margin of at least 25–30 years more than the least wealthy districts before these dangerous temperatures are reached. Due to the high population density and economic importance of the region, these findings have significant implications for public health and urban planning as global temperatures continue to rise.

1. Introduction

Global temperatures have increased by 1.2 °C since the beginning of the industrial age, and are on course to increase by 3 °C–5 °C by the end of the century (IPCC 2022). The effects of elevated temperatures are expected to be more severe in urban versus rural areas, due in part to the 'urban heat island' effect (Liu *et al* 2022). Fine-scale distribution of temperatures can also vary within cities themselves, and can be related to socio-economic status (Harlan *et al* 2007, Byrne *et al* 2015, Hsu *et al* 2021). In Hong Kong there is a spatial correlation between the surface urban heat island effect and inequity (Wong *et al* 2016). However, humans are affected by a combination of air temperature and humidity, meaning health implications may be overlooked by studies focusing on temperature alone (Raymond *et al* 2020). Extreme temperatures in the future are likely to lead to elevated mortality in human populations (Mora *et al* 2017), with implications not only for public health but economic stability (UCCRN 2018). It is crucial therefore that we assess and understand urban temperatures at a human scale to mitigate climate threats and maximise the wellbeing of our societies.

Temperatures are predicted to continue increasing across the globe (IPCC 2022). At the same time the proportion of the global population living in urban centres is expected rise to around 65% by 2050 (IPCC 2013). Currently temperatures regularly exceed 35 °C in over 300 cities globally, affecting roughly 200 million people (UCCRN

Technical Report 2018). This will increase to over 970 cities by 2050, representing around 1.6 billion people (UCCRN Technical Report 2018). Heatwaves can affect the overall functioning of cities by placing higher demands on energy infrastructure (Fung *et al* 2006), reducing water availability (Vicuña *et al* 2018) and impacting food security (Rosenzweig and Hillelm 2018). Temperature extremes also have wide ranging psychological and sociological implications, including higher incidences of mental health hospital admissions (Nori-Sarma *et al* 2022), increased online hate speech (Stechemesser *et al* 2022), and escalations of violence and conflict (Plante *et al* 2017). The most profound and basic effect on humans however is direct mortality (Hajat *et al* 2014, Vicedo-Cabrera *et al* 2021, Zhao *et al* 2021). The proportion of the global population expected to experience conditions conducive to heat-related excess death is expected to double from ∼30% to ∼70% by 2100 (Mora *et al* 2017).

The proliferation of man-made surfaces within cities absorb heat from the sun and radiate it back into the environment over time, leading to elevated local air temperatures (Liu *et al* 2022). This effect is exacerbated by a reduction in vegetation cover, which not only provides shade but actively reduces ambient air temperatures via the mechanism of transpiration (Shishegar 2014, Rahman *et al* 2020). Combined with the heat generated by energy usage, cities can become several degrees warmer than nearby rural environments (Liu *et al* 2022), an effect that can extend many hundreds of meters above and around urban perimeters and is called the 'urban heat island' effect (Bornstein 1968). Features that modulate temperatures along urban-rural gradients can however also vary significantly within cities themselves (Hong *et al* 2019, Ramsay *et al* 2023). Cities are not uniformly urbanised, all districts do not occur at the same elevation, nor do they have the same numbers of trees or gardens. These features spatially mediate the intensity of the urban heat island effect, and commonly vary according to the socio-economic status of city districts (Harlan *et al* 2007).

Cities across the world have developed historical inequalities due to legacies of colonialism (Dill and Crow 2014, Baffoe and Roy 2022), racial or religious segregation (Thorat and Attewell 2007, Grove *et al* 2017), war (Bircan *et al* 2016), and more insidious divisions that have become socially ingrained due to political and economic policies (Nijman and Wei 2020). In colonial times, affluent sections of society built homes atop hills with the very intention of avoiding the summer heat (Kenny 1995). During the industrial revolution the wealthy districts of European cities were planted with trees to help clean the polluted air (Johnston 2015). While urban inequality has deep historical roots, it is legacy is gaining renewed focus through the lens of anthropogenic climate change.

Some studies investigating the relationship between the urban climate and wealth inequality have previously used surface temperatures derived from satellites (e.g. Harlan *et al* 2007, Byrne *et al* 2015, Wong *et al* 2016, Hsu *et al* 2021). While this allows for broad spatial patterns in temperature to be visualized and correlated with demographic information, humans are affected predominantly by a combination of air temperature and humidity (Pal and Eltahir 2015). 'Wet-bulb temperatures' (hereafter referred to as *Tw*) integrate a combination of heat and humidity that considers the effect of evaporative cooling. *Tw* of 35 °C defines a threshold beyond which the human body is unable to cool its self via perspiration, representing a physiological limit to human survival (Raymond *et al* 2020). Meteorological data from weather stations provides air temperature and humidity—and has been used in many studies investigating urban climate (e.g. Chen and Jeong 2018, Wang *et al* 2022)—but this data is often resolved at coarse spatial resolution. For example, in Hong Kong there are 48 weather stations but 452 voting wards. Extreme heat and humidity can be highly localised, and therefore the use of low resolution data may lead to substantial underreporting of extreme conditions with respect to human health (Raymond *et al* 2020). High resolution data can therefore improve our understanding of urban climate effects on human health, and facilitate policy development (Ma *et al* 2023).

Hong Kong is a subtropical city in South-East Asia, and is highly economically developed, being a global finance and logistics hub. Because of this, Hong Kong contains many high-income districts, but there also exists a significant wealth divide. The richest 10% in earn 40 times more than the bottom 10%, with 24% of the population living below the poverty line (HK Census & Statistics Department 2016). The Gini coefficient—a measure of income inequality where 0 is perfect equality and 1 is maximal inequality—for Hong Kong stands at over 0.5, indicating 'considerable disparity' (HK Economic Analysis Division 2017). This places Hong Kong alongside countries such as Botswana, Belize and Mozambique in terms of wealth inequality.

Here I present an analysis of *Tw* in Hong Kong. I couple census data with recently available 30 × 30 m resolution climate models to examine how the income of districts and their physical characteristics are correlated with human-experienced microclimates. I use three climate warming scenarios to project into the future, examining the temporal window within which different districts of Hong Kong exist before they experience temperatures that are detrimental to human health. I hypothesise that wealthy districts will be more buffered from the effects of future climate change than less wealthy districts, leading to them reaching thresholds of human physiological tolerance sooner. Urban populations are facing increasing challenges arising because of elevated temperatures. This presents problems for economic sustainability as well as human health and wellbeing. Understanding the fine-scale distribution of urban temperatures—and how these relate to socio-economic patterns—should be seen as a first step in developing policies to future-proof cities against climate change.

2. Methods

2.1. Local geography and climate

Hong Kong is a semi-autonomous territory of 1110 km^2 in South-East Asia (22.3193° N, 114.1694° E). It has a sub-tropical climate dominated by seasonal monsoons from May until September. The region experiences summer temperatures of 25 °C–30 °C, high temperatures of 30 °C–35 °C, with relative humidity of 80%–85% during warm months (HK Observatory n.d.). The topography is hilly and coastal, and the dominant natural habitat is subtropical evergreen forest, though almost all of this is secondary forest.

2.2. Demographic data

Economic (median income) and population information for each voting ward in Hong Kong was downloaded from publicly available government census data collected in 2016 (HK Census and Statistics Department) (figure 1).

2.3. Environmental data

For current climate data I used recently available climate layers generated by Morgan and Guénard (2019). The authors used 20 years (1998–2017) of data from up to 43 local Hong Kong Observatory weather stations to create a downscaled climate model for Hong Kong at 30 × 30 m resolution. From the climate layers presented by Morgan & Guenard I used the average maximum temperature and relative humidity of the warmest month, as extreme rather than mean conditions are likely to have the most significant effect on the human population. I used the package 'HeatStress' in R (Casanueva 2019) to combine air temperature and humidity into 'wet bulb globe temperature' (hereafter referred to as ***Tw***) (figure 1). ***Tw*** of 35 °C or above determines a threshold beyond which the human body is no longer able to cool it is self by sweating, and prolonged exposure (∼6 h) is deemed prohibitive to human survival (Pal and Eltahir 2015).

For future climate projections I averaged from an ensemble of nine global circulation models at 1 × 1 km resolution from WorldClim2 (Fick and Hijmans 2017). I projected temperatures for the period 2080–2100 and used three shared socio-economic pathways (SSP245, SSP370, and SSP585) representing low, medium and high levels of projected climate warming (figure S1). Tree cover data was obtained from Landsat Tree Canopy Cover version 3.0 (Sexton *et al* 2013) (figure 1). This dataset defines the number of trees above 5 m in height at 30 × 30 m resolution for the year 2015. It is worth noting that other topographical features affect the local climate, such as elevation, proximity to water bodies, wind speed and aspect. However, these variables were included in the original downscaled climate models provided by Morgan and Guenard (2019), therefore fitting them again as predictors in subsequent models would be circular. Geo-spatial data layers used in analyses can be viewed in table 1.

Table 1. Layers used in spatial data extraction and statistical analyses and their original source.

Layer	Units	Resolution	Source
Temperature	°C	30 × 30 m	Morgan and Guenard (2019)
Humidity	%	30 × 30 m	Morgan and Guénard (2019)
Tree Cover	%	30 × 30 m	Sexton *et al* (2013)
Climate projections	°C	1 × 1 km	Fick and Hijmans (2017)
Income	HKD	Voting ward	HK Census & Statistics Dept (2016)
Population	People/Km	Voting ward	HK Census & Statistics Dept (2016)
Human made surfaces	%	30 × 30 m	Brown de Colstoun *et al* (2017)

2.4. Defining urban areas

More than half of Hong Kong is covered by country parks which are not urbanised, yet they fall within the delineated boundaries of voting wards. I therefore created new shapefiles that defined the boundary between urban areas and vegetated areas, so that data would only be extracted from within the urban zone for each ward. To do this I used a dataset on human made impermeable surfaces (Brown de Colstoun *et al* 2017), which matched the climate model resolution at 30 × 30 m. I cropped this data to the extent of Hong Kong, and then delimited a threshold for the human made surface layer at a value of 85%. I created a polygon from the extent of this resulting layer (figure 2) and tested its accuracy by overlaying it upon a composite aerial photograph of Hong Kong (figure 2(b). The created polygon matched very closely with the boundary between the city and the surrounding natural landscape. I intersected this polygon with the publicly available voting ward boundaries, resulting in a shapefile of voting wards with boundaries defined

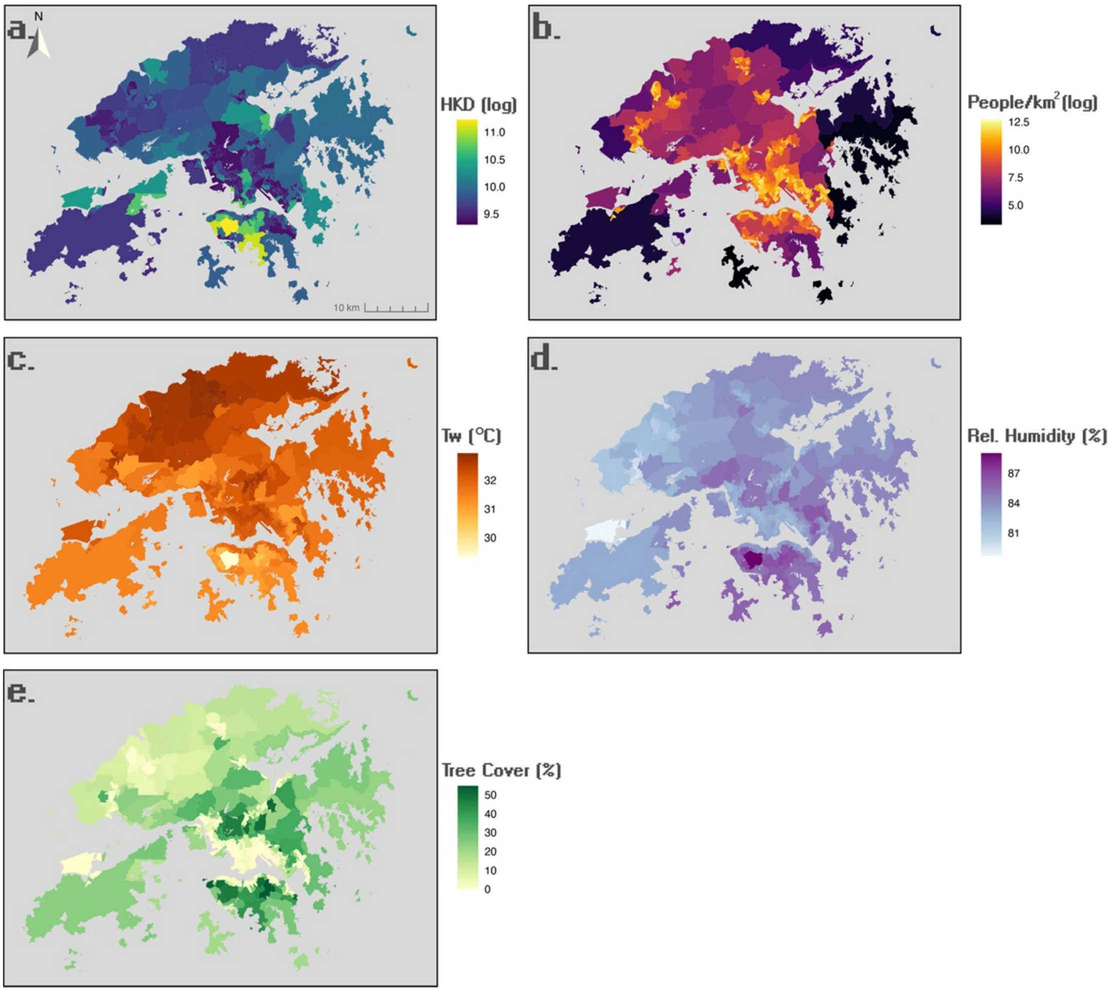

Figure 1. Spatial map of data used in statistical analyses. Data shown here were extracted only for urbanised areas, but are represented here the entire voting ward scale for ease of visualization.

by urbanised areas only. All spatial data manipulation was carried out in R version 4.1.2 (R Core Team 2021).

2.5. Statistical analyses

All statistical analyses were carried out in R version 4.1.2 (R Core Team 2021). Using the defined urban boundaries for all 425 voting wards in Hong Kong I extracted the mean value for each environmental variable using the package 'Raster' in R (Hijmans 2022) (figure 1). I initially tested to see if there were significant differences in current ***Tw*** among districts based on their income. I fitted a linear model comparing ***Tw*** against log-transformed median income. Visual inspection of the data revealed potential non-linear relationships, so I fitted an additive model (GAM) using the same variables and compared the suitability of each model using Aikake's Information Criterion (AIC) and R^2. Both AIC and R^2 suggested that the additive model was superior (figure S2), and so I continued using GAM for subsequent analyses. I tested to see if the main effect of income remained significant whilst controlling for spatial location by including the coordinate centroid of each voting ward as a random effect.

Based on three climate scenarios of varying severity I calculated the 'thermal safety margin' for each voting ward i.e. the number of years it would take for ***Tw*** to regularly reach or exceed 35 °C. This was derived from the rate of warming between the year 2000 and the period 2080–2100 by subtracting the present temperature from the future temperature for each 1 × 1 km^2 and dividing by the number of years. This method assumes that the rate of warming will be consistent through time. I again used GAM to explore the relationship between log-transformed median income of voting wards and thermal safety margin for each climate scenario. Finally, I ran simple linear models to explore what features of the urban environment were associated with temperature and income, including tree cover and population density as predictors,

To facilitate the interpretation of GAM outputs I calculated the first derivatives of the splines for each model, highlighting where along the predicted line the trend was significantly different to zero using the Deriv. R package (Simpson 2021). This method splits the line into 200 sections and calculates the 95% confidence interval around each section. Points along the

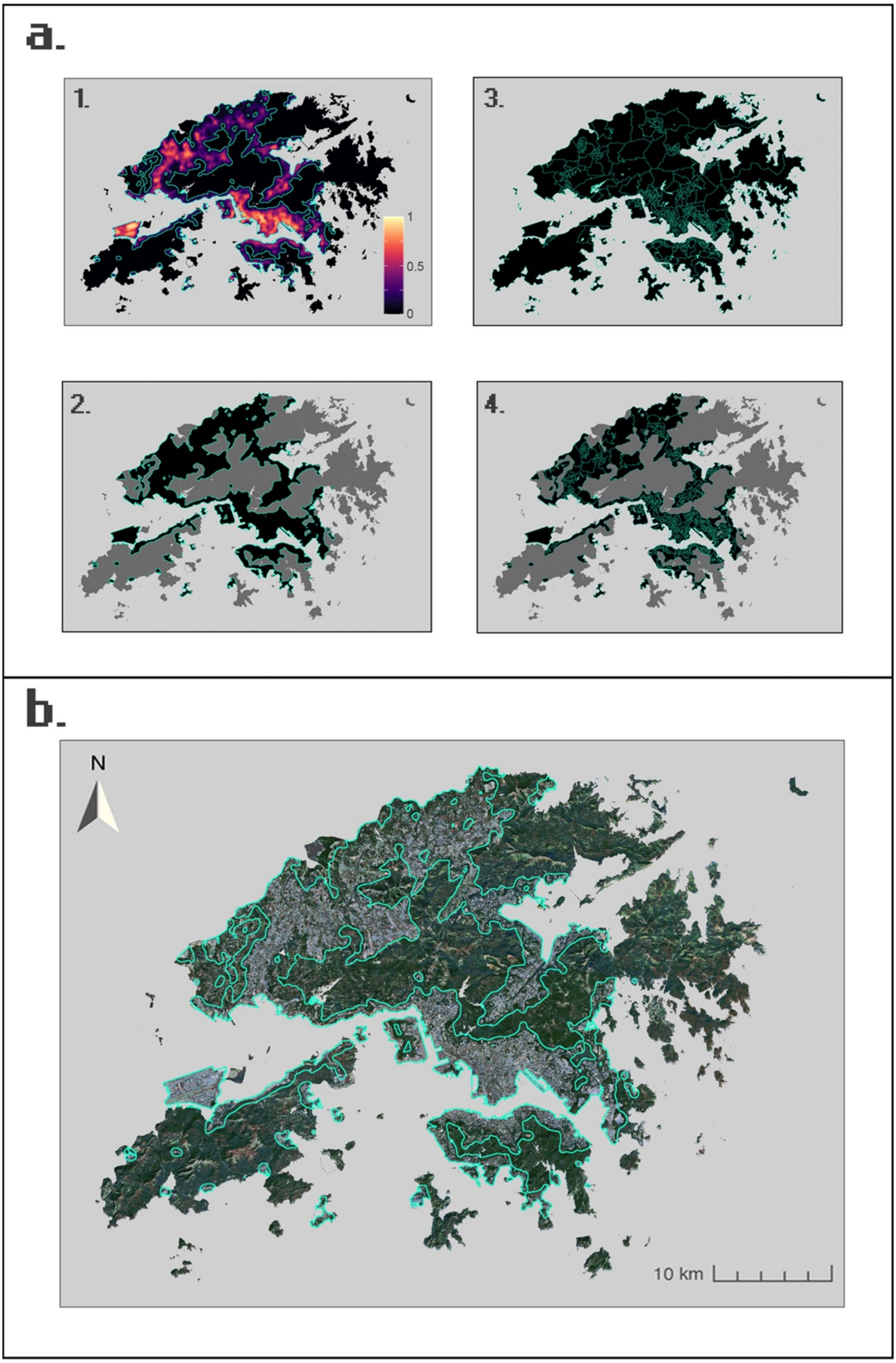

Figure 2. Visual representation of workflow for delineating urban areas of the territory of Hong Kong. (a.1.) A threshold was defined at of 85% human made impervious surfaces (Brown de Colstoun *et al* 2017), to define the boundary between urban and non-urban areas. (a.2.) A new polygon was created from this layer. This was combined with (a.3.) the official boundaries of Hong Kong voting wards to create (a.4.) A new shapefile containing only the urban boundaries of Hong Kong voting wards. Figure 1(b) The boundary polygon was tested for accuracy by overlaying onto a composite aerial photograph of Hong Kong (adapted from 1:100 000 Orthophoto Map of Hong Kong, www.landsd.gov.hk/en/spatial-data/open-data.html). The polygon defined from human made impervious surfaces matched very closely with the visual boundary between urban and rural areas. Reproduced with permission from Hong Kong Government Data Portal.

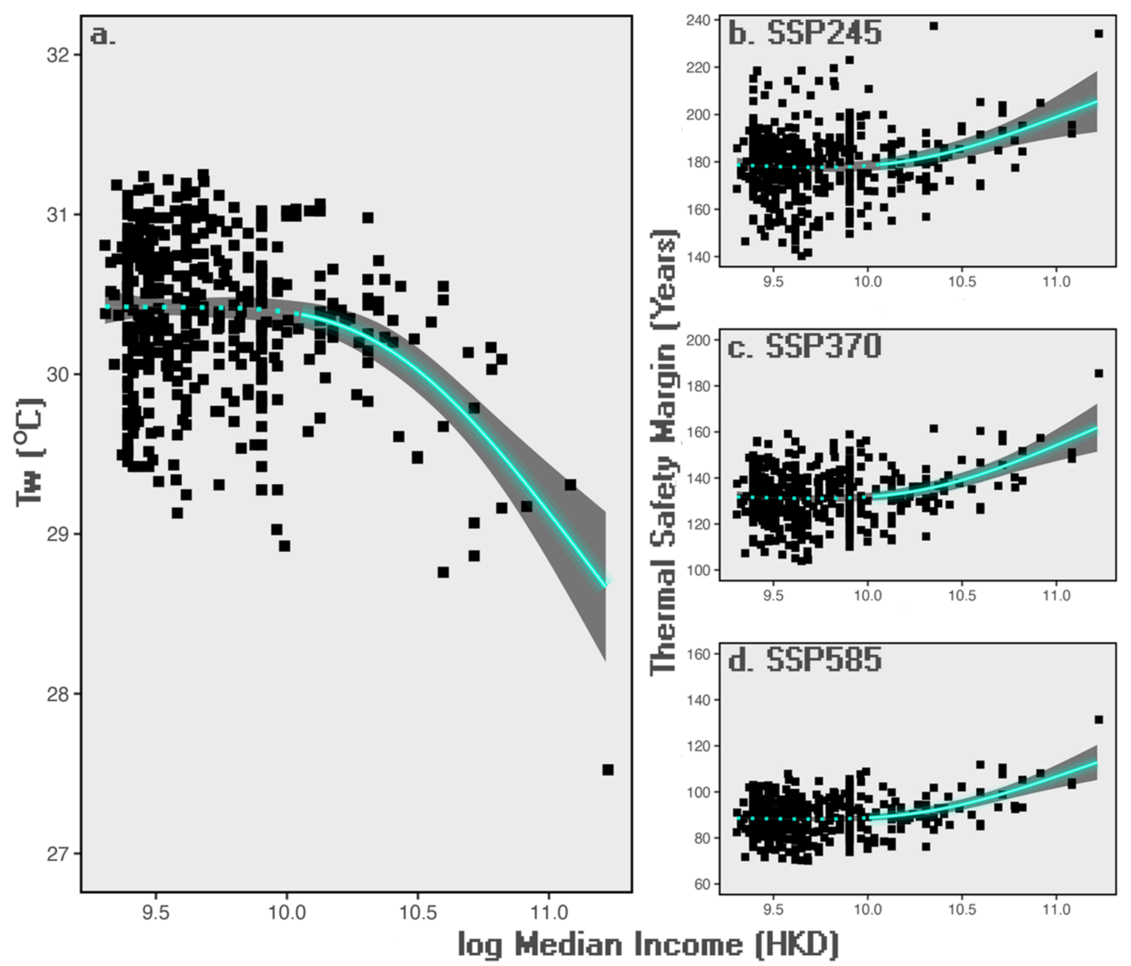

Figure 3. (a) Wet bulb globe temperature (***Tw***) vs median income of voting wards in Hong Kong. Predictions showed a significant non-linear relationship, where ***Tw*** began to decrease in wards with a median income above 23 000 HKD per month. (b)–(d) Thermal safety margin vs median income of voting wards in Hong Kong. Wards with a median income above 23 000 HKD per month were predicted to have a significantly greater thermal safety margin than those with an income below 230 000 HKD per month. Thermal safety margin is defined as the number of years (from the year 2000) taken for each ward to experience ***Tw*** of 35 °C. SSP scenarios were each projected from an ensemble of nine general circulation models. Points represent individual voting wards, fitted lines are from generalised additive models (GAM), with shaded polygons representing 95% confidence intervals.

predicted line where the confidence interval diverges from 0 relative to the initial first derivative are considered significant.

3. Results

3.1. Income and *Tw*

Median income varied among wards from 11 000 HKD to 75 000 HKD per month (mean 17 837 HKD). ***Tw*** also varied among wards, from 27.5 °C to 31.3 °C (mean 30.4 °C). Median income was significantly correlated with ***Tw***, with high income wards exhibiting lower temperatures than low-income wards (figure 3, **GAM**; edf = 2.73, $F = 21.75$, $p < 0.001$, $R^2 = 0.13$). This effect remained significant when spatial location was controlled for in the model ($p < 0.001$). The relationship was non-linear, where wards became significantly cooler after an income threshold of 23 000 HKD. Wards with income above 23 000 HKD became 0.25 °C cooler for every 10 000 HKD increase in monthly median income.

3.2. Thermal safety margin

Projections showed significant differences in thermal safety margin for voting wards of Hong Kong based on income. For all climate warming scenarios the wealthiest districts had a thermal safety margin of 25–30 years more than less wealthy districts (figure 3 SSP245—**GAM**; edf = 2.4, $F = 8.14$, $p < 0.001$, $R^2 = 0.053$. SSP370—**GAM**; edf = 2.6, $F = 15.18$, $p < 0.001$, $R^2 = 0.1$. SSP585—**GAM**; edf = 2.65, $F = 18.57$, $p < 0.001$, $R^2 = 0.12$). Climate warming scenarios differed however in the projected number of years taken for these temperatures to become common in Hong Kong. Based on the least severe warming scenario, it was expected that ***Tw*** of 35 °C would not be experienced in Hong Kong until the later end of the following century (2180). This safety margin decreased to 2130 for intermediate levels of warming

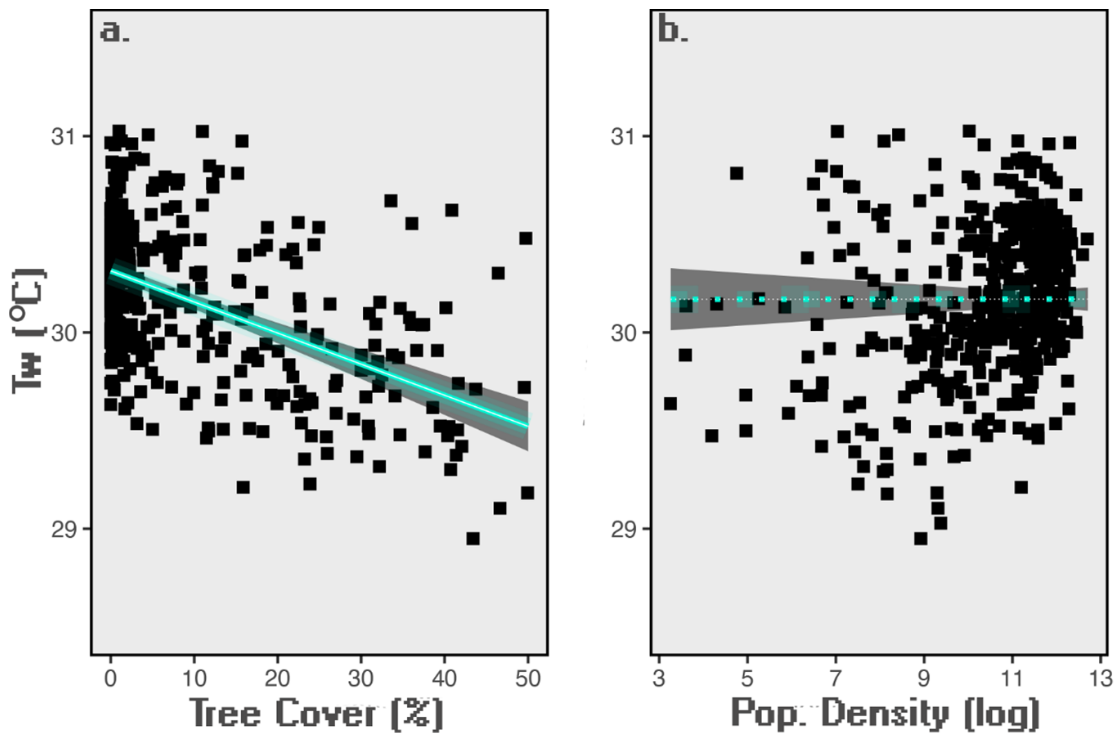

Figure 4. (a) Wet bulb globe temperature (***Tw***) vs Tree Cover (%). Wards with highest tree cover percentages were 1 °C cooler than those with no tree cover. Points represent individual voting wards, fitted lines are from linear mixed effects regression (LMER), with shaded polygons representing 95% confidence intervals. (b) Wet Bulb Globe Temperature (***Tw***) vs log Population Density of voting wards in Hong Kong. Population density was not significantly correlated with *Tw*.

and the most severe predictions expected ***Tw*** of 35 °C to be common place in Hong Kong before the end of this century (2080–2100).

3.3. Urban features and temperature

Tree cover was a significant predictor of *Tw,* where districts exhibiting greater tree cover had lower temperatures than those with fewer trees, although the effect size was small (LM: df = 447, slope = −0.02, se = 0.01, $t = -11.2$, $p < 0.001$, $R^2 = 0.27$). Population density had no significant relationship with *Tw*. Wards with the highest tree cover were 0.8 °C cooler than those with the lowest tree cover, and for every 10% increase in trees *Tw* decreased by 0.1 °C (figure 4).

4. Discussion

I set out to explore the relationship between human-experienced urban climates and wealth inequality in Hong Kong, hypothesising that wealthier districts would be cooler and more buffered against climate warming than less wealthy districts. I found that monthly income correlated with local wet-bulb temperatures in voting wards of Hong Kong, with wealthier districts being significantly cooler than less wealthy districts, which was in line with my *a priori* hypothesis. Under higher warming projections, most districts in Hong Kong would be expected to experience temperatures at the limit of human tolerance as the norm by the end of the century. In contrast, based on the lowest rates of warming these temperatures would not be expected as a standard feature of the climate until late in the following century. Regardless of warming rate, the wealthiest districts would have at least another 25–30 years of thermal safety before experiencing the same harmful temperatures as less wealthy districts. These findings highlight the need to proactively buffer the urban environment from extreme temperatures—particularly in low to mid-income districts—which tend to house the highest proportions of vulnerable people (Yang and Kanavos 2012).

The results presented here have clear implications for urban policy in this globally important region. Over 60% of the global population currently live in the Asia-Pacific region, and are responsible for over 30% of global economic output (World Bank ICP, 2020). Despite this, our knowledge of the human-experienced thermal environment in Asian cities is lacking. The relationship between income and ***Tw*** shown here provides evidence for climate inequality in this region, a pattern that I assume to be widespread. Conditions at the limit of human survival will begin to occur regularly in the future as the climate warms, affecting predominantly those in low and middle income districts. The income of districts in cities is often correlated with other social factors such as age, health, disability, and job type. Low income areas tend to have higher proportions very young inhabitants (Mattingly *et al* 2011) a demographic group that faces increased risk from heat (Wilhelmi *et al* 2004, Pal and Eltahir 2015). Similarly, populations in low income areas tend to have lower overall health (Yang and Kanavos 2012), which is also a risk factor during extreme events (Gronlund 2014). Job type also interacts with heat risk, as those with higher income jobs are more likely to work in air conditioned offices, or have the flexibility to work from home. Low income areas include a higher proportions of people working outdoors, or in other non-thermally buffered environments, which further exacerbates the effect of extreme heat (Gronlund 2014).

The baseline temperatures used in this analysis were generated from 20 years of downscaled meteorological data (Morgan and Guénard 2019) and averaged within districts. As such, the results presented here indicate when harmful temperatures are likely to occur as yearly norms across entire city areas rather than as localised events or heatwaves. At a relative humidity of 85%, which is common in Hong Kong, the ambient temperature must reach 36.3 °C to generate ***Tw*** of 35 °C. Temperature recordings of up to 37 °C are already currently recorded from weather stations in Hong Kong (HK Observatory n.d.), and ***Tw*** of 35 °C have been recorded already this century from other subtropical coastal regions (Raymond *et al* 2020). It is therefore highly possible that *Tw* temperatures of 35 °C could be reached during extreme events or anomalous individual days in Hong Kong much sooner than projected by these results.

My findings show that tree cover is a relatively poor buffer against wet-bulb temperatures in Hong Kong, an observation that was unexpected based on findings from other cities (Shishegar 2014, Rahman *et al* 2020). Increasing the number of trees in cities is generally seen as a relatively easy and low-cost mechanism by which to reduce ambient temperatures, but it is possible that the increased humidity associated with higher vegetation cover may exacerbate ***Tw*** in tropical and subtropical regions (Jamei *et al* 2020). Studies in Hong Kong have shown that green roofing is inefficient due to the verticality of the built environment, and that street level tree planting can reduce temperatures (Ng *et al* 2012), though this study measured temperature directly rather than incorporating humidity. Sparsely planted trees in high urban density areas of Hong Kong could provide greater benefit, though these still significantly increase local humidity (Wang *et al* 2022). It is important that future research in this region incorporates ***Tw*** rather than direct ambient air temperature in order to develop the best policies.

This study focussed on the urban environment in Hong Kong and projected the climate into the future, however the urban environment its self is also likely to change significantly. The government expects the population of Hong Kong to grow from 7.3 million to 8.4 million by 2050 (HK Census and Statistics Department 2022, 2023). Significant new development will be required to meet the increased housing demand, and ideally new development should be prioritised in areas with the lowest risk of extreme temperatures. This is challenging in Hong Kong, as the landscape is extremely rugged and much of the accessible land is already occupied. The government is currently pursuing a new flagship 'Northern Metropolis' development project along the border with mainland China. My results show that these areas of the territory exhibit the lowest thermal safety margins, with ***Tw*** expected to exceed 35 °C before the end of the century based on the most severe projections. The government is also pursuing large scale land reclamation projects in the south, such as the 'Lantau Tomorrow Vision'. While reclamation projects come with their own suite of environmental and economic issues (Wang *et al* 2014), from an urban climate perspective they are likely to be preferable in Hong Kong as they will be buffered from extreme temperatures for many decades in comparison to more continental northern regions.

To improve our understanding of the effect of extreme heat on humans in urban environments we should try to collect microclimate data directly, rather than rely on downscaled models or coarse weather station data. Networks of temperature and humidity dataloggers should be installed throughout urban areas, including inside and outside residential buildings, hospitals, education facilities and workplaces. Understanding interior temperatures is important, as the recent pandemic has shown us that events can occur whereby governments have the ability to restrict people's movement and confine them to their homes or workplaces. Should this happen during a heatwave in the future it could lead to significant mortality, particularly in less wealthy districts where not only is it hotter, but people can less afford to run their air conditioning for prolonged periods. Researchers should also employ volunteer participants to carry or transport dataloggers upon their person during their daily lives to directly measure human-experienced temperatures over 24 h periods (Emery *et al* 2021). The data can be integrated to generate biophysical models of human body temperatures at fine spatiotemporal resolutions throughout the world's major cities without over-reliance on extrapolations. This should be seen as the first step in understanding the true magnitude of the threat posed by extreme heat events in cities worldwide.

Extreme climates in urban areas represents a significant emerging health threat for human populations (UCCRN Technical Report 2018). Generalisable patterns are becoming clear from a variety of cities that this will also interact with socio-economic status (Harlan *et al* 2007, Byrne *et al* 2015, Wong *et al* 2016, Hsu *et al* 2021). People living in less affluent neighbourhoods will have to cope with the combined stresses of global climate change on top of an already more challenging existence. Unless significant action is taken, temperatures prohibitive to human survival could be experienced in Hong Kong within the lifetimes of people alive today, a pattern that is likely reflected in other cities regionally. This will not only lead directly to heat induced mortality, but will severely impact the functioning and economic stability of the region. Climate change has moved from a distant to a proximal threat (NOAA 2022). It is now the responsibility of local governments and other developmental stakeholders to limit the potential damage.

Data availability statements

All data are publicly available from the following sources:

HK Census and Statistics—www.censtatd.gov.hk/en/

Morgan & Guenard HK Climate Models—https://doi.org/10.5194/essd-11-1083-2019

Global Forest Cover—https://doi.org/10.1080/1538947.2013.786146

Future Climate Scenarios—www.worldclim.org/

Human Made Surfaces—https://doi.org/10.7927/H4P55KKF

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